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RAPID RESPONSE OF A SAND-DOMINATED RIVER TO INSTALLATION AND REMOVAL OF A TEMPORARY RUN-OF-THE-RIVER DAM

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ABSTRACT

Run-of-the-river dams (RORDs) comprise the vast majority of dams on river systems and are commonly removed as a part of stream restoration strategies. Although these dams are routinely removed, few studies have documented the geomorphological responses of sand-bed rivers to the removal of RORDs. We examined the response of a large sand-bed river located in South-Central Kansas, USA, to the installation and removal of a dam that is installed annually for seasonal recreational purposes. Channel adjustments were tracked using cross-sections sampled over the course of 7 months as the dam was installed and subsequently removed. Multivariate spatiotemporal analysis revealed emergence of channel stability when the dam was in place for most cross-sections, except for those immediately adjacent to or at great distances from the dam. Our results provide an approximation for how sand-bed rivers respond to RORD construction and removal and are useful for guiding management decisions involving preservation or restoration of connectivity. Results of this study suggest that sand-bed rivers are resilient and recover quickly when transient RORDs are removed. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: dam removal; run-of-the-river dam; fluvial geomorphology; sand-bed river; Great Plains

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INTRODUCTION

Dams have long been recognized as essential contributions to societies that come at a pervasive and detrimental cost to riverscapes (Baxter, 1977). The mid-1900s was a period of significant dam construction in the USA. Given that the average dam life span is 50 years (Doyle *et al*., 2003b), approximately 85% of dams are nearing the end of their lifespan and are in need of maintenance or removal (Evans *et al*., 2000). Run-of-the-river dams (RORDs) represent 97% of dams within the USA (Federal Emergency Management Agency (FEMA) and USA Army Corps of Engineers (USACE), 1996) and pose regulatory challenges because there are few ecological or economic benefits to justify their continued operation beyond their useful lifespan (Vedachalam and Riha, 2013). Dam removal is a common restoration strategy (e.g. Hart *et al*., 2002; Gleick *et al*., 2009), and over 700 dams were removed worldwide in the last 100 years (American Rivers *et al*., 1999; Gleick *et al*., 2009), 57% of which were in the USA (Pohl, 2002). Research regarding hydrologic, hydraulic and geomorphic forms and processes associated with dams are still burgeoning fields and much remains to be learned about channel response to dam construction and removal.

Run-of-the-river dams extend the entire width of a channel, have no structures that exceed the elevation of the bankfull channel and have no mechanism to regulate discharge so that water flows freely over the crest of the structure (Csiki and Rhoads, 2010). The hydrologic effect of RORDs is negligible because there is no flow inhibiting structures; however, they can have dramatic hydraulic and geomorphic impacts. The main effects associated with RORDs are the development of low-velocity pools upstream of the dam (Stanley and Doyle, 2002), which can result in sediment deposition within the impounded area (Friedl and Wuest, 2002; Vanoni, 2006). Downstream of dams, intense scour can occur at the base of structures as the stream reach degrades in order to re-establish sediment load through erosion of bed and bank materials (Bollaert and Schleiss, 2003; Doyle and Harbor, 2003). The river response to RORD removal depends upon the amount of sediment stored behind the impoundment, which can range from negligible to complete infilling (e.g. Wildman and MacBroom, 2005;

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Csiki and Rhoads, 2014). When low volumes of sediment are stored in the upstream impoundment, there is minimal response to the removal of the dam (Skalak *et al.*, 2009; Csiki and Rhoads, 2010, 2014). When large volumes of sediment are stored behind the impoundment, a large pulse of sediment is introduced downstream, and the river responds as if a large dam was removed (Poff and Hart, 2002). To date, studies have documented channel conditions prior to dam removal (e.g. Draut *et al.*, 2011; Brenkman *et al.*, 2012) and post-dam conditions (e.g. Doyle *et al.*, 2003b; Wildman and MacBroom, 2005; Major *et al.*, 2008; Pearson *et al.*, 2011) of large dam removal projects. However, much less is known about pre-dam conditions in general or what the effects of removing a RORD might have on a sand-bed river.

Large rivers in the Great Plains are typically sand-dominated alluvial rivers without confining valley walls (Graf, 2005). Great Plains rivers are especially susceptible to altered hydraulics and sediment regimes associated with dams because of their low entrainment thresholds and weak bank materials (Montgomery and Buffington, 1997). Great Plains rivers are highly fragmented by anthropogenic barriers and Plains states rank amongst those with the most in-stream barriers within the USA (Perkin *et al.*, in press). Large rivers within the Great Plains have a high proportion of the largest reservoirs in the USA (Graf, 2005), and rivers with large dams (>10 m) have dramatically altered flow regimes (Costigan and Daniels, 2012). Large dam structures on Great Plains rivers have resulted in rapid channel narrowing as vegetation encroaches because of lower or absent flood events (Julian *et al.*, 2011). Great Plains rivers with large, regulating dams on them may have up to 91% less standard active area than unregulated rivers in the region (Williams, 1978; Graf, 2006). Given that RORDs are such common features on contemporary Great Plains riverscapes (Perkin *et al.*, in press) and that RORD removal is a growing restoration technique, understanding potential effects of dam removals on Great Plains rivers will help direct conservation action and inform management of sand-bed rivers.

The goal of this work was to document how a sand-dominated river responds to the construction and removal of a RORD. The specific objectives of this study were to document the spatiotemporal extent of changes in channel morphological characteristics that occurred as the result of a RORD installation and removal. We quantify the geomorphic conditions prior to, during and after installation of a temporary RORD on the South Fork Ninnescah River (SFNR) in South-Central Kansas, USA. Our study is unique in that it captures repeated measurements of pre-dam, dammed and post-dam conditions for a sand-bed system. Results advance dam removal science in a region currently lacking such consideration and provide valuable baseline data for how sand-bed rivers in the Great Plains might respond to the construction and removal of RORDs.

MATERIALS AND METHODS

Study site

The Camp Mennoscah Dam (CMD) is located on the SFNR in South-Central Kansas, USA (Figure 1). At CMD, the SFNR drains approximately 1680 km^2 in a low-relief region. The SFNR flows east-southeast through tallgrass prairie within the High Plains physiographic region, which is characterized by 3- to 5-m-thick loess deposits that overlie thick deposits of Pleistocene and/or Pliocene alluvium (Mandel, 2008). The SFNR drains sandy areas, and as a result, the river is wide, shallow and straight with a bed that is continuously moving at most discharges and a bedload that is sand (Costigan *et al.*, 2014).

Mean daily discharge is recorded at a US Geological Survey gage (07145200) located approximately 18 river kilometers downstream of the CMD and has a mean annual discharge of 5.8 m^3/s (minimum discharge = 2.8 m^3/s; maximum = 10.5 m^3/s; 1951–2012) and mean annual flood discharge of 119 m^3/s (minimum discharge = 7.2 m^3/s; maximum = 510 m^3/s; 1951–2012). During the surveying campaigns, the mean discharge was 2.4 m^3/s (minimum = 0.45 m^3/s; maximum = 18 m^3/s; Figure 2). The maximum observed discharge during the surveying campaign was between the pre-dam survey and the first sample following dam installation. During the surveying campaign, the Great Plains was in the midst of a severe 2-year drought (Perkin *et al.*, in press), and flows in the SFNR were generally less than the 95% confidence intervals of flow for the 61 years of recorded discharge (Figure 2). No channel-forming flows occured during the study period. The headwaters of the SFNR are within the High Plains Aquifer, but this region of the aquifer has experienced no significant change in groundwater levels (Sophocleous, 2000).

The CMD is a 1-m-high dam that is installed annually for seasonal recreational purposes associated with Camp Mennoscah (e.g. canoeing and swimming) and is in place from April through October. There are permanent I-beams fixed to the bedrock approximately every meter across the width of the river (Figure 3A and B). Wood planks are placed horizontally between the I-beams and added in layers until the dam is 1 m in height (Figure 3C and D). The dam was installed on 4 April 2012 and was removed on 7 October 2012. Because the dam has been added and removed from the river annually for at least fifty years, we use 'installation' rather than 'construction' to capture its transient nature.

Historical aerial photographs of the SFNR within the proximity of CMD were available between 1956 and 2010. Aerial photographs were georeferenced to a common datum base at 1 : 5000 using GIS software (ESRI, ArcGIS 10.2). Black and white aerial photographs from 1956 (1 : 20 000) and 1963 (1 : 20 000) were acquired by the USDA and

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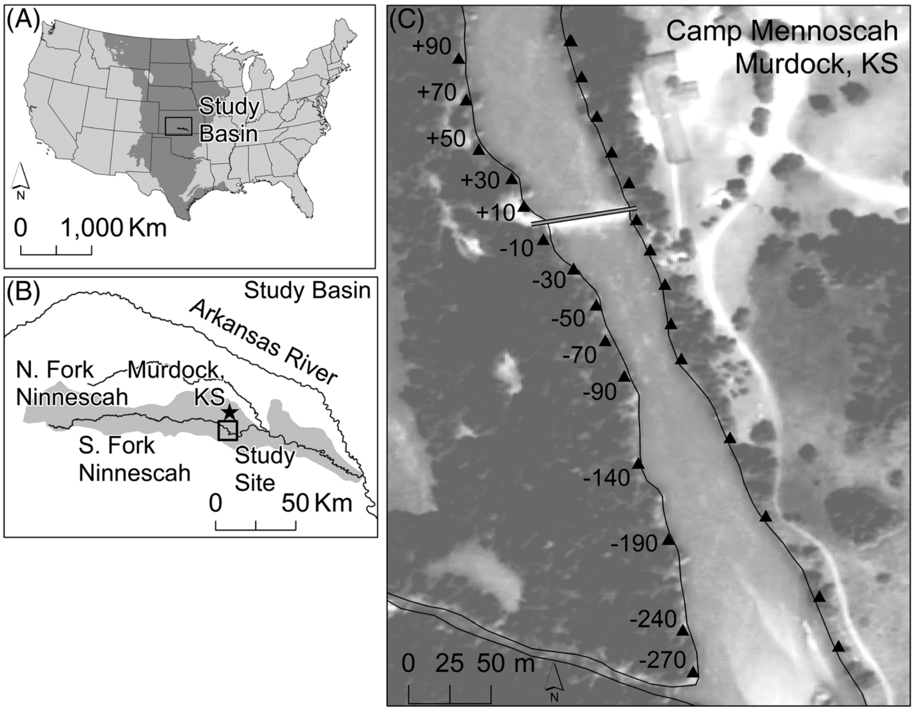

Figure 1. Location of the South Fork Ninnescah River basin within (A) the Great Plains physiographic region and (B) within Kansas and the location of (C) the dam relative to the surveying reach. Positive numbers are cross-sections upstream of the dam. Negative numbers are cross-sections downstream of the dam

obtained from the Kansas Aerial Photography Initiative. Digital orthogonally rectified black and white aerial photographs from 1991 (resolution = 1 m) were acquired from the State of Kansas, and digital aerial photographs from 2010 (resolution = 2 m) from the National Agriculture Imagery Program were obtained from the Kansas Data Access and Support Center. The earliest available images of the SFNR within the proximity of the CMD are from 1956 and show that the I-beams were in the channel at this time (Figure 4). The aerial photographs show there have not been any large changes in the channel morphodynamics (i.e. no avulsions) of the river during this period (Figure 4).

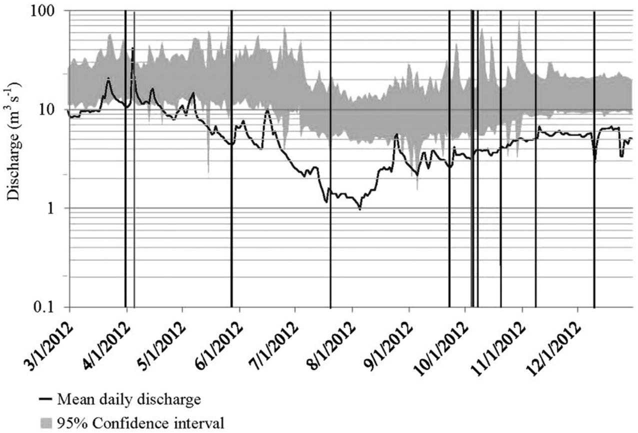

Figure 2. Mean daily discharge of the South Fork Ninnescah River at Murdock, KS, between March 2012 and December 2012. Vertical black lines indicate survey dates, and the vertical grey lines are when the dam was installed (April) and removed (October). The grey area is the 95% confidence intervals of flow for the 61 years of recorded discharge (1951–2012)

Data collection

Ten permanent cross-sections were established prior to CMD installation, on 31 March 2012, to document changes in channel morphology over the course of the dam installation and removal. Five cross-sections were installed in the upstream and downstream direction from the dam. An additional four permanent cross-sections were installed to extend the survey in the downstream section once the dam was installed because of the rapid propagation of downstream changes observed after dam installation. Cross-sections were surveyed during nine field campaigns between 31 March 2012 and 11 December 2012. Cross-sectional endpoints were permanently located where there was a marked break in slope in the floodplain that coincided with an alteration in vegetation from annual to mature perennials. All cross-sections were oriented perpendicular to flow. The distance of each cross-section from CMD was determined in the field. Cross-sections were spaced more densely near the dam where we expected channel changes to be most

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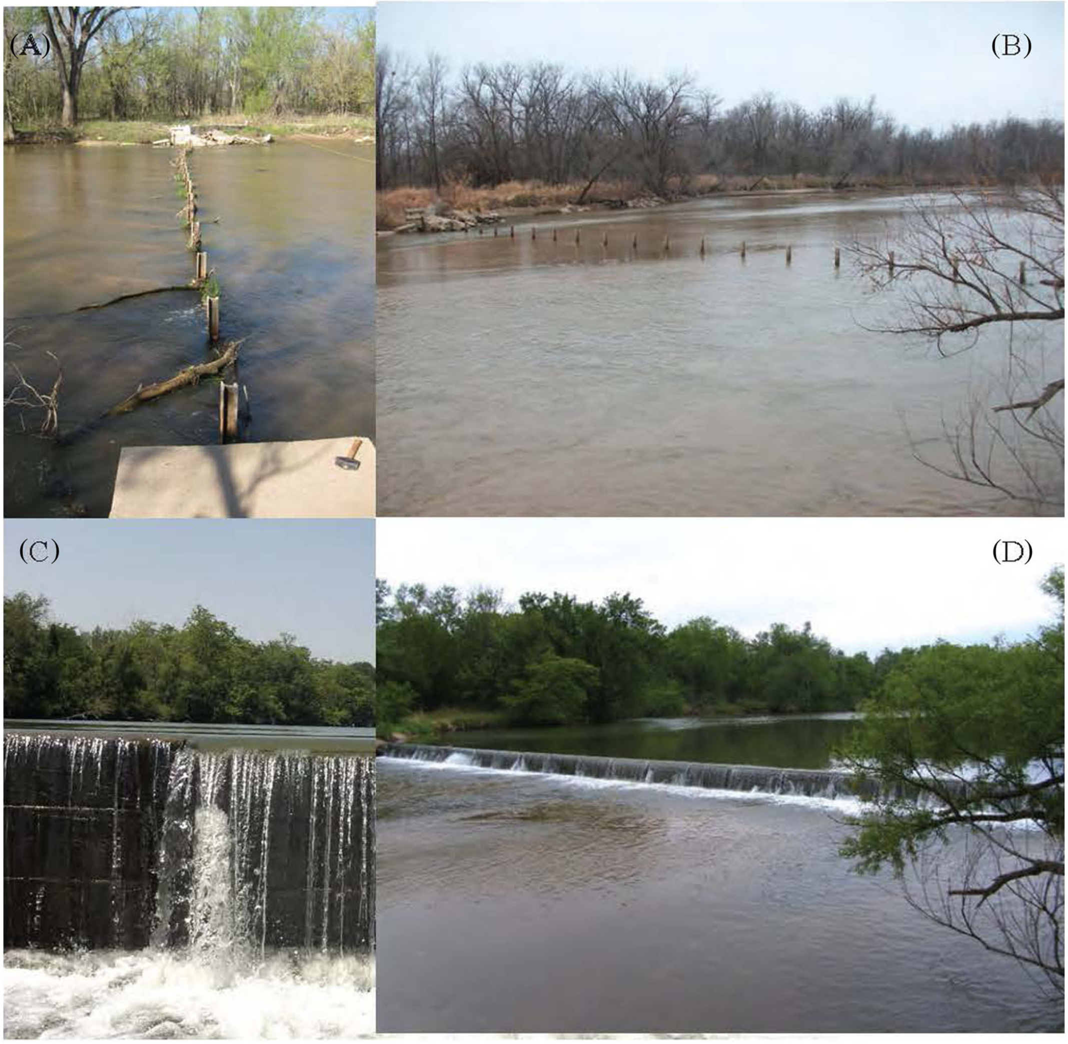

Figure 3. Photographs of the (A and B) permanent I-beams that are in the channel year round that provide foundation for the dam, (C) the installed dam with planks of wood until the dam is 1 m in height and (Cand D) of the dam spanning the entire channel width. Photographs (B) and (D) were taken from the same vantage point. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

pronounced (*sensu* Doyle *et al*., 2003a). All cross-sections are referred to by their distance relative to the dam where upstream cross-sections are designated as positive and downstream distances are designated as negative. Channel change was measured every 60 cm or where there were abrupt slope breaks to document changes in morphology. Elevations were estimated to the nearest 1 mm.

The geomorphic metrics used were mean cross-sectional depth (m), cross-sectional area (m^2), cross-sectional width to depth ratio (W:D), channel braiding (the number of threads), roughness (standard deviation of all depth measurements), coefficient of variation (standard deviation/mean of all depth measurements) and the per cent of the channel that comprised exposed sandbars. Cross-sectional depth is the height of the bed relative to a cross-sectional specific datum.

We visually identified substrate (e.g. sand or bedrock) at each survey point. Bedforms were categorized into units of bedrock, submerged sand lobes and exposed sand bars. Bedforms were mapped in the field using a Trimble Juno GPS unit (post-processing error 1–3 m) during each campaign. Although visual mapping of bedforms provides only qualitative characteristics of bedforms, we believe it still provides valuable information about the response of the bed to installation and subsequent removal of the CMD.

Data analysis

A combination of principal component analysis (PCA), multivariate analysis of variance (MANOVA) and analysis of covariance (ANCOVA) were used to determine

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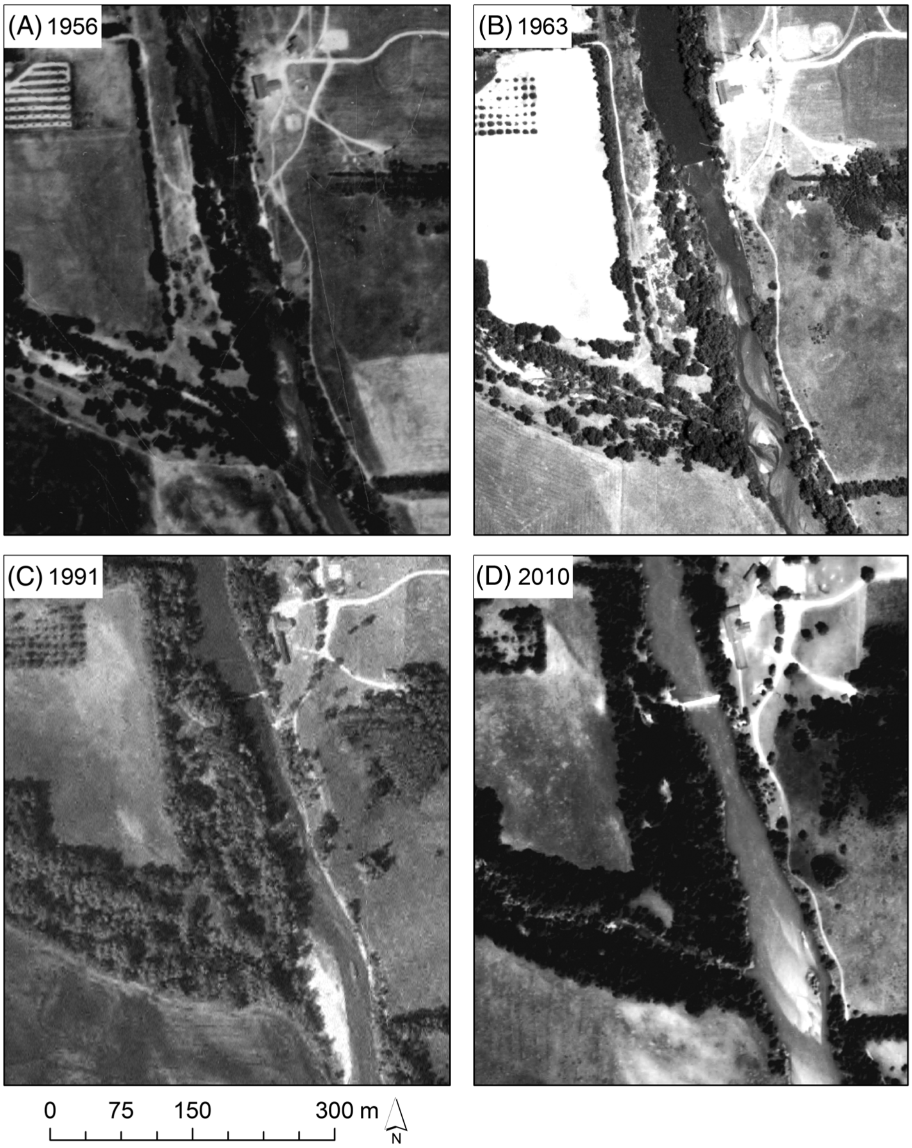

Figure 4. Aerial photographs of the South Fork Ninnescah River at Camp Mennoscah Dam between 1956 and 2010

significant trends associated with the installation and removal of the dam. PCA was used to identify and evaluate gradients in observed channel conditions during the period of observation. Kaiser–Guttman criteria and a broken stick model were used to evaluate the PC scores. The significance of variable loadings on each PC was determined using a loading threshold of 0.50 (Afifi *et al*., 2004). A permutational MANOVA was used to test the effects of the dam on channel morphology over time and along the study reach. We used time since dam installation (pre-dam, during and post-dam), relative location to dam (upstream and downstream) and cross-section location (+/− distance from the dam) as independent variables, and the geomorphic metrics extracted from the cross-sectional profile were the response variables (using Euclidean distances for the associate distance matrix; excluding redundant variables). Redundancy analysis and ANOVA were used to evaluate the fit of the MANOVA model. ANCOVA was used to test for differences between cross-sections whilst accounting for main effects of treatment variables. Variables were tested for normality using the Shapiro–Wilk test prior to the ANCOVA, and those violating the assumption were transformed. Time since dam installation, relative location and cross-section location were used as treatment variables. All statistical analyses were performed in R (v 2.15.2; R Core Team, 2012) using the Vegan package (Oksanen *et al*., 2013).

RESULTS

Bedform morphology changes

Prior to the installation of CMD, the SFNR was characterized by numerous submerged in-channel sand lobes, no exposed bedrock and no exposed mid-channel sand bars (Figure 5). Once the CMD was installed, all bedforms upstream of the dam were eliminated, bedrock was exposed immediately downstream of the dam and numerous exposed mid-channel sand bars developed downstream of the dam (Figure 6). The longer the dam was in place, the larger the spatial extent of the exposed bedrock became. As the exposed bedrock grew, sand bars that developed in the lower extent of the reach increased in area. Once the CMD was removed, there was an immediate flushing of sediment from the upstream section, which resulted in burial of exposed

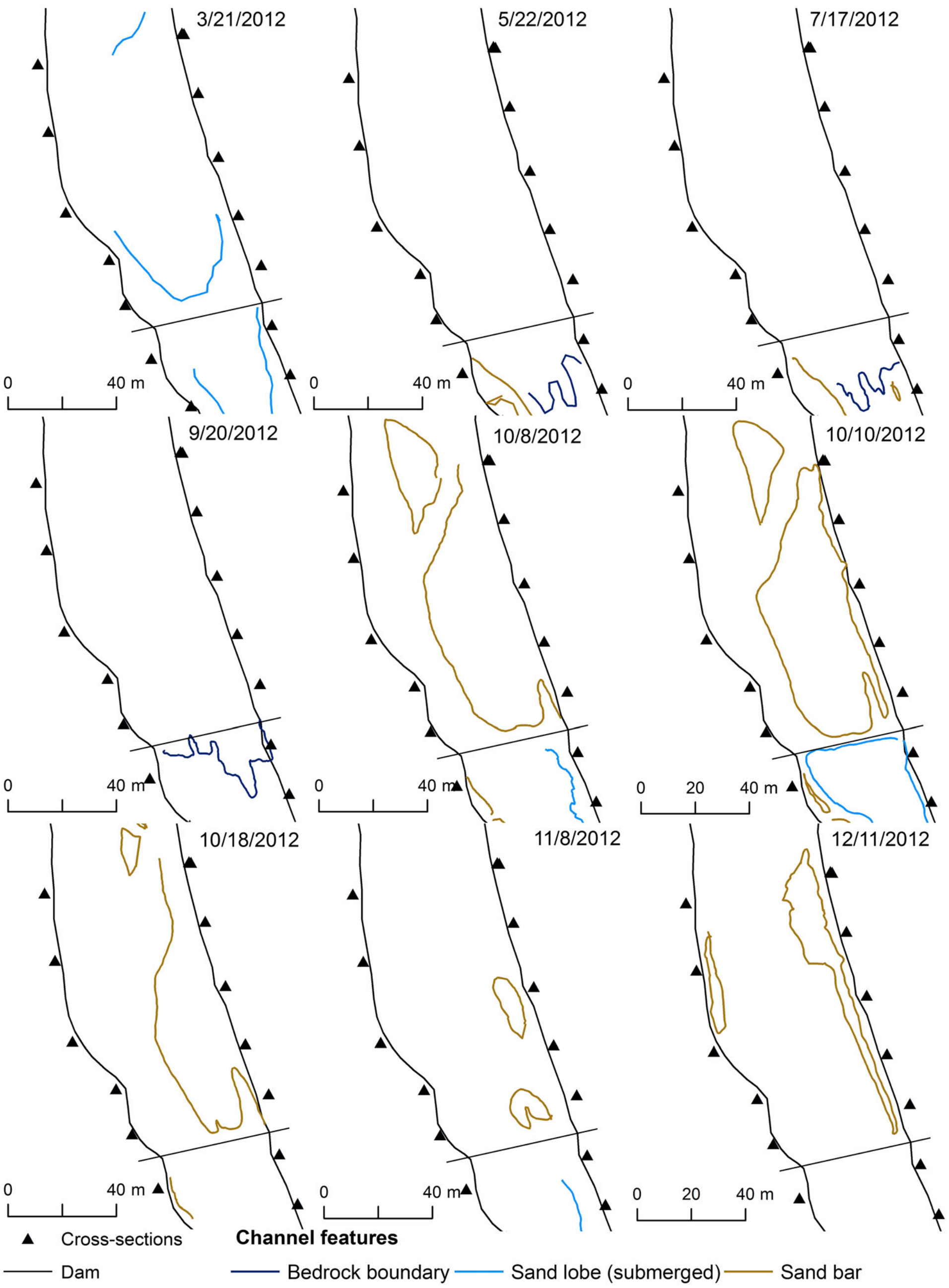

Figure 5. Bedform morphology changes of the upstream section South Fork Ninnescah River for the surveying period. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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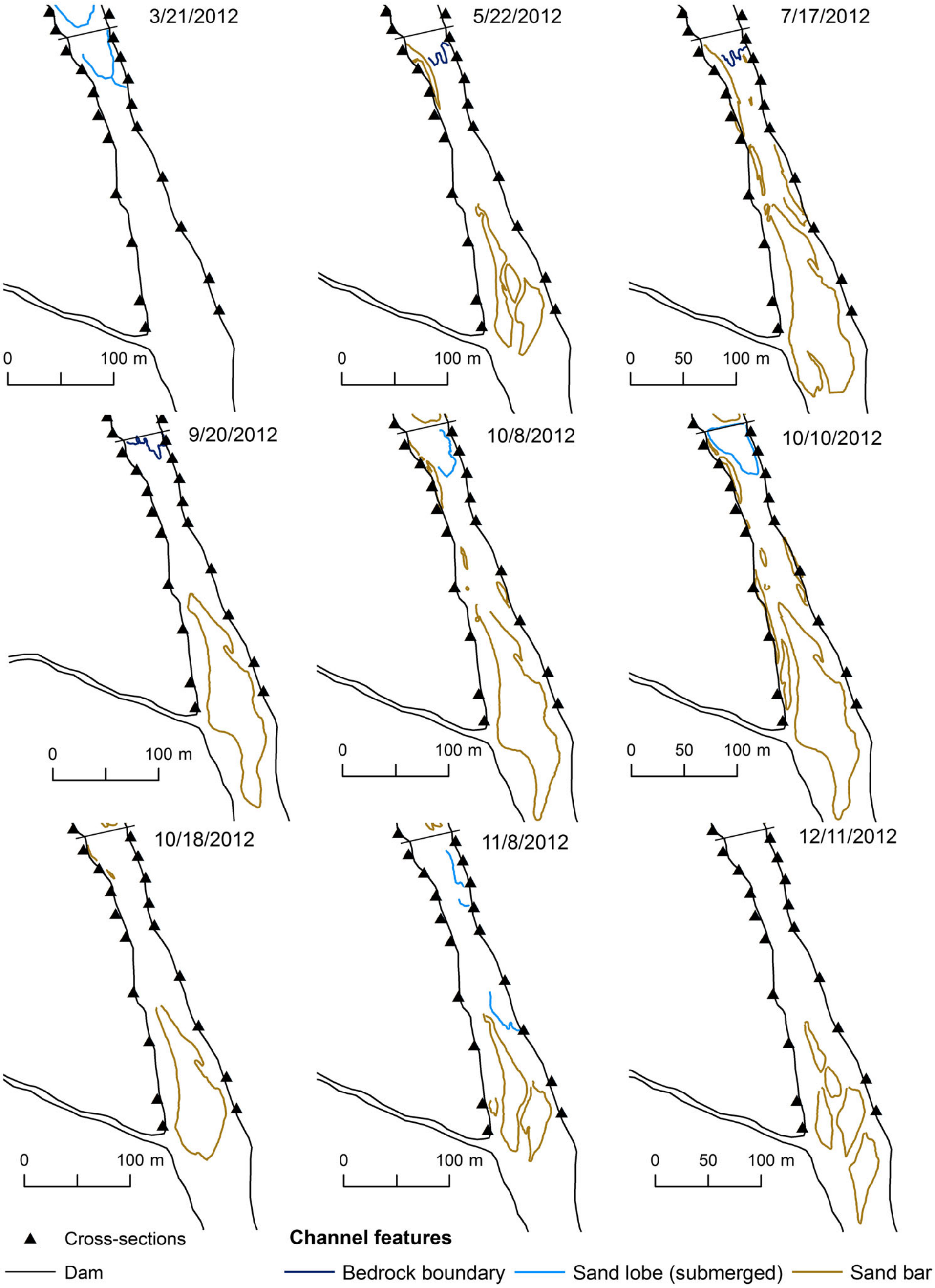

Figure 6. Bedform morphology changes of the downstream section the South Fork Ninnescah River for the surveying period. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

bedrock and formation of large sand bars in the lower sections of the reach. In the upstream section of the study reach, there were large sand bars that became exposed after dam removal. These sand bars diminished in size through time after the CMD was removed and were nearly eliminated by the end of surveying. Immediately after the dam was removed, submerged in-channel lobes developed throughout the reach.

Cross-sectional topography

Upstream reach. Channel profiles of the upstream portion of the survey reach demonstrated that the cross-section closest to the dam (+10 m) was relatively narrow, and the river became wider to until +50 m and then began to narrow again in the upstream direction (Figure 7). The topographic cross-sections of the pre-dam conditions

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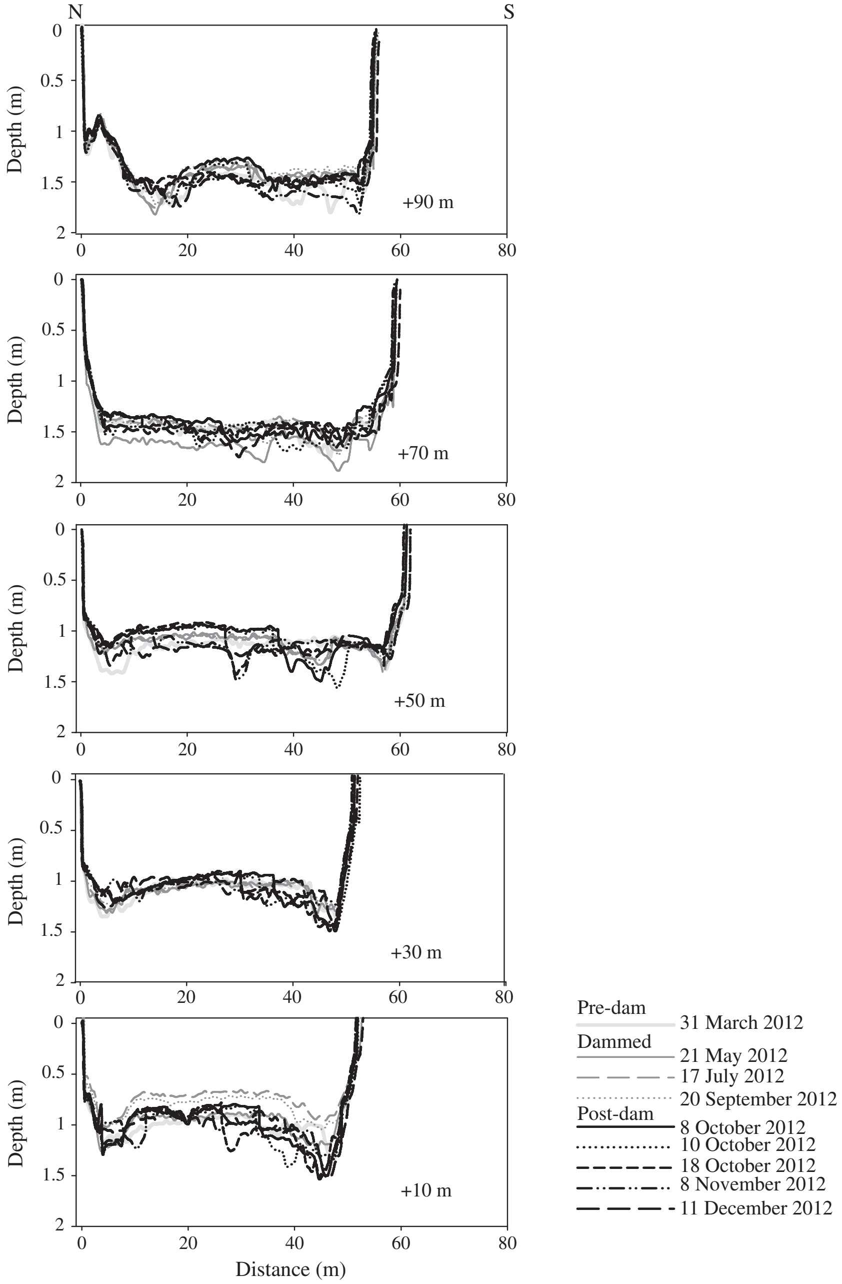

Figure 7. Channel cross-sectional profiles for the upstream reach where the left is the North bank and the right is the South bank of the South Fork Ninnescah River. Cross-sections are numbered where +10 is the first cross-section approached moving upstream and +90 is the furthest upstream from the dam and the upper end of the surveying reach

showed irregular topographic profiles with the greatest magnitude of topographic variation occurring at +10 m. At +50 m, there was a thread close to the left bank during the pre-dam survey that completely filled-in in response to the installation of the dam. At +10 m, between the pre-dam conditions and when the last topographic survey prior to dam removal (20 September) was conducted, the bed aggraded by 21 cm. The most change between sequential sampling campaigns occurred at +10 m between 21 May and 17 July, when the bed aggraded by 27 cm. The second largest change in mean cross-sectional depth occurred at +10 m as a result of the removal of the dam. In general,

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there was a negative relationship between upstream distance from the dam and immediate change in the mean cross-sectional channel depth following installation of the dam. At +90 m, there was some aggradation of the bed, but this was not as much as the cross-sections closer to the dam.

In response to the removal of the dam, the +10 m cross-section showed rapid degradation of the bed to a level lower than pre-dam conditions (Figure 7). For the surveying campaign immediately after the dam was removed, the thalweg along the right bank at +10 m cut 10 cm lower than the pre-dam conditions. Similar to the responses to dam installation, the cross-sectional profiles closer to the dam were consistently more dynamic than those further away from the dam following removal. At cross-section +50 m, the formation of a new thread in the middle of the cross-section shifted more to the middle of the channel with increasing time since dam removal. The thalweg that was present on the left bank at +50 m in the pre-dam conditions was not degraded to the same level following dam removal. At +90 m, there was readjustment of sediment within the cross-sectional profile so that the thalweg shifted and the bed degraded in areas other than where sediment was deposited when the dam was installed. By the end of the surveying campaign, the mean of the cross-sectional channel depths had reached pre-dammed conditions, and cross-sections became stable.

Downstream reach. Initial channel topographical surveys of the downstream reach indicated that the cross-sections narrowed in the downstream direction, away from the dam. In particular, at −90 m, the channel was narrowest (30 m), but the channel began to rapidly expand where it reached its widest (72 m) at −270 m from the dam (Figure 8). The pre-dam conditions demonstrated dynamic bedforms with irregular profiles at cross-sections −10 to −90 m. Cross-sections −140 through −270 m were added after the dam was installed.

In response to the installation of the dam, −10 to −90 m showed rapid degradation. The cross-sections closest to the dam degraded to bedrock, which was on average 40 cm below pre-dam conditions at −10 m. Although −90 m was the narrowest cross-sectional profile, the profile degraded only 21 cm on average as a response to the installation of the dam. There was rapid aggradation of the bed throughout the surveyed reach once the dam was removed. The dam was removed on 7 October, and on 8 October, the bed at −10 m aggregated on average 27 cm relative to the 20 September surveying campaign. On 10 October, the −10 m cross-section had aggregated on average an additional 4 cm, and then 8 days later on 18 October, the bed aggregated on average an additional 9 cm. The cross-sections near the end of the surveying reach did not have pre-dam conditions, but the repeat measurements of these profiles also demonstrated that the bed was still responsive to the installation and removal of the dam at the end of the surveying reach. At −270 m, the thalweg was very dynamic, moving about the cross-section, and followed a similar pattern to the cross-sections that were closer to the dam. The furthest downstream cross-sections returned to pre-dam cross-sectional channel depths rapidly after the removal of CMD. The cross-sections close to the dam also returned to pre-dam mean cross-sectional channel depth rapidly once the dam was removed.

Cross-sectional geomorphic variables

The results of the PCA of the geomorphic variables for all cross-sections indicated that the first two PC axes explained 65% of the variance in the data (Figure 9A, Table I). PC1 explained 38% of the variance in morphologic characteristics and represented a gradient from greater mean depth, reduced W:D, less braiding and fewer sand bars (i.e. a confined channel) to greater W:D, increased braiding and a greater per cent area of sand bar (i.e. an open channel). PC2 explained 27% of the variation and represented an upstream to downstream gradient in channel area with smaller areas and consistent depths (i.e. upstream cross-sections) to larger areas and variable depths (i.e. downstream cross-sections).

Temporal variability across all surveying campaigns was overlaid on the spatial patterns to assess spatiotemporal effects of the dam. Amongst cross-sections in close proximity to the dam (+/−10 m, +/−30 m), installation of the dam caused channel adjustments in opposing directions for upstream and downstream cross-sections (Figure 9B and C). With increased distance from the dam, channel adjustments in upstream and downstream locations converged in directionality when the dam was in place, specifically in the direction of a confined, homogeneous channel (i.e. negatively along PC1; Figure 9D and E). Amongst cross-sections located furthest away from the dam (+/−90 m), responses differed, specifically smaller channel area and homogeneous depths upstream and increased channel confinement or negative movement along PC1 downstream when the dam was in place (Figure 9F). As downstream distance from the dam increased, the channel became progressively more open, and the effects of the dam were less obvious (Figure 9G). The PCA bi-plots also revealed emergence of channel stability for portions of the channel when the dam was in place. Sampling points between 30 and 90 m of the dam indicated tighter clustering in multivariate space when the dam was in place, despite these measurements being taken 2–3 months apart (Figure 9C–F). For samples in close proximity to the dam (10 m), points were highly variable (broadly separated in multivariate space) when the dam was in place (Figure 9B).

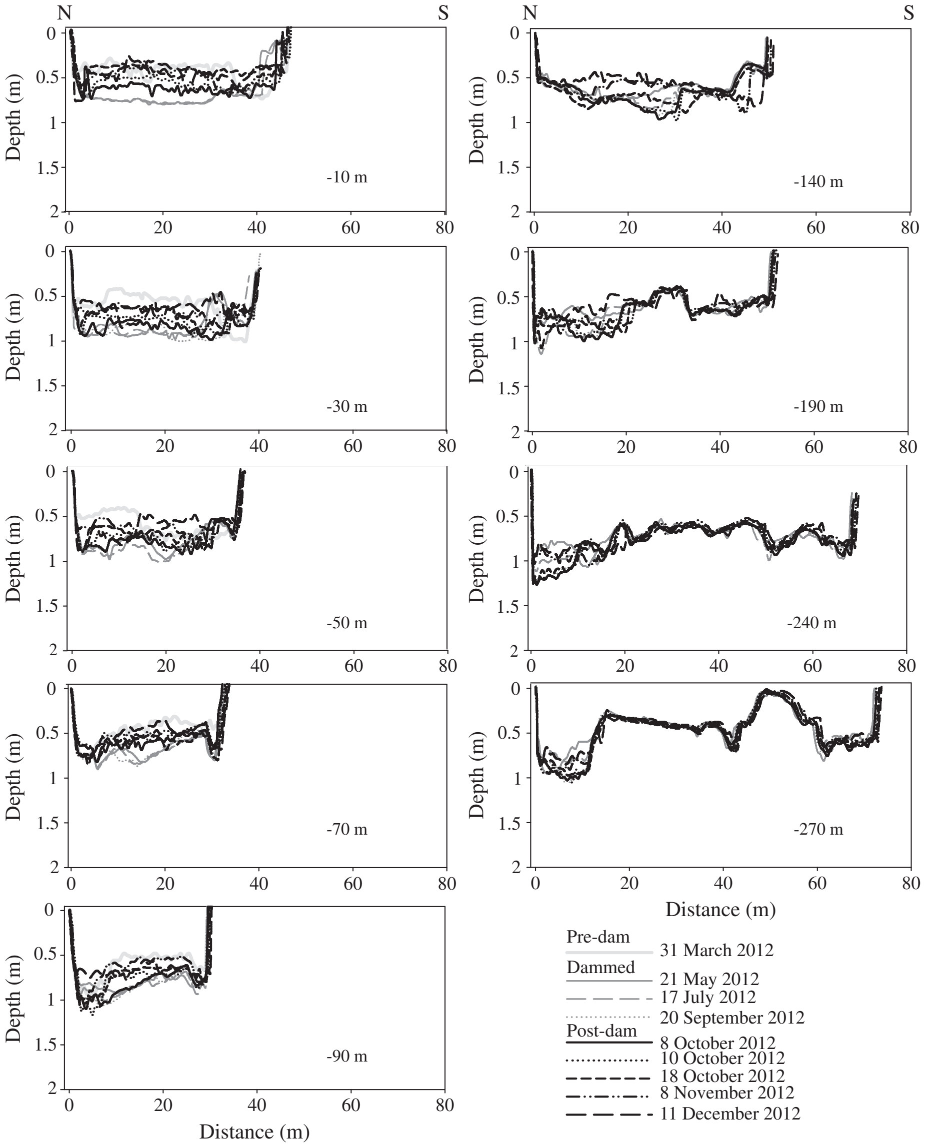

Figure 8. Channel cross-sectional profiles for the downstream reach where the left is the North bank and the right is the South bank of the South Fork Ninnescah River. Cross-sections are numbered where −10 is the first cross-section approached moving upstream and −270 is the furthest upstream from the dam and the lower end of the surveying reach

The results of the MANOVA (Table II) indicated that channel morphology along the study reach and throughout the study period was influenced by the installation and removal of the dam. However, morphological differences were more strongly explained by cross-section location (i.e. upstream versus downstream) and position (i.e. distance from dam). Time since dam installation explained only 0.1% of the total variation in the dataset. When time since dam installation was used as an interaction term with relative position, it was much more significant but still only explained a very small portion of the variance ($R^2 = 0.06$).

The ANCOVA indicated that variation in morphology within each cross-section for the study period was nonsignificant. Variations in area, roughness and W:D associated with both position relative to the dam as well within each cross-section did not change over the study period, although pre-dam conditions suggested slightly larger channel areas and slightly lower width to depth ratios. The range in roughness values remained relatively consistent.

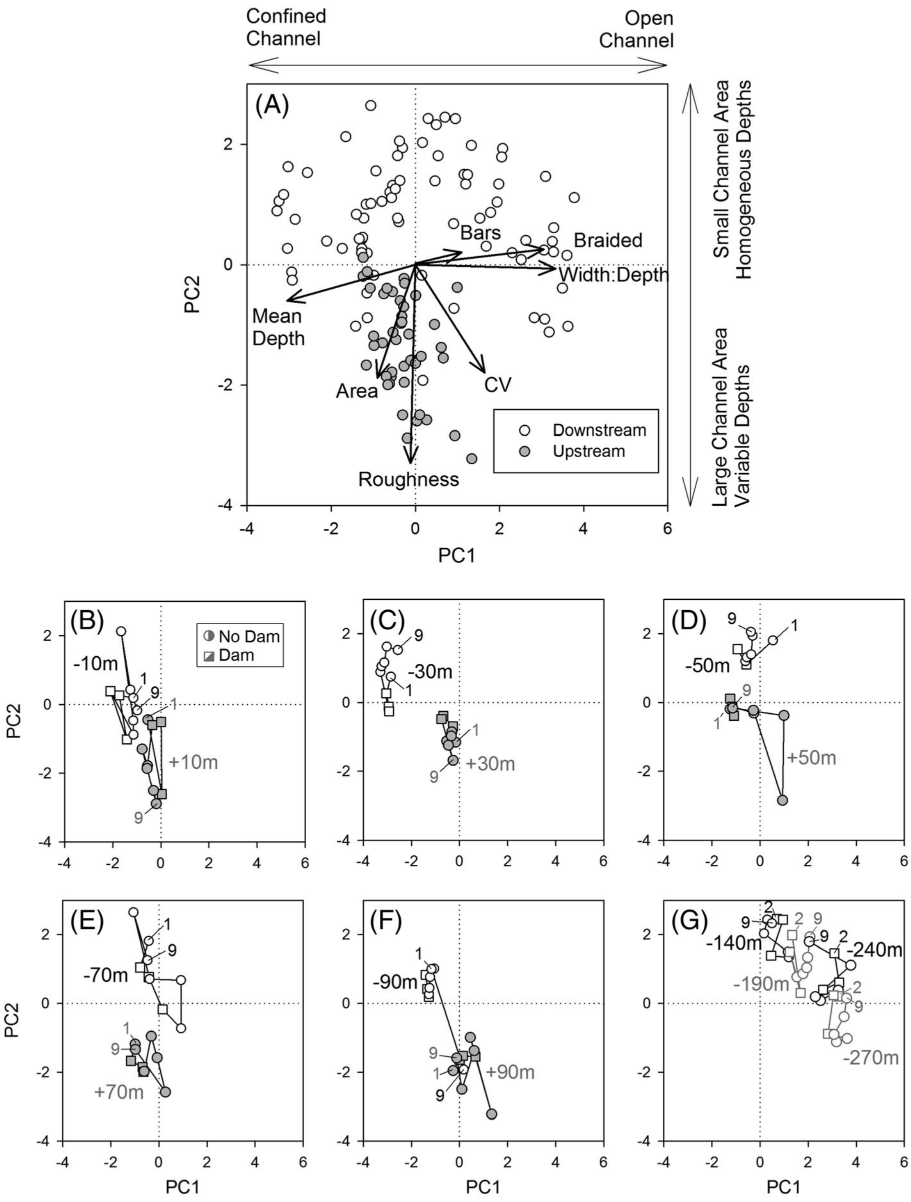

Figure 9. Principal component analysis for the first two axes of (A) geomorphic variables and the spatiotemporal effects of the dams for all surveying campaigns for (B) +/−10 m, (C) +/−30 m, (D) +/−50 m, (E) +/−70 m, (F) +/−90 m and (G) −140 m, −190 m, −240 m and −290 m

DISCUSSION

Our results demonstrate rapid response in the bedform morphology and cross-sectional profiles of the SFNR as a result of the installation and removal of a transient RORD. Prior to the installation of the dam, the river was characterized by numerous submerged sand lobes and the bed was comprised of only sand. When the dam was installed, there were no longer any submerged sand lobes and instead multiple exposed sand bars formed throughout the downstream portion of the study reach. Immediately downstream of the dam and following installation, sediment was removed, exposing bedrock. Once the dam was removed, there was rapid movement of the bed materials from the upstream impounded area that resulted in the bedrock becoming completely covered and exposed sand bars emerging throughout the sampling reach the following day. The upstream portion of the reach showed aggradation of the bed with the dam in place and degradation of the bed when the dam was removed; the opposite pattern occurred in the downstream reach. Spatiotemporal analysis suggested the emergence of channel stability when the dam was in place except for cross-sections immediately adjacent to the dam.

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Table I. Principal component (PC) loadings and explained variance for the first two components for geomorphic variables extracted from cross-sectional profiles

	PC1	PC2
Area	−0.08	−0.45
W:D	**0.55**	−0.01
Roughness	−0.01	**−0.69**
Braided	0.49	0.04
CV	0.36	**−0.51**
Sandbars	0.21	0.01
Mean depth	**−0.53**	−0.23
Standard deviation	1.64	1.38
Proportion of variance (%)	38.4	27.0
Total variance explained (%)	38.4	65.4

CV, coefficient of variation.
Variables loading significantly on a PC axis are shown in bold.

Results of our study demonstrated rapid channel erosion immediately downstream of the dam and negligible dam effects near the border of the study reach. Our findings are consistent with other studies of dam removals that demonstrate the most geomorphic change to the channel occurs close to the dam (Doyle *et al*., 2003a; Draut *et al*., 2011; Cannatelli and Curran, 2012). In their study of several RORDs in the Midwestern USA, Csiki and Rhoads (2014) found evidence for only one of their study sites producing substantial downstream channel erosion that was attributed to a scour zone that developed well downstream from the 3-m-high dam. Csiki and Rhoads (2014) suggested increased depths in the downstream reached was due to minimal and temporary storage of sediment in the impounded area that was able to pass over the dam during high flow conditions and to the non-existent scour zone. Skalak *et al*. (2009) found that RORDs had no measureable effect on the amount of bedrock exposed on the streambed in channels characterized with coarser sediment found in those streams compared with those found in the SFNR. Skalak *et al*. (2009) noted that the dams of their study did increase mean grain-size downstream of the dam. Even Great Plains rivers with large impoundment structures maintain much of their bedform complexities (Graf, 2006). Great Plains rivers with large dams on them that have broad alluvial valleys with high sediment loads are able to maintain channel complexity that is only 14% less than unregulated rivers in the region (Graf, 2006). Although bank materials along the SFNR are sandy, they are also mantled by vegetation, likely making incision the most efficient mechanism to equilibrate the sediment load in the downstream portions of the river. Our findings suggest that bed material grain size, as it relates to entrainment thresholds and bank cohesion, represents a critical control on system response to RORD removal, which had been previously shown as a critical control on a system to construction of a large (>10 m) impoundment structure (Graf, 2006).

Table II. Results of the MANOVA model comparing the main effects of the dam time period, cross-section location and position above or below dam

	Ndf, Ddf	*F*	R^2	*p*-value
Time	2, 83	3.383	0.0096	0.015*
Location	1, 83	111.350	0.1573	0.000***
Position	12, 83	37.713	0.6393	0.000***
Time × location	2, 83	2.709	0.007	0.031*
Time × position	20, 83	2.438	0.069	0.000***

The Ndf and Ddf are the numbers of degrees of freedom in the numerator and denominator, respectively, for calculating the *F* statistic.
***$p \leq 0.001$.
*$p \leq 0.05$.

The response of the SFNR was similar to the findings of Doyle *et al*. (2003a), who found the channel morphology immediately following dam removal was very close to the pre-dam channel with few bank adjustments. According to the spatiotemporal PCA, many of the cross-sections returned to their pre-dam condition by the completion of the field campaign (i.e. less than 7 months). Similar to the findings of this study, Doyle *et al*. (2003a) found that channel evolution was rapid, and the upstream reach degraded immediately following removal of the dam, likely attributable to unconsolidated fine sediment that comprise the reservoir and channel sediment. Rates of change at the SFNR were much more rapid relative to another recent case study of a dam removal on a river with a sand-filled impoundment. Pearson *et al*. (2011) document the channel response to the removal of Merrimack Village Dam, a 4-m-high dam, which took place over several weeks on the Souhegan River in New Hampshire, USA. The varying heights of the dams and consequently differing amount of sediment stored within the impoundments likely explain the large differences in the time for the river to process out all of the sediment. The CMD is much shorter (1 m versus 4 m), more transient (installed and removed annually versus removed after 100 years), removed faster (a few hours versus two phases over a few weeks) and has a bed composed of finer materials when compared with the dam studied by Pearson *et al*. (2011).

Theoretical models suggest that streams may take decades to return to a stable state with respect to sediment budgets (Hart *et al*., 2002; Pizzuto, 2002). Pizzuto (2002) hypothesized that sand-bed impounded streams are process driven, wherein erosion is dependent on the mechanism of incision rather than high flow events (i.e. event driven). Pearson *et al*. (2011) found that their system with a sand-filled impoundment responded to both process-driven and event-driven systems so that the channel evolved substantially faster than the timeframe proposed by Pizzuto (2002). Even

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in the midst of a severe drought where no channel-forming discharged occurred, the SFNR responded much more rapidly to the CMD installation and removal than expected when compared with theories that were developed for systems with larger grain sizes or those that have cohesive sediment. The SFNR is characterized with high volumes of sediment continuously being introduced, the small grain sizes and unconsolidated sediment that comprise the bed. If the dam had stayed in place until the reservoir completely filled with sediment, then it is likely that the SFNR would respond in a similar manner with previous findings of coarser bed river. Given more time for sediment to deposit and accumulate, it is likely that sediment within the reservoir would have begun to consolidate and would be more resistant to erosion than the unconsolidated sediment that filled the reservoir of the current study.

Our findings suggest removal of RORDs in sand-bed rivers might lead to rapid restoration of approximate natural channel conditions. Our results demonstrated that the SFNR maintained channel complexity even when the dam when in place, which has been shown for Great Plains rivers that have had large dams on them for many decades (Graf, 2006). The CMD has been installed and removed for several years (i.e. at least since 1956), and as such, we do not have a true pre-dam approximation. Although our measurements only represent short-term conditions, we believe that the SFNR had achieved channel stability when the dam was put in place. This conclusion is supported by our observations of rapid return of pre-dam conditions following removal of the RORD. Because RORDs are so common in the Great Plains and are often targeted for stream restoration and pre-dam conditions are lacking for many systems, the results of this study may be considered as an approximation for how the morphology of sand-bed rivers respond to the removal of RORDs.

Our findings suggest that the sand-bed rivers can return to pre-dam conditions rapidly. In the context of stream fishes, return of previously altered habitats to more natural conditions within a single reproductive season suggests dam removals are likely to benefit fish communities that are negatively affected by barriers such as RORDs over very short periods (Perkin *et al.*, in press). Given that RORDs compromise habitat connectivity for short-lived species in particular, our findings suggest the rapid responses in channel morphology following dam removal might be highly beneficial to some of the most imperilled fishes in the Great Plains (Perkin and Gido, 2011). This point is of particular relevance considering recent calls for the removal or mitigation of small barriers throughout the central Great Plains (Perkin *et al.*, in press).

Within the USA, it is expected that the Great Plains will be the first to experience severe hydrologic changes because of global climate change (Milly *et al.*, 2005). Predictions of streamflow based on climate change models of the region suggests that surface water resources may prove to be unsustainable in the Great Plains (Brikowski, 2008). It is likely that many of the reservoirs in Kansas, USA, may fail as soon as 2026 (Brikowski, 2008). In order to mitigate the potential hazards associated with dam failure, removal or other remediation practices must occur (e.g. tighter regulation of groundwater extraction, Steward *et al.*, 2013). This study provides valuable baseline data for the response time of sand-bed rivers to RORD removal and suggests that rapid responses to dam removal represent substantial recovery potential in terms of re-establishing natural sediment distributions. These findings support previous conclusions that suggest even rivers with considerable damage caused by anthropogenic alterations are capable of recovery (Allan and Flecker, 1993).

CONCLUSIONS

Our study documents channel responses to the installation and removal of a RORD by a large sand-bed river. RORDs such as the one considered here are the most commonly removed dam types and will be a priority for dam removal and stream restoration practices for the foreseeable future. Although the scale of our study is relatively fine (in terms of spatiotemporal extent), we believe our results provide an approximation for how sand-bed rivers might respond to dam construction and removal. Dam installation caused rapid sediment deposition upstream and equally rapid sediment erosion downstream, but dam removal reversed these processes and the river re-adjusted to channel conditions representative of the pre-dam period. Spatiotemporal analysis demonstrated the emergence of channel stability when the dam was in place, except immediately adjacent to and at great distances downstream from the dam. Even small barriers such as RORDs are capable of disrupting geomorphic processes and consequently habitat heterogeneity of sand-bed rivers. Our findings suggest that sand-bed rivers characterized by abundant sediment loads are capable of rapid recovery of sediment distributions once RORDs are removed.

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