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Beaver dam analogue configurations influence stream and riparian water table dynamics of a degraded spring-fed creek in the Canadian Rockies

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ABSTRACT

Beaver dam analogues (BDAs) are intended to simulate natural beaver dam ecohydrological functions including modifying stream hydrology and enhancing stream-riparian hydrological connectivity. River restoration practitioners are proactively deploying BDAs in thousands of degraded streams. How various BDAs or their configurations impact stream hydrology and the riparian water table remains poorly understood. We investigated three types of BDA configurations (single, double and triple) in a spring-fed Canadian Rocky Mountain stream over three study seasons (April-October; 2017-2019). All three BDA configurations significantly elevated the upstream stage. The deepest pools occurred upstream of the triple-configuration BDAs (0.46 m) and the shallowest pools occurred upstream of the single-configuration (0.36 m). Further, the single-BDA configuration lowered stream stage and flow peaks below it but raised low flows. The double-BDA configuration modulated flow peaks but had little influence on low flows. Unexpectedly, higher flow peaks and low flows were recorded below the triple-BDA configuration, owing to groundwater seep. Similar to the natural beaver dam function, we observed an immediate water table rise in the riparian area after installation of the BDAs. The water table rise was greatest 2 m from the stream (0.14 m) and diminished with increasing lateral distance from the stream. Also noted was a reversal in the direction of flow between the stream and riparian area after BDA installation. Future research should further explore the dynamics of stream-riparian hydrological connections under various BDA configurations and spacings, with the goal of identifying best practices for simulating the ecohydrological functions of natural beaver dams.

KEYWORDS

Castor canadensis, beaver dam analogues, BDA, ecohydrology, mountain creek, riparian area, stream

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Stream and riparian water table responses to beaver dam analogues

1 INTRODUCTION

A formidable challenge in restoring degraded streams is re-establishing stream-riparian area connectivity. Streams in drought-prone areas often become incised and subsequently disconnected from riparian areas after beavers (*Castor canadensis*) are removed (Pollock et al., 2014). Anecdotal and modelling evidences suggest that the return of beavers improves the two-way flow of water and sediments between streams and riparian areas (Stout, Majerova & Neilson, 2017), and regulates the processes critical in restoring wetland conditions (Fairfax & Small, 2018; Pilliod et al., 2018). However, there may be asymmetry in the effects of key species removal and restoration owing to unexpected feedbacks that reinforce the effects of the species loss (Marshall, Hobbs & Cooper, 2013). While it is ultimately up to the beavers whether they want to recolonize degraded streams and associated riparian areas (Dewas et al., 2012), there is tremendous potential for restoring these streams using alternate, process-based restoration strategies such as restoring beavers to streams (Johnson et al., 2020).

Many stream restoration practitioners are already partnering with beaver. This is because of the growing recognition of how beavers engineer channel spanning dams and their effects on river corridors (Harvey & Gooseff, 2015). Beaver dams increase hyporheic exchange and ponding (Janzen & Westbrook, 2011), decrease stream velocity (e.g., Stout et al., 2017) and increase aggradation (e.g., Butler & Malanson, 2005; Pollock, Beechie & Jordan, 2007). Additionally, beaver dams develop backwater impoundments (Stout et al., 2017) that indirectly control the health and biodiversity of riparian areas and ensure relatively consistent streamflow year-round (Pollock et al., 2014; Puttock et al., 2017; Westbrook, Cooper & Baker, 2011). Multiple beaver dams in sequence may have stronger control over the ecohydrologic and geomorphic processes regulating streams and riparian areas than a single dam (Polvi & Wohl, 2012). As a result, beavers are keystone species progressively acknowledged for exerting disproportionately large hydrogeomorphic and ecohydrological effects on the watershed-scale environment compared with their abundance (Puttock et al., 2017; Rosell, Bozser, Collen & Parker, 2005). The current influence of beavers on mountain streams is however greatly reduced compared to that prior to the European fur trade (Persico & Meyer, 2013).

In the absence of natural beaver recolonization, dam structures intended to mimic the form and function of beaver dams, called beaver dam analogues (BDAs) are used for restoring degraded streams. BDAs are low tech and inexpensive, constructed to be permeable instream structures made up of branches, mud and rock (Pilliod et al., 2018; Pollock et al., 2018; Scamardo & Wohl, 2020). There are three generic BDA designs that differ in structure, materials and desired outcomes (Pollock, Wheaton, Bouwes & Jordan, 2011; Pollock et al., 2018), sometimes referred to as standard BDAs (Scamardo & Wohl, 2020). The types are, 1) starter dams – vertical posts with willow woven between the posts (wicker weave) and fill material (e.g., cobble, vegetation, and mud) placed upstream, 2) post lines and wicker weave – just post lines with wicker weaves, which are highly permeable, and 3) reinforced existing or abandoned natural beaver dams which involves simply reinforce existing or abandoned natural structures using vertical posts. Recently, Scamardo and Wohl (2020) installed two types of BDA: 1) traditional post and willow BDAs (Pollock et al., 2018) made up of few large wood posts (diameter >0.10 m) inserted in the stream bed with thinner branches woven between posts and staked on the downstream end of BDA, and 2) non-traditional wood-jam BDAs built of large logs partially buried in the banks across the bed and perpendicular to flow. These BDAs were also individually dispersed structures.

BDAs have been deployed in thousands of degraded streams (Lautz et al., 2019). Similar to natural beaver dams, BDAs aggrade the channel and stream bed (Scamardo & Wohl, 2020) and thus raise water tables in the riparian area (Briggs, Lautz, Hare & González-Pinzón, 2013; Feiner & Lowry, 2015; Karran, Westbrook & Bedard-Haughn, 2018). A higher riparian water table helps to support healthy riparian plant communities (Dittbrenner et al., 2018; Silverman et al., 2019; Westbrook, Cooper & Baker, 2006) while slowing of stream water helps moderate stream temperatures (Majerova et al., 2015; Weber et al., 2017). BDAs are not intended to be long-term infrastructures. Rather, they are intended to be short-lived and initiate positive ecological and hydrogeomorphic feedback loops such that beaver can reoccupy the site at some future date (Pollock et al., 2018).

BDAs are deployed in a variety of configurations, ranging from one individual structure to multiple structures installed in sequence. For example, Orr et al. (2020) used five individual structures dispersed over a small scale restoration reach of 2.25 km, and Bouwes et al. (2016) installed 100+ BDAs on the large scale restoration of Bridge Creek, in Oregon, USA. The BDA configuration is flexible and should depend on the hydrogeomorphic and ecologic settings (Pilliod et al., 2018) and also on the restoration project goal(s) (Pollock et al., 2011). Commonly, multiple BDAs are installed in sequence (Charnley, 2018; Pilliod et al., 2018), since short sequences of natural beaver dams can have an exaggerated impact on surface water storage and flow attenuation (Stout et al., 2017). Further, installing multiple BDAs should add redundancy to the system, which may be useful in ensuring some BDAs persist following larger flow events. However, the efficacy of different BDA configurations, which would be useful to restoration practitioners and regulators in making informed decisions on their use, has not been studied in a scientific context (Lautz et al., 2019; Pilliod et al., 2018). Thus, the goals of our study were to compare the effects of different BDA configurations on stream hydrology, and also test the efficacy of a single-BDA configuration in raising the riparian groundwater table. We hypothesized that the stream stage and stream discharge would be greater affected by having multiple BDAs in sequence. We also expected an increase in and stabilization of the riparian groundwater table following the installation of a single BDA.

2 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Ann & Sandy Cross Conservation Area (ASCCA), a 19.4 km^2 natural area in the rolling foothills of the Canadian Rocky Mountains, located 32 km southwest of downtown Calgary, near the town of Priddis in Alberta. Prominent hydrogeology of the region includes Paskapoo Formation, which is an extensive Paleocene-aged fluvial mudstone and sandstone complex and supports more groundwater wells than any other aquifer system in the Canadian Prairies (Grasby et al., 2008). There are a number of springs in ASCCA and most of them flow year-round. Pine Creek is a spring-fed mountain stream that flows west-east in ASCCA. It is a tributary of the Bow River which flows into the South Saskatchewan River. Dominant vegetation ecology of ASCCA consists of an overstory of balsam poplar (*Populus balsamifera*), trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) with an understory of shrubs including prickly rose (*Rosa acicularis*) and snowberry (*Symphoricarpos albus*) mixed with tall anemone (*Anemone virginiana* var. cylindroidea), smooth brome (*Bromus inermis* ssp. Inermis), bluejoint (*Calamagrostis canadensis*), northern reed (*Calamagrostis stricata* spp. Inexpansa) and small bottle sedge (*Carex utriculata*) graminoids. Thirty-year (1981-2010) mean seasonal (May-October) temperature and precipitation normals in the region are 12.2 ℃ and 63.5 mm, respectively.

Historically, ASCCA's topography, vegetation cover and hydromorphology made favourable beaver habitat; remnant beaver dams in Pine Creek watershed are still visible. Beavers were lost from the conservation area by the early 1990s as a result of illegal trapping (G. Shyba, pers. comm.). They are unable to naturally re-disperse into the site as the creek downstream is fenced down to its bed. In an attempt to re-establish this keystone wildlife species in ASCCA, the Alberta Institute for Wildlife Conservation reintroduced a pair of beavers on May 18, 2018 (White, 2016), but not to the study reach. In the absence of beaver, Pine Creek has degraded. The stream is incised, and the riparian vegetation coverage is severely reduced, which makes the site poor beaver habitat.

2.2 Methods

We studied a 1072-m long reach of the north arm of Pine Creek. The reach has an average stream width of 0.63 m, W-E and N-W slopes of 1.22% and 0.21%, respectively, and an approximate elevation of 1150 m above sea level. A total of six BDA structures were installed between August 3 and 9, 2018 along the study reach. The BDAs were installed as single (BDA-6), double (BDA-2, BDA-1) and triple (BDA-5, BDA-4, and BDA-3) configurations following Pollock et al. (2011). Each BDA was constructed from co-linear wooden posts (1.0 m long and ~0.07 m in diameter) driven into the stream bed by hand in one line. Aspen branches harvested onsite were interwoven between the posts and the structures were further reinforced with mud from the stream bed to achieve a consistent stream stage at each (~0.60 m). BDA width ranged from 0.77 to 0.49 m, depending on the local creek width.

Stream stage was monitored at four locations along the study reach in the thalweg, starting in May 2018. Stream gauges (SG (levelogger junior 3001, Solinst, Ontario, Canada); SG-4 – SG-1) were installed upstream of the BDAs, and downstream of each BDA configuration (Fig. 1). Stage was converted to discharge with a rating curve. An OTT MF Pro – Water Flow Meter (OTT Hydromet, Loveland, CO, USA) was used to measure streamflow and develop the rating curve. For May-October of 2018-2019, the stream stage was observed at each gauge at 15-min intervals. The barometric pressure was concurrently measured every 15-min with a barrologger (Solinst) inserted into a dry standpipe located in the riparian area; data were used to correct levelogger observations. Rainfall observations were obtained from the Alberta Environment and Parks rain gauge at Priddis (station ID 3033505), located 7.5 km west of the study reach at 1371 m elevation.

We monitored BDA pond level immediately upstream of each BDA (PG-6 to PG-1) between April 2019-August 2019. Levels were measured by housing an automatic levelogger (levelogger junior 3001, Solinst, Georgetown, Ontario, Canada) in a perforated PVC pipe (length = 1.0 m; diameter = 0.035 m) inserted 0.30 m into the streambed. The leveloggers monitored temperature-compensated levels at 15-min intervals, corrected for barometric pressure as described above, and averaged over the BDA configurations. Daily means were used for plotting pond water levels and conducting statistical analysis in all cases.

Three groundwater (GW) wells (1, 2, 3) were installed in June 2017 in the riparian area to the south of BDA-6, at distances of ~2, 7, and 13 m from the stream. The wells were built by inserting a 1.75 m long PVC pipe (diameter = 0.035 m; bottom 1.25 m perforated and wrapped with 1.5 µm polypropylene mesh net) to a depth of ~1.25 m following Westbrook et al. (2006). The pipes were outfitted with automatic leveloggers (Levelogger Junior 3001, Solinst, Georgetown, Ontario, Canada). Water levels in the GW wells were observed during the study period (frost-free periods of 2017-2019), except the levels from well-2 could not be retrieved for 2019 due to instrument malfunction. Leveloggers recorded temperature-compensated water levels continuously at 15-min intervals throughout the three ground frost-free seasons (April/May-October) of 2017-2019, and corrected for barometric pressure as described earlier.

2.3 Data analysis

SPSS 26.0 package (SPSS, Chicago, IL, USA) was used for statistical analyses (Landau & Everitt, 2004). Separate linear mixed-effects models (LMEM) used the entire dataset (Munir & Westbrook, 2020) to predict the fluctuations in stream stage, streamflow, BDA pond water level and riparian GW table in response to the fixed effects of BDA-configuration (single, triple and double), rainfall, BDA pond water level, stream stage and streamflow as applicable. A random variable of BDA configuration (distance from the top of the reach) was used to cover the effects of upstream/downstream configurations on the predictor and outcome variables. For GW table as a response variable, both the depth to GW table and absolute elevation values were separately tested and found to have equivalent significance; therefore, to be consistent with other analyses, the depth to GW table was used for final analysis. Any significant interactions between rainfall and other predictors (BDA pond level, stream stage, streamflow) were not only the result of collinearity, for example, the interaction of rainfall with BDA configurations had different significance (F or t and p values) for stream stage and streamflow. A compound symmetry covariance structure was used in all LMEM applications. Daily mean stage and discharge values were obtained by subtracting daily downstream values from corresponding upstream values; these data were used in the model. Before analyses, all data were tested for normality and homogeneity of variance using the Kolmogorov-Smirnov test and Levene's test, respectively. Regressions and 1:1 fit (s) were also performed where useful to validate the models developed. A significance level of 95% ($p<0.05$) and/or LogWorth (-log10(p)) ($p<0.01$) was used. The goodness of fit was reported as R^2 value.

3 RESULTS

Total May-October rainfall measured at the nearby rain gauge was lower in 2017 (160 mm) than in 2018 (277 mm) or 2019 (317 mm). Mean seasonal air temperature was higher in 2017 (12.3 ℃) than 2018 (11.7 ℃) or 2019 (11.5 ℃). A large rainfall event of 57.5 mm occurred on June 21, 2019. However, the site received 135.1 mm of rain between 21 June and 7 July 2019, with at least 0.5 mm of rain falling on 15 of those 20 days. Smaller rainfall events (10-30 mm) over the study period also significantly influenced the surface and shallow floodplain hydrology of this study creek.

3.1 BDA pond water level

BDAs were successfully constructed in early August 2018 along Pine Creek to achieve a ponded depth of approximately 0.50 m at each. The BDAs failed twice during the 13-month experiment – once over winter and again following intense summer rainstorms – via undercutting. All BDAs were repaired at the end of April 2019 following ice-off, but were not repaired following the summer rainstorms. Automated BDA pond water levels measured on the day following BDA installations (August 10, 2018) were significantly higher than those recorded on the last day of their final failure (August 5, 2019; Fig. 2A; paired t-test; $p<0.001$). During the BDA deployment period, most of the structures were fatally damaged by the extreme rainfall event occurring on June 21, 2019, and started fully draining after the very rain period ending July 7, 2019 (Fig. 2B, 2C). Among the triple configuration BDAs, the middle BDA (4) continued to hold more water than the upstream BDA (5) by 12%. On average, the triple configuration series held 26% and 6% more water than the single and double configurations, respectively. There was greater water storage above the triple configuration than the single and double configurations for a total of 87 days and 61 days, respectively.

Overall, BDA configuration was a significant predictor of pond water level. The pond water level increased immediately upstream of all BDA configurations ($p<0.001$; LogWorth = 12.31; Table 1, Fig. 2A). However, the mean water levels (± SE) at the triple (0.47 ± 0.00 m) and double (0.44 ± 0.00 m) configurations were higher than that at the single (0.37 ± 0.01 m) configuration (Fig. 2C). Rainfall was also a significant predictor of BDA pond water level, and all three BDA configurations showed increased ponding in response to rainfall/events. Increases in pond water levels upstream of BDAs 6, 5 and 4 in response to the largest rainstorms were greater than those at upstream of BDAs 3, 2 and 1 (Fig. 2B).

3.2 Stream stage and flow

Stream stage and discharge were lower at the gauging stations downstream of BDA installations than upstream of them (Fig. 3A, 3C, 4A, 4C). Similar stage and discharge trends 120 m downstream of double configuration at SG-1 and the same distance upstream of single configuration at SG-4 were also observed (Fig. 3D, 4D). The one exception was the triple configuration, where the downstream stage at SG-2 was higher than that at the upstream stage at SG-3 (Fig. 3B, 4B). Single configuration BDA (6) mitigated stormflow by lowering the downstream stage and increasing baseflow compared to the double configuration that simply reduced both downstream stage and discharge.

Paired t-tests (pre- vs post-BDA installation) were significant, which indicated that all BDA configurations resulted in elevated stream stage while only single-configuration (BDA-6) impacted stormflow (Table 2).

To factor out changes in stream hydromorphology owing to BDA configuration, rainfall, and pond water level predictors, LMEMs were performed. Overall, both the stream stage and flow before BDA installations were significantly different from those recorded after the BDA installation. Further, the triple- and double-configurations had more influence on stream stage and flow than the single-configuration (BDA-6). We present the stream stage and flow prediction expressions generated by the statistical models as:

$$\text{Stream stage} = 0.0025 + 0.0009\ (\text{single-config.})\ \text{or}\ 0.0107\ (\text{double-config.})\ \text{or}\ 0.0098\ (\text{triple-config.}) + 0.0069 \times \text{BDA pond level}$$

$$= 0.0025 + 0.42\ (\text{BDA pond level}) \times 0.1144\ (\text{single-config.})\ \text{or}\ 0.0369\ (\text{double-config.})\ \text{or}\ -0.1513\ (\text{triple-config.}) + 0.0002 \times \text{rainfall}$$

$$= 0.0025 + 2.28\ (\text{rainfall}) \times -0.0001\ (\text{single-config.})\ \text{or}\ -0.0002\ (\text{double-config.})\ \text{or}\ 0.0003\ (\text{triple-config.}) + 0.42\ (\text{BDA pond level}) \times (2.28\ (\text{rainfall}) \times 0.0008)$$

$$\text{Streamflow} = 3.5277 + 0.2422\ (\text{single-config.})\ \text{or}\ 9.4017\ (\text{double-config.})\ \text{or}\ 9.1595\ (\text{triple-config.}) - 4.7780 \times \text{BDA pond level}$$

$$= 3.5277 + 0.42\ (\text{BDA pond level}) \times 23.79\ (\text{single-config.})\ \text{or}\ 49.40\ (\text{double-config.})\ \text{or}\ -73.19\ (\text{triple-config.}) + 0.1304 \times \text{rainfall}$$

$$= 3.5277 + 2.28\ (\text{rainfall}) \times 0.1890\ (\text{single-config.})\ \text{or}\ 0.2310\ (\text{double-config.})\ \text{or}\ -0.4200\ (\text{triple-config.}) + 0.42\ (\text{BDA pond level}) \times (2.28\ (\text{rainfall}) \times 0.2497)$$

Rainfall and BDA pond water level were not significant predictors for stream stage and flow; however, there was a two-way interaction between rainfall and BDA configuration, which revealed that there were significant increases in streamflow and stage at the upstream of single and double configurations (at SG-4 and SG-2, respectively). We also found a three-way interaction between rainfall, BDA configuration and BDA pond water level, which demonstrated the incremental stage and flow upstreams of these configurations. Individually, the rainfall, which was a non-significant predictor in the model (LMEM: $p=0.296$, 0.177), was collinear with stream stage and flow (one-way ANOVA: $p<0.001$, $n = 169$).

The discharge responses to rainfall events varied across upstream and downstream of BDA-configurations. Relationships between above- and below-BDA configuration rainfalls and discharge data for summary metrics of peak event discharge and total event discharge are shown in Fig. 5A, 5B, 5C, 5D, and 5E, 5F, 5G, and 5H, respectively. Below single- and double-configurations, both the peak event and total storm event discharges showed more attenuating responses to rainfall events compared to those at above these structures. The one exception was the triple-configuration where upstream SG-3 measured lower flow compared to the downstream SG-2. Deeper analyses of discharge data revealed that downstream of BDA sequences, the average peak flows at SG-3 (4.5 l/s) and SG-1 (16.2 l/s) were smaller than corresponding upstream of BDA measurements (at SG-4 by 39% ($p<0.018$, $n = 19$) and SG-2 by 63% ($p<0.001$, $n = 19$)). Simultaneously, downstream of BDA sequences the average total event discharge at SG-3 (74.5 m^3) and SG-1 (57.3 m^3) were smaller than corresponding upstream of BDA sequences at SG-4 by 28% ($p<0.019$, n = 19) and SG-2 by 88% ($p<0.001$, n = 19). For the triple-configuration, the downstream (SG-2) average peak flow and total event discharge (34.7 l/s and 488.9 m^3, respectively) were higher than those measured upstream (SG-3) by 670% and 554%, respectively ($p<0.001$, n = 19).

3.3 Riparian groundwater hydrology

Stream hydrology was found to relate to the riparian GW table post-restoration, as reflected by uninterrupted and stable links of BDA ponding and upstream stage with GW levels at monitoring wells (Table 3; Fig. 6, 7). Mean GW levels at monitoring wells 1, 2 and 3 were -0.46, -0.40 and -0.68 m during 2017, and -0.39, -0.66 and -0.83 m during 2018 study years (negative values indicate WT is belowground). After the BDAs were installed, the mean GW levels in 2019 were -0.32 m at well-1 and -0.65 m at well-3. BDA-6 was built on 3 Aug 2018. Two days later, GW levels had risen by 0.53 m at well-1, 0.30 m at well-2 and 0.05 m at well-3, which showed that the effects of the BDA decreased with increasing distance from the stream ($p<0.05$; n = 308). Detailed pre- vs post-BDA installation differences in riparian GW levels and elevations driven by a single-configuration BDA and augmented by ponding and rain events are shown in Fig. 6A and 6B. One of the largest rain events occurring on 21 June 2019 caused the GW table to rise from 1127.15 and 1126.99 masl at wells 1 and 3 (recorded on 20 June) to 1127.34 and 1127.30 masl, respectively. Pre-BDA installation, hydraulic gradient (Fig. 6B) indicated flow from the riparian area to the stream. As soon as BDA-6 was installed there was a flow reversal wherein stream water flowed below ground toward the riparian area. The two large rainstorms transiently created a flow reversal in the opposite direction. A paired t-test comparing riparian GW levels pre- (9 Aug 2017-2 Aug 2018) and post-installation (5 Aug 2018-5 Aug 2019) informed significant increases in GW levels post-deployment of single-configuration BDA (Table 3; $p<0.001$; n = 131).

To find out whether the single-configuration (BDA-6) and associated pond water level, rainfall and stream stage were significant predictors for shallow GW hydrology of the riparian area, we conducted a LMEM with a random effect of well location (Table 3) to account for hydrological variations possibly caused by these variables. We found a significant interaction between BDA pond water level and stream stage (SG-4), and significantly elevated GW levels at well-1 and 3 ($p<0.001$); though, individually, ponding increased level at well-1 only ($p<0.001$), and upstream stage raised water elevation at well-3 alone ($p<0.001$). Rainfall was a common significant predictor of GW level at both wells; however, there was an interaction of rainfall with ponding, which demonstrated GW elevations at both wells. The LMEM results we obtained were also validated by linear regression models for demonstrating how rainfall, stream stage and ponding had controls on GW elevations at wells 1 and 3 (Fig. 7A, 7B). Riparian GW levels measured at each well were separately plotted against the corresponding predicted values generated by the models to construct 1:1 fit in each case (Fig. 7C, 7D).

5 DISCUSSION

Our findings have important implications for those in management who may be considering the installation of BDAs. We showed that BDAs modified stream and riparian area hydrology at this site in ways consistent with how natural beaver dams modify stream and riparian area hydrology. Having more BDAs installed in a sequence generally enhanced their influence on stream hydrology. However, diffuse spring inputs to the stream can obscure the hydrologic influence of BDAs.

5.1 Surface-water: ponding and elevation

Surface water ponding upstream is one of the well-recognized functions of natural beaver dams and has been frequently reported (e.g., Pollock et al., 2014; Puttock et al., 2017; Stout et al., 2017). Rarely though is BDA-induced ponding investigated (Bouwes et al., 2016; Orr et al., 2020; Scamardo & Wohl, 2020). We found that all three BDA configurations created upstream ponds. While all the BDAs were the same height, there was a difference in pond depth depending on the type of configuration. The deepest ponds were recorded at the immediate upstreams of triple-configuration (0.46 ± 0.09m) followed by the ponding levels at double- (0.43 ± 0.10m) and single-configurations (0.36 ± 0.08m). This finding supports the notion that a multiple structure BDA configurations can create deeper pools, similar to the function of natural beaver dams (Pilliod et al., 2018; Pollock et al., 2018). Of all configurations, the double-configuration appeared to modulate the impacts of storm events and sustain consistent depth the most, which could be attributed to their lowest position on reach slope. Secondarily, rainfall was a key factor in raising pond level. BDA configuration and rainfall did not have a meaningful interaction, which is likely the result of the low crest BDA design we used which was prone to quickly overtopping by stormflow, similar to the observations made by Bouwes et al. (2016). Substantially lowered pond levels at all BDAs except BDA-4 were noticed upon complete failure of BDAs at the end of this experiment (August 5, 2019) compared to elevations recorded soon after their installation (August 5, 2018). Prolonged functioning of the middle BDA (4) of the triple-configuration could indicate that the number of dams in a sequence matters when it comes to the persistence of the upstream ponding and depth. Where natural beaver dams occur in sequence, Westbrook, Ronnquist and Bedard-Haughn (2020) found a lower likelihood of all dams in the sequence failing during large rainfall events.

5.2 Stream stage and flow

One of the key reasons why hundreds of BDAs have been installed across first to third-order streams during the last two decades in Western North America (see Pilliod et al., 2018; Pollock et al., 2014) is to alter stream hydrology. Natural beaver dams are known to reduce hydrograph peaks (Hillman, 1998) and elevate baseflows (Westbrook, Cooper & Butler, 2013); only a few studies have reported that BDAs performed similarly, for example, Bouwes et al. (2016). We found mixed results of the effectiveness of BDA in altering stream hydrology as did Scamardo and Wohl (2020). The single-BDA configuration lowered stream stage and flow peaks after rainfall events and raised base stage and low flows. The double-BDA configuration, however, modulated peaks but had little influence on base stage and low flows. Little or no changes in base stage and flow could be due to the interaction of steeper slope (1.22%) of the reach in which the double-BDA configuration was installed or weak hydrological connectivity of the stream with the adjacent historical riparian wetland. Unexpectedly, higher peaks and base stage/flow were recorded downstream of the triple-configuration than upstream of it following rainfall events. Higher stage and flow downstream of the triple-BDA configuration seemed not to result from the BDA structures but the inflow of water from groundwater seep. The year we started monitoring the stream reach (2017) was a regional drought, and so we did not observe the spring water addition at the place where we installed the triple-BDA configuration. However, 2018 and 2019 were considerably wetter years, and we observed groundwater exfiltrating into the stream. We anticipate that without the interference of these three external springs, the triple-configuration might have lowered stream peaks during rainfall events more than the single- and double-BDA configurations. Our findings though indicate that it would be worthwhile for future studies to further test how different numbers of BDA installed in sequence cumulatively influence stream flows. Our results also suggest that it is important to assess BDA effectiveness along in gaining and losing stream reaches in order to provide stream restoration practitioners with clear design guidance.

5.3 Riparian water table response

BDA installation led to a quick water table rise in the riparian area. Similar to natural beaver dams (Westbrook et al., 2006), the water table rise was largest near the stream and tapered off with increasing distance from the stream. At 13 m from the stream, there was no significant increase in the water table. Our multivariate mixed model indicated that fluctuations in the riparian water table can be predicted by the height of stream ponding, at least at the one BDA we studied. The rises in the riparian water table we observed post-BDA installation were also found for BDAs installed by Bouwes et al. (2016) and Orr et al. (2020), but our values are on average 0.10 m and 0.11 m greater than they reported. Our results are not consistent with the observations of Scamardo and Wohl (2020) who noted an absence of water table response to BDA installation. However, Scamardo and Wohl cited low permeability of floodplain soils as the likely reason, which was not the case in for riparian soils of Pine Creek. The conflicting results among studies indicate further research is needed to determine under which site conditions BDAs are likely to raise riparian water tables.

Flow reversal was the dominant process to elevate the riparian water table as the amount of water ponding in the stream was sufficient to reverse the hydraulic gradient and drive stream water into riparian soils, similar to what is observed in places where there are natural beaver dams (Majerova et al., 2015; Schmadel, Neilson & Kasahara, 2014). It did not take a very tall BDA structure to cause a flow reversal, as the BDAs were built to raise stream stage only to 0.6 m and the ponding was confined mostly within the channel. The flow reversal we observed was similar to what occurred in a nearby stream when the beaver built small, in-channel dams (Janzen & Westbrook, 2011). Rainstorms elevated BDA pond levels, which in turn raised the riparian GW table. Therefore, there is an opportunity to investigating the isolated role of rainfall in rising the riparian GW table. The BDA-ponding link to riparian GW table under associated predictors of stage and rainfall was confirmed using a 1:1 fit between the measured and model-predicted values. Further, the creek we investigated was surrounded by a seasonal graminoid marsh wetland characterized by hydric soil which was reported to have relatively uniform and as high as hydraulic conductivity of 0.29 m hr^{-1} (He, Vepraskas, Skaggs & Lindbo, 2002; Surridge, Baird &

Heathwaite, 2005). Therefore, soil permeability might have augmented the stream-riparian connectivity and consequent flow reversals.

Considering that a single BDA, while small, was able to effectively raise the riparian water table within 13 m of the stream by changing the hydrologic connectivity of the stream and riparian area, we anticipate that multiple BDAs installed in sequence - with varying numbers and spacings –would expand the portion of the riparian area over which riparian water tables are raised. Future research should explore the dynamics of stream-riparian hydrological connection under various BDA configurations with the goal of identifying whether installing sequences of BDAs compound riparian water table rises so as to provide the evidence with which clear guidelines for BDA use by stream restoration practitioners can be developed.

6 CONCLUSIONS

This study explores the effectiveness of unique BDA configurations in mimicking the ecohydrological functions of natural beaver dams in a degraded spring-fed creek. First, the single-, double- and triple-configurations did not differ in responding to rainfall/events for developing immediate upstream ponding post-installation. Though, deeper, and relatively persistent ponds were developed upstream of the triple-configuration configuration, suggesting that a multi-configuration BDA construct can be more effective than a single-configured BDA. Second, single- and double-configurations partially lowered the downstream stage and discharge by modulating rainfall events and increasing or sustaining the base stage and discharge. The triple-configuration did not perform as expected; downstream stage and flow were elevated rather than reduced, likely due to GW seepage. Results highlight how local hydrological controls when present could have a stronger influence on stream hydrology than BDAs. Third, we found that even the singularly configured BDA we used created sufficient upstream ponding to cause a flow reversal, represented the hydrological function of natural beaver dams on enhancing stream-riparian hydrological connectivity. Our findings reflect that while all BDA configurations used are unlikely to provide 100% similar ecohydrological functions and alike those of natural beaver dams, multiple-configuration BDAs are likely to pond deeper and longer, while the stand-alone BDA we tested likely develop stream-riparian groundwater connectivity in riparian soils of sufficient hydraulic conductivity. We recommend further testing of different BDA configurations – varying heights, widths and spacings – in order to advance the development of guidelines for stream restoration practitioners on BDA installation and use.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are publicly archived in [github] at: https://github.com/TariqMunir/Munir-Westbrook-Supplementary-Data_BDAs.git

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TABLES AND FIGURES WITH CAPTIONS

Table 1. Statistical analysis results of a linear mixed-effects model with fixed effects of BDA configuration (single, double, triple) and rainfall, random effects of BDA configuration (distance from top of the reach), and an outcome variable of BDA pond water level.

Effect / terms	BDA configuration pond water level (m)			
	df	F	p	LogWorth (-log10(p))*
BDA configuration (overall model)	2, 583	15.99	**<0.001**	12.31
single-configuration	1, 96	7.18	**0.009**	3.23
triple-configuration	2, 290	19.03	**<0.001**	8.72
double-configuration	1, 193	22.09	**<0.001**	8.80
(triple-configuration – double-configuration)	-	2.74	**0.006**	-
(double-configuration – single-configuration)	-	5.24	**<0.001**	-
Rainfall	1, 583	4.05	**0.045**	1.35
BDA config. × rainfall	2, 583	1.25	**0.047**	1.21

* A LogWorth value of >2.0 shows significance at 0.01 level ((-log10(0.01) = 2). Bold p values show p<0.05.

Table 2. Statistical analyses results of 1) paired t-tests between pre- and post-BDA treatment stream stage and discharge, and 2) a linear mixed-effects model with fixed effects of BDA configuration (single, double, triple), pond level (BDA-1 – BDA-6) and rainfall measured over 2018-2019, random effects of BDA configuration (distance from top of the reach) and the outcome variables of stream stage and streamflow*.

Effect/term	Stream stage (m)			Streamflow (l/s)		
	df	F or t-ratio	p/ LogWorth (-log10(p))	df	F or t-ratio	p/ LogWorth (-log10(p))
PAIRED t-TEST (Pre- vs post-BDA)						
1-config. (2018 SG4 – SG3) vs (2019 SG4 – SG3)	1, 55	1.40	**0.043**	1, 55	1.7	**0.049**
3-config. (2018 SG3 – SG2) vs (2019 SG3 – SG2)	1, 55	4.38	<**0.001**	1, 55	-0.21	0.834
2-config. (2018 SG2 – SG1) vs (2019 SG2 – SG1)	1, 55	2.30	**0.025**	1, 55	0.17	0.863
LINEAR MIXED-EFFECTS MODEL						
BDA configuration	2, 285	98.20	<**0.001**/ 32.44	2, 285	206.2	<**0.001**/ 55.38
Tukey: 1-config. (stage/flow = 0.060/2.40) vs 3-config. (stage/flow = 0.08/9.74)	2, 285	5.62	<**0.001**	2, 285	9.08	<**0.001**
Tukey: 1-config. vs 2-config. (stage/flow = 0.065/1.75)	1, 285	-7.79	<**0.001**	1, 285	-10.41	<**0.001**
Tukey: 3-config. vs 2-config.	2, 285	13.87	<**0.001**	2, 285	20.22	<**0.001**
Rainfall	1, 285	1.10	0.296	1, 285	1.83	0.177
BDA pond level	4, 285	1.15	0.251	2, 285	1.67	0.197
BDA config. × BDA pond level	2, 285	166.37	<**0.001**/ 47.88	2, 285	109.26	<0.**001**/ 35.22
BDA (1-config.) × BDA pond level (0.4233m) × rainfall (2.28mm)	2, 285	2.16	0.**032**/ 1.50	2, 285	2.82	0.**005**/ 4.62

* pre- and post-treatment periods are late June 2017 to early August 2018, and early August 2018 to early August 2019, respectively. Stage or flow value used was a difference between above and below a configuration. A LogWorth value of >2.0 signifies 0.01 level ((-log10(0.01) = 2) and provides strength of significance with greater the value more the strength. Bold p values show significance at 0.05 or 0.01 level.

Table 3. Statistical results of 1) a paired t-test between pre- and post-BDA treatment groundwater table, and 2) a mixed-effects model with fixed effects of BDA-6 pond water level, rainfall and stage, and random effect of groundwater well location, and an outcome variable of riparian groundwater table *.

Effect / term	Riparian groundwater table wells						
	1 (2 m south)			2 (5 m south)		3 (13 m south)	
	df (n=131)	F/t ratio	p (% effect)	t-ratio	p	F/t ratio	p (% effect)
PAIRED t-TEST (pre- vs post-BDA)	-	37.95	**<0.001**	3.62	**<0.001**	-1.07	0.285
Linear mixed-effects model							
BDA-6 mean water level (0.3472 m)	1, 72	106.93	**<0.001** (73%)			1.14	0.290
Rainfall (2.44mm)	1, 72	6.45	**0.027** (10%)	Well-2 was not monitored during 2019 due to malfunction of the level logger; therefore, not included in LMEM		5.34	**0.003** (17%)
Stage (0.0674m)	1, 72	3.74	**0.045**			51.41	**<0.001** (78%)
BDA pond water level × rainfall	1, 72	1.54	**0.009**			4.40	**0.040**
Rainfall × stage	1, 72	1.59	0.211			3.91	0.052
BDA pond water level × stage × rainfall	1, 72	2.21	0.142			3.44	0.068

* depth to GW table. Pre- and post-treatment periods are late June 2017-early August 2018, and early August 2018-early August 2019, respectively. For linear mixed-effects model, only 2019 data is used since pond water level was available for 2019 only. Stage measurements are from SG-4.

Fig. 1. Location of study stream equipped with beaver dam analogue (BDA)/configurations, pond gauges (PG), stream gauges (SG) and groundwater (GW) monitoring wells at Ann & Sandy Cross Conservation Area near Calgary in Alberta, Canada. Six BDAs (BDA-6 to BDA-1) from upstream to downstream are shown by red bars along ~1075 m long reach. 1, 2 and 3 red bars represent single-, double-, and triple-configurations, respectively. A group of same configurations is called a series. Each BDA is instrumented with an upstream PG (PG-6 to PG-1). Four SGs (SG-4 to SG-1, shown by cross signs) before and after each of the three configuration/series were installed to monitor stream stage and discharge. A 13 m long transact, south of BDA-6 was installed with three shallow GW monitoring wells at ~2, 5 and 13 m distances (shown by black spheres). One surface spring fed the creek (tele-blue line) and three groundwater springs merged with the creek (black arrows). Instrumentations may not be up to the scale.

Fig. 2. Beaver dam analogue (BDA) water level elevations measured after BDA installation in August 2018, and BDA failure in August 2019 (A). Mean daily BDA pond water levels (B), averaged over three BDA configurations (single-, double- and triple-configuration) series (C).

Fig. 3. Mean daily stream stage upstream and downstream of: single-configuration BDA-6, with a hyetograph on top x-axis and right y-axis (A), triple-configuration series (B), double-configuration series (C). Overall stage upstream and downstream of study reach (D). The hyetograph is applicable for all four figure panels.

Fig. 4. Mean daily streamflow upstream and downstream of: single-configuration BDA-6, with a hyetograph on top x-axis and right y-axis (A), triple-configuration series (B), double-configuration series (C). Overall streamflow upstream and downstream of study reach (D). The hyetograph is applicable for all four figure panels.

Fig. 5. Observed peak discharge relationship between above (x-axis) and below (y-axis) a BDA configuration/series is shown by plotting all storm events (n = 19) extracted from a continuous time series of streamflow logged during August 2018 and August 2019. Relationships between discharges at upstream and downstream of: single-configuration BDA (A), triple-configuration series (B), and double-configuration series (C) are drawn. Overall peak discharge upstream and downstream of reach is shown by D. Likewise, observed total event discharge relationships are also shown. Relationships between total event discharges at upstream and downstream of: single-configuration BDA-6 (E), triple-configuration series (F), and double-configuration series (G) are shown. Overall total event discharge upstream and downstream of reach is shown by H.

Fig. 6. Mean daily rainfall (bars), and riparian groundwater levels (lines) at three monitoring wells during May-Oct of 2017-2019 (A). The wells were 1.25 m deep from soil surface and ~2, 7 and 13 m south of BDA-6 (single-configuration). The GW levels at well-2 are missing in 2019 due to levelogger's malfunction. Negative values indicate belowground water level. Hydraulic gradients pre- and post-installation of BDA (6) are shown during study years (B). Overall, pre-BDA installation hydraulic gradient

indicates flow from the riparian area to the stream. Post BDA installation hydraulic gradient shows flow reversal from stream toward riparian area.

Fig. 7. Impacts of stream stage (A) and a single-configuration BDA-6 pond water level (B) on riparian water levels at well-1 and well-3 during 2019. Goodness of fit (R2) between modelled and observed riparian groundwater table at well-1 (C) and well-3 (D).

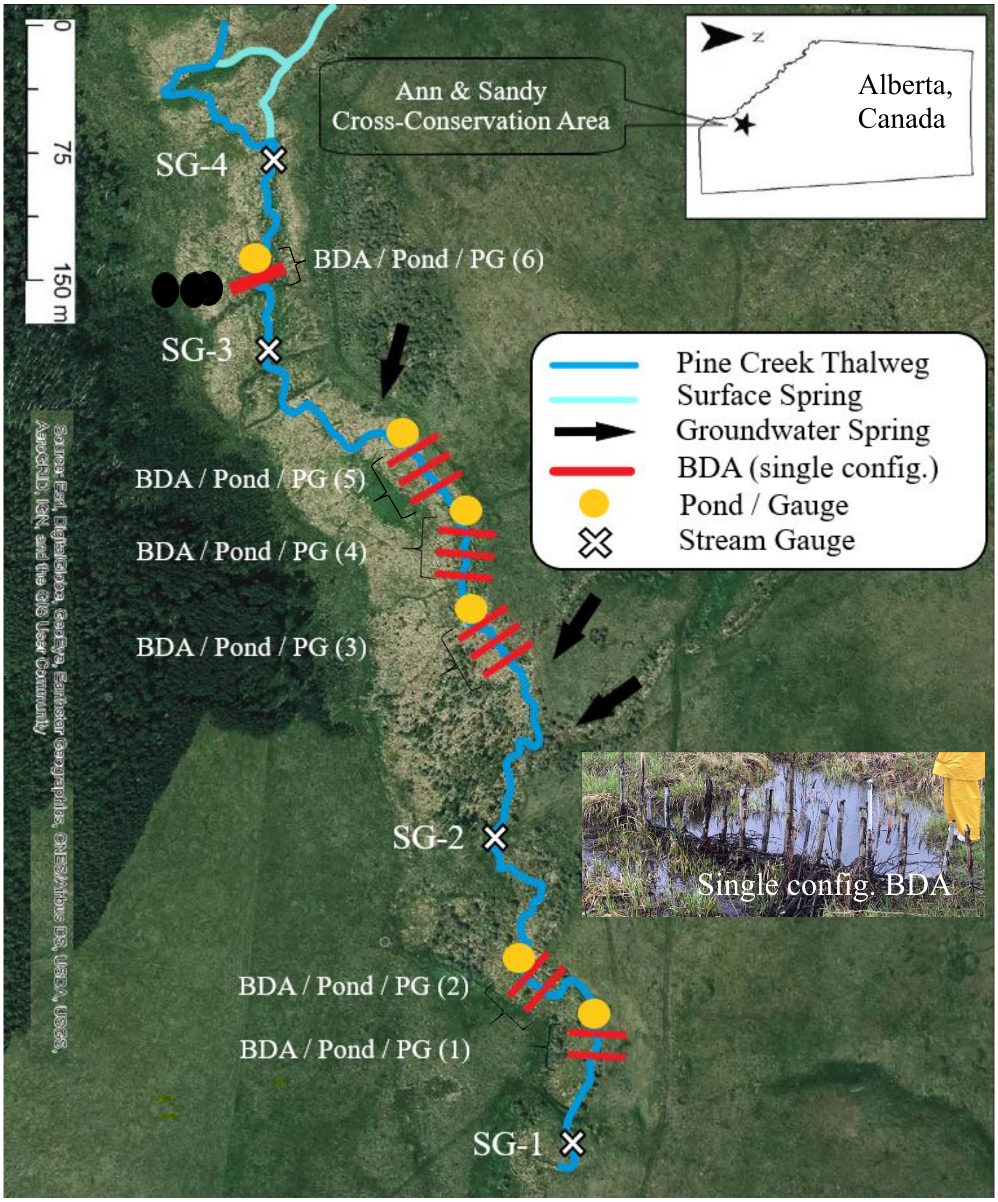

0
75
150 m
Ann & Sandy
Cross-Conservation Area
N
Alberta,
Canada
SG-4
BDA / Pond / PG (6)
SG-3
Pine Creek Thalweg
Surface Spring
Groundwater Spring
BDA (single config.)
Pond / Gauge
Stream Gauge
BDA / Pond / PG (5)
BDA / Pond / PG (4)
BDA / Pond / PG (3)
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
SG-2
Single config. BDA
BDA / Pond / PG (2)
BDA / Pond / PG (1)
SG-1

Fig. 1

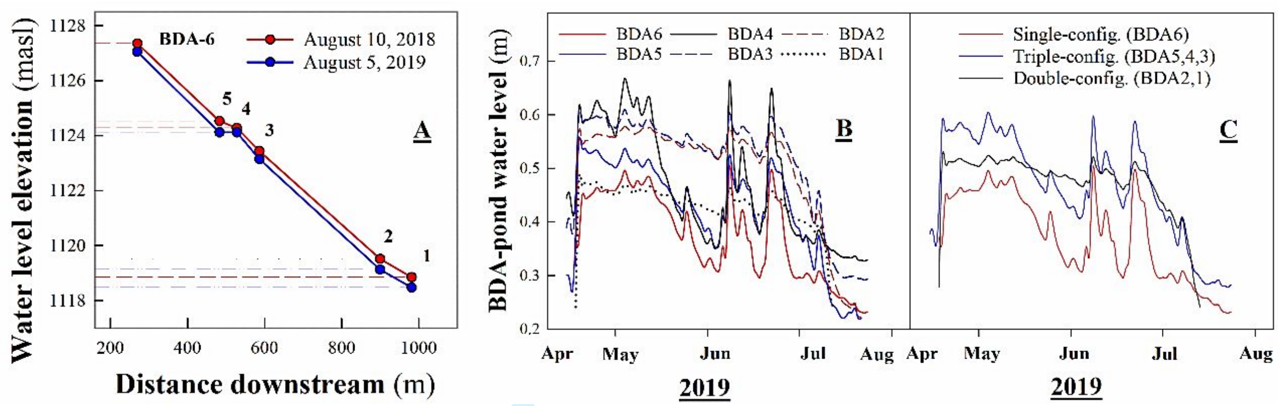
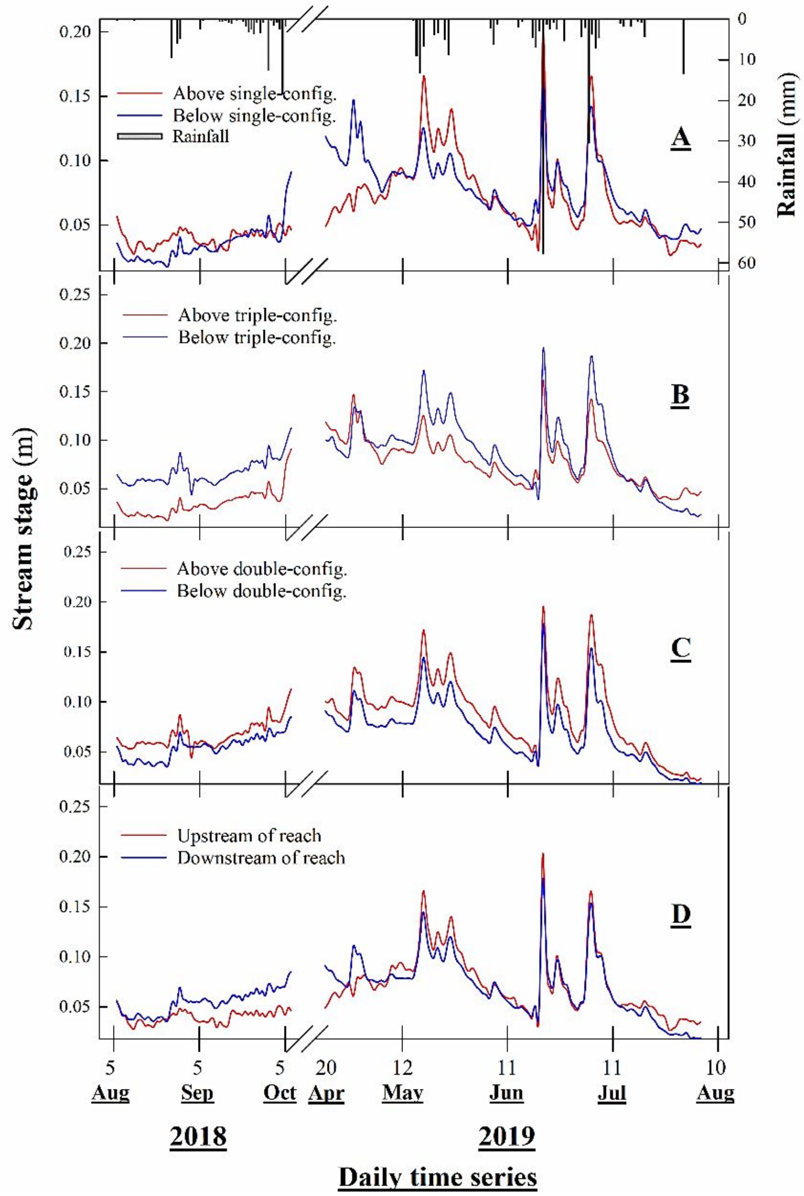

Water level elevation (masl)
Distance downstream (m)
BDA-6
August 10, 2018
August 5, 2019
A
BDA-pond water level (m)
BDA6
BDA5
BDA4
BDA3
BDA2
BDA1
B
Single-config. (BDA6)
Triple-config. (BDA5,4,3)
Double-config. (BDA2,1)
C
Apr
May
Jun
Jul
Aug
2019

Fig. 2



693

694

695 Fig. 3

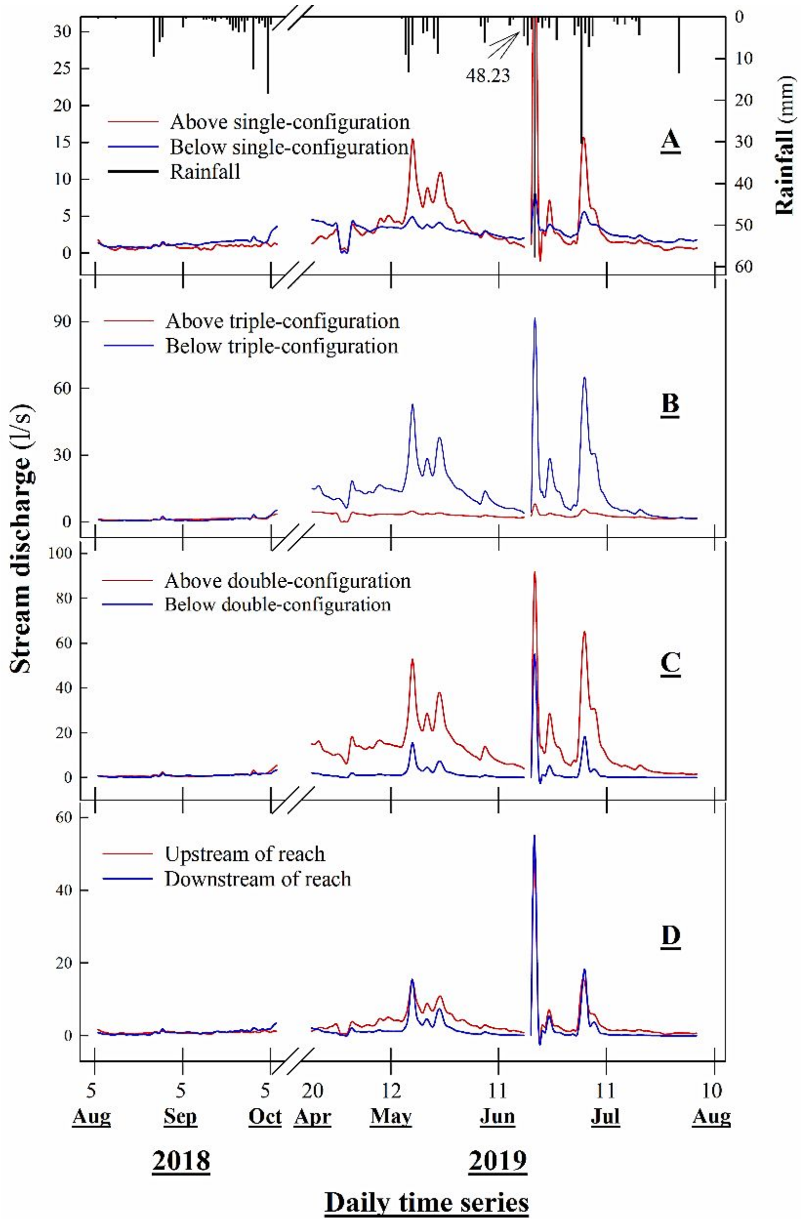

48.23
Above single-configuration
Below single-configuration
Rainfall
A
Rainfall (mm)
Above triple-configuration
Below triple-configuration
B
Stream discharge (l/s)
Above double-configuration
Below double-configuration
C
Upstream of reach
Downstream of reach
D
5 Aug
5 Sep
5 Oct
20 Apr
12 May
11 Jun
11 Jul
10 Aug
2018
2019
Daily time series

Fig. 4

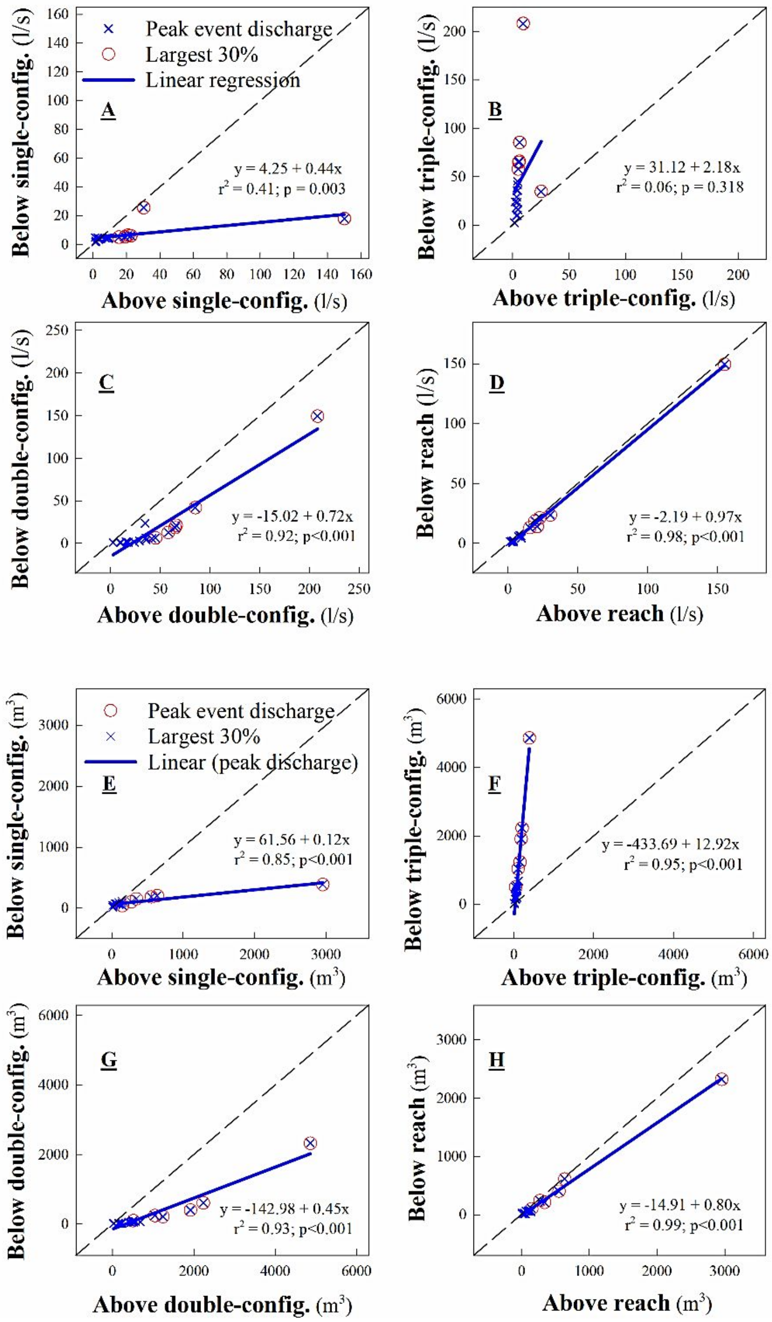

Peak event discharge
Largest 30%
Linear regression
A
y = 4.25 + 0.44x
r² = 0.41; p = 0.003
Below single-config. (l/s)
Above single-config. (l/s)
B
y = 31.12 + 2.18x
r² = 0.06; p = 0.318
Below triple-config. (l/s)
Above triple-config. (l/s)
C
y = -15.02 + 0.72x
r² = 0.92; p<0.001
Below double-config. (l/s)
Above double-config. (l/s)
D
y = -2.19 + 0.97x
r² = 0.98; p<0.001
Below reach (l/s)
Above reach (l/s)
Peak event discharge
Largest 30%
Linear (peak discharge)
E
y = 61.56 + 0.12x
r² = 0.85; p<0.001
Below single-config. (m³)
Above single-config. (m³)
F
y = -433.69 + 12.92x
r² = 0.95; p<0.001
Below triple-config. (m³)
Above triple-config. (m³)
G
y = -142.98 + 0.45x
r² = 0.93; p<0.001
Below double-config. (m³)
Above double-config. (m³)
H
y = -14.91 + 0.80x
r² = 0.99; p<0.001
Below reach (m³)
Above reach (m³)

Fig. 5

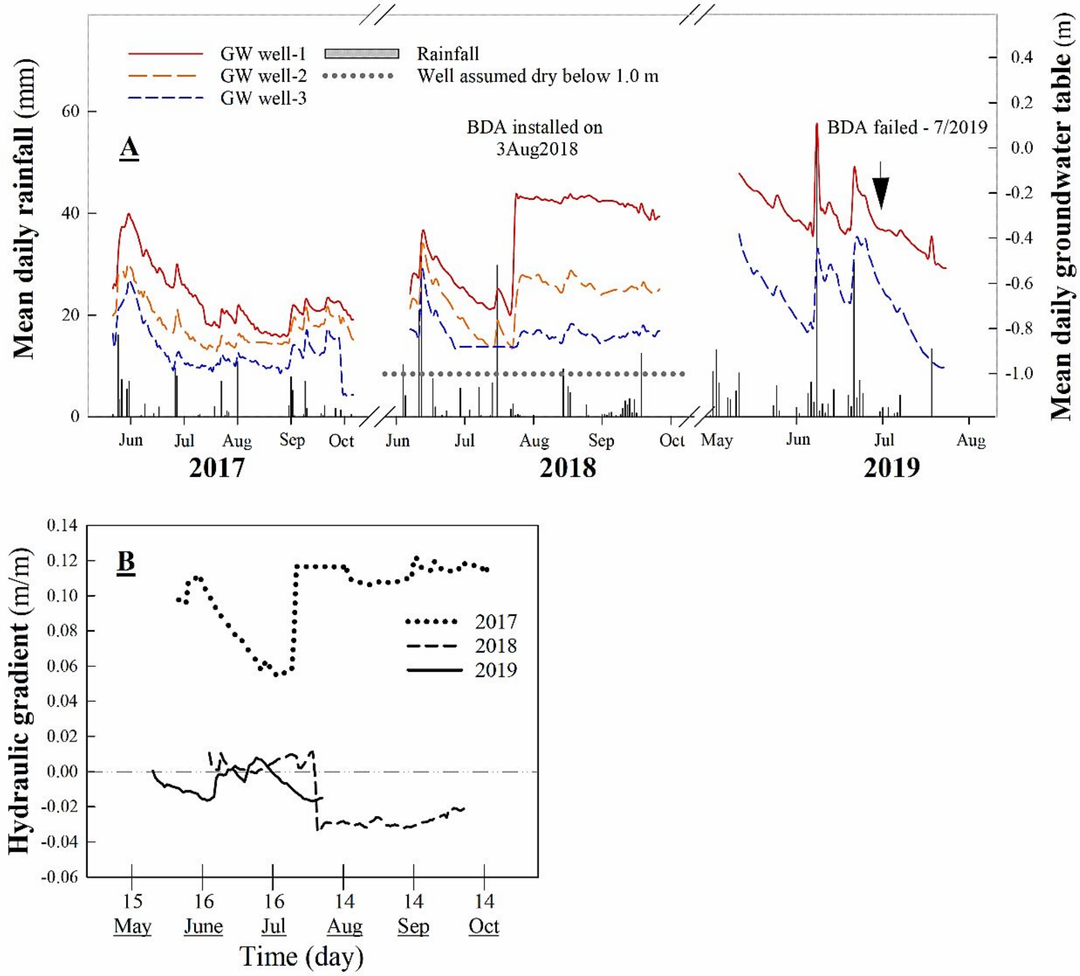
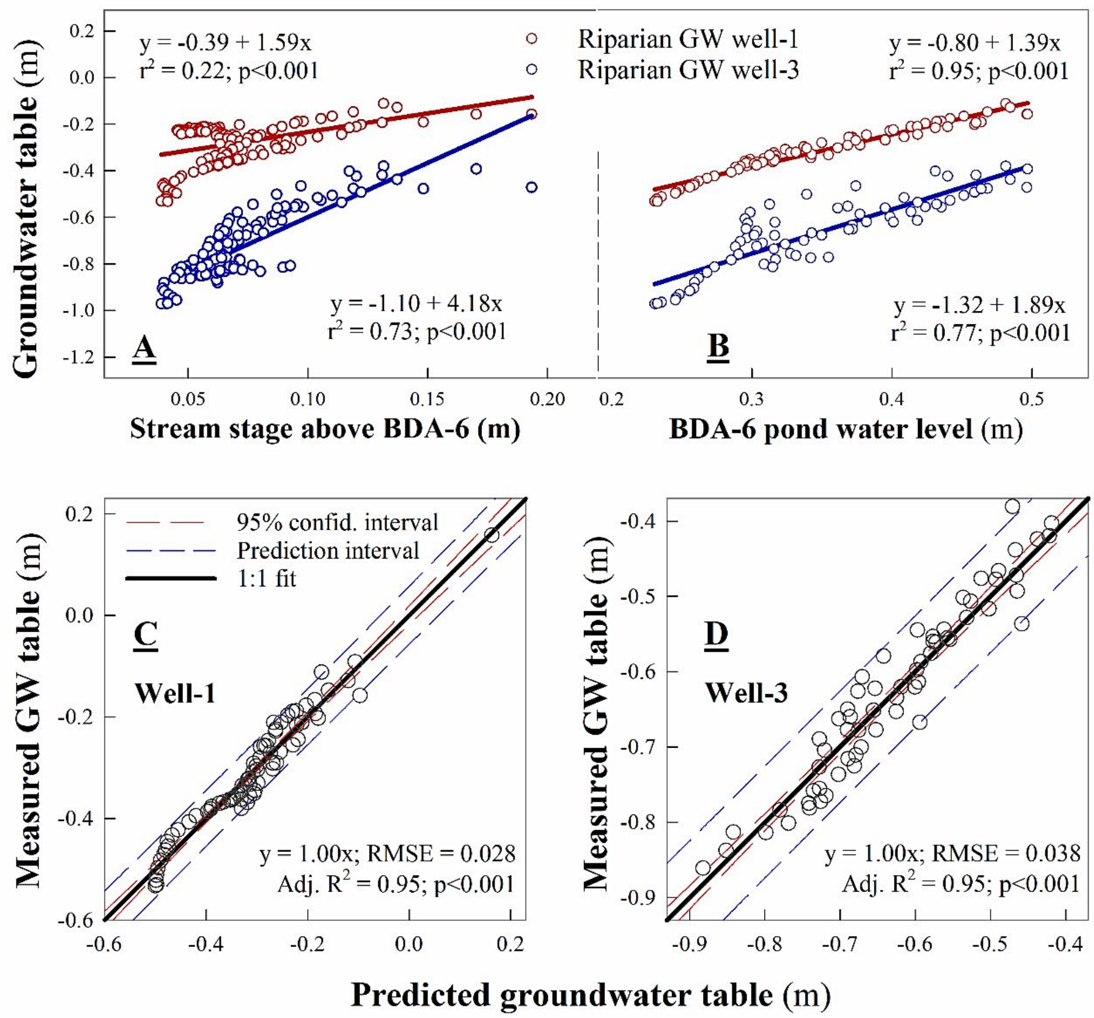

A
GW well-1
GW well-2
GW well-3
Rainfall
Well assumed dry below 1.0 m
BDA installed on 3Aug2018
BDA failed - 7/2019
Mean daily rainfall (mm)
Mean daily groundwater table (m)
Jun Jul Aug Sep Oct
2017
Jun Jul Aug Sep Oct
2018
May Jun Jul Aug
2019
B
2017
2018
2019
Hydraulic gradient (m/m)
15 May
16 June
16 Jul
14 Aug
14 Sep
14 Oct
Time (day)

Fig. 6

716



717

718 Fig. 7

719