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Groundwater-Mediated Influences of Beaver-Mimicry Stream Restoration: A Modeling Analysis

Andrew L. Bobst, Robert A. Payn, and Glenn D. Shaw

Research Impact Statement: Some purported benefits of beaver-mimicry stream restoration require changes in groundwater flow. Models allow exploration of patterns in groundwater-mediated effects of different design strategies.

ABSTRACT: Beaver-mimicry stream restoration (BMR) involves the alteration of a stream channel to approximate the effects of beaver activity. Project objectives often include increasing groundwater storage and dry-season streamflow, but limited data are available to understand the nature of its effects on groundwater dynamics. We developed generic groundwater models of mountain headwater streams to investigate the effects of installing a single beaver-mimicry structure (BMS) using different restoration designs in varied hydrogeologic settings. The magnitude of changes in dry-season net stream gains from a single BMS was always a minor component of the channel water balance, and would be too small to measure in the field; however, the modeled patterns of change caused by a single BMS help to understand the underlying mechanisms. All tested scenarios caused increases in groundwater recharge from the stream, which resulted in increased groundwater levels, and groundwater outflow from the model domain. For scenarios that did not include evapotranspiration, most treatments in gaining and losing settings caused slight increases in dry-season net stream gains, but in strongly losing settings net stream gains were reduced. The addition of simulated evapotranspiration often resulted in decreased dry-season net stream gains, since evapotranspiration increased with groundwater elevations. BMR design and siting influence the types of hydrologic effects that should be anticipated.

(KEYWORDS: hydrology; streamflow; groundwater hydrology; surface water/groundwater interactions; drought.)

INTRODUCTION

Evident shifts in the climate at higher elevations suggest that consideration of changes in seasonal to interannual water storage should be a high priority for water planning in mountainous watersheds. Field observations and climate change predictions from extensive literature regarding mountainous areas indicate that snowpack accumulation is likely to decline and that accumulated snow is likely to melt earlier in the year, which will result in lower dry-season streamflows (Cayan et al. 2001; Barnett et al. 2005; Clow 2010; Naz et al. 2018). Shifts in precipitation from snow to rain are major driver of reduced snowpack (Knowles et al. 2006; Berghuijs et al. 2014), which is expected to diminish seasonal hydrologic storage even where total annual precipitation increases. Stream restoration projects that increase seasonal (or longer) hydrologic storage can

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be used to mitigate this loss of snowpack storage in an attempt to sustain fluvial corridor ecosystems and human infrastructure.

With a common objective to increase water storage, beaver-mimicry stream restoration (BMR) is becoming an increasingly common practice (Pollock et al. 2014, 2018; Bouwes et al. 2016; Weber et al. 2017; Lautz et al. 2019). These projects typically include the installation of multiple instream beaver-mimicry structures (BMSs; a.k.a. beaver dam analogs) that are designed to have an ecohydrological function similar to beaver dam complexes (Pilliod et al. 2018; Pollock et al. 2018; Lautz et al. 2019; Nash et al. 2021). BMSs include an on-channel structure and an associated upstream pool, which causes the stage of the stream and adjacent groundwater levels to increase upstream of the structure. The treatments may also include activation of side channels at high flows, inundation of the floodplain during high flows, or seasonal filling of off-channel ponds. The additional seasonal inundation caused by BMSs often enhances groundwater recharge, and they are often advertised to increase dry-season streamflows.

Numerous studies have provided observational evidence that natural beaver activity and BMR increase groundwater levels in the alluvial aquifer, typically by less than 1 m (Westbrook et al. 2006; Janzen and Westbrook 2011; Majerova et al. 2015; Bouwes et al. 2016; Pollock et al. 2018). Some investigations have observed little change in groundwater levels following the implementation of BMR or wet meadow restoration projects (Klein et al. 2007; Scamardo and Wohl 2020), suggesting that the observed changes in groundwater elevations are dependent on the type of treatment used, the hydrogeologic setting, and the monitoring design. Dry-season streamflows are often suggested to increase following BMR; however, quantifications of these increases have been limited, likely due to the difficultly in quantifying small changes in streamflow with confidence (Burns and McDonnell 1998; Gurnell 1998; Westbrook et al. 2006; Pollock et al. 2007, 2018; Janzen and Westbrook 2011; Nyssen et al. 2011; Majerova et al. 2015; Bouwes et al. 2016; Wegener et al. 2017; Hunt et al. 2018). Some researchers have suggested that increases in streamflow due to wet-meadow restoration will be too small to measure and the higher groundwater elevations would also cause higher groundwater evapotranspiration (ET_{gw}) (Nash et al. 2018, 2020). This increase in ET_{gw} may more than offset the increased net stream gains that would be otherwise be expected. While the changes in surface-water storage due to the creation of on-channel ponds behind BMSs are evident, the changes in groundwater flow patterns relevant to driving seasonal subsurface storage are not well understood, especially in the context of project designs that are most likely to meet hydrologic objectives.

When groundwater recharge increases along a restored stream reach, the additional water will ultimately be partitioned between different potential outputs from the reach, such as groundwater discharge to the stream, down-valley groundwater outflow, or evapotranspiration. Aquifer properties and the proximity of seasonal groundwater mounds to surface waters will determine the time needed for higher hydraulic heads to propagate through the aquifer and increase groundwater discharge to streams (Theis 1940; Bredehoeft et al. 1982; Bredehoeft 2002; Kendy and Bredehoeft 2006). The concept of mounding helps to aggregate perspectives on the timing of both water and energy movement through the alluvial aquifer.

Past research has demonstrated that streams with more sinuosity or more complex bed topography (e.g., pool-riffle sequences, beaver dams, or BMSs) exhibit more hyporheic exchange between the stream and the underlying aquifer under steady-state conditions (Harvey and Bencala 1993; Kasahara and Wondzell 2003; Cardenas et al. 2004; Kasahara and Hill 2006; Cardenas 2008, 2009; Gomez-Velez et al. 2017). Work in the steady-state perspective has been critical to understanding the fundamental drivers of stream subsurface exchange, but the need for more dynamic and scalable conceptualizations of hyporheic flow has become clear as the attention of land managers is shifting toward seasonal water storage for ecosystem or human demands (Gomez-Velez et al. 2017). For example, modeling of transient hyporheic exchange or lateral contributions from hillslopes has shown that variations in alluvial groundwater levels over time play an important role in determining the exchange of water between streams and their associated alluvial aquifers (Wroblicky et al. 1998; Woessner 2000; Chen and Chen 2003; Boutt and Fleming 2009; Malzone et al. 2016; Schmadel et al. 2016; Gomez-Velez et al. 2017; Ward et al. 2017). Short-term variations in stream stage due to diel cycles or storm events have also been shown to cause substantial lateral water exchange between surface waters and the banks, resulting in bank storage (Sawyer et al. 2009; Gomez-Velez et al. 2017). Studies of changes in storage dynamics due to wet-meadow restoration on gaining streams suggest that groundwater levels rise in response to the treatment, but these increases do not result in meaningful changes in groundwater discharge to the stream during the dry season (Nash et al. 2018). Dynamic models of hyporheic water exchange that include periodic off-channel inundation have only rarely been developed to understand the influence of changing groundwater recharge (Helton et al. 2014),

and to our knowledge have not been developed to understand the related hydrologic effects of BMR activities. From this perspective, stream restorations that are intended to increase seasonally dynamic hydrologic storage may be treated as manipulative experiments with potential to advance the evolving science of fluvial corridor hydrology (Harvey et al. 2019).

The potential for stream restoration to influence seasonal water storage in local alluvial aquifers partly depends on the hydrogeologic setting that determines the overall gaining or losing nature of the stream (Larkin and Sharp 1992; Winter et al. 1998; Woessner 2000). Stream reaches where alluvial groundwater elevations are substantially lower than the streambed are unlikely to experience local increases in dry-season net stream gains since the resulting groundwater mounds would be unlikely to be of sufficient magnitude to reverse or reduce stream loss during the dry season. In contrast, where groundwater levels are substantially higher than the stream stage, only mounds created by substantial recharge farther from the channel are likely to persist long enough to create seasonal time scale storage that results in meaningful local increases in dry-season net stream gain (Cardenas 2009; Nash et al. 2018).

In this study, we explore the simulated influence of different BMR treatment designs in various hydrogeologic settings. We used simulations of dynamic stream/aquifer systems in MODFLOW to explore the general nature of effects to the groundwater system. The modeled scenarios were inspired by the choices in BMR design frequently considered in the intermountain western United States (U.S.) and were implemented in the context of the different hydrogeologic settings of stream corridors common in these systems. We focus on the influence of BMR on alluvial aquifers in less constrained reaches of the fluvial corridor, where the effects of seasonal variation in groundwater recharge from the stream or connected surface waters dominates over the effects of variation in lateral recharge from hillslopes. In these systems, recharge from surface waters at higher flows creates higher water tables and seasonally transient groundwater mounds in the regions surrounding seasonal sources of recharge. This conceptualization complements studies that have focused on the changes in lateral groundwater inflow due to changes in stream stage for gaining streams (Nash et al. 2018) to extend understanding of the effect of BMR treatments to settings where alluvial recharge originates predominantly from stream-derived surface waters (Westbrook et al. 2006) and to systems where streams are generally losing.

METHODS

We developed MODFLOW groundwater models of hypothetical stream corridors to evaluate the general nature of hydrologic effects from varied BMR treatment designs in different hydrogeologic settings (Figure 1; Table 1). These models included the addition of a single BMS and various off-channel inundation scenarios. We recognize that most BMR treatments include the installation of several BMSs, but chose to focus on the mechanics of a single structure to aid in the fundamental scientific understanding necessary for effective management decisions involved with selecting BMR locations and designs. The potential for interactions between a sequence of structures to cause emergent, nonadditive hydrologic behavior may be a useful direction for future research. Sensitivity analysis was used to evaluate how variations in site-specific hydrogeologic characteristics change the hydrologic effects of BMR treatments.

Numerical models were developed based on a simplified conceptual model of the effects of BMR installations on an incised stream with a snowmelt-dominated hydrograph, focusing on settings where variation in groundwater recharge from the channel or channel-connected surface waters is the dominant influence on storage in the alluvial aquifer. This setting is common for stream restoration activities in the intermountain west of the Unites States, and modeling scenarios in this setting were inspired by discussions with stream restoration practitioners in the headwaters of the Missouri River in southwest Montana, USA. These simple models are not intended to represent the absolute behavior or complexities of any single system or design, but are intended to provide an understanding of the types of changes in groundwater dynamics that might be expected.

The modeled scenarios were designed to evaluate how the addition of a single BMS to a stream affects groundwater-mediated hydrologic connections through the fluvial corridor. Three versions of each modeling scenario (Figure 1; Table 1) were developed to simulate differing hydrogeologic settings, where the boundary conditions were defined to simulate a stream reach that was generally gaining (G), losing (L), or strongly losing (SL) within the model domain.

Conceptual Model

Simulated fluvial corridors were based on streams with alluvial aquifers assumed to be 5–20 m thick. Alluvial aquifers of this size are consistent with second to fourth-order streams in the intermountain

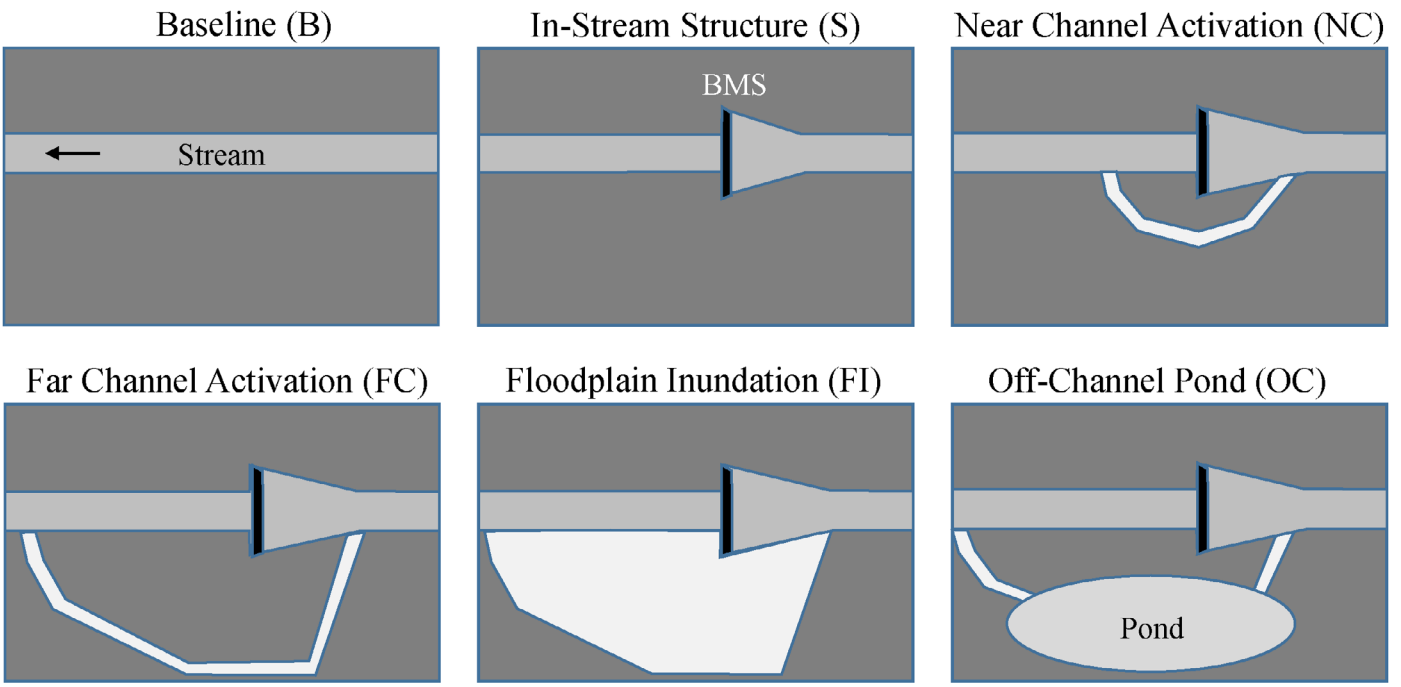

FIGURE 1. Plan views of conceptual schematics for scenarios selected to explore common beaver-mimicry stream restoration (BMR) treatment designs (also see Table 1).

TABLE 1. Summary of models used to explore various BMR designs in different hydrogeologic settings.

	Hydrogeologic setting		
Design scenario	**Gaining stream (G)**	**Losing stream (L)**	**Strongly losing Stream (SL)**
Baseline (B)	G-B	L-B	SL-B
On-Channel Structure (S)	G-S	L-S	SL-S
Near Channel Activation (NC)	G-NC	L-NC	SL-NC
Far Channel Activation (FC)	G-FC	L-FC	SL-FC
Floodplain Inundation (FI)	G-FI	L-FI	SL-FI
Off-Channel Pond (OC)	G-OC	L-OC	SL-OC

west, which also tend to be areas where natural beaver dams persist through high flows (Macfarlane et al. 2017). Floodplain soils that develop from overbank deposition are often dominated by fine-grained deposits. However, the alluvial sediments that make up the aquifer are typically composed of coarser-grained sands and gravels, due to the higher preservation potential of coarse-grained sediments in a fluvial corridor (Aslan 2013). Sand aquifers have saturated hydraulic conductivities (K) ranging from about 10 to 100 m/day (Heath 1983). Bedrock underlies the alluvium (Figure 2), and bedrock with limited secondary permeability normally has a K value less than 1 m/day (Heath 1983).

For a given reach of the stream corridor, groundwater enters an alluvial aquifer from upstream alluvium, and from uplands and bedrock along the lateral edges (Shaw et al. 2014). Our conceptual model focuses on areas where inflow from the upstream alluvium is typically substantially higher than the lateral inputs. Groundwater can leave a reach of the corridor via subsurface flow paths through the downstream alluvium. For the purpose of this study, we assume alluvial groundwater loss to, or gain from, deeper regional aquifers are negligible.

Analysis of the seasonal storage generated by BMR requires a detailed understanding of the dynamics of surface-subsurface exchange of water between the alluvial aquifer and surface waters driven by differences in head. Streams often vary between gaining and losing over a range of scales in both space and time (Prudic 1989; Winter et al. 1998; Woessner 2000; Niswonger and Prudic 2005). We are considering streamflows and stream stages in settings with a snowmelt-driven hydrologic regime. In areas with relatively low lateral contributions like intermountain basins, the associated seasonal changes in stream stage and the resulting potential for off-channel floodplain inundation at higher flows are a primary control on groundwater recharge and the formation of groundwater mounds.

The movement of water between the aquifer and atmosphere via precipitation and ET_{gw} may also be important to understand the influence of BMR, particularly considering the potential for increased water availability to plants. A common goal of BMR is to reestablish or expand the riparian zone (Pilliod et al. 2018). Where the water table is close to the land surface ET_{gw} can supply much of the water used by wetland plants, and ET_{gw} can be a substantial portion of the groundwater budget (Leake and Gungle 2012). Local precipitation and snowmelt can provide groundwater recharge when water is able to infiltrate through the vadose zone. Groundwater recharge from this infiltration likely occurs during large precipitation events or snowmelt, but under normal circumstances, this contribution is small compared to other inputs to a reach control volume.

Based upon this conceptual model, a finite volumetric groundwater budget for a control volume of the alluvial aquifer (Figure 2) during a given period of time can be expressed as:

$$G_{\text{in-al}} + G_{\text{in-lat}} + S_{\text{in}} + R = G_{\text{out-al}} + S_{\text{out}} + \text{ET}_{\text{gw}} + \Delta S, \quad (1)$$

where $G_{\text{in-al}}$ and $G_{\text{out-al}}$ are alluvial groundwater inflow and outflow; $G_{\text{in-lat}}$ is lateral groundwater inflow; S_{in}, and S_{out} are groundwater recharge and discharge from/to surface waters; R is groundwater recharge from local precipitation; ET_{gw} is groundwater evapotranspiration; and ΔS is the change in the volume of water stored in the aquifer.

Net changes in storage (ΔS) at the same time of year over multi-year time scales are expected to be near zero if there are no major alterations to the system (i.e., long-term dynamic equilibrium). However, the potential to increase local storage of water that could then contribute to dry-season streamflow within a given reach would necessarily arise from increasing the seasonal amplitude of ΔS around zero. When ΔS is positive groundwater mounds form, and when ΔS is negative these mounds dissipate. As the mounds dissipate water is partitioned among various outputs, such as water flowing to the stream (S_{out}), flowing out of the control volume as groundwater ($G_{\text{out-al}}$), or being used for ET_{gw}.

Baseline Numerical Models

We used MODFLOW 2000 (Harbaugh et al. 2000; Aquaveo 2013) to construct simple, yet spatially and temporally explicit, numerical groundwater flow models of alluvial aquifers influenced by overlying surface waters. MODFLOW was developed by the USGS and is a broadly applied numerical solution for groundwater head distributions. Modeling details, including a discussion of model limitations and assumptions, such as how MODFLOW addresses the nonlinear groundwater flow equation, are provided in Supporting Information.

The models were constructed to represent a reach of an alluvial aquifer 1000 m long, 100 m wide, and 10 m thick (Figures 2 and 3). Aquifer properties were homogeneous and isotropic throughout the model domain and were based on literature values for an unconfined coarse sand aquifer (K = 25 m/day; specific yield (S_y) = 0.2; Freeze and Cherry 1979; Heath 1983; Fetter 1994).

The models simulated transient hydrologic conditions over time and were run for 5 years (1,826 days) using 261 weekly stress periods and daily computational time steps. In MODFLOW, "stress periods" are the feature that allows for nonsteady-state modeling, such that boundary conditions can vary among stress periods but are constant within a stress period.

Specified flux boundary conditions were used to simulate groundwater inflow through the upstream alluvium, and along the lateral edges of the model domain to simulate hillslope contributions (Figure 3).

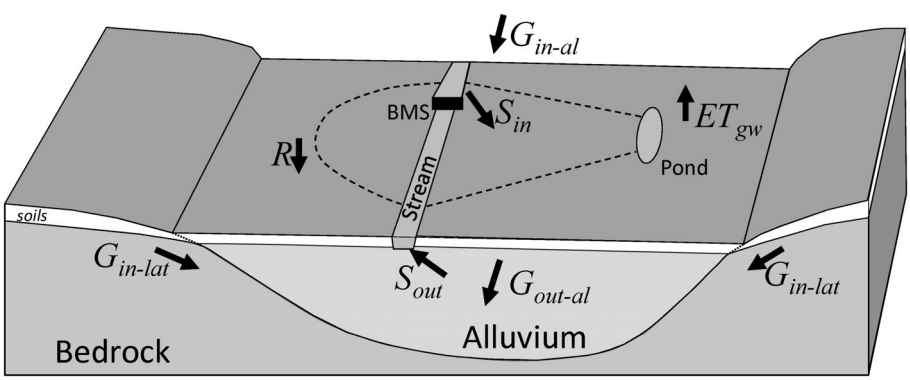

FIGURE 2. Conceptual block model of the stream/aquifer system used to design the simplified groundwater modeling domains for the BMR model scenarios (see Equation 1 for term definitions).

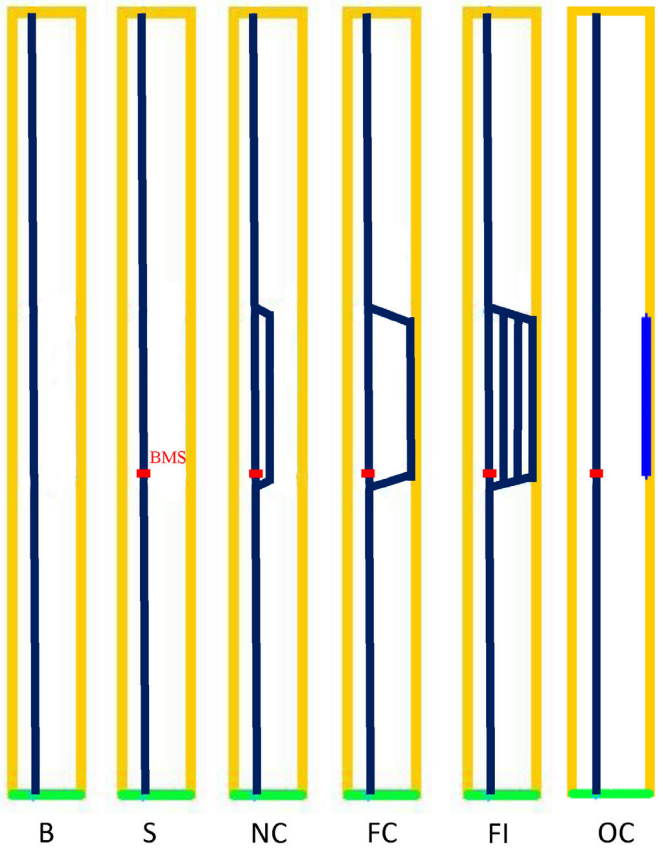

FIGURE 3. Plan view of the numerical models for each of the treatment types. The models had specified flux boundaries (yellow) along the upstream and lateral edges, drains (green) along the downstream edge, and stream boundaries on the cells adjacent to surface flow (dark blue). For the OC scenario, the pond was simulated by adding a river boundary (bright blue) at the same location as the FC channel. The red boxes show the beaver-mimicry structure (BMS) locations. The main channel always had flow and side channels which were active only during high flows in the NC, FC, and FI scenarios.

Alluvial inflow was at a constant 95 m^3/day and lateral inflow was held constant at 5 m^3/day (Figure 4). These inflows were selected because they are reasonable given the permeability of the aquifer, and they provided a slightly gaining stream in the gaining setting, and a slightly losing stream for the losing setting. The rates were held constant because effects due to changes in aquifer saturated thickness (and therefore transmissivity) and hydraulic gradients at the edges of the model domain are anticipated to be slight relative to the effects from the restoration. Constant external boundaries also allow an unconfounded perspective on storage phenomena driven only by dynamic changes in stream stage and groundwater recharge from surface waters within the model domain.

At the downstream end of the model domain, groundwater outflow was simulated using the drain package (Figures 3 and 4) (Banta 2000). Drains only remove water from the model domain, and that only occurs when the groundwater elevation is higher than the drain elevation. The amount of water that drains remove is determined by the difference between the groundwater elevation and the drain elevation, and by a conductance term. We adjusted the drain elevation to create models of stream reaches that were generally gaining, losing, or strongly losing (Winter et al. 1998) (Table S1.1). The drain conductance was set to 10 m^2/day, which provided for adequate groundwater outflow, and did not create flooding. For these models, the drain conductance can be viewed as proportional to the alluvium's cross-sectional transmissivity (i.e., the saturated cross-sectional area of the alluvial aquifer times K; Käser and Hunkeler 2016), so it represents the ease with which water can move down-valley through the alluvial aquifer.

The STR stream package (Prudic 1989) was used to simulate the bidirectional exchange of water between

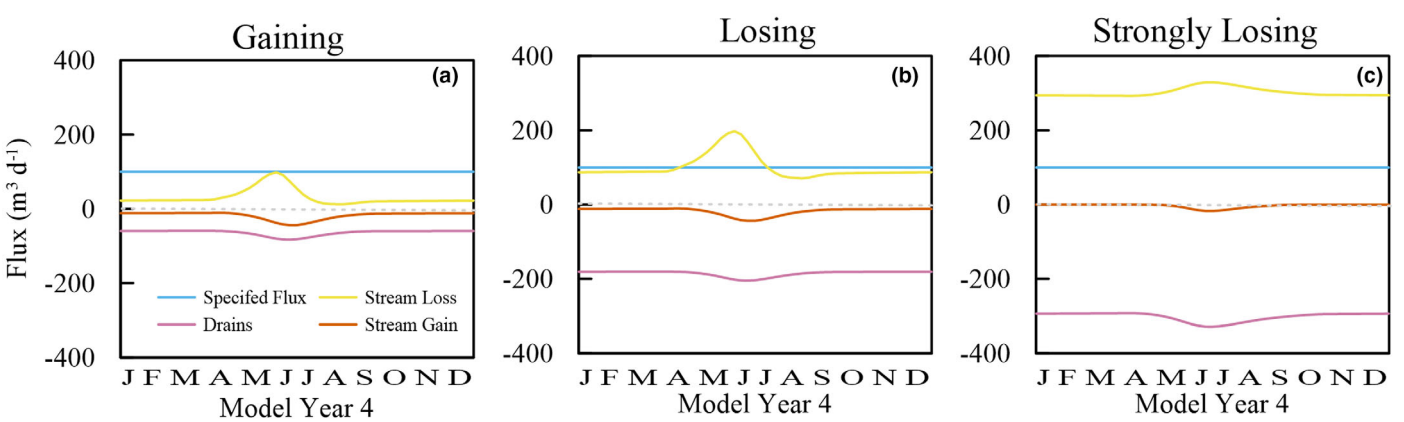

FIGURE 4. Flux values for the boundaries in the baseline models over the last year of simulations (model year 4) for gaining (a), losing (b) and strongly losing (c) hydrogeologic settings. Positive values are inputs to the aquifer, and negative values are outputs from the aquifer.

stream channels and the alluvial aquifer (Figure 3). The STR package allows the stream to be gaining water from or losing water to the aquifer depending on the relative elevation of the stream surface (stage) and the groundwater elevation in each associated underlying cell. The STR package includes simple channel hydraulic simulation that calculates the stream stage based on the amount of stream discharge (e.g., m^3/s), the channel geometry, and Manning's roughness coefficient (Barnes 1967; Prudic 1989). The annual streamflow hydrograph (Figure 5) at the upstream end of the reach was identical for each modeled year, and was based on a simplified symmetrical snowmelt-driven stream hydrograph, with an average streamflow of 100 L/s, peak flows of 420 L/s, and baseflows of 37 L/s. The top of the streambed was set 1 m below the floodplain surface. The amount of water moving between the stream and the aquifer depends on the difference in head between them, the streambed conductance, and the permeability of the aquifer. We used streambed conductance values of 0.5 m^2/day/m based on a vertical hydraulic conductivity of a silt bottom (K_{bed} = 0.5 m/day) because pools with fine-textured beds typically cover a much greater proportion of the streambed than riffles in our study streams (see Supporting Information S1.1). The STR package does not simulate unsaturated flow, but we considered this to be an appropriate simplification given that recharge occurs over several months (Figure 5), and the depth to groundwater is only a few meters (Niswonger and Prudic 2005).

Effects of ET_{gw} were not included in the modeling scenarios to allow for unconfounded comparisons of the fundamental behavior of groundwater storage among simulations. However, ET_{gw} was included in the sensitivity analysis to evaluate potential effects

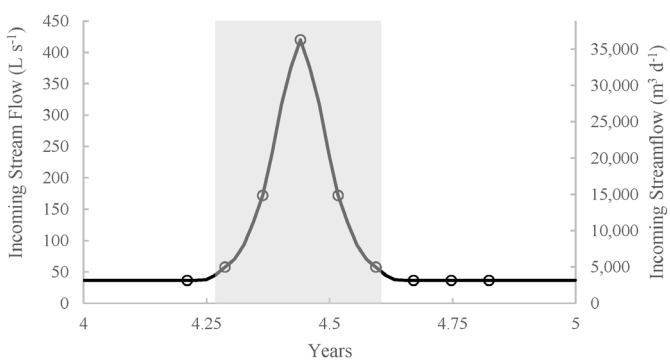

FIGURE 5. The simplified snowmelt-driven stream hydrograph used for model boundary conditions based on the stream package. The duration of diversion is shown in gray, as defined by the period when 10% of the streamflow was diverted in the NC, FC, and FI scenarios. The model output times shown with circles on this figure reflect the outputs shown for model year 4 in Figure 8a. Note that values are provided in both L/s and m^3/day to provide perspective for results from both the groundwater and surface-water perspectives.

to the dynamic water balance. More thorough exploration of the effects of evapotranspiration on the water balance deserves its own effort, and is underway in parallel research. Groundwater recharge from local precipitation was assumed to be negligible at the reach scale (Chen and Chen 2003), as is typical for semi-arid areas in southwest Montana, USA.

Analysis across BMR Scenarios

The simulated influence of BMSs was added to the baseline MODFLOW models to evaluate changes in model outputs. The model outputs of interest included groundwater recharge from surface waters (gross stream loss), groundwater discharge to surface waters (gross stream gains), net stream gains (gross stream gains minus gross stream loss), and down-valley groundwater outflow. Groundwater level dynamics were also evaluated. Five BMR treatment configurations were simulated in the gaining, losing, and strongly losing hydrogeological settings to evaluate the implications of different BMR designs (Table 1; Figures 1 and 3). These treatments were inspired by designs used for BMR projects that we have monitored in southwest Montana, USA. The treatments included installation of a BMS that creates: (1) an on-channel pond (S), (2) an on-channel pond with seasonal reactivation of a side channel near the stream (NC), (3) an on-channel pond with seasonal reactivation of a side channel further from the stream (FC), (4) an on-channel pond with seasonal inundation of the floodplain (FI), and (5) an on-channel pond with seasonal filling of an off-channel pond (OC).

The creation of an on-channel pond was a part of all treatment scenarios, and was simulated by introducing a step in the slope of the streambed relative to the baseline configuration. The upstream portion of the step had a relatively shallow slope to represent the pool behind the BMS. At the bottom of the pool, the streambed dropped 1 m from one cell to the next, to the level of the baseline, to represent the change in stream stage created at the location of the BMS. While this approach simulates the change in stream stage (the boundary condition for the groundwater model), it does not simulate the additional storage added to the surface-water system due to the on-channel pond. For this study this approach is intended to simulate a BMS; however, the effect would be similar for other topographic elements on the streambed, such as natural or constructed riffles.

Streamflow was routed into side channels for the NC, FC, and FI scenarios (Figures 1 and 3). Ten percent of streamflow was routed into the side channels when stream discharge was greater than 40 L/s. This configuration resulted in side-channel activation for

19 weeks each year, from mid-April to early-August (Figure 5). The conductance of the streambed sediments for the side channels was simulated as being the same as the main channel. Since various conceptualizations could be used to justify both higher and lower values, we believe that this is an appropriate simplification.

The influence of an off-channel pond for the OC scenario (Figures 1 and 3) was simulated using the head-dependent boundary condition implemented in MODFLOW's river package (Harbaugh et al. 2000). The river package simulates groundwater/surface-water exchange almost identically to the stream package (Brunner et al. 2009), except channel hydraulics are not simulated and the stage is explicitly defined in the river package. We conceptualized the pond as a floodplain depression that is filled when a side channel is activated during high flows in the spring. After filling, the stage in the pond decreased until mid-September, at which point the pond went dry and thus ceased to provide recharge. The change in pond stage over the summer was based on the simulated loss to infiltration (recharge to the aquifer) and reasonable rates of open-water evaporation, given a pond approximately 30 m wide by 200 m long, and with 600 mm/year of evaporation. Off-channel ponds, or groups of ponds, of this size are common features of natural beaver complexes (e.g., see Wegener et al. 2017). To maintain conservation of mass in the water budget, calculated streamflows were reduced at the start of snowmelt by the amount of water that is needed to account for the total annual infiltration and evaporation from the pond. Filling the pond required between 8.5% and 12.6% of streamflow for 1 week in the early spring, depending on the setting.

Assessing Independent Parameter Sensitivity for the Far Channel Scenario

The influence of different hydrologic parameters on the inferred effects of BMR on groundwater storage dynamics was evaluated by independently perturbing parameter values for aquifer K, aquifer S_y, streambed conductance, and drain conductance in the baseline and far channel (FC) scenarios in each of the hydrogeologic settings. The FC scenario was used since provided the largest influence of the non-off-channel pond scenarios, and therefore was reasonably representative of most BMR treatments. ET_{gw} was also added to the model to provide a cursory evaluation of its potential importance to the water balance.

Each of the tested parameters was varied within realistic values for the northern Rocky Mountains of the U.S. The tested K and S_y values were appropriate for unconsolidated sediments from silt to gravel (Heath 1983). In most unconsolidated sediments S_y and K are related by the pore structure of the sediment (Heath 1983); however, we treated S_y and K as independent parameters in this sensitivity analysis to assess their unique influences. The streambed conductance values represent streams with the same geometry, but with bed sediments ranging from clay to sandy gravel. The drain conductance value influences the rate at which water discharges from the downgradient model boundary, and so represent settings ranging from a downstream constriction (e.g., a bedrock notch) to a downstream reach with a thicker and wider accumulation of high permeability sediments. Tested maximum ET_{gw} rates (ET_{max}) were based on literature values for bare soil to dense willow stands, and the evapotranspiration extinction depth (ET_{XD}) was based on values from grass to trees in soils ranging from silty-clay loam to sand (Johns 1989; Lautz 2008; Leenhouts et al. 2006; Persson 1995; Scott et al. 2004; Shah et al. 2007).

The primary criterion used to compare the sensitivities of simulated storage dynamics to variation in parameter values was the difference in net stream gain between the baseline and FC model in mid-August of the 4th model year (stress period 240). Changes in groundwater recharge from surface waters and groundwater discharge to surface waters were also evaluated for stress period 240, and are included in the Supporting Information (Sections S2.3 and S2.4). This first-order approach only provides information about the independent influence of the parameter values tested, and does not include interactions between parameters. Sensitivity analysis is discussed in greater detail in Supporting Information (Section S2).

RESULTS

Simulation results provide a heuristic illustration of how general patterns in the groundwater budget components and the head distribution in the aquifer respond to different BMS strategies. To evaluate the effects of BMR on the annual groundwater budget, we focused on summary statistics for model year 4 (the last year modeled), and effects during the dry season were evaluated over a week in mid-August of year 4 (stress period 240). Comparisons of differences in summary statistics relative to the baseline model provide perspective on the influence of BMR on hydrologic patterns driven by design choices, and how these patterns differ in systems where the stream is gaining, losing, or strongly losing. The sensitivity analysis provides perspective on the relative

influence of site-specific hydrologic properties on the nature of the alluvial aquifer's response to restoration.

BMR Scenarios

While this exercise was hypothetical in nature and does not reflect the complexity of a real stream, the use of deterministic models under controlled conditions generates data that allow the calculation of metrics that directly reflect how a restored stream might be expected to differ from its unrestored condition in terms of its interactions with the alluvial aquifer, even when the effects of a single BMS are more subtle than could be measured in the field. Hence, these modeling results represent general patterns in the hydrologic response that would be expected from common decisions regarding BMR design in differing hydrogeologic settings.

Recharge from Gross Stream Loss. All BMS treatment types in all settings caused groundwater recharge from gross stream loss within the model domain to increase, both on an annual basis and during the dry season (Tables 2 and 3; Figure 6a and 6b). In general, the results showed that the change in recharge from surface waters was lowest in the

TABLE 2. Summary of annual water budget results for model year 4.

Scenario	Change in gross stream loss (m^3/year)	change in gross stream gain (m^3/year)	Change in net stream gain (m^3/year)	Change in ground water outflow (m^3/year)	Average change in annual head amplitude (m^3/year)	Change in dynamic storage (m^3/year)
G-S	20,285	19,122	−1,163	1,408	0.04	782
G-NC	19,923	18,551	−1,371	1,381	0.04	782
G-FC	20,396	18,851	−1,545	1,367	0.04	857
G-FI	20,168	18,834	−1,333	1,411	0.05	920
G-OC	8,869	4,714	−4,155	4,289	0.07	1,344
L-S	15,686	14,363	−1,324	1,357	−0.15	−3,070
L-NC	15,053	14,013	−1,040	1,386	−0.06	−1,159
L-FC	15,523	14,329	−1,194	1,375	−0.05	−1,096
L-FI	15,426	14,125	−1,301	1,385	−0.05	−998
L-OC	3,468	17	−3,451	3,711	0.14	2,713
SL-S	12,282	7,402	−4,880	3,711	0.00	−1
SL-NC	11,566	6,781	−4,785	3,659	0.00	−22
SL-FC	12,200	7,301	−4,899	3,714	0.00	45
SL-FI	12,042	7,112	−4,930	3,755	0.01	136
SL-OC	5,355	−135	−5,491	5,220	0.12	2,367

TABLE 3. Summary of results for mid-August of model year 4 (Stress Period 240).

Scenario	Change in gross stream loss (m^3/day)	Change in gross stream gain (m^3/day)	Change in net stream gain (m^3/day)	Change in groundwater outflow (m^3/day)	Minimum head change (m)	Maximum head change (m)	Average head change (m)
G-S	55.2	60.7	5.5	4.9	0.01	0.18	0.08
G-NC	54.2	59.9	5.7	4.8	0.01	0.19	0.08
G-FC	54.9	60.8	5.8	4.9	0.01	0.18	0.08
G-FI	54.4	60.8	6.4	5.1	0.01	0.19	0.08
G-OC	19.3	31.3	11.9	16.0	0.10	0.78	0.55
L-S	42.2	48.0	5.9	4.8	0.01	0.18	0.07
L-NC	41.3	47.4	6.0	4.7	0.01	0.18	0.08
L-FC	41.8	48.0	6.2	4.8	0.01	0.18	0.08
L-FI	41.1	48.0	6.8	5.0	0.01	0.19	0.08
L-OC	5.7	18.3	12.6	14.8	0.03	0.50	0.25
SL-S	27.9	26.3	−1.6	9.5	0.02	0.19	0.09
SL-NC	21.4	20.1	−1.3	5.9	0.02	0.19	0.09
SL-FC	27.4	26.2	−1.2	9.6	0.02	0.19	0.09
SL-FI	26.6	25.8	−0.8	9.9	0.02	0.20	0.09
SL-OC	1.8	8.4	6.6	20.5	0.03	0.38	0.20

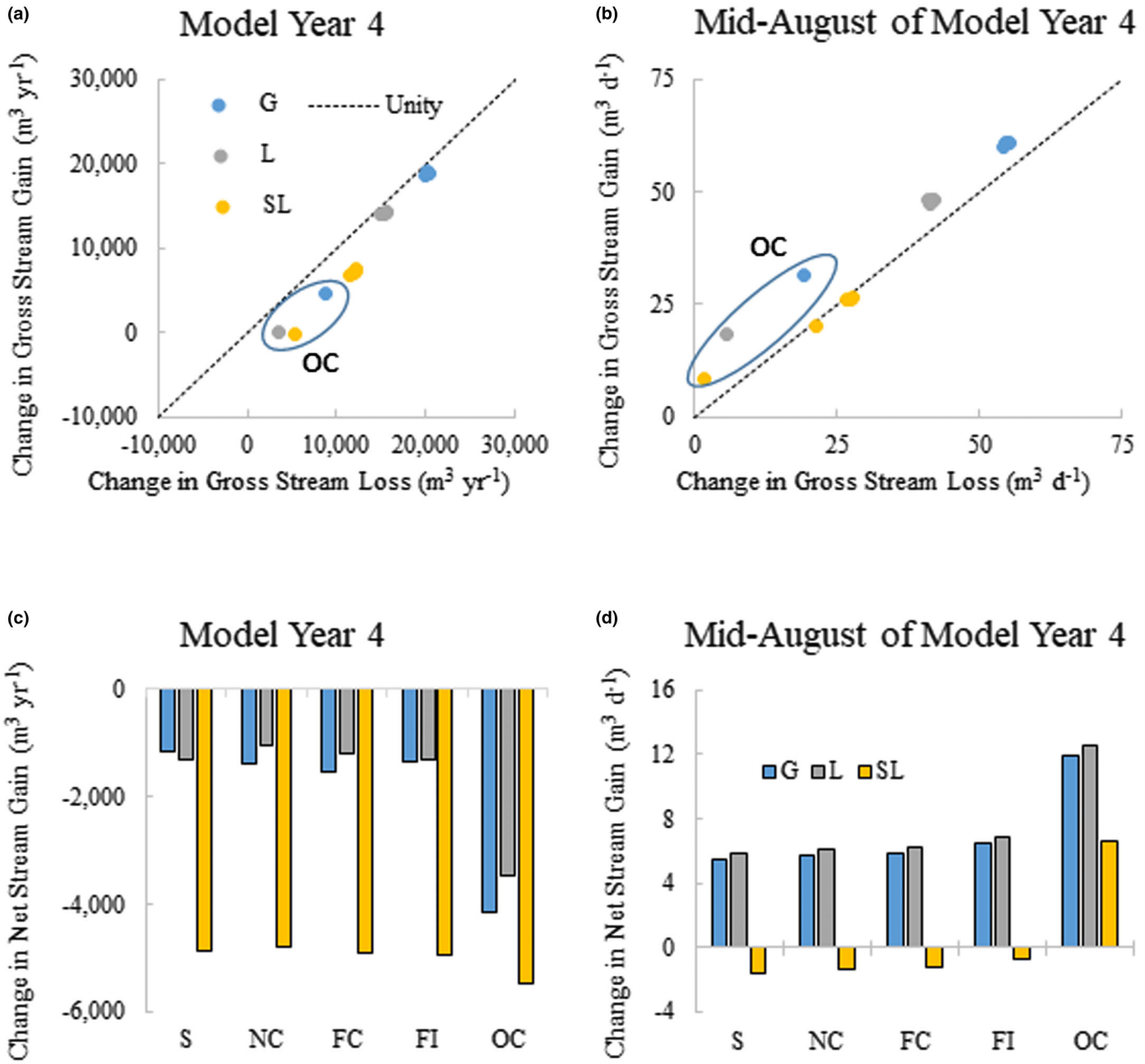

FIGURE 6. Top panels represent simulated gross stream gains (i.e., groundwater discharge to the stream) plotted vs. gross stream loss (i.e., groundwater recharge from the stream) within the model domain, based on (a) annual totals during model year 4 and (b) average values for a week in mid-August. Off-channel pond scenario results are highlighted. The bottom panels represent change in net stream gain resulting from restoration for all model scenarios and groundwater settings, based on (c) annual totals during model year 4 and (d) average values for a week in mid-August.

strongly losing stream setting and greatest in the gaining stream setting. This pattern reflects how treatments cause portions of the stream to become more strongly losing, and that shift is most pronounced when that portion of the stream was gaining prior to treatment. For all settings, the OC treatment resulted in the smallest change in gross stream loss (Figure 6a and 6b).

Discharge to Gross Stream Gain. Similar to the effects on gross stream loss, gross stream gain from groundwater within the model domain increased for most treatments in all settings, both on an annual basis and during the dry season (Tables 2 and 3; Figure 6). These increases were largely proportional to the increases in gross stream loss (Figures 6a and 6b). The OC treatment resulted in the smallest

change in gross stream gain for all settings (Figure 6).

Net Stream Gain. All BMR treatments in all settings caused a reduction in the average annual net stream gain (Figure 6c). While the increased gross stream losses were partly offset by increased gross stream gains after treatment, the net effect on an annual basis was for the stream to lose more water to the aquifer (Figures 6c and 7), which was balanced in the water budget primarily by increases in subsurface down-valley flow, as discussed below.

Model results during the dry season were markedly different from the annual average results (Figures 6c, 6d, and 7). All BMR treatments in the gaining and losing settings resulted in increases in dry-season net stream gains (Table 3), with the OC treatment causing the largest increase. In the strongly losing setting, all treatments other than OC resulted in decreased net stream gains (Table 3). The largest of these simulated increases represented a 0.4% increase in mid-August streamflow, which would be immeasurably small from a field perspective.

Down-Valley Groundwater Outflow. All treatment types in all settings resulted in an increase in groundwater outflow from the downstream end of the model domain (Tables 2 and 3), balancing the decreases in net stream gain. These increases were similar in the gaining and losing stream settings. In the strongly losing stream setting, groundwater outflow increases were greater. The OC treatments in all settings resulted in groundwater outflow increases 1.4 to 3.1 times greater than the other treatments (Tables 2 and 3).

Groundwater Levels. For all BMR scenarios groundwater mounds formed in recharge zones during high flows and then dissipated as they drained to various outputs during lower flows. The groundwater mound created by the instream structure persisted throughout the year, but expanded and contracted with flow (e.g., Figure 8a). The additional groundwater mounding created by seasonal off-channel inundation (NC, FC, and FI) dissipated rapidly once baseflow was reached. This rapid dissipation caused the S, NC, FC, and FI scenarios to all result in similar changes to dry-season groundwater levels (e.g., Figure 8b). Mid-August groundwater levels near the upstream and downstream ends of the model domain showed slight changes while groundwater levels near and immediately upstream of the BMS and off-channel pond showed more pronounced increases (Table 3 and Figure 8b).

The simulated changes in groundwater levels relative to baseline ranged up to 78 cm. These values are similar to those reported in other studies (Westbrook et al. 2006; Janzen and Westbrook 2011; Majerova et al. 2015; Bouwes et al. 2016; Pollock et al. 2018). Monitoring results from BMR projects associated with our field studies in southwestern Montana also demonstrate a similar response, with maximum observed changes in groundwater levels after BMS installations of about 60 cm (Figure S3.1).

Change in Annual Head Amplitude. The amount of water stored within the unconfined alluvial aquifer and then released on an annual basis will be related by specific yield (S_y) to the spatially aggregated amplitude of annual mounding. To measure this model output, we compared the volume of storage between minimum and maximum heads for each cell during model year 4. For all scenarios other than OC, the simulated changes in average amplitude of groundwater hydrographs due to the addition of BMSs were similar within each hydrogeologic setting

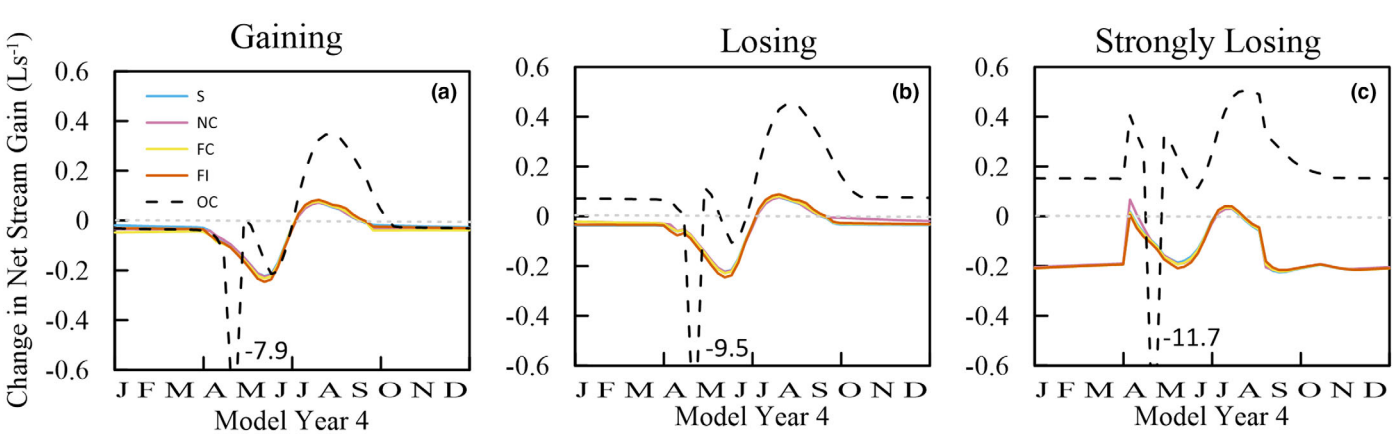

FIGURE 7. The change in net stream gains over model year 4 relative to the unrestored baseline simulation for gaining (a), losing (b) and strongly losing (c) hydrogeologic settings.

(Table 2). In the gaining models, the amplitude increased, indicating that more water was stored and then released from the aquifer within the model domain each year. The losing models showed a decrease in amplitude due to a less variable stream stage near the BMS (Figure 8c). The strongly losing models showed only modest increases or decreases in the amplitude. In all hydrologic settings, the OC scenario resulted larger changes in storage amplitudes than the other scenarios.

Sensitivity Analysis

The sensitivity analysis of the FC treatment scenario allows comparisons of the relative influence of reasonable variation in different model parameters on local alluvial groundwater storage behavior. Even though changes in dry-season net stream gains were negligible compared to streamflows, we explore variation in this response variable as a useful comparative summary metric of local seasonal storage behavior.

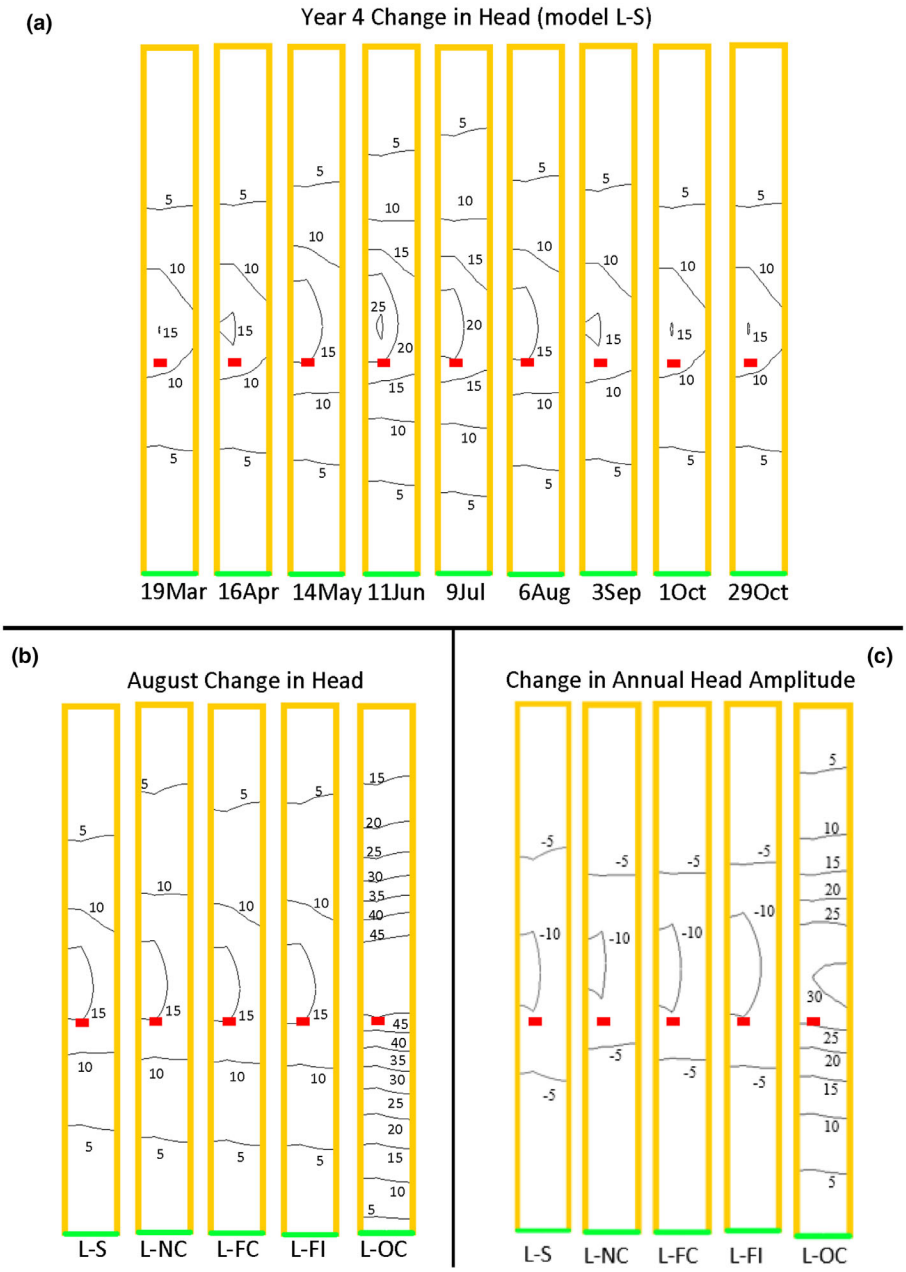

FIGURE 8. Examples of the changes in plan-view spatial head distribution created by BMS structures. (a) Seasonal dynamics in the amount head increased due to a BMS creating an on-channel pond in a losing hydrogeological context (S-L scenario). (b) Comparison of the amount that head was increased in mid-August across all BMS scenarios in the losing hydrogeological context. (c) The change in the seasonal amplitude of mounding compared across all BMS scenarios in the losing hydrogeological context. Red squares denote the location of the BMS and contour labels are in units of cm.

Changes in gross stream loss and gross stream gain which results from the sensitivity analysis are also included in Supporting Information (Tables S2.2 and S2.3).

With respect to the range of parameter values selected for the sensitivity analysis, dry-season net stream gains were most sensitive to the changes in the K of the aquifer, S_y of the aquifer, and ET_{max} values (Table 4). Variation in streambed conductance and drain conductance had the least influence (Table 4). The greatest simulated increase in dry-season net stream gain due to a single BMS during the sensitivity analysis was 10.7 m^3/day (0.12 L/s), while the greatest decrease was −31.5 m^3/day (−0.36 L/s) (Table 4).

In all settings, the greatest increase in late-summer net stream gains due to the FC treatment occurred at the intermediate K value of 2.5 m/day, which would be representative of a silty sand (Heath 1983). K values less than 2.5 m/day caused net stream gains to be lower and caused the models to be less sensitive to the hydrogeologic setting (Table 4), while K values greater than 2.5 m/day caused the net stream gains to be lower and caused the models to be more sensitive to the hydrogeologic setting (Table 4).

In all hydrogeologic settings, the change in net stream gains was larger with higher S_y, and smaller with lower S_y (Table 4). When S_y was 0.02 (the lowest value tested) the FC treatment resulted in decreased dry-season net stream gains in all hydrogeologic settings. When S_y values were 0.3 or 0.4 the FC treatment resulted in increased dry-season net stream gains in all hydrogeologic settings.

The model results were least sensitive to streambed conductance and drain conductance. However, the differences in the influence of BMR among hydrologic settings were less pronounced when low conductance terms were used (Table 4).

When ET_{gw} was added to the gaining and losing stream models, a direct and linear decrease in dry-season net stream gain emerged as the maximum ET rate (ET_{max}) increased (ET_{XD} was held at 2 m; Table 4). The strongly losing stream model responded similarly up to 600 mm/year, but at 1200 mm/year, the effect was lower than would result from a linear relationship since the groundwater level was held near the extinction depth. The simulation where ET_{max} was 600 mm/year and ET_{XD} was 1 m resulted in little effect on model predictions compared to models without ET simulation since that extinction depth is near the typical depth to groundwater. Increasing ET_{XD} to 2 m resulted in a noticeable decrease in simulated dry-season net stream gains; however, further increases in extinction depth resulted in little additional influence. Regardless of setting, when ET_{max} was 300 mm/year or greater (with an ET_{XD} of 2 m), or when ET_{XD} was 2 m or greater (with ET_{max} at 600 mm/year), the effect of the treatment was a decrease in dry-season net stream gains.

TABLE 4. Summary of sensitivity analysis (FC models). Response values are differences in weekly averages during mid-August of year 4.[a]

Hydrogeologic setting	Change in net stream gain (m^3/day)				
Hydraulic conductivity (K; m/day)	0.025	0.25	2.5	25[b]	250
G	2.6	6.8	8.5	5.8	−14.8
L	2.6	6.8	8.8	6.2	−20.7
SL	2.6	7.0	8.7	−1.2	−31.5
Specific yield (S_y; unitless)	0.02	0.1	0.2[b]	0.3	0.4
G	−3.5	0.8	5.8	8.7	10.1
L	−3.7	0.9	6.2	9.1	10.7
SL	−8.4	−7.6	−1.2	3.5	6.8
Streambed conductance (m^2/day/m)	0.005	0.05	0.5[b]	5	50
G	−0.7	−1.6	5.8	1.7	0.1
L	−0.3	−1.6	6.2	1.6	−0.8
SL	−0.3	−3.2	−1.2	1.0	−1.1
Drain conductance (m^2/day)	0.1	1	10[b]	100	1,000
G	10.3	8.7	5.8	5.0	4.8
L	10.3	8.9	6.2	5.1	5.1
SL	10.3	9.0	−1.2	−3.3	−3.4
Maximum ET rate (ET_{max}; mm/year)[c]	0[b]	150	300	600	1,200
G	5.8	2.2	−1.4	−7.6	−25.0
L	6.2	2.4	−1.1	−10.1	−26.3
SL	−1.2	−6.6	−11.2	−17.1	−22.0
ET extinction depth (ET_{XD}; m)[c]	0[b]	1	2	3	5
G	5.8	5.4	−7.6	−11.9	−10.1
L	6.2	6.2	−10.1	−14.0	−5.8
SL	−1.2	−1.2	−17.1	−9.2	−4.4

[a]The change in net stream gain is calculated as the difference between a baseline model with the parameter of interest at the value indicated, and the FC scenario with the parameter at the same value.
[b]Values used for scenario testing.
[c]For testing the effects of ET_{max} ET_{XD} was set to 2 m, and for testing ET_{XD} ET_{max} was set to 600 mm/year.

DISCUSSION

Results from modeling the effects of different BMR design choices provide a basis for understanding the general types of groundwater-mediated influences that should be expected from common restoration activities. These effects are modified depending on

site-specific hydrologic characteristics. Together, this information is useful for developing site-selection strategies and restoration designs that are likely to meet project objectives.

While this study focused on BMR, the hydrologic patterns illustrated by these modeling exercises also provide insight into the effects of streambed topography and intermittent off-channel streamflows on hydrologic storage in the fluvial corridor. Increased access to the floodplain is an objective in many types of stream restoration, and the potential effects from floodplain inundation are important in many stream corridors.

Influences of Different BMR Designs

Changes in the bidirectional movement of water between the stream and the aquifer are the predominant driver of groundwater-mediated influences from BMR. Installing a BMS directly causes a higher stream stage above the structure, and adjacent groundwater levels rise until a new dynamic equilibrium is established. When BMR treatment designs include intermittent flow through side channels, or floodplain inundation, the geographic pattern of groundwater recharge is also altered. Our modeling (using 1 m tall BMSs) showed increases in groundwater levels by up to 78 cm, which is similar to values reported in other studies (Westbrook et al. 2006; Janzen and Westbrook 2011; Majerova et al. 2015; Bouwes et al. 2016; Pollock et al. 2018), and to values we have observed during our field studies in southwestern Montana.

The response time of seasonal dynamic storage is determined by the response of the hydrologic system to an excitation in hydraulic head (i.e., mechanical energy) in areas of recharge, and the subsequent dissipation of the resulting groundwater mound. Interpreting seasonal dynamics of groundwater mounding provides perspective on how the spatiotemporal distribution of groundwater discharge to a stream responds to the alteration of hydraulic gradients crated by increased groundwater recharge during high streamflows. The time that it takes for a groundwater mound to dissipate explains the magnitude of dry-season effects from different BMR treatments. The rate of mound dissipation is directly related to the transmissivity of the aquifer. Rapid dissipation of mounds for our scenario testing (with aquifer K values of 25 m/day) explains why all treatment scenarios in our models without off-channel ponding had similar effects on dry-season net stream gains and suggests that in many settings the persistence of groundwater mounds may be more important than the spatial distribution of recharge.

Regardless of the BMS type, the ubiquitous consequences of simulated restoration included increased recharge to groundwater (gross stream loss) and increased down-valley groundwater outflow. This suggests the potential for BMR treatments to create storage that extends beyond the treatment reach, which may represent influence beyond seasonal time scales. Depending on the geometry of the downstream aquifer, the increase in groundwater outflow may lead to larger spatial scale, and longer time scale, flow paths that discharge to outputs such as stream gains and evapotranspiration.

Simulated enhancement of seasonal groundwater mounding created by periodic off-channel inundation illustrates the need for conceptual models of fluvial corridors that incorporate a wider array of variably saturated flow paths. For example, the "gill-lung" analogy (Sawyer et al. 2009) provides for unidirectional movement of water from groundwater to the stream (gill), or variably saturated bidirectional movement of water between the stream and its banks (lung); however, intermittently active subsurface flow paths sourced from periodic inundation by surface waters are both variably saturated and unidirectional. This may also represent a hot spot of biogeochemical influence on water quality driven by episodic transport and alternation between aerobic and anaerobic processes (McClain et al. 2003; Boano et al. 2014). This work supports building evidence that the evolution of hyporheic conceptual models to a more holistic fluvial corridor science needs to include transient hyporheic flow paths that are driven by recharge from periodic inundation, which may borrow traits from both gills and lungs (Sawyer et al. 2009; Ward and Packman 2019). Holistic models will also need to account for the associated dynamics of both water and energy movement on stream subsurface exchange along fluvial corridors (e.g., dynamic storage age selection models, Harman et al. 2016).

Influences of Site Characteristics

The results of the sensitivity analysis aid in selecting sites with the appropriate hydrogeologic properties for achieving restoration objectives. The sensitivity analysis suggested that variation in hydraulic conductivity (K), specific yield (S_y), and groundwater evapotranspiration (ET_{gw}) are important considerations in restoration design, because independent variation in these characteristics drove more variation in groundwater storage dynamics than streambed or drain conductance.

Intermediate K values (as for a silty sand) provided the greatest increase in late-summer

streamflows due to striking a balance between allowing more recharge and providing longer storage times. Models with lower K values had groundwater mounds that dissipated more slowly, but the magnitude of the flow was less. For models with higher K values, the groundwater mounds dissipated too rapidly to maintain seasonal time scale storage. At sites with relatively high K values increasing the distance between the area of off-channel inundation and the stream could be used to maintain seasonal time scale storage, but in most stream restoration projects, the distance that water can be diverted using gravity will limit the location of recharge to the floodplain.

Larger S_y values allow a larger volume of water to be stored in the aquifer for a given change in head, and the change in head is strongly influenced by the change in stream stage created by the BMS. In general, S_y increases with grain size due to increased drainage capacity of the courser substrates, so values for clays are quite low while values for gravel and cobbles are high. Since S_y and K are typically related, a balance is needed between maximizing storage volume (course sediments) and providing the intermediate K values discussed above.

The tradeoff between dry-season net stream gains and ET_{gw} showed that ET_{gw} may cause the influence of aquifer storage to be reduced when higher groundwater levels allow for higher ET_{gw}. These effects would be less pronounced if pretreatment depth to groundwater was shallow since the plants would not be water limited prior to treatment. Similarly, higher ET_{gw} would be negligible if posttreatment groundwater levels and capillary zones were below the root depth. Sensitivity analyses of evapotranspiration rates provide a general demonstration of how evapotranspiration and net stream gains are in direct competition for stored groundwater (Chen and Chen 2003). In many cases, this competition caused simulated treatments that would have otherwise increased net stream gains to show a decrease instead, similar to the results of Nash et al. (2018).

The sensitivity analysis also demonstrated how the hydrogeologic setting (net gaining, losing, or strongly losing) may not always be a critical influence on the changes in groundwater recharge regimes resulting from BMR. Differences in the gaining or losing nature of the stream had little influence on simulated dry-season net stream gain when K was low, when drain conductance was low, or when streambed conductance was either high or low (Table 4). The lack of an effect with lower K, lower drain conductance, and higher streambed conductance all suggest that when water can flow to the stream much more easily than it can flow through the aquifer, the water will flow to the stream regardless of setting. The results with low streambed conductance values showed that the opposite is also true; when it is difficult for water to flow to the stream, it will flow out through the aquifer instead. Thus, while the overall gaining or losing nature of a stream is an important characteristic of the fluvial corridor, it cannot be used in isolation to anticipate how the system will respond to restoration activities. Instead, the character of the fluvial corridor needs to be evaluated holistically (Ward and Packman 2019).

Considerations for Achieving Restoration Objectives

The restoration objectives and the site conditions should guide the restoration design. Objectives for a BMR project may include increasing the extent and vigor of riparian vegetation (increased ET_{gw} in the treatment area), increasing dry-season net stream gains in the treatment area, or increasing groundwater outflow through the subsurface of the fluvial corridor (Pilliod et al. 2018). All of these objectives will require an increase in groundwater recharge, but it is the partitioning of that water among these different outputs that will determine if project objectives are met. While each of these objectives is individually worthwhile, their achievement is inherently mutually limited because they are competing for the enhanced recharge (Equation 1).

To increase the extent and vigor of the riparian vegetation, the priority should be to increase groundwater elevation in the root zone over as large an area as possible. An aquifer with a relatively low K, such as a silt, is more likely to meet this objective since groundwater mounds would dissipate slowly. These areas may require several years to become saturated due to the movement of water being limited by the low K, but once they are saturated, they will hold the water for longer following high streamflows. A fine substrate, such as would exist in historical wetlands, would also likely be more suitable for the viability of planted riparian vegetation (e.g., willows, Castro-Morales et al. 2014).

To increase dry-season net stream gains in the area near the treatment, BMR design should promote increased recharge during high streamflows that increase the extent, magnitude, and duration of groundwater mounds that can drive discharge to the stream through the dry season. The persistence of groundwater mounds will depend on the distance between groundwater recharge and the stream, the transmissivity of the aquifer, and the duration of recharge. For our models, treatments that included off-channel ponds provided the greatest influence since the groundwater mounds associated with them remained fully formed through the dry season. Sites with a substrate composed of silty sand also provided

the greatest increase in dry-season net stream gains. Treatment reaches upstream of bedrock notches (low drain conductance), where down-valley groundwater flow would be limited, would also promote increases in net stream gain within the treatment reach. Even in ideal settings, a single BMS is unlikely to meaningfully influence local streamflow.

When the objective of the BMR treatment is to increase long-term average streamflows over areas larger than the treatment reach the design should focus on increasing groundwater outflow to contribute to higher heads over a more extensive aquifer area. The most groundwater outflow will occur at sites where the most gross stream loss occurs and where that water can easily flow through the aquifer at a depth where it is less accessible to plants. That is, sites with strongly losing streams, high permeability aquifer materials, and an unrestricted groundwater flow path down gradient (e.g., an open valley without bedrock notches).

CONCLUSIONS

The groundwater-mediated effects of BMR will vary based on the hydrogeologic characteristics of the treated site and the treatment design. The results of this modeling exercise illustrate important considerations for site selection and BMR design relative to project objectives. The simulated groundwater-mediated changes in net stream gain within the treatment reach due to a single BMS were immeasurably small compared to streamflow, and higher evapotranspiration of groundwater caused decreases in simulated dry-season net stream gains in many settings. However, all simulated BMR treatments caused increases in groundwater recharge that elevated groundwater levels near the BMS and increased down-valley groundwater outflow from the treated reach. Increased down-valley groundwater outflow may ultimately increase larger-scale groundwater storage that results in increased flows downstream of the restoration site.

DATA AVAILABILITY STATEMENT

The three baseline models and the 15 models for the treatment scenarios (Table 1 of the main text) are publicly available through the HydroShare database: http://www.hydroshare.org/resource/d3b23a5e59cb408c8953b6eff2ee7b73.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Details of the numerical groundwater modeling, sensitivity analysis, and monitoring examples.

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AUTHOR CONTRIBUTIONS

Andrew L. Bobst: Conceptualization; formal analysis; funding acquisition; investigation; methodology; writing – original draft; writing – review and editing. Robert A. Payn: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing – original draft; writing – review and editing. Glenn D. Shaw: Conceptualization; methodology; supervision; writing – review and editing.

LITERATURE CITED

Aquaveo. 2013. "Groundwater Modeling System (GMS), v. 9.2." https://www.aquaveo.com/.

Aslan, A. 2013. "Fluvial Environments." In *Encyclopedia of Quaternary Science*, edited by S.A. Elias, 663–75. Elsevier. https://doi.org/10.1016/B978-0-444-53643-3.09988-X.

Banta, E.R. 2000. "MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model; Documentation of Packages for Simulating Evapotranspiration with a Segmented Function (ETS1) and Drains with Return Flow (DRT1)." *U.S. Geological Survey Open-File Report 00-466*. https://pubs.er.usgs.gov/publication/ofr00466.

Barnes, H.H. 1967. "Roughness Characteristics of Natural Channels." U.S. Geological Survey Water-Supply Paper 1849. https://pubs.er.usgs.gov/publication/wsp1849.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier. 2005. "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions." *Nature* 438: 303–09. https://doi.org/10.1038/nature04141.

Berghuijs, W.R., R.A. Woods, and M. Hrachowitz. 2014. "A Precipitation Shift from Snow towards Rain Leads to a Decrease in Streamflow." *Nature Climate Change* 4: 583–86. https://doi.org/10.1038/NCLIMATE2246.

Boano, F., J.W. Harvey, A. Marion, A.I. Packman, R. Revelli, L. Ridolfi, and A. Wörman. 2014. "Hyporheic Flow and Transport Processes: Mechanisms, Models, and Biogeochemical Implications." *Reviews of Geophysics* 52: 603–79. https://doi.org/10.1002/2012RG000417.

Boutt, D.F., and B.J. Fleming. 2009. "Implications of Anthropogenic River Stage Fluctuations on Mass Transport in a Valley Fill Aquifer." *Water Resources Research* 45: 1–14. https://doi.org/10.1029/2007WR006526.

Bouwes, N., N. Weber, C.E. Jordan, W.C. Saunders, I.A. Tattam, C. Volk, J.M. Wheaton, and M.M. Pollock. 2016. "Ecosystem Experiment Reveals Benefits of Natural and Simulated Beaver Dams to a Threatened Population of Steelhead (*Oncorhynchus mykiss*)." *Scientific Reports* 8: 1–12. https://doi.org/10.1038/srep28581.

Bredehoeft, J.D. 2002. "The Water Budget Myth Revisited: Why Hydrogeologists Model." *Groundwater* 40: 340–45. https://doi.org/10.1111/j.1745-6584.2002.tb02511.x.

Bredehoeft, J.D., S.S. Papadopulos, and H.H. Cooper. 1982. "Groundwater: The Water Budget Myth." *Scientific Basis of Water Resource Management* 51: 57. https://doi.org/10.2172/7166138.

Brunner, P., P.G. Cook, and C.T. Simmons. 2009. "Hydrogeologic Controls on Disconnection between Surface Water and Groundwater." *Water Resources Research* 45: 1–13. https://doi.org/10.1029/2008WR006953.

Burns, D.A., and J.J. McDonnell. 1998. "Effects of a Beaver Pond on Runoff Processes: Comparison of Two Headwater Catchments." *Journal of Hydrology* 205: 248–64. https://doi.org/10.1016/S0022-1694(98)00081-X.

Cardenas, M.B. 2008. "The Effect of River Bend Morphology on Flow and Timescales of Surface Water-Groundwater Exchange across Pointbars." *Journal of Hydrology* 362: 134–41. https://doi.org/10.1016/j.jhydrol.2008.08.018.

Cardenas, M.B. 2009. "Stream-Aquifer Interactions and Hyporheic Exchange in Gaining and Losing Sinuous Streams." *Water Resources Research* 45: 1–13. https://doi.org/10.1029/2008WR007651.

Cardenas, M.B., J.L. Wilson, and V.A. Zlotnik. 2004. "Impact of Heterogeneity, Bed Forms, and Stream Curvature on Subchannel Hyporheic Exchange." *Water Resources Research* 40: 1–14. https://doi.org/10.1029/2004WR003008.

Castro-Morales, L.M., P.F. Quintana-Ascencio, J.E. Fauth, K.J. Ponzio, and D.L. Hall. 2014. "Environmental Factors Affecting Germination and Seedling Survival of Carolina Willow (*Salix caroliniana*)." *Wetlands* 34: 469–78. https://doi.org/10.1007/s13157-014-0513-6.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. "Changes in the Onset of Spring in the Western United States." *Bulletin of the American Meteorological Society* 82: 399–415. https://doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2.

Chen, X., and X. Chen. 2003. "Stream Water Infiltration, Bank Storage, and Storage Zone Changes Due to Stream-Stage Fluctuations." *Journal of Hydrology* 280: 246–64. https://doi.org/10.1016/S0022-1694(03)00232-4.

Clow, D.W. 2010. "Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming." *Journal of Climate* 23: 2293–306. https://doi.org/10.1175/2009JCLI2951.1.

Fetter, C.W. 1994. *Applied Hydrogeology*. Upper Saddle River, NJ: Prentice Hall.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall Inc.

Gomez-Velez, J.D., J.L. Wilson, M.B. Cardenas, and J.W. Harvey. 2017. "Flow and Residence Times of Dynamic River Bank Storage and Sinuosity-Driven Hyporheic Exchange." *Water Resources Research* 53: 8572–95. https://doi.org/10.1002/2017WR021362.

Gurnell, A.M. 1998. "The Hydrogeomorphological Effects of Beaver Dam-Building Activity." *Progress in Physical Geography* 22: 167–89. 10.1177%2F030913339802200202.

Harbaugh, A.W., E.R. Banta, M.C. Hill, M.G. McDonald, and C.G. Groat. 2000. "MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model User Guide to Modularization Concepts and the Ground-Water Flow Process." *U.S. Geological Survey Open-File Report 00–92*. https://pubs.er.usgs.gov/publication/ofr200092.

Harman, C.J., A.S. Ward, and A. Ball. 2016. "How Does Reach-Scale Stream-Hyporheic Transport Vary with Discharge? Insights from rSAS Analysis of Sequential Tracer Injections in a Headwater Mountain Stream." *Water Resources Research* 52: 7130–50. https://doi.org/10.1002/2016WR018832.

Harvey, J.W., and K.E. Bencala. 1993. "The Effect of Streambed Topography on Surface-Subsurface Water Exchange in Mountain Catchments." *Water Resources Research* 29: 89–98. https://doi.org/10.1029/92WR01960.

Harvey, J.W., J.D. Gomez-Velez, N.M. Schmadel, D. Scott, E. Boyer, R. Alexander, K. Eng, et al. 2019. "How Hydrologic Connectivity Regulates Water Quality in River Corridors." *Journal of the American Water Resources Association* 55: 369–81. https://doi.org/10.1111/1752-1688.12691.

Heath, R.C. 1983. "Basic Ground-Water Hydrology." *U.S. Geological Survey Water-Supply Paper 2220*. https://pubs.er.usgs.gov/publication/wsp2220.

Helton, A.M., G.C. Poole, R.A. Payn, C. Izurieta, and J.A. Stanford. 2014. "Relative Influences of the River Channel, Floodplain Surface, and Alluvial Aquifer on Simulated Hydrologic Residence Time in a Montane River Floodplain." *Geomorphology* 205: 17–26. https://doi.org/10.1016/j.geomorph.2012.01.004.

Hunt, L.J.H., J. Fair, and M. Odland. 2018. "Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California." *Journal of the American Water Resources Association* 54: 1127–36. https://doi.org/10.1111/1752-1688.12675.

Janzen, K., and C.J. Westbrook. 2011. "Hyporheic Flows along a Channelled Peatland: Influence of Beaver Dams." *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques* 36: 331–47. https://doi.org/10.4296/cwrj3604846.

Johns, E.L. 1989. *Water Use by Naturally Occurring Vegetation Including an Annotated Bibliography*. New York: American Society of Civil Engineers.

Kasahara, T., and A.R. Hill. 2006. "Hyporheic Exchange Flows Induced by Constructed Riffles and Steps in Lowland Streams in Southern Ontario, Canada." *Hydrological Processes* 20: 4287–305. https://doi.org/10.1002/hyp.6174.

Kasahara, T., and S.M. Wondzell. 2003. "Geomorphic Controls on Hyporheic Exchange Flow in Mountain Streams." *Water Resources Research* 39: 1005. https://doi.org/10.1029/2002WR001386.

Käser, D., and D. Hunkeler. 2016. "Contribution of Alluvial Groundwater to the Outflow of Mountainous Catchments." *Water Resources Research* 52: 680–97. https://doi.org/10.1002/2014WR016730.

Kendy, E., and J.D. Bredehoeft. 2006. "Transient Effects of Groundwater Pumping and Surface-Water-Irrigation Returns on Streamflow." *Water Resources Research* 42: 1–11. https://doi.org/10.1029/2005WR004792.

Klein, L.R., S.R. Clayton, J.R. Alldredge, and P. Goodwin. 2007. "Long-Term Monitoring and Evaluation of the Lower Red River Meadow Restoration Project, Idaho, U.S.A." *Restoration Ecology* 15: 223–39. https://doi.org/10.1111/j.1526-100X.2007.00206.x.

Knowles, N., M.D. Dettinger, and D.R. Cayan. 2006. "Trends in Snowfall versus Rainfall in the Western United States." *Journal of Climate* 19: 4545–59. https://doi.org/10.1175/JCLI3850.1.

Larkin, R.G., and J.M. Sharp. 1992. "On the Relationship between River-Basin Geomorphology, Aquifer Hydraulics, and Ground-Water Flow Direction in Alluvial Aquifers." *Geological Society of America Bulletin* 104: 1608–20. https://doi.org/10.1130/0016-7606(1992)104%3C1608:OTRBRB%3E2.3.CO;2.

Lautz, L., C. Kelleher, P. Vidon, J. Coffman, C. Riginos, and H. Copeland. 2019. "Restoring Stream Ecosystem Function with Beaver Dam Analogues: Let's Not Make the Same Mistake Twice." *Hydrological Processes* 33: 174–77. https://doi.org/10.1002/hyp.13333.

Lautz, L.K. 2008. "Estimating Groundwater Evapotranspiration Rates Using Diurnal Water-Table Fluctuations in a Semi-Arid Riparian Zone." *Hydrogeology Journal* 16: 483–97. https://doi.org/10.1007/s10040-007-0239-0.

Leake, S.A., and B. Gungle. 2012. "Evaluation of Simulations to Understand Effects of Groundwater Development and Artificial Recharge on Surface Water and Riparian Vegetation, Sierra Vista Subwatershed, Upper San Pedro Basin, Arizona." *U.S. Geological Survey Open-File Report 2012–1206*. https://pubs.er.usgs.gov/publication/ofr20121206.

Leenhouts, J.M., J.C. Stromberg, R.L. Scott, S.J. Lite, M. Dixon, T. Rychener, E. Makings, D.G. Williams, D.C. Goodrich, W.L. Cable, L.R. Levick, R. McGuire, R.M. Gazal, E.A. Yepez, P. Ellsworth, and T.E. Huxman. 2006. "Hydrologic Requirements of and Consumptive Ground-Water Use by Riparian Vegetation along the San Pedro River, Arizona." *U.S. Geological Survey Scientific Investigations Report 2005–5163*. https://pubs.er.usgs.gov/publication/sir20055163.

Macfarlane, W.W., J.M. Wheaton, N. Bouwes, M.L. Jensen, J.T. Gilbert, N. Hough-Snee, and J.A. Shivik. 2017. "Modeling the Capacity of Riverscapes to Support Beaver Dams." *Geomorphology* 277: 72–99. https://doi.org/10.1016/j.geomorph.2015.11.019.

Majerova, M., B.T. Neilson, N.M. Schmadel, J.M. Wheaton, and C.J. Snow. 2015. "Impacts of Beaver Dams on Hydrologic and Temperature Regimes in a Mountain Stream." *Hydrology and Earth System Sciences* 19: 3541–56. https://doi.org/10.5194/hess-19-3541-2015.

Malzone, J.M., C.S. Lowry, and A.S. Ward. 2016. "Response of the Hyporheic Zone to Transient Groundwater Fluctuations on the Annual and Storm Event Time Scales." *Water Resources Research* 52: 5301–21. https://doi.org/10.1002/2015WR018056.

McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, et al. 2003. "Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems." *Ecosystems* 6: 301–12. https://doi.org/10.1007/s10021-003-0161-9.

Nash, C.S., G.E. Grant, S. Charnley, J.B. Dunham, H. Gosnell, M.B. Hausner, D.S. Pilliod, and J.D. Taylor. 2021. "Great Expectations: Deconstructing the Process Pathways Underlying Beaver-Related Restoration." *Bioscience* 71: 249–67. https://doi.org/10.1093/biosci/biaa165.

Nash, C.S., G.E. Grant, J.S. Selker, and S.M. Wondzell. 2020. "Discussion: "Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California" by Luke J.H. Hunt, Julie Fair, and Maxwell Odland." *Journal of the American Water Resources Association* 56: 182–85. https://doi.org/10.1111/1752-1688.12796.

Nash, C.S., J.S. Selker, G.E. Grant, S.L. Lewis, and P. Noël. 2018. "A Physical Framework for Evaluating Net Effects of Wet Meadow Restoration on Late-Summer Streamflow." *Ecohydrology* 11: 1–15. https://doi.org/10.1002/eco.1953.

Naz, B.S., S.C. Kao, M. Ashfaq, H. Gao, D. Rastogi, and S. Gangrade. 2018. "Effects of Climate Change on Streamflow Extremes and Implications for Reservoir Inflow in the United States." *Journal of Hydrology* 556: 359–70. https://doi.org/10.1016/j.jhydrol.2017.11.027.

Niswonger, R.G., and D.E. Prudic. 2005. "Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow beneath Streams — A Modification to SFR1." U.S. Geological Survey Techniques and Methods 6-A13. https://pubs.er.usgs.gov/publication/tm6A13.

Nyssen, J., J. Pontzeele, and P. Billi. 2011. "Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium." *Journal of Hydrology* 402: 92–102. https://doi.org/10.1016/j.jhydrol.2011.03.008.

Persson, G. 1995. "Willow Stand Evapotranspiration Simulated for Swedish Soils." *Agricultural Water Management* 28: 271–93. https://doi.org/10.1016/0378-3774(95)01182-X.

Pilliod, D.S., A.T. Rohde, S. Charnley, R.R. Davee, J.B. Dunham, H. Gosnell, G.E. Grant, M.B. Hausner, J.L. Huntington, and C.S. Nash. 2018. "Survey of Beaver-Related Restoration Practices in Rangeland Streams of the Western USA." *Environmental Management* 61: 58–68. https://doi.org/10.1007/s00267-017-0957-6.

Pollock, M.M., T.J. Beechie, and C.E. Jordan. 2007. "Geomorphic Changes Upstream of Beaver Dams in Bridge Creek, an Incised Stream Channel in the Interior Columbia River Basin, Eastern Oregon." *Earth Surface Processes and Landforms* 32: 1174–85. https://doi.org/10.1002/esp.1553.

Pollock, M.M., T.J. Beechie, J.M. Wheaton, C.E. Jordan, N. Bouwes, N. Weber, and C. Volk. 2014. "Using Beaver Dams to Restore Incised Stream Ecosystems." *Bioscience* 64: 279–90. https://doi.org/10.1093/biosci/biu036.

Pollock, M.M., G. Lewallen, K. Woodruff, C.E. Jordan, and J.M. Castro. 2018. *The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains, Version 2.01*. Portland, Oregon: United States Fish and Wildlife Service. https://www.fws.gov/media/beaver-restoration-guidebook.

Prudic, D.E. 1989. "Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite-Difference, Ground-Water Flow Model." *U.S. Geological Survey Open-File Report 88–729*. https://pubs.er.usgs.gov/publication/ofr88729.

Sawyer, A.H., M.B. Cardenas, A. Bomar, and M. Mackey. 2009. "Impact of Dam Operations on Hyporheic Exchange in the Riparian Zone of a Regulated River." *Hydrological Processes* 23: 2129–37. https://doi.org/10.1002/hyp.7324.

Scamardo, J., and E. Wohl. 2020. "Sediment Storage and Shallow Groundwater Response to Beaver Dam Analogues in the Colorado Front Range, USA." *River Research and Applications* 36: 398–409. https://doi.org/10.1002/rra.3592.

Schmadel, N.M., A.S. Ward, C.S. Lowry, and J.M. Malzone. 2016. "Hyporheic Exchange Controlled by Dynamic Hydrologic Boundary Conditions." *Geophysical Research Letters* 43: 4408–17. https://doi.org/10.1002/2016GL068286.

Scott, R.L., E.A. Edwards, W.J. Shuttleworth, T.E. Huxman, C. Watts, and D.C. Goodrich. 2004. "Interannual and Seasonal Variation in Fluxes of Water and Carbon Dioxide from a Riparian Woodland Ecosystem." *Agricultural and Forest Meteorology* 122: 65–84. https://doi.org/10.1016/j.agrformet.2003.09.001.

Shah, N., M. Nachabe, and M. Ross. 2007. "Extinction Depth and Evapotranspiration from Ground Water under Selected Land Covers." *Ground Water* 45: 329–38. https://doi.org/10.1111/j.1745-6584.2007.00302.x.

Shaw, G.D., M.H. Conklin, G.J. Nimz, and F. Liu. 2014. "Groundwater and Surface Water Flow to the Merced River, Yosemite Valley, California: ^{36}Cl and cl^{-} Evidence." *Water Resources Research* 50: 1943–59. https://doi.org/10.1002/2013WR014222.

Theis, C.V. 1940. "The Source of Water Derived from Wells." *Civil Engineering* 10 (5): 277–80.

Ward, A.S., and A.I. Packman. 2019. "Advancing our Predictive Understanding of River Corridor Exchange." *Wiley Interdisciplinary Reviews: Water* 6: e1327. https://doi.org/10.1002/wat2.1327.

Ward, A.S., N.M. Schmadel, S.M. Wondzell, M.N. Gooseff, and K. Singha. 2017. "Dynamic Hyporheic and Riparian Flow Path Geometry through Base Flow Recession in Two Headwater Mountain Stream Corridors." *Water Resources Research* 53: 3988–4003. https://doi.org/10.1002/2016WR019875.

Weber, N., N. Bouwes, M.M. Pollock, C. Volk, J.M. Wheaton, G. Wathen, J. Wirtz, and C.E. Jordan. 2017. "Alteration of Stream Temperature by Natural and Artificial Beaver Dams." *PLoS One* 12: 1–23. https://doi.org/10.1371/journal.pone.0176313.

Wegener, P., T. Covino, and E. Wohl. 2017. "Beaver-Mediated Lateral Hydrologic Connectivity, Fluvial Carbon and Nutrient Flux, and Aquatic Ecosystem Metabolism." *Water Resources Research* 53: 4606–23. https://doi.org/10.1002/2016WR019790.

Westbrook, C.J., D.J. Cooper, and B.W. Baker. 2006. "Beaver Dams and Overbank Floods Influence Groundwater-Surface Water Interactions of a Rocky Mountain Riparian Area." *Water Resources Research* 42: 1–12. https://doi.org/10.1029/2005WR004560.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. "Groundwater and Surface Water a Single Resource." U.S. Geological Survey Circular 1139. https://pubs.er.usgs.gov/publication/cir1139.

Woessner, W.W. 2000. "Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought." *Groundwater* 38: 423–29. https://doi.org/10.1111/j.1745-6584.2000.tb00228.x.

Wroblicky, G.J., M.E. Campana, H.M. Valett, and N. Dahm. 1998. "Seasonal Variation in Surface-Subsurface Water Exchange and Lateral Hyporheic Area of Two Stream-Aquifer Systems." *Water Resources Research* 34: 317–28. https://doi.org/10.1029/97WR03285.