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Logjam Characteristics as Drivers of Transient Storage in Headwater Streams

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Key Points:

- Mean arrival time increases with surface water storage for a given discharge and skewness depends on water storage in the channel
- Observed complexities in transient storage behavior depend largely on surface water flow upstream of a logjam(s)
- Logjam characteristics that maximize channel storage (multiple jams, low permeability) also promote a greater hyporheic exchange volume

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Logjams in a stream create backwater conditions and locally force water to flow through the streambed, creating zones of transient storage within the surface and subsurface of a stream. We investigate the relative importance of logjam distribution density, logjam permeability, and discharge on transient storage in a simplified experimental channel. We use physical flume experiments in which we inject a salt tracer, monitor fluid conductivity breakthrough curves in surface water, and determine breakthrough-curve skewness to characterize transient storage. We then develop a companion numerical model in HydroGeoSphere to reveal flow paths through the subsurface (or hyporheic zone) that contribute to some of the longest transient-storage timescales. In both the flume experiments and numerical simulations, we observe backwater formation and an increase in hyporheic exchange at logjams. Observed complexities in transient storage behavior depend largely on surface water flow in the backwater zone. As expected, multiple successive logjams provide more pervasive hyporheic exchange by distributing the head drop at each jam, leading to distributed but shallow flow paths. Decreasing the permeability of a logjam or increasing the discharge both facilitate greater surface water storage and volumetric rate of hyporheic exchange. Understanding how logjam characteristics affect solute transport through both the channel and hyporheic zone has important management implications for rivers in forested, or historically forested, environments.

Plain Language Summary

Logjams in a stream create zones of slower moving water and locally force water to flow through the streambed, creating zones of temporary retention in stagnant areas of the stream and shallow subsurface. We refer to these areas as zones of transient storage. We investigate the relative importance of the spacing of logjams, how tightly packed a logjam is with fallen branches and leaves, and the amount of stream flow on transient storage in a simplified experimental channel. We use a physical scaled model of a river in which we inject a salt tracer and measure its flow downstream using data loggers. We also develop a companion computer model to simulate water and salt movement in the stream and streambed. In both our physical model and computer model, we observe an increase in surface water retention and surface water-subsurface water exchange at logjams spaced closely together and more tightly packed. Less water stored on the surface corresponds with more stagnant flows in surface dead zones and more overall transient storage. Understanding how logjam characteristics affect the downstream flow of chemicals has important implications for stream water quality and the management of forested, or historically forested, watersheds.

1. Introduction

Spatial heterogeneity in flow paths within a river corridor drives stream solute exchange between fast-flowing areas and zones of relatively slower flow that cause transient storage. Transient storage can be generally segregated into surface transient storage—where water flows slowly through recirculation zones and stagnant areas of low velocity—and subsurface transient storage (controlled by hyporheic exchange—where stream water flows through the subsurface and returns to the channel). Transient storage has numerous benefits to river corridor ecosystem services and processes including (a) increased biogeochemical cycling (Battin et al., 2008; Fischer et al., 2005; J. Harvey & Gooseff, 2015; Marttila et al., 2018; Tonina & Buffington, 2009); (b) nutrient and pollutant processing (Ensign & Doyle, 2005; Hall et al., 2002; J. W. Harvey & Wagner, 2000; Stewart et al., 2011); (c) increased habitat diversity and thermal refugia (Hester & Gooseff, 2010; Mulholland et al., 2004); and (d) flow attenuation (Herzog et al., 2018). Transient storage can be increased by morphologic and geologic features that create spatial heterogeneity in water velocity and drive alternate patterns of downwelling and upwelling along the bed. Examples of such features include bedforms and other variations in channel cross-sectional

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geometry (Bencala, 1983; Ensign & Doyle, 2005; Gooseff et al., 2007; J. W. Harvey & Bencala, 1993; Kasahara & Wondzell, 2003), logjams (Ader et al., 2021; Hester & Doyle, 2008; Marttila et al., 2018; Sawyer et al., 2011), and variations in alluvial thickness and grain-size distribution (J. W. Harvey et al., 1996). Here, we focus on the effects of logjams as an important morphologic element that creates both surface transient storage in the channel (e.g., backwater zones) and subsurface transient storage in porous media (e.g., hyporheic exchange zones).

Logjams directly enhance transient storage in a number of ways. Logjams obstruct flow and increase hydraulic resistance within the channel, thus creating hydraulic head gradients that drive hyporheic exchange. Logjams directly influence surface transient storage by creating low-velocity zones within the channel (Gippel, 1995); enhancing the formation of backwater pools (Beckman & Wohl, 2014; Kaufmann & Faustini, 2012; Livers & Wohl, 2016; Richmond & Fausch, 1995); creating scour pools that enhance residual pool volume (Ensign & Doyle, 2005; Fausch & Northcote, 1992; Mao et al., 2008); and creating marginal eddies (Zhang et al., 2019).

Logjams also indirectly affect surface and subsurface transient storage by increasing the erosion and deposition of sediment (Wohl & Scott, 2017). Logjams locally enhance entrainment of bed material and erosion of the channel bed and banks (Buffington et al., 2002). Studies of the effects of logjams on floodplain-sediment dynamics emphasize how the obstructions created by logjams can result in changes in bedforms via overbank flows and vertical accretion or bank erosion, channel avulsion, and formation of secondary channels (e.g., Sear et al., 2010; Wohl & Scott, 2017). Logjams commonly create high spatial variability in average bed grain size and alluvial thickness upstream and downstream of a jam (Massong & Montgomery, 2000). Advective pumping, induced by streamflow over a spatially heterogeneous and permeable bed, leads to a distribution of pore-water flow paths in the streambed (Elliott & Brooks, 1997; Vaux, 1968; Wörman et al., 2002), which in turn enhances the magnitude of subsurface transient storage via hyporheic exchange (Fanelli & Lautz, 2008; Hester & Doyle, 2008; Lautz et al., 2006; Sawyer & Cardenas, 2012; Sawyer et al., 2011).

As might be expected, previous work indicates that greater roughness (e.g., J. W. Harvey et al., 2003) and spatial heterogeneity within a channel (e.g., Gooseff et al., 2007) equate to greater potential for transient storage. A growing body of research describes wood as a driver of channel spatial heterogeneity (e.g., Buffington & Montgomery, 1999; Collins et al., 2012; Faustini & Jones, 2003) and as a driver of transient storage (e.g., Ader et al., 2021; Doughty et al., 2020; Kaufmann & Faustini, 2012; Mutz et al., 2007; Sawyer & Cardenas, 2012; Sawyer et al., 2011; Wilhelmsen et al., 2021). Recent work used bulk electrical conductivity (Doughty et al., 2020) and fluid electrical conductivity (Ader et al., 2021) to examine surface and subsurface transient storage in a small stream with and without the presence of logjams and found that the direct presence of wood increases transient storage and does so at a greater magnitude than other geomorphic variables, such as bedform dimensions. Wilhelmsen et al. (2021) combined flume experiments with a numerical model to analyze the effects of jam complexity, in combination with channel planform complexity, on the hyporheic flow regime of small streams. Their numerical simulations suggest that logjams decrease the turnover length that stream water travels before interacting with the hyporheic zone by an order of magnitude and that the widest range of hyporheic residence times arise where logjams and multiple channel threads co-occur. While these field and modeling studies have shaped our understanding of transient storage around logjams and channel morphologies of varying complexities, an opportunity exists to test the effects of logjam characteristics on transient storage patterns. No study, to our knowledge, has used empirical data to comparatively examine transient storage in a stream as the number of logjams increases (e.g., longitudinal distribution density) nor have any addressed how the structure of jams (e.g., permeability) influences transient storage.

These characteristics of logjams are important to understand because in natural settings, jams vary in size, shape, and permeability depending on the abundance and composition of large wood and coarse particulate organic matter (see terminology in Table 1). Quantifying logjam characteristics in the field has proved challenging (Livers et al., 2020; Manners et al., 2007) and physical and numerical modeling approaches are commonly used to further constrain field variables. Recent work explores the influence of jam sorting and organizational structure on logjam permeability (Spreitzer et al., 2019) and resulting hydraulic impacts (Follett et al., 2021; Ismail et al., 2020; Schalko et al., 2018). A small number of physical modeling studies have relied on natural wood to study hydraulics and geomorphology (e.g., Beebe, 2000; Mutz et al., 2007; Schalko, 2020; Schalko & Weitbrecht, 2021; Spreitzer et al., 2021), but none have used natural wood to examine logjam accumulation characteristics (Friedrich et al., 2022). Knowledge of how logjam characteristics influence hydrologic function is pertinent to river management as wood is increasingly used to restore a more natural hydrologic function to rivers

Table 1
Wood Terminology Definitions

Term	Definition	References
Large wood	Wood >10 cm in diameter and 1 m in length	Wohl et al. (2010)
Channel-spanning logjam (logjam or jam)	Accumulation of at least three pieces of large wood that spans the entire bankfull channel	Livers and Wohl (2021)
Coarse particulate organic matter	Any organic material that is less than 1 cm in diameter or is composed of non-woody organic material (i.e., leaves)	Tank et al. (2010)
Engineered logjam	Constructed logjam used to achieve river restoration and stabilization target goals	T. Abbe et al. (2003)
Longitudinal distribution density	Number of jams per channel length, defined here as per 50 cm	Wohl and Beckman (2014)
Permeability	Ease with which fluid passes through the logjam, influenced by connectedness of pore spaces within the logjam	Manners et al. (2007)

(Grabowski et al., 2019; Roni et al., 2014). Limited understanding of how logjam characteristics relate to specific hydrologic effects constrains our ability to maximize functions of constructed logjams to promote ecosystem services provided by transient storage.

Here, we address some of the gaps in understanding the relationship between logjam characteristics and transient storage at varying discharges and logjam configurations. Our study objective is to assess the relative response of transient storage to binary changes in logjam permeability (high vs. low), logjam longitudinal distribution density (single vs. multiple jams along a given length of channel), and discharge (high vs. low). We achieve this objective through a two-part approach. We use flume experiments, specifically focusing on measuring salt breakthrough curves in the channel, to address faster timescales of transient storage. Because breakthrough curves measured in surface water often fail to capture some of the longer residence times in the hyporheic zone (J. W. Harvey et al., 1996) and do not reveal spatial information about flow paths, we also numerically simulated coupled surface-subsurface flow in flume experiments to resolve longer tracer flow paths through the subsurface. We treated the jams themselves as an extension of the porous medium with adjustable permeability. We test four hypotheses: (H1) increasing logjam longitudinal distribution density enhances transient storage; (H2) decreasing the permeability of a single logjam enhances transient storage; (H3) a single low-permeability logjam creates a comparable increase in transient storage to multiple high-permeability logjams; and (H4) increasing discharge enhances transient storage.

2. Methods

2.1. Flume Experiments

Flume experiments took place at Colorado State University's Engineering Research Center using a 9-m long and 1.2-m wide flume with a rectangular cross section and smooth sidewalls (Figure 1). Flow was delivered continuously to the flume via pipes and pumps from a non-recirculating reservoir of water. A cobble-filled baffle dissipated flow energy at the upstream end of the flume and a reinforced 250-micron mesh screen at the downstream end of the flume trapped any mobilized sediment. Flume geometry was selected to mimic a mountain headwater stream with measured logjams and transient storage (Ader et al., 2021) within the constraints of the physical flume structure. We sized sediment to maintain an immobile bed and used a coarse sand overlain by a gravel topcoat. A summary of all flume attributes including channel dimensions and sediment depths is included as Table S2 in Supporting Information S1.

We used natural wood pieces of varying size to create logjams in the flume (Figure 1). We ensured a similar wood load per jam by quantifying the wood volume per each jam using a water displacement test. We estimated jam porosity from this wood (solid) volume divided by the overall jam volume, as estimated from the digital elevation model, which is described below (Livers et al., 2020). Each constructed jam was pinned by one large immobile key piece of wood to avoid jam mobility. To change the permeability of a single jam, we added fine sediment and coarse particulate organic matter, mainly in the form of leaves, pine needles, and bark. Coarse particulate organic matter was measured using a graduated cylinder packed tightly with the fine material and reflected in the porosity estimate. To further reduce the permeability of the jam for the purpose of illustrating the binary extremes of high permeability versus low permeability, we added in plastic impermeable material to the jam (less than one quarter of the total jam volume contained this material) (Figure 1).

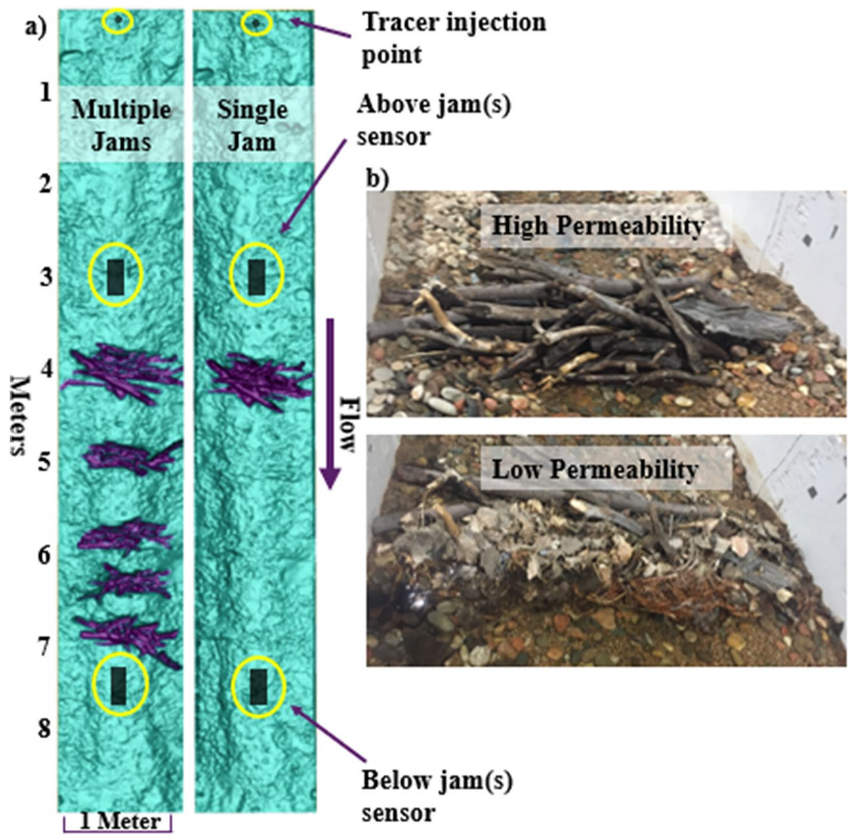

Figure 1. Flume configuration (9-m long, 1.2-m wide) for (a) longitudinal distribution density experiments and (b) permeability experiments. (a) Shows the change in jam quantity from a single jam to multiple jams (runs HHS and HHM shown here). (b) Shows the change in packing for a single logjam from a more permeable jam to a less permeable jam with coarse particulate organic matter additions (runs LHS and LLS shown here). Data were collected at sensors above and below the experimental reach. However, we use the "below jam(s)" sensor data for results and analyses because they best represent the combined effects of logjam distribution density and permeability changes.

Table 2
Flume and Numerical Model Runs With Discharge and Logjam Characteristics (Number of Jams and Permeability)

Run	Discharge	Logjam permeability	Logjam longitudinal distribution density
HHS	High	High	Single
LHS	Low	High	Single
HLS	High	Low	Single
LLS	Low	Low	Single
HHM	High	High	Multiple
LHM	Low	High	Multiple
HLM	High	Low	Multiple[a]
LLM	Low	Low	Multiple[a]

Note. All runs were conducted in flume and numerically simulated unless otherwise noted. A replicate was run for all flume trials.
[a]Numerical model only. A flume run with multiple low permeability logjams was not conducted.

A list of all flume runs is included as Table 2. We implemented tracer experiments with sodium chloride (NaCl) to characterize transient storage flow paths via fluid conductivity. We added 360-g of NaCl dissolved in 3.78 L of water to the flume at the injection point (Figure 1) via a pulse injection. In a NaCl pulse injection, a dissolved tracer mass is introduced to the stream over a very short period of time (on the order of seconds). The duration of application is considered instantaneous because it is negligible relative to the time of advective transport through the reach (Payn et al., 2008). The tracer was fully mixed prior to injection and the pulse injection occurred at the pour-over weir, where there was strong turbulence, to further promote mixing (T. J. Day & Day, 1977). The ability to resolve transient storage depends in part on the relative travel times through zones of faster flow and zones of relatively slower flow, as well as the exchange rates between them. Given our expectation of short transport times (on the order of minutes) in this flume system and the turbulent flow in the channel, we deemed a pulse injection sufficient to load even some of the slower flow paths with salt. The first 3-m of the flume served as a mixing zone before reaching the study logjams. The experimental set-up of the flume was constrained by the flume dimensions, as the flume was not originally built with hyporheic studies in mind. The experimental section where jams and fluid conductivity sensors were placed spanned from 3.0 to 7.5 m (Figure 1). No jams or sensors were placed in the last 1.5-m of the flume (from 7.5 to 9.0 m) to minimize interference from backwater effects near the sediment screen. We measured specific conductivity at 10-s intervals during the tracer tests using Onset Computing HOBO U-24 fluid electrical conductivity loggers (data loggers). Data loggers recorded fluid conductivity measurements for 30 min following the pulse to allow ample time for the flume to return to background solute concentrations. Sensor placement was uniform across all flume trials. We deployed one data logger upstream of the NaCl injection point to measure background fluid conductivity, and two data loggers 0.3-m upstream and downstream of the logjam(s) in the monitoring reach, at 3 and 7.5 m from the top of the flume (Figure 1). We only report data from the downstream sensor for clarity as it represents both the above and below logjam effects. The measured instream conductivity signals represent the combined effects of surface transient storage in the channel (e.g., backwaters, eddies) and subsurface transient storage (e.g., hyporheic exchange). We attempted to separate out surface and subsurface transport processes in the flume using electrical resistivity methods adapted from the field (Doughty et al., 2020). However, our results were not successful in resolving hyporheic exchange at the small scale of our flume. Thus, we rely on a paired numerical model to gain insight into longer subsurface flow paths.

We set high and low discharge values that ranged over a factor of 10 (0.001 and 0.01 m^3/s). Discharge rates were determined based on a series of trials using pulse injections at various discharges to best determine appropriate binary "high" and "low" discharges. Initial flume runs suggested that the tracer was flushed too quickly to measure with accuracy above 0.01 m^3/s, and below 0.001 m^3/s there was not enough flow to replicate a consistent discharge. Discharge readings were obtained from a flow meter with ±0.2% accuracy. Discharge for all flume runs was fully turbulent. We ran a replicate for each flume trial to ensure consistency in flume trial results. A digital elevation model for the flume was constructed using structure from motion (Westoby et al., 2012). Images were captured at regular downstream intervals with a camera mounted at a consistent elevation and we used ground-control points along the flume bed for additional adjustment. Images were processed using Agisoft Metashape Professional. The resulting digital elevation model had a resolution of less than 1 mm.

2.2. Numerical Modeling Simulations

We numerically simulated all flume runs in HydroGeoSphere to visualize longer duration flow paths moving through the subsurface (Aquanty Inc., 2015; Brunner & Simmons, 2012). Our model builds on the approach of Wilhelmsen et al. (2021) used to numerically simulate surface water-groundwater interactions in flume systems with the presence of logjams. Specifically, the Saint Venant equations for two-dimensional flow in the surface water are coupled to the three-dimensional Richards equation for flow in porous media, and the jams are treated as porous media. In our HydroGeoSphere code, the Saint Venant equations and the Richards equation are coupled at the sediment-water interface through continuity of hydraulic head and conservation of water mass. The coupled equations and parameter definitions are available in Supporting Information S1. While this approach cannot reproduce vertical variations in flow within the surface water or exchange of momentum due to turbulence across the bed, it has been shown to be effective for representing stream-groundwater interactions at this flume scale (Wilhelmsen et al., 2021). Using the flow fields in the surface water and subsurface, we also solved the advection-dispersion equation for transport of a conservative "solute" (electrical conductivity, which was assumed to be proportional to chloride concentration). We also solved the advection-dispersion equation for groundwater age in the sediment only (Supporting Information S1). The goal of the latter step was to assess hyporheic residence times and visualize some of the longer timescales of subsurface flow independent from travel times in the surface water.

The numerical model domain matches our flume dimensions. We defined the base and sides of the model as no-flow boundaries to represent the bottom and sides of the flume environment. At the upstream boundary of the flume domain, a specified inflow flux was assigned to simulate the stepped spillway. At the downstream outlet, a critical depth boundary condition was given to match flume observations. The vertically averaged Saint Venant equation was solved on a 2-D finite-element mesh stacked upon the subsurface grid. The surface of the model domain was discretized with an unstructured, triangular mesh with maximum element length of 2.0 cm. For comparison, the grain diameter of flume sediments ranges up to 17 mm and therefore choosing a finer mesh would have been inconsistent with the concept of a porous continuum. The subsurface domain of our model was discretized into 10 vertical layers. The three near-surface sediment layers represent the gravel and coarse sand topcoat layer of the flume and were assigned element heights of 0.005 m and hydraulic conductivity of 2.5×10^{-3} m/s. The deeper seven mesh layers represent the underlying coarse sand layer and were assigned an

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Table 3
Model Parameters and Values

Variable	Definition	Value	Unit
$K_{shallow}$	Hydraulic conductivity of shallow gravel and coarse sand stratum	2.5×10^{-3}	m/s
K_{deep}	Hydraulic conductivity of deep coarse sand stratum	8.9×10^{-4}	m/s
K_{high_jam}	Hydraulic conductivity of high-permeability logjams	6	m/s
K_{low_jam}	Hydraulic conductivity of lo-permeability logjams	3	m/s
θ	Porosity of sediments	0.3	–
	van Genuchten alpha	3.548	1/m
	van Genuchten gamma	3.162	–
θ_{high_jam}	Porosity of high-permeability jams	0.7	–
θ_{low_jam}	Porosity of low-permeability jams	0.35	–
α_l	Longitudinal dispersivity	0.02	m
α_t	Transverse dispersivity	0.02	m
n	Manning's coefficient	0.01	$s/m^{1/3}$

element height of 0.028 m and hydraulic conductivity of 8.9×10^{-5} m/s. Logjams were simulated as a porous medium with varying permeability (Table 3). The hydraulic conductivity of the more permeable logjam(s) was set to 6 m/s, while the value for less permeable logjam(s) was set to 3 m/s. Although jams are represented in the model physics as a porous medium, we considered them to be part of the surface water system and did not treat flow through the jams as part of the hyporheic zone for the estimation of hyporheic fluxes or residence times. Properties of the sediment and jams were initially chosen based on existing literature values (e.g., Wilhelmsen et al., 2021) and refined through sensitivity testing to yield the best visual fit between observed and modeled breakthrough curves for the overall set of trials. While adding more layers of sediment or changing the permeability of individual jams may have further improved the observation-model fit for individual trials, our goal was not to reproduce every detail of the flume observations but rather to capture the overall changes between trial runs with the simplest parameterization of jam and sediment properties. Model parameters are included in Table 3, and further details of the governing equations are given in Supporting Information S1.

2.3. Data Analysis and Visualization

Tracer tests are commonly interpreted for transient storage residence times using solute breakthrough curves from stream sensors (e.g., Anderson et al., 2005; Lautz et al., 2006; Tonina & Buffington, 2007; Wondzell, 2006; Wörman et al., 2002). We plotted in-stream fluid conductivity data against time as breakthrough curves for each flume run and numerical model simulation. To examine differences in breakthrough curves across discharge and logjam characteristics, we analyzed the following information based on the temporal moments of breakthrough curves: mass, mean arrival time, variance, and skewness (Gupta & Cvetkovic, 2000; C. F. Harvey & Gorelick, 1995). The mean arrival time of the injected tracer at the point of observation is commonly used to describe advection patterns; variance is used to describe dispersion and diffusion characteristics. The statistical moment of skewness represents the asymmetry of the breakthrough curve based on solute retention and can be used as a proxy for the amount of transient storage (Nordin & Troutman, 1980). We interpret skewness here as an indicator of transient storage in both the surface water and subsurface alluvium (e.g., Doughty et al., 2020; Lees et al., 2000), though it is likely most sensitive to the shortest surface flow timescales of transient storage in the channel (J. W. Harvey et al., 1996). Higher values of skewness indicate more tailing behavior exhibited in the breakthrough curve, and therefore, more transient storage. We calculated all temporal moments in Matlab (MATLAB, 2020). A full explanation of the calculation of the temporal moments and resulting values is included in Supporting Information S1, but we focus on changes in mean arrival time and skewness resulting from changes in logjam characteristics and discharge. Both parameters are influenced by the shape of the solute breakthrough curve and amount of mass that arrives later (the plume's tail). In general, the mean arrival time should primarily reflect the characteristic timescale of flow in the channel (which has faster flow paths and conveys a larger mass of solute compared to the hyporheic zone), while skewness should reflect to the importance of transient storage arising from interaction of mobile and less mobile flow paths in the surface domain and the shallower, faster flowing areas of the subsurface domain. Flume run and numerical simulation times were standardized to include 1 min of background data prior to the NaCl pulse injection and a total time of 30 min, recognizing that skewness is sensitive to the length of observation (e.g., Nordin & Troutman, 1980). Fluid conductivity readings in the flume return to background levels in under 10 min, so a run time of 30 min for the purpose of consistency in the plots does not affect estimates of tailing in the breakthrough curves.

Statistical analyses were performed in R Studio (R Core Team, 2022). Given our small data set, we heavily rely on visual trends where statistical analysis is limited due to sample size. We statistically assessed how dependent variables (skewness and mean arrival time) changed with independent variables describing logjam characteristics and discharge. The independent variables were the number of logjams (single or multiple), discharge (high or low), and permeability (high or low). We fit multiple two-way ANOVA models based on our hypotheses (Table S1 in Supporting Information S1). Tukey adjusted pairwise comparisons were calculated using *emmeans* R package (Lenth et al., 2020). A significance level alpha of 0.05 was used in all statistical analyses.

We used model outputs to visualize surface water depth, exchange rates across the sediment-water interface, and age of hyporheic water in the subsurface. Groundwater age is similar in concept to a residence time and includes the effects of both advection and dispersion (Therrien et al., 2006). We also estimated a mean hyporheic residence time from the age simulations. To do so, we integrated the product of age and hyporheic flux across the sediment surface within upwelling zones and divided by the integral of the hyporheic flux across these same upwelling zones.

3. Results

Results from the flume experiments and model simulations are consistent (Figure S1 in Supporting Information S1) and provide similar trends in temporal moments representing transient storage between trials (Figure 2). Flume results were also consistent across replicate runs. Model runs tend to underestimate the tails of the breakthrough curves, more so in the cases with multiple jams, leading to smaller mean arrival times and skewness for the models than the observations (Figure 2), but further improvements to the fit would have required changing the permeability of each jam in the multiple jam models, and we opted for less parameterization for the sake of simplicity. Across our results we often see skewness values decrease as surface water storage and hyporheic exchange volumes increase. This suggests that greater surface water volume stored in the channel results in greater inundation, which leads to less skewness or transient storage. We interpret these results as indicators of more uniformity in flow paths through the surface due to less separation of highly mobile and highly immobile flow paths in the channel as submergence increases. Thus, testing our hypotheses becomes more complex as we use skewness as a metric of transient storage given that complexities in transient storage behavior depends largely on surface water flow upstream of a logjam(s). To address this, we specifically comment on trends in skewness for each hypothesis but also comment on surface storage volumes and metrics of hyporheic exchange to provide greater insight into the behavior of different discharges and logjam characteristics.

Model outputs show a typical relationship where faster hyporheic fluxes equate to shorter hyporheic residence times (Figure S3a in Supporting Information S1). The model simulations generally show a region of hyporheic mixing that forms beneath one or multiple jams. The ages of hyporheic water in those regions are on the order of minutes (Figure 4). Water of older age also exists within the subsurface, but some of this water exits the subsurface at the downstream boundary of the flume. In other words, the hyporheic zone does not vertically fill the flume sediment. Hyporheic fluxes across the bed are greatest immediately upstream and downstream of jams (Figure 5). Because there is more area for downwelling in the backwater that forms upstream of jams and less area for upwelling downstream, the upwelling velocities are faster.

H1. *Increasing logjam longitudinal distribution density enhances transient storage*.

Results suggest that adding more logjams increases the volume of surface water storage and hyporheic exchange, but not necessarily transient storage. To the extent that multiple jams create more backwater, they will also slow down mean arrival time (Figure 3). Tukey adjusted pairwise comparisons between mean arrival time and the number of jams indicated slower advection with more jams in both the flume runs and model simulations ($p = 0.02$). Given that multiple jams tend to store more water in the channel, which corresponds with more inundation and therefore less separation of flow paths, multiple jams have

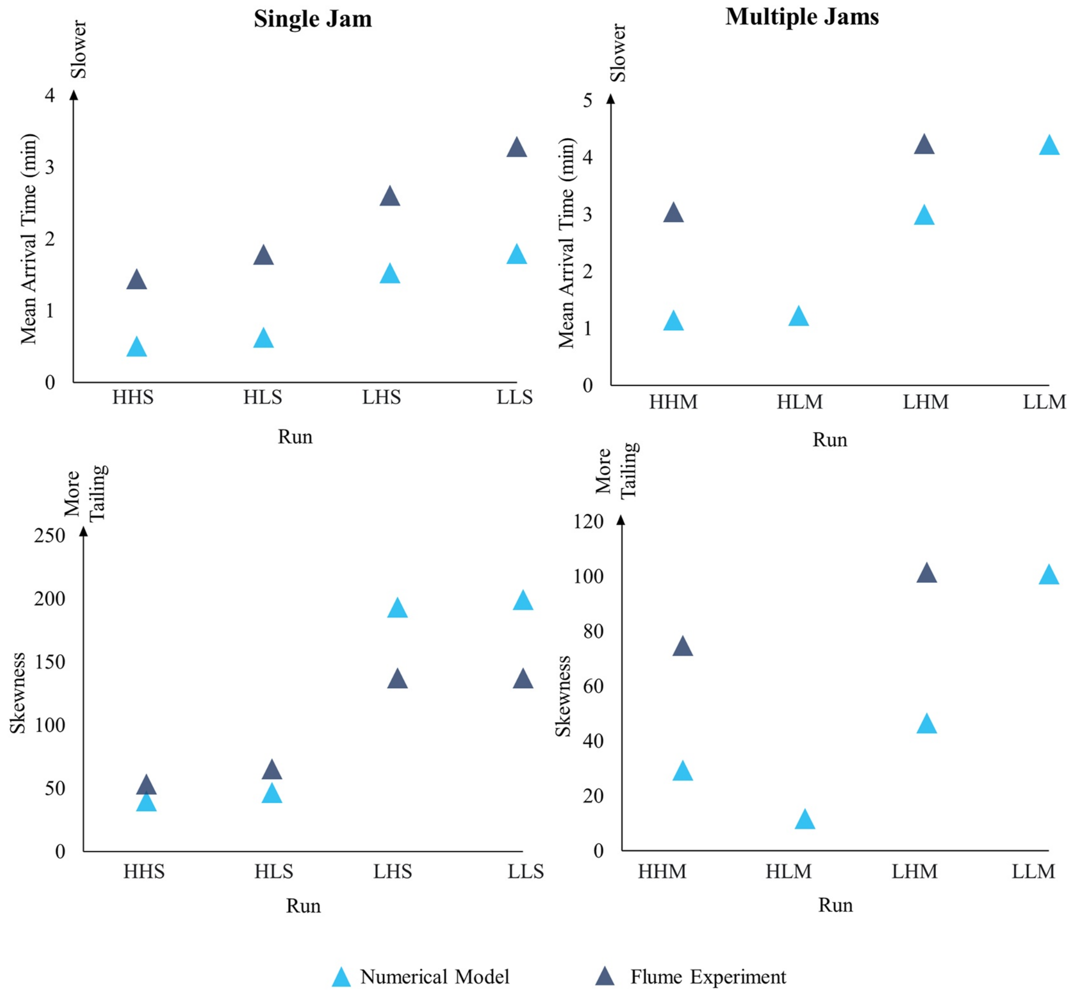

Figure 2. Mean arrival time and skewness for flume runs and numerical simulations as permeability and discharge change with the presence of a single or multiple logjams. Note, the different axis scales when comparing the single jam plots to the multiple jam plots. Refer to Table 2 for a more detailed description of the naming convention used to describe each model run.

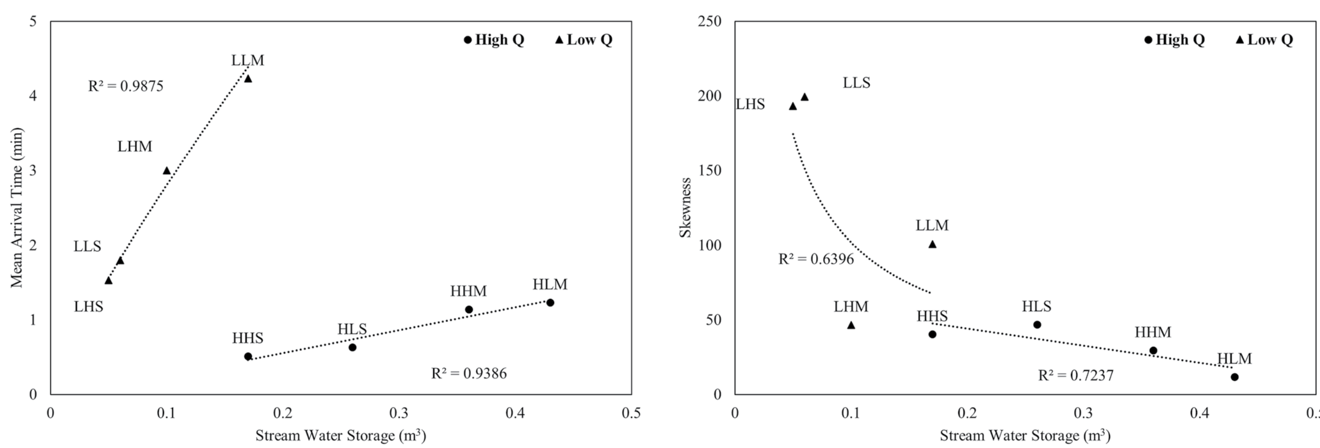

Figure 3. Plots comparing stream water storage in the channel against mean arrival time and skewness. The plot of mean arrival time versus stream water storage shows a linear trend of increasing mean arrival time with increasing surface water storage volume. The plot of skewness versus stream water suggests that skewness generally decreases with an increase in surface water storage.

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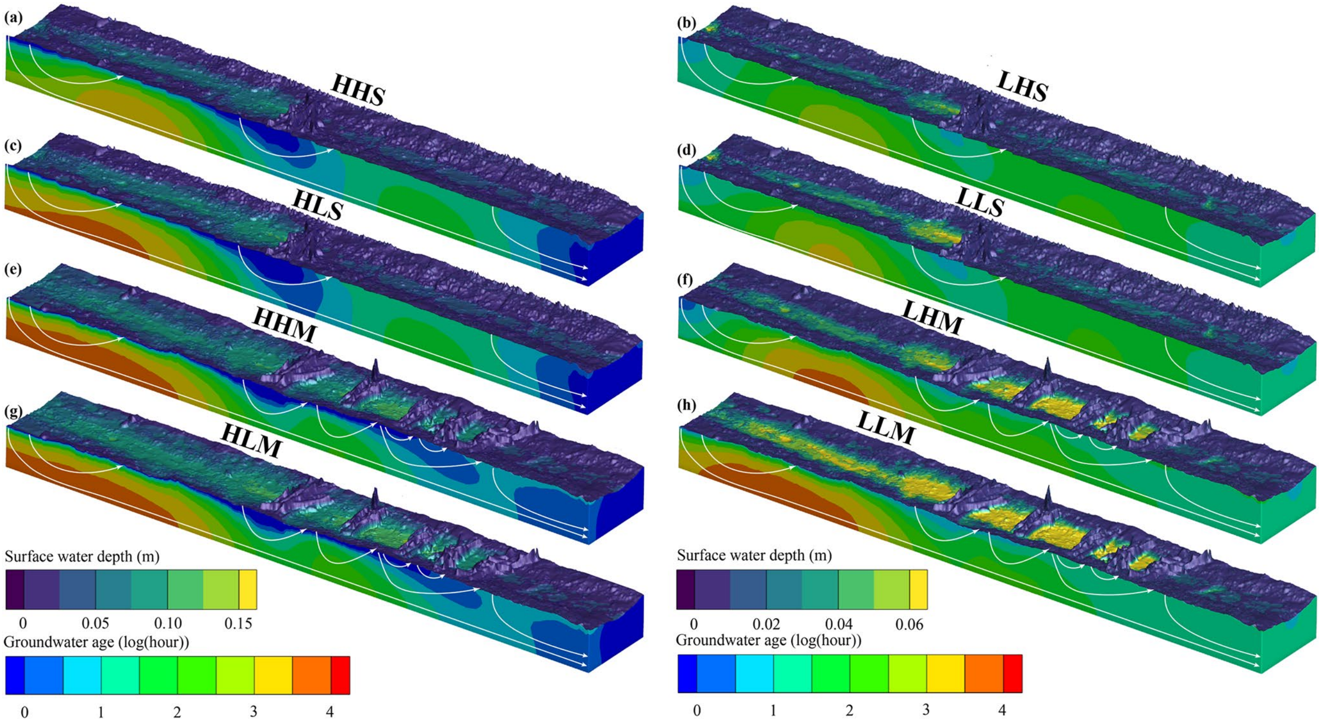

Figure 4. Simulated surface water depth (m) and groundwater age (log(hour)) for the eight flume scenarios with different logjam permeability, number of logjams, and/or stream discharge. Scenarios correspond with those defined in Table 2 where (a) is HHS, (b) is LHS, (c) is HLS, (d) is LLS, (e) is HHM, (f) is LHM, (g) is HLM, and (h) is LLM. Refer to Table 2 for a more detailed description of the naming convention used to describe each model run. The connectivity between groundwater and surface water increases when surface water encounters a logjam. The elevated surface water level upstream causes more water to infiltrate into the streambed upstream of the logjam and exfiltrate downstream of the logjam. Comparing the scenarios of single logjams (a–d) and multiple logjams (e–h), a single jam drives a deep zone of fast exchange, while multiple jams drive shallower but connected and repeated zones of fast exchange.

lower skewness compared to a single jam (Figure 3). Model outputs show that increasing the longitudinal distribution density of logjams results in a greater inundated area and thus a laterally expanded hyporheic exchange zone (Figure 4). We further see an increase in hyporheic exchange with more jams when comparing additional hyporheic metrics (Table S3 in Supporting Information S1). The addition of more jams corresponds with a greater volumetric rate of hyporheic exchange and greater mean hyporheic age. Given that the head drop is also distributed at each jam when there are multiple successive jams, hyporheic flow paths are shallow but more longitudinally pervasive. Thus, greater logjam longitudinal distribution density facilitates more surface water storage as well as longer residence time in the subsurface (Figure 5), but as the backwater extends between logjams and the head drop between each jam becomes less defined, we see a decrease in transient storage (skewness). In other words, a single jam is more likely to have less channel water storage, more stagnant flows in surface dead zones, and slower hyporheic exchange flows with longer residence times, which in turn leads to greater skewness or transient storage (Figures 2 and 3).

H2. *Decreasing the permeability of a single logjam enhances transient storage.*

Results suggest that a less permeable jam slightly enhances transient storage. Values of skewness and mean arrival time generally increase marginally as logjam permeability decreases (Figure 2), but the change is not significant across the flume and model results ($p = 0.9$ for mean arrival time and $p = 0.7$ for skewness). Mean arrival time values (Table S3 in Supporting Information S1) suggest that a more tightly packed jam results in slower movement of the tracer down the channel regardless of discharge. Skewness values (Table S3 in Supporting Information S1) suggest that a less permeable logjam increases transient storage (although it is important to note that this trend is also driven by lower flows). Observations of backwater extent in the flume suggest a less permeable jam has a more profound impact on increasing retention in surface water relative to a more permeable jam (Figure S2 in Supporting Information S1) and surface water storage increases with lower permeability (Figure 3). As more logs and coarse particulate organic matter are added to a single logjam, greater backwater and low-velocity flow fields form. Model outputs

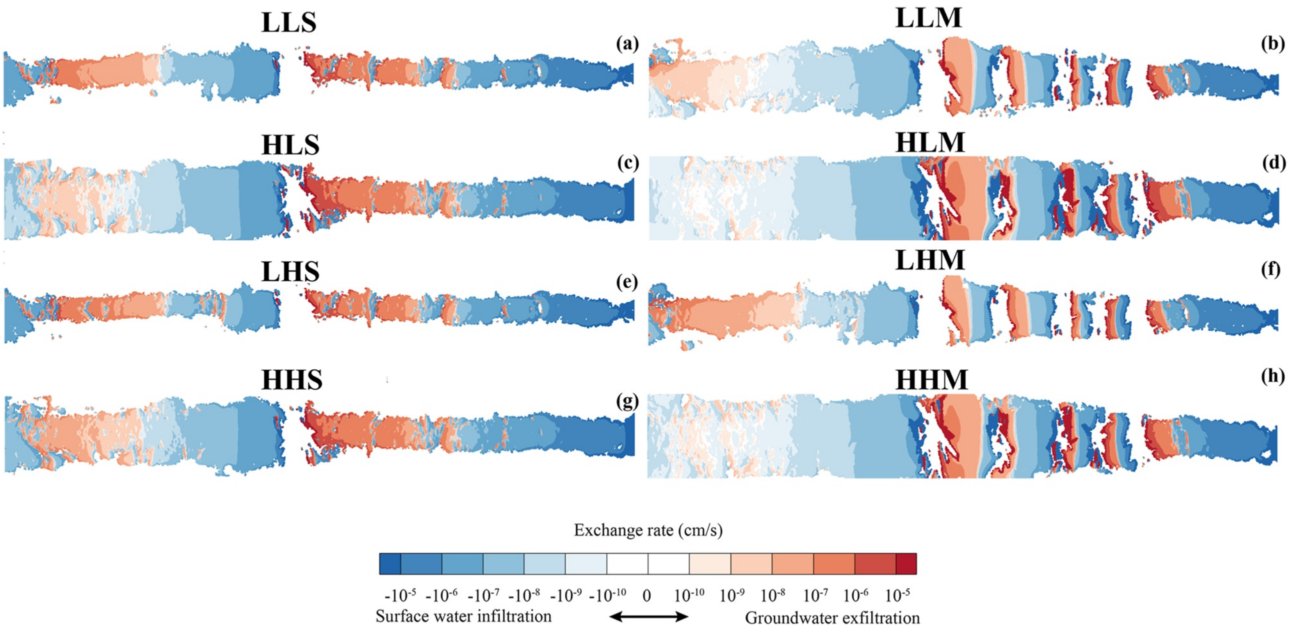

Figure 5. Top-down view of simulated exchange rates across the wetted streambed for the eight scenarios where the logjam permeability, quantity of logjams, and/or discharge change. Scenarios correspond with those defined in Table 2 where (a) is LLS, (b) is LLM, (c) is HLS, (d) is HLM, (e) is LHS, (f) is LHM, (g) is HHS, and (h) is HHM. Refer to Table 2 for a more detailed description of the naming convention used to describe each model run. White areas lie outside the sediment-water interface and represent either the sediment-jam interface or dry areas outside the active channel. The area in front of each logjam is the hotspot for surface water infiltration, while the area behind the logjam is the hotspot for groundwater exfiltration. The submerged areas are different due to changes in backwater effects. Generally, more logjams, higher flow rates, or lower logjam permeability create more of a backwater effect and thus extend the area available for exchange with the subsurface.

further show that an increase in rising surface-water level behind a less permeable logjam resulted in a greater magnitude of water infiltrating into the water-sediment interface upstream of the logjam and exfiltrating downstream of the logjam (Figure 5). A more tightly packed jam results in a greater volumetric hyporheic exchange rate (Figure S3 in Supporting Information S1).

H3. *A single low-permeability logjam creates a comparable increase in transient storage to multiple high-permeability logjams.*

We compared transient storage between a single low-permeability logjam and multiple high-permeability logjams to better understand the relative effects of these logjam characteristics. We observed that the two configurations enhance transient storage potential in different ways. Mean arrival times and mean hyporheic age increase between a single low-permeability jam and multiple high-permeability jams (Figure 2; Table S3 in Supporting Information S1). In other words, flow paths are slower when more jams are present rather than when permeability is changed. Similarly, multiple jams results in a greater volume of surface water storage and volumetric rate of hyporheic exchange (Figure 3; Table S3 in Supporting Information S1). Transient storage (skewness) increases with the presence of a low permeable jam compared to multiple highly permeable jams (Table S3 in Supporting Information S1). In other words, less channel water storage and more stagnant flows in surface dead zones result in greater transient storage in the low permeability single jam configurations. We also simulated a scenario with both increased logjam longitudinal distribution density and decreased permeability (not shown in the flume), which resulted in the greatest increase in surface water storage and volumetric rate of hyporheic exchange of all logjam scenarios (Figure 2).

H4. *Transient storage increases at higher discharge for all scenarios.*

Counter to our hypothesis, transient storage increases at low discharge for all the results (Figure 2). Both mean arrival times ($p = 0.01$) and skewness ($p = 0.003$) significantly decrease with greater discharge in both the flume and model. When discharge is greater, jams are more submerged, and stagnant zones in the channel become more mobile. The contrast between slow-moving and fast-moving zones is reduced in the surface water. At low discharge, large variations in stagnant and faster-moving channel segments appear, leading to more transient storage in stagnant zones. The mean hyporheic age has differing relationships

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with skewness at high and low discharge (Figure S3 in Supporting Information S1). At low discharge, less transient storage corresponds with greater mean hyporheic age while at high discharge there is less of a clear trend. We see more surface water storage and a greater volume of hyporheic exchange in our modeled simulations during high discharge (Figure 3; Figure S3 in Supporting Information S1). Generally, the greater volume of water stored in the channel equates to more inundation and less skew or transient storage (Figure 3). When stream discharge increases, hyporheic exchange rates also increase (Table S3 in Supporting Information S1), which should contribute to more subsurface transient storage, but the tailing behavior reflected in skewness appears more sensitive to surface transient storage.

4. Discussion

Our primary objective was to evaluate the influences of changes in (a) logjam longitudinal distribution density, (b) logjam permeability, and (c) discharge on transient storage. Using a combination of physical and numerical modeling allowed for better constraint of both surface and subsurface flow paths. The influences of logjam characteristics and discharge relate across our flume-scale experiments and numerical simulations via channel water storage volume. The greater the surface water storage in the channel, regardless of whether it is due to jam permeability, the number of jams, or discharge, the less skewness present (Figure 3 and Table S3 in Supporting Information S1). We attribute this to a relationship between channel water storage and more stagnant flows in surface dead zones, slower hyporheic exchange flows with longer residence times, and more overall transient storage.

4.1. Complexities in Transient Storage Flow Paths

We infer, based on our results, that skewness in the breakthrough curves (and thus transient storage) is more sensitive to surface flow paths than subsurface flow paths. For example, a mean arrival time of only minutes in the flume is likely consistent with a combination of slow flow in surface transient storage zones plus some of the fastest flow through subsurface zones (Figure 4). This is consistent with previous field-scale work showing that breakthrough curves measured in surface water often fail to capture some of the longer hyporheic flow paths (J. W. Harvey et al., 1996). Thus, we use numerical experiments to reveal more about the nature of the hyporheic zone. When we look at the relationship between transient storage and hyporheic processes, as guided by our numerical model, we see an intuitive relationship of faster hyporheic flux corresponding to shorter hyporheic residence times (Figure S3 in Supporting Information S1). In other words, it is hard to have both a fast flux (strong connection between mobile surface water and immobile subsurface) and long residence times in the immobile subsurface. As has been shown in past studies (e.g., Cardenas et al., 2004; Cardenas et al., 2008; Pryshlak et al., 2015; Sawyer & Cardenas, 2009), the two tend to work against each other (greater exchange rates tend to occur with shorter residence times). We can also think about this in the context of conserving water mass where flow rate in will equal volume divided by the characteristic residence time in a well-mixed container at steady state. Presumably, the most transient storage would occur when both are maximized, but the likelihood of this occurring in nature is low.

The numerical simulations also give us insight into the relationship between hyporheic residence times and skewness. While not obvious, Figure S3b in Supporting Information S1 shows that some of the longer hyporheic residence times occur for cases with greater skewness (this trend is specific to low discharge). From this we can infer that the characteristics that enhance skewness and overall transient storage have a likelihood of also creating slow hyporheic flows (long residence times in subsurface transient storage). We can conceptually illustrate this in the case of less stream water storage, more stagnant flows in surface dead zones, and slower hyporheic exchange flows with longer residence times. Similarly, the average rate of hyporheic exchange decreases as overall transient storage (skewness) goes up (Figure 3c in Supporting Information S1), which we attribute to the same conceptual reasoning as the trend in average hyporheic residence time. Hyporheic exchange volumes (Table S3 in Supporting Information S1) provides further insight into the nature of the hyporheic zone. The size of the hyporheic zone goes down a bit as overall transient storage (skewness) goes up. This makes sense because size of the hyporheic zone depends in part on wetted area, which increases with channel water storage, and as the results suggest, more channel water storage corresponds with less skewness (Figure 3).

Results suggest that decreasing the permeability of a jam slightly increases transient storage, but more so increases surface water storage and the volume of hyporheic exchange. Studies addressing jams with lower permeability due to beaver activity have found that stream reaches with beaver dams exhibit a greater degree of hyporheic interaction (e.g., Lautz et al., 2006; Briggs et al., 2013). Our results agree with these findings and suggest that lowering the permeability of a jam, enhances surface water storage as well as the average hyporheic exchange flux (Table S3 in Supporting Information S1). Our results comparing multiple jams to a single jam suggest that multiple jams tend to store more water in the channel, which corresponds with more inundation, less separation of flow paths, and subsequently lower skewness compared to a single jam, regardless of whether that jam has high or low permeability (Figure 3). We see this decline in transient storage (skewness) as a result of more uniformity in flow paths through the surface due to less separation of highly mobile and highly immobile flow paths in the channel as submergence increases. This fits with what we might expect to see based on past work. Ader et al. (2021) found that the effects of large wood on surface and subsurface transient storage may be very local, implying the need for multiple wood pieces and logjams to influence segment-scale transient storage. Our observations confirm this inference and suggest that multiple logjams lead to more distributed flow paths and more pervasive reach-scale exchange. The head drop between the upstream and downstream of a logjam is another key mechanism in enhancing hyporheic exchange fluxes and the quantity, permeability, and spacing of logjams determines this head drop. We speculate that when the five logjams are set closely enough, they correspond with the head drop of at least a large, low permeable logjam and will certainly increase the hyporheic exchange. When the five logjams are set far enough from each other, they have less of an effect on hyporheic exchange. The optimal spacing of jams should associated with the number and permeability spacing of logjams (maybe the permeability ratio of the shallow sediment to the logjam) and requires more laboratory and numerical work in the future.

We observed complex dynamics in the relationship between logjam distribution density, permeability, discharge, and transient storage. As logjams accumulate in a stream channel and as the permeability decreases with the addition of newly recruited wood and fine material, upstream pooling increases, driving surface and hyporheic flow paths and heightened complexity of the stream system (T. B. Abbe & Montgomery, 1996; Sear et al., 2010). Evolution in jam complexity (both in terms of permeability and longitudinal distribution density) can result in activation of the floodplain and other variably inundated portions of the hyporheic zone as backwater extent and flow depth increase behind jams and subsequently cause more frequent overbank flows (Doughty et al., 2020; Gooseff et al., 2006; Wondzell et al., 2009). Changes in inundation area have been shown to have a profound influence on hyporheic connectivity at field scales on the order of tens of square kilometers (Helton et al., 2014). We see this in our results where increasing logjam longitudinal distribution density of logjams, the amount of coarse particulate organic material in a jam, or flow leads to an increase in wetted area (Figure 5). This further fits into our result that the simulated size of the hyporheic zone decreases a bit as overall transient storage increases because the size of the hyporheic zone depends in part on wetted area, which increases with channel water storage, and more channel water storage equals less transient storage (skewness).

We infer from our results that channel water storage and inundation extent have an important role on transient storage and hyporheic exchange (Figure 3). Our observations suggest less channel water storage corresponds with more stagnant flows in surface dead zones, and slower hyporheic exchange flows with longer residence times, and more overall transient storage. Runs with more jams tend to store more water in the channel and skewness tends to decrease with water storage (Figure 3). Greater water storage in the channel leads to more uniformity in flow paths through the surface due to less separation of highly mobile and highly immobile flow paths in the channel as submergence increases. While that relationship will certainly be different in the field and flume, we expect that generally more channel water storage and inundation lead to fewer dead zones and thus transient storage is still likely true in some form. Existing work provides evidence for both increased transient storage during low discharge conditions, when the water table near the stream is low (J. W. Harvey & Bencala, 1993; J. W. Harvey et al., 1996; Wroblicky et al., 1998) and during high discharge conditions, when the stream experiences greater channel wetted area and floodplain inundation (Doughty et al., 2020; Nyssen et al., 2011; Wilhelmsen et al., 2021). Comparisons of mean arrival times and skewness show consistencies in enhanced transient storage with decreased discharge across our results. Our results show less skewness and shorter mean arrival times when discharge increases (Figure 2). In the flume, flow paths are better resolved at low discharge when we can load more of the flow paths with a short salt pulse. We suspect understanding the role of discharge in these environments is dependent on sensitivity to detecting the smallest fraction of long flow paths. We further suspect that the pervasive hyporheic exchange observed with the presence of multiple successive logjams likely has physical limits within the bounds of discharge. For example, as more flow overtops or bypasses jams, backwater effects will become relatively less important with relative submergence during when a substantial portion of the flow overtops/overpasses the jam and in-channel discharge, and backwater effects will asymptote during overbank flooding in alluvial valleys.

4.2. Experimental Limitations

We were limited by the physical attributes of the flume we had access to during COVID-19 (a wooden 9-m long and 1-m wide flume). We believe that the constraints on the distance between the tracer injection location and the first jam could be one contributing factor as to why our flume experiments and model simulations are not always closely matched. Breakthrough curves comparing flume experiments and numerical simulations align well across discharges when a single jam is present (Figure S1 in Supporting Information S1). However, we see less alignment in the flume and model breakthrough curves when multiple logjams are present. This makes sense given the increased complexity and variability present in the multiple logjams flume configuration. Each logjam has a unique permeability and internal structure that cannot be captured in the numerical model where logjams are assigned a uniform high and low permeability value. When we compare breakthrough curve plots to skewness and mean arrival time plots for the flume and numerical model, we see an offset between the calculated mean arrival time and the visually observed peak arrival time for the flume data. The simulated mean arrival time is often on the order of a minute shorter than the observed peak arrival time, and we attribute this to the greater mass retained in the observed tails. The heavy mass under the tail in the flume breakthrough curves shifts the calculated mean arrival time later. This offset in mean arrival times is particularly apparent in the multiple jam scenarios where there is more retention. Less agreement between the multiple jam flume and model breakthrough curves also points to the challenges in modeling complex logjam scenarios. Once again, each logjam in our multiple logjam scenario has a unique structural composition and permeability, despite efforts to make those characteristics as uniform as possible. Thus, the variability in logjam characteristics at the multiple jam scale becomes inherently more difficult to model without increasing the number of parameters. We did not attempt to create a low permeability multiple jam configuration in the flume given how challenging it is to physically emulate the same permeability across multiple jams. It was difficult to adjust the permeability of our single jam to meet our desired low permeability configuration and we suspect that our results would more strongly show that decreasing the permeability of a jam enhances surface storage and hyporheic exchange if we had been able to further reduce the permeability of the single jam.

Both the flume and model results reflect simplification of the river corridor in which the floodplain is bounded laterally, such that surface water and hyporheic flow paths can only expand laterally up to the flume walls. Similarly, hyporheic flow paths are also limited at depth by the flume bottom. The extent of these flow paths in natural streams could depend strongly on the depth of alluvial cover (Tonina & Buffington, 2009), which is in turn influenced by the presence of large wood, because logjams store sediments (Massong & Montgomery, 2000; Montgomery et al., 2003). Buxton et al. (2015) looked at spawning redds and the nonlinear effects of obstruction density and hydraulic conductivity on hyporheic exchange. While not specific to logjams, their results support our findings broadly by showing that hyporheic flux and volume increased with obstruction density but differ in other findings (residence time showed an inverse relation with redd density due to trade-offs between the rate of change in hyporheic flux and volume). We suspect that the latter effects do not emerge in our study in part due to the restricted depth of alluvium (Tonina & Buffington, 2011) and because of a narrower range of obstruction densities. Additionally, the lack of fine sediment accumulation in the logjam backwaters, the rigid lateral boundaries, and the impermeable boundary underlying the sediment fill in the flume may all have influenced subsurface flow paths. The interacting effect of jams, sediment storage, and longer, deeper hyporheic exchange flows cannot be tested in these experiments but is an area for future research.

4.3. Management Implications

Our results suggest increases in hyporheic exchange rates and surface water storage volumes with more logjams and more fine material in a logjam. Thus, when thinking about designing engineered logjams to promote surface water-groundwater exchange or restoration targeting hyporheic exchange, we infer that those scenarios with opportunities to recruit more wood or facilitate the formation of multiple jams, as well as retain coarse particulate organic matter that reduces logjam permeability, will promote surface water storage and hyporheic exchange rates. Although the specific magnitudes of transient storage and hyporheic exchange at the field scale cannot be determined from flume-scale experiments, the general trends (e.g., the substantial increase in exchange rates and surface water storage with more logjams and more fine material in a logjam) should be consistent across flume to field scales.

Zones of transient storage are important components of stream systems, and similar to other stream habitats, have suffered degradation as a consequence of human activity. Efforts to incorporate channel elements that promote hyporheic exchange have started to emerge as a step toward restoring stream ecosystems and associated hydrologic functions (Crispell & Endreny, 2009; Hester et al., 2018). Additions of complex logjam formations in altered river reaches may increase hyporheic interactions by slowing stream water velocity, forming backwaters, increasing flow complexity, and diverting water to the subsurface. Some morphologic features may also retain coarse particulate organic material that decreases the permeability of a logjam while creating the redox gradients necessary for certain biogeochemical functions. Nevertheless, successful applications of stream management and restoration utilizing logjams is dependent upon understanding the role of different large wood distributions (ranging from more dispersed distributions to many successional jam structures to tightly packed jams) on transient storage. Although the hyporheic benefits of ongoing installation of morphologic features may be considerable, to our knowledge they are not currently included as project design goals (Hester & Gooseff, 2010) and few studies quantify the impact of restoration features on hyporheic function (Crispell & Endreny, 2009; Kasahara & Hill, 2006; Wade et al., 2020). Adding hyporheic benefits of existing installations as an explicit design goal where appropriate, modifying the design parameters of such features to maximize benefits as possible, and considering additional features explicitly for hyporheic benefit are all needed to incorporate and quantify transient storage benefits in restoration projects.

5. Conclusions

Results from tracer experiments in our flume experiments and numerical modeling simulations provide insight into how logjam characteristics and discharge drive transient storage. The impact of logjam characteristics and discharge relate across our flume-scale experiments and numerical simulations via the volume of surface water stored in the channel. More surface water volume stored in the channel equates to more inundation and thus less skew or transient storage, presumably because "dead zones" are far less stagnant when more of the channel is inundated and activated. Thus, observed complexities in transient storage behavior depend largely on surface water flow upstream of a logjam(s). We see the expected relationship of faster hyporheic flux corresponding with shorter hyporheic residence times. We infer that solute breakthrough skewness is more sensitive to surface flow paths than subsurface flow paths. The size of the hyporheic zone decreases slightly as overall transient storage increases because the size of the hyporheic zone depends in part on wetted area, which increases with channel water storage, and more channel water storage equals less transient storage (skewness).

From the observed differences in surface transient storage between stream segments with greater and lesser amounts of large wood and more or less permeable jams, we infer that river management designed to foster surface and subsurface transient storage can effectively focus on retaining wood (either by continuing recruitment and transport or fixing engineered logjams in place) and retaining coarse particulate organic matter. We conclude that surface water storage and hyporheic exchange volume is greater when there are many jams (large longitudinal distribution density) with low permeability (tight packing of wood pieces) and that transient storage is greater at low discharge when there are more opportunities for stagnant flow. An increase in surface and subsurface transient storage can, in turn, improve stream health and makes a case for river managers to strategically implement wood in river restoration designs.

Moving forward, additional work is needed to explore whether a change in longitudinal distribution density or permeability has a nonlinear effect on transient storage. Other studies have shown that logjams create nonlinear effects on stream metabolism (N. K. Day & Hall, 2017); spatial heterogeneity of physical channel characteristics (Livers et al., 2018; Livers & Wohl, 2016), including channel and floodplain planform (Buffington & Montgomery, 1999; Wohl, 2011); retention of particulate organic matter (Beckman & Wohl, 2014); and animal biomass and biodiversity (Herdrich et al., 2018; Venarsky et al., 2018). We expect that transient storage might follow a similar pattern of nonlinearity, but the binary nature of this experimental set-up did not allow for such exploration. River science and management have a need for further understanding into the details of specific logjam characteristics and their influence on transient storage residence time and understanding patterns and predictive abilities around these characteristics has important implications for river corridor function.

Data Availability Statement

The data analyzed for this paper are available as Marshall et al. (2022). Data loggers used in flume experiments are Onset Computing HOBO U-24 fluid electrical conductivity loggers and HOBOware Pro version 3.7.8 (Onset Computing Onset Computer Corporation, 2022) was used with a software license to configure loggers and download logger data, available at https://www.onsetcomp.com/products/software/hoboware. Numerical modeling simulations were run in HydroGeoSphere (Aquanty Inc., 2015), available under a license at https://www.aquanty.com/hydrogeosphere. Temporal moment calculations were done in Matlab (MATLAB, 2020) under an academic license of version 9.9.0 or later, available at https://matlab.mathworks.com/. Statistical analyses and figure creation were done in open-source R Studio software (R Core Team, 2022) using version 4.2.1, available at https://www.R-project.org/.

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