Logjam Characteristics as Drivers of Transient Storage in Headwater Streams

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Key Points:

- Transient storage is maximal when there are many jams (large longitudinal distribution density) with low permeability (tightly packed jam).
- Solute breakthrough in the flume is more sensitive to surface flow paths than subsurface flow paths, suggesting much of the observed transient storage occurs in backwater zones behind jams.
- Configurations with greater transient storage also have the greatest rates of hyporheic exchange and longest residence times in the subsurface.

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 use breakthrough-curve skew to characterize transient storage. We then develop numerical models 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 and numerical model, we observe an increase in backwater and hyporheic exchange at logjams. Observed complexities in transient storage behavior may 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 more surface water storage and elevate the surface water level upstream of a logjam, thus increasing hyporheic exchange. Multiple logjams with low permeability result in the greatest magnitude of transient storage, suggesting that this configuration maximizes solute retention in backwater zones, while hyporheic exchange rates also increase. 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.

1 Introduction

Spatial heterogeneity in flow paths within a river corridor drives stream solute exchange between mobile areas of the channel and relatively immobile transient storage zones. 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 in part 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 i) increased biogeochemical cycling (Fischer et al., 2005; Battin et al., 2008; Tonina & Buffington, 2009; Harvey & Gooseff, 2015; Marttila et al., 2018); ii) nutrient and pollutant processing (Harvey & Wagnert, 2000; Hall et al., 2002; Ensign & Doyle, 2005; Stewart et al., 2011); iii) increased habitat diversity and thermal refugia (Mulholland et al., 2004; Hester & Gooseff, 2010); and iv) 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 geometry (Bencala, 1983; Harvey & Bencala, 1993; Kasahara & Wondzell, 2003; Ensign & Doyle, 2005; Gooseff et al., 2007), logjams (Hester & Doyle, 2008; Sawyer et al., 2011; Marttila et al., 2018; Ader et al., 2021), and variations in alluvial thickness and grain-size distribution (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 (for example, backwater zones) and subsurface transient storage in porous media (for example, hyporheic exchange).

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 (Richmond & Fausch, 1995; Kaufmann & Faustini, 2012; Beckman & Wohl, 2014; Livers & Wohl, 2016); creating scour pools that enhance residual pool volume (Fausch & Northcote, 1992; Ensign & Doyle, 2005; 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 stream-flow over a spatially heterogeneous and permeable bed, leads to a distribution of pore-water flow paths in the streambed (Wörman et al., 2002), which in turn enhances the magnitude of subsurface transient storage via hyporheic exchange (Lautz et al., 2006; Hester & Doyle, 2008; Fanelli & Lautz, 2008; Sawyer et al., 2011; Sawyer & Cardenas, 2012).

As might be expected, previous work indicates that greater roughness (e.g., 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., Mutz et al., 2007; Sawyer et al., 2011; Sawyer & Cardenas, 2012; Kaufmann & Faustini, 2012; Doughty et al. 2020; Ader et al., 2021; 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 broadest 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., 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 (Manners et al. 2007, Livers et al., 2020) 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 (Schalko et al., 2018; Ismail et al, 2020; Follett et al., 2021). 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 (Roni et al., 2014; Grabowski et al., 2019). 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 versus low), logjam distribution density (single versus multiple jams along a given length of channel), and discharge (high versus 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 (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 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) increasing 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) transient storage increases at higher discharge for all scenarios.

Table 1. Wood terminology definitions.

Term	Definition
Large wood	Wood >10 cm in diameter and 1m in length
Channel-spanning logjam (logjam or jam)	Any accumulation of large wood within the bankfull channel in w
Coarse particulate organic matter	Any organic material that is less than 1 cm in diameter or is com
Engineered logjam	Constructed logjam used to achieve river restoration and stabiliz
Longitudinal distribution density	Number of jams per channel length, defined here as per 50 cm.
Permeability	Ease with which fluid passes through the logjam, influenced by c

2 Methods

2.1 Flume configuration

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 to the flume via pipes and pumps from a 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.

We sized sediment to maintain an immobile bed and used a gravel subsurface sediment with a pebble topcoat. A summary of all flume attributes is included as Supplemental Information.

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 and number of large wood pieces per each jam. 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 coarse particulate organic matter, mainly in the form of leaves, pine needles, and bark. We also added a plastic impermeable material to the jam to further reduce its permeability (Figure 1).

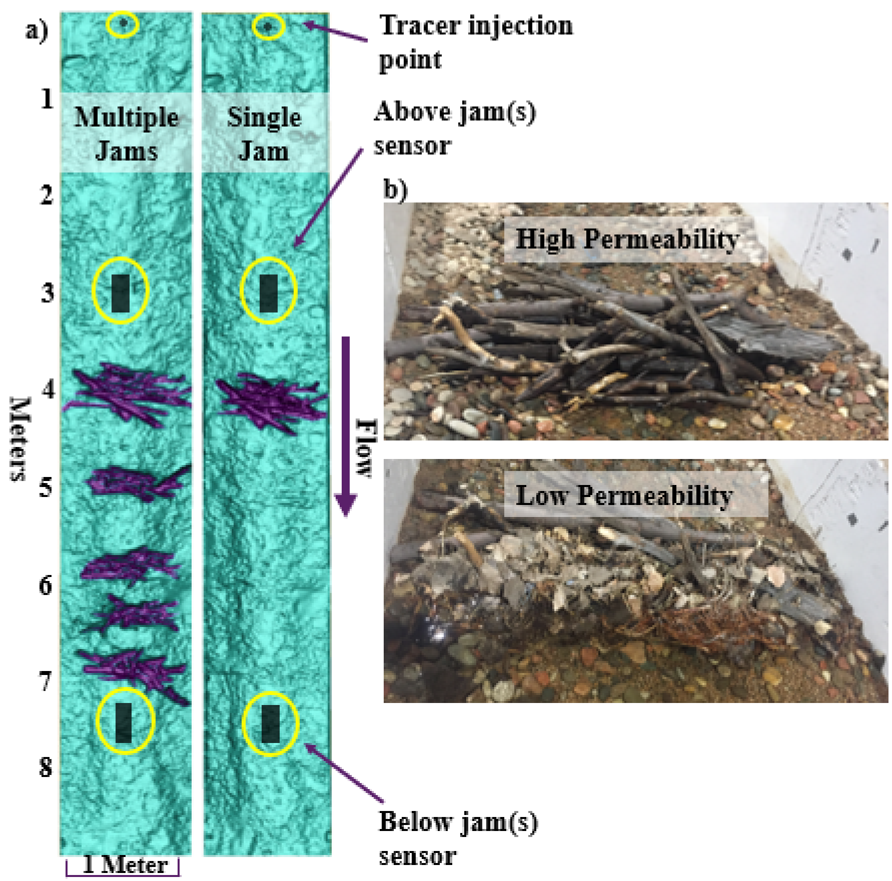

Figure 1. Flume configuration (9-m long, 1.2-m wide) for (a) longitudinal distribution density experiments and (b) permeability experiments. (a) shows the change in jam quantity from a single jam to multiple jams. (b) shows the change in permeability for a single logjam from a more permeable jam to a less permeable jam with coarse particulate organic matter additions. 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.

A list of all flume runs is included as Table 2. We implemented tracer experiments with sodium chloride (NaCl) to characterize surface 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. The ability to resolve transient storage depends in part on the relative travel times through the mobile portion of the channel and transient storage zones, as well as the exchange rates between them. Given our expectation of short transport times (on the order of minutes) in this flume-scale system, we deemed a pulse injection sufficient to load even some the slower flow paths with salt. The first 3-m of the flume served as a mixing zone. 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 minutes 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 m 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 upstream sensor data are included in the Supplemental Information. The measured instream conductivity signals represent the combined effects of surface transient storage in the channel (e.g., backwaters, eddies) and subsurface transient storage via hyporheic exchange.

We set high and low discharge values that ranged over a factor of 10 (0.001 m^3/s and 0.01 m^3/s). Initial test runs suggested that tracer was flushed too quickly to measure with accuracy above 0.01 m^3/s. Discharge readings were obtained from a flow meter with $\pm 0.2\%$ accuracy. Discharge for all flume runs was fully turbulent, allowing relaxation of Reynolds number scaling (Peakall et al., 1996). We ran replicates for all flume trials. A digital elevation model for the flume was constructed using structure from motion. 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 Flume Data Analysis

Tracer tests are commonly interpreted for transient storage residence times using solute breakthrough curves from stream sensors (e.g., Wörman et al., 2002, Anderson et al., 2005, Lautz et al., 2006, Wondzell, 2006, Tonina and Buffington, 2007). We plotted in-stream fluid conductivity data against time as breakthrough curves for each flume run. 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 skew (Harvey & Gorelick, 1995; Gupta & Cvetkovic, 2000). 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 channel and in underlying aquifer materials (e.g., Lees et al., 2000; Doughty et al., 2020), though it is likely most sensitive to the shortest timescales of transient storage in the channel (Harvey et al., 1996). Higher values of skew 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 calculation of the temporal moments is included in the Supplemental Information; here, we focus our analysis on mean arrival time and skew. The former reveals changes in travel times through the mobile zone in the channel, and the latter reveals changes in the interaction of mobile zones with transient storage zones. Flume run times were truncated to include one minute of background data prior to the pulse NaCl injection and a total time of 30 minutes to provide comparable skew values between runs. Fluid conductivity readings in the flume return to background levels in under 10 minutes, so truncation does not affect estimates of tailing in the breakthrough curves.

Statistical analyses were performed in R Studio (R Core Team, 2020). We statistically assessed how dependent variables (skew 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 (Supplemental Table 3). Tukey adjusted pairwise comparisons were calculated using *emmeans* R package (Lenth, 2020). A significance level alpha of 0.05 was used in all statistical analyses.

2.3 Numerical Modeling

We numerically simulated all flume runs in HydroGeoSphere to visualize longer duration flow paths moving through the subsurface (Aquanty Inc. 2015; Brunner & Simmons, 2012). The model domain mirrors our flume dimensions of 1.2 m wide, 9.0 m long, and 0.1 m deep. 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 HydroGeoSphere model solves wave approximations of the Saint Venant equation for surface flow, the Richards equation for subsurface flow, and the advection-dispersion-diffusion equation for groundwater age. The surface flow equation is 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, therefore choosing a finer mesh would have been inconsistent with the concept of a porous continuum. The subsurface domain of our model is discretized into ten vertical layers. The three near-surface sediment layers represent the gravel and coarse sand top coat layer of the flume and are 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 are assigned an element height of 0.028 m and hydraulic conductivity of 8.9×10^{-5} m/s. Sediment hydraulic properties are consistent with Wilhelmsen et al. (2021) (Table 3). Logjams were simulated as a porous medium with varying permeability (Table 3) to test the effect of this parameter on hyporheic flow and subsurface transient storage. The hydraulic conductivity of the more permeable logjam(s) is 1 m/s, while the value for less permeable logjam(s) is 0.5 m/s. It is important to note that because we treat the jams as a porous medium, we also chose to include flow paths through the jams as part of "subsurface" transient storage.

For each simulation in HydroGeoSphere, we visualized subsurface flow paths in Tecplot. We also visualized groundwater age throughout the subsurface, which was computed using the groundwater age mass-transport equation embedded in HydroGeosphere. Groundwater age is similar in concept to a residence time and includes the effects of both advection and dispersion (Therrien et al. 2006). We calculated this age only for visualization purposes, as it could not be used to construct residence time distributions because of the zero-age boundary condition at the bottom of the water column. To compute residence time distributions in the subsurface, we released particles at the water-sediment or water-jam interface and analyzed the flux-weighted residence times of the 9000-18000 particles that returned to the surface water. From the flux-weighted residence time distribution, we calculated the mean travel time in the subsurface and the skew. It is important to note that the model-derived mean travel time in the subsurface is not directly comparable with the flume-derived mean travel time, as the former only considers travel due to advection in the subsurface, while the latter considers salt transport due to advection and dispersion in the surface and subsurface. We report both values, as both represent different aspects of solute travel through the interconnected stream-groundwater system. Similarly, skew in the model-derived hyporheic residence time distribution is not directly comparable with skew in the salt breakthrough curve. We report both values to quantify the weighting of longer solute residence times (in one case, for the entire flume system, and in the other case, for the hyporheic zone specifically). We also calculated average hyporheic fluxes for each simulation. Model parameters are included in Table 3 and more on the governing equations is in the

Supplemental Information.

Table 2. Flume and numerical model runs with discharge and logjam characteristics (number of jams and permeability). All runs were conducted in flume and numerically simulated unless otherwise noted. Replicates were run for all flume trials.

Number of Jams	**Logjam Permeability**	**Discharge**
1	High	High
1	High	Low
1	Low	High
1	Low	Low
5	High	High
5	High	Low
5**	Low	High
5**	Low	High

**Numerical model only

Table 3. Model parameters and values

Variable	Definition	Value	Unit
$K_{shallow}$	Hydraulic conductivity of shallow gravel and coarse sand stratum	2.5×10^{-2}	m/s
K_{deep}	Hydraulic conductivity of deep coarse sand stratum	8.9×10^{-2}	m/s
K_{high_jam}	Hydraulic conductivity of high permeability logjam	1	m/s
K_{low_jam}	Hydraulic conductivity of low permeability logjam	0.5	m/s
	Porosity of sediments	0.3	-
	van Genuchten alpha	3.548	1/m
	van Genuchten gamma	3.162	-
$_{high\_jam}$	Porosity of high permeability jams	0.7	-
$_{low\_jam}$	Porosity of low permeability jams	0.35	-
$_{l}$	Longitudinal dispersivity	0.02	m
$_{t}$	Transverse dispersivity	0.02	m
n_x, n_y	Manning's coefficient	0.03	s/m$^{1/3}$

3 Results

H1) Increasing logjam longitudinal distribution density enhances transient storage

Results from the flume support our hypothesis that an increase in logjam longitudinal distribution density enhances the magnitude of transient storage. We observed an increase in skew and mean arrival time in the flume results with an increase in logjam longitudinal distribution density (Figure 2). Tukey adjusted pairwise comparisons between mean arrival time and the number of jams indicated slower advection with more jams ($p<0.0001$). In other words, not surprisingly, more logjams in the flume result in slower movement of the tracer down the channel. Pairwise comparisons between skew and the number of jams indicate an increase in skew with more jams present ($p<0.0001$), meaning that more jams increase retention. Numerical modeling simulations further support this hypothesis. Increasing the longitudinal distribution density of logjams results in a greater extent of hyporheic zone (Figure 3). Mean subsurface arrival time and skew both increase with the addition of multiple logjams in the numerical model (Figure 2). We see a 14% increase in hyporheic exchange fluxes with multiple jams present compared to a single jam at low flow and a 2% increase in hyporheic exchange at high flow (Supplemental Table 5). Multiple successive jams provide more pervasive exchange by distributing the head drop at each jam, leading to distributed but shallow flow paths (Figure 3). Thus, greater logjam longitudinal distribution density facilitates more surface water storage as well as downwelling into the subsurface (Figure 4).

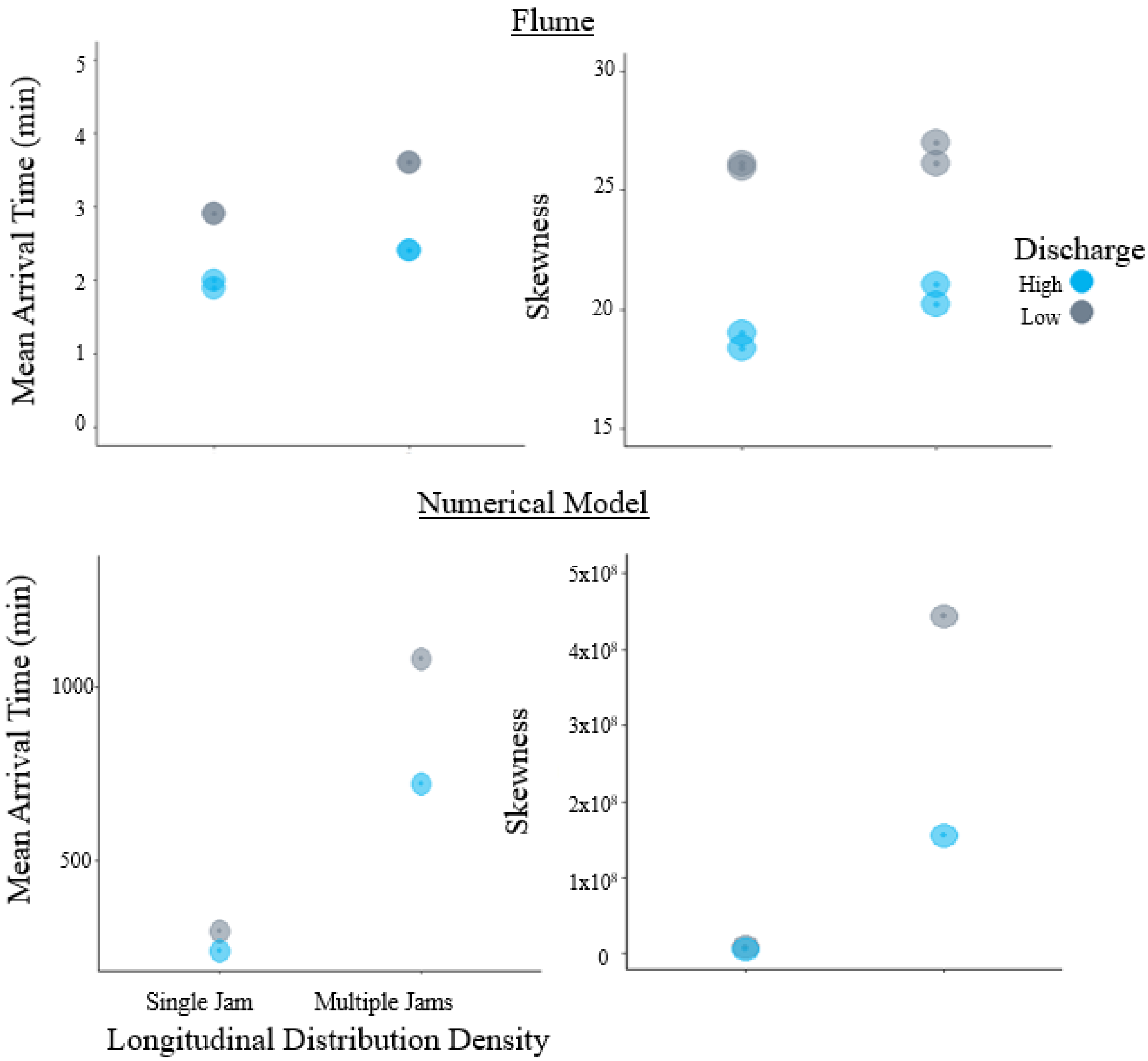

Figure 2. Mean arrival time and skew for flume runs and numerical model simulations where the longitudinal distribution density of logjams went from a one logjam (single) to five logjams (multiple). Both mean arrival time and skew increase with multiple jams. Note that flume-derived transient storage statistics are particularly sensitive to surface water flow, while model-derived transient storage statistics only focus on flow in the subsurface (they are not directly comparable). There are no replicate runs for the numerical model results.

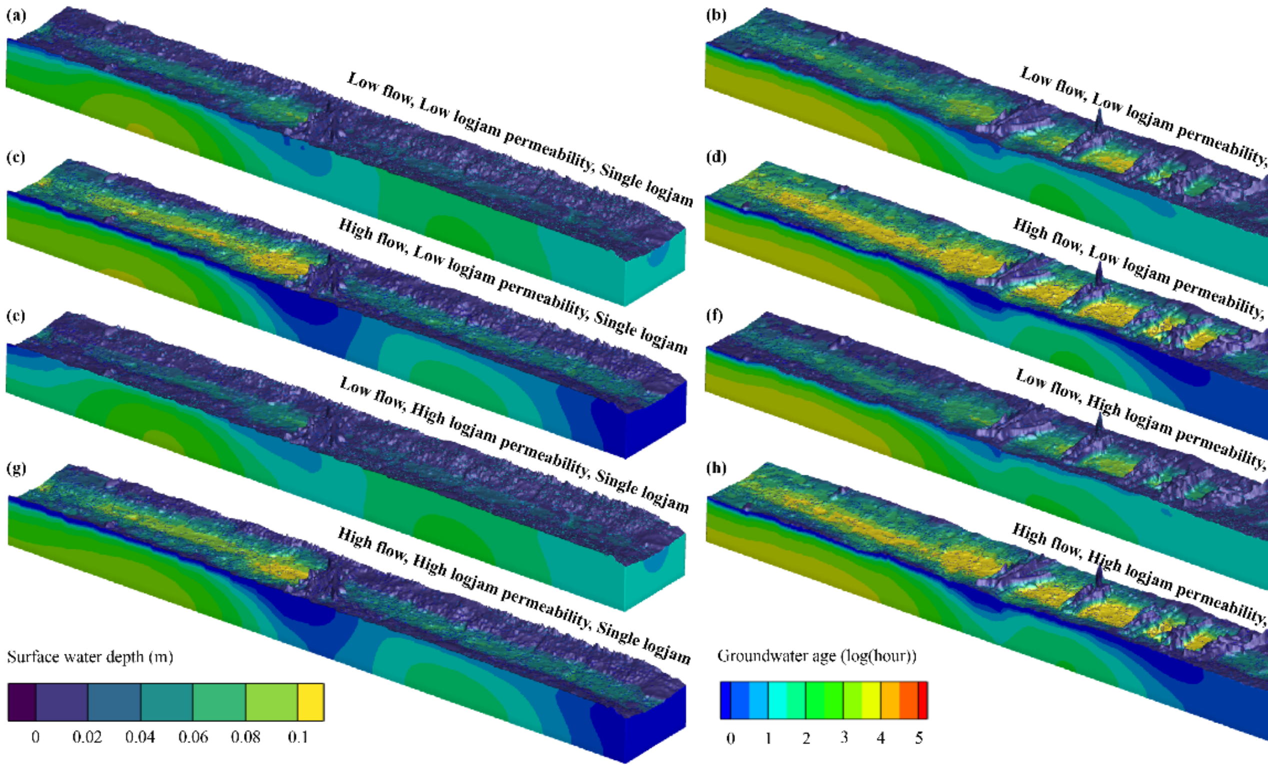

Figure 3. HydroGeoSphere simulated surface water depth (m) and groundwater mean age (log(hour)) for the eight flume scenarios where the logjam permeability, number of logjams, and/or discharge change. The surface water level and connectivity between groundwater and surface water are increased when surface water encounters a logjam. Rising surface water level causes more water to infiltrate into the water-sediment interface in front of the logjam and exfiltrate out behind the logjam. Comparing the scenarios of single logjams (left) and multiple logjams (right), a single jam drives a deep zone of fast exchange, while multiple jams drive shallower but connected and repeated zones of fast exchange.

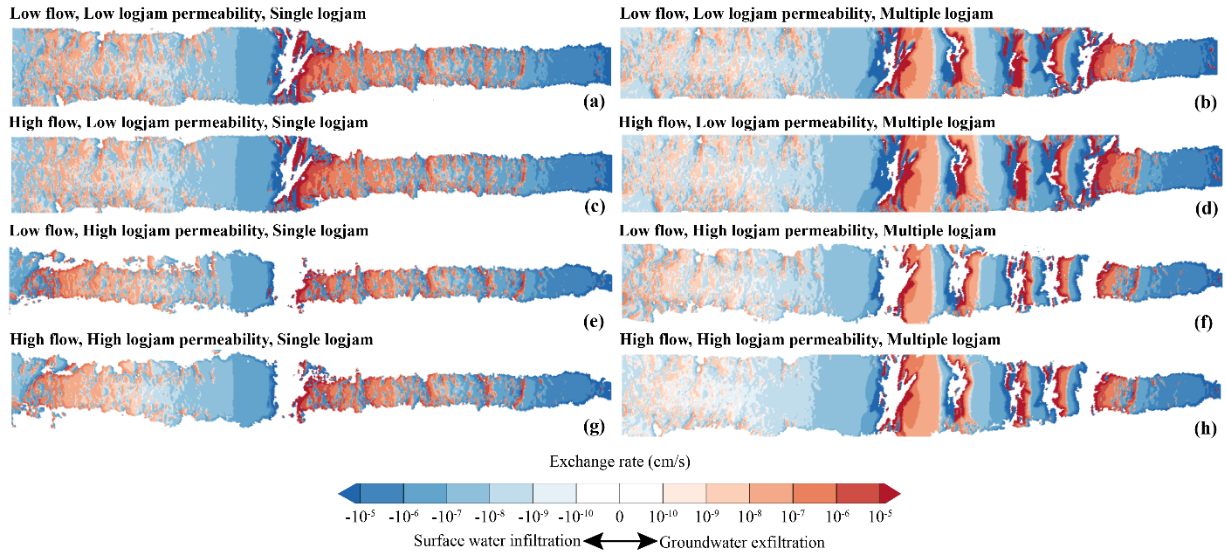

Figure 4. HydroGeoSphere simulated exchange rates across the water-sediment interface and water-jam interface for the eight scenarios where the logjam permeability, quantity of logjams, and/or discharge change. The area in front of each logjam is the hotspot for surface water infiltration, while the area behind the logjam is the hotspot for groundwater exfiltration. The submerged area of the flume in these scenarios are different due to changes in backwater effects. Generally, more logjams, higher flow rates, or lower logjam permeability will create more of a backwater effect and thus extend the area available for exchange with the subsurface.

H2) Decreasing the permeability of a single logjam enhances transient storage

Results support our hypothesis that a decrease in logjam permeability enhances the magnitude of transient storage (Figure 5). Visual 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 6). As more wood and coarse particulate organic matter are added to a single logjam, greater backwater and low-velocity flow fields form. Model simulations 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 in front of the logjam and exfiltrate out behind the logjam (Figure 4). Thus, hyporheic exchange is increased around the logjam.

Surface mean arrival time increased as the permeability of the jam decreased in the flume (p=0.0001). In other words, a more tightly packed jam results in slower movement of the tracer down the channel regardless of discharge. We observed the same trend in subsurface mean arrival time in the model (Figure 5). Pairwise comparisons of skew and permeability in the flume results suggest that a less permeable logjam increases surface water retention compared to a more permeable logjam in the flume (p=0.0087). Skew in the model increases by 300% as the permeability decreases at low discharge and increases by over 160% as the permeability decreases at high discharge.

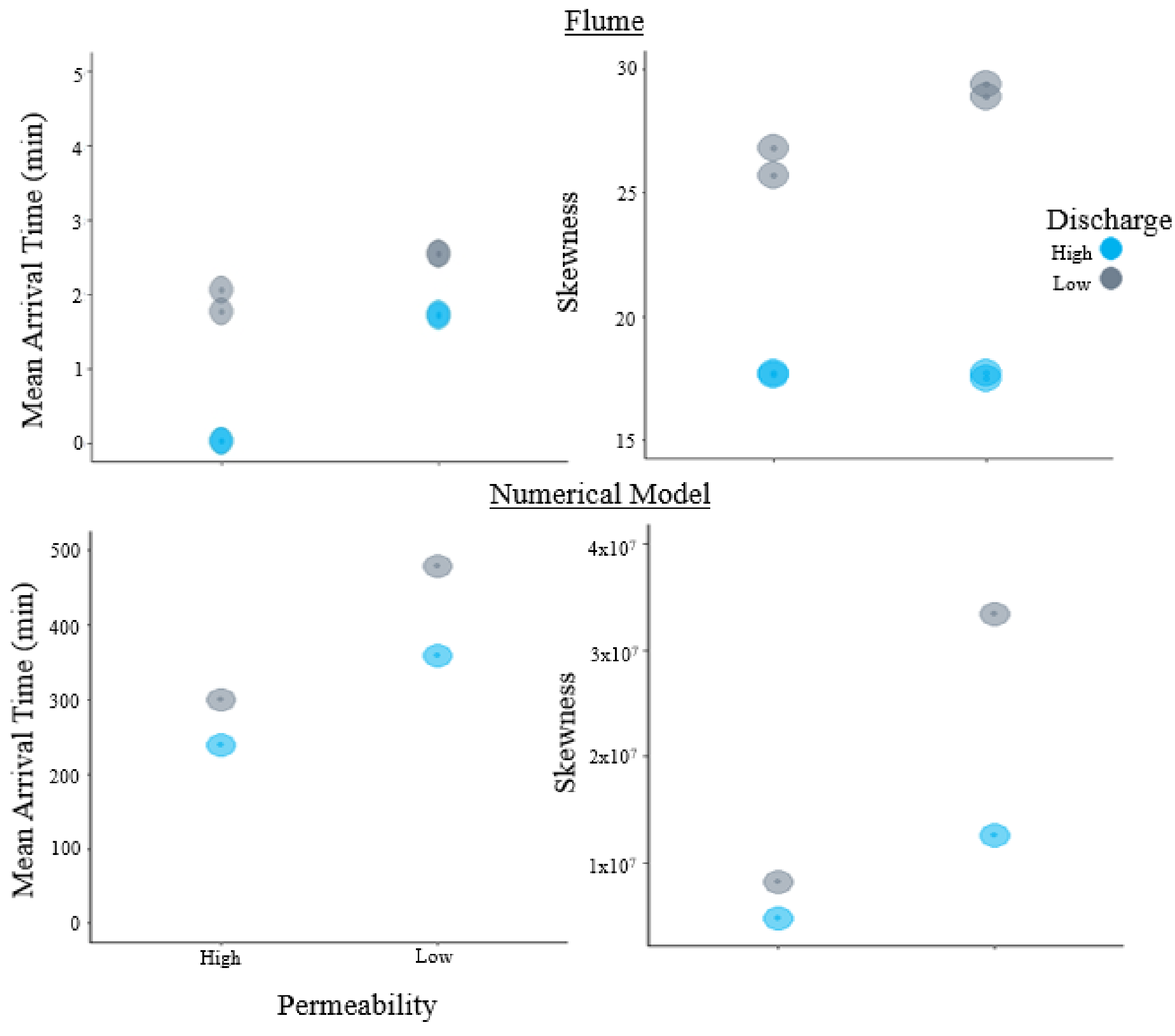

Figure 5. Mean arrival time and skew for permeability flume runs and numerical model simulations where the permeability a single logjam went from high to low. Both mean arrival time and skew increase as jam permeability decreases (i.e., the logjam is more tightly packed). Note that flume-derived transient storage statistics are particularly sensitive to surface water flow, while

model-derived transient storage statistics only focus on flow in the subsurface (they are not directly comparable). There are no replicate runs for the numerical model results.

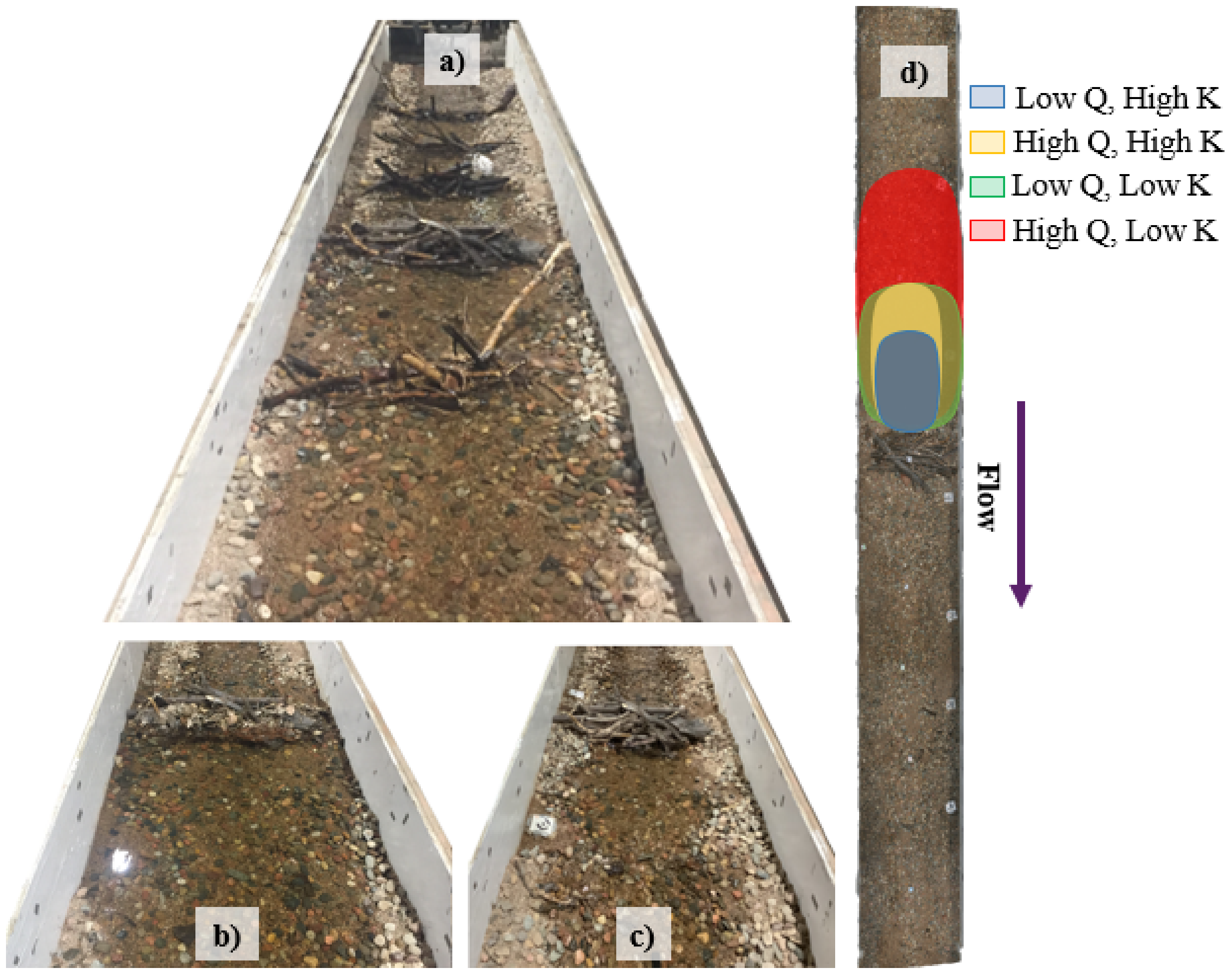

Figure 6. Backwater extents of flume runs with visual of inundation extents for a) multiple jams at high flow, b) logjam with low permeability at high flow, c) logjam with high permeabiltiy at high flow, and d) backwater mapping for single jam flume runs; Q indicates flow and K indicates hydraulic conductivity (permeability). Backwater extent is greater as permeability is decreased and as the longitudinal distribution density is increased. When comparing the backwaters of a single logjam, the greatest backwater corresponds with a low permeability jam at high flow. The smallest backwater extent corresponds with a high permeability jam at low flow.

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. Mean arrival times for the flume and model show a clear increase in time the tracer takes to move through the surface and subsurface between a single low-permeability jam and multiple high-permeability jams (Figure 7). In the flume, the tracer moves significantly slower when multiple jams are present ($p<0.0001$). Modeling results also showed approximately a 120% increase in subsurface mean arrival time with the presence of multiple high permeability jams compared to a single, low permeability jam (Figure 7).

Skew response was different based on discharge in the flume (Figure 7). Under low-discharge conditions, more skew is observed in a single low-permeability jam compared to multiple high-permeability jams ($p=0.002$). Under high discharge conditions, more skew is observed in multiple high-permeability jams compared to a single low-permeability jam ($p=0.0007$). In other words, permeability is playing a greater role in enhancing transient storage in the flume at a low discharge compared to high discharge. Skew was greatest in the multiple high-permeability logjam numerical modeling simulations relative to a single low-permeability logjam, regardless of the discharge (Figure 7). We observed approximately a 24% increase in hyporheic exchange at low flow and 12% increase at high flow in the multiple high-permeability logjam simulation compared to the single low-permeability logjam simulation (Supplemental Table 5). We simulated a scenario with both increased logjam longitudinal distribution density and decreased permeability (not shown in the flume), which resulted in the greatest magnitude of hyporheic exchange and surface backwater increase of all logjam scenarios.

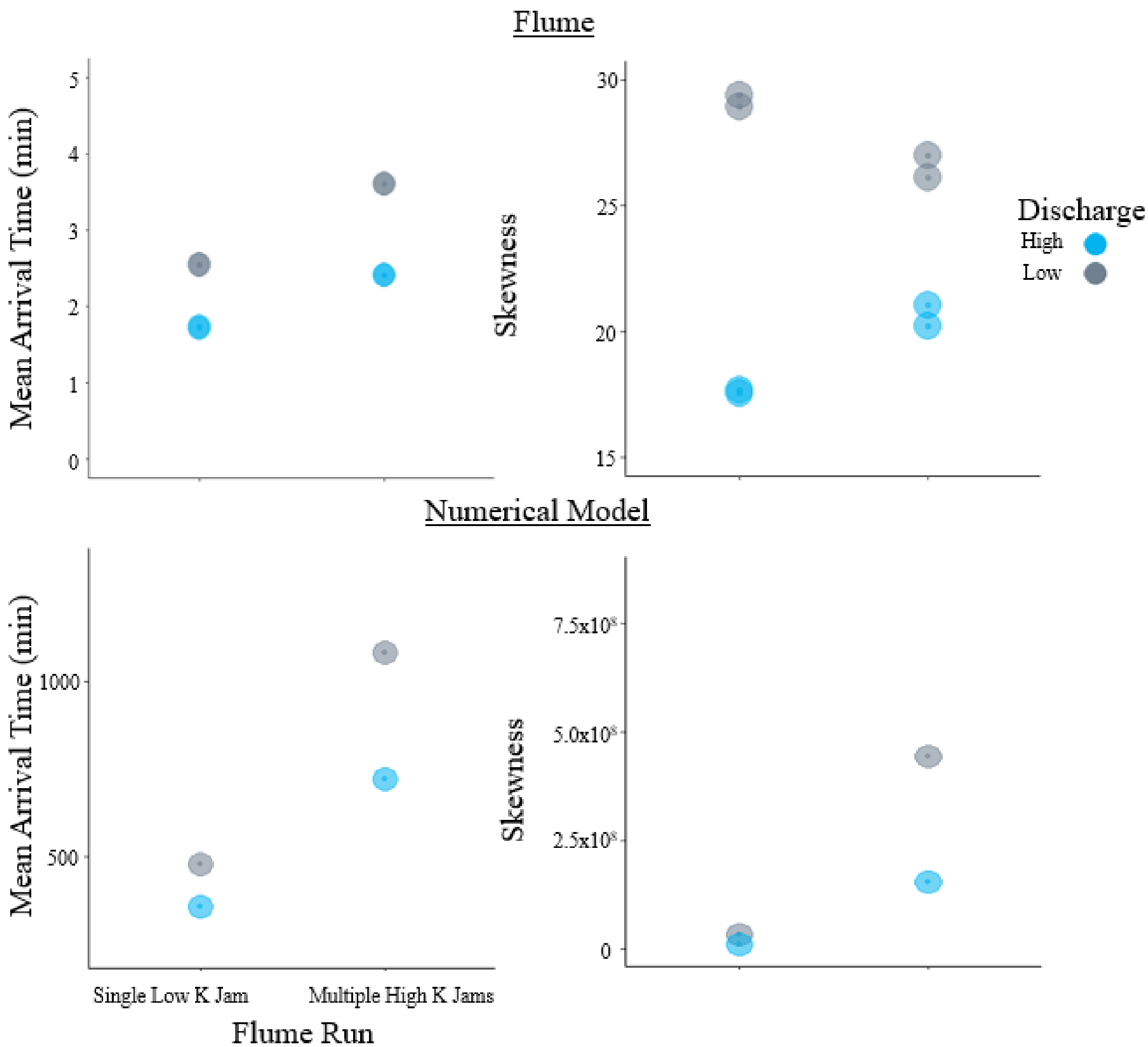

Figure 7. Comparison of skew and mean arrival time values between a single low permeability logjam and multiple high permeability logjams. We see greater mean arrival times in multiple high permeability jams relative to a single low permeability jam. For skew, results between the flume and model vary based on discharge. Note that flume-derived transient storage statistics are particularly sensitive to surface water flow, while model-derived transient storage statistics only focus on flow in the subsurface (they are not directly comparable). There are no replicate runs for the numerical model results.

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

Numerical model simulations and flume runs suggest that discharge has complex effects on transient storage, likely depending on the timescale of storage. Both flume and models show an increase in backwater when discharge increases (Figure 3 and 6). We observed that increasing the discharge to the flume both can store more surface water and elevate the surface water level in front of a logjam (Figure 6). Similarly, the submerged area of the model increased by about 20% at higher flows for all configurations (Supplemental Table 5).

Mean arrival times of surface and subsurface flow paths decrease with increasing discharge in both the flume and model. In the flume, this indicates quicker surface water flow paths with greater discharge. In the model, this indicates faster subsurface exchange rates when discharge increases (Figure 2, 5, and 7). Across flume trials, skew significantly increases at low discharge compared to high discharge ($p<0.0001$ averaged over the number of jams or averaged over permeability). Numerical model simulations suggest that lower discharge also facilitates a greater magnitude of skew as logjam characteristics increase in complexity (i.e., when more jams are present and when a single jam is less permeable) (Figure 2, 5, and 7). We infer that that there is more Gaussian flow at high discharge as solutes moves quickly through the system and the breakthrough plots show a lack of heavy tails (see Supplemental Plots). Consequently, at low discharge, we observe more heavy tailing behavior. This may be a matter of how easy it is to resolve that smallest fraction of flows that stick around the longest and overall sensitivity in the flume/model. However, the combined results also suggest a more complex behavior that may depend largely on surface water flow in the backwater zone.

4 Discussion

Our primary objective was to evaluate the influences of changes in (i) logjam longitudinal distribution density, (ii) logjam permeability, and (iii) discharge on transient storage. Using a combination of physical and numerical modeling allowed for better constraint of both surface and subsurface flow paths. Results suggest that increasing the longitudinal distribution density and decreasing the permeability both increase transient storage, regardless of the discharge. This fits with what we expected to see based on past work. Ader et al. (2020) 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. Studies evaluating hyporheic interactions around beaver dams (e.g., Lautz et al.,2006; Briggs et al., 2013) indicate that stream reaches with beaver dams exhibit a greater degree of hyporheic interaction. Our results showing transient storage around low permeability logjams with permeability similar to that of a beaver dam support this understanding that a more tightly packed logjam can enhance transient storage.

4.1 Complexities in Transient Storage Flow Paths

We assume, based on our results, that the flume is more sensitive to surface flow paths and the numerical model to 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. However, it is too short for the slowest flow through the subsurface (see groundwater ages in Figure 3). We therefore use the numerical model to quantify the behavior of the longest solute travel times in the subsurface. Both physical experiments and numerical models represent simplifications of real conditions, but 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. In the models, it is unclear whether more skew (which we interpret as more transient storage) equates to a greater hyporheic exchange flux or longer residence times (Supplemental Table 5). As has been shown in past studies (Cardenas et al., 2004; Cardenas et al., 2008; Sawyer and Cardenas; 2009; Pryshlak et al., 2015), the two tend to work against each other (greater exchange rates tend to occur with shorter residence times).

We observed complex dynamics in the relationship between logjam distribution density, permeability, discharge, and transient storage. As logjams accumulate in a stream channel and accumulate more fine material, upstream pooling increases, driving surface and hyporheic flow paths and heightened complexity of the stream system (Abbe and Montgomery, 1996; Sear et al., 2010). Evolution in jam complexity (both in terms of permeability and longitudinal distribution density) can result in the activation of the floodplain and other portions of the hyporheic zone that might otherwise be dormant (Gooseff et al., 2006; Wondzell et al., 2009; Doughty et al., 2020). 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 both longitudinal distribution density of logjams and the amount of coarse particulate organic material in a jam leads to an increase in wetted area and exchange fluxes between the surface water and groundwater (Supplemental Table 5).

Existing work provides evidence for both increased transient storage during low discharge conditions, when the water table near the stream is low (Harvey and Bencala, 1993; Harvey et al., 1996; Wroblicky et al., 1998) and during high discharge conditions, when the stream experiences greater channel wetted area and floodplain inundation (Nyssen et al., 2011; Doughty et al., 2020; Wilhelmsen et al., 2021). Comparisons of mean arrival times and skew in the surface and subsurface show consistencies across the flume and model. Our results show less skew and shorter mean arrival times when discharge increases (Figures 2, 5, 7). In the flume, flow paths are better imaged at low discharge when we can load more of the flow paths with a short salt pulse. In the models, all the mean arrival times are already limited to the subsurface (a transient storage zone), so skew is only telling us about the longest transient storage times in that case, and a larger skew indicates a wider, heavier-tailed distribution of residence times. We suspect understanding the role of discharge in these environments is dependent on sensitivity to detecting the smallest fraction of flows that stick around the longest, which becomes increasingly challenging to do at higher discharge. Both the flume and model results reflect simplification of the river corridor in which flow paths cannot access a floodplain. We recognize that longer and deeper flow paths might be constrained by the base of the sediment box in the flume and impermeable walls of the model. The extent of these flows in natural streams could depend strongly on the depth of alluvial cover (Tonina and Buffington, 2009), which is in turn influenced by the presence of large wood, because logjams store sediments (Massong and Montgomery, 2000; Montgomery et al., 2003). 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.

4.2 Management Implications

Our simulation of multiple low-permeability logjams enhanced hyporheic exchange by the greatest magnitude, suggesting that this configuration maximizes hyporheic exchange potential. 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 best maximize transient storage. Although the specific magnitudes of surface transient storage and hyporheic exchange at the field scale cannot be determined from flume-scale experiments, the general characterization (for example, 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 and 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 and Gooseff, 2010) and few studies quantify the impact of restoration features on hyporheic function (Kasahara and Hill, 2006; Crispell and Endreny, 2009; 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.

1. Conclusions

Results from tracer experiments in our flume and numerical modeling simulations provide insight into how logjam characteristics influence transient storage. The presence of multiple channel-spanning logjams and decreased logjam permeability facilitates more opportunities for solute retention and processing in zones of transient storage. Solute breakthrough in the flume is more sensitive to surface flow paths than subsurface flow paths, suggesting much of the observed transient storage occurs in backwater zones behind jams. Configurations with greater transient storage also have the greatest rates of hyporheic exchange and longest residence times in the subsurface. 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 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 transient storage is maximal when there are many jams (large longitudinal distribution density) with low permeability (tight packing of wood pieces). An increase in 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 (Day and Hall, 2017); spatial heterogeneity of physical channel characteristics (Livers and Wohl, 2016; Livers et al., 2018), including channel and floodplain planform (Buffington and Montgomery, 1999; Wohl, 2011); retention of particulate organic matter (Beckman and 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.

Acknowledgments

This research was supported by National Science Foundation Hydrologic Sciences (award 1819068). We thank Ian Gambill, Emily Iskin, Sawyer McFadden, and Karl Wilhelmsen for assistance with flume runs and numerical modeling and Ann Hess for consulting on statistical analysis.

Open Research

The data analyzed for this paper are included in tables in the Supporting Information accompanying this paper. Sample scripts for calculating temporal moments from the flume breakthrough curves and raw conductivity data files can be accessed via HydroShare: http://www.hydroshare.org/resource/5535e4618ce545f5a66087ca784d7150

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