SAN JOAQUIN RIVER PULSE FLOWS

by

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of the requirements for the degree

of

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in

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DEDICATION

This work is dedicated to my parents. I cannot thank you both enough for all the time and effort you put into helping me proofread and providing feedback on my countless projects. Even during the hard times when I felt overwhelmed, your unwavering support and encouragement kept me going. I am forever grateful for all that you both have done to get me to this point in life.

With love,
Your Daughter

ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Paul Hook for his help and advice on this project. This project wouldn't be what it is today without your extensive knowledge of hydrology and detailed reviews. Thank you for your guidance and patience.

Thank you to my coworkers at USBR especially Michael Wolfe, Jeff Gallmann, and Kaitlyn Willems for collecting flow measurements and cleaning up the discharge data. This project wouldn't have been possible without this data. All your insights on the gauging stations and flow on the San Joaquin River were very helpful. Your support and patience over the past few years has meant a lot.

Chad Moore, thank you for discussing the potential topics to study for my professional paper and pitching the idea of examining attenuation on the San Joaquin. I must admit I had never heard of the word "Attenuation" until you brought it up. I appreciate the feedback you gave me at various points throughout this project.

Tom Johnson, thank you for planning these pulses. Without these planned pulses, examining natural event pulses alone would have been much more difficult. I hope more planned pulses occur in the future to see how they all compare. Especially now that the river channel has been altered by the high flows of water year 2023.

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Conversion Factors

Quantity	US Customary Units	SI Units	To Convert US Customary Unit to SI Unit, Multiply US Customary Unit by	To Convert SI Unit to US Customary Unit, Multiply SI Unit by
Area	Square Feet (ft^2)	Square Meters (m^2)	0.092903	10.764
	Square Miles (mi^2)	Square Kilometers (km^2)	2.59	0.3861
Flow	Cubic Feet per Second (cfs)	Cubic Meters per Second (cms)	0.028317	35.315
Length	Feet (ft)	Meters(m)	0.3048	3.2808
	Miles (mi)	Kilometers(km)	1.6093	0.62139
Temperature	Degrees Fahrenheit (°F)	Kelvin (K)	(K-32)/1.8	(1.8 x K)+32
Velocity	Feet per Second (ft/s)	Meters per Second (m/s)	0.3048	3.2808
Volume	Cubic Feet (ft^3)	Cubic Meters (m^3)	0.028317	35.315
	Acre Feet (af-ft)	Cubic Decameters (dam^2)	1.2335	0.8107

Throughout this paper, I use US Customary Units to be consistent with the agencies that are responsible for collecting and publishing the discharge data I analyzed, US Geological Survey and US Bureau of Reclamation, and to facilitate communication with stakeholders. The units used most widely for water management purposes in the San Joaquin Valley, and in the United States as a whole, are cubic feet per second for discharge, acre feet for large water volumes, feet for water levels, and miles or feet for distances. My intended audience includes agency colleagues, water-users, riparian landowners, and flood hazard managers who use US Customary Units.

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ABSTRACT

The San Joaquin River (SJR) was once home to the largest spring runs of Chinook salmon on the west coast, but due to diversions and impoundments, salmon were nearly eradicated. After an 18 year-long lawsuit, a settlement created the San Joaquin River Restoration Program to achieve two goals: (1) restoring and maintaining self-sustaining salmon populations from California's Friant Dam to the confluence of the Merced River, while (2) avoiding adverse water supply impacts to all Friant water-users. Part of the settlement states that "flushing flows," also known as planned pulses, will be implemented to reach these goals. These planned pulses are typically deployed to mitigate adverse impacts of regulated rivers and restore or maintain the benefits of a naturally flowing river. Dams alter natural flow by reducing sediment transport, fragmenting habitat, and can eliminate native species. My study examines how planned pulses in 2018 and 2022 behaved as they moved 52 miles (84 km) downstream of Friant Dam. I found that the behavior of both planned pulses was similar despite different dam release operations. Both pulse events attenuated, broadened and decreased in height, by 76 to 84% from the first to the last river station. Travel times were observed between planned pulses, the pulses' initial arrival travel rate ranged from 1.5 to 2 miles per hour (mph) (2.4 to 3.2 km/h) which was quicker than the pulses' peak at 0.9 to 1 mph (1.5 to 1.6 km/h). In addition, I applied my methods to a natural pulse event that had comparable results to the planned pulses. Difficulty in determining pulse end times resulted in uncertainty and inaccuracy in estimates of pulse total volumes at downstream gauging stations making it impractical to estimate water losses or gains. To improve the accuracy of pulse timing and volume measurements, future work should refine methods for identifying pulse start and end time, separating baseflows from flood flows, and calculating total event volume and peak discharge. Utilizing hydrologic and hydraulic models to examine past and future planned and natural pulses would help to generalize findings across a wider range of conditions. My analysis of planned pulse behavior is a step towards understanding all types of pulses on the SJR and can, in turn, assist water managers with important decisions on river releases downstream of Friant Dam.

INTRODUCTION

More than half the world's rivers are dammed (Cook 2015). Dams provide water storage, hydroelectric power, flood control, and recreation. As beneficial as these services are, negative impacts have occurred to river systems. Dams alter natural stream flows by reducing sediment transportation, fragmenting habitat, and sometimes eliminating native species in downstream reaches. These consequences have put pressure on water managers to modify operations to reduce downstream environmental impacts. One modification used by water managers is pulse flows, also known as flushing flows, environmental flows (EFs), or flow experiments (FEs). Pulse flows reestablish episodic high flows and learn how to manage dam releases for long-term benefits to downstream ecosystems (Olden et al 2014 & Owusu et al 2020). By recreating high flow pulses, features that were previously degraded or removed by a dam's altered flow can sometimes be restored.

Managers must consider how pulses attenuate as they move downstream. Attenuation is the phenomenon in which pulse or wave height decreases and wavelength increases while traveling downstream (Figure 1) (Ferencz et al. 2019; Asselman et al. 2022). Knowing how pulses attenuate can be valuable when planning for dam releases because the peak release height and duration may affect channel change, occurrence of flooding, and surface and groundwater exchange between channels and floodplains. In principle, water managers want to plan dam releases to benefit the downstream water-user community and ecosystem as much as possible. Planned pulse events are an opportunity to learn how attenuation occurs under different situations and can, in the long run, improve implementation of pulse flows to benefit downstream ecosystems. Since every river system is unique, how pulses and flood waves behave and their effects on ecosystems will vary from location to location.

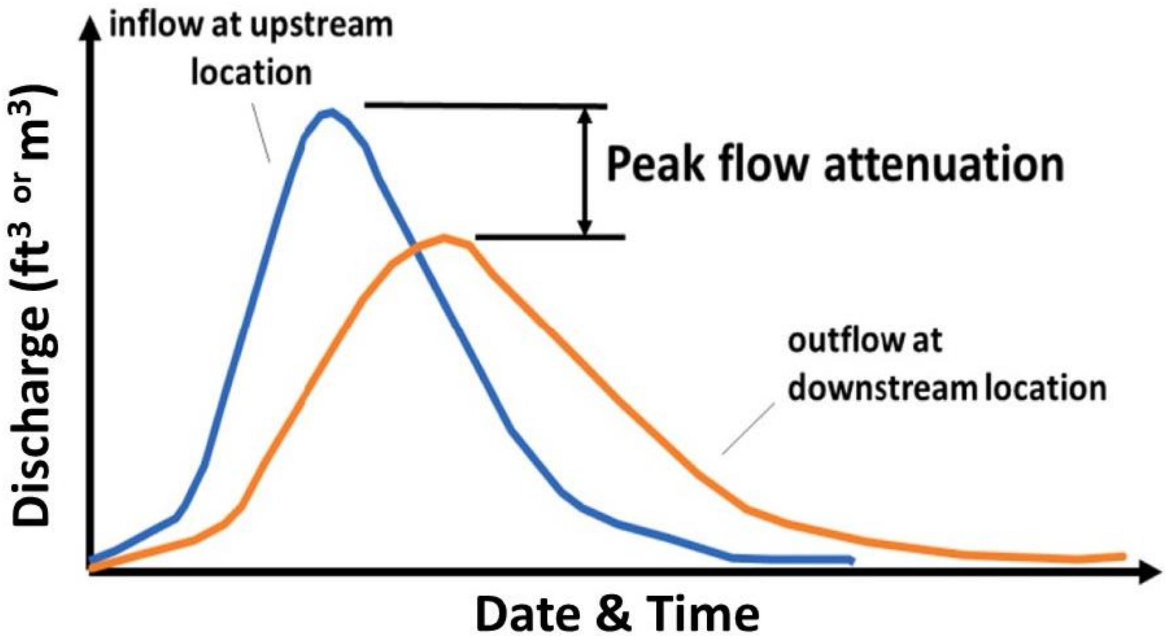

Figure 1. Pulse Flow Attenuation (Asselman et al. 2022).

In this study, I examined pulse attenuation on the San Joaquin River (SJR) in California. Planned releases from Friant Dam (Figure 2) in April 2018 and February 2022 provided an opportunity to see how pulses traveled downstream. Other unplanned pulses have occurred due to natural events such as high runoff years or tributaries that became the main contributor to flows downstream of Friant Dam. Unlike natural pulses or unplanned emergency dam releases, planned pulses have controlled shapes and rates. My analysis of artificial pulse behavior is a step towards understanding all types of pulses on the SJR and can, in turn, assist water managers with important decisions on river releases downstream of Friant Dam.

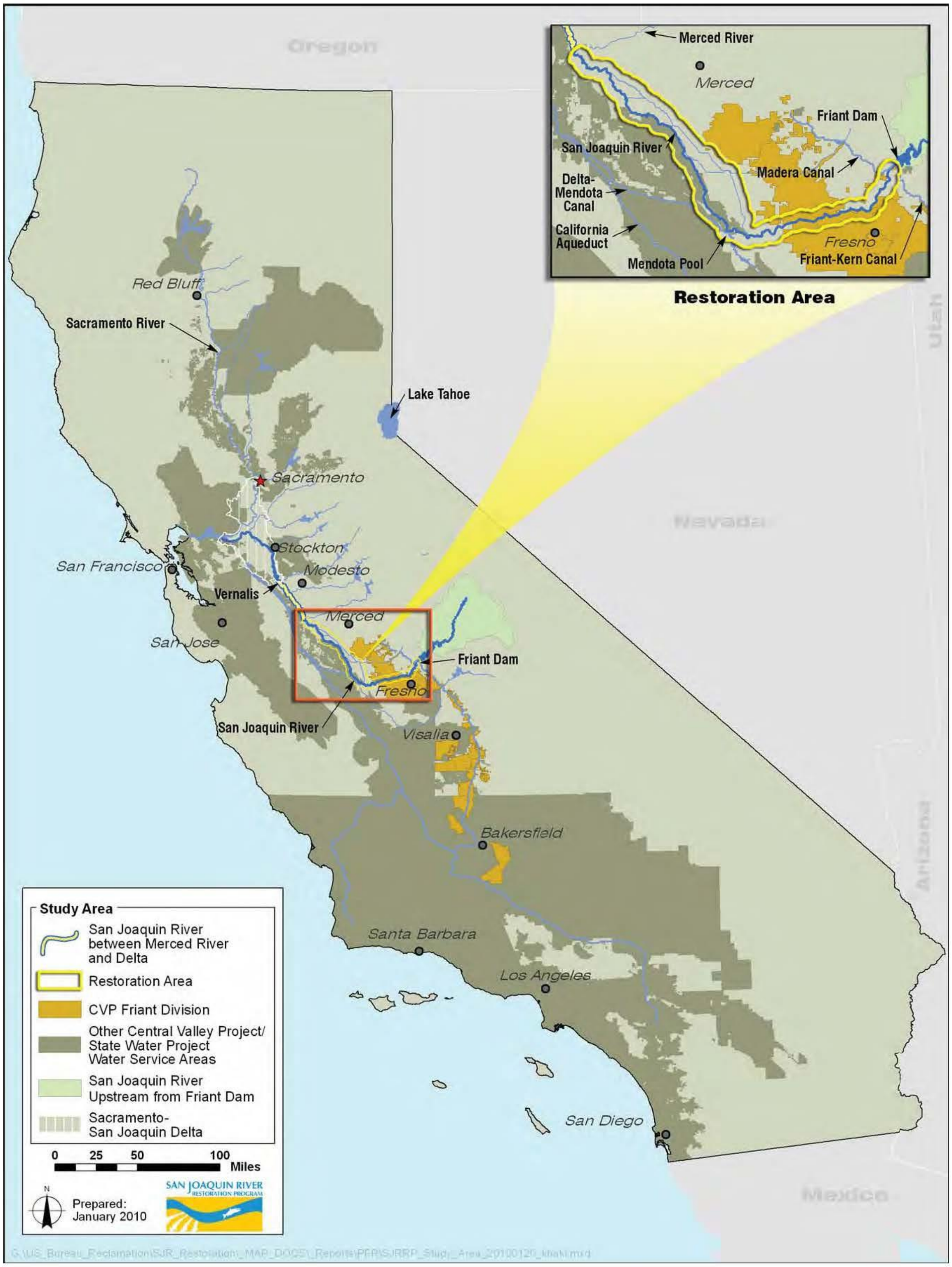

Figure 2. San Joaquin River and San Joaquin River Restoration Project Area (SJRRP Draft EIS 2011).

BACKGROUND

Planned pulse flows on the San Joaquin River (SJR) are a result of a lawsuit in 1988 and its settlement in 2006 that occurred due to the elimination of Chinook salmon (*Oncorhynchus tshawytscha*) spring run. Friant Dam's water operations resulted in the dewatering of downstream river reaches on the SJR where salmon would naturally migrate and spawn (Yoshiyama et al. 1998). As a result of the lawsuit and settlement, plans were made to return flow downstream of the dam to restore the spring run salmon to the SJR river, which was once one of the largest spring runs on the west coast (CDFG 1990; Yoshiyama et al. 1998).

The San Joaquin Watershed is home to the SJR, the second longest river in California, after the Sacramento River (Figure 2). This watershed sits between the Sierra Nevada mountains to the east and the Coastal Range to the west. The headwaters of the SJR are in the high Sierra Nevada mountains where snowmelt is the river's main source of water. The main stem of the SJR is more than 300 miles (483 km) long and drains approximately 13,500 square miles (~35,000 km^2) or 8.6 million acres (3.5 million hectares) as measured at the Vernalis gauge station (Figure 2), then empties into the Sacramento-San Joaquin Delta (McBain and Trush, Inc., 2002; CEPA 2004). For this study, I focus on the 52 (84 km) river miles downstream of Friant Dam.

Friant Dam construction broke ground in 1939 and was completed in 1942 by the United States Bureau of Reclamation (USBR). The concrete dam stands 319 feet (97 m) tall and stores 520,500 acre-feet (ac-ft) in Millerton Lake. The watershed above the dam drains 1,676 square miles (4,341 km^2). Before Friant Dam, the annual average unimpaired snowmelt peak flows ranged from 3,500 cubic feet per second (cfs) to over 30,000 cfs, with typical values in the

10,000 cfs to 15,000 cfs range (Figure 3A & 3B). Over 95,000 cfs was observed after rain on snow events in 1862 and 1997 (McBain & Trush, Inc. 2002). Unimpaired runoff, also known as natural river flow, refers to the amount of natural runoff that would flow past Friant Dam if there were no dams, diversions, or import of water from other watersheds. In the years after the construction of Friant Dam, most of the SJR flow was diverted into two canals, and only minimal flow was released into the river channel to meet the needs of downstream water rights holders. The average annual unimpaired water yield of 1,801,000 ac-ft upstream of the dam, based on water years 1906 to 2002, dropped to 695,500 ac-ft below the dam, based on post dam water years 1950 to 2000 (Figure 3C), reducing flows to the lower reaches of the SJR by over 60% (McBain & Trush, Inc. 2002). These diversions dewatered large stretches between Friant Dam and upstream of the Merced River confluence disconnecting the river from the Pacific Ocean. In addition to lack of water downstream of Friant Dam, no fish ladders were created at the dam to allow for upstream migration in high flow years (Bork et al. 2012).

Before the construction of Friant Dam, the SJR supported one of the largest spring runs of Chinook salmon on the west coast, averaging 200,000 to 500,000 spawners a year (CDFG 1990; Yoshiyama et al. 1998). Historically, spring run Chinook salmon were known to spawn as far as 54 miles (87 km) upstream of the current location of Friant Dam (McBain and Trush, Inc., 2002). Construction of the dam eliminated access to these upstream reaches, but 30,000 to 56,000 spring run Chinook salmon were observed downstream of the dam after completion. In 1951, 62%-71% of SJR water was diverted from the river channel resulting in the dewatering of downstream river reaches and causing the extinction of the spring salmon run and the decline of other native fish in the SJR above the Merced River confluence

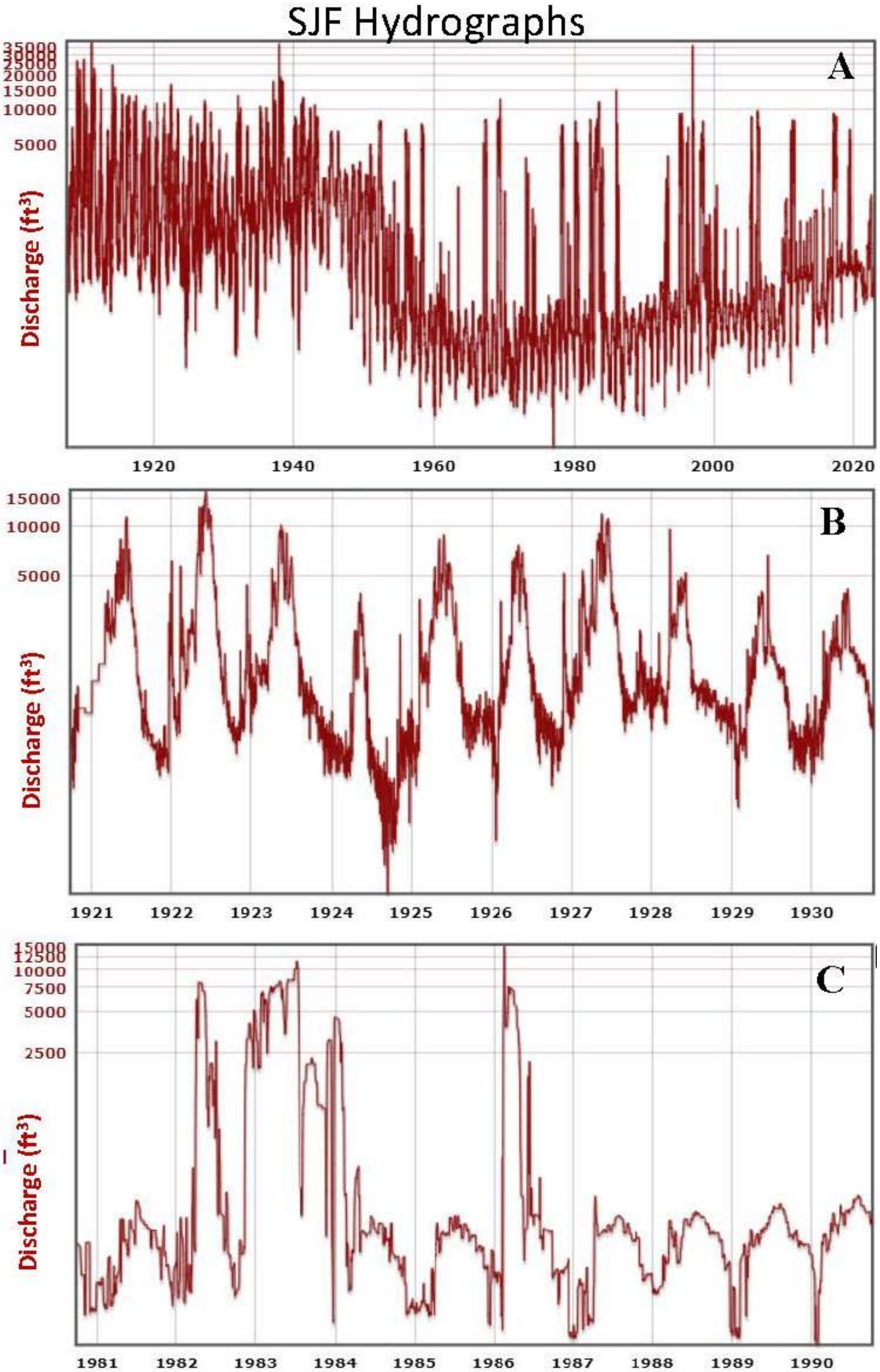

Figure 3: Hydrographs of gauging station, SJF, located 1.6 river miles downstream of Friant Dam. A) 1907-2022: Entire daily discharge record. B) 1920-1930: Pre Friant Dam. C) 1980-1990: Post Friant Dam. The dam was completed in 1942. Y axis in logarithmic scale.

(McBain and Trush, Inc., 2002; Traum et al. 2014). This decrease in water flowing in the river channel reduced the frequency, magnitude, and duration of flows important to fluvial geomorphic processes, over bank flow and inundation area, riparian vegetation, and water temperature (McBain and Trush, Inc., 2002).

In 1988, Natural Resources Defense Council (NRDC) and other environmental groups filed a lawsuit against the USBR for violating California's Fish and Game Code §5937 which states that dams will always allow sufficient water to keep fish in "good condition" downstream of the dam (Smith 2014). In 2006, a settlement was made that outlined two goals (Natural Resources Defense Council versus Kirk Rodgers, Stipulation of Settlement, 2006): (1) Restoration Goal- "To restore and maintain fish populations in "good condition" in the main stem of the San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally reproducing and self-sustaining populations of salmon and other fish." (2) Water Management Goal- "To reduce or avoid adverse water supply impacts to all the Friant Division long-term contractors that may result from the Interim Flows and Restoration Flows provided for in the Settlement."

In 2009, the San Joaquin River Restoration Act directed the Secretary of Interior to implement the settlement and create the San Joaquin River Restoration Program (SJRRP) to perform the necessary work (SJR Restoration Settlement Act 2009). In addition to establishing general requirements for allocation of water to downstream flows for the restoration program, the settlement called for "flushing flows" when annual runoff exceeds the long-term median, classified as "normal wet" or "wet" year types. The main goal of these "flushing flows" is to mobilize spawning gravels (NRDC et al. v Kirk Rodgers 2006). "Flushing flows" are referred to as pulse or environmental flows in this paper. Pulse flows are infrequent on the SJR due to the limitations of water allocated to the SJRRP each water year and downstream channel capacity. The SJRRP has carried out two planned pulse events in April 2018 and February 2022. One objective of the most recent planned pulse release was to monitor sediment mobility. The second objective was to observe pulse attenuation for biological benefits.

RESEARCH QUESTION & OBJECTIVES

The planned pulses that occurred in April 2018 and February 2022 on the San Joaquin River (SJR) provided an opportunity to examine these events in detail to gain insight on how pulses behave. Learning how pulses change down the SJR can provide background to help guide Friant Dam operations and manager's decisions. The overarching question of my project is, how do pulse or environmental flows translate downstream of Friant Dam on the SJR? I had two specific objectives, the first involving hydrologic data analysis and the second addressing broader environmental issues:

1) Determine how pulse flows attenuate and volume changes down the SJR within 52 miles (84 km) downstream of the Friant Dam.
2) Review the analysis methods and effects of pulse flows in case studies in other river system and determine if similar methods can be used to further understand how pulses translate down the SJR.

This was an pilot study, setting the foundation for potential use of models to analyze past and future data.

METHODS

STUDY AREA

The focus of my project is the 52 river miles (84 km) downstream of Friant Dam known as reaches 1 and 2A (Figure 4A). Reach 1, 38.6 river miles (62.1km) long, starts at Friant Dam and ends just upstream of river station Gravelly Ford (GRF). Within this reach, there are three gauging stations that monitor flow. Two intermittent tributaries, Cottonwood Creek (CTK) and Little Creek (LDC), can generate natural pulses such as in March 2018. These tributaries typically contribute little to no flow to the SJR but can contribute a significant amount during precipitation events. Tributary flows can cause managers to reduce dam releases due to SJR channel capacity limitations and risk of flooding. The primary land uses of this reach are gravel mining and agriculture (Figure 4B). There is a history of gravel mining in and around the SJR channel. Today there are active quarries adjacent to the river. Some gravel pits that are no longer in use have filled with water and have been altered to reduce their impacts on river temperatures, limit water recaptured during low flows, and improve salmon migration through projects to meet the SJRRP's restoration goal (Fontaine et al. 2015).

Reach 2A starts with GRF and ends with river station Bifurcation (SJB, SJR near Chowchilla Bypass Bifurcation Structure) about 52 river miles (84 km) downstream of Friant Dam. Within this reach, there are two river stations that capture flow data and no major tributaries. The streambed is primarily sandy compared to the Reach 1, which is gravel. Agriculture is the main land use in this reach (Table 1).

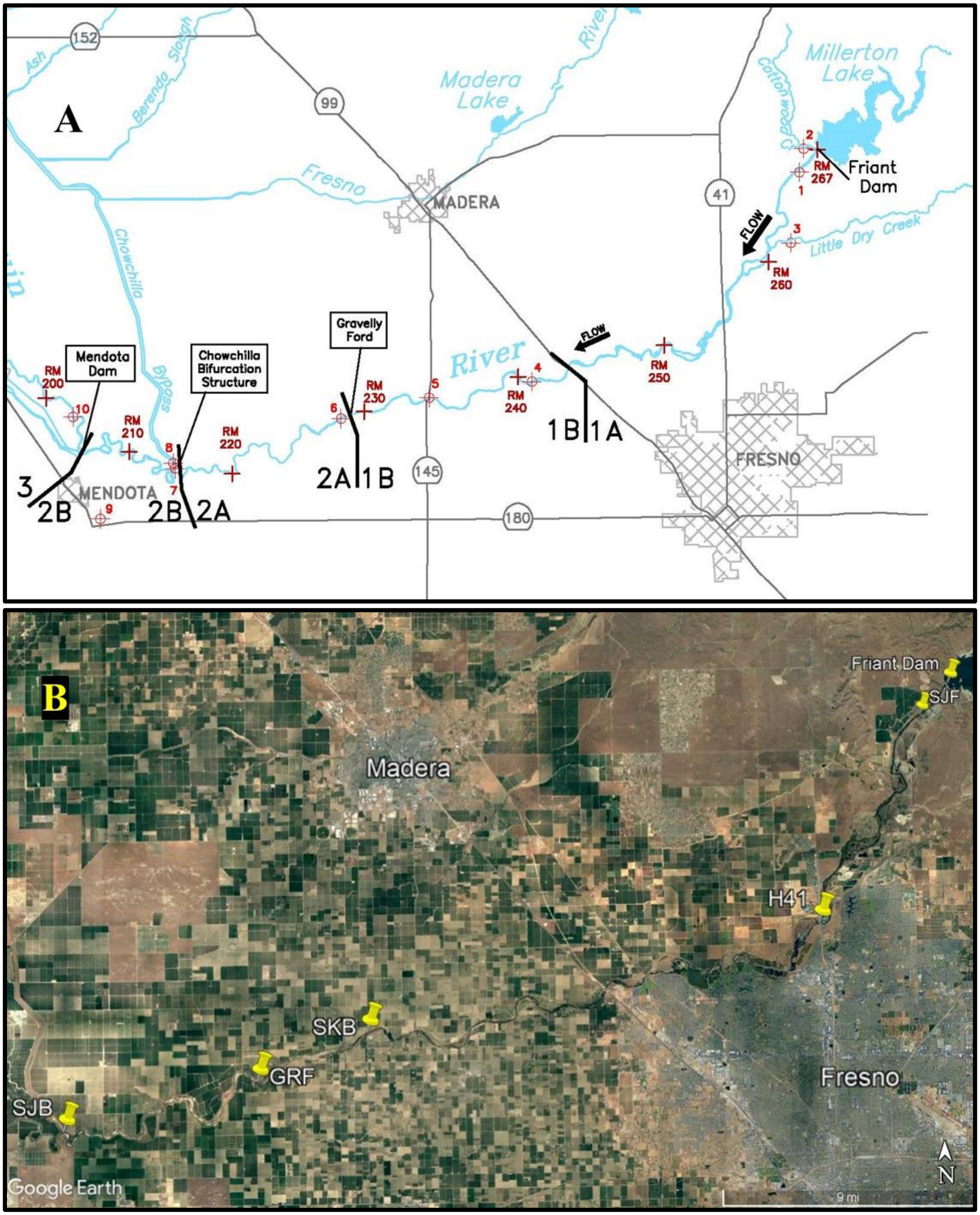

Figure 4. A) Reaches of Interest, focus on Reach 1 to the end of Reach 2A (McBain and Trush, Inc., 2002). B) SJR with Gauging stations.

Table 1. Gauging stations used for SJR discharge data and two tributaries that contribute to the SJR when flowing.

River Station	Code		River Mile	Drainage Area	Elevation	Operating Agency
	CDEC	USGS		sq mi	ft	
River Release	MIL	11250110	0	1,638	330	USBR
SJR Below Friant	SJF	11251000	1.6	1,676	297	USGS
Highway 41	H41	11252275	12.5	1,785	260	USBR
Skaggs Bridge	SKB	11252975	35.5	1,809	210	USBR
Gravelly Ford	GRF	11253058	40	1,818	190	USBR
Bifurcation	SJB	11253115	51.6	1,822	170	USBR
Reach 1 Tributaries into the SJR						
Cottonwood Creek	CTK	11250500	0.2	35.6	355	USBR
Little Dry Creek	LDC	11251500	7.0	57.9	357	USBR

CDEC: California Data Exchange Center; https://cdec.water.ca.gov/
USBR: United States Bureau of Reclamation
USGS: United States Geological Survey

The climate of the San Joaquin Valley has long, dry summers with an average low and high of 61.4°F and 98.2°F. Historically, July and August are the hottest months. Winters are short and characterized by fog with an average low and high of 35.7°F and 55.2°F, respectively. Annual rainfall in the valley bottom averages 5 to 15 inches (12.7 to 38.1cm) typically occurring from November to April (McBain and Trush, Inc., 2002; Traum et al. 2014). In the upper SJR watershed, precipitation predominately falls as snow above 5,500 to 6,000 ft where temperatures typically are less than 32°F in the winter. During the summer, the upper watershed is usually 10 to 30°F cooler than the valley floor (McBain and Trush, Inc., 2002)

Average annual evapotranspiration (ET) downstream of Friant Dam was 53.2 in (135.1 cm) from 1961 to 2003. Most of the annual ET, 64%, occurs during the months May to October. ET typically exceeds rainfall amounts except in December and January (Traum et al. 2014).

DATA SOURCES

I used discharge data from the U.S. Geological Survey (USGS) and USBR gauging stations identified in Table 1 and Figure 4B to analyze pulse behavior. All the gauging stations other than Cottonwood (CTK) record discharge at 15-minute intervals and report it on the California Data Exchange Center (CDEC) website. Having discharge values at 15-minute intervals allowed detailed evaluation of pulse travel.

The USBR provided hourly data from Friant Dam's release to the river which excludes releases into the two canals, Friant-Kern and Madera. In this paper, all dam release values are for the flow release into the river. The USGS river station SJF, at river mile 1.6 (2.6 km) below the dam directly tracks Friant Dam releases except when the intermittent tributary, CTK, is flowing. USBR operates the other four gauging stations, H41, SKB, GRF, and SJB. The Highway 41 gauge (H41) represents the combined flow from the dam release and the two tributaries if they are flowing.

PULSE ANALYSIS

To describe how pulses traveled downstream, I estimated the times of each pulse's initial arrival, peak, and return to baseline level and compared them to the dam releases. Pulse arrival time at each station was identified by a distinct increase in discharge. Peak discharge values were also distinct. The return to pre-release baseline was not always clear as described below. Due to the difficulty of determining the end of the pulse, calculating volume losses between gauging stations was challenging.

Planned Pulse April 2018

In the April 2018 planned pulse, increased dam releases occurred from April 4 at 07:00 through April 6 at 07:00 (PST) then returned to the pre-event flow, 350 cfs (Table 2). The start of the pulse was stepped up three times until the peak discharge, 1,250 cfs, was reached. This peak discharge was held for three hours and then ramped down in five steps over 43 hours.

Table 2. Timeline of river releases changes for the planned April 2018 pulse.

Date	**Time**	**Change**	**From**	**To**
	PST	**cfs**	**cfs**	**cfs**
4/4/2018	7:00	200	350	550
	8:00	200	550	750
	9:00	500	750	1250
	12:00	-200	1250	1050
	16:00	-500	1050	550
4/5/2018	7:00	-75	550	475
	14:00	-75	475	400
4/6/2018	7:00	-50	400	350

For the downstream river stations, the pulse start was defined as when flow increased compared to the pre-pulse, relatively steady baseline flow and continued to trend upward. I used the standard deviation of discharge during pre-pulse steady flow to characterize background flow variability, focusing on periods where flow was steady for 12 hours or more within 15 days before the pulse event. Hydrographs were examined to determine the time when an increase in discharge of more than one standard deviation had occurred between timestamps. The peak was identified as maximum discharge flanked by rising and falling discharge. If the maximum discharge held for more than one time stamp, even if it dropped temporarily and returned to the maximum, the midpoint of the time at maximum was selected as the peak time.

The end of the planned pulse event was defined as the point when discharge returned to the pre-event steady flow mean or when a new upward trend was observed indicating an increase in flow unrelated to the planned event. I determined the mean pre-pulse steady baseline flow for a 24-hour period ending two hours before indicators of the pulse start to ensure the mean was not influenced by the planned pulse and that it represented the most recent steady flow before the event. Sometimes the pulse broadened as it moved downstream which made changes on the tail end of the pulse difficult to identify. In these situations, a range of potential end times were estimated by assuming the peak times were at 10-15% of the total event duration. For example, if the time from start to finish was 12 hours, the estimated end time would be 80 to 120 hours (12h/0.15=80h;12h/0.1=120h). A combination of these methods and return to pre-event steady flow mean was used for river stations from H41 downstream to SJB. The upstream station, SJF, had a distinct end due to its proximity to the dam's release, which allowed the return to pre-event baseflow to be identified clearly.

The end time estimation approach described above was adapted from the "triangular unit hydrograph" method, which represents event hydrographs as triangles with their peaks at a fixed fraction of the total event length (NRCS 2007; NOHRSC 2001). In this case, event end times were estimated for hydrographs without distinct visual end points by assuming that peak timing as a percentage of event duration was consistent. Both the start and end of the pulse were clear at the upstream station, H41, and the peak occurred at approximately 10-15% of the total event time. This range of percentages was used to estimate end times when they were indistinct at downstream gauges. First, the time from event start to peak time was determined. Next, that time was divided it by 0.1 and 0.15 to bracket the approximate 10-15% range of percentages for peak timing.

Planned Pulse February 2022

Two successive pulses were released from February 23 at 23:00 (PST) through February 25 at 22:00 (PST). This event had a two-step ramp up process for the first pulse and was held at 1,500 cfs for 11 hours (Table 3). The ramp down process was done with one step which returned the release to pre-event flow of 400 cfs. There was a period of 18 hours at the pre-event flow level before the start of the second pulse, which again occurred as a two-step ramp up to the peak flow, 1,500 cfs. Peak flow was held for eight hours and was ramped down in three-steps to the pre-event flow, 400 cfs.

Table 3. Timeline of river releases changes for the planned February 2022 pulses.

Date	Time	Change	From	To
	PST	**cfs**	**cfs**	**cfs**
2/23/2022	23:00	500	400	900
2/24/2022	0:00	600	900	1500
	11:00	-1100	1500	400
2/25/2022	5:00	500	400	900
	6:00	600	900	1500
	14:00	-300	1500	1200
	18:00	-300	1200	900
	22:00	-500	900	400
2/26/2022	0:00	0	400	400
2/27/2022	8:00	150	400	550
2/28/2022	18:00	100	550	650

The same methods described for the April 2018 single-pulse event were used to identify start and peak times. The end of the first pulse was identified as either the time when flows returned to pre-event mean stable flow or the lowest discharge between the two pulse peaks. The start of the upward trend after the end of the first pulse was considered the start time of the second planned pulse. Due to a dam release change on February 27, with an increase from 400 to 550 cfs, defining the end of the planned two pulse event was even more difficult than the April 2018 event. Return to pre-event steady flow, an extended period of steady flow, or an increase in flow after the planned event due to other causes were used to define the end.

Travel Time, Attenuation and Volume Changes

The start times and peak times for events were used to calculate travel times between river stations. Travel time between gauging stations and cumulative travel times from the dam to each station were calculated. Hydrographs were used to observe how pulse peaks attenuated as the pulse moved downstream. The difference between river stations' peak discharge was calculated to determine if a rate of pulse decay was comparable between the two planned pulses and potentially other unplanned pulse events. The attenuation of the pulse peaks, both single and double, were analyzed between stations.

Total volume for the entire event, the rising limb to the peak, and peak to falling limb were calculated for all river stations to understand where water gains or losses happened. This approach was complex due to uncontrolled and unknown factors like bank storage exchange rate. For simplicity, soil moisture and bank storage exchange rate were not considered. For the entire event, from start to end, total volume (ft^3) was calculated for each timestamp by multiplying discharge rate in cfs by duration, either fifteen minutes or one hour. These incremental values were then summed between the start and end time stamp and converted into acre-feet (ac-ft).

RESULTS

PLANNED PULSE APRIL 2018

The 2018 single-pulse hydrographs show the general downstream changes expected: delayed peak with reduced height, and spreading out over time (Figure 5A). The pulse hydrograph shape at SJF is ridged and square mirroring the dam release with only slightly rounding of the sharp changes (Figure 5B). As the pulse moves downstream through the other four stations, the shape becomes increasingly smooth and rounded, resembling a more natural flood wave (Figure 5C). The pulse end times span a wide range because the wavelength increases as the wave height decreases, diffusing the pulse out as it travels downstream. Based on Friant Dam records, no changes in the river release happened from April 7 to April 20, 2018, at 10:30PST. Lacking any later flow changes to act as markers, it was difficult to pinpoint or even bracket the end times for the stations below SJF and H41.

Start times for the pulse at all river stations were distinct and met the criteria of a continuous upward trend and an increase in flow that was greater than one standard deviation from pre-event steady flow (Table 4). As the pulse moved downstream the broadening and reduction in wave height caused the total time of the event to be extended. Due to the indistinct end at the lower river stations a range for potential end times were calculated based on the ratio

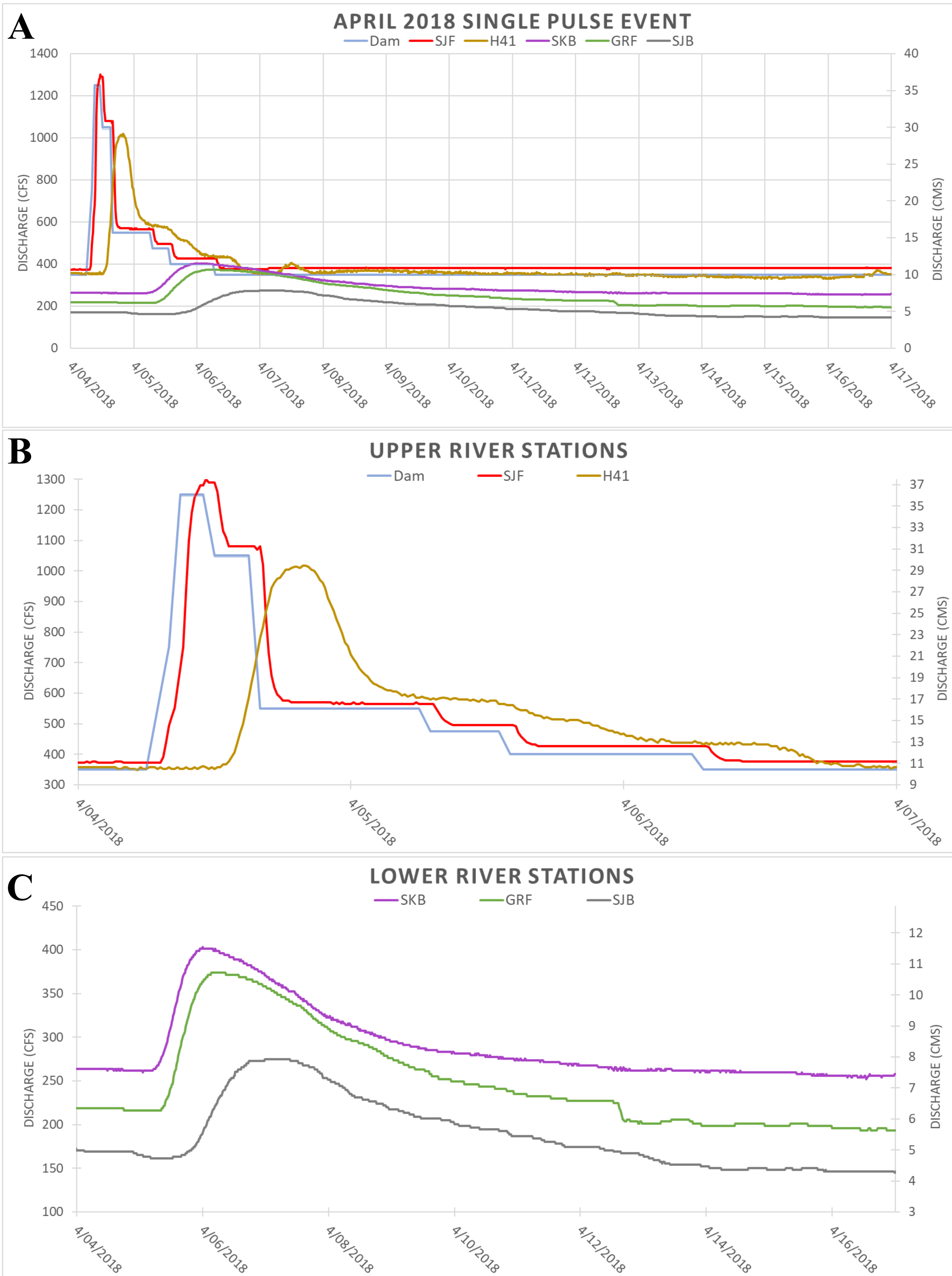

Figure 5. A) April 2018 Pulse event B) Upper River Stations; C) Lower River Stations.

of time from start to peak compared to the entire event at H41, which was about 0.12 for this event (7 h/58 h). The end times in Table 4 are based on this ratio and are used for estimates of total volume. SJF's start, peak, and end times were also clearly identifiable based on the abrupt changes in slope, which allowed me to calculate that the rising limb, from start to peak, was around 7% of the entire event. I did not use this site to determine the end time range for other sites due to the rigidness of the hydrograph, which I thought suggested it would not be a good representation of the downstream gauging stations.

Table 4. April 2018 Pulse Event Data

River Stations	Steady Flow Mean ± Std Dev	Start	End	Total Time	Time to Peak	Total Volume		Peak	Peak Date & Time
	cfs	m/dd/yyyy hh:mm	m/dd/yyyy hh:mm	Hours	Hours	Ft^3	ac-ft	cfs	m/dd/yyyy hh:mm
Dam Release	350	4/4/2018 7:00	4/6/2018 7:00	48	3	100,710,000	2,312	1,250	4/4/2018 10:00
SJF	373±1	4/4/2018 7:30	4/6/2018 10:30	51	4	107,634,600	2,471	1,300	4/4/2018 11:15
H41	355±5	4/4/2018 12:45	4/6/2018 23:00	58	7	116,092,890	2,665	1,018	4/4/2018 19:45
SKB	263±2	4/5/2018 5:15	4/11/2018 17:30	156	19	179,483,805	4,120	403	4/6/2018 0:00
GRF	217±2	4/5/2018 8:30	4/12/2018 19:45	179	22	181,976,940	4,178	374	4/6/2018 6:00
SJB	166±2	4/5/2018 13:00	4/19/2018 8:15	331	40	221,320,260	5,081	275	4/7/2018 4:45

An odd drop in flow can be seen at GRF on April 12 that is not observed on the upstream and downstream stations (Figure 5C). This drop might be a result of a water surge or potential error in the measurement instruments, but it did not influence the estimate of the end time.

Analysis of the pulse's initial arrival and peak time found that the peak discharge traveled downstream at a slower travel rate, approximately 1 mile per hour (mph) (1.6 km/h), than the initial rise of the pulse, which traveled at approximately 2 mph (3.2 km/h) (Figure 6, Left). From the release to the end of Reach 2A, at river station SJB, it took 30 hours for the initial arrival of the pulse and about 67 hours for the peak to arrive. Because the pulse spreads out as it travels downstream, the peak is delayed more than the front end of the pulse.

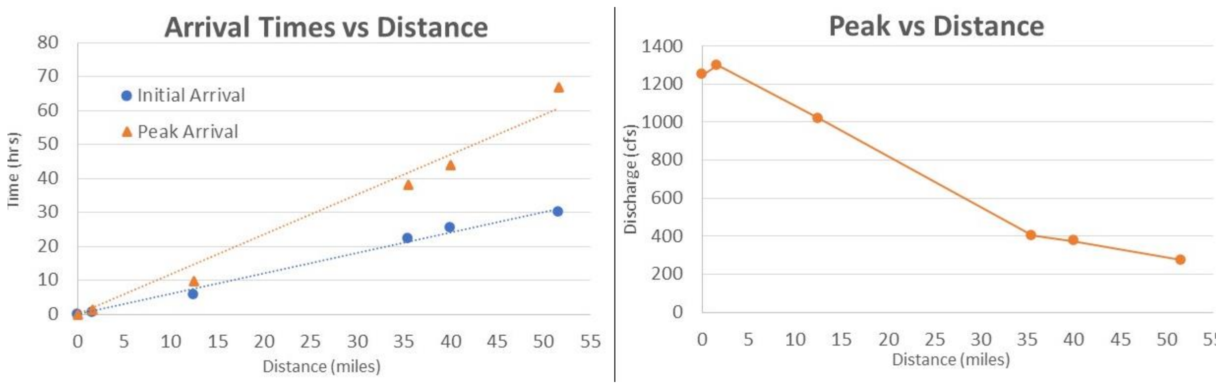

Figure 6. (Left) April 2018 start time & peak time (Right) peak discharge versus distance downstream of Friant Dam for each gauging station.

The attenuation of the peak height averaged about 21 cfs per mile, falling from 1,300 cfs at the first station to 275 cfs 52 miles (84 km) downstream (Figure 6, Right). Station SJF, immediately below the dam, showed an increase of 50 cfs compared to reported discharge from the dam's release, possibly due to flaws in the outlet calibration used to estimate outflow or errors in gauging station's discharge measurements. The lowest peak was 275 cfs at SJB, which was about one-fifth as high as the first peak at SJF. The overall event duration, from start to end, increased from 2 days to 14 days moving downstream (Table 4). The decrease in peak discharge and increase in the entire event time demonstrates the broadening of the pulse as it traveled downstream (Figure 5).

Based on the start and end time of the pulse, the greatest estimated volume of water to pass a station was observed at SJB and the least was detected at SJF. The dam released a total of 2,312 ac-ft. The estimated total volumes for each station are questionable due to the uncertainty of the pulse end times.

PLANNED PULSE FEBRUARY 2022

As with the April 2018 single planned event, attenuation of the successive pulses was observed in February 2022. Like the previous planned pulse, the hydrographs become less square, and the shape gradually smooths out as the pulses travel downstream (Figure 7A). The distinction between the two pulses for the upper river stations, SJF and H41 (Figure 7B), was again more evident than the three downstream gauging stations (Figure 7C). Similarly, like the April 2018 event, the SJF hydrographs reflected the dam release changes clearly, even showing the three-step ramp down on the falling limb of the second pulse. H41's hydrograph does not clearly show the three-step ramp down for the second pulse, but the first pulse's falling limb appears to have a steeper slope than the second pulse, and the second pulse has subtle changes in slope that might be due to the downwards steps. Roughly 11 miles (18 km) of travel can smooth and round out the sharp river release changes.

Determining the first pulse start time was more apparent for all gauging stations as compared to identifying the start of the second pulse because the second pulse began before the first ended (Table 5, Figure 7). All river stations experienced a distinct upward trend greater than their standard deviation for preceding steady flows allowing the first start time to be identified. There was an 18-hour gap between the two pulses in which dam releases were returned to the pre-event steady flow rate. This period between the two dam release pulses became more subtle and distorted for all river station moving downstream. There was 13-hours between pulses at SJF compared to other stations that ranged from 15 minutes to 2.5 hours. This decrease in time between pulses resulted in the first pulse's end time being defined as the lowest point between the two peaks for most stations. At SJB the two pulses are difficult to distinguish from one

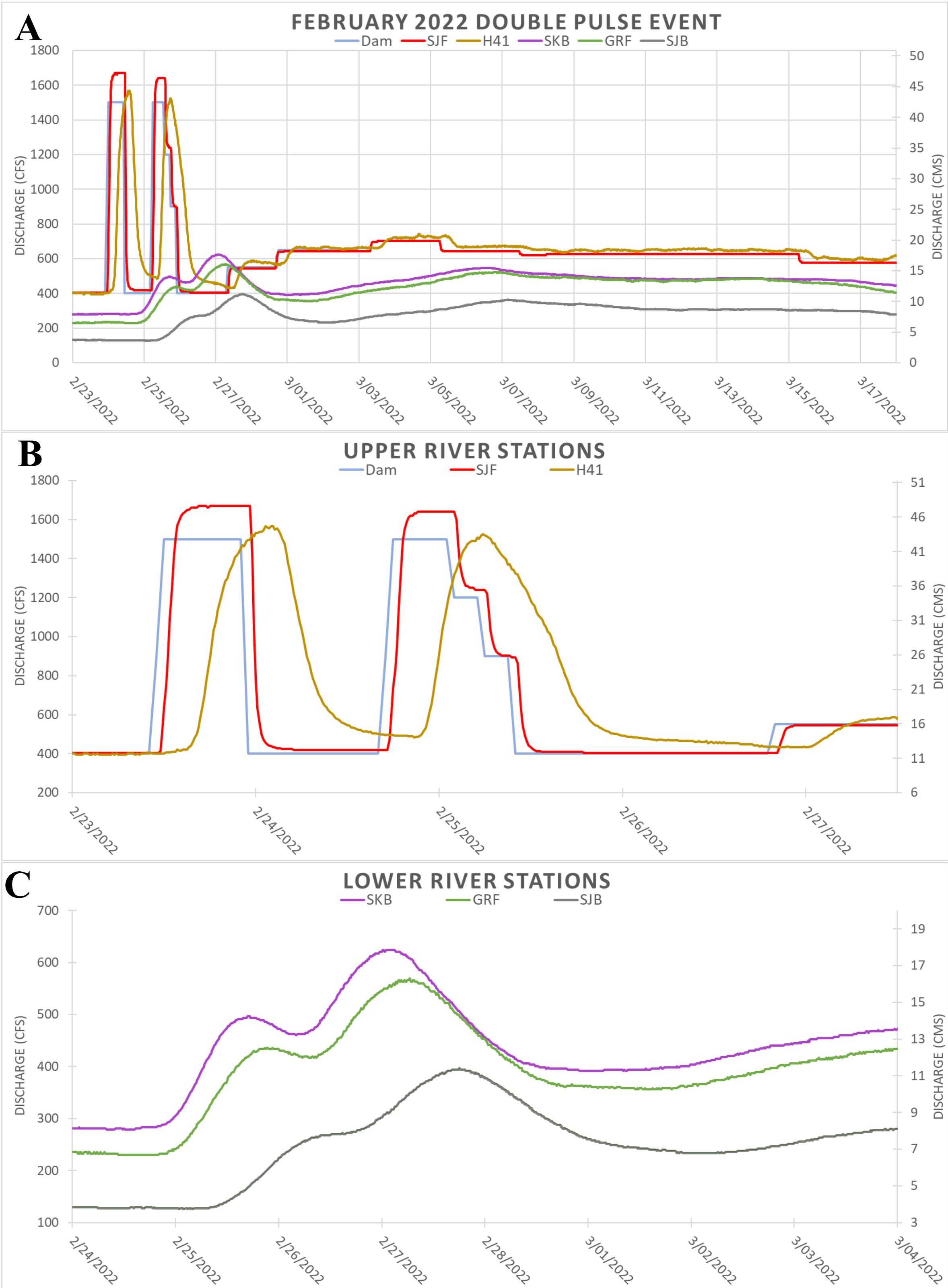

Figure 7. A) Feb.2022 Double pulse event B) Upper River Stations C) Lower River Stations.

Table 5. February 2022 Pulse Event Data

1st Pulse	Steady Flow Mean ± Std Dev	Start	End	Total Time	Time to Peak	Total Volume		Peak	Peak Date & Time
	cfs	m/dd/yyyy hh:mm	m/dd/yyyy hh:mm	Hours	Hours	ft^3	ac-ft	cfs	m/dd/yyyy hh:mm
Dam Release	400	2/23/2022 23:00	2/24/2022 11:00	12	6	61,740,000	1,417	1,500	2/24/2022 5:00
SJF	404 ±1	2/23/2022 23:30	2/24/2022 17:00	18	8	76,598,558	1,758	1,670	2/24/2022 7:45
H41	400±4	2/24/2022 1:00	2/25/2022 8:45	32	13	99,935,213	2,294	1,567	2/24/2022 14:00
SKB	281±2	2/24/2022 19:45	2/26/2022 4:00	32	21	48,675,735	1,117	497	2/25/2022 17:00
GRF	232±2	2/24/2022 20:15	2/26/2022 6:45	35	26	44,220,531	1,015	436	2/25/2022 21:45
SJB	128±2	2/25/2022 8:15	2/26/2022 15:30	31	31	23,444,230	538	273	2/26/2022 15:00

2nd Pulse		Start	End	Total Time	Time to Peak	Total Volume		Peak	Peak Date & Time
		m/dd/yyyy hh:mm	m/dd/yyyy hh:mm	Hours	Hours	ft^3	ac-ft	cfs	m/dd/yyyy hh:mm
Dam Release		2/25/2022 5:00	2/25/2022 22:00	17	4	75,780,000	1,740	1,500	2/25/2022 9:00
SJF		2/25/2022 5:30	2/26/2022 7:00	26	6	92,574,064	2,125	1,640	2/25/2022 11:30
H41		2/25/2022 9:00	2/27/2022 6:30	46	9	128,712,604	2,955	1,526	2/25/2022 17:45
SKB		2/26/2022 4:15	2/28/2022 15:00	59	21	109,286,624	2,509	624	2/27/2022 1:45
GRF		2/26/2022 9:15	3/1/2022 14:15	77	21	123,609,162	2,838	570	2/27/2022 6:30
SJB		2/26/2022 16:00	3/1/2022 22:15	78	26	86,855,138	1,994	397	2/27/2022 18:15

Entire Event	Steady Flow Mean	Start	End	Total Time	Time to Peak	Total Volume		Peak	Peak Date & Time
	cfs	m/dd/yyyy hh:mm	m/dd/yyyy hh:mm	Hours	Hours	ft^3	ac-ft	cfs	m/dd/yyyy hh:mm
Dam Release	400	2/23/2022 23:00	2/25/2022 22:00	47	N/A	162,000,000	3,719	1,500	2/24/2022 5:00
SJF	404 ±1	2/23/2022 23:30	2/26/2022 7:00	56	N/A	188,051,128	4,317	1,670	2/24/2022 7:45
H41	400±4	2/24/2022 1:00	2/27/2022 6:30	78	N/A	229,084,500	5,259	1,567	2/24/2022 14:00
SKB	281±2	2/24/2022 19:45	2/28/2022 15:00	91	N/A	158,377,577	3,636	624	2/27/2022 1:45
GRF	232±2	2/24/2022 20:15	3/1/2022 14:15	114	N/A	171,591,713	3,939	570	2/27/2022 6:30
SJB	128±2	2/25/2022 8:15	3/1/2022 22:15	110	N/A	110,785,551	2,543	397	2/27/2022 18:15

another, but there is an identifiable step where change rate in flow steadied out. This lack of trough between the two pulses made defining the first pulse end and start time of the second pulse indistinguishable.

Due to a separate river release increase of 150 cfs, that occurred 34 hours after the end of the pulse release, determining the end of the entire event was difficult. This non-pulse-related dam release shortened the timespan of the entire event and prevented flows from returning to pre-event steady flow means. If this change had not happened, the end times would have likely extended past the stated second pulse end times. None of the stations except SJF returned to the pre-event steady flow mean, so I used the point when a steady flow was observed for more than four hours as the end time.

The first pulse's initial arrival at each station traveled more quickly than the second pulse. The first traveled at about 1.7 mph (2.7km/h) versus 1.5 mph (2.4 km/h) for the second. There was no major difference between the travel rate for the two pulses. They both traveled at roughly 0.90 mph (1.5km/h) (Figure 8, Left). From the release to the end of Reach 2A, at river station SJB, it took 33 hours for the initial arrival of the first pulse and about 58 hours for the peak to arrive. For the second pulse event, the initial arrival took 35 hours to arrive at SJB and the peak arrived 57 hours (Figure 8, Left). The peaks were delayed compared to the initial arrival of the pulses due to the spreading out of the pulse as it moved downstream.

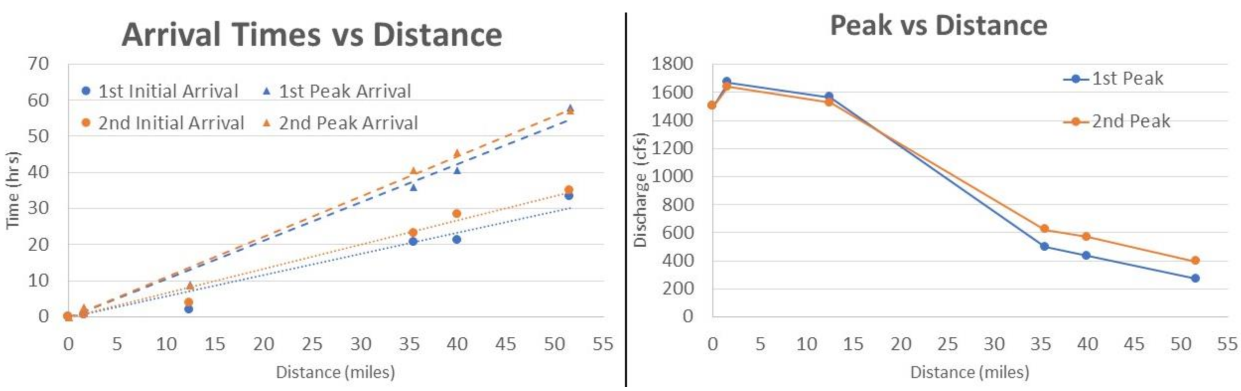

Figure 8. (Left) February 2022 start & peak time for both pulses; (Right) Pulse 1 & 2 peak discharge versus distance downstream of Friant Dam for each gauging station.

The attenuation of the first peak height averaged about 29 cfs per mile, falling from 1,670 cfs at the first station to 273 cfs, 52 miles (84 km) downstream. The second peak decreased from 1,640 to 397 cfs which averaged a loss around 26 cfs per mile (Figure 8, Right). Overall, the greatest reduction in peak flow was observed between H41 and SKB. For the first pulse, peak flow was 1,567 cfs at H41 and 497 cfs at SKB, a loss of 1,070 cfs. The second pulse had slightly less loss between the two stations, 902 cfs, from 1,526 cfs to 624 cfs.

Based on the start and end times of the first and second pulse, the greatest volume of water to pass a station was observed at H41 and the least was observed at SJB (Table 5). Since the end of both pulses was truncated, the first by the second pulse and the second by the unrelated dam release increase, calculating the total volume accurately for the individual pulse events was not possible. Looking at both pulses together with the intervening 18 hours of baseline flow included (Table 5), volume increased between most stations besides H41 to SKB and GRF to SJB. Estimating losses or gains between stations was highly dependent on start and end times, and in this situation the end time of the second pulse could not be estimated resulting in inaccurate and sometimes illogical results.

PULSE EVENT COMPARISION

The planned pulse events of 2018 and 2022 were different in duration, magnitude, and number of pulses but many characteristics, like travel time and peak attenuation, were comparable (Table 6). For the dam release, the April event lasted 48 hours whereas the February's first pulse event lasted for 12 hours and the second pulse lasted 17 hours with an 18-hour period of baseline flow between. The start of both events ramped up stepwise with each increase ranging from 200 to 600 cfs over two or three hours. The ramp down for the April 2018 event was the most gradual occurring over 43 hours with five steps compared to the February 2022 second and final pulse with three steps over eight hours. One major difference was how the first February 2022 pulse had no ramp down steps, just one change from the peak discharge, at 1,500 cfs, to the pre-event release, 400 cfs. Despite these differences, both planned pulses, 2018 and 2022, displayed similar travel times, peak attenuation, and volume changes.

Table 6. River release details for planned pulses

Planned Pulse Event	Duration	Pre-Pulse Release	Peak Discharge	Peak Discharge Duration	Start to Peak	# of Steps Ramp Up	Peak to End	# of Steps Ramp Down
	Hours	cfs	cfs	Hours	Hours		Hours	
April 2018	48	350	1,250	3	2	3	43	5
Feb. 2022 First Pulse	12	400	1,500	11	1	2	Instant	1
Feb. 2022 Second Pulse	17	400	1,500	8	1	2	8	3

Travel Times

Initial pulse rise and peak arrival times for both planned pulses had roughly comparable travel times (Figure 9, Table 7). Figure 9 shows for both events the initial pulse arrival traveled faster than the peak discharge. The 2018 pulse took longer compared to 2022 first pulse to initially arrive at all the river stations besides SJB, but the overall time to arrive at SJB was about two hours earlier than the 2022 pulse (Table 7). Both 2018's H41 and GRF initial arrival travel times were about four hours slower than the 2022 first pulse (Table 7).

Based on the travel rates between stations, in both planned pulse events, pulses moved at a faster rate between the upper stations than the downstream stations for both the initial arrival and peak arrival. The only case that did not follow this trend was the 2022 first pulse's initial arrival at SKB and GRF. Estimated travel between these stations was 30 minutes, which resulted in a greater travel rate, 9 mph, than between the upstream gauging stations, 2-3 mph. The 2018 event reported around three hours for the initial pulse arrival where the second pulse of 2022 reported five hours for this reach.

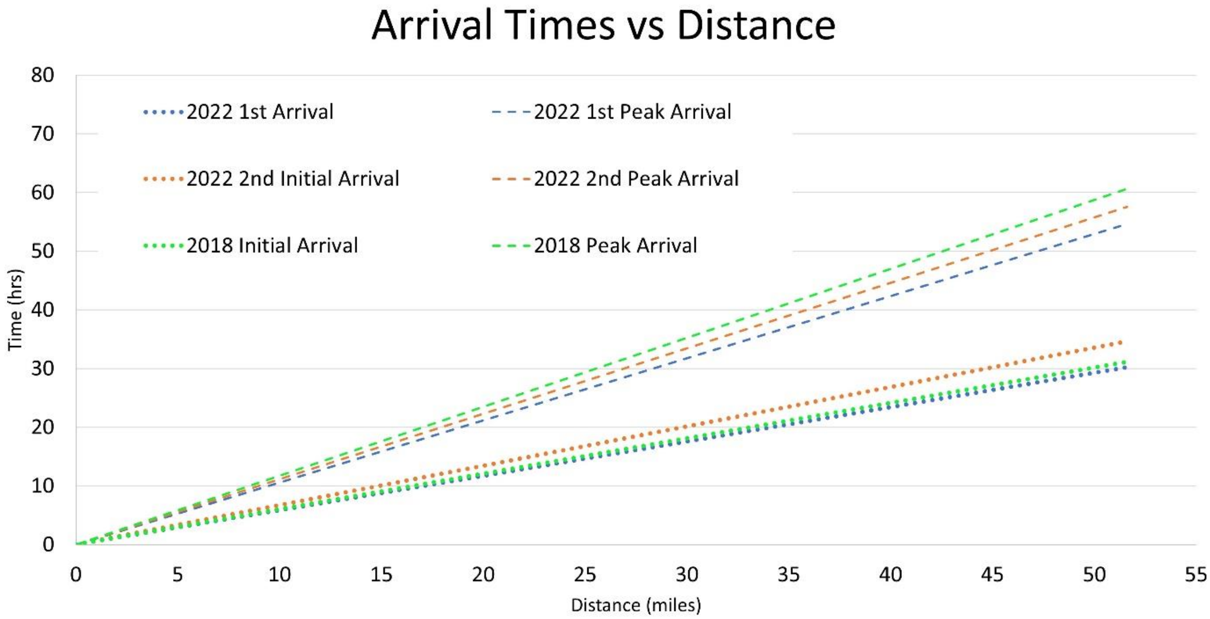

Figure 9. Comparison of initial and peak arrival times for pulse events in 2018 and 2022. smoother edges for both events.

Table 7. Comparison of planned pulses travel times in hours from Friant Dam release.

River Station	River Miles	April 2018 Initial Arrival	Feb. 2022 1st Pulse Initial Arrival	Feb. 2022 2nd Pulse Initial Arrival	April 2018 Peak	Feb. 2022 1st Peak	Feb. 2022 2nd Peak
Friant Dam	0	0:00	0:00	0:00	0:00	0:00	0:00
SJF	1.6	0:30	0:30	0:30	1:15	2:45*	2:30*
H41	12.5	5:45	2:00	4:00	9:45	9:00*	8:45
SKB	35.5	22:15	20:45	23:15	38:00	36:00*	40:45*
GRF	40	25:30	21:15	28:15	44:00*	40:45*	45.50
SJB	51.6	30:00	33:15	35:00	66:45*	58:00	57:15*

***Multiple peak discharge timestamps. The median was taken to calculate travel times.**

Pulse Attenuation

Both planned pulse flows displayed strong attenuation as the pulses traveled down the river. The height of the peaks for both events decreased distinctly as the pulse broadened out or, in 2022, the two pulses broadened, merged, and became one. The April 2018 pulse peak decreased about 78% from SJF to SJB or about 1.5% per mile, similarly February 2022 event decreased around 84% for the first pulse than 76% for the second, about 1.7 and 1.5% per mile, respectively.

The entire pulse event duration increased as the pulses moved downstream in both 2018 and 2022. As expected, the upper river stations had shorter pulse durations than the downstream stations. Upstream gauging stations ranged from 51 hours at SJF and 58 hours at H41 compared to 156 hours at SKB to 331 hours at SJB for the April 2022 event. February 2022's first pulse durations ranged from 18 to 31 hours whereas the second pulse was 26 to 78 hours moving downstream of SJF. The first pulse's timespan for SJB was truncated due to the arrival of the second pulse resulting in the entire event time to be shorter than the upstream stations, SKB and GRF. For the second pulse, SJB's entire event time was typical of what is seen when pulses attenuate, the pulse's timespan increased while moving downstream causing SJB's second pulse took place for 78 hours. The April 2018 planned pulse duration was longer than the February 2022 pulse event because no flow changes in dam releases happened once flows returned to pre-event levels. The next change in dam release occurred 14 days later. Plus, the ramp down of the 2018 pulse was over 43 hours in five steps before returning to pre-event baseline flows, allowing the pulse's tail end to diffuse down the river gradually. In situations where the tail end dropped gradually, I estimated a range of possible end times based on the assumption that peak times were at 10-15% of the total event duration.

Volume

For all volume calculations, interactions of subsurface flows or storages such as alluvial aquifers were not considered. In addition, the pre-event baseflows were not removed from volume totals. Uncertainty in the estimated end times affected the accuracy of the total volume and volume losses or gains between each gauging station.

Overall, the total estimated volume decreased between river stations downstream of H41 for the February 2022 planned pulse, but April 2018's event gradually increased in total volume as the pulse moved down river. Based on peak discharge and total estimated volume, both planned pulses resulted in an increase in peak discharge and total estimated volume from Friant Dam's river release to the first gauging station, SJF, 1.6 miles downstream. Peak discharge increased by 50 cfs for the April 2018 event whereas the February first and second pulse resulted in a 170 and 140 cfs increase. The total event volume release for 2018 was 2,312 ac-ft compared to the slightly higher total volume of 2,471 ac-ft estimated for SJF (Table 4). Looking at the February 2022 event as a whole, from the start of the first pulse to the end of the second pulse, the total volume release from the dam was 3,719ac-ft, but the volume estimated 1.6 miles downstream at SJF was 4,317ac-ft (Table 5).

Due to the methods used to determine pulse end times the results for total estimated volume and volume changes for each gauging stations are unreliable and probably inaccurate. This uncertainty grows greater from the upper river stations to the lower due to the end time becoming indistinguishable.

DISCUSSION

SAN JOAQUIN RIVER PLANNED PULSES

Even with different dam release operations the two planned pulse events responded similarly. The estimated travel time and attenuation of the 2018 and 2022 pulses showed that the initial arrival of the pulse travels quicker than the peak and the peak attenuates at about 1.6% per mile. Determining travel time and peak attenuation are not dependent on the pulse end time, but the end time is highly influential for calculating pulse volumes, gains and losses. Due to the complexity in determining the end time, the volume results were inconsistent and illogical e.g., inexplicable volume gains without apparent inputs. Despite the complex nature of defining a pulse's end time other factors may have caused both unusual and typical responses in travel times, peak attenuation, and volume.

Travel Times

Overall, the travel times appeared to be consistent among the three pulses suggesting that other pulses, either planned or unplanned, could have similar results. Travel time between stations is affected by the selected start time for the arrival or peak of the pulse at each gauging station and how the dam release was performed. The amount of time and the stepwise increases made to reach the peak release, along with the duration the peak dam discharge, will influence the travel time. Other factors that could affect the travel rate of a pulse are pre-event bank and soil conditions. Both water year 2018 and 2022 were categorized as normal dry years meaning the San Joaquin Watershed received 2.1 to 2.5 million ac-ft (Null & Viers 2012). Other SJR pulse events from different water years should be examined to compare travel times between stations to determine how consistent they are.

Other factors that could influence travel times are the pulse shape and duration. The peak discharge has little effect on travel time, but the pulse shape and duration can influence it (Asselman et al. 2022). The SJF hydrograph is rectangular in shape, H41 has steeper rising and falling slopes, but the downstream stations' slopes are more gradual with increasingly smoother, rounded edges for both events. Faster travel rates between the upper gauging stations than the lower stations were observed for both the 2018 and 2022's initial arrival and peak suggesting the pulses that are more rigid with steep slopes move faster than pulses with smoother and more gradual slopes. The shape could explain why the upper river stations saw a faster moving pulse, but it could also be an effect of distance from the dam's release or slope gradient.

SJF, being the closest station to the dam's release had the most consistent initial arrival time of 30 minutes for all planned pulses, but the peaks of the 2022 event traveled slower than the 2018 peak. The slower peak travel rates of 2022 were probably due to the sustained peak discharge causing a broad peak and the median of the range being used as the peak time. There travel rates continue to support that the initial flows move faster than the peak discharge (Figure 9).

In cases where peak discharge lasted two or more timestamps, the median was used as the peak timestamp, but for research purposes, I compared travel times based on the first time stamp the peak discharge was observed. Basing travel time on the first arrival timestamp of the peak discharge resulted in a travel time from the dam to SJB of around 63 hours for the 2018 pulse and the 2022 first pulse, and about 59 hours for the second 2022 pulse peak. These total travel times for the peak discharge from Friant Dam to SJB were within five hours of the travel times based on the median timestamp. This difference showed that when calculating travel times, the criteria that are chosen (the peak's first or median timestamp for highest discharge) must be consistent for all gauging stations, but there were not large discrepancies between the two methods.

Pulse Attenuation

Observing how pulses attenuate down the SJR under a wide range of conditions could provide insight into the potential for varying river features and processes in different reaches to increase or decrease peak discharge attenuation. Identifying areas with different riverbank exchange rates or knowing prior bank moisture conditions could aid in predicting the rate of attenuation and resulting in reductions of downstream flooding (Asselman et al 2022). Randle & Samad (2008) found that peak attenuation increased when flows were below bankfull discharge and the riverbank's moisture content was low on the Platte River, Nebraska. Bankfull discharge, also known as channel capacity, refers to flow at a level that is about to overtop banks and spread onto the floodplain which can occur every one to two years (Leopold et al. 1995). I hypothesize that like the Platte River, attenuation on the SJR will be greatest during dry periods when the riverbanks are less saturated. The likelihood of peak attenuation is expected to decrease during or just after a storm, preventing downstream water level from dropping as much and increasing the chances of unwanted flooding (Randle & Samad 2008; Asselman et al. 2022). Randle & Samad (2008) found that peak discharge increased as the peak traveled downstream as a result of storm runoff.

Another factor to consider is different features along the river that could contribute to peak attenuation such as gravel pits, side channels, or holding ponds. These features could be used to increase peak attenuation deliberately by allowing flows to be redirected out of the main channel into these temporary storages when the river reaches a specific level. Similar features were identified in a study to contribute to peak attenuation and reduced flood risk to downstream areas (Asselman et al. 2022).

More research is needed on what floodplain features or bank moisture conditions affect attenuation. Examining past natural pulses or river changes that occurred during different seasons or water levels could highlight areas or riverbank conditions that could accelerate attenuation. The gravel pits no longer used at river mile 13 (21 km) could prove to be a contributor to attenuation depending on the river's water level (Figure 10). Discovering which river reaches reduce peak discharge could aid water managers when making decisions on flood releases.

Volume

The methods used to calculate total volume and changes in volume between gauging stations were highly influenced by the end time which was difficult to define for most stations. These methods resulted in inconsistences and inaccurate findings especially for the 2022 February double pulse event. With these uncertainties, some patterns emerged from both planned pulses. For example, total estimated volume and peak discharge increased from the dam's river release to SJF and in April's event estimated volume increased steadily downstream.

Figure 10. Gravel pits at river mile 13. Star is location of gauging station H41. Downstream of station on both the left and right riverbank are several gravel pits no longer in use. Arrows point to various gravel pits to help distinguish them from open fields.

Based on the apparent increase from Friant Dam's release points to SJF, it can be inferred that either reported the dam release volumes were too low or the river discharge volumes were too high. The tributary, Cottonwood Creek, was contributing little to no flow for both planned pulses. It is possible that the dam's river release records were inaccurate due to the calculation methods used by the dam operators. Several configurations of outlets can be used for the river release to reach the desired flow. Configurations can consist of any combination of three powerplants and/or four 96-inch (244 cm) valves and/or two 18-inch (46 cm) valves. A 1953 USBR document states that the outlet valves were not designed to be accurate measuring devices (Thomas 1953). Since then, no upgrades have occurred meaning the valves' accuracy are uncertain. Determining which outlets are inaccurate would be problematic because isolating release points may not be possible with downstream water demands. Another factor is that the water level of the reservoir effects the net head on the outlets reducing or increasing flows as the level changes. Typically, the reservoir level does not change quickly, besides during periods of high run off upstream of the reservoir like snowmelt or large rain precipitation event.

Another notable contrast was the steady increase in total volume at each gauging station as the April 2018 pulse traveled downstream whereas the February 2022 pulse volume change between each station was inconsistent in direction and magnitude. Due to the high uncertainty in pulse end times these patterns may be false, but comparing the conditions of each event may provide possible explanations for the different responses of volume as the pulses moved downstream. One question is why volume appeared to increase downstream in April 2018 without obvious source of water. It could be hypothesized that the soil moisture content was greater for the April 2018 event than in 2022. By the start of the April pulse, about 9 inches (23 cm) of rain had been recorded for the water year and the last major rain event occurred March 21 to 23 with a total of 3 inches (7.6 cm). In addition, 0.57 inches (1.45 cm) of rain was recorded over April 7 and 8 during the period the pulse was traveling through the lower river stations. For the February 2022 event, 7 inches (18 cm) of rain had been recorded during the water year before the start of the pulse event with the last major rain event occurring in December 2021. Only 0.05 inches (0.13 cm) of rain was recorded February 23, when the planned pulse event started. From these rain reports it could be inferred that the soil was more saturated in April 2018 than in February 2022, providing a possible reason for a volume increase as the April 2018 pulse traveled downstream. Soil moisture and other factors need to be further investigated due to unreliability of the volumes calculated.

Historically, the river reach from Friant Dam to SJB has been known for losing water into the banks because of groundwater being over pumped adjacent to the river (McBain and

Trush, 2002). Before the implementation of restoration flows, the SJR would lose connectivity to the Pacific Ocean, typically going dry a few miles downstream of gauging station, GRF, due to meeting the demand of 5 cfs for a water contract. In 2009 when SJRRP intermittent flow releases started, studies found that net seepage losses were greatest at the start of higher flows and decreased over time (Traum et al. 2014). Better insight into what exchanges occur between the river channel and adjacent lands could improve the estimation of total volume at gauging stations for past and future pulse or steady flows.

To reduce the uncertainty of volume calculations more pulses need to be compared, losses and gains during non-pulse flows periods should be made, and improved criteria of defining pulse end times needs to be developed. More information is needed to identify river reaches that are experiencing volume losses or gains.

NATURAL PULSE

To see if the methods used to analyze the planned pulses could be applied to natural pulse events on the SJR, I took a closer look at an event that occurred in March 2018 (Figure 11). This event inspired the April 2018 planned pulsed event. This natural, unplanned pulse event was a product of about 3 inches (7.6 cm) of rain over a three-day span that caused the tributaries below the dam, Cottonwood (CTK) and Little Dry Creek (LDC), to start flowing. Over the three days, CTK and LDC hydrographs peaked on the third day with daily average discharge of 26 and 445 cfs, respectively. In response to the increase in tributary flows, Friant Dam operators cut the river release from 300 to 130 cfs causing the SJF hydrograph to have a trough instead of a peak

(Figure 11). This action made the tributaries the main source of flow into the SJR. Both tributaries enter above the Highway 41 gauging station (H41).

Irregular inputs from the tributaries caused confusion in defining the start times of the event. H41 displayed multiple peaks ranging from around 350 to 2,370 cfs, probably due to variation in storm intensity and runoff. Parsing out which hydrograph changes were caused by tributary flows was problematic (Figure 11A & 11B). I tried to apply the same procedure used to define the planned pulse events' start and end times. To determine the start time for H41, I also looked at when the tributaries started to influence flow at H41 (Figure 12). The start time is debatable and could be any of the three small rises on March 21 or 22 or a major rise on March 23. This decision depends on what the analyst considers to be a part of the pulse event. For this situation, I would perform my analysis by calculating the characteristics for different start times and see how they compare to the downstream stations. The minor pulses that occurred between March 21 to 22 could be seen as isolated events since the tributaries or river release appear not to be the source. Figure 12 suggests the most appropriate pulse start time was March 22 at 18:00, resulting in two pulses observed at H41, with a small pulse preceding the main pulse. Like the planned pulses, the pulse hydrographs downstream of H41, increased in wavelength and decreased in wave height, appearing as a single pulse peak with a more gradual increase in slope than at H41 (Figure 11C). The initial, gradual slope increases at the three lower stations extended over two or three days and could be interpreted as remnants of initial minor rises observed at H41. There were distinct rises at all three downstream stations that resembled the main rise at H41, but their beginnings would not have been identified with the rule I used for the planned pulses (discharge greater than one standard deviation above preceding steady flow).

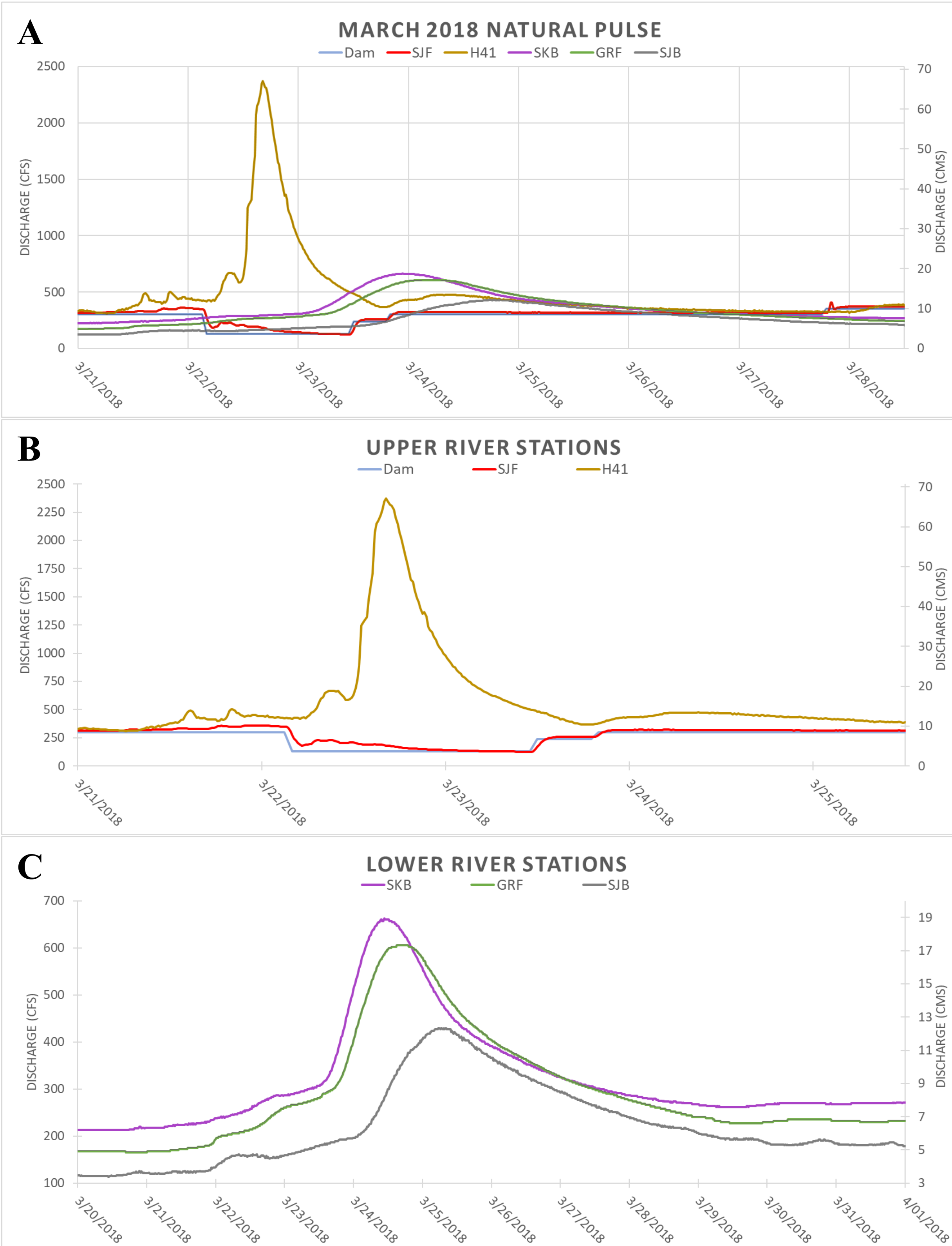

Figure 11. A) March 2018 pulse event B) Upper River Stations C) Lower River Stations.

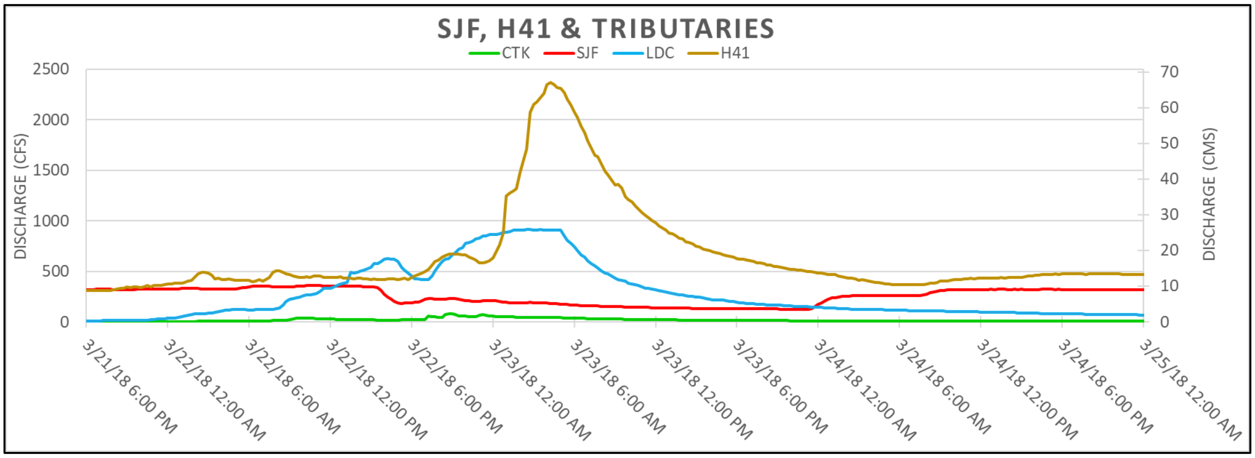

Figure 12. March 2018 Natural Pulse event. Hydrograph of tributaries, CTK & LDC, and H41.

The pulse end time for all river stations could be defined plausibly by when steady flows lasted four or more hours. Alternatively, a range could be calculated from the percentage of time from start to peak compared to the entire event as done for the 2018 planned pulse. Because discharge at the lower river stations never returned to within 5% of their pre-event steady flow mean, that could not be used to define the end time.

Using the same start time criteria as for the planned pulses produced some illogical results. For example, the initial pulse arrival times for stations SKB and SJB would be earlier than the upstream stations' arrival time resulting in negative travel times. Different criteria are clearly needed for pulse events with gradual or irregular beginnings.

The peak was the single feature that was clear at all gauging stations starting at H41. Peak travel time and rate could be estimated based on the time of greatest discharge for each station (besides SJF, which was above the main runoff source, Little Dry Creek), following the methods used for the planned pulse events. Based on the maximum peak between H41 and SJB, the peak traveled at around 0.75 mph (1.21 km/h), slightly slower than the planned pulse peaks.

Based on hydrographs (Figure 11), the March 2018 pulse attenuated downstream from H41 to SJB, essentially like the planned April 2018 pulse did. The attenuation of the peak height averaged about 58 cfs per mile with a fall from 2,372 cfs at H41 to 430 cfs at SJB, about 82% decrease (Figure 13).

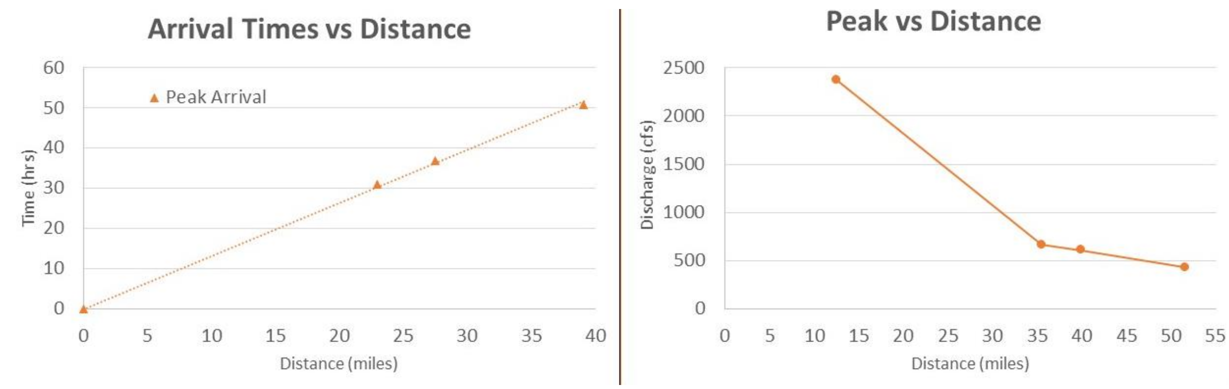

Figure 13. (Left) March 2018 peak time (Right) peak discharge versus distance downstream of Friant Dam for each gauging station.

The decrease in peak discharge, delay of peak arrival, and broadening of the pulse wave as it traveled downstream demonstrates that attenuation concept applies equally well to natural and planned pulses even though stand and end times may be less distinct for natural events.

Volume was not calculated for the natural pulse because the primary reason for this exercise was to determine if the methods applied to the planned pulses could be applied to unplanned natural pulses. To attempt a volume estimate, different criteria would be needed to ensure the March 2018 pulse’s start and end times are reasonable. Based on a quick assessment, the methods used to calculate volume for the planned events could be applied to this natural pulse event but would have the same challenges. The change in volume from one river station to the next may not be as consistent as in the planned pulses due to unknown local inflow contributions or unseen processes occurring in the river channel bed and banks. Even so, further analysis of pulse volume changes should be done for natural events to learn more about which river reaches are gaining or losing volume.

Natural pulse events are more complex than planned pulses due to the uncontrollable factors such as inflow from tributaries, irregular storm runoff rates, or unseen processes happening in the riverbanks. In the case I examined, these factors made the identification of the start and end of the natural event difficult due to the gradual rise or fall in flow from unknown release points between gauging stations and other natural processes such as bank storage exchange rates. Depending on the details of other natural events, there could be several peaks due to periods of localized heavy rain or runoff as seen in March 2018. Based on this exercise the methods used to calculate travel time, peak attenuation, and volume changes can be applied to other natural unplanned pulses, but might have to be modified, such as creating a range of start and end dates, to handle the various situations that occur with natural events.

FUTURE WORK

Since this was a pilot study, it provided insight into how applicable the methods used here might be to future planned pulse events and natural pulse events. Looking into other methods of differentiating the start and end time of a pulse, separating out baseflows from flood flows, totalizing event volumes, and comparing peak discharges could improve the accuracy of measures of pulse timing and volume. Using different methods, or a combination of methods, like the straight-line method or triangular unit hydrograph, could facilitated manual analyses, such as this one, making it easier to parse out the different features of a pulse (Fischer et al.

2021; NRCS 2007; NOHRSC 2001). Analyzing past natural pulses would increase the sample size used to compare travel times, peak attenuation, and volume changes between situations that differ in peak magnitude and duration, pulse shape, and ramp up and ramp down processes and help to determine if there are general patterns or not. There are several potential natural pulses or dam river release changes in existing records that could be examined to expand knowledge of pulse behavior on the SJR.

Using hydrologic and hydraulic models to run different scenarios, such as wet vs dry years or varying tributary flows, and to incorporate channel characteristic (slope, soil moisture content, channel roughness coefficient, etc.) would provide a broader picture of how SJR pulses behave. Since planned pulses are not common on the SJR, models are a valuable tool, but physical models are complicated and involve a learning curve for skills that the typical hydrographer might not possess. Implementing models such as HEC-RAS along with a bank storage model (Randle & Samad 2008), the "Flood" package for the statistical program R (Fischer et al. 2021), WAQUA (Asselman et al. 2022) or other combinations of models that take into consideration channel characteristics and bank storage could help identify river features that affect peak attenuation.

Field work can provide valuable information that models cannot, but it can be time and money intensive. With the aid of models, efficiency could be improved by using the models to highlight areas of interest along the river. Ground truthing and monitoring in areas of interest could provide data on soil moisture under different weather patterns, what river level cause flow to spill over berms or levees, or other channel and hydrologic characteristics. Learning more about the channel and floodplain within 52 miles (84 km) downstream of Friant Dam would aid USBR water manager's when making decisions on water releases.

PULSE FLOWS

More planned pulses will occur on the SJR for research and biological reasons. Managers of other river systems altered by impoundment have performed planned pulses finding a mixture of responses. The reasons for and effects of planned pulses vary from location to location, but the core goal is typically to mitigate adverse impacts of regulated rivers and restore or maintain the benefits of a naturally flowing river (Owusu et al. 2020). Many impounded river systems have seen negative responses of abiotic and biotic factors to the deviation from natural flow regime caused by dams. The reduction or elimination of macroinvertebrates and fish populations, decline in sediment transport, and loss of seasonal high or low flows are common effects of dams on river systems (Poff & Zimmerman 2010; Olden et al. 2014; Cook 2015; Gillespie et al. 2015). Operators of several dams in the United States have performed planned pulse flows for research purposes or for routine management.

Glen Canyon Dam, Arizona, on the Colorado River has experienced several pulse flows or "high flow experiments", which are how they are labeled in that region. Planned pulses on the Colorado River are recorded as far back as 1965 and as recently as 2018 (Olden et al. 2014; USGS 2018; USBR 2023). Objectives were to reduce the impacts of the dam, which included reduced turbidity and sediment transport, erosion of sandbars, and beaches, increased vegetation, and reduction or elimination of native fish (Cook 2013; USGS 2018). Due to the lack of sediment being transported downstream, sandbars and beaches had eroded away. These sandbars and beaches provided slow and warm water for fish nurseries, and sand to be moved by wind to fill in gullies and protect cultural sites and camp spots for recreators (USGS 2018). There were several trials to determine the timing, magnitude, and duration of the release that would benefit the downstream ecosystem most. It was determined planned pulses should occur when the tributaries downstream of Glen Canyon Dam had contributed large quantities of sediment into the main channel. The planned pulse would transport this sand downstream to build up or create new sandbars, then flows would be reduced to prevent the erosion of the recently created sandbars (Cook 2013; USGS 2018). Now these planned pulses typically occur in October but not every year because it depends on the availability of water and the amount of sediment in the main channel. Since these planned pulses have been implemented, sandbars and beaches have returned and native fish populations have improved.

In Nebraska, on the Platte River, managers are implementing pulse flows to improve habitat for threatened and endangered bird species. Historically, migrating birds like whooping cranes and piping plovers would rest or nest on sandbars in the Platte River. Due to the lack of vegetation, birds could see potential predators. This type of habitat was created due to the large amounts of sediment transported during snowmelt runoff, which removed vegetation, kept the river wide and shallow, and deposited sediment in new bars and islands. As a result of dams and water diversions, 70% of the flow has been removed. In turn sandbars and riverbanks have become overgrown, narrowing the river channel (PRIP 2023). The overgrown sandbars have reduced the areas where migrating birds are protected from predators by open lines of sight. Under current management, pulse flows occur in spring ranging from 5,000 to 8,000 cfs for three days (PRIP 2023). Through models and studies, these pulse’s characteristics were derived by examining how pulses attenuated downstream, ensuring that the peak did not decay before reaching downstream sandbars that were targeted. The river hydraulic model, HEC-RAS, needed to be calibrated and coupled with a bank storage model to achieve accurate results (Randle & Samad 2008).

Glen Canyon Dam and the Platte River are just two examples of pulse flows studied and implemented in the United States. Olden et al. (2014) reviewed "flow experiments" or planned pulses and identified 113 pulse studies representing 102 dams across 20 countries based on their literature review's criteria. Globally most pulse studies focus on flow magnitude rather than examining flow duration or rate of change (Gillespie et al. 2014). Mixed positive and negative responses to pulse flows were found, which could be attributed to the fact that no two river systems are the same (Olden et al. 2014; Gillespie et al. 2014). Due to the lack of research on pulse attenuation, determining effective methodology to study how pulses attenuate and how this affects downstream river reaches was difficult. Pulse flows are highly affected by their environment and the river characteristics, making their results situational. Due to the range of responses, it is important to study more rivers and dams and diversify the focus on different characteristics of pulses such as duration, attenuation, or ramp up and down methods.

CONCLUSION

My analysis showed that the planned pulses of 2018 and 2022 attenuated downstream and that the pulse behavior was affected by the duration of the peak discharge, the ramp up and down process performed at the dam's river release, and the complexity of the pulse (single vs multiple peaks, natural vs planned). As seen with other planned pulses on different river systems, there are several reasons to performing routine pulses, but trial and error may be needed to understand which flow levels would provide the most benefit downstream. In the SJR, implementing pulses could help achieve the goals of the San Joaquin River Restoration Program to restore the spring run Chinook salmon to encourage migration or restore stream habitat. Further investigation needs to be performed to characterize consistent pulse behaviors on the SJR. Knowing how pulses attenuate downstream can help water managers make more informed decisions on water releases and improve dam operations.

REFERENCES CITED

Asselman, N., de Jong, J. S., Kroekenstoel, D., &; Folkertsma, S. (2022). The importance of peak attenuation for flood risk management, exemplified on the Meuse River, the Netherlands. *Water Security,* 15(100114), 100114. https://doi.org/10.1016/j.wasec.2022.100114

Bork, K. S., Krovoza, J. F., Katz, J. V., & Moyle, P. B. (2012). *The Rebirth of California Fish & Game Code Section 5937*. In Symposium: The public trust doctrine: 30 years later (3rd ed., Vol. 45, pp. 809-913). Davis, CA: University of California, Davis, School of Law.

CDFG: California Department of Fish and Game, 1990. Status and management of spring-run Chinook salmon, CDFG; *Inland Fisheries Division for California Fish and Game Commission*, Sacramento, CA.

CEPA: California Environmental Protection Agency. (2004). Regional Water Quality Control Board Central Valley Region. The Control of Salt and Boron Discharge into the Lower San Joaquin River

Cook T. (2013, February 11). A flood of controversy on the Colorado River. *Earth Magazine: The Science behind the Headlines*. Retrieved from https://www.earthmagazine.org/article/releasing-flood-controversy-colorado-river/

Cook, T. (2015, March 3). Can dam releases restore river ecosystems?. *Earth Magazine: The Science behind the Headlines*. Retrieved from https://www.earthmagazine.org/article/can-dam-releases-restore-river-ecosystems/

Ferencz, S. B., Cardenas, M. B., & Neilson, B. T. (2019). Analysis of the effects of dam release properties and ambient groundwater flow on surface water-groundwater exchange over a 100-km-long reach. *Water Resources Research,* 55. https://doi.org/10.1029/ 2019WR025210

Fischer, S., Schumann, A., & Bühler, P. (2021). A statistics-based automated flood event separation. *Journal of Hydrology X,* 10(100070). https://doi.org/10.1016/j.hydroa.2020.100070

Fontaine J., Victorine, R. , & Goodsell, J. (2015 October). *San Joaquin River Parkway Sycamore Island Pond Isolation Project Draft Environmental Assessment.* San Joaquin River Restoration Program. US Bureau of Reclamation.

Gillespie, B. R., Desmet, S., Kay, P., Tillotson, M. R., & Brown, L. E. (2015). A critical analysis of regulated river ecosystem responses to managed environmental flows from reservoirs. *Freshwater Biology*, 60(2), 410–425. https://doi.org/10.1111/fwb.12506

Leopold, L. B., Wolman, M. G., &; Miller, J. P. (1995*). Fluvial processes in geomorphology*. Dover Publication.

McBain and Trush, Inc., ed., (2002), *San Joaquin River restoration study background report: Arcata, Calif., prepared for Friant Water Users Authority*, Lindsay, Calif., and Natural Resources Defense Council, San Francisco, Calif., http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/mcbainandtrush_2002.pdf.

Natural Resources Defense Council versus Kirk Rodgers, Stipulation of Settlement, 2006, CIV S-88-1658 LKK/GGH (United States District Court Easter District of California, September 13, 2006), *http://www.restoresjr.net/program_library/06-Settlement_Related/index.html*.

Natural Resources Defense Council versus Kirk Rodgers, Stipulation of Settlement, 2006, CIV S-88-1658 LKK/GGH (United States District Court Easter District of California, September 13, 2006), *http://www.restoresjr.net/program_library/06-Settlement_Related/index.html*.

NOHRSC: National Operational Hydrologic Remote Sensing Center. (2001). *Unit Hydrograph Technical Manual*. National Operational Hydrologic Remote Sensing. Retrieved from https://www.nohrsc.noaa.gov/technology/gis/uhg_manual.html

NRCS: National Resources Conservation Service. (2007, March). *National Engineering Handbook*. Chapter 16. U.S. Department of Agriculture, Washington, D.C.

Null, S. E., and J. H. Viers (Center for Watershed Sciences, University of California, Davis). 2012. *Water and Energy Sector Vulnerability to Climate Warming in the Sierra Nevada: Water Year Classification in Non-Stationary Climates.* California Energy Commission. Publication number: CEC-500-2012-015.

Olden, J. D., Konrad, C. P., Melis, T. S., Kennard, M. J., Freeman, M. C., Mims, M. C., Bray, E. N., Gido, K. B., Hemphill, N. P., Lytle, D. A., McMullen, L. E., Pyron, M., Robinson, C. T., Schmidt, J. C., & Williams, J. G. (2014). Are large-scale flow experiments informing the science and management of freshwater ecosystems?. *Frontiers in Ecology and the Environment,* 12(3), 176–185. https://doi.org/10.1890/130076

Owusu, A. G., Mul, M., Zaag, P., & Slinger, J. (2020). *Re-operating dams for environmental flows: From recommendation to practice*. River Research and Applications, 37(2), 176–186. https://doi.org/10.1002/rra.3624

PRIP: Platte River Recovery Implementation Program. (2023). *Water Plan*. Retrieved from https://platteriverprogram.org/about/water-plan

Poff N.L. & Zimmerman J.K.H. (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55, 194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.

Thomas, C. W. (1953). *Discharge coefficients for gates and valves as determined by field and laboratory studies*. Design and Construction Division, Denver, CO; Bureau of Reclamation.

USBR: U.S. Bureau of Reclamation. (2023, February 22). Glen Canyon Dam Long-Term Experimental and Management Plan. *Glen Canyon Dam Long-Term Experimental and Management Plan*; Upper Colorado Basin. Bureau of Reclamation. Retrieved from https://www.usbr.gov/uc/progact/amp/ltemp.html

USGS: Southwest Biological Science Center. (2018, November 1). *High-flow experiments on the Colorado River* . U.S. Geological Survey. Retrieved from https://www.usgs.gov/centers/southwest-biological-science-center/science/high-flow-experiments-colorado-river?qt-science_center_objects=0#overview

U.S. Geological Survey, 2023, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed [Jan. 2023], at URL [http://waterdata.usgs.gov/nwis/]. DOI http://dx.doi.org/10.5066/F7P55KJN

Randle, T. J., & Samad, M. A., (2008) Sedimentation and River Hydraulics Group-Technical Service Center, (2008). *Platte River in central Nebraska modeling of pulse-flow release*

SJRRP: San Joaquin River Restoration Program. Draft EIS. (April 2011). *Draft Program Environmental Impact Statement/ Environmental Impact Report*. Sacramento, California: U.S. Dept. of the Interior, Bureau of Reclamation.

SJR Restoration Settlement Act: San Joaquin River Restoration Settlement Act. (2009, March 30). Public Law No. 111-11, 123 Stat. 1349

Smith, F. E. (2014). *Purpose and Intent of Fish and Game Code Section 5937, The Public Trust and In Good Condition* (Ser. 294, Publication). Sacramento, CA: California Sportfishing Protection Alliance. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/CSPA%20et%20al/part2/cspa_294.pdf

Technical Report No. SRH-2008-2. Denver, CO; U.S. Dept. of the Interior, Bureau of Reclamation.

Traum, J.A., Phillips, S.P., Bennett, G.L., Zamora, Celia, and Metzger, L.F., 2014, Documentation of a groundwater flow model (SJRRPGW) for the San Joaquin River Restoration Program study area, California: U.S. Geological Survey Scientific Investigations Report 2014–5148, 151 p., http://dx.doi.org/10.3133/sir20145148.

Yoshiyama, R. M., Fisher, F. W., & Moyle, P. B. (1998). Historical abundance and decline of Chinook salmon in the Central Valley region of California. *North American Journal of Fisheries Management*, 18(3), 487–521. https://doi.org/10.1577/1548-8675(1998)018<0487:haadoc>2.0.co;2