Title

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Assessment of the use of grade control for improved groundwater storage on a tributary in Muir Woods

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LA 227: Restoration of Rivers and Streams

Instructor: Prof. Matt Kondolf

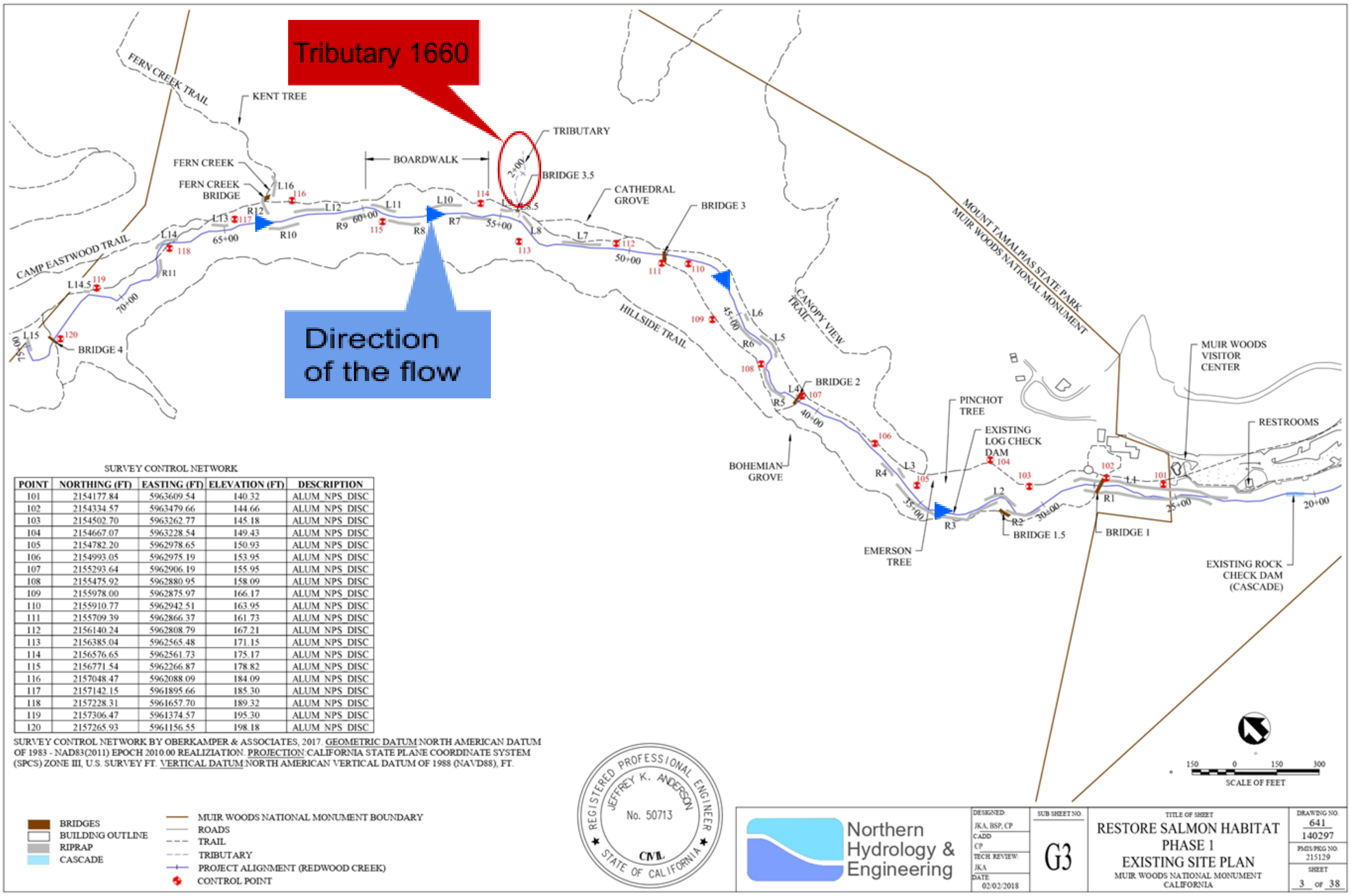
Abstract

In 2019 grade control modifications were made to a tributary to Redwood Creek in Muir Woods National Monument as a way to evaluate the possible use of check dams to improve groundwater storage. This study seeks to evaluate the effectiveness of the grade control in 1) controlling or reversing incision due to prior land use changes and channel modification and 2) storing groundwater in areas adjacent to the tributary. Our results from initial monitoring efforts suggest that check dams could be effective in inducing aggradation of the streambed and reducing incision and in storing groundwater near the floodplains. However, we recommend continued monitoring to confirm their effectiveness as the tributary continues to evolve.

Introduction

Muir Woods National Monument is an old-growth redwood forest near the southern end of *s. sempervirens* range. According to Schmidt et al (2021), post-colonial new land use and channel modifications could have lowered the groundwater elevation compared to pre-European conditions. This creates an issue for the forest, *s. sempervirens* being a shallow root specie, thus needing shallow groundwater to thrive. Thus, the incised channels threaten these trees by increasing groundwater discharge into streams and consequently decreasing the groundwater available to *s. Sempervirens*. Additionally, Zekster et al (2004) note the dependence of steelhead trout (*Oncorhynchus mykiss*) on groundwater flows to prevent the loss of habitat in Redwoods Creek during dry periods.

In the context of a larger project in 2019 to restore salmonid habitats in Redwood Creeks (Figure 1), the National Park Service implemented a pilot project on one of the tributaries of Redwood Creek, Tributary 1660, to test a groundwater enhancement technique. They installed check dams of rip rap and woody debris in the incised tributary to increase water retention and encourage infiltration. This pilot project aims to determine if these grade control structures can reverse the incision of the channel and recharge the groundwater. If the approach is promising, it may be implemented on other tributaries.



SURVEY CONTROL NETWORK

POINT	NORTHING (FT)	EASTING (FT)	ELEVATION (FT)	DESCRIPTION
101	2154177.84	5963609.54	140.32	ALUM_NPS_DISC
102	2154334.57	5963479.66	144.66	ALUM_NPS_DISC
103	2154502.70	5963262.77	145.18	ALUM_NPS_DISC
104	2154667.07	5963228.54	149.43	ALUM_NPS_DISC
105	2154782.20	5962978.65	150.93	ALUM_NPS_DISC
106	2154993.05	5962975.19	153.95	ALUM_NPS_DISC
107	2155293.64	5962906.19	155.95	ALUM_NPS_DISC
108	2155475.92	5962880.95	158.09	ALUM_NPS_DISC
109	2155978.00	5962875.97	166.17	ALUM_NPS_DISC
110	2155910.77	5962942.51	163.95	ALUM_NPS_DISC
111	2155709.39	5962866.37	161.73	ALUM_NPS_DISC
112	2156140.24	5962808.79	167.21	ALUM_NPS_DISC
113	2156385.04	5962565.48	171.15	ALUM_NPS_DISC
114	2156576.65	5962561.73	175.17	ALUM_NPS_DISC
115	2156771.54	5962266.87	178.82	ALUM_NPS_DISC
116	2157048.47	5962088.09	184.09	ALUM_NPS_DISC
117	2157142.15	5961895.66	185.30	ALUM_NPS_DISC
118	2157228.31	5961657.70	189.32	ALUM_NPS_DISC
119	2157306.47	5961374.57	195.30	ALUM_NPS_DISC
120	2157265.93	5961156.55	198.18	ALUM_NPS_DISC

SURVEY CONTROL NETWORK BY OBERKAMPER & ASSOCIATES, 2017. GEOMETRIC DATUM:NORTH AMERICAN DATUM OF 1983 - NAD83(2011) EPOCH 2010.00 REALIZIATION. PROJECTION:CALIFORNIA STATE PLANE COORDINATE SYSTEM (SPCS) ZONE III, U.S. SURVEY FT. VERTICAL DATUM:NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD88), FT.

DESIGNED: JKA, BSP, CP
CADD: CP
TECH. REVIEW: JKA
DATE: 02/02/2018
SUB SHEET NO. G3
TITLE OF SHEET: RESTORE SALMON HABITAT PHASE 1 EXISTING SITE PLAN
MUIR WOODS NATIONAL MONUMENT CALIFORNIA
DRAWING NO. 641 140297
PMIS/PKG NO. 215129
SHEET 3 OF 38

Figure 1: Map of the Tributary 1660 and the main stem courtesy of NPS

The parameters for which data were collected, including topography, groundwater elevation, and precipitation, are important to understand the hydrological response of the tributary to the restoration project, as highlighted by the literature. The topography is very important in the context of valley-bottom streams, such as Tributary 1660. Vidon (2012) finds that the groundwater in the riparian zone, situated between the hillslope and the stream, principally comes from uphill, but its level is mainly influenced by the water level in the stream. Burt (2002) confirms this importance by explaining that if the floodplain is located between a slope and the stream, uphill water is still important but there is an increased importance of the river. The stream serves as a reference point for the water table level, thus justifying the use of grade control to raise the water level to increase the groundwater recharge. Particularly, for intense precipitations, both Vidon (2012) and Burt (2002) notice a reversal of the groundwater flow. During these events, the water from the stream infiltrates and increases the groundwater reserves, whereas the normal underground flow depletes the groundwater reserves to supply the river. As also noticed by Burt (2002) while looking at cross-sections, the topography of the valley in which the tributary is located could also have an influence. Voltz (2013) supplements this idea and increases the complexity by looking at the hydraulic gradients not only perpendicular to the stream but also parallel to the stream. He thus showed that the hydraulic gradients are mainly directed down-valley and have limited shifts during storms.

The effect of precipitation on groundwater is more complicated and localization dependent. While Dai (2017) found that, on an annual average, the water table increases quadratically with precipitations, the response to specific events is more complex. Indeed, Vidon (2012) did not find any correlation between the precipitation during a storm and the water table height, and Zhang (2017) established that there is an optimal rainfall intensity for the water table response. Below this intensity, most of the water is intercepted before filling the groundwater reserves and above this intensity, water starts to run off into the stream where, in absence of obstacles, it flows downstream without infiltrating into the ground. This last part is what the grade control implemented is trying to prevent, to give water in the stream time to infiltrate..

Morphological features of the stream can also have an influence on the groundwater. For instance, Magliozzi et al., (2018) demonstrated that large woody debris, weirs, or log dams can create roughness and variability of the vertical hydraulic gradient, thus improving hyporheic exchange. On the same note, the creation of pools and riffles impacts the water table level, as the water upwells at the riffle and downwells at the head of the riffle because of variations in the average channel gradient (Kasahara & Hill, 2006).

Experiments monitoring streams after the installation of grade control have also previously been conducted. The Bureau of Reclamation finds in a report published in 2020 that grade control has a positive impact on the infiltration of stream water into the ground. Based on the monitoring of Grade Control Structures (GCS) at the Heard Scout Pueblo study site in the city of Phoenix, an eroded and incised channel submitted to high flows, GSC can increase stream infiltration by 15% during storms. Simulations conducted as part of the study more precisely showed that not all structures had the same effect, but many of them had an increase in infiltration depth upstream.

Methods

Groundwater Monitoring

Prior to the installation of check dams in tributary 1660, the National Park Service (NPS) installed three groundwater monitoring wells on the floodplains of the stream in 2018. They hand-augered monitoring wells to depths between five and sixteen feet below the ground surface and installed Solinst *leveloggers* in each well to obtain water level continuously. From these data, we were able to calculate the hydraulic gradients between well 1 and well 3 and, well 4 and well 3 to characterize the movement of groundwater in the longitudinal direction and transverse direction.

Additionally, we used daily total precipitation data collected by NPS at Highway 1 bridge on Redwood Creek to compare precipitation trends with groundwater levels. For our study we used monthly total precipitation data to classify each month as having either dry (less than .5”), low rainfall (.5” to 3”), or high rainfall (greater than 3”). This was then compared to the difference in groundwater elevation between maximum groundwater elevation and minimum groundwater elevation for each month. We then used independent t-tests on the difference of the means to determine if there was a significant difference between the average monthly variability in groundwater elevation following the construction of the check dams. Additionally, we compared changes in groundwater elevations following a precipitation event with the magnitude of the event.

Survey Methods

To measure changes in the channel geometry, traditional survey methods were used to obtain longitudinal profiles and transects across the top (T6), middle (T5), and bottom(T4) of Tributary 1660. Figure 2 shows the location of these transects along with the locations of the groundwater monitoring wells on Tributary 1660. As part of the pilot project, the National Park Service surveyed Tributary 1660 twice: once in July 2019 to establish pre-project conditions and a second time in October 2019 just after the completion of the project. They did this by first establishing benchmarks of known elevation at both ends of each transect. They then used these benchmarks to georeference their lidar data and create a digital elevation model(DEM) for the tributary. The NPS defined the location of each data point using northing and eastings.

To determine if the pilot project had an effect on sediment deposition, our team resurveyed tributary 1660 using rod-level methods and equipment (i.e. measuring tape, an automatic level, and a grade rod). To resurvey the cross-sections of each transect, we spread a measuring tape from the benchmark on the left bank of the tributary to the benchmark on the right bank. We then used an automatic level and grade rod to determine the elevation at each station as we moved across the tape from the benchmark on the left bank to the benchmark on the right bank. This process was repeated for each transect T4, T5, and T6. To help visualize the effect of sediment deposition, our team overlaid the two data sets collected by the National Park Service over our data. Since the National Park Service recorded the location of each data point using northing and eastings, we converted our stations to eastings and plotted the Eastings vs Elevation of all three data sets on the same plot.

To resurvey the longitudinal profile, our team established a benchmark at the thalweg of T4. From this benchmark, we spread a measuring tape to the second point of significant elevation change higher in the tributary. We then used an automatic level and grade rod to determine the elevation at this second point. After recording the elevation and distance from the T4 benchmark, we used the second point as our updated benchmark location and repeated the process. We recorded the location of each data point as the distance from the T4 benchmark. To overlay the longitudinal profiles collected by the National Park Service, we converted northings and eastings to the distance from the T4 benchmark and plotted the distance vs. the elevation of all three data sets on the same plot.

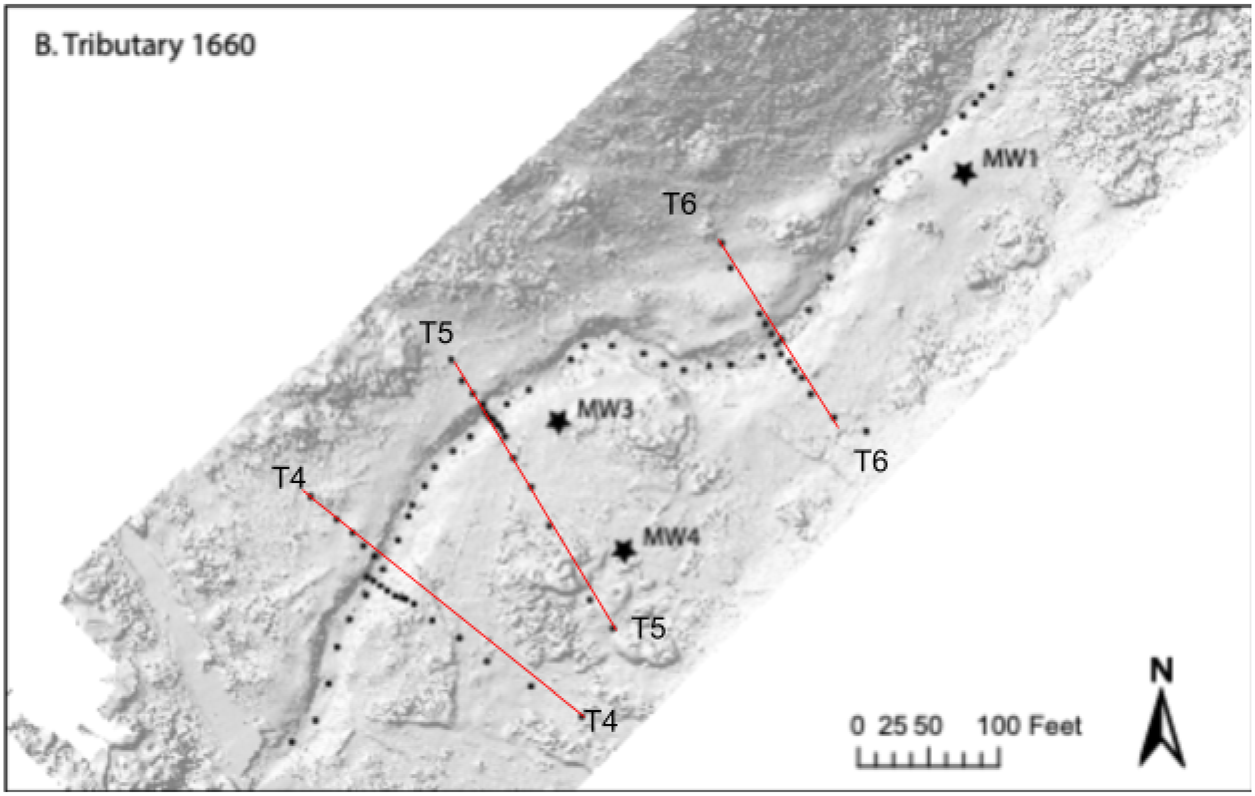


Figure 2: DEM of tributary 1660 watershed showing the locations of transects and groundwater monitoring wells taken during the original as-built survey (DEM courtesy of NPS).

Results

Groundwater Results

Figure 3 shows the groundwater elevation above sea level with respect to time along with the total daily precipitation. From this plot, one can observe that the elevation of groundwater does not vary more than five feet over the course of the study, despite yearly low precipitation for the duration of the majority of the study. Additionally, one can see that there is a significant increase in groundwater elevation following a larger precipitation event in water year 2022 (WY22).

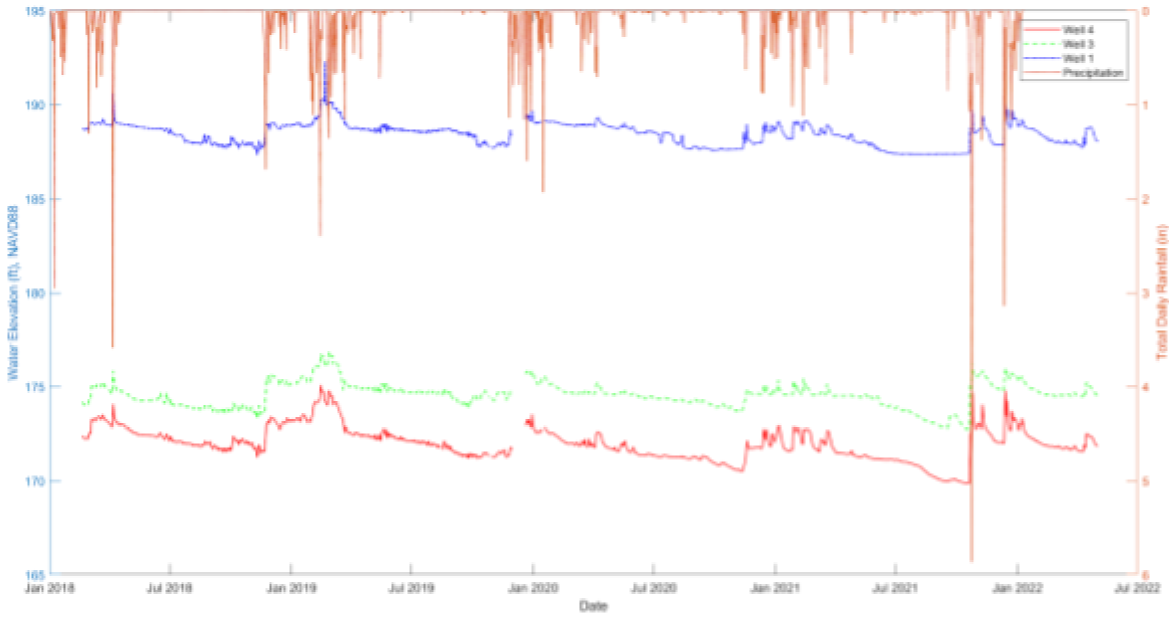
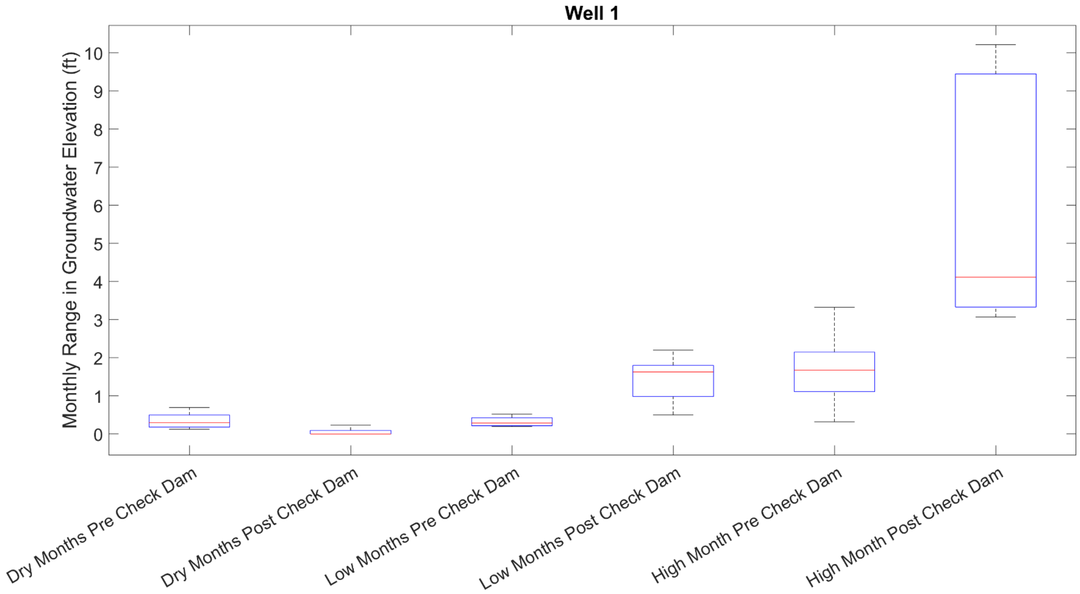


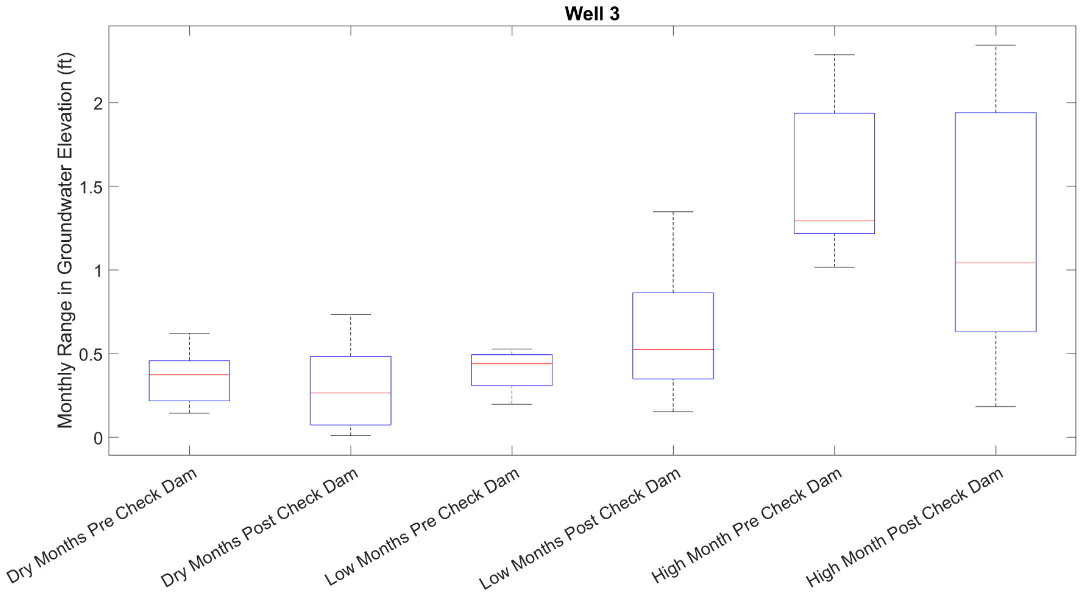
Figure 3: Mean Daily Groundwater Elevation and Total Daily Precipitation over time at 3 monitoring wells along Tributary 1660

Figure 4: Hydraulic gradient between well 3 and other wells over time.

To understand the flow of groundwater outside of the channel we also calculated the hydraulic gradient over time (figure 4). The hydraulic gradient along the stream is in the direction of well 1 towards well 3 (in the direction of topographic slope and streamflow). In contrast, the hydraulic gradient in the transverse direction is from well 3 towards well 4 (from the channel into the floodplain). Additionally, during the post-project monitoring project, the magnitude of the hydraulic gradient between well 3 and well 4 increased which would drive more water from the stream into the floodplain.

To better quantify the monthly variability of groundwater elevation, figure 5 shows a box plot of the monthly range in daily groundwater elevations for each category, pre-, and post-construction, and dry, low rainfall, and high rainfall months. These figures show that during low rainfall months, well 1 and well 3 experienced an increase in the median monthly range of groundwater elevation after check dams were installed on the tributary. Interestingly, well 4 saw a decrease in the median monthly range of groundwater elevation. This change was particularly noticeable for well 1. Well 1 also saw an increase in average monthly range in groundwater elevation for high rainfall months while wells three and four saw lower median monthly ranges for high rainfall months. During dry months there seemed to be a decrease in the monthly range of groundwater elevation for wells one and three while well four saw little change. Performing independent t-tests, as shown in table 2 on the difference of the means for each grouping of data, we found that only well one showed statistically significant ($p < .05$) changes to the monthly ranges of groundwater elevation.


Well 1
Monthly Range in Groundwater Elevation (ft)
0
1
2
3
4
5
6
7
8
9
10
Dry Months Pre Check Dam
Dry Months Post Check Dam
Low Months Pre Check Dam
Low Months Post Check Dam
High Month Pre Check Dam
High Month Post Check Dam


Well 3
Monthly Range in Groundwater Elevation (ft)
0
0.5
1
1.5
2
Dry Months Pre Check Dam
Dry Months Post Check Dam
Low Months Pre Check Dam
Low Months Post Check Dam
High Month Pre Check Dam
High Month Post Check Dam

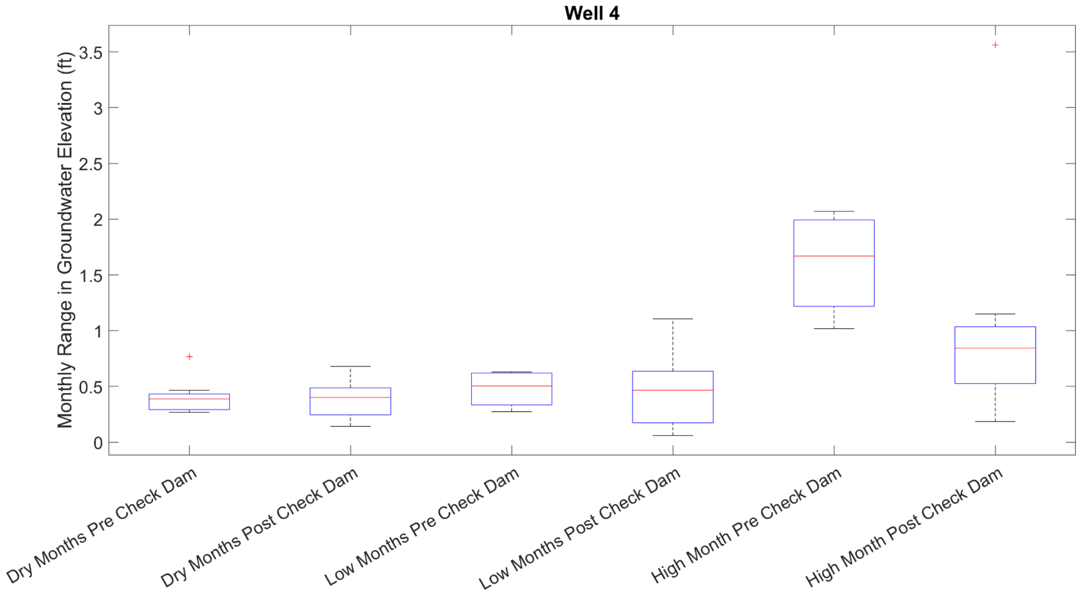


Figure 5: Monthly ranges of Groundwater Elevation are categorized by pre- and post-construction of check dams and as dry months (<.5"), low rainfall (.5" to 3"), and high rainfall (>3").

	Dry month	Low rainfall month	High rainfall month
Well 1 (pre-construction)	0.34 ±0.075	0.32 ±0.59	1.7 ± 3.2
Well 1 (post-construction)	0.052 ±0.20	1.4 ±0.14	5.9 ±1.1
Well 3 (pre-construction)	0.36 ±0.15	0.40 ±0.14	1.5 ±0.51
Well 3 (post-construction)	0.31 ±0.26	0.61 ±0.41	1.2 ±0.80
Well 4 (pre-construction)	0.40 ±0.15	0.48 ±0.17	1.6 ±0.45
Well 4 (post-construction)	0.40 ±0.17	0.47 ±0.36	1.1 ±1.1

Table 1: Reported mean (±SD) monthly range in groundwater elevation in feet for pre-and post-construction dry, low rainfall, and high rainfall months.

	Dry month	Low rainfall month	High rainfall month
Well 1	0.0077	.0021	0.0077
Well 3	0.52	0.25	0.40
Well 4	0.94	0.95	0.24

Table 2: P-values from independent t-tests comparing the average values of ranges in groundwater elevation over a monthly period.

Survey Results

We plotted the recorded eastings against elevations for T4, T5, and T6. In each cross-section the pre-construction transect is represented in black, the As-Built is plotted in green, and the data we collected is plotted in red. In T5 and T6, however, there is evidence of aggradation since our data show shallower channels compared to the black Pre-Construction and green As-Built cross-sections (figure 6, figure 7). To visualize the temporal changes to Tributary 1660's longitudinal profile, we plotted distance vs elevation for each data set. In the profile, the as-built data is plotted in green, and our data is plotted in red(figure 7). T4 is roughly located on the lower left section of the longitudinal profile, while T6 is located in the upper right portion of the figure. The longitudinal profile similarly shows that there is more aggradation higher up in the tributary than there is in the lower sections. While conducting our survey of the longitudinal profile we noticed the formation of pools behind the check dams.

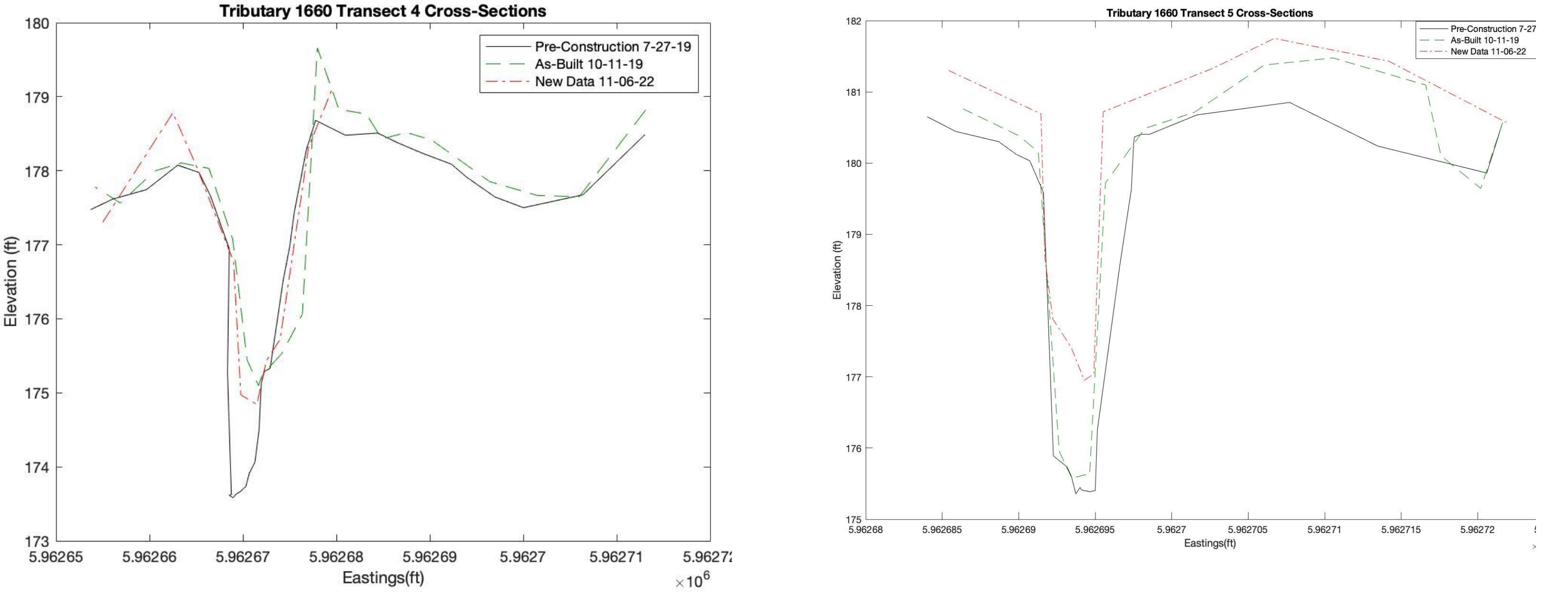


Figure 6: T4 and T5 Cross-Sections

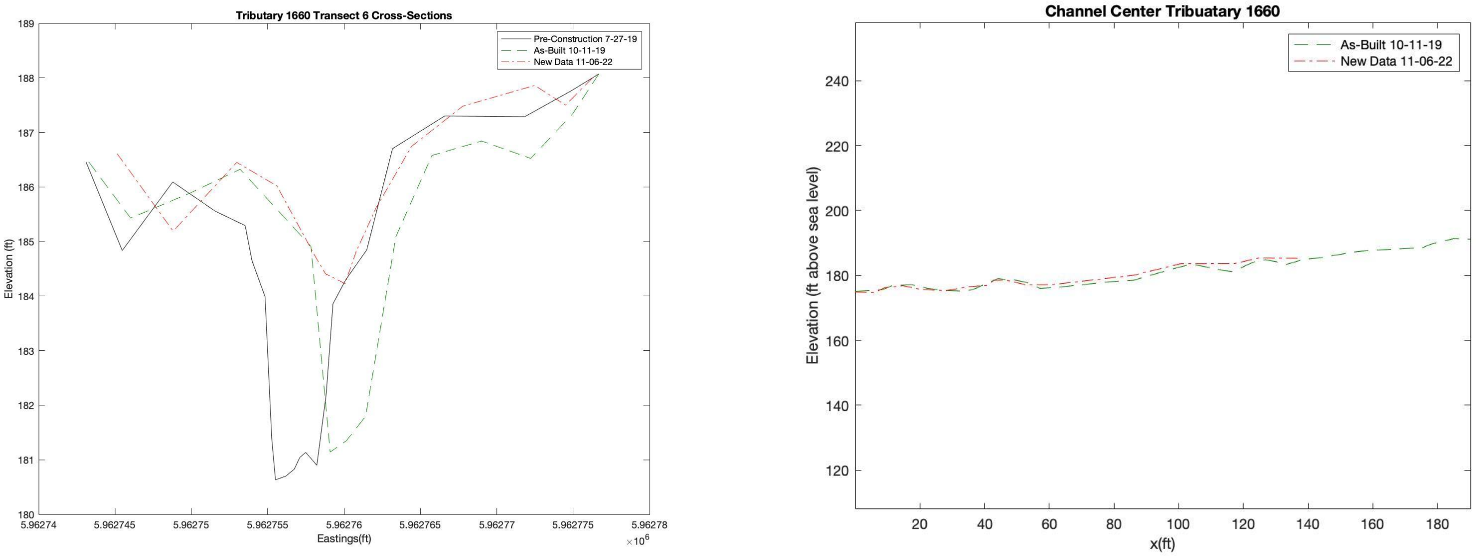


Figure 7: T6 Cross-Section and Tributary 1660 Longitudinal Profile

Discussion

Our preliminary results suggest that the grade control intervention is plausibly resulting in more groundwater storage on the floodplains of tributary 1660. This could be beneficial in providing high baseflows for the tributary and the main stem to better serve *O. mykiss*. However, there does not seem to be much change in the overall elevation of the groundwater table which is needed to support *S. sempervirens.*

Based on our analysis of the hydraulic gradients around well 3, the hydraulic gradient has increased in the transverse direction following the intervention suggesting that within our study area, Tributary 1660 is an influent stream, as water flows from the channel towards the floodplain. The increase in magnitude also suggests that there is an increase in driving forces of groundwater into the floodplains likely resulting in greater groundwater storage in the watershed. To the effect of Vidon and Burt's observations or groundwater flow reversal during intense events, we do not observe this phenomenon but do note that for Tributary 1660, water during high precipitation events seems to flow more slowly from the stream into the floodplain. Particularly during high precipitation events in 2021, we note that the hydraulic gradient nearly reaches zero. Additionally, our results concur with Voltz's observation that the hydraulic gradients are mainly directed down-valley and have limited shifts during storms. In Tributary 1660, there are limited shifts in hydraulic gradients directed down-valley following storms as the hydraulic gradient between well 1 and 3 remains fairly constant. Developing our understanding of the topography could aid in our understanding of how processes in the tributary influence baseflows in the mainstem. This suggests that in higher events, the groundwater storage could be important in supporting recession flow in Tributary 1660 and in areas down-valley of our watershed, providing a more suitable fish habitat for longer following the period of rainfall.

Using the average monthly range in groundwater elevation as a proxy for the variability in groundwater elevation, we find that only at well 1 did check dams affect groundwater variability. Interestingly, of the wells on tributary 1660, well 1 is located furthest upstream of the check dams. While well 1 is the only well to show statistically significant results, well 3 and well 4 show opposite trends of decreasing variability. This may be due to their location in a less steep portion of the watershed. Groundwater stored by check dams near well 1 is likely flowing downhill towards wells 3 and 4 where it is stored, decreasing the shock that rainfall events or dry spells may have the groundwater elevation. However, we likely need more data to conclude that check dams are effective at improving groundwater storage or decreasing variability. Collection of additional data such as groundwater residence time, or modeling surface and groundwater interaction may yield more insight as avenues for future study.

From our cross-sectional data, one can conclude that aggradation is occurring in the channel resulting in the formation of a more natural channel with pools. Aggradation is particularly noticeable in transect six which could help to explain the observed stronger effects of the intervention at well one; the reduction in the amount of incision due to aggradation and resulting higher bed surface elevation should correlate with elevated groundwater levels (Burt 2002). Additionally, it is in this section that one can observe the formation of less incised pools which would allow water to collect but do not necessarily impede longitudinal connectivity. The need for high-flow events for water to overtop the check dams may prevent groundwater storage around wells three and four. Rainfall has been relatively low since the installation of check dams with the exception of WY22, so flows high enough to evolve the pool system may not have had time to develop. We would expect that as the incision is reduced upstream, sediment supply will increase to the downstream pools allowing them to aggrade more rapidly. As a result, we recommend continued monitoring in future years to better understand how the channel will evolve and whether the check dams will have an effect on groundwater storage at wells three and four. Additionally, further monitoring will help to increase the sample size of groundwater measurements improving the power of our study.

To widen the monitoring to the entire riparian zone could also improve the understanding of tributary hydrology. In the literature, one can find many parameters that influence the water table level, from the vegetation cover to the nature of the soil. An interesting one for our case is the microtopology, small variations of the ground level. Frei (2010) explains that in the riparian zone, microtopology can significantly increase the groundwater depth, by storing surface water, preventing it from getting into the stream and generating runoff, giving it time to infiltrate into the ground. The effects increase with the average size of the humps and hollows of the ground in the riparian zone. For these reasons, we would recommend an expansion of the study to consider the entire watershed in more detail to better separate the effects of infiltration on the floodplains and hillslopes from the effects of infiltration occurring in the channel.

Conclusion

Initial monitoring results of tributary 1660 suggest that check dams could be effective in storing groundwater, however, continued monitoring will be needed to confirm their effectiveness. In particular, we recommend monitoring efforts following high-intensity rainfall events to understand how the evolution of the channel (reduced incision and development of pools and riffles) affects the storage of groundwater. Additionally, hydraulic modeling and measurements of baseflows in the tributary would aid in developing a better understanding of the groundwater dynamics in the watershed. Hydraulic modeling would help to determine the optimal rainfall intensity for groundwater storage and aid in understanding how to better group data for analysis. Lastly, modeling the entire watershed would aid in the analysis of the groundwater system as one could create a more detailed water budget for richer analysis. This would allow for a separation of baseflow effects, evapotranspiration, direct infiltration, and hyporheic exchange dependent on the data collected.

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Appendix A: Survey Data

Trib 1660: Longitudinal Profile		
Date: 11/6/22 Time: 2:30PM		
Conditions: Mostly Sunny		
Station	Elevation	Notes
0	174.85244	GC
5.8	174.69244	GC
9.05	176.22244	Pool
14.75	176.84244	
20.6	175.63244	Pool
28.1	175.33244	Riffle
35.4	176.58244	Riffle
40.9	176.92244	GC
42.85	178.50244	GC
46.55	178.56244	GC & TP1
52.8	177.12244	
61	177.18244	
86.1	180.07244	TP2
100.6	183.63244	
117.3	183.67244	
124.8	185.38244	
137.1	185.29244	TP3
145.05	187.89244	
164.65	188.94244	
178.45	191.50244	TP4
214.3	187.60244	TP5
295	183.35244	TP6
337.6	182.45244	

Trib 1660: T4		
Date: 11/6/22 Time: 1:50PM		
Conditions: Mostly Sunny		
Station (ft)	Elevation	Notes
31.5	179.09244	Left Monument
28.3	178.31244	
24.4	175.72244	
22.5	175.43244	
21.2	174.84244	
19	174.97244	
18	176.77244	
12.8	178.08244	
9.65	178.78244	
0	177.30244	Right Monumnet

Trib 1660: T5		
Date: 11/6/22 Time: 1:18PM		
Conditions: Mostly Sunny		
Station	Elevation	Notes
70.7	180.5709	Left Monument
55.8	181.4309	
41.3	181.7509	
33.5	181.3309	
19.6	180.7209	
18.4	177.0409	
17.2	176.9509	

15.5	177.4209	
13.2	177.8109	
12.2	178.6709	
11.7	180.6909	
0	181.3009	Right Monument

Trib 1660: T6		
Date: 11/6/22 Time: 11:15AM		
Conditions: Mostly Sunny		
Station	Elevation	Notes
51.3	188.06977	Left Monument
48	187.49977	
44.7	187.85977	
37	187.47977	
31.5	186.73977	
27.7	185.60977	
25.6	184.81977	
24.4	184.22977	
22.3	184.40977	
21.2	184.72977	
17.1	186.01977	
12.8	186.44977	
6	185.18977	
0	186.60977	Right Monument