Factors Affecting Water Levels in Little Traverse Lake

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Executive Summary

Periodic flooding along the shores of Little Traverse Lake (LTL) has recently focused attention on the factors affecting lake water levels and possible remedies for high water. Flow impediments from channel constrictions at road crossings and dams built by American beaver (*Castor canadensis*) along Shalda Creek downstream of LTL have been recognized as the primary contributors to elevated water levels, but consensus on their relative importance and appropriate solutions has been elusive. Investigations by a private consultant have emphasized the removal of downstream beaver dams within Sleeping Bear Dunes National Lakeshore to prevent undesirable high water levels, while studies by the National Park Service (NPS) concluded that beaver dams have little effect on periodic flooding at LTL.

This report integrates existing information to provide an independent and holistic technical perspective on the factors affecting water levels in LTL. It synthesizes available information on hydrologic conditions in LTL and Shalda Creek, including the physical and biological factors affecting them. Existing water level data were also quantitatively analyzed to determine the effects of beaver dams on water levels in LTL.

Residential development along the shores of LTL occurred primarily within the last 50 years, and at least 24 % of homes were built during the last 30 years. During this time, beavers, which had been functionally extirpated from the region by the fur trade, had recolonized Shalda Creek likely from a colony on nearby Narada Lake that has been present for at least 40 years. As the Shalda Creek beaver population grew, dams were established increasingly farther upstream and reached the vicinity of County Road 669 (Bohemian Road) by 2012. Since then, beavers have built dams on Shalda Creek in at least eight locations. With the exception of two dams near Lake Michigan, each of these have been breached by local residents at least once, and sometimes several times. In most cases, beavers have rebuilt the dams.

The available information indicates that channel constrictions at road crossings have been and continue to be a primary driver of periodic flooding along LTL. Two independent hydraulic simulation studies found that the existing culvert at West Traverse Lake Road limits drainage from LTL, and that replacing it with a full-span box culvert would significantly reduce the frequency and duration of nuisance flooding. The previous culvert at County Road 669 also contributed to past flooding, but this was replaced during 2020, and the current 30-foot box culvert has been shown to have minimal effects on LTL water levels.

Previous studies yielded disparate conclusions on the effects of beaver dams along Shalda Creek. Ambiguous and often conflicting results were derived from subjective visual interpretations of water level data, partly because water levels are inherently confounded by multiple interacting and changing factors on the landscape. Recently completed studies, including hydraulic simulations by NPS staff, found that beaver dams on upper Shalda Creek do contribute to elevated LTL water levels when the lake is below nuisance water levels, but beaver dams alone have minor effects when streamflow and LTL water levels are higher.

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This report uses the approach of water level recession analysis and finds that beaver dams on Shalda Creek reduce the rates of water level decline in LTL following storm events but have no discernable effect on how decline rates vary with water level. Regardless of beaver dam presence, overall rates of water level declines in LTL were higher during 2016-2017 but were less sensitive to water levels than in 2020-2022. Differences between these time periods could be a result of unrelated changes in channel hydraulics along Shalda Creek or limitations in the available data.

Additional factors likely contribute to periodic flooding along the shores of LTL such as (a) naturally low conveyance capacity along Shalda Creek due to channel conditions not associated with flow obstructions, (b) a shallow water table along the lake margin, and (c) periods of high water levels in Lake Michigan. These factors are inherent features of the landscape that create variable conditions through time and are not amenable to management actions.

Factors Affecting Water Levels in Little Traverse Lake and Shalda Creek

1. Introduction

Periodic flooding of yards, crawl spaces, and septic systems at homes along the shores of Little Traverse Lake (LTL) has stimulated considerable interest in the factors affecting lake water levels (Good Harbor Bay Watershed Steering Committee 2015). Concerns over water levels in LTL and nearby Lime Lake date back to when residential development began in the mid-20th century but have increased significantly during the last few decades as more homes were built. Low water levels promote shoreline erosion and create inconveniences to recreational use, while high water levels contribute to water quality degradation when septic systems are flooded (Good Harbor Bay Watershed Steering Committee 2015).

Flow impediments from channel constrictions at road crossings and dams built by American beaver (*Castor canadensis*) along Shalda Creek downstream of LTL have been recognized as the primary contributors to elevated water levels, but consensus on their relative importance and appropriate solutions has been elusive (Burgess 2018). Gosling Czubak Engineering Sciences attributed periodic flooding along LTL to an undersized culvert at County Road 669 (CR669, or Bohemian Road), which was replaced in 2020, and ongoing beaver dam activity (Gosling Czubak Engineering Sciences 2014, 2015d, 2015b, 2015a, 2015c, 2020). The National Park Service (NPS) Water Resources Division highlighted road crossings at CR669 and West Traverse Lake Road (WTLR) as causes of undesirable high water levels, but their analyses suggested that beaver dams have appreciable effects on LTL only during low water levels (Martin 2012, 2015, Martin and Kim 2018, Schook and Martin 2022). The primary disparity in these previous investigations has centered on whether beaver dam removal is a viable approach to preventing periodic flooding of residences along LTL.

Sleeping Bear Dunes National Lakeshore (SLBE) manages the majority of Shalda Creek. Alterations to natural hydrologic, geomorphic, and ecological processes along Shalda Creek are significant resource management concerns to regional stakeholders, and any interventions such as beaver dam removal require compelling scientific evidence. Within SLBE, a prime management objective is the maintenance of unimpeded natural processes to the greatest possible extent (Vana-Miller 2002). This objective is consistent with broader NPS policies, which include managing streams to "protect stream processes that create habitat features such as floodplains, riparian systems, woody debris accumulations" and "when conflicts between infrastructure (such as bridges and pipeline crossings) and stream processes are unavoidable, NPS managers will first consider relocating or redesigning facilities rather than manipulating streams" (National Park Service 2006). Riparian wetlands near the outlet of LTL also support unusually diverse communities of herbs and aquatic macrophytes, including a population of the cut-leaved water parsnip (*Berula erecta*) which is a threatened species within the State of Michigan (Mechenich et al. 2009). Upper Shalda Creek and the outlet of LTL have been designated as a critical area requiring restoration due to impacts from land use stressors and pollutants (Good Harbor Bay Watershed Steering Committee 2015).

In order to provide an independent and holistic technical perspective on factors affecting water levels in LTL, the Water Resources Division of the NPS engaged Colorado State University to (1) summarize the available information on hydrologic conditions in LTL and Shalda Creek, including the physical and biological factors affecting them; and (2) quantitatively analyze existing water level data to determine the effects of beaver dams on water levels in LTL.

Previous reports attempted to determine the effectiveness of beaver dam removals based on subjective visual interpretation of water level hydrographs that occurred over relatively short time periods (Gosling Czubak Engineering Sciences 2014, 2015d, 2015b, 2015a, 2020, Martin 2015, Martin and Kim 2018). The lack of quantitative data analyses in previous efforts has resulted in ambiguous and often conflicting results that have hampered consensus among stakeholders. In this report, water level recession analysis was used to examine how beaver dams along Shalda Creek affect the release of water from LTL following storm events. The receding segments of a hydrograph (i.e., when water levels are declining) express the processes affecting watershed drainage, and statistical analysis of these characteristics provides an objective and quantitative basis for assessing changes (Wittenberg 1994, Tallaksen 1995). Recession analysis is widely used to quantify impacts to watershed drainage patterns from changes in land and water use, climate, and channel network hydraulics (Wang and Cai 2009, 2010a, 2010b, Thomas et al. 2013, Gebrehiwot et al. 2021).

2. Study Area Description

Shalda Creek and LTL are part of the Good Harbor Bay Watershed, within the Cleveland Township, Leelanau County, Michigan (Figure 1). The landscape is composed of rolling hills and vegetation is primarily deciduous forest. Surficial geology within the watershed is unconsolidated Quaternary glacial and lacustrine sediments with thicknesses ranging from 100 to 700 ft (Farrand and Bell 1982, Handy and Stark 1984), underlain by Devonian metasedimentary rocks of the Traverse Group (Milstein 1987). Hilly uplands along the watershed perimeter are formed in coarse-textured end moraine deposits, while the lowlands along Shalda Creek and surrounding LTL and Lime Lake are composed of fine sediments interbedded with sand and gravel (Farrand and Bell 1982). The northern portion of the watershed bordering Lake Michigan is mantled with sand dunes ranging up to 100 ft thick. The watershed area at the LTL outlet and head of Shalda Creek is 18.3 mi^2.

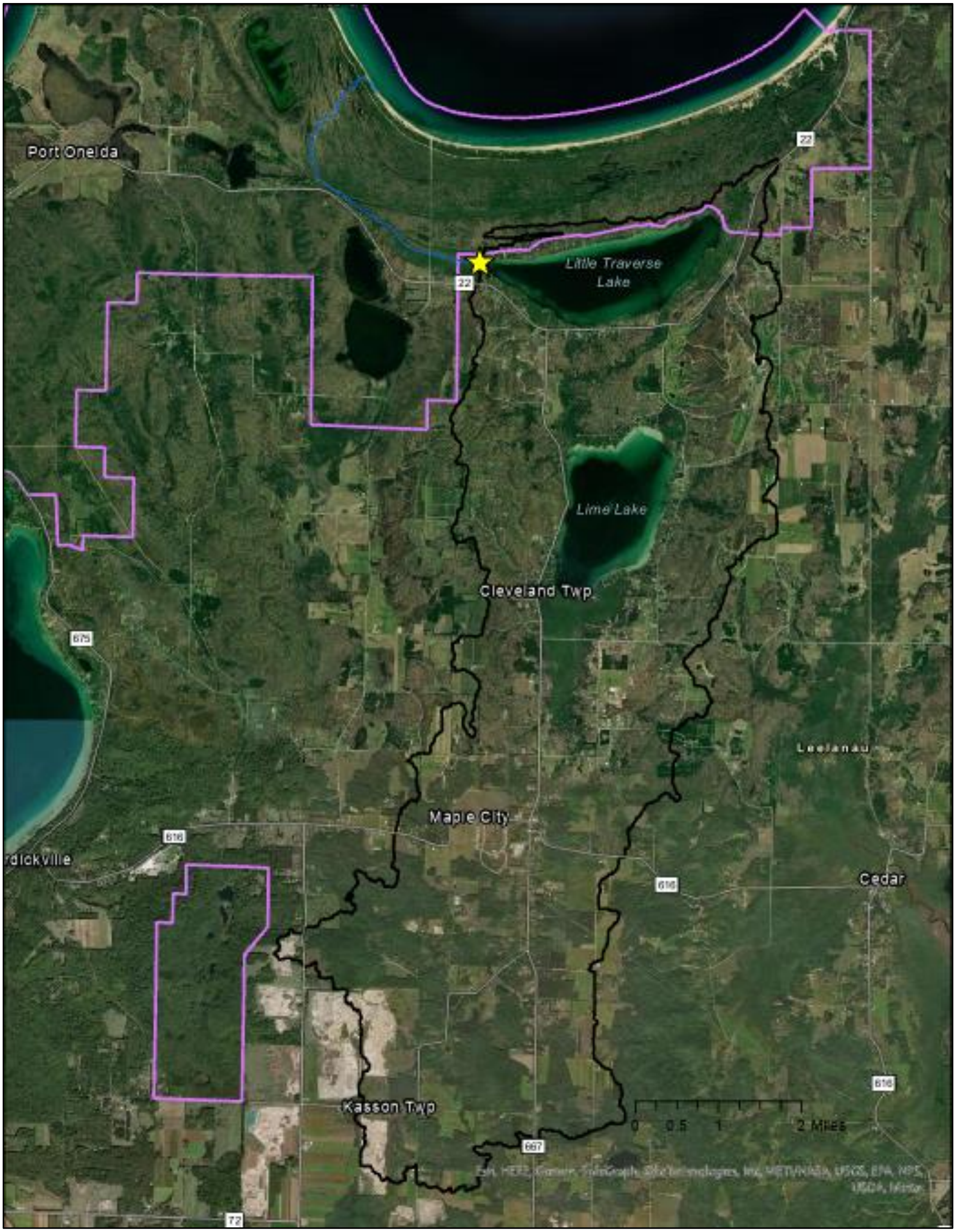

Figure 1. Watershed boundary (black line) at the outlet of Little Traverse Lake and the head of Shalda Creek (yellow star). Sleeping Bear Dunes National Lakeshore boundary shown in purple.

Factors Affecting Water Levels in Little Traverse Lake and Shalda Creek

2.1. Little Traverse Lake

Little Traverse Lake covers approximately 640 acres, with an average depth of 5-10 feet and a maximum depth of 54 feet (Michigan Institute for Fisheries Research 1949, Seites-Hettinger 2014). The lowlands surrounding the lake are composed of poorly drained, mucky soils beneath white-cedar (*Thuja occidentalis*) swamps (Fessell 2007), while less disturbed portions of the shoreline support herbaceous wetland plant communities of bulrush (*Scirpus* sp.), sedge (*Carex* sp.) and cattail (*Typha* sp.) (Fessell 2007). Although numerous seeps and small springs occur along the southern shoreline, the primary surface water inflow is Shetland Creek, which drains Lime Lake (Michigan Institute for Fisheries Research 1949, Seites-Hettinger 2014). Shallow groundwater slowly seeps into LTL from various perimeter locations, with the depth and volume of groundwater varying seasonally and in response to precipitation. Approximately half of the shoreline has been developed for residential land use (Fessell 2007, Seites-Hettinger 2014). Outflows from LTL pass through a 64x43-inch corrugated metal arch culvert beneath WTLR (Gosling Czubak Engineering Sciences 2014, Martin 2015), which crosses the lake outlet. It has been reported that nuisance flooding of crawl spaces and septic systems occurs when LTL water levels reach 595.65 feet, while undesirable low water levels occur below 595.20 feet (Gosling Czubak Engineering Sciences 2014). Thus, the preferred range of water levels in LTL is 0.45 feet.

2.2. Lime Lake

Lime Lake covers about 670 acres with a maximum depth of 67 feet, with inflows provided by several springs and small tributaries (Michigan Institute for Fisheries Research 1948, Seites-Hettinger 2011). Much like LTL, the lowlands surrounding Lime Lake are composed of mucky soils and white-cedar swamps, and roughly half of the shoreline is under residential development (Seites-Hettinger 2011). The outlet of Lime Lake is a hardened rock dam with an open top that does not impose any additional restriction at high water levels.

2.3. Shalda Creek

Shalda Creek originates at the outlet of LTL and flows 3.20 mi through dune and swale topography to its confluence with Lake Michigan (Figure 2). The channel meanders through an unconfined swampy bottomland to CR669, below which the stream corridor is moderately confined between parallel dunes until it is joined by Narada Creek. Downstream of this confluence, Shalda Creek flows through alternating dunes and swales until it debouches into Lake Michigan. Most of the channel consists of uniform runs with occasional short gravel riffles at former beaver dams, although gravel riffles are more common near the stream mouth (Boyle and Hoefs 1993, Mechenich et al. 2009). Outside of the riffles, the channel boundary material is a thin and discontinuous veneer of sand overlying marl that is typically covered with 1-2 ft of muck. Downed trees and large woody debris are common within the channel, and peat-bearing fens and seeps are common along the banks, particularly downstream of CR669. Extensive beds of aquatic and emergent vegetation occur within the channel (Boyle and Hoefs 1993, Mechenich et al. 2009), and the adjacent bottomland is dominated by white-cedar swamps (Hazlett 1988). Beaver dams have occurred in at least nine locations along Shalda Creek.

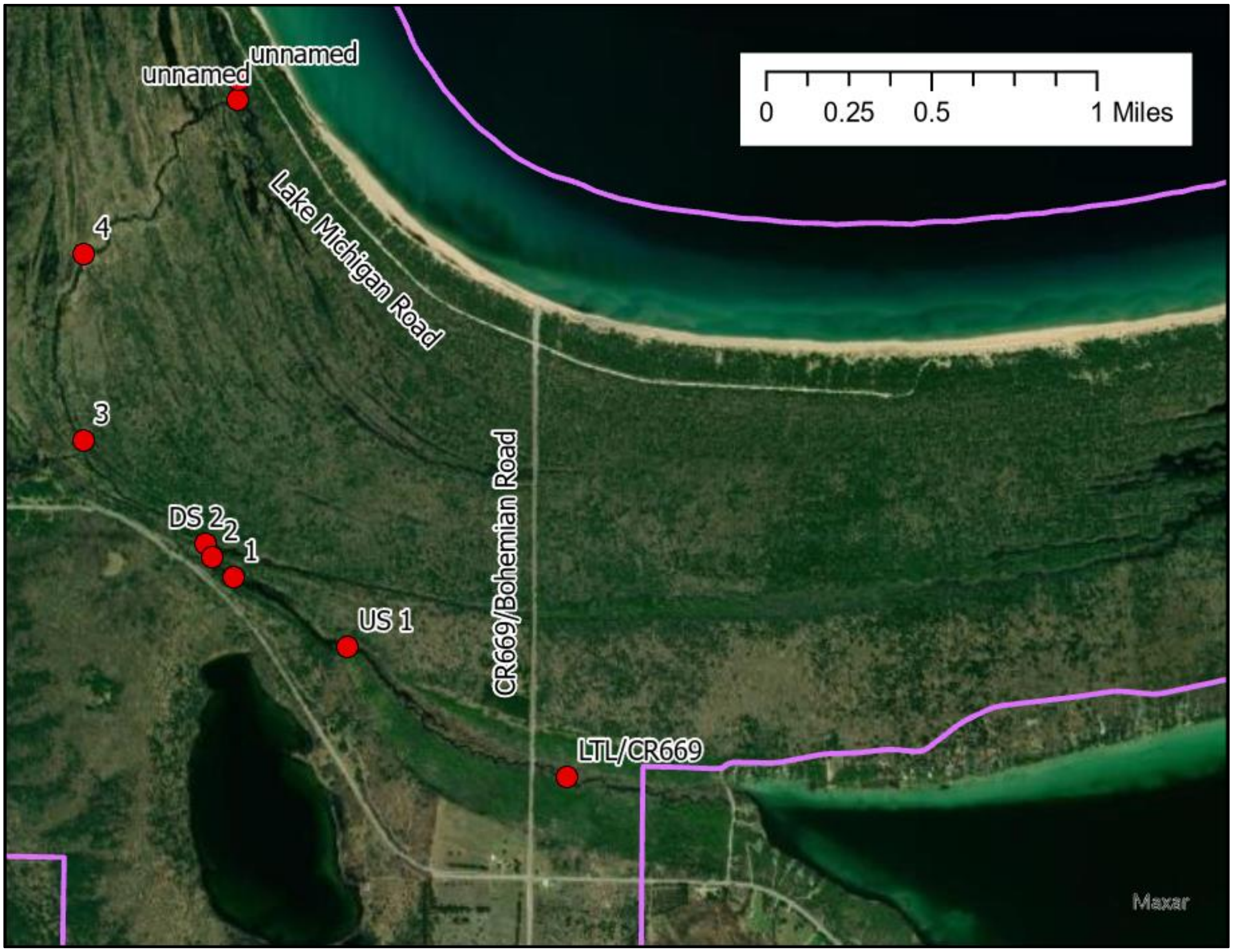

Figure 2. Previously document beaver dam locations on Shalda Creek. Sleeping Bear Dunes National Lakeshore boundary shown in purple.

2.4. History of Residential Development

Residential development along the shores of LTL, Lime Lake, and other nearby lakes increased rapidly beginning in the 1950s, with extensive construction of summer homes during the 1970s and 1980s (Steinberg et al. 1994). Michigan Department of Natural Resources staff noted that 107 dwellings were visible from the water of LTL in 1995, increasing to 141 dwellings visible in 2013 (Seites-Hettinger 2014). While a more detailed analysis of the timing of development around LTL was not undertaken, available accounts indicate that most residences are less than 50 years old and at least 24 % of homes were built during the last 30 years.

2.5. History of Beaver Activity

Beavers are a natural part of the Shalda Creek system, although they were likely scarce during the early stages of modern residential development. These native ecosystem engineers were once prevalent throughout the western Great Lakes region prior to the fur trade (Johnson-Bice et al. 2018). Heavy exploitation from 1650 through the late 1800s significantly reduced their abundance and likely caused local extirpations in some areas. Populations began to recover during the early 20th century with the establishment of closed trapping seasons and expanded rapidly thereafter due to reintroduction programs, predator elimination, and forest conversion through selective timber harvesting. By the 1930s, beavers were abundant throughout much of Michigan (Johnson-Bice et al. 2018), although outbreaks of diseases such as Tularemia suppressed beaver populations in some areas through the 1950s (Lawrence et al. 1956). Beavers are now once again common throughout their historic range (Johnson-Bice et al. 2018).

Available information suggests that beavers recolonized Shalda Creek within the last four decades. The earliest reports indicate that beaver occupied Otter Lake during 1982 (Handy and Stark 1984), and Narada and Tucker Lakes during 1986 (Hazlett 1988). By 2003-2006, beaver activity was widespread throughout SLBE and within the study area, with the lower segment of Shalda Creek being “frequently impounded by beaver” (Fessell 2007). By this time, the expanding beaver colony at Narada Lake had built several dams along Narada Creek, a tributary of Shalda Creek. Beaver occupation was also noted at Shell Lake, Tucker Lake, Hidden Pond, Hatt Pond, North Bar Lake, Round Lake, and Otter Lake. Active beaver dams were also present on Otter Creek and Good Harbor Creek (Fessell 2007).

In response to concerns over LTL water levels in 2011, WRD staff detected a beaver dam (US 1 in Figure 2) on Shalda Creek about 800 feet downstream of WTLR using satellite imagery from April 2012 (Martin 2012). Further investigation in 2014 documented four beaver dams (US 1, 1, 2, DS 2) between 0.82 and 1.74 miles downstream of CR669, with the farthest downstream dam raising nearby water levels in Shalda Creek by approximately 3.33 feet (Gosling Czubak Engineering Sciences 2014, 2015c). Between September 2014 to November 2020, beaver dams occurred at six locations along Shalda Creek downstream of CR669, and at one location about 400 feet upstream of CR669 (LTL/CR669) (Gosling Czubak Engineering Sciences 2014, 2015c, 2015b, 2020). During this time, Little Traverse Lake Property Owners Association (LTLPOA) members were permitted to conduct periodic beaver dam removal “experiments” within SLBE boundaries, in an attempt to document any reductions to flooding along the shores of LTL. Beaver rebuilt the dams after each removal and sometimes established dams at nearby locations (Gosling Czubak Engineering Sciences 2014, 2015c, 2015b, 2020). During site visits in August and November 2021, a beaver dam was observed between WTLR and CR669 (LTL/CR669) and at least four dams were present between CR669 and the confluence with Lake Michigan. Other than the two unnamed dams near Lake Michigan, the active dams observed in 2021 were where past removals had occurred.

In summary, it appears that beavers have regularly occupied Shalda Creek below CR669 for at least 20 years, likely re-establishing from a locus on Narada Lake that has been occupied for at least 40 years. As this population increased, dams were established farther upstream along Shalda Creek and reached the vicinity of CR669. Since 2014, beavers have dammed Shalda Creek in at least nine locations between LTL and Lake Michigan. With the exception of two dams near Lake Michigan, each of these have been breached by LTLPOA members at least once, and sometimes several times. In most cases, beavers have rebuilt the dams.

A summary of beaver dam occurrences and removals along Shalda Creek, synthesized from available reports and the LTLPOA website, was compiled in Table 1. These public data show that beaver dams were removed or breached at least 25 times between September 2014 and December 2021.

Table 1. Summary of reported beaver dam removal activities.

Date	Dam ID	Comments	Source
09/19/2014	Dam 1		GC 2015
09/26/2014	Dam 2 and 3		GC 2015
10/09/2014	Dam 4		GC 2015
07/20/2015	Dam 1		GC 2015b
04/13/2016	Dam 1		LTLPOA
04/18/2016	Dam 7	Labeled Dam 7 in data	LTLPOA
04/22/2016	Dam 1		LTLPOA
07/13/2016	LTL/CR669		GC 2017
09/28/2016	Dam 1		GC 2017
06/30/2017	LTL/CR669		GC 2017
08/05/2017	Dam 2		GC 2017
08/10/2017	Dam 1		GC 2017
08/16/2017	Dam 1 U/S		GC 2017
08/29/2017	LTL/CR669		GC 2017
09/05/2017	Dam 1 U/S		GC 2017
09/28/2017	LTL/CR669		GC 2017
10/28/2017	LTL/CR669		GC 2017
07/29/2019	Dam at Jones		LTLPOA
06/28/2020	LTL/CR669		GC 2020
07/06/2020	LTL/CR669	Location unclear in notes	LTLPOA
10/27/2020	LTL/CR669		GC 2020
10/31/2020	Dam 1		GC 2020
11/07/2020	LTL/CR669		GC 2020
11/08/2020	Unknown	2 dams removed location unknown	LTLPOA
11/15/2020	Unknown	Dam removed location unknown	LTLPOA
11/21/2020	Unknown	Dam removed location unknown	LTLPOA
12/08/2020	Unknown	Dam removed location unknown	LTLPOA
04/28/2021	Unknown	"DO" in records	LTLPOA
07/16/2021	Unknown	"DO" in records	LTLPOA
07/26/2021	Unknown	"DOx2" in records	LTLPOA
07/26/2021	Unknown	"DOx2" in records	LTLPOA
10/10/2021	LTL/CR2669	"DO 10/10" in records	LTLPOA
12/13/2021	Unknown	"DO 12/13" in records	LTLPOA
12/26/2021	LTL/CR669	"DOx2. Tween & FC" in records	LTLPOA
12/26/2021	Dam 1	"DOx2. Tween & FC" in records	LTLPOA

3. Factors Affecting Water Levels in Little Traverse Lake

Channel constrictions at road crossings and beaver dams have been identified as primary causes of periodic flooding along LTL. Additional factors likely contribute to periods of high water in LTL such as (a) naturally low conveyance capacity along Shalda Creek due to channel conditions not associated with flow obstructions, (b) a shallow water table along the lake margin that varies seasonally and in response to precipitation, and (c) high water levels in Lake Michigan.

3.1. Channel Constrictions at Road Crossings

3.1.1. West Traverse Lake Road

The WTLR crossing is an approximately 5-foot high earthen embankment with a 64x43-inch corrugated metal arch culvert (Gosling Czubak Engineering Sciences 2014, Martin 2015). The road embankment height is uniform across the outlet and therefore prevents bypass flows if the culvert is overwhelmed or blocked. Field inspections during 2021 revealed soil erosion on the embankment crest and pavement spalling near the culvert, suggesting that the roadway had been overtopped in the recent past. Gosling Czubak Engineering Sciences (2014) estimated that the roadway is overtopped at discharges exceeding 80 cfs. The WTLR crossing was originally a wooden bridge, which was replaced by a 42-inch culvert in the 1950s when the road was improved (Good Harbor Bay Watershed Steering Committee 2015). This smaller culvert was apparently replaced by the current one in the 1990s (Seites-Hettinger 2014).

There is broad agreement that the current WTLR culvert is undersized and therefore contributes to elevated water levels in LTL (Gosling Czubak Engineering Sciences 2014, 2015d, 2020, Seites-Hettinger 2014, Good Harbor Bay Watershed Steering Committee 2015, Martin 2015). At flows above 60 cfs, the WTLR culvert is under inlet control, meaning that the drainage rate from LTL is limited by the culvert orifice opening and does not increase appreciably with higher water levels (Gosling Czubak Engineering Sciences 2014). At lower flows, discharge is under outlet control, and is limited by downstream hydraulic conditions. Seites-Hettinger (2014) noted that “since the culvert's replacement in the late 1990s, water levels in Little Traverse Lake in the spring and the fall have been much higher than when the old culvert was in place, so high in fact that riparian owners have expressed major concerns over the flooding of their properties." The Good Harbor Bay Watershed Steering Committee (2015) has prioritized the WTLR culvert for replacement and channel restoration.

Gosling Czubak Engineering Sciences (2015c) quantified the cumulative effects of the current WTLR culvert and the previous CR669 culvert (replaced during summer 2020) on LTL water levels using 1-dimensional hydraulic model simulations. They found that these culverts raised LTL water levels at all flows, with increases ranging from 0.4 feet at 20 cfs to 5.4 feet at 500 cfs (Table 2). Their analysis also showed that replacement of both arch culverts with 20- or 30-foot box culverts would eliminate LTL water level increases for the range of discharge commonly occurring on Shalda Creek (less than 60 cfs) and significantly reduce water level rises for higher discharges. While this report does not clarify the effects of the WTLR culvert alone, it does illustrate that the WTLR and CR669 road crossing configurations prior to 2020 significantly contributed to high water levels in LTL.

Table 2. Simulated LTL water level increases associated with various culvert configurations on Shalda Creek (Gosling Czubak Engineering Sciences 2015d). [1]Current culvert at WTLR. [2]Previous culvert at CR669. [3]Current culvert at CR669.

Flow (cfs)	64x43" arch[1] @WTLR + 71x47" arch[2] @CR669	22.8x5.3' arch @WTLR + 21.8x5.7' arch @CR669	20x5' box @WTLR + 20x6' box @CR669	30x5' box @WTLR + 30x6' box[3] @CR669
20	+0.4	0.0	0.0	0.0
60	+0.7	0.0	0.0	0.0
120	+2.5	+0.3	+0.3	+0.2
350	+5.2	+1.9	+1.2	+0.6
500	+5.4	+3.2	+2.4	+1.2

Schook and Martin (2022) used a 1-dimensional hydraulic model calibrated from higher-quality water level and topography data collected with automated RTK GPS sensors to quantify the effects of the current WTLR culvert on LTL water levels, after the replacement of the CR669 with a 30-foot box culvert. Their results showed that the WTLR culvert increases water levels by 0.13 to 1.28 feet for flows ranging from 10 to 120 cfs, in the absence of beaver dams on Shalda Creek (Table 3). When the two beaver dams present during 2021 were included, the cumulative effects of these flow impediments raised LTL water levels by 1.05 to 1.31 feet. They concluded that with the current WTLR culvert in place beaver dams raise LTL water levels by 1.18 feet during low flow conditions, but dams raise LTL levels by just 0.03 feet beyond the primary control of the culvert during high flow conditions, when flooding impacts to lakeshore properties are greatest (Schook and Martin 2022).Similar conclusions were reached by Gosling Czubak Engineering Sciences (2015a), and highlight the fact that the WTLR crossing is the most significant source of flooding in LTL.

Table 3. Simulated effects of the West Traverse Lake Road culvert and beaver dams on water surface elevations (NAVD 88) in Little Traverse Lake (Schook and Martin 2022).

Flow (cfs)	No Dams or WTLR Culvert	WTLR Culvert Only		Dams and WTLR Culvert		Dams Only	
	Elevation	Elevation	Change	Elevation	Change	Elevation	Change
10	593.41	593.54	+0.13	594.72	+1.31	594.72	+1.31
20	593.93	594.16	+0.23	594.98	+1.05	594.88	+0.95
70	595.05	596.13	+1.08	596.33	+1.28	595.34	+0.30
120	595.64	596.92	+1.28	596.95	+1.31	595.83	+0.20

In summary, two independent hydraulic simulation studies found that replacing the current WTLR culvert with a 20- or 30-foot box culvert would significantly reduce flooding on LTL (Gosling Czubak Engineering Sciences 2015c, Schook and Martin 2022). In addition to high water levels on LTL being caused by increased surface water and groundwater inflows, both analyses showed that the primary downstream influence on high LTL water level is culvert constrictions at road crossings during flows exceeding 60 cfs. A full-span box culvert at WTLR would eliminate flow constrictions at flows less than 70 cfs and would raise the water level by only 0.1 to 0.3 feet compared to a no-road crossing situation at discharges of 120 cfs, the highest reported flow rate for Shalda Creek.

3.1.2. County Road 669

The CR669 crossing is a 30-foot concrete box culvert that was installed during July-September 2020 (Gosling Czubak Engineering Sciences 2020). Several feet of fine sediment and muck were present on the streambed beneath the span during 2021 site visits, and the culvert opening height was 4 to 6 feet. The previous CR669 culvert, a 71x47-inch corrugated metal arch, was frequently submerged and significantly contributed to elevated water levels on LTL during high runoff periods (Good Harbor Bay Watershed Steering Committee 2015, Gosling Czubak Engineering Sciences 2015d, Martin 2015), as shown in Table 2. Gosling Czubak Engineering Sciences (2014) reported that the previous CR669 culvert was under inlet control at discharges greater than 120 cfs. According to available information, the current 30-foot box culvert has minimal effects on LTL water levels.

3.1.3. Lake Michigan Road

The Lake Michigan Road crossing on lower Shalda Creek consists of a 64x43-inch corrugated metal arch and a 42-inch corrugated metal pipe (Gosling Czubak Engineering Sciences 2014). Water surface elevations drop approximately 12 feet between LTL and the culvert inlet, which operates under inlet control at discharges greater than 140 cfs, and this crossing is not believed to affect LTL water levels (Gosling Czubak Engineering Sciences 2014).

3.2. Beaver Dams

The effects of beaver dams along Shalda Creek have been the subject of numerous studies. Using subjective visual analysis of manually collected staff gauge data, Gosling Czubak Engineering Sciences (2014, 2015a, 2015b, 2015d) concluded that beaver dam removal did reduce water levels in LTL during flows below 70 cfs (Gosling Czubak Engineering Sciences 2015d, 2015b, 2015a), but "beaver dam control without culvert modifications will continue to produce high lake levels at flows near or above 70 cfs" (Gosling Czubak Engineering Sciences 2014). In reviewing these reports, NPS Water Resources Division staff found no unequivocal evidence that beaver dam removals during 2014-2015 and 2017 alleviated LTL flooding but did agree that beaver dams produce localized water level rises along Shalda Creek. Limitations such as data quality, the use of subjective qualitative analyses, and a failure to account for confounding factors such as frequent water level fluctuations from precipitation events during and preceding each beaver dam removal precluded definitive results (Martin 2015, Martin and Kim 2018). Simulations with a calibrated hydraulic model were recommended to determine the location and height of beaver dams affecting LTL water levels (Martin 2015).

In response, Gosling Czubak Engineering Sciences (2020) updated their earlier analyses with data from 2015-2020, including continuous water level data provided by the NPS (Martin et al. 2016, Martin and Kim 2018). Their main conclusions were that LTL drainage was impaired by any beaver dams located upstream of CR669, and for larger dams located downstream of CR669.

They recommended the removal of any beaver dams between LTL and CR669, and removal of any dams downstream of CR669 when water levels at this crossing reached 594.0 feet (Gosling Czubak Engineering Sciences 2020).

Schook and Martin (2022) quantified the effects of the two beaver dams present during autumn 2021 on LTL water levels using a calibrated 1-dimensional hydraulic model. They found that beaver dams taller than 3.7 feet can affect lake water levels when located within 1.3 miles of LTL (Table 3). These effects are largest at discharges of 20 cfs or less, and the effects diminish with higher flows, which is consistent with Gosling Czubak Engineering Sciences (2014, 2015a, 2015b, 2015d) and peer-reviewed research showing that beaver dams have minimal effects on water levels during flood flows (Neumayer et al. 2020). They concluded that (a) beaver dam removal will not alleviate LTL flooding during high flow periods, since the WTLR culvert is under inlet control and thus not affected by downstream hydraulic conditions, and (b) beaver dam height is difficult to measure and is not a meaningful management criterion (Schook and Martin 2022).

In summary, previous efforts showed that beaver dams on upper Shalda Creek do contribute to elevated LTL water levels, but the effects are most important at lower flows, when the lake elevation is below nuisance flooding levels. Beaver dams have minor effects at higher water levels, when the WTLR culvert is the primary limitation to LTL drainage.

3.3. Shalda Creek Channel Hydraulic Conditions

Slow drainage from LTL is partly attributable to low streamflow velocities caused by the very sinuous and low-gradient channel (average = 0.02 %) of Shalda Creek, which has very high hydraulic roughness due to abundant woody debris and extensive aquatic vegetation growing on the bed and banks (Boyle and Hoefs 1993, Martin 2012, Schook and Martin 2022). Schook and Martin (2022) found that relatively high Manning's *n* (hydraulic roughness parameter) values of 0.06 for the channel and 0.18 for the floodplain of Shalda Creek were required to calibrate a hydraulic model to measured discharge and stream stage. These factors are a natural limitation to streamflow velocity in Shalda Creek and therefore drainage rates from LTL, regardless of other flow obstructions.

3.4. Shallow Water Tables

A shallow water table and seasonally saturated soils also contribute to the flooding of properties along the LTL shoreline (Martin 2015). Shallow water tables reduce the amount of soil pore space available to absorb and store water from runoff and rising lake levels. Therefore, any surplus water supplied to LTL during periods of heavy precipitation will remain on the surface, manifested as shoreline flooding, instead of infiltrating into the ground.

Shallow water tables and saturated soils commonly occur in bottomlands throughout the study area, and groundwater discharge from seeps and springs are prevalent along lake margins and streams (Handy and Stark 1984, Steinberg et al. 1994, Vana-Miller 2002). Frequent precipitation and highly permeable soils produce significant groundwater recharge that maintains lake levels and stream baseflow throughout the region. Within the unconfined surficial aquifer, groundwater moves in localized flow paths from higher terrain to nearby lowlands such as LTL and is ultimately discharged to Lake Michigan via regional flow paths (Handy and Stark 1984, Steinberg et al. 1994), as illustrated in Figure 3. At least 80 % of streamflow and lake water throughout the region is groundwater discharged from surficial aquifers (Holtschlag and Nicholas 1998, Neff et al. 2005).

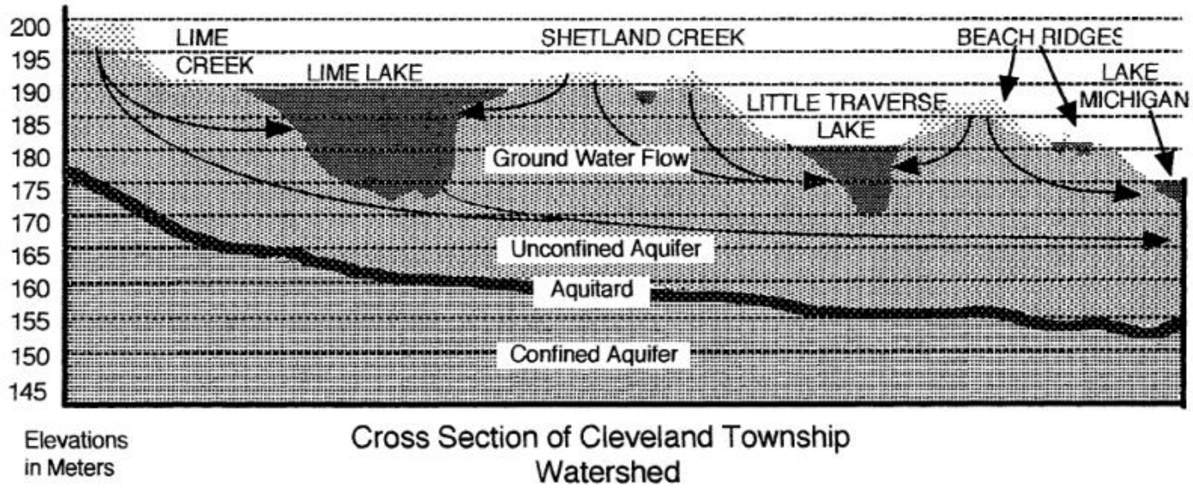

Figure 3. Schematic diagram of groundwater flow paths affecting Little Traverse Lake (Steinberg et al. 1994).

Groundwater levels in the surficial aquifer fluctuate with changing rates of precipitation and recharge (Handy and Stark 1984). Analysis of historic data indicates that shallow groundwater levels and baseflow has increased throughout the region since 1970 (Neff et al. 2005), coincident with increasing precipitation (Gonzalez et al. 2018). This trend likely explains the submergence of an island in Lime Lake during the late 20^{th} century (Steinberg et al. 1994) and is probably a contributing factor to increased flooding along LTL.

The effects of a shallow water table around LTL are reflected in the presence of hydric soils along the eastern and western shoreline, which include approximately 30 % of the lake margin, as shown by the Natural Resources Conservation Service's Web Soil Survey (Figure 4). These hydric soils also correspond to known areas of groundwater discharge at springs and seeps (Michigan Institute for Fisheries Research 1949, Seites-Hettinger 2014). Since these processes are controlled by landscape-scale topography and surface and groundwater flow paths, it is likely that seasonally flooding or saturated soils will occur in these areas regardless of conditions along Shalda Creek.

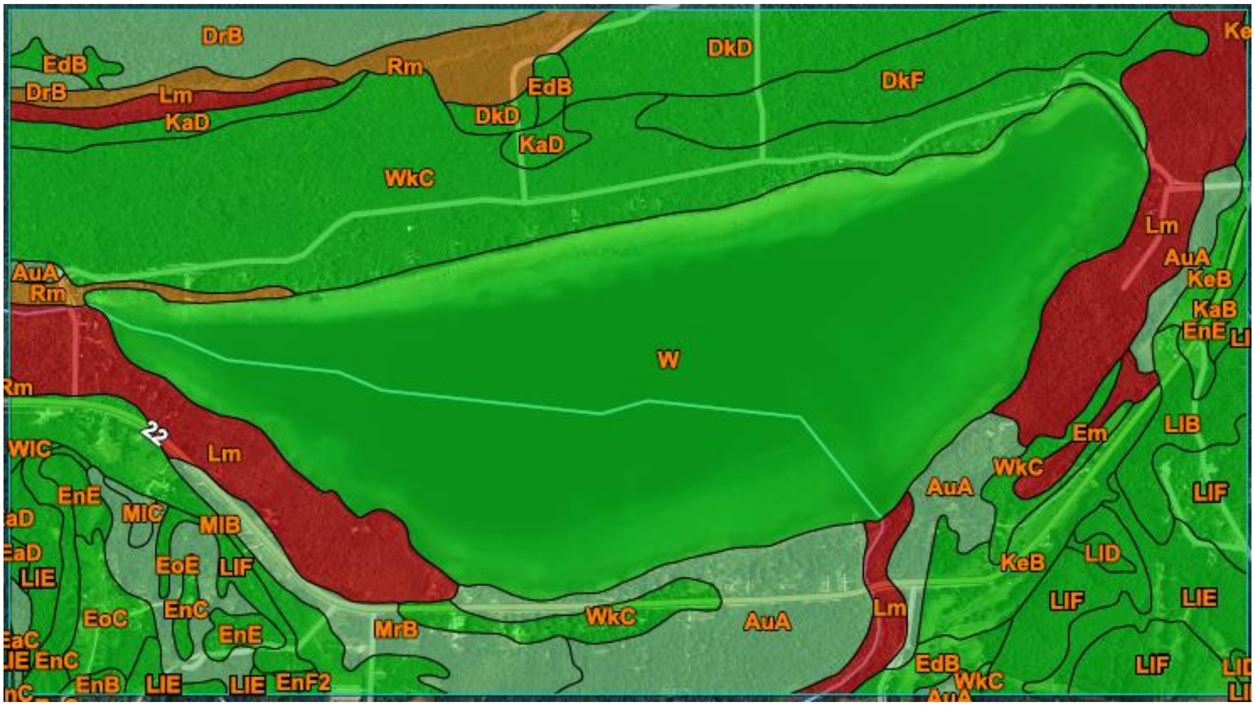

Figure 4. Hydric soils map of Little Traverse Lake. Hydric soils are shown in red and orange, identifying areas where historical near-surface saturation has influenced soil character.

3.5. Lake Michigan Water Levels

High water levels in Lake Michigan during storm surges or periods of sustained strong westerly winds can retard drainage from tributary streams of the western Lower Peninsula (Steinberg et al. 1994, Melby et al. 2012). Under these conditions, water levels in Good Harbor Bay can increase by up to four feet (Steinberg et al. 1994). Since the average water level in LTL is 12 to 14 feet above that of Lake Michigan (Steinberg et al. 1994, Gosling Czubak Engineering Sciences 2014), an increase of four feet in Good Harbor Bay would reduce the hydraulic gradient by approximately 30 %, with a proportional decrease in streamflow velocity and drainage rates in Shalda Creek. Inland flooding from elevated Lake Michigan water levels has been documented elsewhere in Michigan (Melby et al. 2012).

4. Hydrological Characteristics

4.1. Little Traverse Lake

Two average annual water budgets (Steinberg et al. 1994, Canale and Nielsen 1997) indicate that LTL water levels are driven by inflows and outflows of surface water (Table 4). Inflows are primarily supplied by Shetland Creek (71-73 %), while calculated groundwater contributions are about 16 %. Discharge to Shalda Creek is the primary outflow (86-88 %). The average annual inflow is large relative to storage capacity in the lake, producing an average turnover time (or residence time) of 0.4 years (Steinberg et al. 1994). In contrast to LTL, Lime Lake is supplied primarily by groundwater discharge (47-53 %), and 79-83 % of inflows become streamflow that is discharged to LTL via Shetland Creek (Table 5). Note that these lake water budgets were derived by simply balancing periodic streamflow measurements, assuming that evapotranspiration equaled precipitation, and any residuals were attributed to groundwater fluxes (Steinberg et al. 1994, Canale and Nielsen 1997). The prevalence of shallow water tables and ubiquitous groundwater discharge along lake margins throughout the study area (Handy and Stark 1984, Steinberg et al. 1994, Holtschlag and Nicholas 1998, Vana-Miller 2002, Neff et al. 2005) suggest that groundwater inputs for both lakes are significantly larger than reflected in these budgets.

Table 4. Water budgets for Little Traverse Lake.

	Steinberg et al. 1994		Canale and Neilsen 1997	
Component	**Discharge (cfs)**	**Percent**	**Discharge (cfs)**	**Percent**
Shetland Creek	15.3	71	15.87	73
Precipitation	2.8	13	2.36	11
Groundwater Inflow	3.4	16	3.52	16
Total Inputs	**21.5**	**100**	**21.75**	**100**
Shalda Creek	18.4	86	19.13	88
Evapotranspiration	2.8	13	2.36	11
Groundwater Outflow	0.3	1	0.26	1
Total Outputs	**21.5**	**100**	**21.75**	**100**

Table 5. Water budgets for Lime Lake.

	Steinberg et al. 1994		Canale and Neilsen 1997	
Component	**Discharge (cfs)**	**Percent**	**Discharge (cfs)**	**Percent**
S. Lime Creek	4.9	33	5.31	32
Precipitation	3.0	20	2.47	15
Groundwater Inflow	7.0	47	8.79	53
Total Inputs	**14.9**	**100**	**16.57**	**100**
Shetland Creek	11.8	79	13.79	83
Evapotranspiration	3.0	20	2.47	15
Groundwater Outflow	0.1	1	0.31	2
Total Outputs	**14.9**	**100**	**16.57**	**100**

Since March 2014, water levels in LTL were quantified by instantaneous visual measurements at a staff gauge immediately upstream of the WTLR culvert. These manual readings were made primarily during morning hours, at time steps ranging from daily to weekly. Data collection was begun by Gosling Czubak Engineering Sciences (2014) and sustained by the LTLPOA, and all data were obtained from the LTLPOA website (http://www.littletraverselake.org/lake-levels.html) on March 20, 2022.

Continuous stage measurements have been made at the same location by the NPS Water Resources Division and by Len Allgaier, a local resident. The NPS data were collected every 15 minutes from August 2016 to November 2017 using an automated pressure transducer (Hobo U20-L04 Water Level Logger, Onset Corp.) fastened to a fencepost in the channel bed and corrected for barometric pressure using a nearby logger fastened to a tree (Martin et al. 2016).

Factors Affecting Water Levels in Little Traverse Lake and Shalda Creek

Len Allgaier and collaborators collected stage data every 15 minutes from October 2020 to May 2022 using a bubbler line attached to the channel bed. For both continuous stage records, partial days were trimmed from the start and end of each record, and daily mean stage was calculated.

Additional stage data were collected by LTLPOA and NPS along Shalda Creek below the WTLR culvert, and above and below the CR669 crossing. Previous investigations used these data to characterize the localized effects of beaver dams on Shalda Creek stage, but they were not used in the present study since they did not provide additional information on LTL water levels or streamflow in Shalda Creek.

Lake stage measurements from each source were corrected to the NAVD 88 vertical datum using real-time kinematic GPS survey data with elevation accuracy of approximately 1 cm during November 2021. The calculated correction factors were +0.72 ft for the LTLPOA staff gage and the 2016-2017 NPS data. Note that the +0.72 feet adjustment to reference the staff gage to NAVD 88 differs from the +0.8 feet adjustment reported by Gosling Czubak Engineering Sciences (2014). A correction factor of +593.31 ft was added to the continuous stage data collected by Len Allgaier.

Water levels in LTL fluctuate considerably both within and between years (Figure 5). High water levels typically occur between late autumn and early spring, when evapotranspiration rates are negligible. During some winters, ice floe accumulation at the lake outlet may also impede drainage. The highest recorded water level (596.10 ft) occurred in late 2014, and lake levels exceeded the nuisance flooding level of 595.65 ft (Gosling Czubak Engineering Sciences 2014) at other times during 2014, 2018, and 2020. Low water levels commonly occur during the summer months, and water levels have fallen below 595.20 ft during every year in the record.

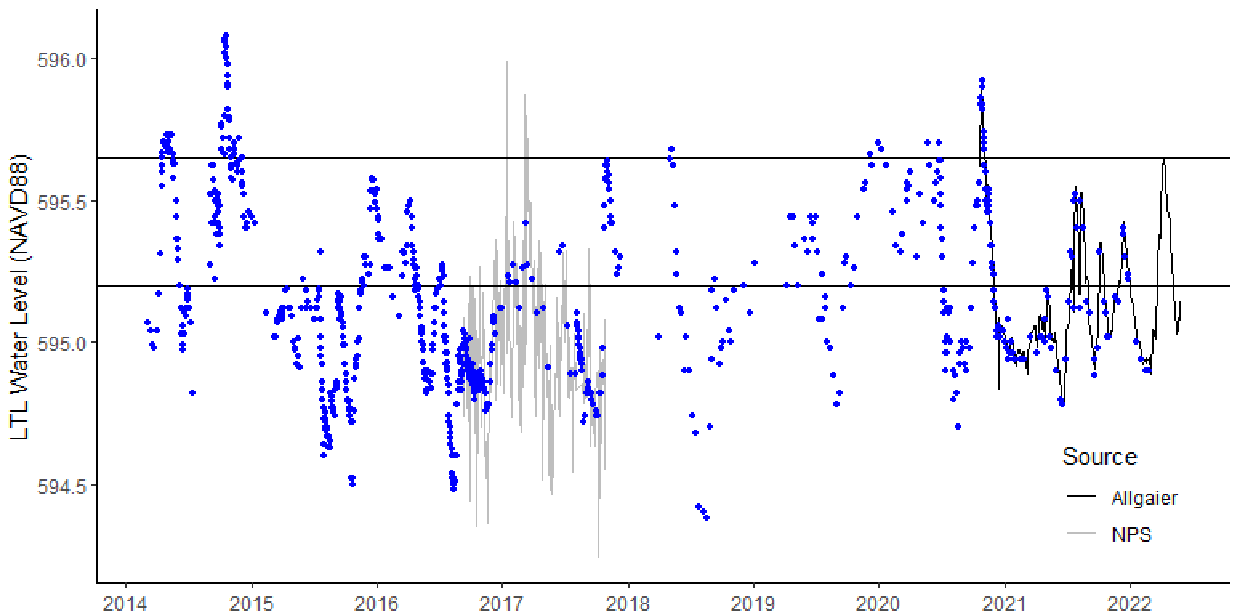

Figure 5. Water levels in Little Traverse Lake, 2014-2022. Blue dots are instantaneous measurements, while solid lines are continuous measurements. Horizontal lines indicate undesirable high (595.65 ft) and low (595.20 ft) water levels, as identified by Gosling Czubak Engineering Sciences (2014).

Factors Affecting Water Levels in Little Traverse Lake and Shalda Creek

Figure 5 shows that continuous water level data collected by the NPS logger during 2016-2017 (Martin et al. 2016) contained significantly larger diurnal fluctuations than the data from Len Allgaier. Diurnal fluctuations in the NPS data averaged 0.27 ft and ranged from 0.06 to 2.08 ft, compared to an average of 0.07 ft and a range of 0.01 to 0.84 ft for the data from Allgaier. The higher level of 'noise' in the NPS data is probably due to issues with sensor quality or calibration with the logger deployed upstream of WTLR since similar issues were not apparent for the downstream NPS loggers that were excluded from this analysis. Summary statistics for the available data sets are shown in Table 6, which indicates that the average water level from each source is at or below the nuisance low water level of 595.20 ft (Gosling Czubak Engineering Sciences 2014).

Table 6. Water level data for Little Traverse Lake (feet; NAVD 88). Data from LTLPOA are instantaneous observations from each day, while those from NPS and Allgaier are daily means calculated from continuous data.

Statistic	LTLPOA	NPS	Allgaier
Start Date	03/07/2014	08/31/2016	10/22/2020
End Date	02/25/2022	11/03/2017	05/26/2022
Average	595.20	595.00	595.10
Median	595.10	595.00	595.10
Minimum	594.40	594.20	594.80
Maximum	596.10	596.00	595.90
Observations	834	430	582

The greater variability in the NPS data (Figure 5 and Table 6) is reflected in the daily mean water level values, as demonstrated in the comparatively poor agreement with LTLPOA instantaneous data (Figure 6). For the subset of days where both instantaneous and continuous measurements were available, the instantaneous measurements explained only about 24 % of the variability in mean daily water levels from the NPS data ($p < 0.001$) with a residual standard error 0.18 ft (n = 146 days). For comparison, the instantaneous measurements explained 98 % of the variability in mean daily water levels from the Allgaier data ($p < 0.001$) with a much smaller residual standard error of 0.04 ft (n = 99 days).

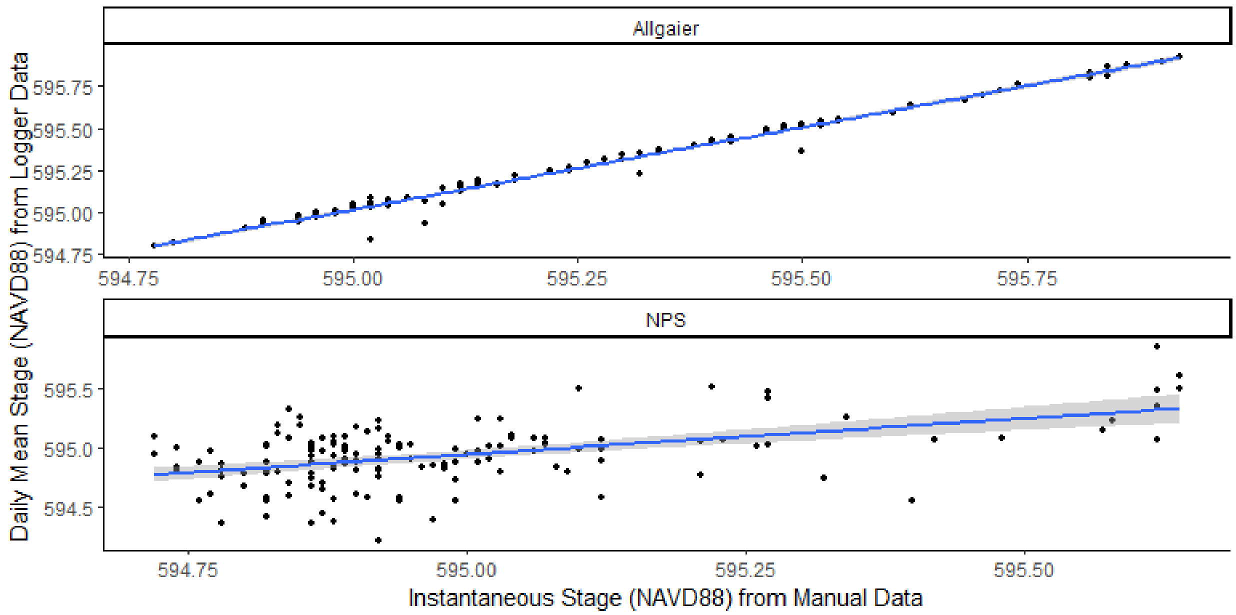

Figure 6. Relationship between instantaneous stage measurements and daily mean water levels on Little Traverse Lake.

Cumulative frequency curves for each data set demonstrate that water levels greater than or equal to 595.65 ft have occurred infrequently since 2014 (Figure 7). Nuisance flooding occurred in 8.5 % of the periodic observations by LTLPOA (March 2014 to February 2022), and only on 2.2 % of days in the continuous Allgaier data (October 2020 to May 2022) and 2.6 % of days in the continuous NPS data (August 2016 to November 2017). In contrast, the frequency of water levels less than or equal to 595.20 ft ranged from 61.0 % of the LTLPOA data to 82.6 % of the NPS data. These data demonstrate that periods of undesirable high water are rare, while undesirable low water levels are rather common throughout all records.

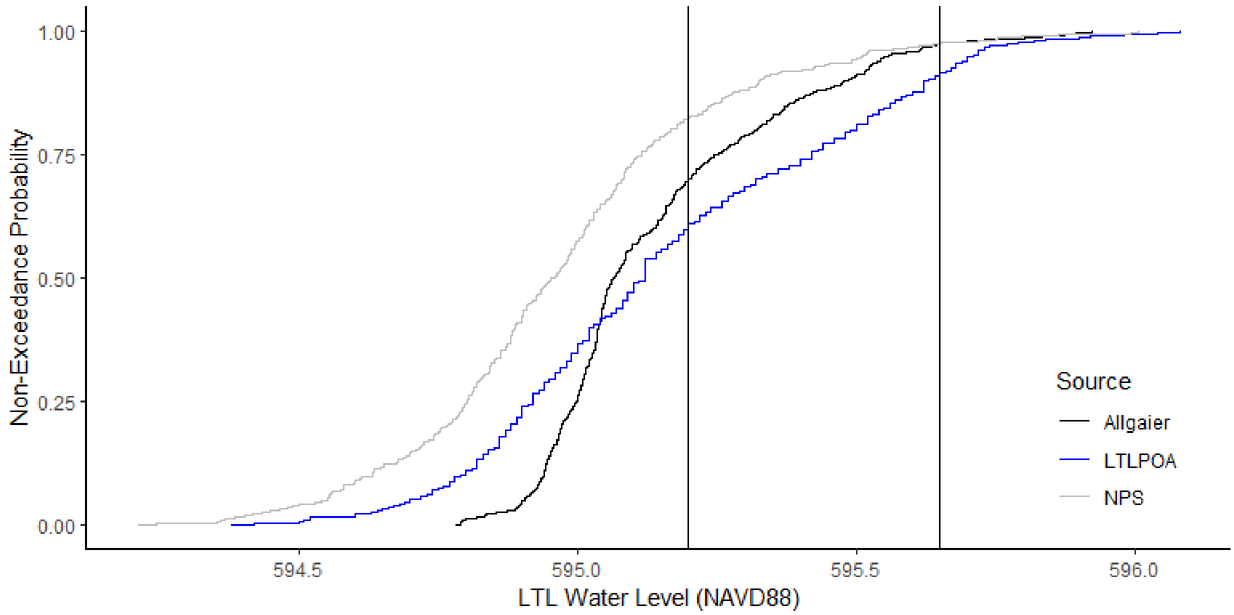

Figure 7. Cumulative water level frequency curves for Little Traverse Lake. The black vertical reference lines indicate undesirable low water levels (left, 595.20 ft) and nuisance flooding levels (right, 595.65 ft).

In summary, water level fluctuations in LTL are driven primarily by variations in streamflow into the lake from Shetland Creek and outflows via Shalda Creek. Although numerous seeps and springs occur along the shoreline, existing reports suggest that groundwater contributions to water level fluctuations are small, while the results presented in Section 4.2 indicate that groundwater contributions to LTL water levels and discharge to Shalda Creek are significantly greater. Periods of high water levels typically occur between late autumn and early spring. Low water levels occur during any time of year but are most common during the summer months. Nuisance flooding at lake levels greater than or equal to 595.65 ft are rare, especially since 2016. In contrast, undesirable low water levels of 595.20 ft or less are common and have occurred during more than half of all observations.

4.2. Shalda Creek

Periodic discharge measurements were made on Shalda Creek at WTLR (n = 70) and Shetland Creek at M-22 (n = 84) during 1992-2021 by the Leelanau Conservancy (2022), and during the present study on 10 November 2021. Both data sets were calculated from velocities measured at 0.6 depth along equal width increments (Rantz 1982), using a SonTek FlowTracker acoustic doppler velocimeter. Additional discharge measurements were made at downstream locations along Shalda Creek during this study, and previously by Handy and Stark (1984) and Boyle and Hoefs (1993), but these data were not used in the analyses.

Considering only years for which at least three measurements were available (n = 13), mean annual discharge on Shalda Creek at WTLR during 1992 to 2021 ranged from 11.2 ± 1.7 (mean ± standard error) to 25.4 ± 3.3 cfs (Table 7), and averaged 18.5 ± 1.1 cfs. This is consistent with the results of Handy and Stark (1984), who estimated mean annual discharge to be about 20 cfs based on less extensive data. Mean annual discharge on Shetland Creek at M-22 during the same period (n = 17) ranged from 7.1 ± 1.4 cfs to 20.9 ± 3.6 cfs (Table 8) and averaged 13.7 ± 0.7 cfs. Caution is warranted in interpreting interannual streamflow dynamics from these limited data.

Table 7. Annual discharge on Shalda Creek measured at West Traverse Lake Road.

Year	Observations	Mean	Std. Error	Minimum	Maximum
1992	5	19.5	3.3	9.3	25.8
1993	6	20.9	0.8	18.4	23.9
1994	6	19.8	2.4	12.0	27.3
1995	5	16.4	1.6	12.4	20.2
1996	6	19.2	2.5	10.5	28.5
1999	3	11.2	1.7	8.2	14.0
2000	5	11.8	1.9	6.0	16.3
2015	5	19.6	2.3	11.5	24.6
2016	3	19.6	2.9	13.8	23.0
2017	3	21.7	4.8	15.3	31.1
2018	5	14.4	4.2	3.5	23.9
2019	6	20.4	3.3	9.0	31.4
2021	7	25.4	3.3	15.6	42.6

Table 8. Annual discharge on Shetland Creek measured at M-22.

Year	Observations	Mean	Std. Error	Minimum	Maximum
1992	5	13.9	2.2	7.6	19.9
1993	6	17.4	2.3	12.8	27.4
1994	5	12.8	1.4	10.0	17.9
1995	4	11.1	0.9	9.5	12.8
1996	6	13.6	2.1	7.5	22.7
1999	3	14.8	6.1	7.0	26.7
2000	5	7.1	1.4	3.9	10.7
2006	4	14.6	5.0	7.2	29.1
2012	4	14.1	4.4	3.5	22.0
2013	3	13.7	3.9	5.9	17.7
2014	3	11.0	6.2	4.4	23.4
2015	5	10.9	3.1	4.7	22.5
2016	3	13.7	1.9	11.0	17.4
2017	3	14.7	3.0	8.8	18.1
2018	5	14.4	3.0	8.3	25.8
2019	6	16.7	1.7	12.8	21.9
2021	7	20.9	3.6	10.6	39.0

The discharge measurements on Shalda Creek and Shetland Creek during 1992-2021 depict stable streamflow regimes on both creeks, and modest seasonal variability for LTL inputs and outputs (Figure 8). Shalda Creek streamflow typically peaks during May, while inflows from

Shetland Creek are highest during May and June (Boyle and Hoefs 1993). Mean monthly discharge is lowest during August on Shalda Creek, and during July on Shetland Creek. Mean discharge during all months and mean annual discharge during all years except 2018 (Tables 7 and 8) is higher on Shalda Creek, suggesting that groundwater inputs to LTL are a significant portion of the lake water budget (Handy and Stark 1984, Steinberg et al. 1994, Holtschlag and Nicholas 1998, Vana-Miller 2002, Neff et al. 2005). The seasonal stability of streamflow within the study area is consistent with observations throughout the region (Holtschlag and Nicholas 1998, Vana-Miller 2002, Neff et al. 2005).

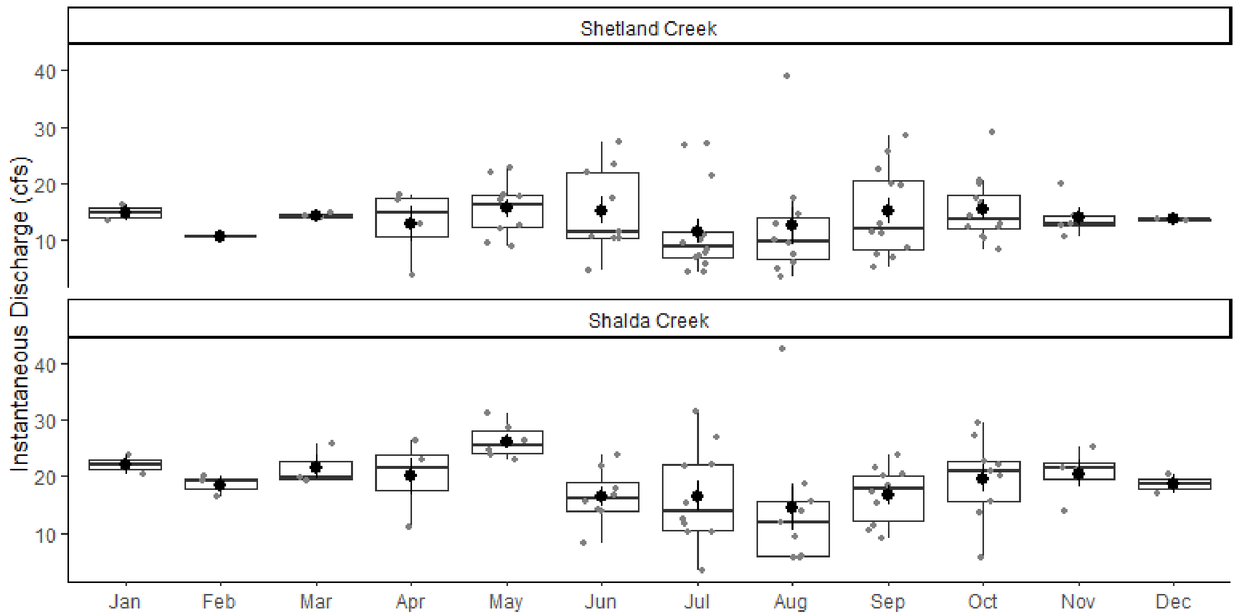

Figure 8. Monthly instantaneous streamflow measurements on Shalda Creek at West Traverse Lake Road and Shetland Creek at M-22, 1992-2021. Grey jittered dots are individual measurements, and black dots with error bars are mean ± standard error. Boxplot centerlines are medians, shoulders are 25^{th} and 75^{th} percentiles, and box whiskers are 5^{th} and 95^{th} percentiles.

The difference between streamflow inputs and outputs on each sampling date suggest that mean monthly net groundwater additions to LTL range from 3.3 ± 0.0 to 7.3 ± 0.3 cfs during the cool season (October to April), and average 10.5 ± 1.3 cfs during May, when Shalda Creek discharge is highest (Figure 9). This indicates that net groundwater discharge to the lake is substantially larger than the 3.1 to 3.3 cfs reported in the existing water budgets (Table 4). Streamflow differences are highly variable during June-October, likely signifying reductions in seasonal groundwater discharge and the increasing importance of streamflow inputs from Shetland Creek.

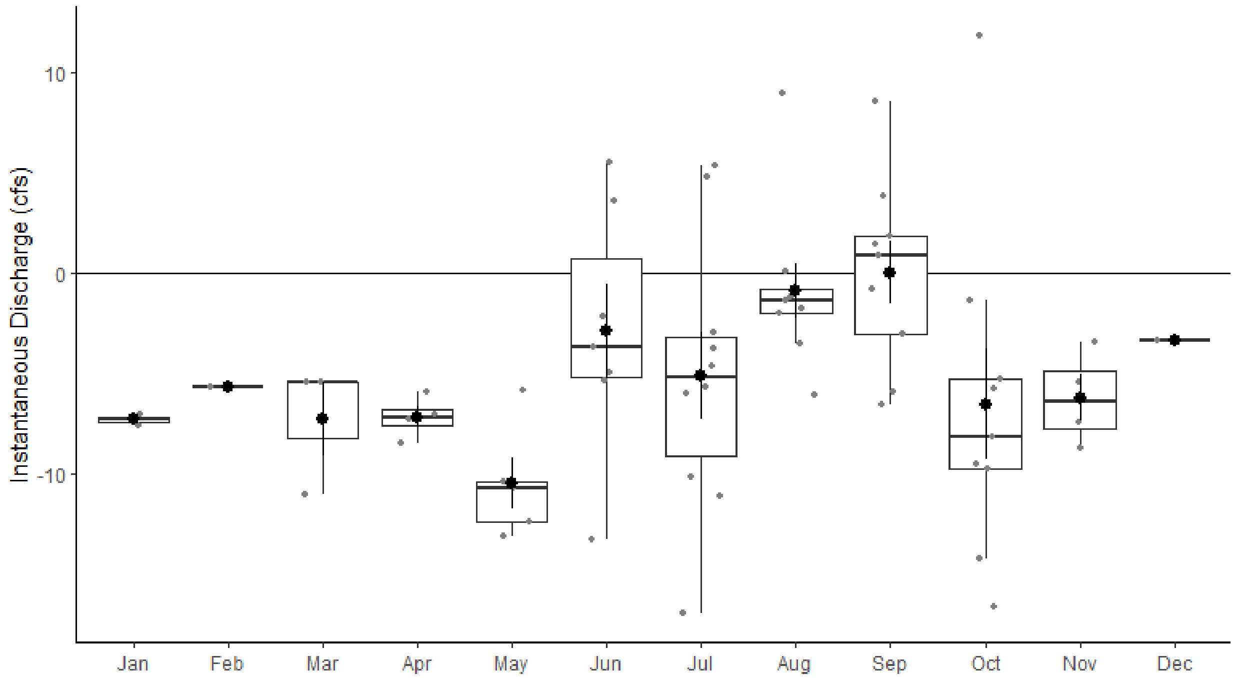

Figure 9. Monthly difference in instantaneous streamflow between LTL inflow (Shetland Creek) and outflow (Shalda Creek). Negative values represent outflows larger than inflows. Grey jittered dots are individual measurements, and black dots with error bars are mean ± standard error. Boxplot centerlines are medians, shoulders are 25th and 75th percentiles, and box whiskers are 5th and 95th percentiles.

In summary, streamflow in Shalda Creek is generally stable within and between years, and mean annual discharge based on periodic measurements is about 18.5 cfs. While discharge from Shetland Creek routed through LTL is the primary source, the available data indicate that groundwater discharge to LTL comprises a significant portion of Shalda Creek streamflow and ranges from 3.3 to 7.3 cfs during the cool season, when calculations are less confounded by evapotranspiration. Streamflow is typically highest during May, and this appears to be heavily influenced by groundwater discharge to LTL, which averages 10.5 cfs. Streamflow declines through the summer, when inputs from Shetland Creek become more important than those from groundwater.

5. Water Level Recession Analyses

Recession analysis was performed using daily mean stage heights (Jones and McGilchrist 1978, Jachens et al. 2020) and the commonly used expression $dH/dt = -aH^b$, where dH/dt is the change in daily mean stage over two consecutive days, H is the average of daily mean stage over the same two consecutive days, and *a* and *b* are fitted parameters. This power law function was linearized as $\log_{10}(-dH/dt) = \log_{10}(a) + b \times \log_{10}(H)$ following Brutsaert and Nieber (1977), and *a* and *b* were obtained by ordinary least squares fitting of the resulting point clouds (Vogel and Kroll 1992). The fitted parameter *a* (intercept in linearized form) is a function of varying hydraulic and hydrologic conditions that affect drainage rates (Bart and Tague 2017, Tashie et al. 2020b). The fitted parameter *b* (slope in linearized form) corresponds to watershed-specific structural properties (Stoelzle et al. 2013,Tashie et al. 2020a, 2020b). Changes in *a* were tested to assess the effects of beaver dams.

Recession segments were defined as periods of consecutive declines in daily mean stage following each peak (Lamb and Beven 1997, Stoelzle et al. 2013,Tashie et al. 2020a). Mean daily stage in LTL decreased on 218 of the 430 days in the 2016-2017 NPS data, comprising 98 discrete recession segments. Segment lengths ranged from 1 to 6 days, with a mean length of 2.2 days and median length of 2 days. Stage declined on 377 of the 582 days in the Allgaeir data and comprised 63 discrete recession segments that averaged 6 days and ranged up to 26 days. The smaller mean and median recession segment lengths in the NPS data appear to be an artefact of the greater diurnal variability in these records, rather than actual differences in water level fluctuations between the two periods.

Each recession segment was classified according to the inferred presence or absence of beaver dams based on the recorded dam removal activities shown in Table 1. Since the actual timing and location of beaver dam occurrences along Shalda Creek are unknown, several assumptions were required to classify recession segments: (1) dams were detected and removed as soon as possible outside of winter months; and (2) dams were rebuilt within two weeks at sites with frequent removals. Following these criteria, it was assumed that 88 recession events from the NPS data during September 2-October 14, 2016 and June 30-October 2, 2017 were not affected by dams, while 130 events during the intervening period reflected the influence of beaver dams. For the Allgaier data, beaver dams were assumed to be absent during 199 events between December 22, 2020 and April 28, 2021 as well as January 6 to May 23, 2022, while dams affected the other 178 events.

Recession analysis indicates differences in LTL drainage rates between the NPS data collected during 2016-2017 and the Allgaier data collected during 2020-2022 (Figure 10). Fitted intercepts (*a*) were higher ($p < 0.001$) and slopes (*b*) were lower ($p < 0.001$) during 2016-2017 regardless of beaver dam presence, as shown by the higher but flatter regression lines. These patterns suggest that water levels in LTL declined after storm events faster during 2016-2017, compared to 2020-2022. It is possible that these differences are due in part to the larger diurnal variability in the noisier 2016-2017 data, where more frequent recession events produced shorter recession lengths and larger decline rates. These patterns could also be a result of changes in channel hydraulics due to aquatic vegetation growth, debris accumulations along Shalda Creek not related to beaver dams, changes associated with the replacement of the CR669 culvert, or the presence of undocumented beaver dams during periods when they were assumed to be absent.

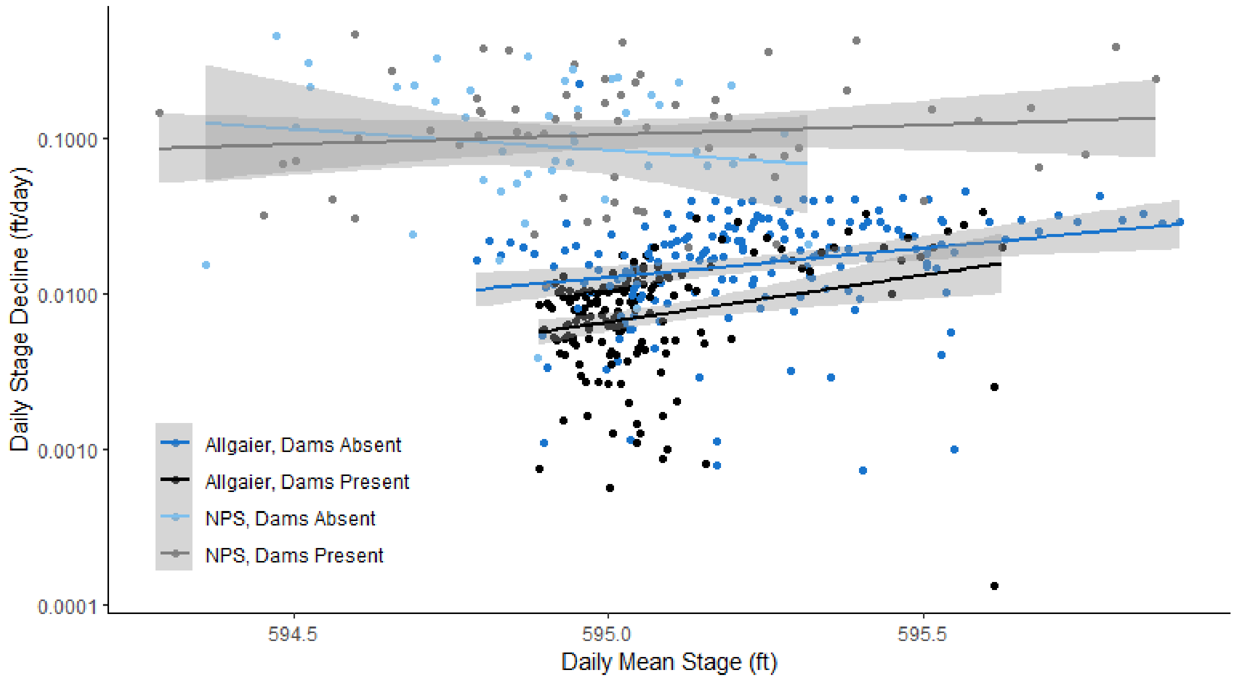

Figure 10. Effect of beaver dams on water level recession curves during 2016-2017 (NPS data) and 2020-2022 (Allgaier data).

For the 2016-2017 NPS data, a higher intercept was obtained when beaver dams were assumed to be absent ($p < 0.001$), suggesting that LTL water levels declined after storm events faster without beaver dams (Figure 10). The recession slopes (*b*) during 2016-2017 did not differ ($p = 0.14$), as illustrated by the overlapping regression confidence intervals (grey bands in Figure 10), indicating that the effect of water level on decline rates did not vary with beaver dam presence.

The 2020-2022 Allgaier data exhibited similar patterns, with significantly different intercepts (*a*; $p < 0.001$) but indistinguishable slopes (*b*; $p = 0.45$) for periods with and without beaver dams (Figure 10). These data show clearer patterns with parallel but separate fitted regression lines, suggesting that water levels declined at slightly lower rates when beaver dams were present, but beaver dams did not change the relationship between water level and decline rate.

In summary, recession analysis indicates that the presence of beaver dams on Shalda Creek reduces the rate of water level declines in LTL after storm events but has no discernable effect on how decline rate changes with water level during each time period. Regardless of beaver dam presence, overall rates of water level decline were higher during 2016-2017 but were less sensitive to LTL water levels, compared to 2020-2022. These patterns could be a result of changes in channel hydraulics due to aquatic vegetation growth, debris accumulations along Shalda Creek not related to beaver dams, or changes associated with the replacement of the CR669 culvert. However, these results could also include artefacts from the noisier NPS data used to characterize 2016-2017 conditions, or the presence of undocumented beaver dams during periods when they were assumed to be absent. During both time periods, beaver dams were associated with lower rates of water level declines in LTL but did not produce measurable changes in the relationship between water levels and decline rates within each period.

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