The Lampreys of the Grass Valley Drainage:

Distribution and Passage Barriers, 2016

including an Assessment of Buckhorn Dam as a barrier to Pacific Lamprey

Submitted under Contract: Grass Valley Creek Anadromous Pacific Lamprey: sediment management and connectivity (Trinity River Resource Conservation District / funding Trinity River Restoration Program), 30 August 2017.

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Introduction

Grass Valley Creek is the first large tributary entering the Trinity River below Lewiston Dam from the south (Figure 1). It drains a region characterized by decomposing granite soils, resulting in a naturally high sand component to the bedload. The drainage has been the focus of projects intended to reduce sand inputs to the mainstem Trinity River (Gaeuman 2010). These include, Buckhorn Reservoir (constructed 1990), the two instream Hamilton Ponds near the mouth (constructed 1988-89) and extensive revegetation and soil stabilization efforts in the upper watershed.

The Trinity Basin is home to three species of native lamprey: the large, migratory anadromous Pacific Lamprey, *Entosphenus tridentatus*; the Pit-Klamath Brook Lamprey, *E. lethophagus*, a resident non-parasitic species (identified in this study); and the Klamath River Lamprey, *E. similis*, a resident parasitic species. The Pacific Lamprey is of particular conservation concern in the Klamath Basin, where it is of traditional importance to local Native American cultures (Petersen-Lewis 2009, Goodman and Reid 2012, 2015). The other two species are each endemic to the Klamath Basin. A primary concern is loss of access to historical habitat due to passage barriers such as dams, road crossings and unsuitable fishways (Goodman and Reid 2012, Moyle et al. 2015).

The goals of this project are to:

1) Distribution: determine the distribution of lampreys in the Grass Valley drainage,
2) Passage Barriers: assess potential passage barriers on Grass Valley and Little Grass Valley,
3) Buckhorn Dam: assess passage issues at Buckhorn Dam, and
4) Hamilton Ponds: evaluate habitat use by larval lampreys (ammocoetes) in the Hamilton Ponds, in order to minimize impacts during management operations (sediment removal).

This report addresses distribution and passage assessments, including Buckhorn Dam. A separate report focuses on distribution and habitat use by ammocoetes in the Hamilton Ponds (Reid and Goodman 2017).

DISTRIBUTION

Methods: Surveys utilized standard methods established by extensive field surveys for lamprey ammocoetes in western North America by Reid and Goodman (Reid and Goodman 2015). Presence/absence were carried out by the author using a Badger ABP-2 (ETS Electrofishing). This equipment is specifically designed for lamprey ammocoetes (larvae, 10-18 cm TL; Figure 1). It uses a weak, slow-pulse electrical current to draw ammocoetes out of the sediment, targeting shallow areas of fine sediment and sands and avoiding impacts to other fishes. Settings were: Rate S - 3.00, Duty S - 25.0, Voltage 150-250. Due to the typical dispersion of ammocoetes in suitable habitat (oxic fines and sands), survey of a single suitable site results in a detection probability of > 90% when ammocoetes when present upstream, increasing to > 95% with three sites (Reid and Goodman 2015).

Figure 1. Lamprey ammocoetes (larvae).

Identification of the three congeneric species (Pacific, Pit-Klamath Brook and Klamath River lamprey) is possible with transformed or adult specimens, but is difficult with ammocoetes (Bond and Kan 1975, Lorion et al 2000, Reid 2014, Reid and Goodman unpublished data). The principal distinguishing character for congeneric ammocoetes is generally muscle segments (myomere) counts (Reid et al. 2014). Pacific and Pit-Klamath Brook lampreys have similar counts (65-72 and 63-71, respectively), while Klamath River Lampreys generally have lower counts than the other two species (60-65). Voucher specimens were collected and will be deposited at Humboldt State University's fish collection.

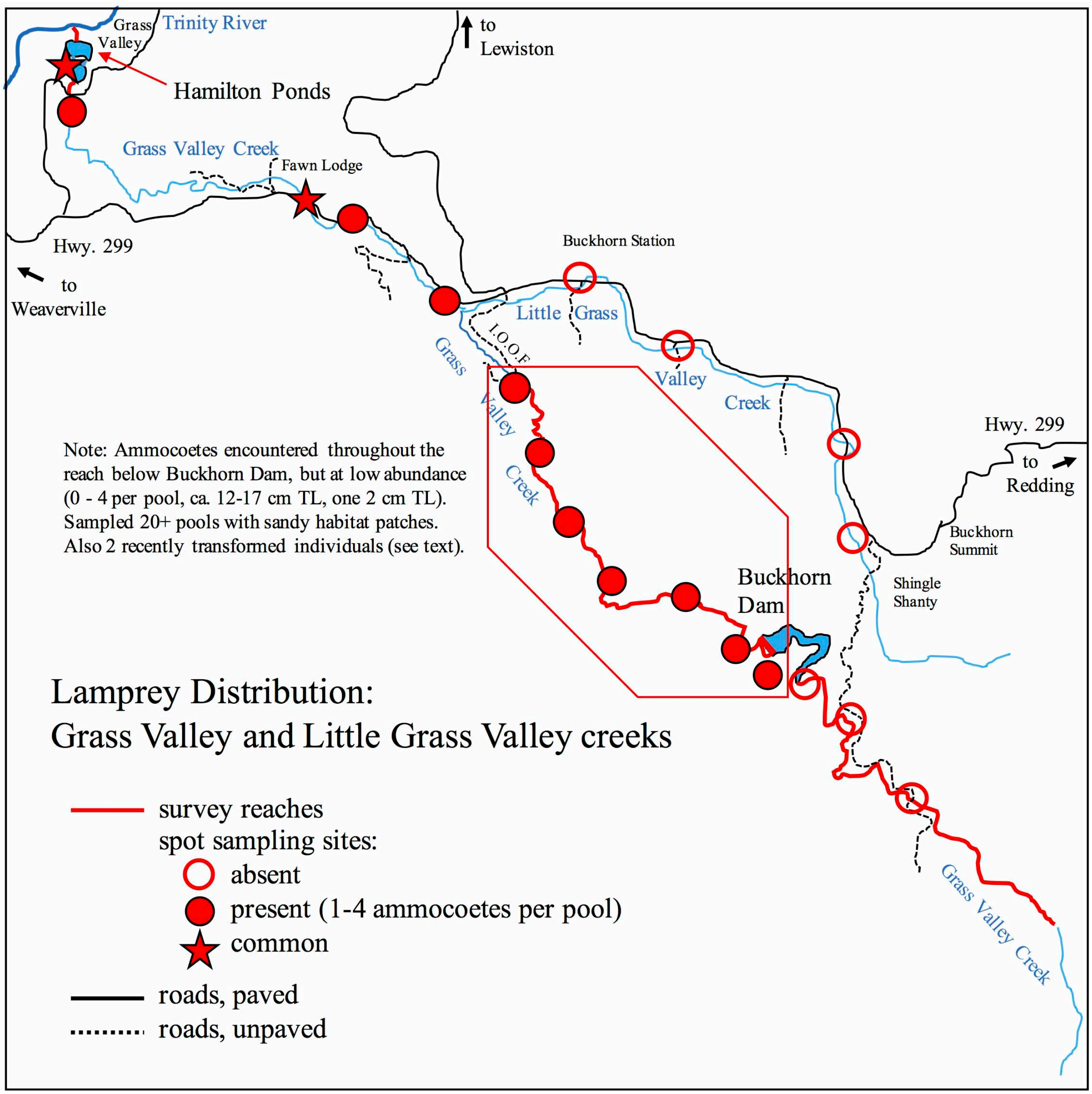

Figure 2. Distribution surveys and presence of ammocoetes in Grass Valley and Little Grass Valley creeks, 2016. At the two sites where ammocoetes were "common", abundances were well over 100.

Results: Mainstem reaches of Grass Valley Creek with public access or landowner permission were walked by the author (Figure 2; September-October 2016). Downstream of Buckhorn Dam walking surveys included sampling in all patches of suitable habitat (sand patches and areas of organic deposition; 20 + pools). Additional spot surveys were made at all public road crossings. Upstream of Buckhorn Reservoir, three surveys each sampled ca. 100 m of stream reaches containing suitable habitat. Extended upstream surveys assessed similar habitat, with declining abundance of fines. Little Grass Valley Creek was surveyed at each public crossing.

In Grass Valley Creek, ammocoetes were encountered from the mouth up to Buckhorn Dam, including the habitat restoration site below the outlet pipe. However, they were only common (over 100 observed) at two sites: Hamilton Ponds and the Hwy. 299 bridge just upstream of Fawn Lodge Road, with a full range of size classes present (2-17 cm TL). Further upstream, ammocoetes were encountered at very low abundance (0-4 per pool) from the confluence with Little Grass Valley upstream to the dam. Only 34 ammocoetes and two transformed juveniles were observed from the IOOF bridge crossing upstream to Buckhorn Dam (6.7 km). This entire reach was surveyed and all suitable sandy habitat was sampled. Nearly all ammocoetes in the reach were relatively large (33:12-17 cm TL); a single 2 cm specimen was seen 1.5 km downstream of the dam. No lampreys were encountered above Buckhorn Dam.

In Little Grass Valley Creek, no lampreys were encountered above the I.O.O.F. entry, a large perched culvert (see Passage). The 600 m reach downstream of the culvert to the confluence with Grass Valley Creek was not accessible for sampling (private), however it appeared to contain little suitable habitat. Only one large ammocoete and a recently transformed juvenile were encountered in the pool at the confluence of Grass Valley and Little Valley creeks, which contained one ca. 20 m^2 patch of sand.

Transformed juveniles (n=8) were occasionally encountered in Grass Valley Creek from the Fawn Lodge Highway 299 bridge upstream to Buckhorn Dam. All are identified as Pit-Klamath Brook Lampreys, *Entosphenus lethophagus*, a species not previously recorded from the Trinity Basin (Figure 3). These specimens and genetic samples have been included in an ongoing review of geographic variability in the species (Reid, Goodman and Docker in prep.). No juvenile or adult Klamath River Lamprey or Pacific Lamprey were observed.

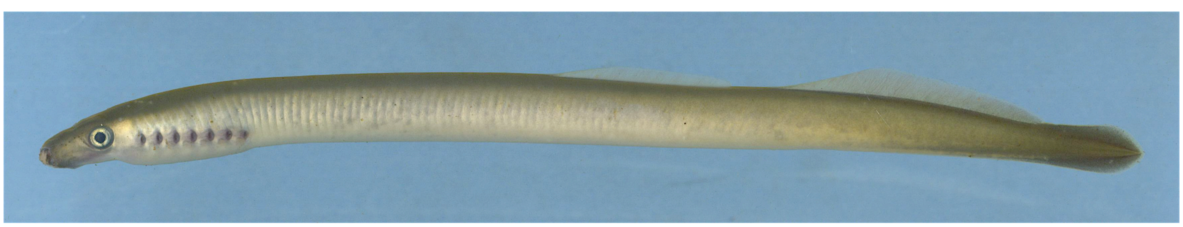

Figure 3. Pit-Klamath Brook Lamprey, *Entosphenus lethophagus*, recently transformed, from Grass Valley Creek, September 2017.

Most lamprey encountered were ammocoetes and could not be identified positively to species. However, the range of myomere counts (63-71, median 68, n=30; Figure 4) in ammocoetes collected from sites above Hamilton Ponds conforms with either Pacific or Pit-Klamath Brook and suggests that no substantial population of Klamath River Lampreys (60-65) was present.

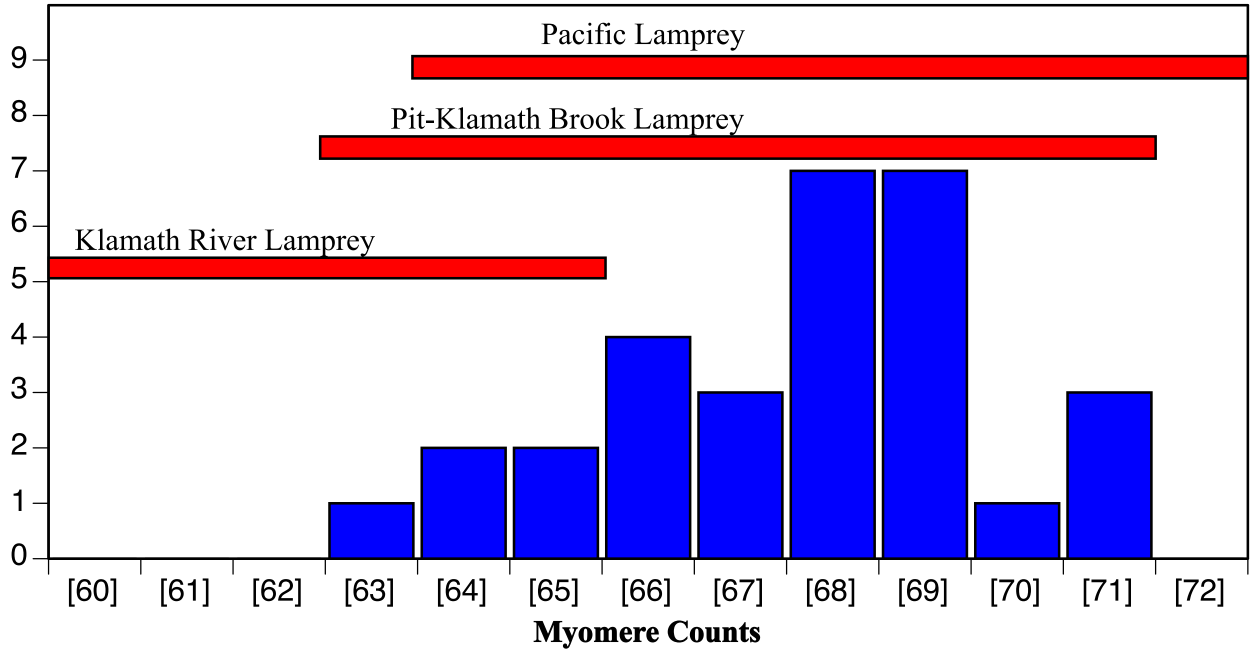

Figure 4. Myomere counts for ammocoetes collected from Grass Valley Creek (n=30). Typical ranges for the three Trinity Basin species are show as bars (Bond and Kan 1975, Lorion et al 2000, Reid 2014, Reid and Goodman unpublished data).

Discussion: Ammocoete abundance in Grass Valley Creek was notably low, generally 0-4 per pool, except at the Fawn Lodge Highway 299 bridge (Figure 5) and in the Hamilton Ponds. Above the Highway 299 bridge they also exhibited a truncated size-distribution, with only a single individual below 12 cm TL. The ammocoetes phase is typically 5-7 years long, and a 12 cm ammocoete is approximately four years old (Beamish and Medland 1988, Meeuwig and Bayer 2005, Reid unpub. data).

Explanations for the low abundance of ammocoetes are uncertain. They may include the generally higher gradient, rocky character of the stream, relatively limited rearing habitat, or high transport rates for fines. Habitat throughout the reaches below Buckhorn Dam is generally moderate gradient with larger substrates. Pool habitat is dispersed with often only small patches of sand suitable for ammocoete rearing, although some pools had as much as ~ 50 m^2 sand and still contained few ammocoetes. The restored reach immediately below the Buckhorn outlet also contained extensive low energy depositional habitat and beds of aquatic vegetation suitable for rearing. However, there is limited spawning habitat (open gravel and small cobble) available for Pacific Lamprey at the base of the dam. The local population of resident brook lampreys, which can spawn in smaller gravels and habitat patches, may not have recovered from disruption of habitat during construction (2012) and is also lacking an upstream source for recolonization. Fish surveys of Grass Valley Creek in 1984 reported that lamprey ammocoetes were common throughout the drainage, although the project focused on salmonids (USFWS 1984). The project included fish abundance surveys up to the future site of Buckhorn Dam and to Shanty Town on Little Grass Valley, as well as reconnaissance presence/absence surveys well above present Buckhorn Reservoir. Due to the minor attention paid to lampreys in this period, it is unclear whether ammocoetes were actually present at all the highest sites in the upper watershed, and there was no information on the species encountered; however, they were clearly more abundant than encountered in 2016.

The truncated size range above Highway 299 also suggests the possibility that conditions have changed just within the last four years. The 2016 surveys followed five years of seasonally low flows (Figure 5). Another possible factor is the apparent shift to summer dam releases through the outflow pipe, rather than over the surface spillway, initiated ca. 2012 (see Buckhorn Dam: Figure 20). Both Pacific and Pit-Klamath Brook lampreys frequently occupy cool-water streams. However, lower or more consistent temperatures in the summer outflow water may play a role, either by cooling the stream excessively or confusing seasonal environmental cues.

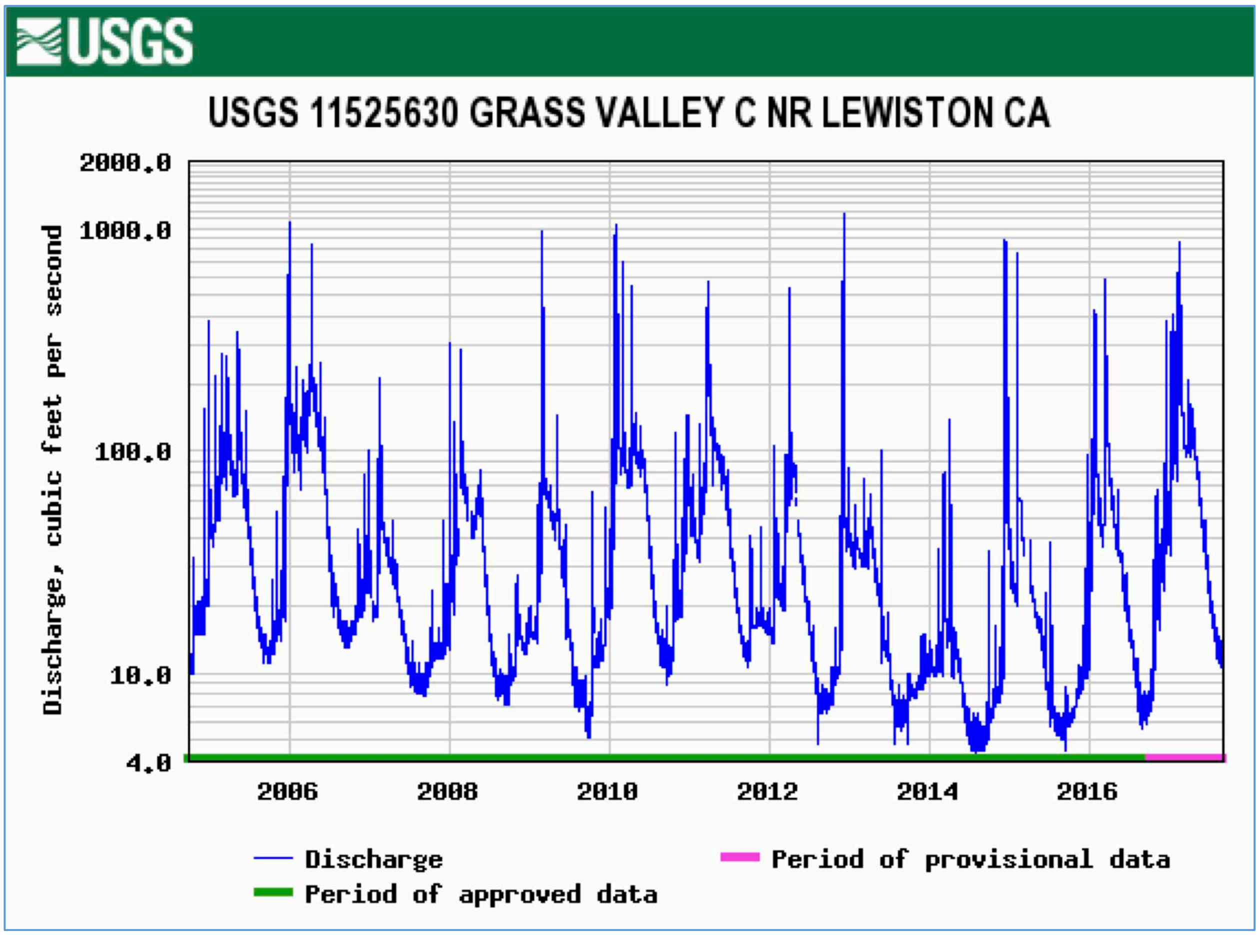

Figure 5. Grass Valley Creek, flow record January 2005 thru August 2017 (USGS Gauge 11525630; at Lewiston Road, just above ponds; 40.68618° N 122.86130° W).

Figure 6. Ammocoete habitat at the Fawn Lodge Highway 299 bridge. This was the only site above Hamilton Ponds with > 4 ammocoetes encountered in a pool. At least 100 ammocoetes and five juveniles were observed here. Note low gradient, open sands, silt and leaf litter.

There is no physical passage barrier preventing Pacific Lamprey from accessing all of Grass Valley Creek up to Buckhorn Dam (see Passage). Nevertheless, the 2016 surveys suggest that Pacific Lamprey are not currently making extensive use of Grass Valley Creek above Grass Valley itself. Ammocoetes sampled during the surveys could not be positively differentiated to Pacific or Pit-Klamath brook lampreys, due to overlap in myomere counts (65-72 and 63-71, respectively). However, the low abundance of ammocoetes upstream of the ponds, as well as the relatively common presence of metamorphosed brook lampreys and absence of Pacific Lamprey macropthalmia suggest that many, if not all, lampreys encountered upstream of Hamilton Ponds were Pit-Klamath Brook lampreys. A single female Pacific Lamprey (~ 60 cm TL) produces from 98,000-238,400 eggs; in contrast a female Pit-Klamath Brook Lamprey (~ 15 cm) produces about 1,000 eggs (Kan 1975), suggesting that, barring a major ammocoete mortality event, abundances would be much higher if the larger anadromous species spawning in the middle reaches of the creek. However, Pacific Lamprey may be spawning in suitable spawning habitat just upstream of the ponds in low gradient reaches of Grass Valley itself, above the ponds. Larvae would be carried downstream into the abundant rearing habitat available in the ponds themselves, where ammocoetes of all sizes were common (see Hamilton Ponds habitat report).

Incidental observation of hundreds of young-of-year ammocoetes (15-20 mm) near the inflow to the upper pond in July 2017 (Reid pers. obs.) further support this scenario.

Presence of Klamath River Lamprey was not confirmed during the surveys. No transformed juveniles were seen during the 2016 surveys or in Hamilton Pond habitat use surveys, and the myomere counts of ammocoetes did not conform to the species (Figure 4). Although there was some overlap, it appears to be the lower tail of a higher distribution typical of the other two species. We are aware of no observations of lampreys feeding on fishes in Grass Valley Creek or the Hamilton Ponds, which would otherwise establish the presence of Klamath River Lamprey, the only species in the lower Klamath Drainage that is parasitic in freshwater. However, an apparent free-swimming adult Klamath River Lamprey was observed in the lower pond in 2008 and the species is common in the mainstem Trinity River below Lewiston Dam (D. Goodman, Pers. Obs.).

The most notable result of these surveys was the extremely low abundance of ammocoetes, of any species, including resident brook lampreys. Ammocoete observations ranged from 0-4 per pool above the mouth of Little Grass Valley Creek. Median densities of ammocoetes downstream near the mouth of upper Hamilton Pond were 13 ammocoetes per m^2 (1-45 per m^2, n=18; Reid and Goodman 2017). The availability of fine sediments for rearing in Grass Valley Creek is certainly much lower than it would have been prior to construction of Buckhorn Dam. Absence of extensive rearing habitat appears to be the primary constraint on local ammocoete populations. Considering that the drainage contains a resident population of Pit-Klamath Brook Lamprey and is available to Pacific Lamprey, both species of concern, management of the creek below Buckhorn Dam would benefit from incorporation of natural levels of fines that have been blocked by the dam.

PASSAGE BARRIERS

Methods: Passage assessments were based on field examination of physical characteristics of instream structures, including features that would facilitate or obstruct passage by upstream-migrating adult Pacific Lamprey and downstream out-migrating juveniles. Presence/absence was checked above and immediately below structures. The passage capabilities and behavior of Pacific Lamprey were based on the author's experience with lamprey passage and available literature (Keefer et al. 2010, 2011; Goodman and Reid 2017, Reid 2017, Zhu 2011).

Features considered likely to impede passage by adult lampreys included:

- overhanging (perched) culvert entries, with sharp edges and no continuous attachment surface, requiring a jumping entry to the culvert.
- discontinuous culvert exits (sharp edges or separation from channel bottom) into high velocity fields requiring a swimming exit.
- sharp corners and edges that break suction, forcing lampreys off the climbing surface or preventing reattachment (e.g. angular lips on walls or cross-channel footings).
- grates or porous surfaces that prevent suction attachment.
- high velocities without alternative routes suitable for lamprey passage or requiring extended burst-attach swimming approaching the limits of burst-attach capabilities and increasing energy expenditures.

Results: All road crossings of the mainstem Grass Valley and Little Grass Valley creeks were examined for lamprey passage issues, as were the low-head overflow structures at the Hamilton Ponds and Buckhorn Dam (Figure 7, Tables 1-2).

Grass Valley Creek itself had only two potential barriers, the outlet structures on the Hamilton Ponds and Buckhorn Dam itself (Table 1). The remaining crossings were all bridges or a natural bottom culvert. None contained in-channel components that would impede lamprey passage. Assessment of the outlet structures on the Hamilton Ponds found that they do not represent a passage barrier or even impediment. They are boulder ramps that resemble natural channel features and contain no attributes that would impede lampreys (e.g. high velocity corridors, overhanging drop structures, acute edges, perforated attachment surfaces). During high flow events there are still low-energy passages routes into the ponds along the channel edges. Buckhorn Dam is discussed separately below.

Little Grass Valley Creek contained eight potential passage barriers (upstream to downstream), each discussed below (Table 2). The drainage is completely blocked at this time by a large perched culvert 600 m upstream of the mouth. This culvert should be the priority passage project in the drainage. Surveys found no lampreys upstream of the culvert (see Distribution). Surveys downstream to the mouth were not possible due to access issues; however, only one ammocoete and one recently transformed juvenile lamprey were found in the pool at the confluence with Grass Valley Creek. Spawning and rearing habitat was available throughout the mainstem of Little Grass Valley (up to Shanty Town), though limited due to small stream size.

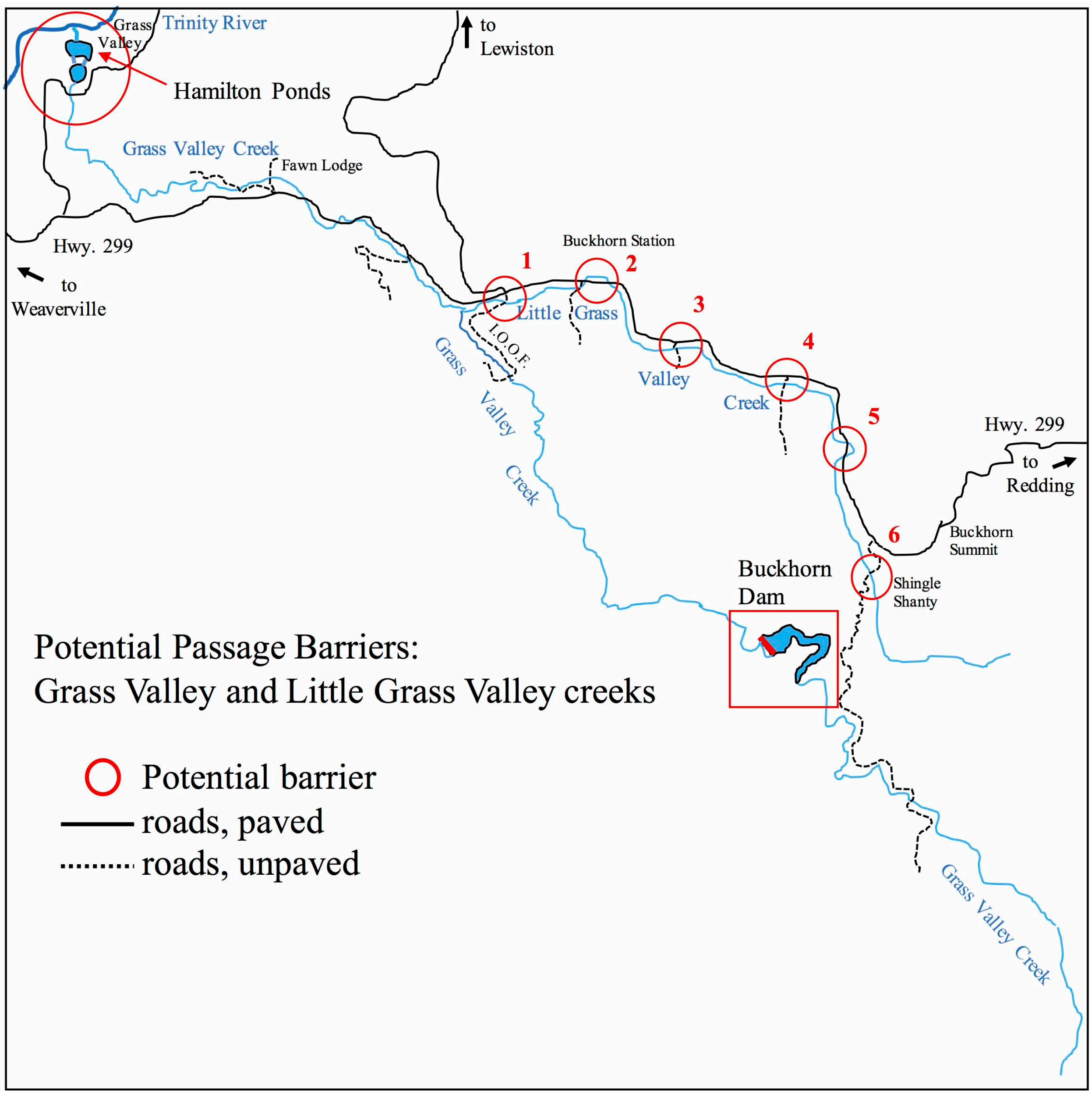

Figure 7. Potential lamprey passage barriers on Grass Velley and Little Grass Valley creeks, 2016. The remaining crossings were all bridges or a natural bottom culvert. Assessment of the outlet structures on the Hamilton Ponds found that they do not represent a passage barrier or even impediment. Buckhorn Dam is discussed separately below.

Table 1. Potential lamprey passage barriers on Grass Valley Creek mainstem (Trinity Co. California).

Site	Type	Latitude	Longitude	Elev.	Map #	Barrier
Grass Valley Creek:						
Hamilton Ponds - outflow 1	cascade	40.69087	122.85903	1,758	-	No
Hamilton Ponds - outflow 2	cascade	40.68976	122.85920	1,766	-	No
Lewiston Road	bridge	40.68659	122.86133	1,775	-	No
Fawn Lodge Road	bridge	40.67538	122.83629	2,069	-	No
Fawn Lodge Fire Station	bridge	40.67655	122.83238	2,075	-	No
Old Hwy. 299	bridge	40.67517	122.82789	2,095	-	No
Hwy. 299 @ Fawn Lodge	bridge	40.67439	122.82677	2,100	-	No
Hwy. 299, double crossing	bridge	40.67223	122.82162	2,160	-	No
Pvt. Entry w/ hairpin	bridge	40.66735	122.81153	2,237	-	No
I.O.O.F. crossing	bridge	40.62326	122.75940	2,735	-	No
Buckhorn Dam	dam	40.65430	122.79633	2,397	-	Potential
Cascade, below upper road	cascade	40.60551	122.73625	3,065	-	No
Upper road crossing - natural bottom	culvert	40.60523	122.73795	3,095	-	No

Table 2. Potential lamprey passage barriers on Little Grass Valley Creek (Trinity Co. California).

Site	Type	Latitude	Longitude	Elev.	Map #	Barrier
Little Grass Valley Creek:						
I.O.O.F. Entry - perched	culvert	40.66272	122.79717	2,408	1	Total
Hwy. 299 @ Buckhorn Station, lower	culvert	40.66492	122.78562	2,500	2a	Partial
Hwy. 299 @ Buckhorn Station, upper	culvert	40.66467	122.78222	2,545	2b	Partial
Decommissioned BLM road	culvert	40.65759	122.77158	2,602	3	No
Pvt. entry (TriL Ranch) - perched	culvert	40.65401	122.75580	2,716	4	Total
Hwy. 299, double-crossing, lower	culvert	40.64595	122.74657	2,878	5a	Total
Hwy. 299, double-crossing, upper	culvert	40.64595	122.74657	2,878	5b	Partial
Shingle Shanty, Buckhorn Dam road	culvert	40.63154	122.74304	3,039	6	Partial

Barrier #1 (Figure 8) - The I.O.O.F. entry over Little Grass Valley Creek is fully blocked by a large perched culvert (5 ft drop) 600m upstream of the confluence with Grass Valley mainstem. This is a complete barrier to passage. Remediation would require replacement with a bridge, a new culvert at/below channel elevation, or a lamprey-specific passage route.

Barrier #2 a, b (Figure 9 - Highway 299 culverts (2) at Buckhorn Station. Both have essentially submerged entries. The interior baffles, while capped by 90° angle iron, have low drops (2-4") that area easily swimmable at low flows/velocities. As flows increase, passage (burst-attach or climbing) is available either over the baffles along the smoothly rounded concrete side-walls or corrugated culvert. These culverts represent a partial passage impediment due to their length and increased effort to pass, but are not impassable and would not particularly benefit by modification, other than replacement with a fully natural bottom.

Barrier #3 (Figure 10) - The decommissioned BLM road culvert is passable either by burst-attach swimming through the flat-bottomed culvert or, more probably, by crawling underneath. The stream has fully excavated under the culvert bottom, providing unimpeded passage. This culvert is not a barrier to lamprey passage, due to the availability of a natural bottom underneath.

Barrier #4 (Figure 11) - The private entry (TriL Ranch) is a perched culvert (5 ft drop) that sticks about 1 ft out of a concrete wall. This is a complete barrier to passage. Remediation would require replacement with a bridge, a new culvert at/below channel elevation, or a lamprey-specific passage route.

Barriers #5 a, b (Figure 12) - The Highway 299 "double-crossing" culverts below Buckhorn Summit are both perched with overhanging edges and low-flow drops at their entries. The lower culvert is the greater challenge, with a 3 ft drop to stream surface; the rocks under the lip provide no access to the culvert. The upper culvert is somewhat better, with a lower drop (1 ft) and currently with a large rock that provides an attachment surface up onto the culvert lip - it is not ideal or permanent. In their current configuration the culvert pair represent a complete barrier to lampreys, since at flows high enough to submerge the entries velocities would be too high to pass upstream. Remediation of these culverts would probably require either raising the outlet pool elevation to submerge their entries, proving a smooth ramped entry or replacement with a bottom at channel elevation.

Barrier #6 (Figure 13) - Shingle Shanty crossing, Buckhorn Dam road. This culvert has a minor entry drop (3 in) that is submerged at most flows. The relatively short length (ca. 30 ft) and unobstructed corrugations represent a minor passage impediment due some increased effort to pass at higher velocities. It would not particularly benefit by modification, other than replacement with a fully natural bottom.

Figure 8. Barrier #1 (Little Grass Valley Creek, see map) - I.O.O.F. entry on lower Little Grass Valley Creek. This is a large perched culvert (5 ft drop) that blocks the drainage, 600m upstream of the confluence with Grass Valley mainstem.

Figure 9. Barriers #2 a,b - Highway 299 culverts at Buckhorn Station.
A) entry to lower culvert, B) entry to upper culvert, C) interior baffle design.

Figure 10. Barrier #3 - The decommissioned BLM road culvert is passable either by burst-attach swimming through the flat-bottomed culvert or, more probably, by crawling underneath. The stream has fully excavated under the culvert bottom, providing unimpeded passage.

Figure 11. Barrier #4 - Private entry (TriL Ranch), a perched culvert (5 ft drop) with an overhanging edge and impassable.

Figure 12. Barriers #5 a, b - Highway 299 "double-crossing" culverts below Buckhorn Summit. A) entry to lower culvert, B) entry to upper culvert.

Figure 13. Barrier #6 - Shingle Shanty crossing, Buckhorn Dam road. The relatively short culvert represents a minor passage impediment due some increased effort to pass at higher velocities. It would not particularly benefit by modification, other than replacement with a fully natural bottom.

BUCKHORN DAM

Background: Buckhorn Dam, constructed in 1991 to retain sediment forms a run-of-the-river reservoir with no irrigation or power generation (Figure 14). It's primary release route is an overflow spillway, with a secondary toe-drain outflow that releases water at the dam base. The dam is 92 ft tall and the total length of spillway is about 700 ft (including 455 ft of ramp and a 20 ft of wall; Figure 16). The long axis of the spillway crest is ~ 150 ft and ramp width is ~75 ft wide. The spillway elevation is 2803.0 ft ASL. Total elevation change is 92 ft to the lower pool.

One goal of this project was to assess the potential for Pacific Lamprey passage over Buckhorn Dam itself. The subsurface intake and release of water from the dam at the toe-drain outlet is a high velocity/high pressure barrier to lampreys and does not serve as an entry point to the reservoir. However, the ramp spillway, which carries all stream flow not diverted by the outlet pipe, offers a wetted route over the dam and into Grass Valley Creek downstream. Buckhorn Dam was visited and the overflow ramp was assessed for potential passage in September and November 2016 to evaluate overflow and dry conditions. Technical drawings were obtained from USBR (USBR 1988). Historical reservoir water levels were obtained from the USBR gauge "GVO" (http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=GVO).

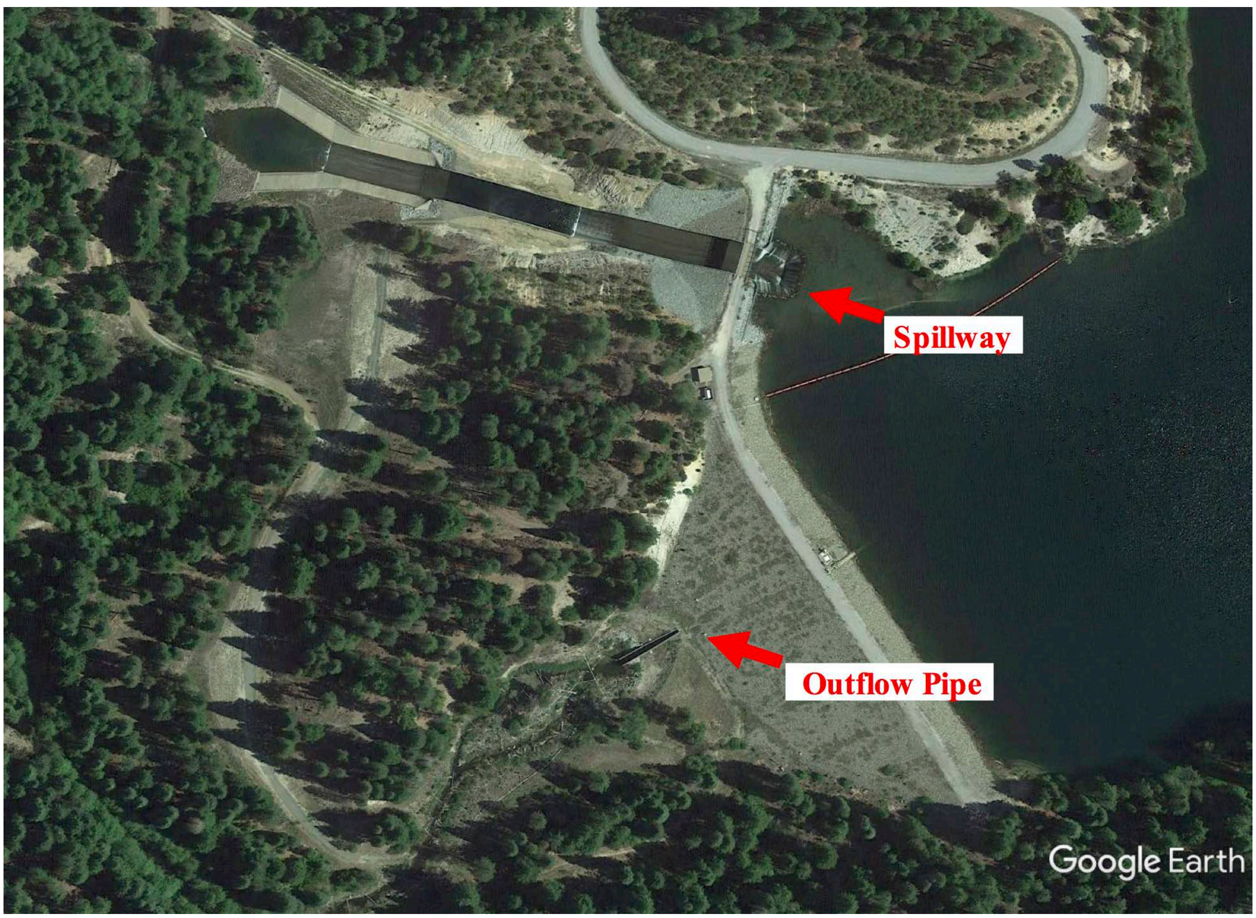

Figure 14. Buckhorn Dam, 28 May 2016. Reservoir elevation at overflow is 2803.0 ft ASL. Total dam height is 92 ft.

The anadromous Pacific Lamprey is considered the most athletic climber in the family Petromyzontiformes (Goodman and Reid 2017). They regularly ascend waterfalls, cascades and man-made obstructions, when feasible, during upstream migrations (Figure 15). They climb by means of suctorial attachment, release and reattachment, typically ascending subaerial inclined and vertical wetted surfaces with an energetically efficient dyno-climbing behavior (derived from moutaineering terminology), flexing the body in a waveform, then extending upward and reattaching by means of their sucker mouth (Zhu et al. 2011). During climbing ascents, lampreys will typically seek subaerial routes where lower velocities exist outside of primary flow, such as shallow flow or even splash zones, where they are partially or completely out of the water (Miller 2012; Petersen-Lewis 2009; Goodman and Reid 2017). In natural settings, Pacific Lamprey are able to ascend even large obstacles like waterfalls (10 m vertical or greater), a skill which provides access to a range of habitats not accessible by jumping (Reid and Goodman in-prep). However, their approach to passing obstacles requires smooth attachment points and rounded surfaces without acute angles, common in natural features, but not typically considered when designing dams or artificial fishways (Keefer et al., 2010). Current investigations on a 50 ft dam on the Eel River has demonstrated that Pacific Lamprey are capable of climbing a 270 ft variable-incline smooth pathway, including vertical reaches, over the dam in a matter of hours (Goodman and Reid 2017, Reid and Goodman in prep.).

Figure 15. Pacific Lamprey climbing a vertical concrete wall.

Assessment: In order to assess the feasibility of Pacific Lamprey climbing up the spillway, we climbed it conceptually from the standpoint of a lamprey, assessing whether any features represented a barrier, starting at Grass Valley Creek and the lower outflow pool (Figure 15, right side).

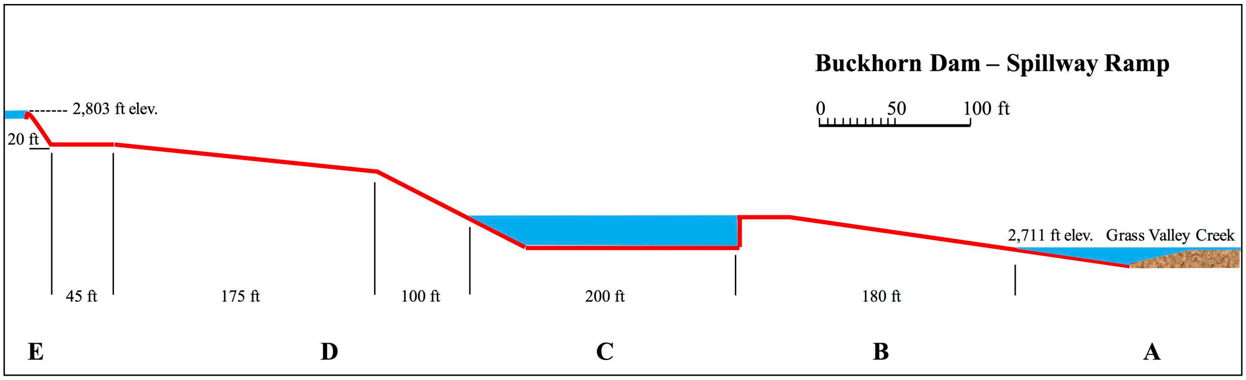

Figure 16. Buckhorn Spillway configuration (adapted from engineering drawing: USBR 1988).

A) Grass Valley Creek and the lower outflow pool (Figure 17) - Water from the spillway exits the lower pool over an armored cobble and small boulder cascade with rock features and no angular concrete edges, similar in form to a steep natural riffle. Since Buckhorn Dam is a run-of-the-river reservoir, flows are equivalent to the creek itself, or somewhat lower depending on outflows through the outlet pipe. There are no passage constraints in this section, which has channel characteristics similar to natural features.

Figure 17. Buckhorn Spillway - Sections A and B: Entry pool and lower ramp (ramp length 180 ft, ~ 8° incline).

B) The lower ramp (Figure 17: length 180 ft, ~ 8° incline) - The entire ramp is smooth concrete at relatively gentle slope with minor joints (no extruding edges or impassable gaps) and has sheet flow at most overflows (photo with reservoir elev. 1803.00). There are no passage constraints in the section. Lampreys demonstrate sub-aerial climbing capability on smooth inclined surfaces of 10° - 80° with little change in performance (Keefer et al. 2011, Goodman and Reid 2017).

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C) The intermediate pool (~200 ft long x 20 ft deep) represents a break from subaerial climbing swim and a potential resting area with ample cover. The pool is deep, dark and has large beds of aquatic vegetation). An average 60 cm adult lamprey swimming at typical speeds of 0.5 Body Lengths/sec would traverse the pool in as little as 4 mins (Reid and Goodman 2016).

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Figure 18. Buckhorn Spillway - Section D: The upper ramp (length 275 ft, ~ 10°- 45 °).

D) The upper ramp (Figure 18; length 275 ft, varies from ~ 10°- 45 °) - The entire ramp is smooth concrete at a variable slope with minor joints (no extruding edges or impassable gaps) and continuous sheet flow at most overflows (photo reservoir elev. 1803.00). This ramp includes the steepest reach (100 ft long and ~ 45°), but this is well within the capability of a climbing lamprey and in experimental settings has not been show to substantially change climb rate. There are no passage constraints in the section. Lampreys demonstrate sub-aerial climbing capability on smooth inclined surfaces of 10° - 80° with little change in performance (Keefer et al. 2011, Goodman and Reid 2017).

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Figure 19. Buckhorn Spillway - Section E: The upper spillway wall (height 20 ft, with a slight incline; photo at reservoir elevation 2803.00 ft).

E) The upper spillway wall (Figure 19; height 20 ft, with a slight incline; photo at reservoir elevation 2803.00 ft) - This is the final challenge for a Pacific Lamprey climbing the spillway. It is 20 ft tall, but unlike many man-made features, the Buckhorn Spillway includes a number of features making it particularly suitable to lamprey passage. 1) At most spill conditions, the long axis of the crest (150 ft) reduces flow to a relatively thin sheet flow and reduces flow velocities. 2) The sheet flow provides a continuous wetted vertical surface without high velocities likely to dislodge a climbing lamprey. 3) The concrete surface is smooth and provides an excellent attachment surface for suctorial climbing. 4) The top of the wall is broadly rounded, allowing a lamprey to continue climbing without encountering an acute edge, which could block movement or break suction. 5) The crest is of sufficient diameter that propulsion vectors (from body and tail) are generally aligned with direction of movement - unlike with a narrow diameter obstacle that requires a lamprey to change directions in order to dive for the bottom. 6) The rounded crest extends over the top and down on the reservoir side, providing a continuous attachment route into the refuge of low energy water below the outflow current. 7) The nature of the spillway is such that there are multiple paths up the wall with variable flow conditions and velocities. 8) Even in higher flow conditions, there will be a smooth, low-velocity wetted pathway up the end wall where the spillway meets the dam.

Flow management considerations: The Buckhorn spillway is only passable at times of overflow, lampreys can't climb dry surfaces, and when flows down the ramp are relatively shallow (Figure 20). During high flow events when water depth and velocities down the ramps exceed burst-attach locomotion or require extreme effort, lampreys are also unlikely to climb the ramp. However, they may be able to follow the water surface along the wetted vertical sidewalls. The critical swimming speed for Pacific Lamprey is near 0.85 m/s (Mesa et al. 2003). However, they can pass higher velocities over a short distance using burst and attach locomotion. Nevertheless, the limit for successful passage of even a short distance is apparently near 2.5 m/s (Keefer et al. 2010). The considerable length of the Buckhorn Spillway represents a substantial challenge even under ideal conditions. Therefore, optimum opportunities for passage will be when the spillway is providing shallow sheet flow and relatively low boundary velocities, ideally with water depths less than the thickness of an adult lamprey (~ 0.13 ft).

Lamprey may migrate nearly year round, but the principal migration in northern California generally occurs from January thru June (Reid and Goodman unpubl. data). During the January thru June period (2010-2016), reservoir overflow elevations were within:

0.13 ft of spillway elevation 60% of the time (714/1199 daily records)
0.20 ft of spillway elevation 82% of the time (984/1199)
0.30 ft of spillway elevation 96% of the time (1149/1199)

For periods with flow elevations > 0.13 ft and lasting more than one day the median high flow event was 18 days (15 events: 2-146 days). For periods with flow elevations > 0.2 ft and lasting more than one day the median high flow event was 6.5 days (16 events: 2-56 days). During periods of higher flows, intermediate pools would provide refuge areas for transiting lampreys.

In 2012 a habitat enhancement project was completed at the toe drain outlet and reservoir outflow management was altered to provide consistent water flow through the outlet pipe. This management has apparently resulted in extended periods of no spill down the overflow ramp (Figure 20). The timing of flow deficit sufficient to prevent flow over the spillway appears to be associated with low summer flows prior to the resumption of winter rains (July - December).

From 2010 thru 2016, extended periods without overflow:

110 days	01 August	- 19 November	2012
121 "	22 July	- 20 November	2013
16 "	04 April	- 19 April (?)	2014
191 "	10 June	- 18 December	2014 (data gap: 20 Aug - 17 Dec)
160	12 July	- 19 December	2015
78 "	29 July	- 15 October	2016

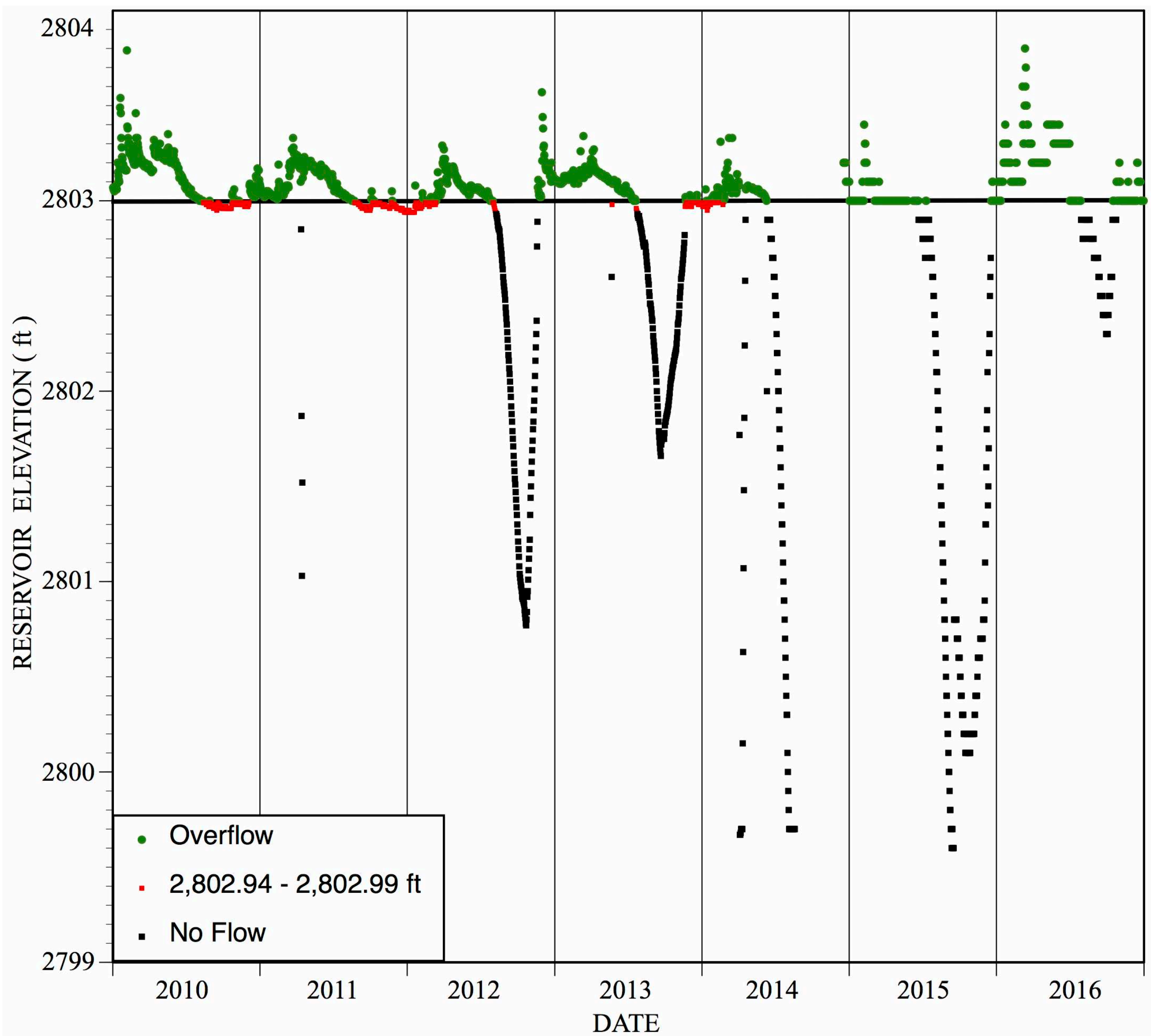

Figure 20. Buckhorn Reservoir elevation, 1 January 2010 - 31 December 2016. Spill down ramp occurs at design elevation of 2,803.00 ft and above (green). However, the record suggests that spill may also be occurring from gauge levels of 2,802.94 ft up (shown in red). Source: http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=GVO. Note that considerable water was already flowing over the spillway at a gauge reading of exactly 2,803.00 (Figure 18).

Discussion: The overflow spillway ramp at Buckhorn Dam presents no impassable features for adult Pacific Lamprey, although it represents a substantial challenge even under ideal conditions, due to its height and length. The spillway ramps are at angles that Pacific Lamprey are able to climb under sheet-flow conditions. The final wall at the top of the ramp (20 ft) represents a climbing challenge. However, Pacific Lamprey are known to pass 30 ft smooth vertical granite waterfalls, and the wall itself is not vertical but somewhat inclined. The deep entry and intermediate pool provide resting refuges. Optimum opportunities for passage occur when the spillway is providing shallow sheet-flow and relatively low boundary velocities, ideally with water depths less than the thickness of an adult lamprey (~ 0.13 ft). Management of reservoir outflows should insure that there is some flow over the spillway at least thru June, if not year round, and that periods of shallow spills are maximized (reservoir elev. 2,803.0 - 2,803.15 ft).

Were Pacific Lamprey to pass the dam and spawn upstream, outmigrating juvenile lampreys would be likely to move over the spillway during high flow events. The drop onto the concrete apron at the base of the wall represents a possible threat of injury. In nature, lampreys frequently move downstream over falls; however, the flow is typically into a deep plunge pool at the base, which reduces impact risks. Were lampreys to colonize Grass Valley Creek upstream of the dam, some form of water retention structure on the upper apron might be considered in order to form a shallow cushioning pool.

At this time Pacific Lamprey do not appear to be using Grass Valley Creek immediately downstream of the dam, and none were encountered in surveys above (see Distribution). Therefore, the presence or absence of lampreys above the dam could not be used to test its suitability for lamprey passage. Direct testing of passage success would be possible with introduction of migrating adults into the lower pool during suitable flow conditions (Goodman and Reid 2017). Additionally, continued monitoring for Pacific Lamprey ammocoetes at upstream sites would indirectly detect colonization.

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