University of Nevada, Reno

Effects of packstock use and backpackers on water quality in

Yosemite National Park, California

A thesis submitted in partial fulfillment of the requirements for the degree of

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by

Harrison A. Forrester

Dr. Alan C. Heyvaert/Thesis Advisor

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We recommend that the thesis
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HARRISON FORRESTER

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Alan C. Heyvaert, Ph.D., Advisor

David W. Clow, Ph.D., Committee Member

Adrian A. Harpold, Ph.D., Committee Member

Paul J. Hurtado, Ph.D., Graduate School Representative

David W. Zeh, Ph. D., Dean, Graduate School

May, 2016

Abstract

Visitor use in designated Wilderness increases the potential for negative effects on water quality. However, effects from specific types of visitor use such as backpacker camping, packstock (horse and mule) trail use, and packstock grazing are difficult to quantify and isolate from background environmental processes. To determine the effects of visitor use on water quality in Wilderness in Yosemite National Park, we collected and analyzed surface-water samples for fecal indicator bacteria (*Escherichia coli*), nutrients (nitrogen, phosphorus, and carbon), suspended sediment concentration (SSC), and hormones (e.g. estrogen compounds) during the summers of 2012-2014. We collected samples upstream and downstream from different types of visitor use at routine intervals (weekly or biweekly) during steady flow (non-storm) conditions and during episodic storms. Additionally, we sampled upstream and downstream from meadows, and targeted different types of visitor use during a park-wide synoptic sampling campaign (n=63). Statistically significant ($P \leq 0.05$) increases in *Escherichia coli* (*E. coli)* and SSC occurred downstream from packstock stream crossings compared to upstream conditions during routine sampling (median difference: 3 CFU 100ml^{-1}, and >0.3 mg l^{-1}, respectively) and during storms (median difference: 32 CFU 100ml^{-1}, and 2.9 mg l^{-1}). During routine sampling, significant increases also occurred downstream from backpacker camping for *E. coli* (median difference: 1 CFU 100ml^{-1}) and estrogen hormones were detected. No significant increases were detected for any of the measured water quality indicators downstream from packstock grazing. Most of the synoptic sample

concentrations were near or below detection limits. Our results indicate that under current use levels: 1) packstock trail use and backpacker camping have detectable effects on water quality, which are most pronounced during storms; 2) increases in water quality indicators were not detected downstream from meadows where packstock were grazed; and 3) environmental processes in meadows might provide a valuable ecosystem service by reducing human related sources of microbial contamination.

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1. Background and Introduction

Yosemite National Park is located in the central Sierra Nevada, approximately 300 km east of San Francisco, California. The park has a total area of 3,027 km² (NPS 2015). Park elevations range from 610 m (2,000 ft) in the western foothill canyons to 3,997m (13,113 ft) at Mt. Lyell on the eastern Sierra Nevada crest. Glacial erosion of granitic rock has sculpted ridges, cirques and U-shaped canyons throughout the high country (Glazner and Stock 2010). Melting winter snowpack feeds headwater lake outlets and streams that often flow across bedrock and talus. Sub-alpine streams coalesce into rivers, often running through brief stretches of flat, biologically productive meadows. Two major rivers, the Tuolumne River and the Merced River, cascade through slick-rock gorges and pass under immense rock walls in Yosemite and Hetch Hetchy valleys before dropping into foothill canyons on the western park boundary. Vegetation in the alpine region is limited to occasional krummholz pine trees and intermittent alpine meadow-grasses. Mixed-conifer forests inhabit the sub-alpine to lower montane elevations. Oak woodlands and chaparral dominate the western foothill canyons.

Yosemite National Park received its first enabling legislation in 1864 when President Abraham Lincoln signed the Yosemite Grant Act, which designated Yosemite Valley and the Mariposa grove of Giant Sequoia for management by the State of California. This early legislation, although technically not designation as a "National Park", is generally regarded as the birth of the national park idea, where lands "… shall be held for public use, resort, and recreation … inalienable for all

time…" (United States Congress 1864). This event marked the first significant

preservation of public land by the US Congress. Not until 1906 were these lands

transferred to management by the US Federal government, under the jurisdiction of

the US Army and designated as Yosemite National Park. Following the controversial

passage of the Racker Act in 1913, which allowed the construction of O'Shaughnessy

Dam on the Tuolumne River and impoundment of Hetch Hetchy reservoir within

Yosemite National Park, the National Park Service Organic Act was passed in 1916,

creating the National Park Service. The passage of the Wilderness Act in 1964 and

subsequent passage of the California Wilderness Act of 1984 ultimately led to the

designation of more than 94% (2,852 km^2) of Yosemite National Park as

wilderness(NPS 2015).

Visitor use in federally designated wilderness areas (Wilderness), consisting

of backpacker camping, packstock trail use, and packstock grazing, increases risks to

downstream water quality due to ground disturbance (Deluca et al 1998; Cole et al

2008; Cole and Parsons 2013; Kidd et al 2014), contamination from human and

animal waste (Atwill 2008; Ostoja et al 2014), and use of pharmaceutical products

(Bradley et al). Ground disturbance and subsequent erosion of soil during runoff

events (storms) may affect water quality by increasing suspended sediment

concentration (SSC), mobilizing nutrients (nitrogen, phosphorus, carbon), and

reducing water clarity. Urine and feces waste may be deposited directly into water

bodies by packstock at stream crossings, where trails directly cross streams, or by

backpackers while bathing. Furthermore, waste deposited on soil may be mobilized

during storms from meadows grazed by packstock and from trails used by packstock, or from campsites where backpackers do not use appropriate waste disposal techniques. This may result in contamination of surface waters by pathogenic bacteria and nutrients. Hormones (e.g., pharmaceutical estrogen compounds) deposited in waste are contaminants of emerging concern in US National Parks (Landewe 2008, Bradley 2105). Some hormones may disrupt aquatic habitats (Sellin et al 2009), and may also provide information on sources of contamination (Leeming et al 1996).

Reliable studies of visitor use effects on water quality in Wilderness are scarce. One study in Sequoia and Kings Canyon National Parks (SEKI) found no difference in water quality indicators downstream from popular backpacker campsites compared to upstream sampling locations (Clow et al 2013). Another study found that sampling locations at recreational use (backpacker) sites across United States Forest Service (USFS) lands in the Sierra Nevada had the lowest concentration of fecal indicator bacteria (FIB) compared to cattle grazing and unused zones (Roche et al 2013). General park-wide monitoring from 2004-2007 in Yosemite National Park (YOSE) showed that nutrient and *E. coli* samples collected along major creeks and rivers were low and comparable to other Wilderness areas (Clow et al 2011). Notably median *E. coli* values for the entire study were less than 5 colony-forming units (CFU) 100ml^{-1} (Clow et al 2011).

Effects on water quality from packstock use in Wilderness are often a focus of concern for land management agencies, typically in the context of dispersed

overnight grazing in sub-alpine meadows (SEKI 1986; Ostoja et al 2014).

Conclusions from field studies are markedly different. In SEKI, concentrations of *E. coli* where generally low park-wide, mean *E. coli* concentrations in areas downstream from mixed-use (backpackers and packstock) were 2.8 CFU 100ml^{-1}. But *E. coli* concentrations were significantly ($P \leq 0.05$) higher downstream from mixed-use meadows compared to upstream natural background locations. The study concluded that although significant increases in concentrations were detected downstream of mixed-use areas, the inability to isolate different types of visitor use and to account for environmental processes limited the ability to evaluate contributions from various sources, such as packstock, humans, and wildlife (Clow et al 2013). In contrast, *E. coli* samples collected on USFS and National Park Service (NPS) land from 12 "packstock" sampling locations across the Sierra Nevada varied from 0-900 CFU 100ml^{-1}, averaging 280 CFU 100ml^{-1} (Derlet 2006).

Evidence from several studies shows that packstock trail use increases erosion of trails, and packstock stream crossings likely impact water quality. Horse traffic on trails increases erosion and generates more sediment yield than llamas or hikers (Deluca et al 1998). Streambed silt and sand cover are higher downstream than upstream from heavily used packstock stream crossings (Holmquist et al 2015). Although packstock deposit fecal matter on trails, and in some cases, proximal to streams (Atwill 2008), packstock fecal matter often contains few pathogenic microbes (e.g., Cryptosporidium, Giardia, *E. coli*) (Forde et al 1997; Johnson et al 1997; Derlet 2002; Atwill 2008).

Environmental processes in mountain watersheds may influence the detectability and persistence of visitor use effects on water quality. Atmospheric nitrogen is deposited into oligotrophic environments globally, and across the western U.S. including the Sierra Nevada (Sickman et al 2003; Elser et al 2009). Basin characteristics (geology, gradient, vegetation cover) influence nutrient concentrations in stream water (Clow and Sueker 2000; Clow et al 2013). The reach-scale (0.3 km - 1.5 km downstream distance) interchange of surface and sub-surface flow (i.e., hyporheic exchange) influences nutrient cycling (Harvey et al 2013), and enhances filtration of fine sediments and pathogenic microbes at the streambed sediment-water interface (Drummond et al 2014). Previous research under different study conditions suggests that environmental processes in flat meadows may improve water quality through UV inactivation of bacteria (Pommepuy et al 1992), by deposition of suspended sediment and sediment adsorbed FIB in low flow areas (Karwan and Saiers 2012), and from enhanced nutrient cycling through hyporheic exchange (Harvey et al 2013). Upland soil disturbance and fecal deposition from visitor use likely only impact water quality during runoff events (i.e., rainstorms and snowmelt). *Escherichia coli*, fine sediment, and nutrient concentrations increase dramatically during storm flows (McKergow and Davies-Colley 2010; Clow et al 2013).

Visitor use in YOSE consists of backpackers, packstock grazing in meadows from commercial guiding and NPS administrative operations, and trail use by packstock associated with NPS concessionaire operations and NPS administrative

operations. Our hypotheses are: 1) Wilderness users deposit waste and disturb soils on trails, campsites, and in meadows grazed by packstock; we expect that nutrient, pharmaceutical, and microbial deposition from fecal matter and erosion of sediment from disturbed soils will degrade water quality downstream from heavily used areas; and 2) previous research from related water quality fields suggest that environmental processes in meadows may improve water quality; thus, we also expect that water quality indicators will decrease in concentration (i.e. improve) downstream from flat meadow systems relative to upstream (above meadow) sampling locations.

The purpose of this study was to quantify microbial, nutrient and suspended sediment concentrations downstream from locations that represent different types of visitor use in Yosemite National Park. Specific objectives were to: (1) quantify visitor use by a) overnight packstock grazing, b) packstock trail use, and c) backpacker camping; (2) quantify microbial, nutrient, suspended sediment, and hormone concentrations during steady flow conditions and during storms, both upstream and downstream from heavy visitor use and across gradients of visitor use intensity and environmental conditions, including upstream and downstream from meadows.

The paper evaluates results from three main components of this study: (1) paired sampling upstream and downstream from backpacker campsites, packstock stream crossings, packstack grazing, and meadows; (2) paired storm sampling and intensive water quality monitoring upstream and downstream from backpacker

campsites and packstock stream crossings; and (3) park-wide synoptic sampling at numerous sites representative of different types and amounts of visitor use, and natural background conditions. Each of these lines of evidence is evaluated to determine the effects of each type of visitor use (backpacker camping, packstock stream crossings, packstock grazing) on water quality. Mitigation of the effects of visitor use on water quality by environmental process is evaluated with paired sampling upstream and downstream from meadows.

2. "Effects of packstock use and backpackers on water quality in Yosemite National Park, California". Article for submission to Environmental Management.

Background and Introduction

Federally designated wilderness areas (Wilderness) provide primitive recreational opportunities to the general public while preserving natural conditions in large ecosystems (United States Congress 1964). Surface waters are central components of Wilderness ecosystems, and visitors and downstream users rely on them for high-quality drinking water (SFPUC 2012). Visitor use in Wilderness areas, consisting of backpacker camping, packstock trail use, and packstock grazing, increases risks to downstream water quality due to ground disturbance (Deluca et al 1998; Cole et al 2008; Cole and Parsons 2013; Kidd et al 2014), contamination from human and animal waste (Atwill 2008; Ostoja et al 2014), and use of pharmaceutical products (Bradley et al).

Ground disturbance and the subsequent erosion of soil during runoff events (storms) may reduce water clarity by increasing suspended sediment concentration (SSC). Waste (primarily urine and feces) may be deposited directly into water bodies by packstock at stream crossings (where trails directly cross streams) or by backpackers while bathing. Waste deposited on soil may be mobilized during storms

from meadows grazed by packstock, from trails used by packstock, or from campsites where backpackers do not use appropriate waste disposal techniques; this may result in contamination of surface waters by pathogenic bacteria and nutrients (carbon, nitrogen and phosphorous). Hormones (e.g., pharmaceutical estrogen compounds) deposited in waste are contaminants of emerging concern in US National Parks (Landewe 2008, Bradley 2105); some hormones may disrupt aquatic habitats (Sellin et al 2009), and provide information on sources of contamination (Leeming et al 1996).

Natural hydrologic processes in mountain watersheds may mitigate the detectability, persistence, and magnitude of effects from visitor-use on water quality. Ultraviolet radiation in high-elevation meadows and lakes may inactivate pathogenic bacteria (Pommepuy et al 1992; Sinton et al 2002). The exchange of surface and sub-surface flow (i.e., hyporheic exchange) in meadows may increase assimilation of nitrogen, and filtration of SSC and sediment-adsorbed pathogenic bacteria at the streambed sediment-water interface (Harvey et al 2013; Drummond et al 2014). Importantly, the largest effects from visitor use may occur during storms, when pathogenic bacteria, SSC, and nutrients are mobilized into surface waters (McDonald and Kay 1981; Davies-Colley et al 2008; McKergow and Davies-Colley 2010; Clow et al 2013).

Only a few studies have examined the influence of backpacker camping, packstock trail use and packstock grazing on water quality in Wilderness areas. Results from field studies suggest that backpacker camping has minimal or

undetectable effects on water quality during steady flow (non-storm) conditions (Clow et al 2011; Clow et al 2013; Roche et al 2013). Attempts to measure effects from backpacker camping during storms have not occurred before, although other studies have measured greater soil compaction and less vegetation cover in backpacker campsites than control sites, implying greater erosion potential during run-off events (Cole 1983; Cole et al 2008; Cole and Parsons 2013).

In contrast, there is substantial evidence that packstock trail use increases erosion of trails and packstock stream crossings likely impact water quality downstream. Experimental work by Deluca et al (1998) shows that because packstock are heavier than hikers and their weight is supported by a shoe with small surface area, packstock loosen soil on trail surfaces more than hikers. Sediment yield (erosion) from trail surfaces during run-off is limited by the detachment of loosened soil particles; thus, packstock trail use also generates more sediment yield than hikers (Deluca et al 1998). At poorly managed packstock stream crossings the soil from adjacent trails may erode into streams during storms (Kidd et al 2014). During steady flow conditions, disturbance of the stream bed by packstock during crossings likely enhances sedimentation downstream from crossing sites (Holmquist et al 2015).

One field study on overnight packstock grazing in meadows suggests that during steady flow conditions, effects on water quality are small (Clow et al 2013). Results from this study in Sequoia and Kings Canyon National Parks (SEKI) showed that *E. coli* concentrations were significantly ($P \leq 0.05$) greater downstream from

mixed-use meadows (backpacker camping and packstock grazing) when compared to upstream reference locations. But concentrations of *E. coli* where generally low park-wide. During steady flow conditions the mean *E. coli* concentration downstream from mixed-use areas was only 2.8 CFU 100ml^{-1}. During storms in SEKI, the *E. coli* concentrations were higher downstream from a mixed-use meadow than at the upstream reference location, suggesting mobilization of fecal matter deposited in the meadow (Clow et al 2013).

A recent study in Rocky Mountain National Park detected endocrine disrupting chemicals (e.g. estrogen hormones) in water and sediment samples at several locations, the authors suggest that due to the persistence of such chemicals in the environment and their potential effects on aquatic ecosystems, use of pharmaceutical products in the backcountry should be discouraged (Bradley et al 2016).

To protect Wilderness areas in Yosemite National Park (YOSE), managers seek to both understand and mitigate effects of visitor use on natural systems. In YOSE, there is particular concern that packstock stream crossings on frequently used trails may be impacting water quality. Fecal matter on trails used by packstock in the Tuolumne Meadows vicinity of YOSE is often deposited adjacent to streams and, thus, is readily mobilized into streams during storms (Atwill 2008). YOSE has relatively low amounts of overnight packstock use compared to SEKI (Frenzel and Haultain 2012), but there are also persistent concerns that overnight packstock use is impacting water quality (Ostoja et al 2014). In addition, surging backpacker use in

YOSE Wilderness has heightened concerns that erosion from intensely used campsites and emerging forms of contamination are threatening water quality, potentially degrading aquatic ecosystems.

The purpose of this study was to quantify specific types of visitor use in Wilderness in Yosemite National Park and to measure the effects of visitor use on water quality. The main types of visitor use in the study area include camping by backpackers, packstock grazing from commercial guiding and NPS administrative operations, and packstock trail use predominantly associated with NPS concessionaire operations. We conducted paired sampling at 5 stream sites upstream and downstream from specific types of visitor use during the summers of 2012-2014; samples were collected routinely (weekly or biweekly) during steady flow conditions and during storms. Samples were analyzed for constituents indicative of effects from humans or packstock, including *E. coli*, nutrients, suspended sediment, and hormones. In addition, a park-wide synoptic sampling campaign was performed during July 2014 to further examine the effects of different types of visitor use and to evaluate whether environmental processes might mitigate impacts, particularly in meadows.

Methods:

Study Area:

This study examines water quality impacts in Yosemite National Park (YOSE), which is located in the central Sierra Nevada, approximately 300 km east of San Francisco, California. The park has a total area of 3,027 km^2 (NPS 2014), and elevations range from 610 m (2,000 ft) in the foothills to 3,997m (13,113ft) at Mt. Lyell on the Sierra Nevada crest (Fig. 1). Glacial erosion of granitic rock has sculpted ridges, cirques and U-shaped canyons throughout the high country (Glazner and Stock 2010). Melting seasonal snowpack feeds headwater lakes and streams, which primarily flow across bedrock and talus. Sub-alpine streams coalesce into rivers, often running through brief stretches of flat,
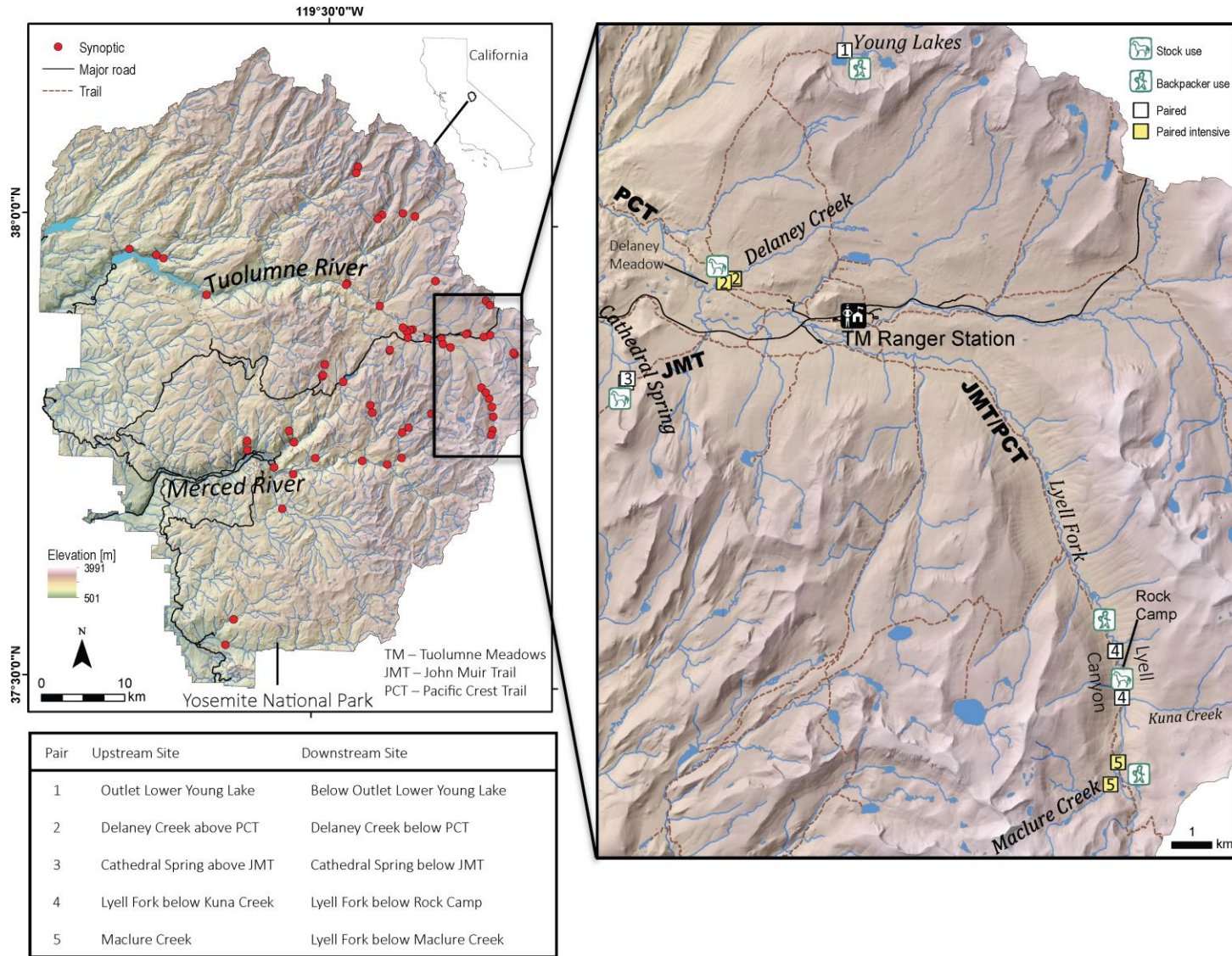
Fig. 1 Study zone overview with sampling locations

Pair	Upstream Site	Downstream Site
1	Outlet Lower Young Lake	Below Outlet Lower Young Lake
2	Delaney Creek above PCT	Delaney Creek below PCT
3	Cathedral Spring above JMT	Cathedral Spring below JMT
4	Lyell Fork below Kuna Creek	Lyell Fork below Rock Camp
5	Maclure Creek	Lyell Fork below Maclure Creek

biologically productive meadows. Two major rivers, the Tuolumne River and the Merced River, cascade through slick-rock gorges and pass under immense rock walls in Yosemite and Hetch Hetchy valleys, before dropping into foothill canyons on the western park boundary. Vegetation in alpine areas is limited to occasional krummholz pine trees and intermittent alpine meadow-grasses. Mixed-conifer forests inhabit the sub-alpine to lower montane elevations. Oak woodlands and chaparral dominate the western foothill canyons.

Designated by the California Wilderness Act of 1984 (P.L. 98 – 425), more than 94% (2,852 km^2) of YOSE is Wilderness (NPS 2015), only accessible by foot or packstock on a 1,300 km network of trails. In YOSE Wilderness, 5 High Sierra Camps (HSCs) exist within potential Wilderness additions that are managed "insofar as practicable" as designated Wilderness (United States Congress 1984). HSCs are operated by the YOSE concessionaire and provide food and lodging services to park visitors.

Backpackers utilize trails, cross-country (off-trail) routes, and campsites throughout the park. Backpacker use is generally concentrated along the High Sierra Camp Loop, the John Muir Trail (JMT), and the Pacific Crest Trail (PCT) (Appendix A). Overnight backcountry trips in YOSE require Wilderness permits, enabling the NPS to monitor and manage backpacker use. Prior to this study, during 1974-2011, backpacker use nights (one night of camping by one backpacker) averaged (± SD) 113,000 ± 22,000 (Fig. 2).
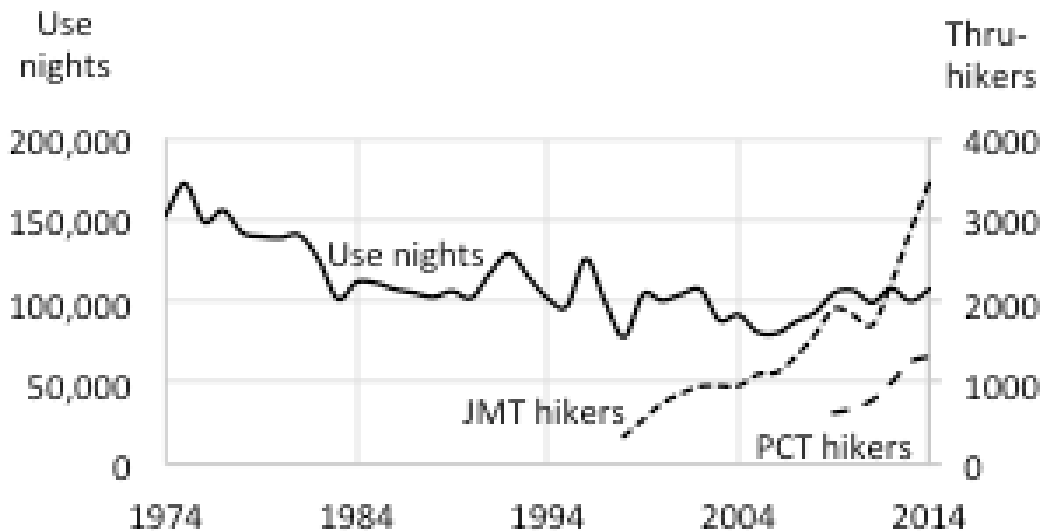
Fig. 2 Backpacker use 1974-2014. Use nights and JMT hikers are recorded by the YOSE Wilderness office and do not include backpackers beginning trips from adjacent USFS trailheads, PCT hikers, and JMT hikers beginning at Mt. Whitney. PCT hikers are recorded by the Pacific Crest Trail Association.
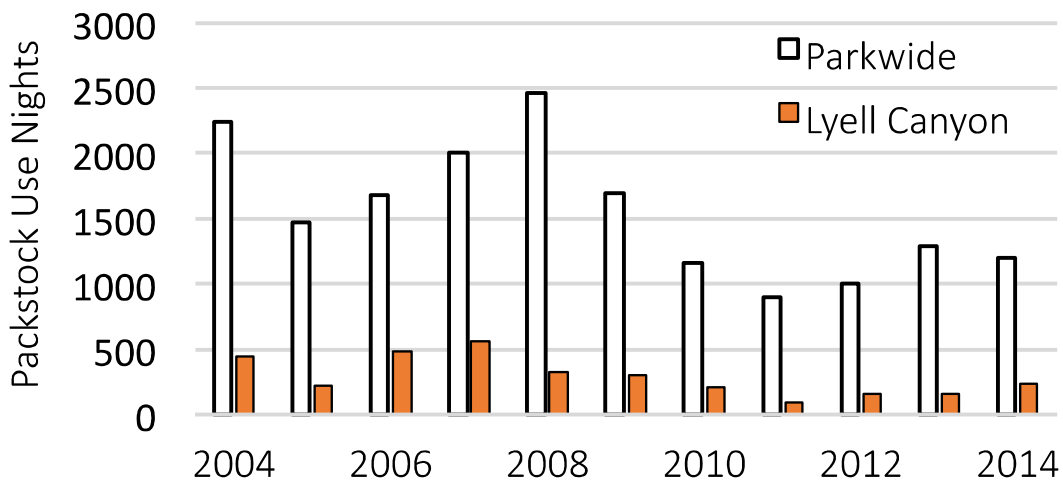
Fig. 3 Reported overnight packstock use; compiled by the YOSE Wilderness Office. Overnight packstock use includes grazing in meadows and overnight stays at packstock camps where supplemental feed is used.

Overnight packstock use includes "free-range" grazing nights and nights when supplemental feed is used without grazing. In YOSE, overnight packstock use is limited to designated grazing zones and campsites, and is reported by commercial and administrative packstock users. Packstock use nights (one night of grazing by one animal) averaged (± SD) 1,766 ± 416/year during 2004-2011 (Fig. 3). A packstock use day (one day of travel by one animal) is defined as travel on trails with minimal grazing. In YOSE, packstock day use consists primarily of recreational day rides, supply trips to HSCs, ranger patrols, and travel between overnight campsites (Acree et al 2010). In 2004, the YOSE Wilderness Office estimated park-wide packstock days at 26,601; 77% of which was from recreational day rides and for supplying High Sierra Camps, both are YOSE concessionaire services. The remaining 23% of packstock day use was associated with administrative, commercial, and private packstock use (Acree et al 2010).

Study Sites:

Routine sampling at five paired sites
Routine samples were collected on a weekly or biweekly interval at paired sampling locations, upstream and downstream from different types of visitor use, to provide information on effects from specific types of visitor use on water quality. During the spring and summer months (May-September) from 2012-2014, we routinely sampled upstream and downstream from: (1) popular backpacker campsites (Lyell

Fork and Young Lakes); (2) packstock stream crossings on frequently used trails that cross streams, where physical interaction (i.e., streambed disturbance, direct fecal deposition) with the stream by packstock is likely or unavoidable (Delaney Creek and Cathedral Spring); and (3) overnight grazing in meadows by packstock (Lyell Canyon) (Fig. 1). At all paired locations, the upstream sampling site was above areas of visitor use, and thus represented natural background conditions. The downstream sampling sites were below areas of visitor use, and thus represented background conditions plus the potential impacts from visitor use.

Storm sampling at two paired intensive sites

Previous studies indicate that fecal matter, nutrient, and suspended sediment concentrations in streams often increase during and following storms (Davies-Colley et al 2008; McKergow and Davies-Colley 2010; Clow et al 2013); thus, water samples were collected at paired sites during storms, when impacts from visitor use are more likely to become evident. To document storm-flow dynamics and to compare concentrations downstream from visitor use with natural background conditions, we installed hydrologic-monitoring equipment (data loggers, pressure transducers, in-stream turbidity sensors, automated water samplers, and telemetry) at two of the paired sampling locations (Delaney Creek and Lyell Fork; Fig. 1). At each of these sites (4 total), data-loggers were programed to record water level (stage) and turbidity on a ten-minute interval. Autosamplers were triggered to collect samples based on a pre-set stage increase (or decrease) over a ten-minute

interval (e.g. 0.06 cm change over a 10 min interval). Local radio telemetry between paired sites enabled synchronized sampling at upstream and downstream locations. At each pair of sites (2 total), ten-minute rainfall was recorded with a tipping bucket rain gage and satellite telemetry provided real-time data, enabling field personnel to retrieve and process autosampler samples in a timely manner.

Synoptic sampling

A synoptic water-quality survey was conducted by sampling streams at 63 Wilderness locations during stable hydrologic conditions (no storms) over a four-day period in mid-July, 2014. Synoptic locations targeted different types of visitor use as previously described, while attempting to maximize spatial distribution. Sites were distributed across major sub-basins, at different elevations, sometimes both upstream and downstream from meadows. Permitted hold times for water samples limited sampling sites to locations that could be sampled and transported back to the laboratory in Tuolumne Meadows within 24 hours (Fig. 1).

Paired sampling upstream and downstream from meadows

The influence of environmental processes in meadows, including mitigation of potential impacts from visitor use, was investigated by sampling upstream and downstream from a variety of meadows at different times during the study. Upstream/downstream sampling occurred in Lyell Canyon during 2012-2014,

Delaney Meadow during 2013 and 2014, and at 10 additional meadows during the

synoptic campaign in 2014 (Fig. 1).

Hormone sampling

The presence of hormones from packstock use and backpacker use was evaluated

by collecting water and sediment samples during the summer of 2013 at each paired

monitoring site, except Lyell Fork below Kuna Creek (Fig. 1). Storm samples for

hormone analysis (water only) were collected at the paired intensive monitoring

sites during July 25 – July 28 (Fig. 1).

Water quality indicators

Nutrients, suspended sediment, fecal indicator bacteria (FIB), and hormones (from

humans and packstock) can be useful indicators of water quality, and in some cases

can be linked to specific types of visitor use. Nutrients (nitrogen, phosphorous, and

carbon) may indicate inputs from fecal matter and provide insight into ecosystem

function (Conley et al 2009; Clow et al 2010). Suspended sediment is an indicator of

erosion, affects water quality, and is an important factor in the fate of microbes in

the aquatic environment (Julian et al 2013; Piorkowski et al 2014). Most FIB are not

pathogenic, but can be used to indicate the presence of fecal matter in water. Total

coliform, fecal coliform, and *E. coli* are commonly used FIB. Total-coliform is a broad

group of bacteria found in soil, water, and submerged vegetation, as well as from

fecal sources (United States Environmental Protection Agency 1989). Fecal coliform

are a subset of the total coliform group, but despite the name also contain bacteria from non-fecal sources (United States Environmental Protection Agency 2012). *Escherichia coli* is a species of fecal coliform bacteria that inhabits the lower intestines of humans and other warm-blooded animals. *E. coli* is the recommended FIB for recreational fresh water because of its exclusive origin from fecal sources and its limited ability to persist and regenerate in the environment outside of the host animal (United States Environmental Protection Agency 2012). Although *E. coli* indicates the presence of fecal matter, it does not necessarily indicate the presence of other common water borne pathogens (e.g., Cryptosporidium, Giardia, *E. coli* O157:H7) (Field and Samadpour 2007).

Hormones related to personal care products (e.g., pharmaceutical-estrogen hormones) indicate contamination of water from human sources, which may disrupt aquatic environments (Kitamura et al 2009; Sellin et al 2009). Additionally, the presence of Coprostanol in sediment may indicate fecal contamination by higher order animals (e.g., packstock, humans) (Bethell et al 1994; Leeming et al 1996; Bull et al 2002; Puglisi et al 2003).

Sample Collection and Analyses

Steady flow (non-storm) water samples were collected from well-mixed streams using standard USGS grab-sampling techniques (United States Geological Survey 2006). Samples were kept cool and shielded from sunlight in soft-insulated coolers

with frozen gel blocks (blue ice) inside the internal compartment of field packs during transport, and processed within 24 h of collection (Rice et al 2012). Samples were analyzed for chemistry in an approved USGS laboratory (Fishman 1993). Analytes and analysis methods included nitrate (NO3-N) by ion chromatography; total dissolved nitrogen (TDN) by alkaline-persulfate digestion; dissolved organic carbon (DOC) by ultra-violet promoted persulfate oxidation with infrared detection, particulate carbon (PC) and particulate nitrogen (PN) by high temperature combustion in an elemental analyzer, and total phosphorus (TP) by NaOH/persulfate digestion, and suspended sediment concentration (SSC) by dry mass. Field blanks and replicates constituted 5% of the sample total. Solute concentrations in the blanks were below method detection limits (MDLs; for specific MDLs see Table 1) 100% of the time for SSC, NO$_3$-N, PN, PC, 91% for TDN, and 60% for TP and DOC. Subsequent analysis of laboratory blank water indicated low concentrations of TP, confirming that TP contamination likely came from blank water, not from field sampling or processing equipment. Median difference between duplicate samples was 0.001 mg l^{-1} for NO$_3$-N, 0.006 mg l^{-1} for TDN, 0.15 mg l^{-1} for DOC, 0.023 mg l^{-1} for PC, 0.3 mg l^{-1} for SSC, <0.017 mg l^{-1} for PN (below MDL), and <0.004 mg l^{-1} for TP (below MDL).

All non-storm *E. coli* samples were collected in sterile, pre-sealed, disposable, 100ml bottles and processed within 24 hours (Rice et al 2012). *Escherichia coli* samples were processed and analyzed at a field laboratory in Tuolumne Meadows using the m-ColiBlue24® membrane filtration method (EPA method 10029) for the

simultaneous detection of Total Coliform and *E. coli* (HACH 1999). The m-ColiBlue24 method involves filtering a water sample through a sterile, gridded, 0.45-μm membrane filter, then placing the filter in a sterile petri dish on Hach m-ColiBlue24 agar and incubating at 35°C for 24 – 48 hours (HACH 1999). Although total coliform concentrations were recorded, those results are not discussed here because of the aforementioned drawback of total coliform as a FIB.

Escherichia coli were enumerated by counting colony forming units using a magnifying glass and hand counter. Results are expressed as colony forming units per 100 ml (CFU 100 ml^{-1}). During routine sampling (steady flow conditions), when the total number of *E. coli* colonies exceeded 200 per membrane, results were reported as ''>200'' according to guidance documentation (HACH 1999). During storms, when *E. coli* concentrations were expected to increase, 1:5 dilutions were made using sample water and sterile, buffered water (HACH 1999). If diluted samples exceeded 200 CFU/membrane, results were reported as >1000 CFU 100 ml^{-1}. Sample bottles, membrane filters, and filter-funnels were pre-sterilized and disposable. Reusable components of the filtration apparatus (filter stand, forceps) were maintained in sterile condition by flame sterilization (Myers et al 2014).

All *E. coli* samples were collected and analyzed in duplicate; the median difference between duplicates was 0 CFU 100ml^{-1}. Concentrations for each sampling event were calculated as the mean of duplicate samples. Blanks comprised 10% of the *E. coli* sample total; all blanks had 0 CFU 100 ml^{-1} of *E. coli*. Negative controls (*Pseudomonas aeruginosa*) and positive controls (*Escherichia coli*) were analyzed

approximately monthly, as recommended by method documentation (HACH 1999). All negative controls were negative for *E. coli* and all positive controls were positive for *E. coli.*

Storm samples were collected using autosamplers, similar to methods used in other studies for collecting water quality samples and FIB samples during storms (Lewis 1996; Davies-Colley et al 2008; McKergow and Davies-Colley 2010; Drummond et al 2014). These samples were retrieved from the field within 48 hours of autosampler collection. Samples for *E. coli* were transferred from non-sterile autosampler bottles to sterile 100-ml sample bottles for transport to the lab. Potential contamination of autosampler-collected *E. coli* samples was evaluated by directly comparing manually triggered autosampler-samples with simultaneously collected grab-samples. Differences between grab-samples and autosampler-samples were small (3 CFU 100ml^{-1}), and concentrations in autosampler-samples were less than or equal to grab-samples, indicating little or no contamination from autosampler equipment.

Selected water and sediment samples were analyzed for a variety of hormones (Appendix D). Sediment samples were collected from depositional environments where fine-grained sediments were accumulating; plugs of sediment were gathered with a stainless steel scoop from 6-10 locations across the sampling site.

Wilderness Use accounting:

Visitor use related to potential water quality impacts was quantified using a combination of sources. YOSE concessionaire operations provided packstock trip data on HSC resupply trips, recreational day-rides, and HSC packstock-supported loop trips. In addition, a motion-sensing camera was installed on the east side of the PCT crossing of Delaney Creek to enhance accuracy of packstock crossing counts on the creek. Reported overnight packstock use and backpacker use data was provided by the YOSE Wilderness Office. Annual backpacker use nights per Wilderness zone were estimated by the YOSE Wilderness Office, using results from a previous backpacker-use study (Kirk and Douglas 2014).

Statistical tests:

A Poisson distribution Generalized Linear Model (GLM) was developed with non-censored *E. coli* concentrations from synoptic sampling locations (Fig. 1) to evaluate the influence of environmental factors and visitor use on water quality. Predictive variables were selected based on previous GLM exercises (Clow et al 2013) and hypothesized impacts from visitor use and mitigating environmental processes (meadows). Predictive variables representing visitor use included backpacker density by Wilderness zone and distance from the nearest trail. Backpacker density was calculated for each Wilderness zone by dividing 2012 – 2014 mean estimated backpacker use nights by the area of the given Wilderness zone. Distance from trails

was selected to indicate the direct physical interaction of packstock trail use at packstock stream crossings and general impacts from visitor use occurring near trails.

Basin characteristics were generated using Streamstats software (United States Geological Survey 2015) and consisted of percent forest cover and relative relief (basin relief/basin perimeter). Forest cover could influence *E.coli* concentrations by shielding UV radiation, and providing inputs of allochthonous organic matter into streams (Wetzel 2001), which may facilitate *E.coli* survival (Garzio-Hadzick et al 2010). In a previous study, Clow et al (2013) found a positive relationship between basin relief and log *E. coli* which might have indicated basin-scale mitigating environmental processes occurring in basins with flat meadows. Prior to fitting the Poisson GLM, two outliers were identified with the Chi-squared test for outliers and removed from the sample set (Zuur et al 2010). Coefficients from the GLM were transformed back to original units by exponentiation, and then standardized to compare the relative influence of each predictive variable.

Differences between paired samples collected upstream and downstream from visitor use and meadows were evaluated using the non-parametric, one-tailed, Wilcoxon Signed Rank test for median difference between matched pairs (Helsel et al 1994). For constituents with censored values (i.e., concentrations below MDL or above the limit of quantification), differences between upstream/downstream samples were evaluated using the Sign test, which only evaluates the sign (±) of the difference between matched pairs. The Sign test is less powerful than the Wilcoxon

Signed Rank test, which evaluates the sign and rank of the absolute value of differences between pairs (Helsel et al 1994). Median differences are only reported for statistically significant results, in some cases, median differences were calculated using ordinal methods for paired-data with censored values, resulting in a semi-quantitative median value (e.g., median difference: >0.3 mg l^{-1} SSC) (Helsel et al 1994). Severely censored parameters (> 50% below MDL) have little statistical power to identify central values (means and medians) and distinguish differences between paired (non-independent) groups (Helsel et al 1994). Because PN and TP were severely censored at most sites during routine sampling, they were excluded from paired tests of routine samples. Tests for significance were evaluated at the 0.05 significance level. Results were not corrected for multiple comparisons.

At the paired-intensive monitoring sites, we developed statistical models to predict continuous (10-minute interval) concentrations of PC, PN, and suspended sediment during storms (Fig. 1). Linear models were fit using ordinary least-squares regression between in-situ turbidity sensor measurements and discrete water samples collected from autosamplers. To meet the assumptions of linear modeling, discrete storm sample concentrations and associated turbidity values were log transformed prior to ordinary least-squares regression (Helsel et al 1994; Zuur et al 2010). If models failed to meet the assumptions of linear modeling, they were excluded from analysis (Zuur et al 2010). Due to a small number of discrete samples per storm event, models were fit by pooling discrete samples across the sampling period between turbidity sensor calibrations, which occurred every 6 to 18 months

(Appendix C)(Lewis 2006). Simulated concentrations of PC, PN, and SSC during storms were back transformed into original units and bias-corrected using the Duan smearing correction (Duan 1983; Lewis 2006). Paired tests were conducted using JMP (version 11) statistical software; linear modeling and predictions were performed in R statistical software (www.r-project.org).

Results

Hydroclimate

April 1 snowpack in the central Sierra Nevada was well below average for each year of the study period, reflecting ongoing drought conditions with 50% of average in 2012, 53% in 2013, and 40% in 2014 (California Department of Water Resources 2015). Shallow spring snowpack led to below average flow conditions at all study sites. At Delaney Creek, surface flow stopped in mid-August each year (Fig. 8). Whereas dry conditions dominated the 2012 summer season, both 2013 and 2014 had periods of monsoonal weather that produced isolated thunderstorms throughout the study area. Thunderstorms did not occur, however, within the study area during the July 2014 synoptic sampling campaign.

Visitor Use

Visitor use data for 2012-2014 indicated that backpacker use was steadily increasing, packstock trail use was concentrated on trail segments used by YOSE concessionaire operations, and packstock grazing was low when compared to historic levels, especially in Lyell Canyon. Annual backpacker use-nights reached a recent maximum in 2014 (124, 000), nearly equal to previous use levels from 1996 (125,000) (Fig.2) (written communication, YOSE Wilderness Office). Most backpacker use was concentrated along the HSC loop and the JMT/PCT corridor (Appendix A). During the study period, 2012-2014, the number of JMT and PCT hikers increased by 70% and 100%, respectively (Fig. 2).

Data on packstock trail use was unavailable for years prior to 2012, thus interannual comparison is limited to the study period (2012-2014). Total packstock trail crossings from concessionaire operations, originating from the concessionaire corral, were 8,600, 8,900 and 10,300 in 2012, 2013, and 2014, respectively (Fig. 4) (written communication, YOSE concessionaire office). Most packstock crossings in the Tuolumne Meadows study area occurred on trail segments used by YOSE concessionaire operations (Fig. 4). Trails used to access commercial use authorization (CUA) campsites and NPS administrative work sites received an average of less than 600 packstock crossings per year, whereas trails segments used to access HSCs received an average 1,600 packstock crossings per year, and the trail segment used by concessionaire day-ride operations received an average of 4,500 packstock crossings per year (Fig. 4) (written communication, YOSE Wilderness Office, YOSE concessionaire office).
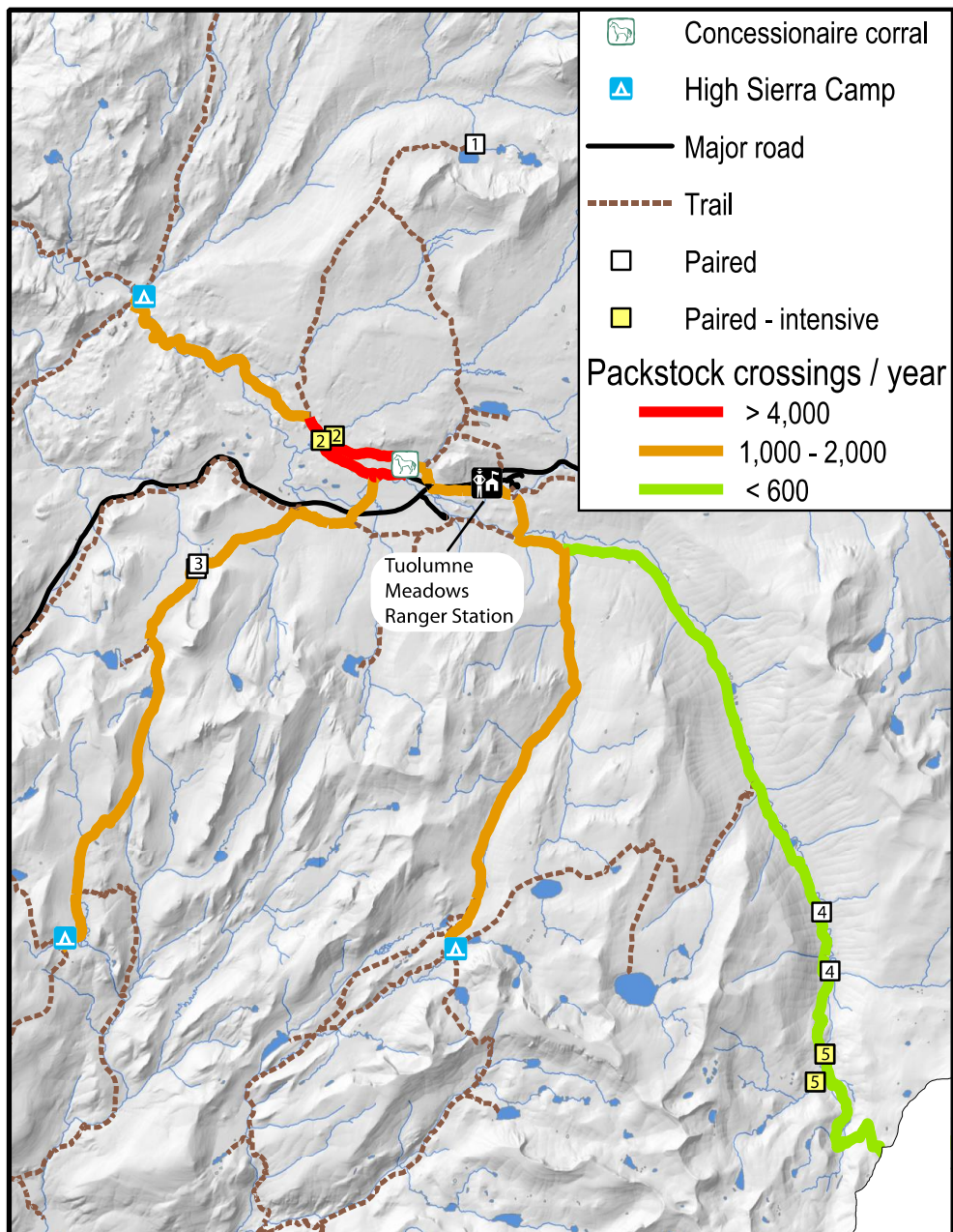
Fig. 4 Mean 2012-2014, annual packstock crossings on trails in the Tuolumne Meadows study area. Paired sampling locations(upstream/downstream): 1) Outlet Young Lakes, below outlet Young Lakes; 2) Delaney Creek above/below PCT; 3) Cathedral Spring above/below JMT; 4) Lyell Fork below Kuna Creek, Lyell Fork below Rock Camp; and, 5) Maclure Creek, Lyell Fork below Maclure Creek.

Reported overnight packstock use data in YOSE is limited to 2004-2014. Park-wide overnight packstock use declined during 2008 – 2011, then slightly increased during 2012-2014 (Fig. 3). The paired packstock grazing sampling locations in Lyell Canyon continued to receive the most overnight stock use in YOSE. However, overnight stock use in Lyell Canyon during the study period was only 50% of the long-term mean. During 2004 – 2011 and 2012-2014, the mean percent of total park-wide packstock use occurring in Lyell Canyon was 19% and 18%, respectively (Fig. 3); during 2012-2014, mean reported overnight packstock use in Lyell Canyon was 55% of the 2004-2011 mean (Fig. 3) (written communication, YOSE Wilderness Office).

Synoptic Sampling; Paired Sampling Upstream and Downstream from Meadows

The July 2014 synoptic water-quality survey targeted different types of visitor use and park operations, especially packstock grazing and High Sierra Camps, while attempting to maximize spatial distribution of sampling locations. Results from park-wide sampling indicated that *E. coli* concentrations generally were low, with 68% of sites at 0 or 1 CFU 100 ml^{-1} *E. coli* and 97 % of sites at less than 12 CFU 100 ml^{-1} *E. coli* (Fig. 5). The largest concentration of *E. coli* occurred downstream from a popular backpacker campsite on Illiluette Creek (>200 CFU 100 ml^{-1}), but no reference sample was collected upstream from the campsite. The second largest concentration of *E. coli* occurred at the outlet of May Lake (35 CFU 100 ml^{-1}),

downstream from May Lake High Sierra Camp, but again, no upstream reference sample was collected to represent natural background conditions. *Escherichia coli* samples collected downstream of popular packstock grazing areas at Matterhorn, Virginia, and Lyell Canyon sites yielded concentrations of less than 12 CFU 100 ml^{-1} (Fig. 5). Dissolved and particulate nutrients, and SSC concentrations were frequently below detection limits: PN (93% non-detects (ND)), TP (90% ND), NO_3 (46% ND), SSC (32% ND), TDN (23% ND).

Twelve meadows (Delaney Meadow, Lyell Canyon and 10 additional meadows) were bracketed, during the synoptic, with upstream and downstream sampling locations to test the hypothesis that environmental processes in meadows improve water quality. Repeated upstream and downstream paired sampling also occurred bi-weekly at Lyell Canyon Meadow during 2012-2014 and weekly at Delaney Meadow during 2013-2014. We tested for reduction in *E. coli* concentrations downstream from meadows; thus, we discarded paired samples from analysis if the upstream sample had 0 CFU 100ml^{-1}. This resulted in removal of 6 pairs at Delaney Meadow, 7 pairs at Lyell Canyon, and 4 pairs from the synoptic meadows. *E. coli* concentrations were significantly lower downstream from Delaney Meadow and Lyell Canyon, with respect to upstream locations, but not the synoptic meadows (Fig. 6). The largest difference in *E. coli* concentrations occurred at Delaney Meadow (median difference = 6 CFU 100 ml^{-1}), which is downstream from the packstock stream crossing on Delaney Creek (Fig. 1).

We investigated effects from visitor use and the influence of environmental factors on *E. coli* concentrations by fitting a Poisson GLM with basin characteristics and visitor use variables. We selected predictive variables based on the *a priori* hypothesis that visitor use variables will increase *E. coli* concentrations and environmental variables will either increase or decrease *E. coli* concentrations, depending on naturally occurring physical mechanisms (e.g. precipitation of fine-sediment adsorbed *E. coli* in low-flow velocities occurring in low-gradient meadows).

The initial set of predictive variables consisted of backpacker density, distance to the nearest trail, basin relative relief, basin percent forest cover, and basin average elevation. The initial model explained 49 percent of the variance in *E. coli* concentrations observed in the synoptic dataset. Model coefficients indicated that basin average elevation had a strong positive effect on *E. coli* concentration, but this effect was not mechanistically interpretable. Therefore, basin average elevation was removed from the set of predictive variables, which reduced the amount of variation in *E. coli* concentration explained by the model. Coefficients of the other predictive variables that are mechanistically interpretable did not change substantially. For example, the coefficient estimate and standard error for backpacker density changed from 2.02 and 1.22, respectively, in the initial model, to 1.83 and 1.19, respectively, in the final model.

The final Poisson GLM explained 32% of the variance in *E. coli* concentrations observed during the synoptic. Visitor use appeared to influence *E. coli*

concentrations; backpacker density had the largest effect (positive) on *E. coli*

concentrations, whereas distance from the nearest trail had a relatively weak

negative effect (Fig. 7). Basin relative relief and percent forest cover both had

positive effects on *E. coli* concentration (Fig. 7). Coefficients from the GLM were

standardized and exponentiated to compare the relative contribution of each

predictive variable. The exponentiated coefficient represents the multiplicative

change in the response variable for a one standard deviation increase in a given

predictive variable. Thus, values greater than one may be interpreted as a positive

effect, and values less than one as a negative effect.
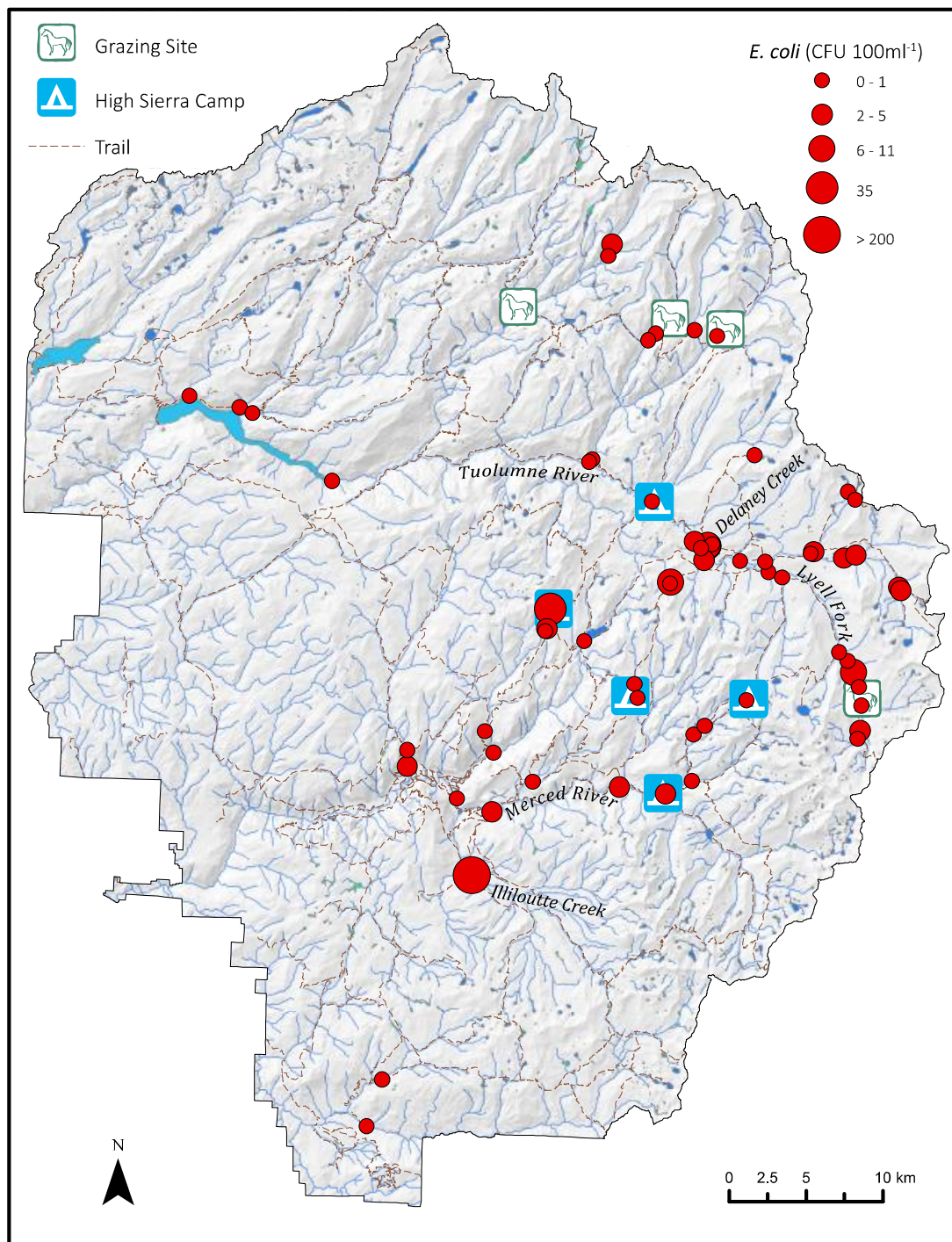
Fig. 5 *E. coli* concentrations from the park wide synoptic survey, July 7-10, 2014. High Sierra Camps in potential Wilderness additions, and four packstock grazing sites, which account for more than 50% of park-wide overnight packstock use (written communication, YOSE Wilderness Office).
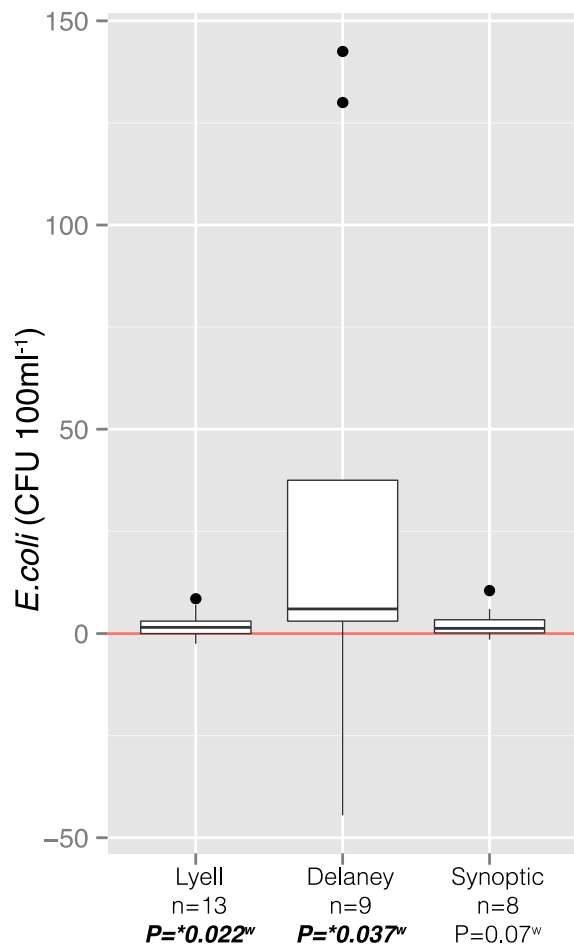
Fig. 6 Boxplots of differences (upstream – downstream) in *E. coli* concentration between paired meadow samples, positive values indicate a decrease in concentrations downstream from the meadow(s). P-values from one-tailed paired tests (w = Wilcoxon Signed Rank); alternative hypothesis: upstream>downstream; number of pairs. Median difference at Delaney Meadow: 6 CFU 100ml^{-1} *E. coli*; Lyell Canyon: 1.5 CFU 100ml^{-1} *E. coli*.

Standardized regression coefficient estimates
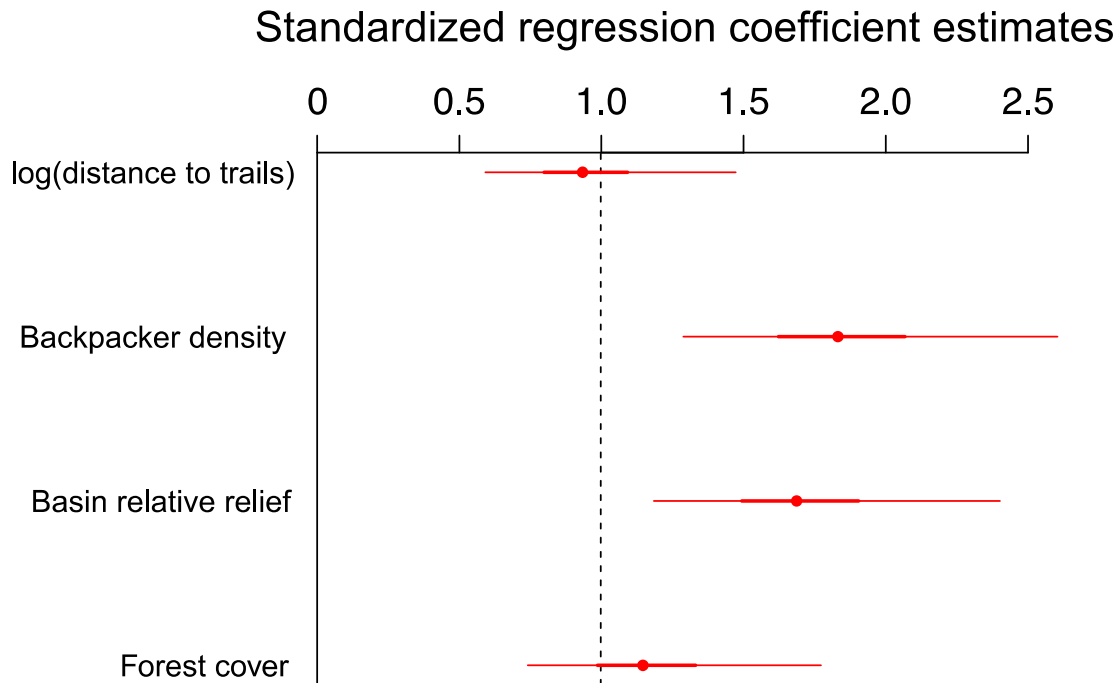
Fig. 7 Standardized and exponentiated regression coefficient estimates from the Poisson GLM of *E. coli* concentration in stream water during the park-wide synoptic sampling campaign. The exponentiated coefficient represents the multiplicative change in the response variable for a one standard deviation increase in a given predictive variable. Thus, values greater than one may be interpreted as a positive effect, and values less than one as a negative effect. Thin red lines are the 95% confidence interval for the estimated regression coefficient.

Concentrations at 5 Paired Sites during Routine Sampling.

We sampled upstream and downstream from specific types of visitor use to measure effects on water quality from specific types of visitor use. Generally, upstream/downstream paired sites had low concentrations and differences between upstream/downstream sites were small or undetectable (Table 1). Most water quality indicators did not significantly differ downstream from backpacker

campsites (Table 1). However, *E. coli* and SSC significantly increased downstream

from backpacker campsites on the Lyell Fork and NO_3 significantly increased

downstream from backpacker campsites at Young Lakes (Table 1). During 2012-

2014, the Lyell Fork received more backpacker camping than Young Lakes. Mean

estimated backpacker use-nights were 6,100 at the Lyell Fork PCT footbridge (Lyell

Canyon Zone) and 800 at Young Lakes (Conness Creek Zone) (Appendix A)(written

communication, YOSE Wilderness Office).
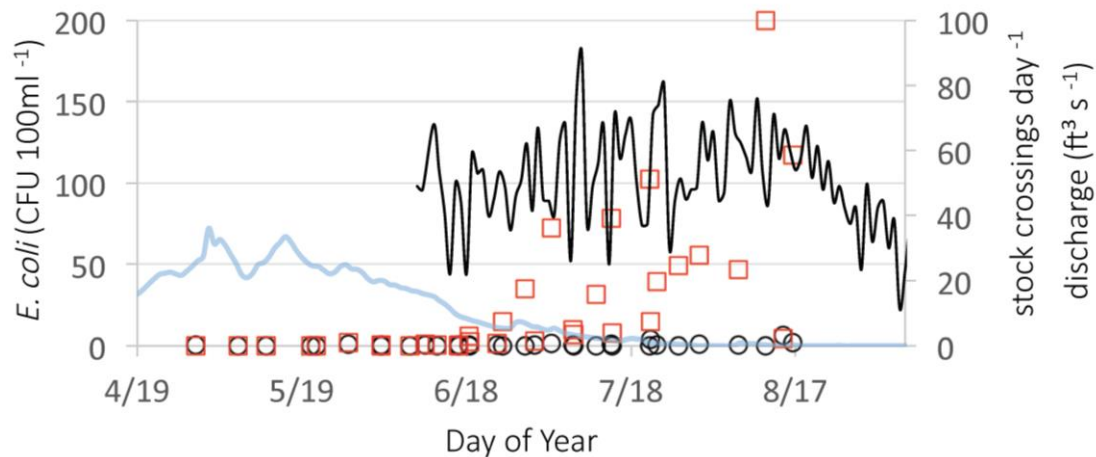
Fig. 8 Day of year vs. *E. coli* concentrations in stream water from routine samples collected 2012-2014, upstream (black circles) and downstream (red boxes) from the Pacific Crest Trail packstock stream crossing on Delaney Creek; mean discharge (blue line), and mean packstock crossings per day (black line); based on data from a motion-sensing camera installed immediately East of the packstock stream crossing.

In contrast to the backpacker campsites, concentrations of several water

quality indicators were significantly greater downstream from packstock stream

crossings than upstream (Table 1). With the exception of DOC at Cathedral Spring,

all water quality indicators had a better than 90% chance of being greater

downstream from packstock stream crossings than upstream (Table 1). Most

significant median differences in water quality indicator concentrations were larger downstream from packstock stream crossings than those observed downstream from backpacker campsites (Table 1).

Escherichia coli, SSC, and DOC concentrations significantly increased downstream from the PCT crossing of Delaney Creek and PC, SSC and NO_3 significantly increased downstream from the JMT crossing of Cathedral Spring (Table 1). Additionally, *E. coli* concentrations appeared to increase during the sampling season downstream from the packstock ford site at Delaney Creek, but not downstream from visitor use areas at other sites (Fig. 7, Appendix B). Compared to Cathedral Spring, Delaney Creek received more packstock crossings and has site characteristics that led to more direct physical interaction with the stream by packstock during crossings. Mean annual packstock crossings, median discharge during sampling events, and wetted width of the stream crossing were all higher at Delaney Creek compared to Cathedral Spring (4,500 vs 1,600, 5 cfs vs 0.2 cfs, and 10m vs 1m, respectively, as shown in Fig. 4). In contrast to the packstock-trail-use sites, water quality indicators did not significantly increase downstream from packstock grazing at the Lyell Canyon Meadow site (Table1). Notably, *E. coli* concentrations significantly decreased downstream from Lyell Canyon Meadow (Fig. 5). At most paired sites the TP and PN concentrations were below MDL for routine samples.

Table 1 Routine samples collected at paired monitoring locations. Water quality indicator and method detection limit (MDL); MDL for Total Phosphorous=0.004 mg L^{-1}; Particulate Nitrogen=0.017 mg L^{-1}. P values from one-tailed paired tests ([w] = Wilcoxon Signed Rank; [s] = Sign), alternative hypothesis: upstream<downstream; number of pairs; significant median-difference.

	backpacker use						stock trail use						stock grazing		
	Young Lakes			Lyell Fork at PCT			Cathedral Spring			Delaney Creek			Lyell Fork Meadows		
	Up<Down P-value	n	median diff	Up<Down P-value	n	median diff	Up<Down P-value	n	median diff	Up<Down P-value	n	median diff	Up<Down P-value	n	median diff
E. Coli (0 CFU 100ml^{-1})	0.203^w	10	-	**0.017^w**	18	1 **CFU 100ml^{-1}**	0.074^w	23	-	**<0.001^w**	36	3 CFU 100ml^{-1}	0.962^w	20	-
TDN (0.05 mg l^{-1})	0.756^s	11	-	0.764^w	16	-	0.055^s	14	-	0.095^s	34	-	0.308^w	19	-
PC (0.05mg l^{-1})	0.817^w	11	-	0.895^s	18	-	**0.014^w**	14	0.04 **mg l^{-1}**	0.055^s	34	-	0.895^s	19	-
SSC (0.1 mg l^{-1})	0.527^s	11	-	**0.046^s**	18	< 0.2 **mg l^{-1}**	**0.011^s**	13	0.2 **mg l^{-1}**	**0.002^s**	34	> 0.3 **mg l^{-1}**	0.212^s	19	-
NO$_3$ (0.007 mg l^{-1})	**0.002^s**	11	> 0.015 **mg l^{-1}**	0.962^w	17	-	**<0.001^w**	14	0.006 **mg l^{-1}**	0.089^s	34	-	0.890^w	19	-
DOC (0.2 mg l^{-1})	0.875^w	5	-	0.373^w	13	-	0.373^w	13	-	**0.011^w**	22	0.08 **mg l^{-1}**	0.767^w	13	-

Table 2 Median concentrations from routine sampling at paired backpacker sites

	Young Lakes		Lyell Fork at PCT	
	Upstream	Downstream	Upstream	Downstream
E. coli (CFU 100ml^{-1})	0.00	0.25	0.00	0.50
TDN (mg l^{-1})	0.087	0.056	0.144	0.138
PC (mg l^{-1})	0.213	0.186	0.111	0.120
SSC (mg l^{-1})	<0.1	0.4	<0.1	0.5
NO$_3$ (mg l^{-1})	<0.007	0.016	0.131	0.118
DOC (mg l^{-1})	1.38	1.17	0.55	0.56

Table 3 Median concentrations from routine sampling at paired packstock stream crossings

	Cathedral Spring at JMT		Delaney Creek at PCT	
	Upstream	Downstream	Upstream	Downstream
E. coli (CFU 100ml^{-1})	0.50	2.50	0.25	6.00
TDN (mg l^{-1})	<0.05	0.062	<0.05	0.054
PC (mg l^{-1})	0.122	0.139	0.081	0.098
SSC (mg l^{-1})	0.1	0.5	0.1	0.3
NO$_3$ (mg l^{-1})	0.010	0.015	<0.007	<0.007
DOC (mg l^{-1})	0.76	0.75	1.40	1.54

Table 4 Median concentrations from routine sampling at paired packstock grazing sites.

	Lyell Canyon Meadows	
	Upstream	Downstream
E. coli (CFU 100ml^{-1})	0.50	0.00
TDN (mg l^{-1})	0.131	0.137
PC (mg l^{-1})	0.135	0.111
SSC (mg l^{-1})	0.2	0.4
NO$_3$ (mg l^{-1})	0.109	0.098
DOC (mg l^{-1})	0.63	0.64

Concentrations at 2 Paired-intensive Sites during Storms

To measure concentrations during storms, when impacts from visitor use are most
likely to become evident, discrete samples were collected with automated samplers
at two pairs of intensive monitoring sites (Fig. 1). At these paired sites the in-situ
recorded turbidity and discrete sample concentrations increased substantially
during storms, both upstream and downstream from visitor use areas, relative to
steady flow conditions (Fig. 8). At automated sites associated with backpacker
camping (Lyell Fork below Maclure Creek and Maclure Creek), five storms were
sampled during 2013 and 2014 (Appendix C). Downstream from the backpacker
campsites (at the Lyell Fork below Maclure Creek), median SSC and PC increased
from 0.5 mg L^{-1} and 0.12 mg L^{-1} during routine sampling (Table 2), to 2.1 mg L^{-1} and
0.46 mg L^{-1} during storm sampling (Table 6), respectively. Maximum *E. coli*
concentrations during storms were an order of magnitude higher than during
routine sampling at Maclure Creek, (120 CFU 100 ml^{-1}) upstream from the
backpacker campsites, as well as downstream from the backpacker campsites at the
Lyell Fork below Maclure Creek (300 CFU 100 ml^{-1}) (Fig. 9). Differences between
storm samples collected upstream and downstream from backpacker campsites
indicated that only PC significantly increased downstream from backpacker
campsites during storms (Table 5).
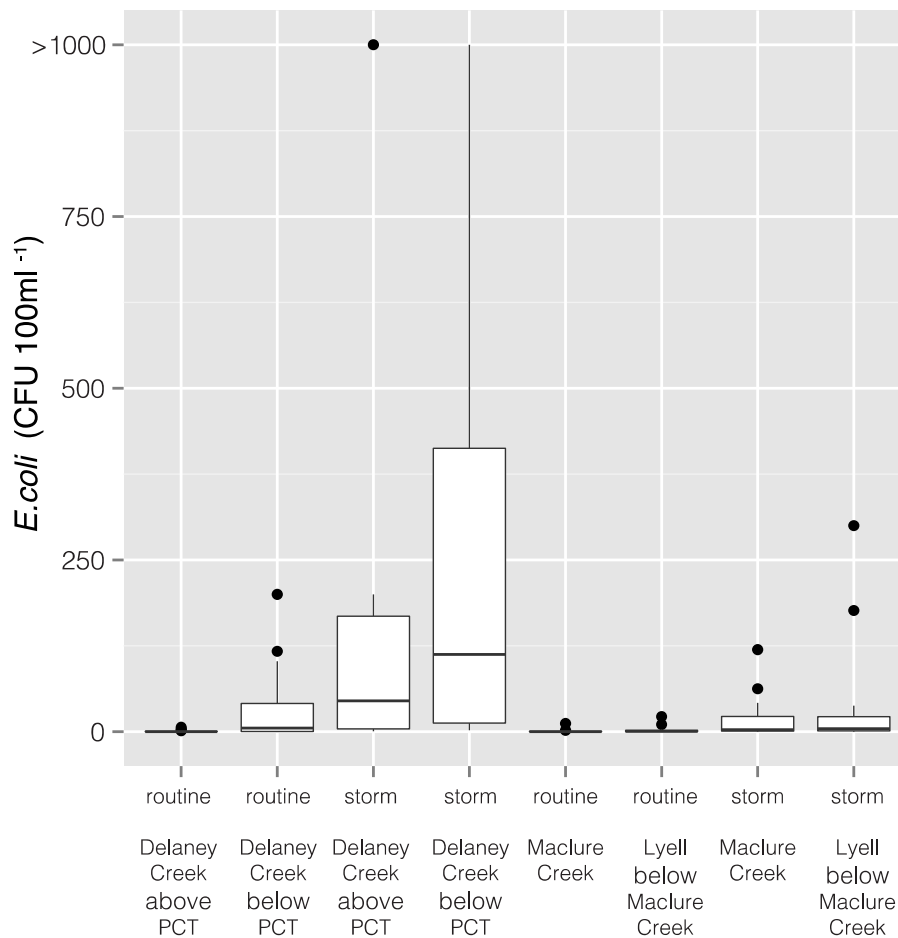
Fig. 9 Boxplots of *E. coli* concentrations in stream water at paired-intensive monitoring sites from routine sampling and storm sampling.

Similarly, five storm events were sampled at the packstock trail use sites (Delaney Creek) during 2013 and 2014. Downstream from the packstock ford site, median SSC, PC, and PN increased from 0.30 mg L^{-1}, 0.09 mg L^{-1}, and below MDL, during routine sampling (Table 2), to 14 mg L^{-1}, 2.96 mg L^{-1}, and 0.177 mg L^{-1}, during storm sampling (Table 6), respectively. *Escherichia coli* concentrations increased substantially during storms both upstream from the packstock ford site at Delaney Creek (1 measurement of >1000 CFU 100 ml^{-1}) and downstream from the

packstock ford site at Delaney Creek (3 measurements of >1000 CFU 100 ml^{-1} (Fig.

8)). In contrast to the backpacker camping sites, differences between

upstream/downstream storm samples at the packstock ford site indicated that

several other parameters also significantly increased downstream from the

packstock ford site during storms (see PC, SSC, DOC in Table 5).

Table 5 Discrete storm samples collected at paired-intensive monitoring locations. Water quality indicator and method detection limit (MDL), P-values from one-tailed paired tests ([w] = Wilcoxon Signed Rank; [s] = Sign), alternative hypothesis: upstream<downstream; number of pairs; significant median-difference.

	backpacker use			stock trail use		
	Lyell Fork at PCT			Delaney Creek		
	Up<Down P-value	n	median diff	Up<Down P-value	n	median diff
E. Coli (0 CFU 100ml^{-1})	0.078[w]	9	-	**<0.001[s]**	18	32 CFU 100ml^{-1}
TDN (0.05 mg l^{-1})	0.951[w]	8	-	0.113[s]	17	-
PC (0.05mg l^{-1})	**0.004[w]**	8	**0.12 mg l^{-1}**	**0.022[w]**	17	**0.45 mg l^{-1}**
SSC (0.1 mg l^{-1})	0.714[w]	14	-	**0.025[s]**	17	**2.9 mg l^{-1}**
NO3 (0.007 mg l^{-1})	0.979[w]	11	-	0.227[s]	17	-
DOC (0.2 mg l^{-1})	0.763[w]	11	-	**0.006[w]**	17	**0.11 mg l^{-1}**
TP (0.004 mg l^{-1})	0.865[w]	6	-	0.179[s]	17	-
PN (0.017 mg l^{-1})	0.102[w]	8	-	0.304[s]	17	-

Table 6 Median concentrations in stream water from storm samples collected at two paired-intensive monitoring sites.

	Lyell Fork at PCT		Delaney Creek	
	Upstream	Downstream	Upstream	Downstream
E. coli (CFU 100ml^{-1})	3.0	4.5	45	112.5
TDN (mg l^{-1})	0.233	0.154	0.125	0.203
PC (mg l^{-1})	0.638	0.460	1.378	4.795
SSC (mg l^{-1})	3.0	1.7	4.2	21.7
NO$_3$ (mg l^{-1})	0.136	0.127	<0.007	<0.007
DOC (mg l^{-1})	1.62	1.01	1.89	3.84
TP (mg l^{-1})	0.0057	<0.004	0.1759	1.0287
PN (mg l^{-1})	0.0360	0.0390	0.0855	0.2545

To fill in gaps between discrete autosampler-collected samples during storms, and to document storm dynamics, in-situ continuous turbidity measurements were used to predict 10-minute interval concentrations of PC, PN, and SSC. Turbidity based log-linear models were established for SSC at the backpacker-camping sites, and for PC, PN, and SSC at the packstock trail-use sites (Appendix C). During three storm events (7/20/2013, 8/19/2013, 7/14/2014), downstream from the backpacker campsites, spikes in turbidity and predicted suspended sediment concentration occurred at the onset of storms. The lag between peak turbidity and predicted SSC was shorter downstream from backpacker campsites than upstream (Fig. 10, Appendix C). During the same storm events, upstream from backpacker campsites, peak turbidity and predicted SSC were generally less than downstream from the backpacker campsites, and aligned with peak discharge, after rain had stopped (Fig. 9, Appendix C). The spikes in turbidity

and predicted SSC that occurred downstream from backpacker campsites may indicate enhanced erosion from compacted soils in and around backpacker campsites.
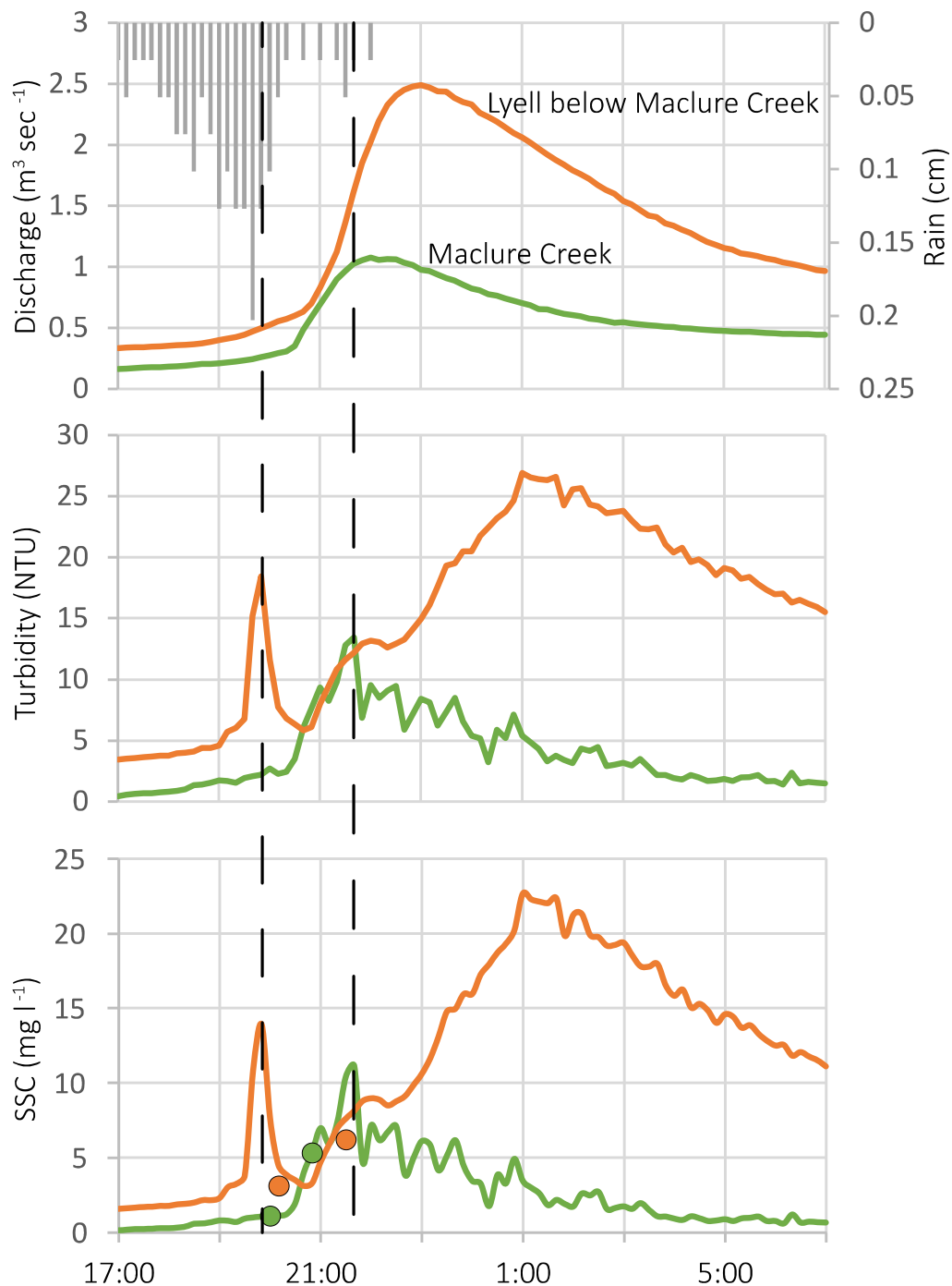
Fig. 10 Continuous discharge, rain (grey bars), turbidity, predicted (lines) and observed (circles) suspended sediment concentration (SSC) in stream water during a storm event on August 19-20, 2013. Green lines and circles = Maclure Creek, orange lines and circles = Lyell below Maclure Creek; vertical dashed lines indicate the time of peak turbidity and predicted SSC at each site.

Table 7 Observed rainfall (total and maximum 10 minute intensity), and predicted maximum concentrations and maximum differences (downstream – upstream) of suspended sediment concentration (SSC), particulate carbon (PC), and particulate nitrogen (PN) in stream water, during three summer storms at the Delaney Creek paired-intensive monitoring sites.

	date	total rain (cm) (max 10 min)		date	total rain (cm) (max 10 min)		date	total rain (cm) (max 10 min)	
	7/3/2013	0(0)		7/25/2013	1.6(0.64)		7/16/2014	1.04(0.99)	
	max upstream	max downstream	max diff	max upstream	max downstream	max diff	max upstream	max downstream	max diff
SSC (mg l^{-1})	2.2	8.2	6.1	147.2	845.7	773.8	44.4	88.9	73.5
PC (mg l^{-1})	0.7	1.71	1.04	7.04	50.4	45.66	6.02	21.91	17.49
PN (mg l^{-1})	0.04	0.11	0.06	0.37	5.86	5.59	0.33	1.04	0.79

At the packstock stream crossing sites, continuous turbidity records were interrupted by lightning interference during some storm events, thus only three storms were analyzed for continuous concentrations. Generally, during each storm, upstream/downstream maximum differences calculated from turbidity based prediction of peak concentration during storms were substantially higher than median differences between autosampler-collected discrete samples (Table 7).

At the upstream/downstream packstock stream crossing sites, the largest concentrations of SSC, PC, and PN occurred during storms on 7/25/2013 (Fig. 10).

During storms on 7/25/2013, the maximum difference (downstream – upstream) between discrete samples for SSC, PC, and PN where 920.4 mg L^{-1}, 42.51 mg L^{-1}, and 7.236 mg L^{-1}, respectively (Fig. 10); the maximum differences between predicted values were less than the maximum differences between observed discrete values for SSC and PN, but not for PC (Table 7, Fig. 10). During storms on 7/16/2014, the maximum difference between discrete samples for SSC, PC, and PN where 33.75 mg L^{-1}, 5.96 mg L^{-1}, and 0.278 mg L^{-1}, respectively; maximum differences between predicted values for SSC, PC, and PN were substantially higher than indicated by the discrete samples (Table 3). During storms on 7/3/2013, the maximum difference between discrete samples for SSC, PC, and PN where 2.4 mg L^{-1}, (- 0.41 mg L^{-1}), and (- 0.033 mg L^{-1}), respectively; again, the maximum differences between predicted values for SSC were substantially higher than indicated by the discrete samples, and predicted PC and PN values indicated a greater concentration downstream from the packstock ford site, rather than a smaller concentration (negative difference) downstream from the packstock ford site, as indicated by discrete samples (Table 3).

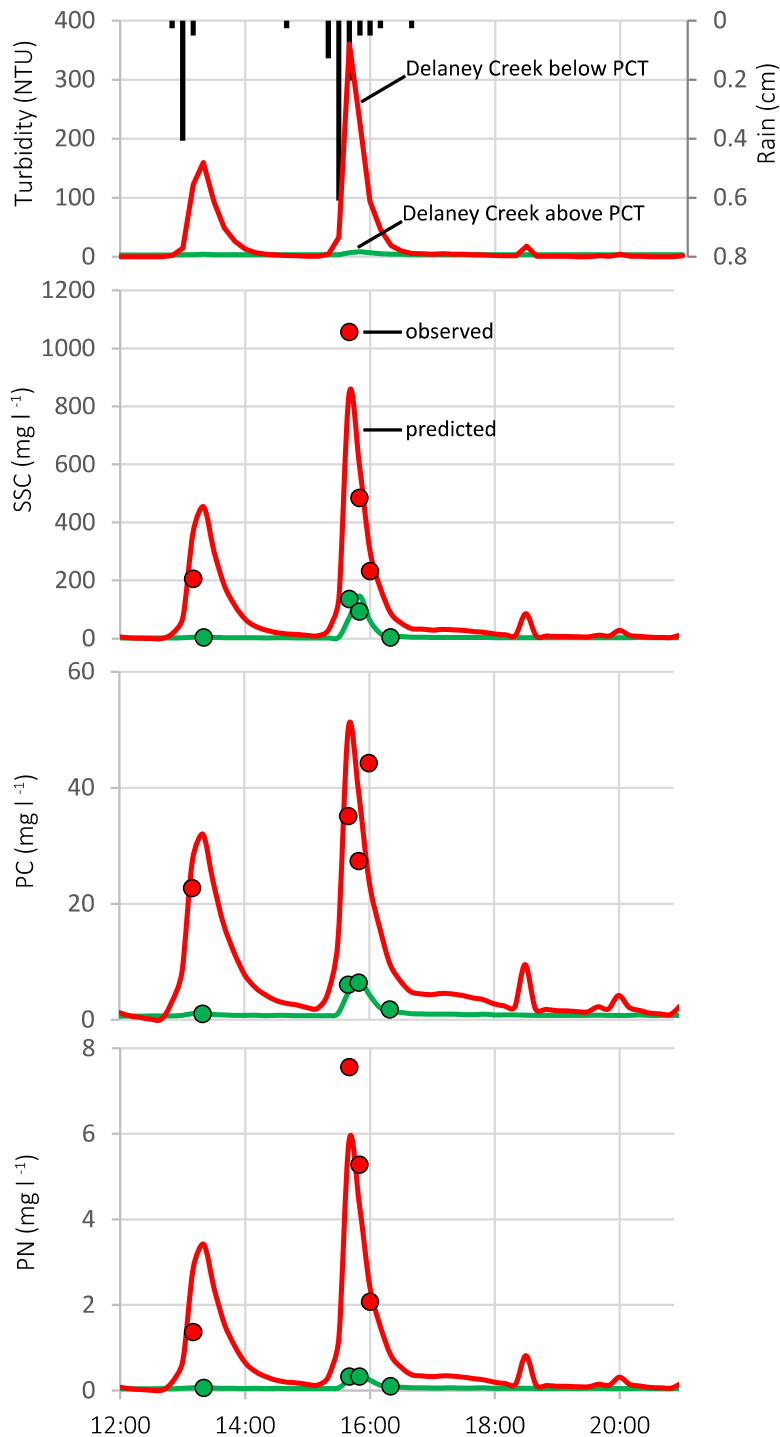**Fig. 11** Continuous turbidity (red and green lines), rain (grey bars), predicted and observed suspended sediment concentration (SSC), particulate carbon (PC), and particulate nitrogen (PN) concentrations in stream water during a storm event on on July 25, 2013. Green lines and circles = Delaney Creek above the PCT packstock ford site; red lines and circles = Delaney Creek below the PCT packstock ford site.

Hormones

During steady flow conditions the concentrations of hormones in water samples were below MDL at all sites except at the Lyell Fork below Rock Camp, where estrogen hormones were detected (Appendix D). During storms, androstene was detected in two storm samples at Delaney Creek below the PCT packstock ford site; concentrations in the corresponding Delaney Creek storm samples collected upstream from the PCT packstock ford site were below MDL (Appendix D). Storm samples collected at the paired backpacker campsites (Maclure Creek, Lyell Fork below Maclure Creek) were below MDL for all constituents.

Concentrations of hormones in sediment samples were below MDL for most constituents at most sites. Androstene was detected at both upstream/downstream sites on Delaney Creek, but concentrations were greater downstream from the ford site than upstream. Androstene concentrations were below MDL at both upstream/downstream sites on Cathedral Spring (Appendix D). Coprostanol was detected in sediment samples downstream from the packstock stream crossings at Delaney Creek and Cathedral Spring; Coprostanol concentrations were greater downstream from stream crossings than upstream. At Delaney Creek, Coprostanol concentrations were below MDL at the upstream site, whereas at Cathedral Spring, Coprostanol was detected at the upstream site. (Appendix D).

Discussion

The purpose of this study was to quantify specific types of visitor use in Wilderness in Yosemite National Park and to measure the impacts of specific types of visitor use on water quality. Our visitor use data show that backpacker use is increasing steadily, but overnight packstock use is substantially less than historic levels and packstock trail use is consistently high on trail segments used by YOSE concessionaire operations.

Our water quality data show that the largest effects from visitor use on water quality occurred during storms, downstream from the packstock ford site on Delaney Creek, which received an average of 4,500 packstock crossings annually. Comparison of storm dynamics upstream and downstream from backpacker campsites suggests that effects from backpacker camping on water quality likely occur at the onset of storms, possibly from enhanced erosion of compacted soils in backpacker campsites. Results from park-wide synoptic sampling shows that during steady flow (non-storm) conditions, concentrations of *E. coli*, nutrients and suspended sediments are low at most sites in YOSE Wilderness and effects on water quality from visitor use in Wilderness are usually below detection limits with the methods used in this study. However, repeated paired sampling upstream and downstream from specific types of visitor use revealed greater concentrations downstream from backpacker campsites and packstock stream crossings than

upstream. Among the sites where greater downstream concentrations were detected, the largest effects occurred downstream from packstock stream crossings. We detected estrogen hormones, a contaminant of emerging concern (CEC), in water that indicate a human source of contamination. Caprostanol, a hormone found in fecal matter from humans and higher order animals, was detected in sediment samples downstream from packstock stream crossings and provided additional evidence of fecal contamination below packstock stream crossings.

Visitor Use Accounting:

We showed that park-wide backpacker-use reached a recent high in 2014, while overnight packstock use in Lyell Canyon meadow, the most popular grazing area in YOSE, was only 50% of the 2004 - 2011 mean. During 2012-2014, NPS concessionaire operations generated 1,000 – 5,000 packstock crossings on trail-segments that access High Sierra Camps and are used for recreational day-rides. By comparison, less than 600 packstock crossings occurred on trail-segments used for overnight commercial and administrative packstock use.

Backpacker Use:

The strongest evidence of effects from backpacker use on water quality occurred during storms. Measurement of potential effects from backpacker camping on water

quality during storms has not been attempted before. However, in the field of
recreation ecology, numerous studies have documented soil compaction and
decreased infiltration rates, which implies increased runoff rates, enhanced erosion,
and effects on water quality during storms as a result of backpacker camping (Cole
1983; Cole 1986; Monz et al 2010). In this study, sharp increases in turbidity and
predicted suspended sediment concentrations downstream from backpacker
campsites, on the Lyell Fork below Maclure Creek, at the onset of storms might
indicate enhanced erosion from compacted soils around backpacker campsites.

Greater concentrations of a few water quality indicators occurred
downstream from backpacker campsites during steady flow conditions, but
generally, these upstream/downstream differences were small. Low concentrations
of *E. coli* and nutrients during steady flow conditions have been documented by
other water quality monitoring studies in the Sierra Nevada (Clow et al 2011; Clow
et al 2013; Roche et al 2013). These studies did not detect changes in water quality
downstream from backpacker campsites. Clow et al (2011) used an
upstream/downstream routine sampling framework, targeting steady flow
conditions, at two pairs of backpacker campsites in Sequoia and Kings Canyon
National Parks (SEKI). However, paired sampling (n=8) at backpacker sites in SEKI
only occurred for 2 years; the substantially larger sample size (n=18) in this study in
YOSE provided more statistical power to detect significant increases in *E. coli* and
SSC. This is one of few studies to detect estrogen hormones in a Wilderness setting.
Estrogen compounds were also detected in water and sediment samples collected in

Rocky Mountain National Park (Bradley et al 2016). However, little is known about the persistence and relative importance of these compounds and other emerging threats to water quality, specifically from backpacker use, in Wilderness.

Packstock Trail Use:

The strongest evidence of effects from packstock stream crossings on water quality occurred during storms. Upstream/downstream differences were greater during storms than during steady flow conditions and data from continuous turbidity-based predictions revealed even larger differences between upstream/downstream sites than indicated by discrete storm samples alone. Although a previous study modeled erosion and sediment delivery to streams at packstock stream crossings (Kidd et al 2014), this is the first study to measure effects from packstock stream crossings on water quality during steady flow conditions and during storms. During steady flow conditions, detectable changes in water quality occurred downstream from packstock stream crossings that received a measured 1,000 – 5, 000 packstock crossings annually, this result is consistent with other studies on erosion rates from trails receiving different types of trail use (i.e., humans, lamas, horses) (Deluca et al 1998), and corresponds with findings on effects from packstock stream crossings on downstream aquatic ecology (Kidd et al 2014; Holmquist et al 2015). Generally, our observations of greater *E. coli*, nutrient, and suspended sediment concentrations downstream from packstock stream crossings are consistent with observations

from agricultural settings (Davies‑Colley et al 2004) and experimental studies

(McDaniel et al 2013).

Additionally, concentrations of *E. coli* appeared to increase during the

sampling season downstream from Delaney Creek, the most heavily used packstock

stream crossing in the study area, which received 4,000 – 5,000 stock crossings

annually. In contrast, downstream from the packstock stream crossing on Cathedral

Spring, which received 2,000-3,000 fewer stock crossings annually than Delaney

Creek, *E. coli* concentrations did not appear to increase during the sampling season.

This result highlights the importance of both total number of crossings and direct

physical interaction with streams. The ford site on Cathedral Spring has a shorter

wetted-width than Delaney Creek and thus received less direct fecal deposition and

less direct physical disturbance of the stream channel by packstock during

crossings. This observation corresponds with other studies that show physical

interaction (i.e., crossing distance) and animal behavior during stream crossings

(i.e., watering, fecal deposition) to be important factors leading to streambed

disturbance and fecal deposition (Davies‑Colley et al 2004; McDaniel et al 2013;

Kidd et al 2014).

Packstock Grazing:

Surprisingly, during steady flow conditions, water quality indicator concentrations

were not greater downstream than upstream from packstock grazing in Lyell

Canyon meadow, the most popular packstock grazing area in YOSE, which received a reported 150 – 250 packstock use nights annually. Results from repeated upstream/downstream sampling at Lyell Canyon and Delaney Creek meadows suggest that during steady flow conditions environmental processes in meadows reduce *E.coli* concentrations. This, in turn, suggests that inputs from packstock grazing in Lyell Canyon were either too small to be detectable or where mitigated by environmental processes occurring in the meadow.

This result contrasts sharply with results from other findings related to packstock grazing in the Sierra Nevada (Derlet 2006; Clow et al 2013). Derlet and Carlson (2006) measured *E. coli* concentrations at 200 CFU 100 ml^{-1} from a single sample collected in YOSE at an unspecified sampling location in "Lyell Canyon". However, the resolution of their sampling method was ± 100 CFU 100 ml^{-1} *E. coli*. Thus, a 100 ml sample containing 2 CFU *E. coli* would generate a sample result of 200 CFU 100 ml^{-1} *E. coli*, ranging 18-100 times higher than *E. coli* concentrations consistently measured in this study at locations throughout Lyell Canyon. Differences in study methods, including this potential for overestimation of *E. coli* concentrations reported by Derlet and Carlson (2006), have been highlighted before (Clow et al 2013; Roche et al 2013).

In SEKI, Clow et al. (2013) measured greater *E. coli* and nutrients concentrations downstream from three meadows frequently grazed by packstock. Meadow gradient (i.e., longitudinal slope) at the packstock grazing sites examined in SEKI is generally higher than Lyell Canyon Meadow in YOSE. Hydrologic

characteristics driven by reach-scale gradient (i.e., high-energy reach vs low-energy reach) influence the suspension of fine-sediment adsorbed *E. coli* bacteria (Piorkowski et al 2014). Mean discharge on the Lyell Fork (50 cf s^{-1}) from 2012-2014 is larger than the discharge on Big Sandy Creek (5 cf s^{-1}) and Whitney Creek (40 cf s^{-1}) in the 2010-2011 SEKI study (Clow et al 2013). Packstock use in the SEKI meadows from 2010-2011 averaged 275 packstock nights, nearly twice the amount in Lyell Canyon Meadow during 2012-2013 (Fig. 3) (Clow et al 2013). This combination of meadow characteristics, hydrology, and amount of packstock use may have contributed to decreases in *E. coli* downstream from Lyell Canyon Meadow and Delaney Meadow. The decrease in *E. coli* downstream from Lyell Canyon Meadow and Delaney Meadow is consistent with observations in other studies that have documented reach-specificity in *E. coli* concentrations (Drummond et al 2014; Piorkowski et al 2014). It is also consistent with model results in Clow et al. (2013) that found a positive relationship between *E. coli* and basin relief, though basin relief was evaluated at the sub-basin scale, not the reach-scale (Clow et al 2013).

Although resource constraints precluded installation of storm monitoring equipment at the paired packstock grazing sites in Lyell Canyon, reduction of *E. coli* concentrations in meadows during steady flow conditions implies that during storms, when concentrations of *E.coli* are elevated, meadows might provide a similar, and potentially larger reduction in microbial concentrations. Additionally, experimental work has shown that during simulated rainfall events, flat (5% slope)

vegetation buffer strips are capable of markedly reducing microbial concentrations from fecal contamination in runoff water (Tate et al 2004). Because the paired meadows in this study had a percent slope between 0-6% (measured by a 10 m digital elevation model), lateral inflow of fecal matter from packstock grazing in meadows might be reduced by vegetation in meadows, mitigating the transport of fecal matter from meadows into streams during storms.

Effects from Visitor Use and Environmental Processes:

Results from the GLM show that *E. coli* concentration has a positive relationship with backpacker density and a negative relationship with distance from trails. Of the predictive variables selected, we found that backpacker density had the strongest influence on *E. coli* concentrations. The positive relationship with basin relief provides additional evidence that environmental processes in flat meadows might decrease *E. coli* concentrations, and the positive relationship with forest cover suggests that allochthonous input from forests may have a small positive effect on *E. coli* concentrations. In SEKI, Clow et al (2013) used a GLM framework to predict E. coli concentrations from a synoptic survey and also found a positive relationship between basin relief and E. coli concentrations. The predictive ability (32% of variance explained) of our GLM is less than the GLM developed by Clow et al (2013) and highlights the need for verification with additional testing in other locations.

Large impacts during storms suggest that hydrologic conditions are a central factor determining the detectability of effects from visitor use on water quality. During this study, annual hydrologic conditions were dry, which likely increased the overall detectability of impacts during steady flow conditions at most locations. With wetter hydrologic conditions, inputs from visitor use could be diluted below detection limits. However, without the occurrence of storms, substantial impacts on water quality related to erosion and fluvial transport of fecal matter, suspended sediments, and nutrients from upland areas into streams would not occur. If summer thunderstorms increase in frequency and intensity as global temperatures rise, then storm-related effects from visitor use on water quality could also increase.

Limitations:

Measuring effects from specific types of visitor use in Wilderness is confounded by the pervasive overlap of different types of visitor use. Regardless of how dominant a given type of visitor use may be, most sites represent a mixture of backpacker use and packstock use. Trails that are used by packstock are also used by backpackers and day hikers. The PCT packstock stream crossing on Delaney Creek received an average of 4,500 packstock crossings and 16,000 hiker crossings each season during this study (as documented by our motion sensing camera). Although backpackers and day hikers crossing Delaney Creek typically avoid fording the creek, the compaction of "social trails" used by backpackers and day hikers to access logs and

other optimal stream crossing points may also contribute to erosion and subsequent increases in SSC during storms. Similarly, meadows that receive overnight packstock use also have backpacker campsites in close proximity. Lyell Canyon Meadow received an average 150 packstock nights each season, the highest amount of any meadow in YOSE, and the Lyell Canyon Wilderness-use-zone received an average 6,100 backpacker use nights (written communication, YOSE Wilderness Office). The detection of estrogen hormones that are from human sources, downstream from Lyell Canyon meadow, the sampling location selected to characterize effects from packstock grazing, (see Fig. 1, Lyell Fork below Rock Camp) highlight the difficulty of characterizing effects from specific types of visitor use.

Quantifying visitor use in Wilderness poses a challenge, and predicting water quality based on visitor use intensity and environmental variables has been shown by this and a previous study (Clow et al 2013) to be difficult. Statistical modeling of water quality with visitor use variables is primarily limited by the predominantly small effect size of visitor use on water quality. Additionally, the logistical constraint of accessing numerous remote sampling locations in rugged terrain leads to small sample sizes. Spatial resolution of visitor use data is limited by the inability to accurately measure Wilderness use at a site-specific spatial scale. Each of these factors contributes to a lack of predictive capability in spatially distributed statistical approaches.

3. Conclusions and Recommendations

This study evaluated effects from specific types of visitor use (packstock use and backpackers) on water quality in Wilderness in Yosemite National Park using novel methods. We utilized telemetry and continuous turbidity measurements at Wilderness sites to improve storm sampling and enable robust assessment of water quality upstream and downstream from visitor use areas during storms. These methods improved our ability to detect changes in water quality during storms, when the greatest effects on water quality from visitor use are likely to occur. The largest effects on water quality observed in this study occurred during storms, downstream from a packstock stream crossing that received an average of 4,500 crossings annually. Comparison of storm dynamics upstream and downstream from backpacker campsites suggests that enhanced erosion from compacted soils in backpacker campsites affects water quality at the onset of storms.

During steady flow (non-storm) conditions, concentrations of *E. coli*, nutrients and suspended sediments are low at most sites in YOSE, with notable exceptions associated with backpacker camping and NPS concessionaire operations. We detected changes in water quality at both pairs of routinely sampled backpacker campsites and at both pairs of routinely sampled packstock stream crossings. These changes were larger downstream from packstock stream crossings than downstream from backpacker campsites. At packstock stream crossings, the

greatest effect occurred downstream from the stream crossing that received the

greatest amount of packstock crossings (Delaney Creek). In contrast to packstock

stream crossings, however, packstock meadow grazing did not appear to affect

water quality indicator concentrations downstream from Lyell Canyon Meadow, the

most popular packstock grazing area in YOSE. Repeated sampling upstream and

downstream from meadows indicated that environmental processes in meadows

provide a valuable ecosystem service by mitigating microbial concentrations

contributed from natural and visitor-use-related inputs.

Implications for Management:

Evidence from this study shows that the largest effects on water quality from visitor

use occur at heavily-used packstock stream crossings, and these effects are

substantially larger during storms than during steady flow conditions. In Yosemite

National Park, high levels of packstock trail use only occur on trail segments used

for concessionaire operations; thus, effects on water quality from packstock stream

crossings can be mitigated by direct management intervention at a few important

stream crossings, including Delaney Creek and Cathedral Spring.

Effects on water quality from packstock trail use can be mitigated by

reducing the total number of packstock crossings that a given stream crossing

receives, or by altering the stream crossing to reduce direct physical disturbance

and fecal deposition from packstock during crossings. Additionally, construction of

erosion control structures on trail approaches to stream crossings would reduce

lateral inputs of eroded sediment and transported fecal matter from adjacent trails

during storms. Because waste from packstock on trails is unmanaged, even with an

improved stream crossing design, effects on water quality will likely persist if total

packstock crossings remain at current levels (e.g. 4, 500 annual crossings at Delaney

Creek).

Backpacker use in YOSE is steadily increasing. Similar to packstock trail use,

the majority of backpacker use is concentrated in known high-use areas. Therefore,

specific campsites of concern could be managed directly to reduce potential effects

on water quality. Erosion of compacted soils in campsites, for example, poses a

threat to water quality, particularly in campsites with direct hillslope - stream

channel connectivity. Also, when campsites are located close to streams (< 60 m)

(LNT 2015), they may pose a greater threat to water quality. Campsites with direct

hillslope - stream channel connectivity, which are also located close to streams

could be managed to receive fewer backpacker use nights. Restoration of ground

cover vegetation around such campsites could further mitigate effects on water

quality by providing a vegetative buffer strip, which has been shown to reduce

transport of suspended sediment and fecal matter into streams.

Recommendations for Future Work:

Among the water quality indicators used in this study, fecal indicator bacteria (*E. coli*), suspended sediment, and particulate nutrients provided the most utility in detecting water quality impacts from visitor use. These water quality indicators are directly related to the physical mechanisms of streambed disturbance and direct deposition of fecal matter into streams during steady flow periods and to runoff from the surrounding landscape during storms. Dissolved nitrogen and phosphorous samples did not indicate effects from visitor use at most sites, which suggests that at current use levels the nutrients contributed from fecal deposition are too low to be detected. In alpine, oligotrophic environments, these nutrients are likely to be internally cycled very efficiently, making them ineffective indicators of effects on water quality. Future studies would save resources by not using these constituents as indicators.

Water quality assessment and the maintenance of *in situ* monitoring equipment in Wilderness is labor intensive. To avoid excessive costs and findings of no-effect, most studies will target areas that are known to receive large amounts of use. Our results show that even with a targeted approach, water quality indicator concentrations during steady flow conditions are likely to be low. Because sediment accumulates through time and integrates deposition from steady flow and storm conditions, sediment sampling provides an efficient addition to water sampling and may provide a general indication of fecal contamination from humans and other large animals (e.g., coprostanol concentrations). This tool could potentially provide useful information without a prolonged study period and with fewer personnel.

In Yosemite National Park, aside from a small number of intensely used areas, effects on water quality from visitor use in Wilderness are difficult to detect. Although random sampling across randomly applied treatments theoretically yields an inference that is generalizable, sample sets collected from the global (true) population of sampling locations found in Wilderness will typically result in numerous non-detects and findings of no-effect. Given the concentrated geographic distribution of visitor use in Yosemite National Park, targeted sampling of known high-use areas is an important study design component that should be used in addition to random sampling. For example, synoptic surveying of water quality in YOSE indicated that during steady flow conditions, *E. coli*, nutrients, and suspended sediment concentrations are low or below method detection limits at most locations. However, the synoptic survey identified two locations with substantially higher concentrations of *E. coli,* these locations should be further investigated with a paired upstream/downstream sampling design. Targeted sampling at these two locations would extend the utility of synoptic sampling by confirming or negating a persistent source of fecal contamination related to visitor use.

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Appendix A: Spatial distribution of backpacker use

Twin Lakes
Tilden Lake
Kerrick Canyon
Kibbie Creek
Frog Creek
Benson Lake
Virginia Canyon
Matterhorn Canyon
McCabe Lakes
Lake Vernon
Laurel Lake
Non-Wilderness
Tiltill Valley
Rancheria Mountain
Pleasant Valley
Non-Wilderness
Cold Canyon
Conness Creek
Miguel Meadow
Cottonwood Creek
Pate Valley
Waterwheel Falls
Glen Aulin
Dog Lake
Ten Lakes
South Fork Tuolumne River
Grant Lakes
Mono Parker Pass
Cathedral Lakes
Elizabeth Lake
May Lake
Rafferty Creek
Evelyn Lake
Lyell Canyon
Yosemite Creek
Snow Creek
Sunrise Lakes
Echo Creek
Vogelsang
Non-Wilderness
Half Dome
Sunrise Creek
Lewis Creek
Merced Lake
Mount Lyell
Little Yosemite Valley
Bridalveil Creek
Illilouette Creek
Washburn Lake
Buena Vista Creek
Clark Range
Ostrander Lake
Alder Creek
Wilderness Zones
Major roads
South Fork Merced River
Chilnualna Creek
Johnson Creek

N

0   10
km

Fig. 12 Wilderness use zones in Yosemite National Park.
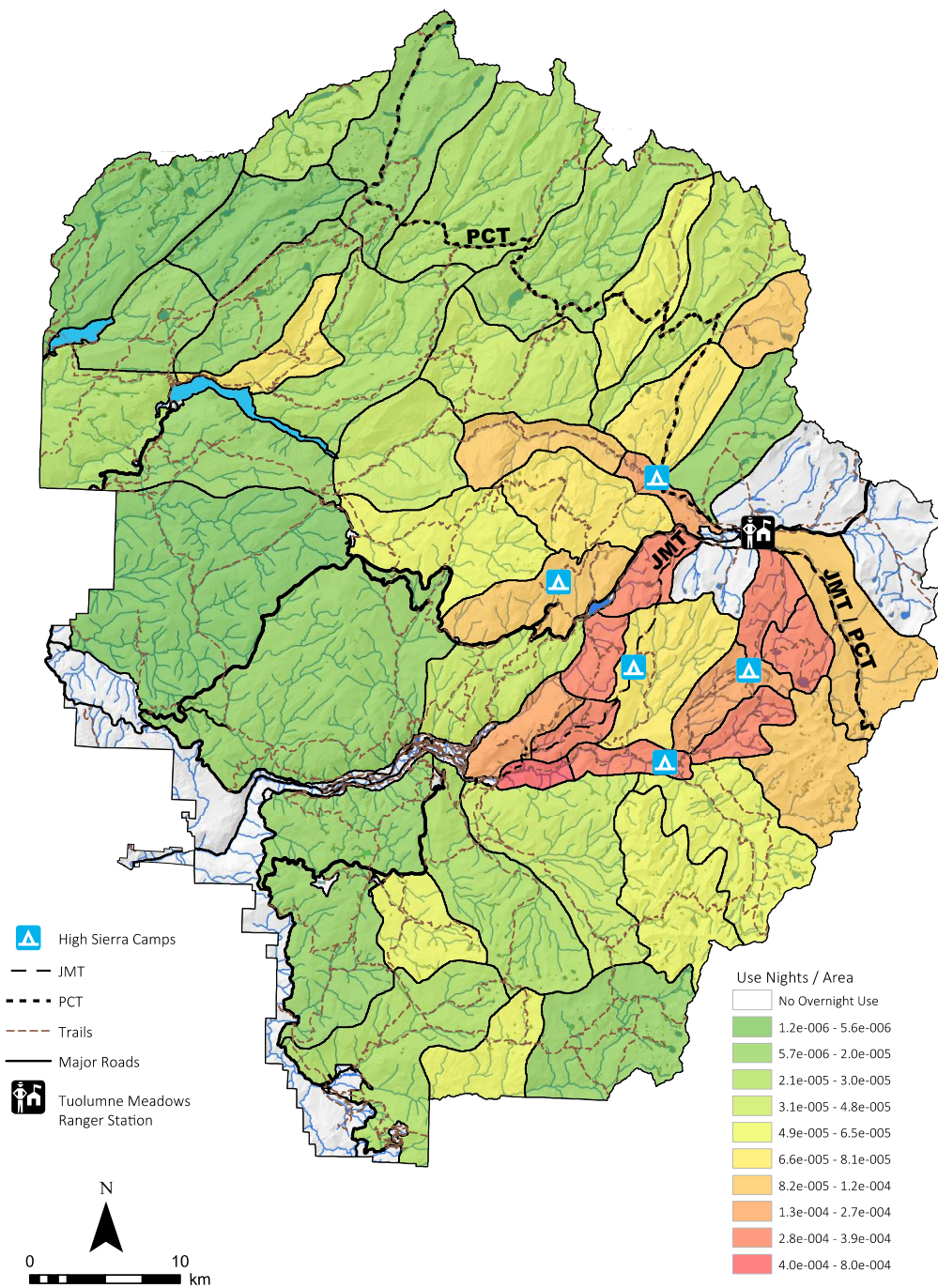
Fig. 13 Mean (2012-2014) estimated annual backpacker use by Wilderness zone, standardized by m². The Pacific Crest Trail (PCT), John Muir Trail (JMT), and High Sierra Camps.
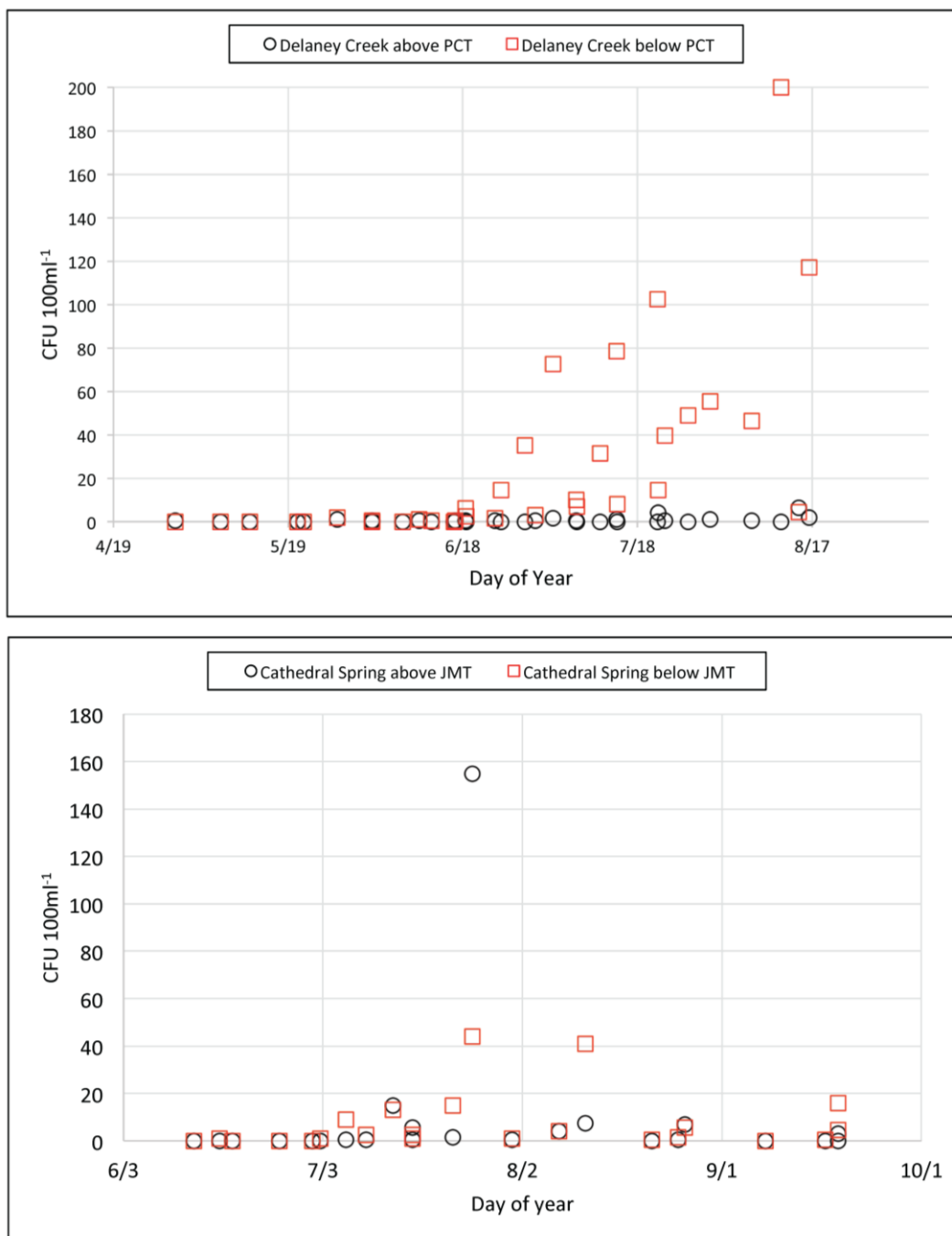
Appendix B: *Escherichia coli* **concentrations during routine sampling.**

Fig. 14 Day of year vs. *E. coli* concentrations in routine samples collected during 2012-2014, at monitoring locations upstream and downstream from packstock trail use.
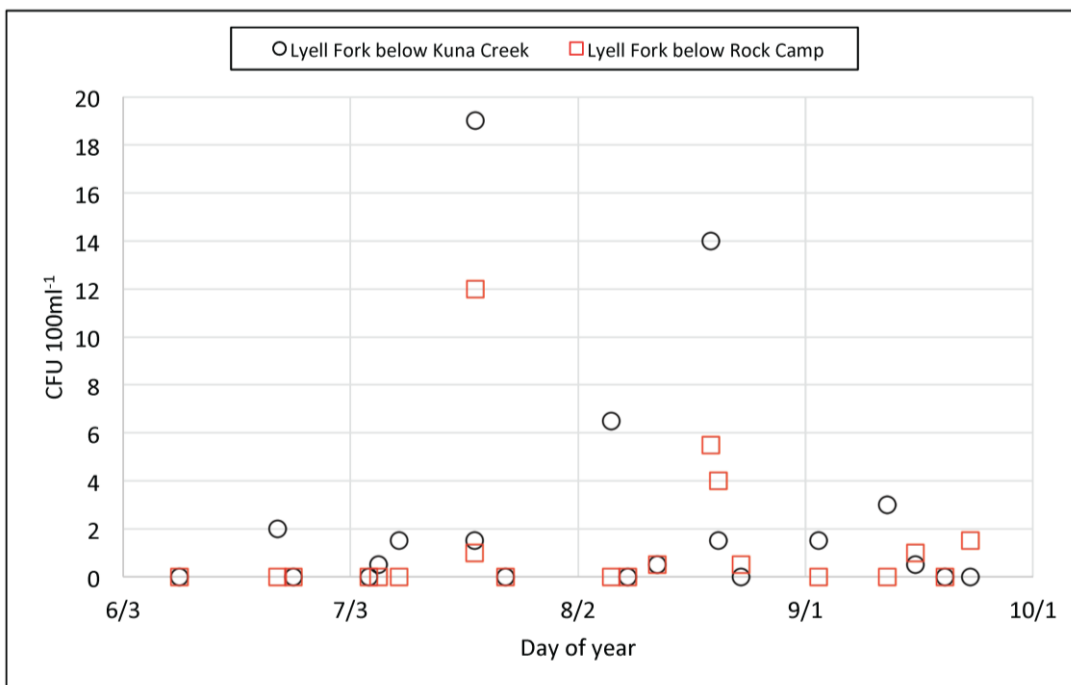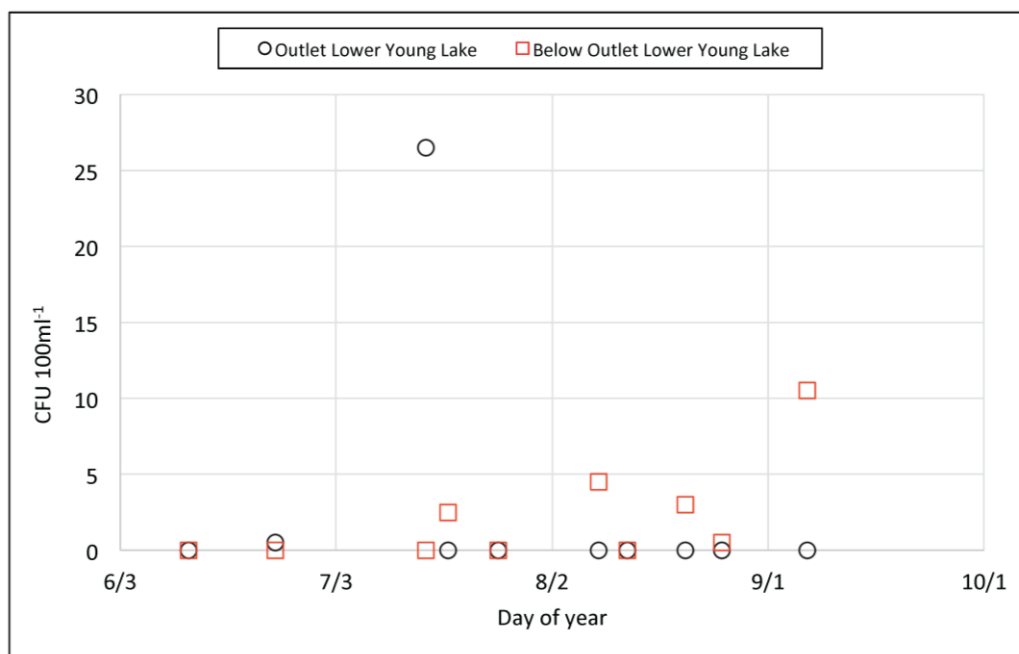
Fig. 15 Day of year vs. *E. coli* concentrations in routine samples collected during 2012-2014, at monitoring locations upstream and downstream from stock grazing.
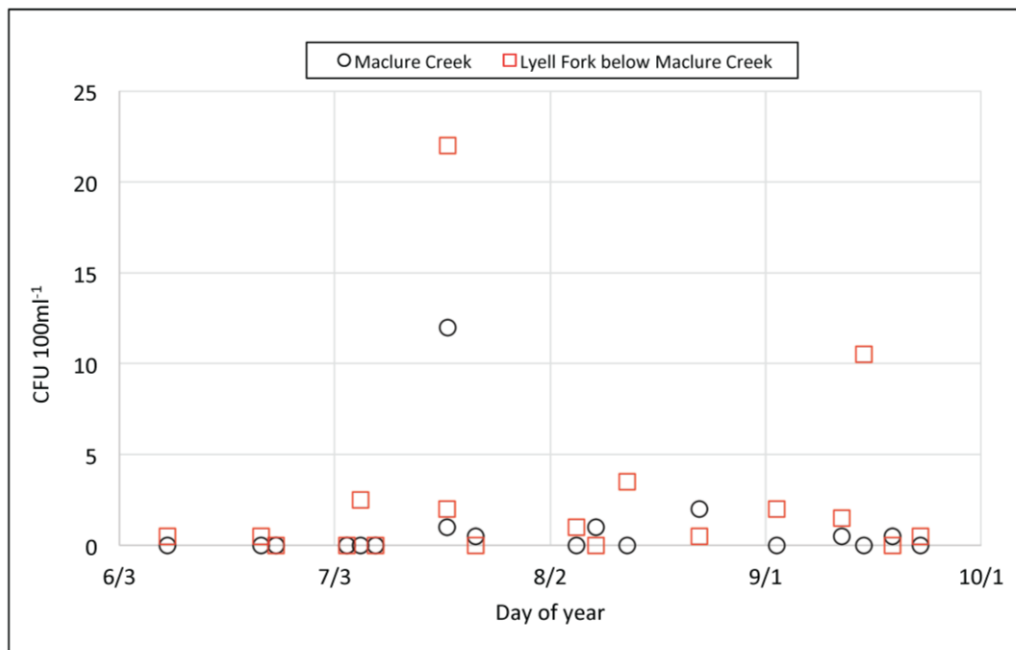
Fig. 16 Day of year vs. *E. coli* concentrations in routine samples collected during 2012-2014 at monitoring locations upstream and downstream from backpacker use

Appendix C: Water quality indicator concentrations during storms.

Tables 8a-b Turbidity based, log-linear models used to predict continuous concentrations during storm events. Model coefficient of determination (R^2); storm events and number of samples used to fit models.

a

Delaney Creek							
storm date				storm date			
7/3/2013, 7/25/2013				7/16/2014			
Above PCT		Below PCT		Above PCT		Below PCT	
Model R^2	n	Model R^2	n	Model R^2	n	Model R^2	n
TSS	0.78	7	0.95	10	0.97	3	0.93	6
PC	0.98	7	0.9	10	0.97	3	0.91	6
PN	0.98	7	0.94	10	0.94	3	0.89	6

b

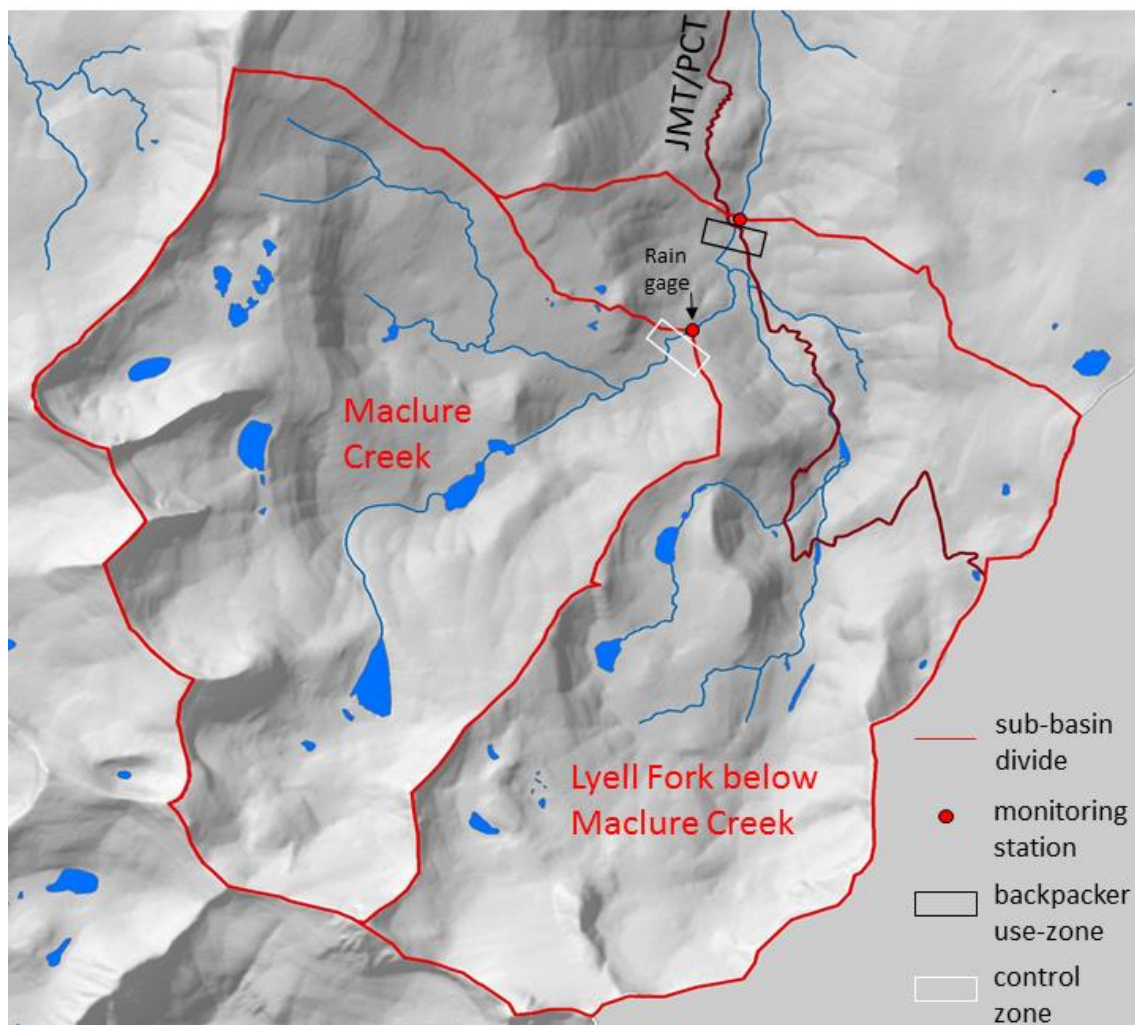| Lyell Fork at PCT				
storm date				
7/20/2013, 7/25/2013 6/26/2014, 7/14/2014, 7/16/2014				
Maclure Creek above PCT		Lyell Fork below PCT		
Model R^2	n	Model R^2	n	
TSS	0.99	12	0.83	12

Fig. 17 Maclure Creek and Lyell below Maclure Creek sub-basins; Maclure Creek rain gage location; simplified contributing zone (area) of lateral inflow at the onset of storm run-off.
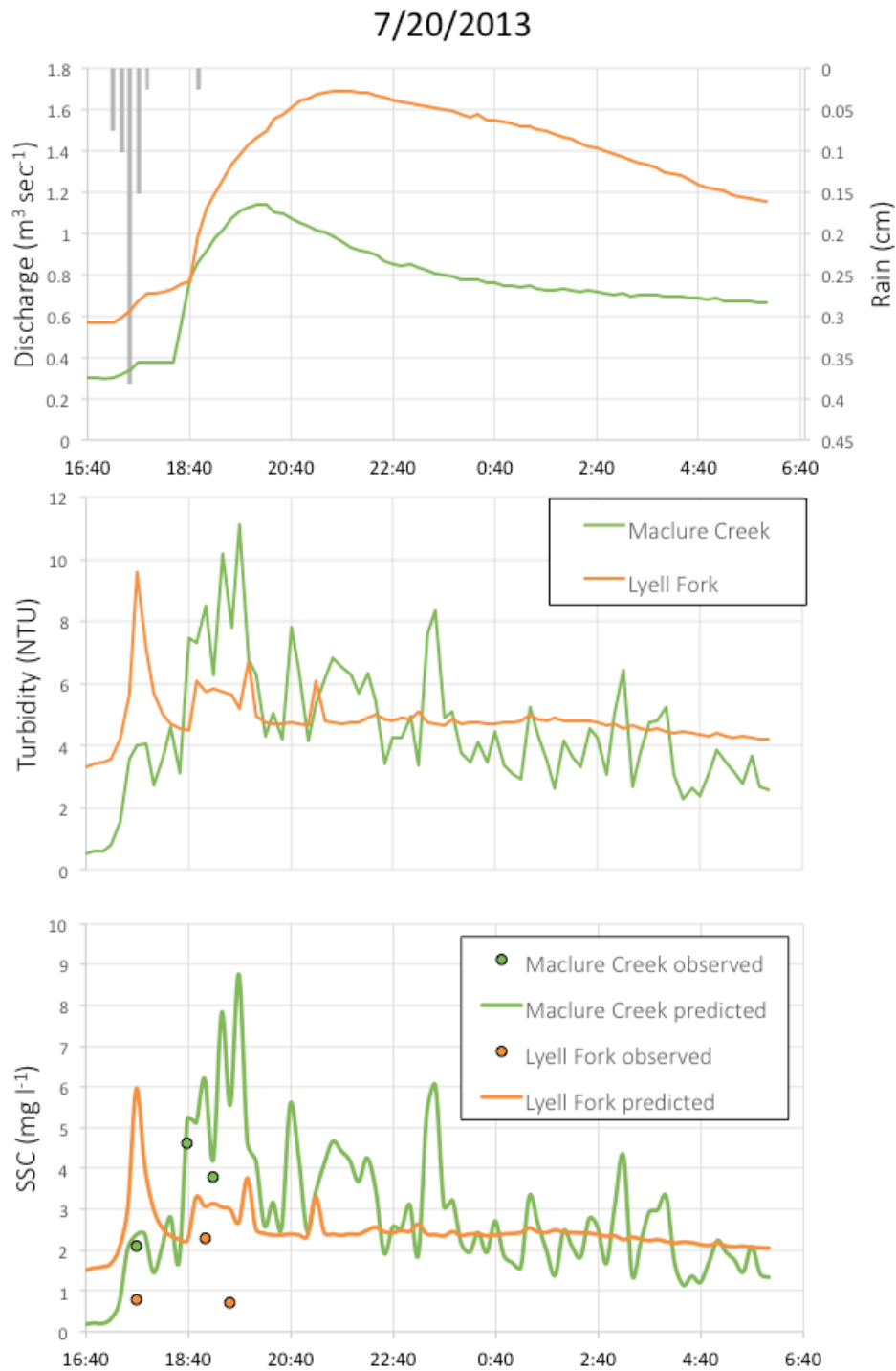
Fig. 18 Discharge, rain (grey bars), turbidity, predicted and observed suspended sediment concentration (SSC) in stream water during a summer storm event.
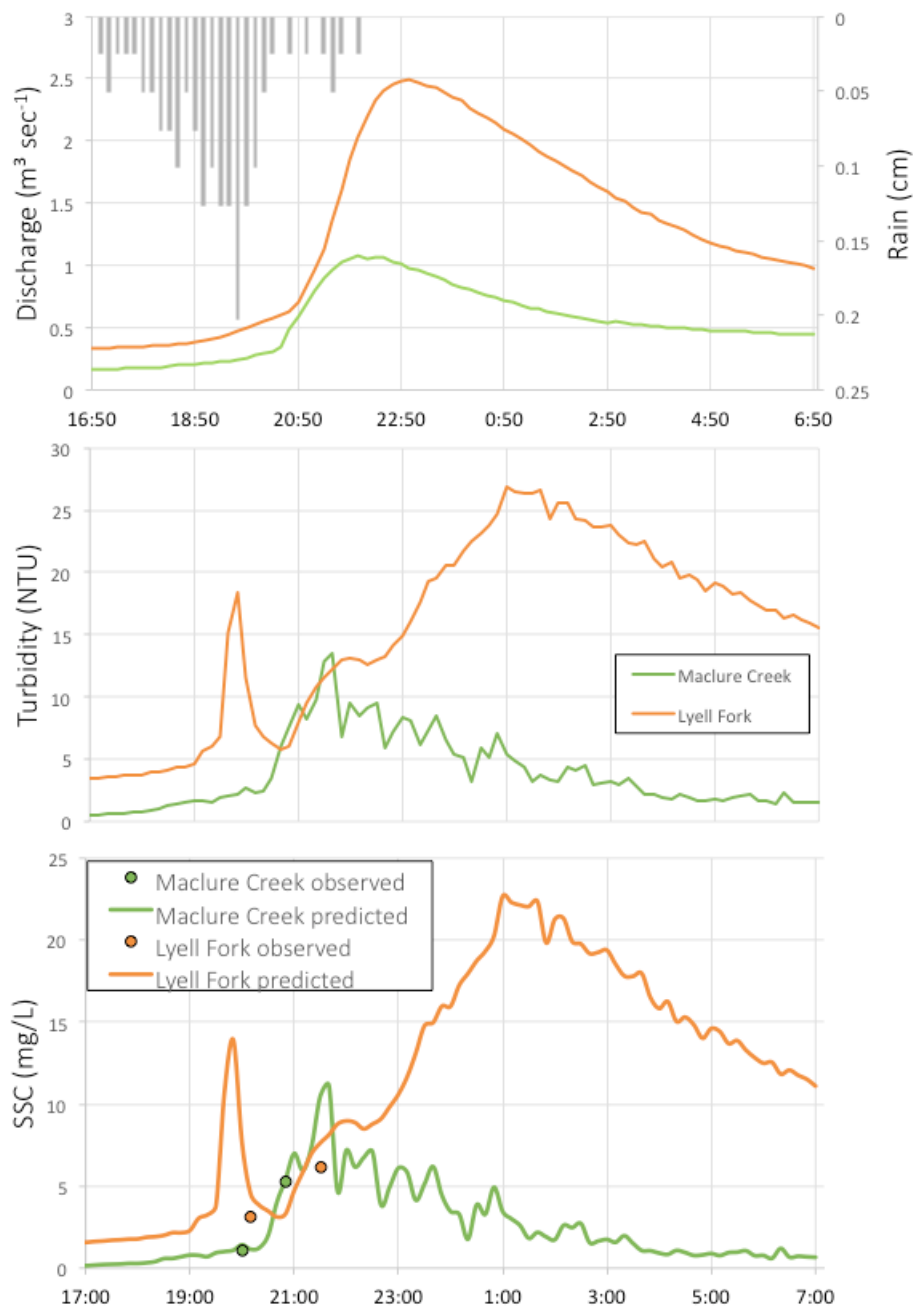
8/19/2013

Fig. 19 Discharge, rain (grey bars), turbidity, predicted and observed suspended sediment concentration (SSC) in stream water during a summer storm event.

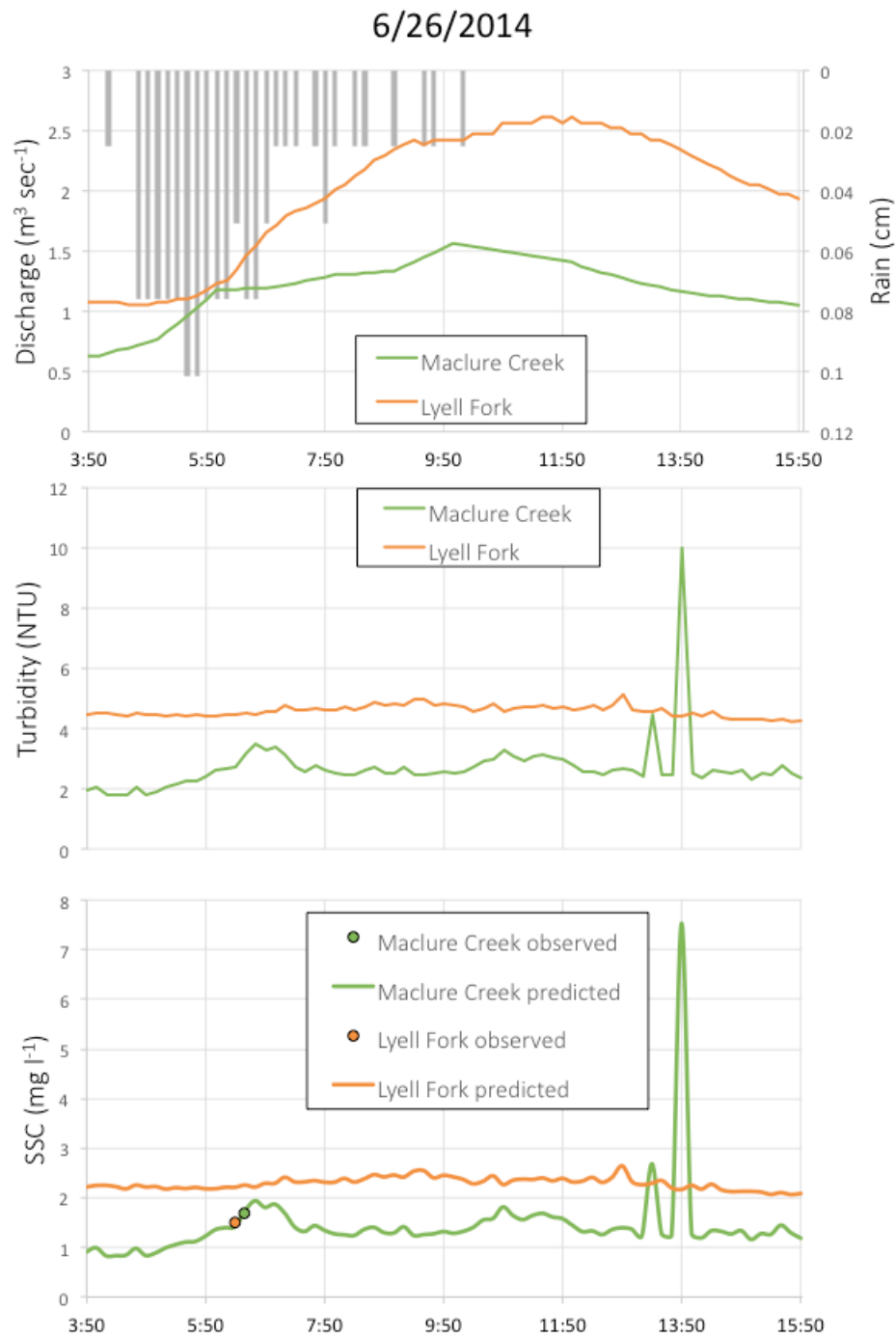**Fig. 20** Discharge, rain (grey bars), turbidity, predicted and observed suspended sediment concentration (SSC) in stream water during a summer storm event.

Fig. 21 Discharge, rain (grey bars), turbidity, predicted and observed suspended sediment concentration (SSC) in stream water during a summer storm event.
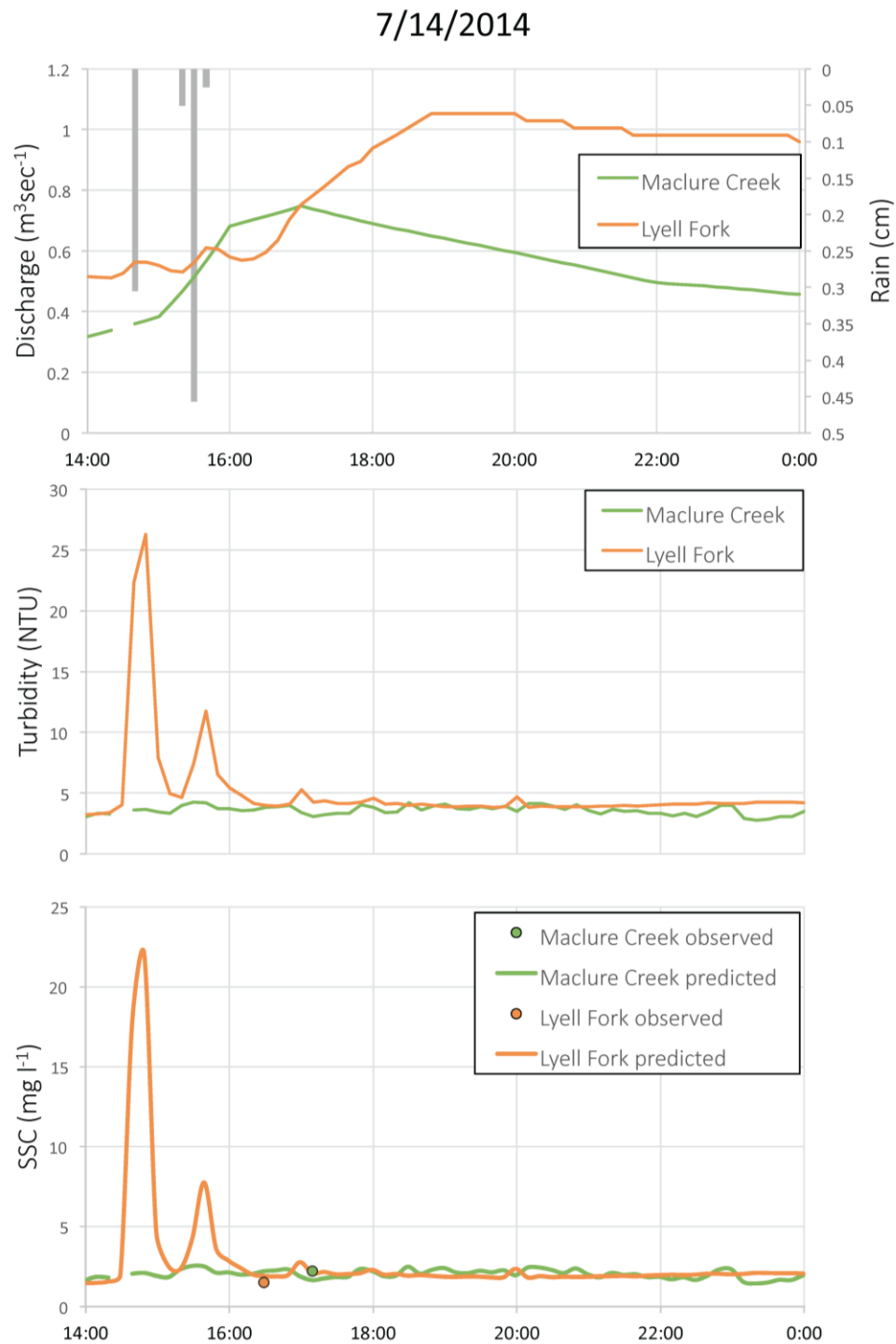
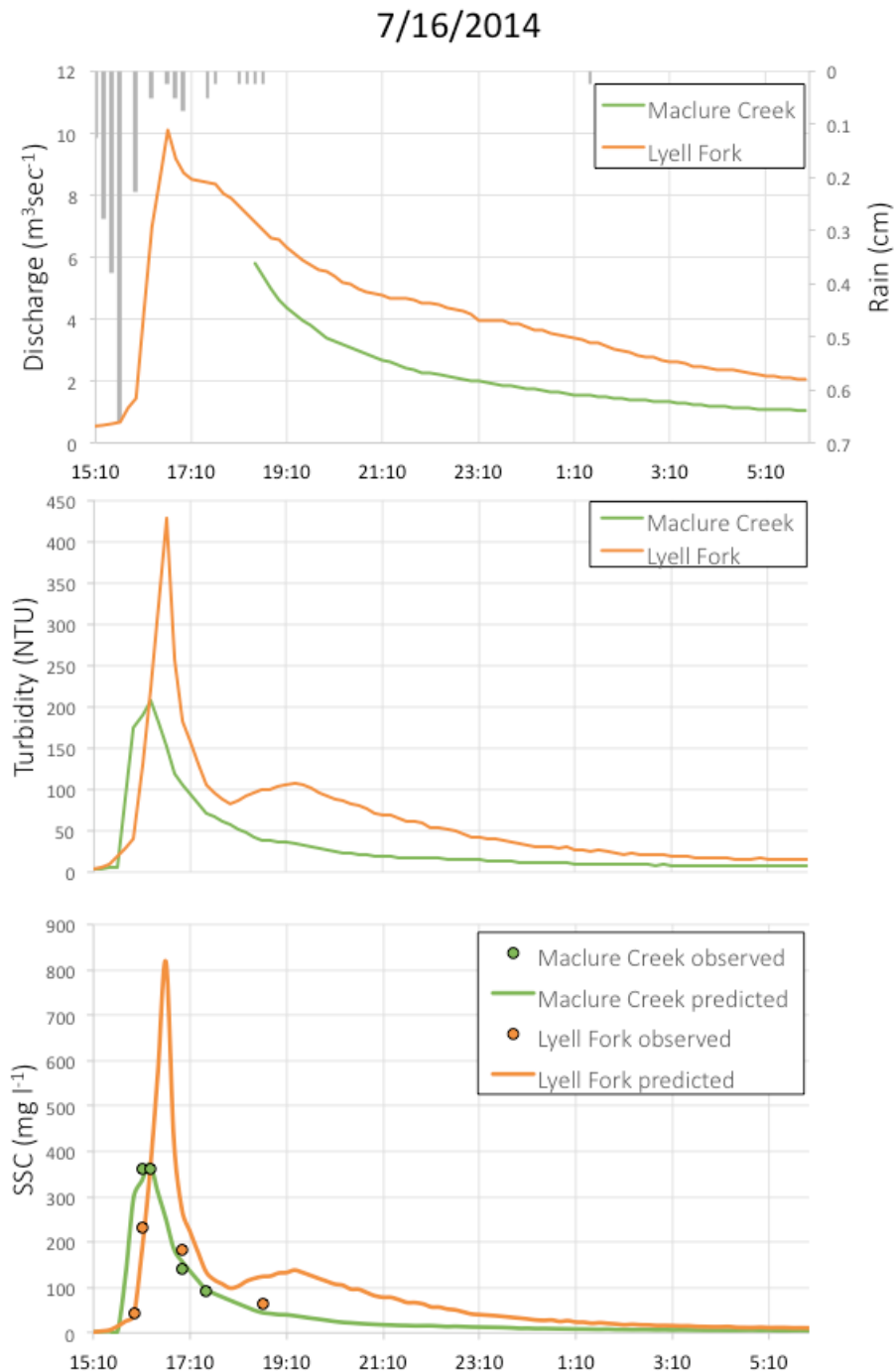**Fig. 22** Discharge, rain (grey bars), turbidity, predicted and observed suspended sediment concentration (SSC) in stream water during a summer storm event.

Appendix D: Hormone sampling

Table 9 Estrogen and testosterone hormone concentrations (ng L^{-1}) in water samples, collected during routine sampling and storm sampling during summer 2013. Corresponding storm samples collected upstream from the Delaney Creek stock stream crossing were below the MDL for Androstene

	Lyell Fork below Rock Camp 7/30/2013	Delaney Creek below PCT 7/25/2013 Storm sample #1	Delaney Creek below PCT 7/25/2013 Storm sample #2
17-alpha-Estradiol	1.189	< 0.8	< 0.8
17-alpha-Ethynyl estradiol	1.214	< 0.8	< 0.8
17-beta-Estradiol	1.191	< 0.8	< 0.8
Estriol	0.616	< 2	< 2
Mestranol	0.855	< 0.8	< 0.8
trans-Diethylstilbestrol	0.967	< 0.8	< 0.8
4-Androstene-3,17-dione	< 0.8	1.156	2.137

Table 10 Androstene and Coprostanol concentrations (µg kg^{-1}) in sediment samples collected during 2013

	Delaney Creek above PCT 7/30/2013	Delaney Creek below PCT 7/30/2013	Cathedral Spring above JMT 7/30/2013	Cathedral Spring below JMT 7/30/2013
4-Androstene-3,17-dione	0.306	0.551	<.758	<.452
3-beta-Coprostanol	< 20.750	233.822	19.829	78.193

Table 11 Hormone analytes measured in water and sediment samples

11-Ketotestosterone

17-alpha-Estradiol

17-alpha-Ethynyl estradiol

17-beta-Estradiol

3-beta-Coprostanol

4-Androstene-3,17-dione

Bisphenol A

Cholesterol

cis-Androsterone

Dihydrotestosterone

Epitestosterone

Equilenin

Equilin

Estriol

Estrone

Mestranol

Norethindrone

Progesterone

Testosterone

trans-Diethylstilbestrol