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An Assessment of Drinking Water Sources in Sagarmatha National Park (Mt Everest Region), Nepal

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This study investigated the bacteriological characteristics and physical parameters of drinking water sources in Sagarmatha National Park, Nepal. The park is located in the southeastern part of the Nepali Himalaya and includes the southern slopes of Sagarmatha (Mt Everest). During the 2016 premonsoon dry season, we sampled 29 community drinking water sources and 5 surface-water sources. The physical properties of the samples ranged as follows: temperature 3–17°C, pH 5.41–7.81, conductivity 33.6–175.5 μS, and total dissolved solids 17.3–94.3 ppm. All of the samples tested met World Health Organization drinking water standards for physical parameters. In terms of fecal contamination, 8 samples contained no CFUs (colony-forming units), conforming to the World Health Organization and Nepali national standards; the remaining 26 samples contained between 1 and 100 CFUs, and this range is rated a low to moderate risk by the World Health Organization but fails to meet the Nepali standards. The data show a positive correlation between bacteria content and temperature, and a weak negative correlation between bacteria content and elevation. Samples from the more populated, lower-elevation (<3500 m) areas had higher levels of Escherichia coli *and of coliform bacteria in general. This suggests that the samples from warmer and lower-elevation areas have a higher proportion of surface water in the drinking water, which would account for their elevated bacterial content. This indicates that the deeper groundwater may be uncontaminated and should be the focus of future investigations.*

Keywords: *Fecal coliform bacteria;* E. coli*; Mt Everest; Sagarmatha; potable drinking water; tourism impact; water quality monitoring.*

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Introduction

The belief that water, sanitation, and good hygiene services are vital for the protection and development of human resources is not new (Fewtrell et al 2004). According to the World Health Organization (WHO 2013), unsafe drinking water and inadequate sanitation practices are responsible for more than 80% of diseases globally, and, specifically, contaminated drinking water contributes to more than 1 billion cases of diarrhea each year, yet over 800 million people lack basic drinking water service (WHO 2017). These problems are more prevalent in developing countries, where unsafe drinking water contributes to a number of health issues (WHO 2017).

The Himalayan Mountains serve as an important water source for over 1 billion people and contain the main headwaters for major river systems, including the Ganges, Yangtze, and Indus (Balestrini et al 2014). Sagarmatha National Park (SNP; Figure 1) is located within the Solukhumbu district of the northeastern Nepali Himalayan Mountains. SNP is situated at 27°30′N to 27°06′N latitude and 86°30′E to 86°60′E longitude and includes the southern slopes of Sagarmatha (Mt Everest). The park was established in 1976 and declared a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Natural Heritage Site in 1979. It covers an area of 1148 km^2 and is the highest-elevation protected area in the world. In 2002, the SNP Buffer Zone, ∼275 km^2, was created to enhance the protection of the SNP.

The Solukhumbu region is home to high-elevation townships and communities, ranging from 2610 m (Phakding) to over 5000 m at Everest Base Camp (EBC). The largest communities in the SNP are Namche Bazaar (population >1600), and the combined townships of Khumjung and Kundee (combined population >1800). The largest communities in the SNP Buffer Zone are

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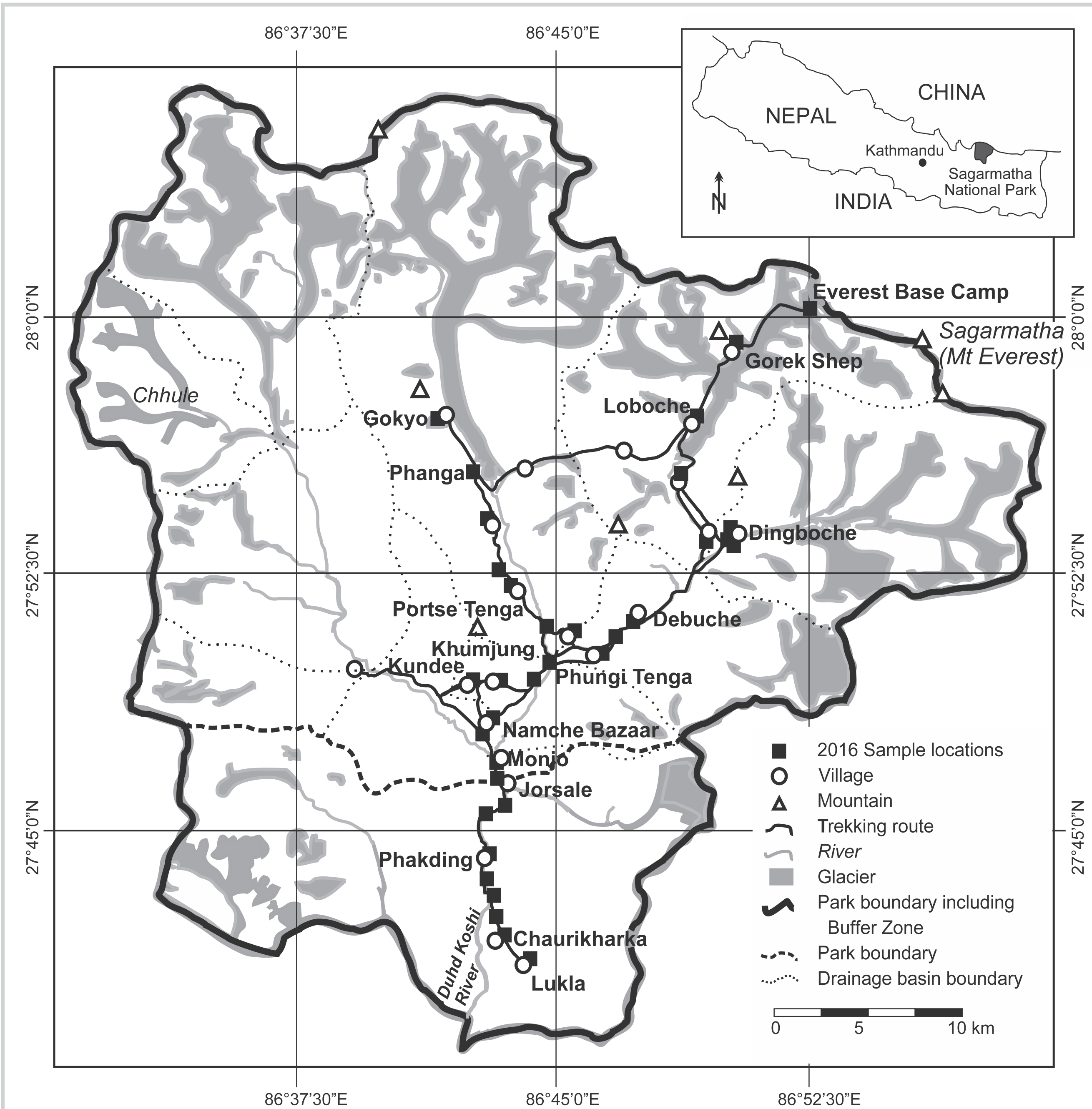
FIGURE 1 Map of Sagarmatha National Park showing locations of samples collected in April/May 2016 along the park's main trekking routes. Land south of the park boundary line is in the park buffer zone. (For sampling locations, see *Supplemental material*, Table S1, http://dx.doi.org/10.1659/MRD-JOURNAL-D-17-00024.S1.)



Lukla (population >230) and Chaurikharka (population >2400) (Government of Nepal 2011). These communities and townships all obtain water from the SNP watershed.

The diversity in culture, vegetation, and wildlife, and the beauty and majesty of the iconic Mt Everest have established the park as a prime destination for tourists (Salerno, Cuccillato, et al 2010; Salerno, Viviano, et al 2010). Since the first ascent of Everest in 1953, over 500,000 trekkers have visited the area now covered by the SNP. International trekkers who visit the SNP are accompanied by a large number of porters and guides (Salerno et al 2013).

Many protected areas, such as the SNP, have promoted tourism to improve their economic conditions (World Tourism Organization [WTO] 2005; Salerno et al 2013). However, the economic benefit of tourism has brought environmental trade-offs, and the negative effects are of significant concern in protected areas.

Recognizing these challenges, the WTO has implemented a Sustainable Tourism Eliminating Poverty program in Nepal to help communities plan, manage, and monitor tourism-related impacts on community health and the environment (WTO 2005). Nonetheless, the growth of tourism in SNP continues to contribute to widespread anthropogenic pressure on and environmental degradation of the mountain ecosystem (Ghimire et al 2013a, b). The impact is visible along popular trekking routes, where improper disposal of nonbiodegradable solid waste (eg water bottles and batteries) has resulted in environmental pollution and significant degradation of major rivers (Ghimire et al 2013a). Sewage is managed either poorly or not at all, and it often flows or is piped directly into streams and rivers (Caravello et al 2007; Ghimire et al 2013a). Despite the extensive pollution of surface water, surface water-contaminated spouts are still used for drinking water. Tourists and trekkers have the necessary technology to sanitize water; however, local communities, guides, and porters drink the untreated water. The water sources are vital to the entire region, yet no study of the sustainability of water resources has been conducted.

Fecal contamination in water sources poses significant health risks; the presence of coliform bacteria, including *Escherichia coli*, can be used as an indicator of fecal contamination of water and potential danger to human health. In natural systems, microorganisms are widely distributed, and their diversity and abundance may be used as an indicator of the suitability of water sources (Okpokwasili and Akujobi 1996). Although a wide range of pathogenic microorganisms can be transmitted to humans via water contaminated with fecal material (see Hodgkiss 1988 and references therein), the isolation and identification of these organisms are complicated processes and seldom quantitative (Cairneross et al 1980; WHO 1983). It is not practical to test water for all of these organisms, and measurement of coliform bacteria (total coliform bacteria and/or fecal coliforms) can be used as an indirect approach based on the assumption that groups of normal enteric organisms will indicate the level of fecal contamination of the water supply (WHO 1983; Harwood et al 2001; Pathak and Gopal 2001; Vaidya et al 2001; Kistemann et al 2002).

The goal of this study was to characterize and monitor potable water quality close to and within SNP using coliform bacteria and *E. coli* as indicators of fecal contamination, in order to inform efforts to improve access to potable drinking water.

Methods

The study area extended from the SNP buffer township of Lukla, along the main trekking route up to EBC, crossing over to Goyko, and then dropping back down to Lukla (Figure 1). Tourist and resident population numbers are highest at the lower elevations; the entire route is characterized by rugged topography and ranges in elevation from 2610 m to 5300 m. SNP has a temperate climate characterized by cold winters, warm summers, and clear seasonality. Temperature varies across seasons from 37°C in summer to −17°C in winter. Average annual precipitation ranges from 450 mm at EBC to 1800 mm at Lukla township, and maximum rainfall generally occurs between June and September, coinciding with the Indian monsoon.

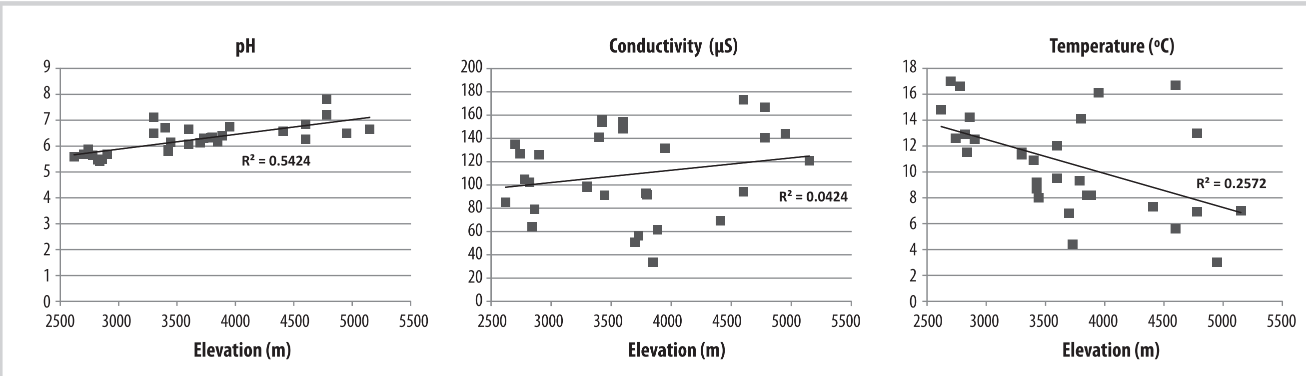
Samples were taken from 34 locations in late April and early May 2016 (Figure 1), including 29 samples from community drinking water sources (generally groundwater-fed springs) and 5 additional samples from surface water and glacial meltwater. Sites along the main trekking route (Figure 1) were selected based on access to and availability of drinking water for local and tourist use. Sample sites included flowing standpipes (water brought by tubing from higher elevations), groundwater-fed springs, and creeks. Springs are generally seepage or filtration springs, and, where possible, these samples were collected directly from the point of discharge. Two of the surface water (creek) samples were selected because they are currently used drinking water sources. None of the samples came from standing or stored water. The major rivers and streams were omitted because they have previously been studied in detail (Ghimire et al 2013a).

Temperature, pH, conductivity, and total dissolved solids (TDS) were measured in the field using a FisherSci Ap85 pH/conductivity meter 13-636-AP85. Samples for bacteria analyses were collected in sterile 60 mL syringes, and 100 mL aliquots of a sample was passed through a 0.45 μm filter at the sample site. After filtration, the filter paper was placed in a sterile test card (manufactured by Micrology Labs) containing a medium with 2 producing chemicals, 1 for detection of the enzyme glucuronidase (produced by *E. coli* strains but not by general coliforms) and 1 for the detection of galactosidase (produced by all coliforms, including *E. coli*). The samples were then placed in a portable field incubator and kept between 20°C and 35°C for 24–48 hours (for detailed field methods, refer to Gruver et al 2017). Sample counts were done using a magnifying glass and a 10× geological hand lens. *E. coli* colonies are royal blue/purple, and coliform bacteria colonies appear to be light green. Coliform bacteria samples were not counted beyond 200 colonies. Two people counted bacteria samples, and duplicate tests were run on every 10th sample.

Results and discussion

Sampling took place during a long dry period; many smaller springs were completely dry, and there was minimal surface-water contamination of springs. Average

FIGURE 2 Physical parameters (pH, conductivity, and temperature) compared to elevation. Regression lines and R^2 values in Figures 2–5 were calculated using Excel.



precipitation in April usually ranges from 56 mm in Lukla to 9 mm at Gorek Shep. However, April 2016 was an unusually dry month, following a 5 year trend of low rainfall in April (Karki et al 2017). The average daily high and low air temperatures recorded for May 2016 were 18°C and 8°C, respectively, for Lukla; 14°C and 4°C for Namche Bazaar; and 8°C and −1°C for Gorek Shep.

Water quality standards

The World Health Organization guidelines for drinking water (WHO 2011) call for less than 600 mg/L TDS, and the drinking water in the SNP falls well within the recommended limit. The observed pH values for drinking water are also within the limit (6.5–8.5) prescribed by these guidelines. WHO (2011) gives risk factors of fecal contamination in drinking water by categories based on ranges of *E. coli* CFUs as: 0 CFU = no risk, 1–9 CFUs = low risk, 10–100 CFUs = moderate risk, and >100 CFUs = high risk.

The Nepali National Drinking Water Quality Standards do not specify physical parameters, but they do state that drinking water only passes their standards if 0 CFU of *E. coli* is present (Central Bureau of Statistics 2008). Any samples containing more than 0 CFU fail Nepali National Drinking Water Quality Standards.

Physical parameters

Drinking water sources (29 samples): Results for physical parameters are shown in Figure 2. Drinking water source temperatures ranged between 3.0°C and 17.0°C, with an average of 10.5 (± 3.8)°C. As expected, the temperatures decreased with increasing elevation ($r = 0.507$, $p = 0.0036$). The warmest temperature sample was from a small lower-elevation village with a continuous-flowing source that, according to the residents, never runs dry. The pH values for drinking water sources ranged between 5.41 and 7.81, with an average of 6.3 (± 0.6). The ranges in TDS and conductivity in the samples were relatively small. The average TDS was 55.9 (± 21.0) parts per million (ppm), with a range between 17.3 and 94.3 ppm, whereas the average value for conductivity was 110.3 (± 38.1) µS, with a range between 33.6 and 173.4 µS. As Figure 2 indicates, the samples showed a strong positive correlation between pH and elevation ($r = 0.736$, $p < 0.001$) and a weak correlation between elevation and both conductivity and TDS ($r < 0.3$); however, both conductivity and TDS had p values >0.05.

Surface water sources (5 samples): The 5 samples were taken directly from surface-water sources, including 2 community drinking water sources at Lobuche and Lukla. The Lukla township drinking water source prior to treatment (gravel-sand filtration) is a combination of shallow spring and surface waters. The other 2 samples were from EBC glacial meltwater and the Dudh Koshi River. Glacial meltwater is commonly used as drinking water at EBC, where most tourists boil or otherwise treat it before use. The Dudh Koshi is rarely used as a drinking water source.

The temperature of the surface-water samples ranged between 1.0°C and 12.5°C (Figure 2) and decreased with increasing elevation. The warmest sample was from the lowest-elevation village in the study area, Lukla. The coolest samples came from a fast-flowing spring at Lobuche (the highest-elevation village) and glacial meltwater taken directly beside the glacier at EBC. The pH values for surface-water sources ranged between 5.40 and 6.84. TDS values were between 25.2 and 78.5 ppm, and the values for conductivity were between 50.2 and 175.5 µS. Only the Lobuche surface water is used as a regular community drinking water source. The water at EBC is generally treated prior to use, and the water at Lukla is treated with a sand-gravel-sand filtration system completed in 2016.

Correlations among physical parameters: We tentatively interpret the relationship between increasing pH and increasing elevation as being the result of the geology and water–rock interactions. The highest-elevation rocks in the sample area are limestone, whereas the majority of the study area geology consists of schists, gneiss, and leucogranites (Stöcklin 1980). Limestone has a much higher pH than the other rocks, and this might influence the pH of the samples.

Temperature directly correlated with elevation, as predicted. However, there is significant scatter in the data. There are 2 likely explanations for this. First, air temperature is likely to impact the water temperature of shallow springs, which would then be influenced by vegetation and orientation. Second, the amount of surface water in the springs used for drinking water would influence the temperature. This might also explain the scatter in the conductivity data, because samples with more surface-water contamination would have a shorter residence time in the subsurface and therefore would have lower TDS values and lower conductivity. This explanation will be tested further using geochemical data from 2016 and 2017.

E. coli and coliform bacteria in general

All 29 drinking water samples and the 2 surface-water samples used for community drinking water sources were analyzed for *E. coli* and total coliform bacteria ($n = 31$ total samples). The maximum number of *E. coli* CFUs per 100 mL sample was found in samples taken at Lukla (~2900 m elevation), Jorsalle (~2860 m), Phungi Tenga (~3300 m), Dingboche (~4400 m), Phanga (~4600 m), and Portse Tenga (~3800 m). With the exceptions of Dingboche and Phanga, all samples collected above 3800 m had fewer than 3 *E. coli* CFUs. Four locations had no *E. coli* CFUs: Debuche (~3720 m), Khumjung (~3980 m), Kundee (~3886 m), and Phanga National Park Office (~3850 m).

A similar pattern was observed for total coliform, with samples collected at lower elevations generally containing more total CFUs than those from higher-elevation locations. The only sample in the region to test negatively for total coliforms was from the Khumjung School, which uses water piped from a different drainage basin. Figures 3 and 4 graph the relationships among elevation, physical parameters, and *E. coli* and total coliform CFUs. These plots show a moderate correlation between total coliform CFUs and elevation ($r = 0.505$ and $p < 0.0038$) and weak correlations between total coliform CFUs and temperature and pH ($r = 0.376$ and 0.404, respectively, both with $p < 0.05$). *E. coli* behaved differently, with no reliable correlations ($r < 0.4$ and $p > 0.05$) with respect to elevation, pH, temperature, and conductivity. In general, the lower-elevation, warmer samples were more likely to test positive for total coliform CFUs, whereas there appeared to be no correlation between *E. coli* CFUs and physical parameters.

Of the 31 water samples, 8 contained no coliform bacteria CFUs, conforming to World Health Organization and Nepali National Drinking Water Quality Standards; 13 samples contained between 1 and 9 CFUs, which is considered low risk by the World Health Organization but does not meet Nepali National Drinking Water Quality Standards; and the remaining 10 samples contained between 10 and 100 CFUs, placing them in the World Health Organization's moderate risk category and failing the Nepali National Drinking Water Quality Standards.

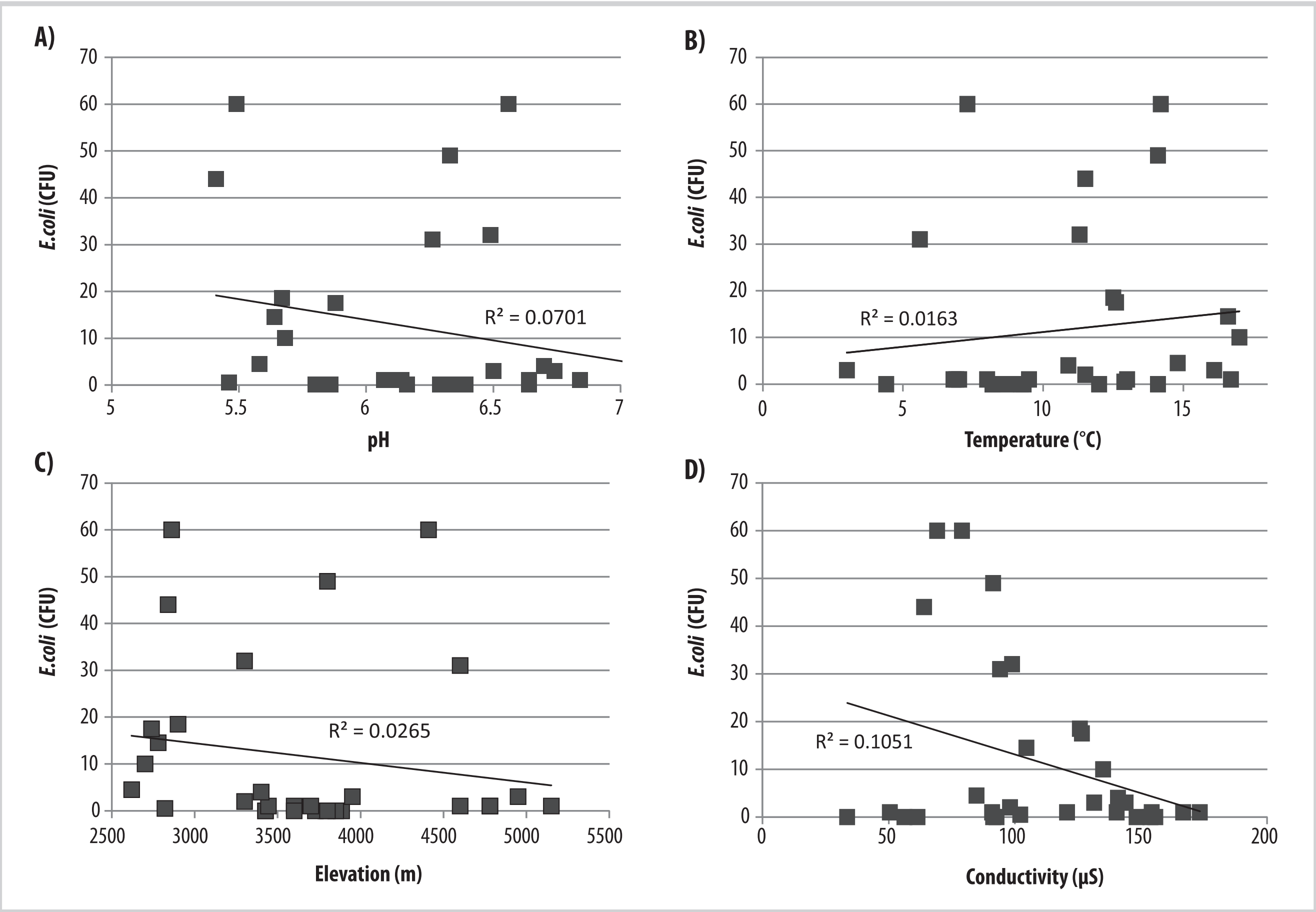
The lower-elevation towns (Lukla, Chaurikharka, Monjo, and Namche Bazaar) have the biggest resident populations, the highest density of tourists, and correspondingly highest levels of *E. coli* in the water. A subset of the lower-elevation samples highlights the correlations among CFUs, elevation, and physical parameters. Figure 5 plots the physical parameters by elevation (<3500 m) and by the number of *E. coli* CFUs. The lower-elevation samples showed a direct correlation between increasing elevation and increasing pH, increasing conductivity/TDS, and decreasing temperature (Table 1). Although *E. coli* CFUs showed only a weak correlation with physical parameters (see Figure 5; Table 1), the lower-elevation samples had higher average CFU counts, with a mean of 15 CFUs per sample (standard deviation [SD] 19), as opposed to a mean of 8.5 CFUs in the higher-elevation towns (SD 18). The same relationship held true for total coliforms: The lower-elevation samples had a mean of 93 CFUs per sample (SD 81), whereas the higher-elevation samples had a mean of 35 CFUs (SD 51). The lower-elevation towns also have a higher density of livestock, greater area devoted to agriculture, and greater deforestation. Combined, this suggests that fecal contamination of drinking water sources is likely anthropogenic.

Resource management and tourism

Availability of, and access to, clean drinking water in SNP is a complex problem involving environmental degradation, economics, natural disasters (climate change and earthquakes), and governance. Increasing numbers of tourists and their refuse are placing serious pressure, with serious environmental consequences, on the unique SNP and SNP Buffer Zone ecosystems (Byers 2005; Ghimire et al 2013a, b). The number of visitors to the region reached a maximum in the early 2000s of >35,000 per year (not including guides and porters). As many tourists do not complete the entire trek to EBC, the majority of tourism occurs in the lower-elevation towns, particularly in Namche Bazaar and the SNP Buffer Zone. Together, the lower-elevation towns of the SNP Buffer Zone (including Lukla, Chaurikharka, and Monjo) and Namche Bazaar account for over 9000 people, or almost 70% of the regional population (SNP Office 2016). Hence, there are clear correlations among population, tourism, and fecal contamination of drinking water in the region, with the lower-elevation towns containing almost double the CFUs of *E. coli* compared to values found at higher elevations.

Despite the negative effects of tourism, many protected areas, such as the SNP, promote it to improve economic conditions, generate revenue, and provide

FIGURE 3 Number of *E. coli* CFUs compared to pH, temperature, elevation, and conductivity.



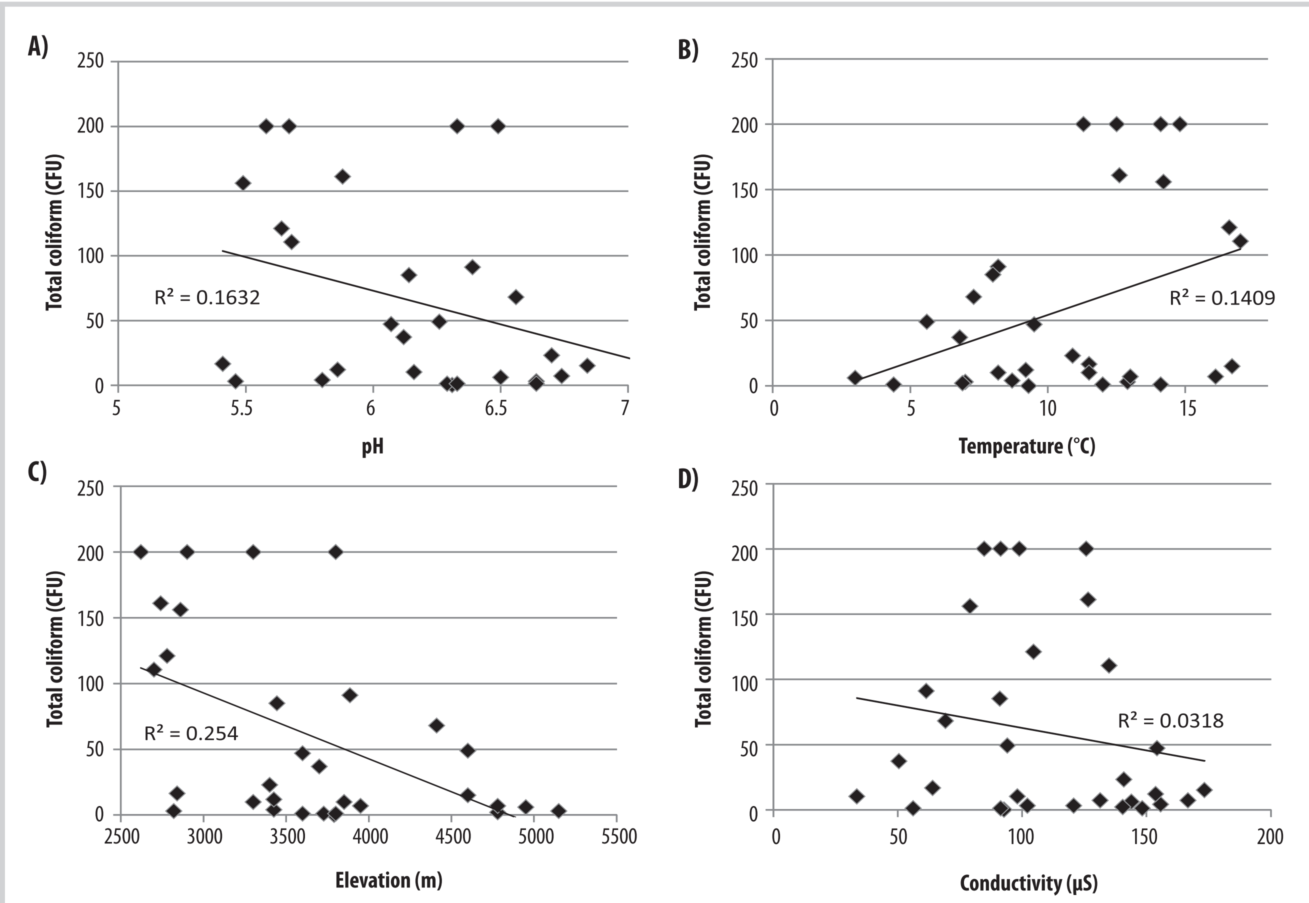
direct income and employment opportunities for the local population (WTO 2005; Salerno et al 2013). Local and regional governments, nongovernmental organizations, and communities struggle to reconcile conflicting outcomes associated with economic growth based on tourism and the ability of existing infrastructure to handle issues such as human waste disposal. Continued monitoring of water quality, specifically fecal contamination, can be used as a key indicator of the effects of tourism.

Within the SNP and SNP Buffer Zone, there is much debate about how to develop a sustainable economy without exacerbating environmental and cultural degradation. The current park management plan (DNPWC 2005, 2006) emphasizes community self-governance and support of local economic development, including local stewardship of natural resources, the growth of a self-regulated tourism industry, local natural resource production systems (such as hydroelectric generation), and a multistakeholder governance system (Daconto and Sherpa 2010). In 2006, Daconto and Sherpa (2007) met with Sherpa community leaders, Department of National Parks and Wildlife Conservation staff, and Buffer Zone Committee members to identify topics of key interest regarding the future of SNP. A factor of major importance to stakeholders was the impact of tourism, and the need to develop and support self-regulation and governance of both tourism and natural resources. Providing stakeholders with water-quality data generated from studies such as this will strengthen their ability to address these issues as a community.

Climate change and mountain hydrology

The issue of potable water in the SNP is complex and involves economic (particularly tourism), political, and natural/environmental variables. A factor of particular concern to the future of the region is how climate change will impact water resources, and hence how water resources are managed is highly important. The first studies of *E. coli* and coliform bacteria in SNP (Sharma et al 2010; Ghimire et al 2013a, b) focused entirely on the major rivers and lakes within the park and concluded that all of the rivers contained *E. coli* and other coliform bacteria, especially at lower elevations. Ghimire et al (2013a) suggested that contamination of surface water in

FIGURE 4 Number of all coliform CFUs compared to pH, temperature, elevation, and conductivity.



SNP was primarily the result of unmanaged and/or poorly managed solid waste disposal and open defecation. Refuse is not transported outside the SNP for disposal, and poorly managed solid waste disposal is visible throughout the park—especially in larger villages, where sewage is piped into nearby streams and rivers (authors' personal observations; Caravello et al 2007).

This phenomenon does not appear to impact tourist impressions of the region; most visitors to the SNP appear to be satisfied with current conditions, including water quality (Salerno et al 2013). Salerno et al (2013) focused on tourist impressions of environmental conditions in SNP and suggested that although there was room for growth in tourist numbers, current environmental conditions would significantly limit growth and further development.

Our samples were intentionally collected during the premonsoon dry season to minimize the effects of surface water on drinking water sources. During our 2016 fieldwork, many residents indicated that it had been a particularly dry year, and that many springs and small tributaries had run dry at the lower-elevation sampling sites. These observations are supported by the annual Nepali government report by the Ministry of Population and Environment, Department of Hydrology and Meteorology, which stated that precipitation in April 2016 was unusually low, following a 5 year trend of decreasing premonsoon precipitation (DMH 2016; Karki et al 2017). In 2016, the higher-elevation drinking water sources appeared normal, whereas the lower-elevation springs generally seemed to be affected by low seasonal precipitation. Although not conclusive, these observations support our hypothesis that the waters found in the lower-elevation samples have a significant contribution from surface water, which would potentially increase fecal contamination.

Globally, the hydrology of semiarid mountainous regions is dominated by snowmelt runoff (Serreze et al 1999), which provides important landscape features for year-round water retention, long-term water storage, and a source of runoff for downstream users (Viviroli et al 2011; Schlaepfer et al 2012). The variability of precipitation in mountain regions results in water movement along multiple pathways, both over and through the hillside. Current understanding of mountain aquifers is sparse due to the combination of geological complexity, extreme head gradients, and dramatically

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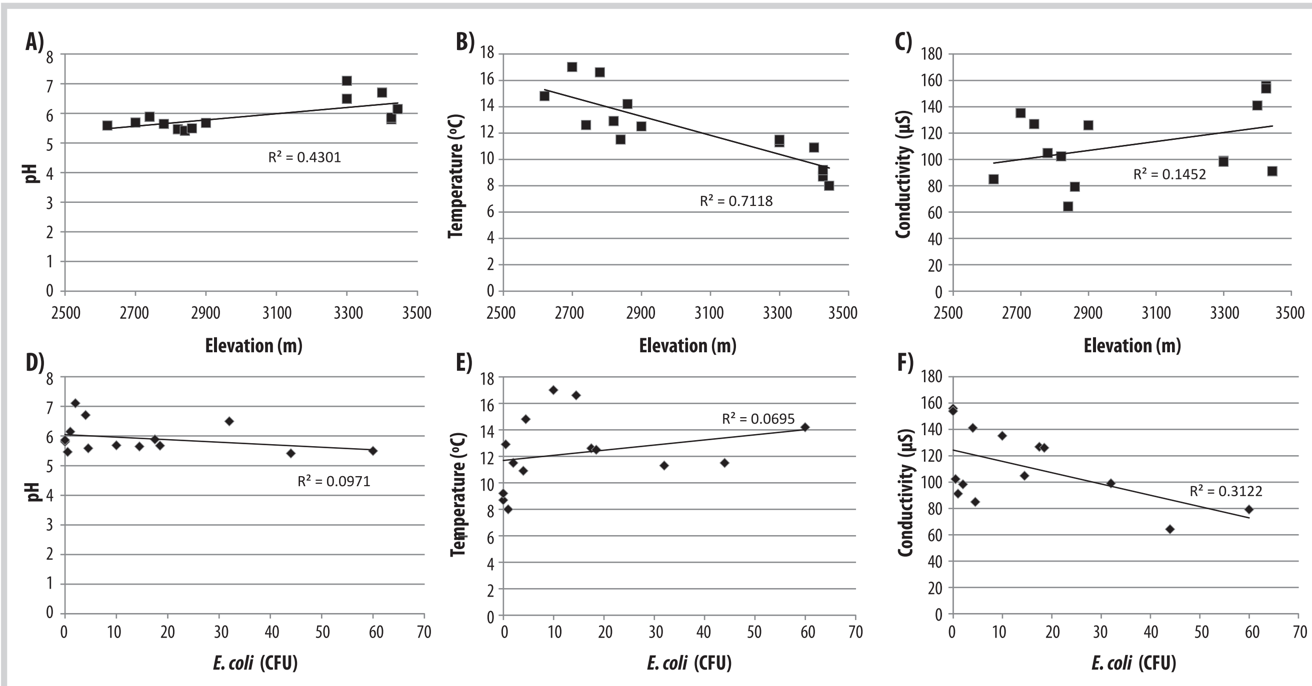
FIGURE 5 Water pH, temperature, and conductivity compared to elevation and to number of *E. coli* CFUs for lower elevations (<3500 m) only.



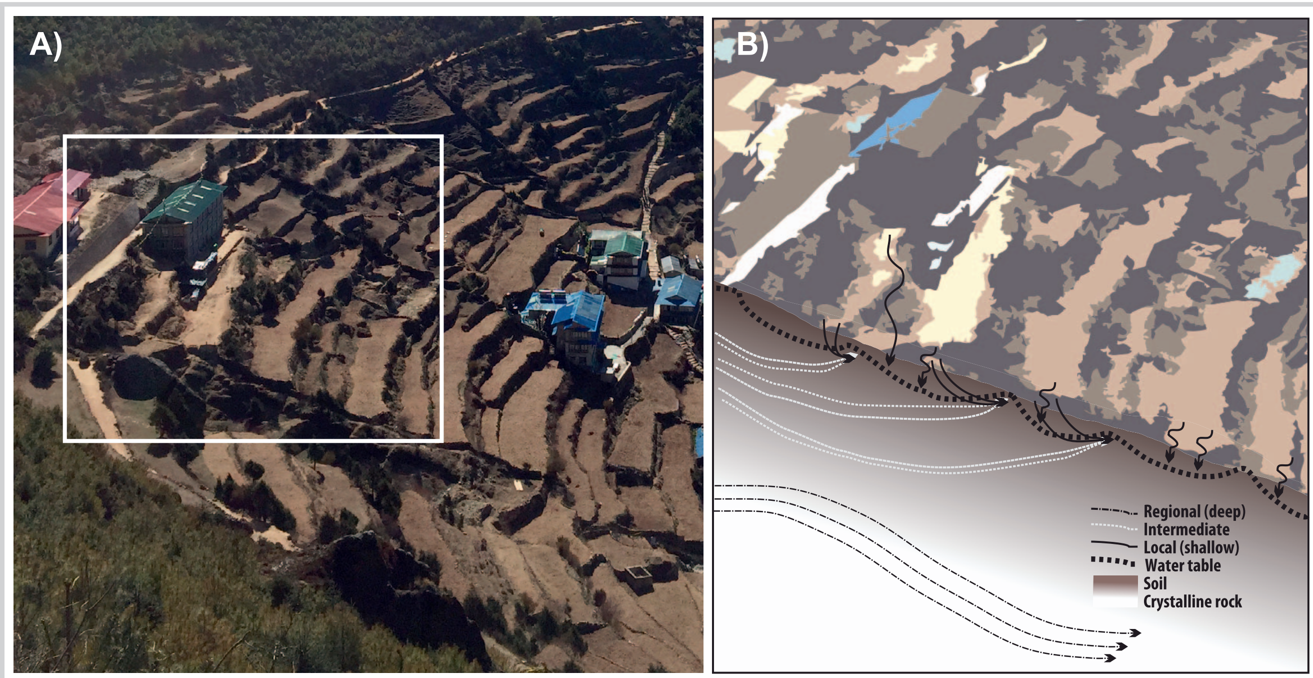
fluctuating recharge driven by seasonal snowmelt (Liu et al 2004; Manning and Caine 2007). Groundwater flow occurs primarily through fractures in these crystalline catchments, reducing the effectiveness of the classic porous medium approach for understanding surface–groundwater interactions (Hazen et al 2002). However, it is generally accepted that, in areas such as SNP, the presence of a fractured, faulted subsurface geology combined with macropores (created by burrowing organisms and decay of plant roots) results in shallow subsurface flow that feeds the hillside springs commonly used for drinking, especially during heavy precipitation such as monsoon rains.

Figure 6 shows the typical style of cultivation in SNP. Slopes are terraced to provide flat fields for growing crops and grazing livestock. This facilitates the penetration of

TABLE 1 Pearson's correlation coefficients (r) and p values for data plotted in the figures.

	Elevation	pH	Temperature	Conductivity
All drinking water samples ($N = 29$)				
Elevation		$r = 0.736$ $p < 0.001$	$r = 0.507$ $p = 0.0036$	$r = 0.206$ $p = 0.266$
E. coli	$r = 0.168$ $p = 0.365$	$r = 0.264$ $p = 0.142$	$r = 0.131$ $p = 0.481$	$r = 0.324$ $p = 0.075$
Total coliforms	$r = 0.505$ $p = 0.0038$	$r = 0.405$ $p = 0.024$	$r = 0.376$ $p = 0.037$	$r = 0.178$ $p = 0.337$
Lower-elevation samples ($N = 14$)				
Elevation		$r = 0.656$ $p = 0.011$	$r = 0.843$ $p < 0.001$	$r = 0.381$ $p = 0.179$
E. coli	$r = 0.338$ $p = 0.237$	$r = 0.312$ $p = 0.278$	$r = 0.131$ $p = 0.481$	$r = 0.264$ $p = 0.362$
Total coliforms	$r = 0.473$ $p = 0.087$	$r = 0.192$ $p = 0.51$	$r = 0.457$ $p = 0.100$	$r = 0.24$ $p = 0.409$

FIGURE 6 Namche Bazaar: (A) photo taken in 2016 showing typical cultivation style; (B) sketch of inset area from (A) illustrating how agriculture and slope alteration affect drainage and subsurface downslope flow. (Photo by Kirsten Ngaire Nicholson)



surface water into the soil layer and deeper into the shallow flow zone. As most people in SNP live below 4000 m, where there is also a higher density of agriculture and tourism, this region is more susceptible to surface-water contamination of the shallow springs used for drinking water. Our results clearly suggest that there is significant fecal contamination of drinking water in the study area, that human activity (by local residents and/or tourists) is the main cause of this contamination, and that surface-water contamination of shallow springs, used as primary drinking water sources, facilitates increased fecal levels at lower elevations. Further research of deeper groundwater is necessary to determine if it is less contaminated, and possibly more potable, than the surface water.

Water-quality degradation is further complicated by current global warming trends. The Himalaya Mountains contain the headwaters of many hydrological systems, which provide freshwater to more than 1 billion people (Ives and Messerli 1989), yet glacial melting is affecting traditional seasonal precipitation patterns (Alford and Armstrong 2010), and concurrent changes to regional climate patterns are impacting surface water (Green et al 2011). The recession of the Himalayan glaciers (Kaser et al 2005; Vuille et al 2008) will likely cause hydrological changes, including a reduction in dry-season water discharge, an increase in peak discharge (Barnett et al 2005), and a general decrease in water resources (IPCC 2007). Despite these threats, there are few detailed studies of the current and future impacts of global warming on Himalayan water resources, and even less is known about the impact of global warming on the subsurface (eg soil water and groundwater; Holman 2006; Green et al 2007; Bovolo et al 2009).

Few studies have focused on seasonal precipitation patterns, catchment storage dynamics, and groundwater recharge in mountainous regions within the framework of global warming (Ajami et al 2011). Dettinger and Earman (2007) stated that the challenges of understanding climate-change effects on groundwater are unprecedented, as neither the direct nor the indirect effects on hydrological processes and groundwater resources have been sufficiently explored. SNP's reliance on shallow groundwater (in the form of shallow springs) makes these communities particularly vulnerable.

Conclusions

Our study shows the following:

- Drinking water within the SNP region currently meets current World Health Organization drinking water standards for pH and TDS. Physical properties of samples ranged as follows: temperature 3.0–17°C, pH 5.41–7.81, conductivity 33.6–175.5 μS, and TDS 17.3–94.3 ppm.
- *E. coli* contamination ranged from 0 CFU (meeting both World Health Organization and Nepali water-quality standards) to over 100 CFU, which falls into the World Health Organization's moderate risk category and fails

to meet the Nepali National Drinking Water Quality Standards.
- For fecal contamination, most of the lower-elevation (<3500 m) drinking water sources had low to moderate risk, according to World Health Organization standards, and failed to meet Nepali National Drinking Water Quality Standards, whereas most of the higher-elevation (>3500 m) drinking water sources met those standards.
- Population, tourist numbers, and surface-water contamination appear to be the controlling factors in fecal contamination of drinking water sources.
- Continued monitoring of physical parameters and *E. coli* and other coliform bacteria will be essential as the Nepalese government and others work to benefit sustainably from the expanding tourism industry, particularly in SNP.

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Supplemental material

TABLE S1 Sampling locations for the 29 drinking water sources (springs).

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