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Glacial Transport of Human Waste and Survival of Fecal Bacteria on Mt. McKinley's Kahiltna Glacier, Denali National Park, Alaska

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Abstract

Each year, over 1000 climbers attempt an ascent of Mt. McKinley via the West Buttress, located on the 77-km-long Kahiltna Glacier in Denali National Park and Preserve, Alaska. Climbers generate over two metric tons of human waste annually, the majority of which is disposed of in crevasses. To assess potential health impacts of this management practice, we conducted field studies and a laboratory experiment to document the persistence of fecal bacteria in a variety of glacial microclimates. Low concentrations of fecal bacteria found in water samples collected over two melt seasons from the Kahiltna River support the argument that bacteria can survive in a glacial environment for an extended period of time. We documented Kahiltna Glacier surface velocities and used a simple flow model to predict the time and place that human waste will emerge in the ablation zone. Based on surface velocities we predict that waste buried in major camps will emerge at the glacier surface in as little as 71 years after traveling 28 km downstream. Our results show fecal microorganisms are persistent in a glacial environment, these pathogens pose a minor threat to human health, and buried human waste can be expected to emerge at the glacier surface within decades.

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Introduction

The Kahiltna Glacier, a 77-km-long valley glacier draining from the south side of Mt. McKinley in Denali National Park and Preserve, Alaska, provides access each season for over 1000 climbers attempting to ascend the highest mountain in North America. Ninety-four percent of climbers use the popular West Buttress climbing route, located almost entirely on the Kahiltna Glacier (Denali National Park and Preserve, 2010; Fig. 1). With such high levels of use, the National Park Service (NPS) must intensively manage human activity on Mt. McKinley (or ''Denali,'' as most Alaskans call the mountain) to mitigate the potentially negative impacts of heavy use on the glacial environment (Denali National Park and Preserve, 2006). In particular, human waste disposal on the Kahiltna Glacier has become an issue with the increasing number of climbers attempting Mt. McKinley. Based on an average trip length of 18 days (Denali National Park and Preserve, 2010; Table 1) and an average daily stool weight of 106 g (Cummings et al. 1992), we estimate that Mt. McKinley climbers annually generate over two metric tons of human waste (Fig. 2). The NPS is concerned about the impacts that disposal of this waste, under past and current management practices, will have on overall human health of the mountain's visitors as well as on water quality of the Kahiltna Glacier and downstream Kahiltna River. This study assesses the nature of those impacts by predicting the fate of buried waste as it travels downglacier over coming decades.

Waste disposal practices on the West Buttress (WB) climbing route have evolved over the past 60 years of increasing recreational use (Robinson, 2010). Initially, climbing was unmanaged; both human waste and trash were left on the glacier surface, contaminating the majority of the climbing route. Starting in the late 1970s, NPS rangers dug a 3 to 4 m deep pit in the snow at two heavily used camps: Camp 1 and Camp 5 (Fig. 1; camp numbers and associated common names of camps are listed in Table 1). Each latrine pit was temporarily crowned with an open plywood outhouse (Fig. 3); at the end of each climbing season the outhouses were removed but the waste was covered with snow and abandoned, left to be transported down-glacier. Elsewhere on the mountain, where latrine pits were not provided, climbers were required to dispose of all human waste in crevasses, where the waste would be more deeply buried over time. These efforts were generally effective at keeping the glacier surface clean of most human waste, except above Camp 5 (4300 m), where the highest portion of the climbing route and Camp 6 itself were notoriously contaminated. In that windswept environment, deep crevasses were difficult to find, especially by altitude-fatigued climbers, and surface waste disposal was still common. In summary, until 2001 virtually all waste generated on the mountain was disposed of in latrine pits, crevasses, or inappropriately on the glacier surface (Robinson, 2010).

In 2001, NPS collaborated with the American Alpine Club to run a pilot program testing use of a small, lightweight portable toilet called the Clean Mountain Can (CMC; Fig. 3). By 2004, over 500 climbers used CMCs to remove their waste from the historically polluted Camp 6. The pilot program was effective at minimizing contamination of surface snow, and evolved into the current policy of requiring all climbers to carry and use CMCs. However, collection and transport of a climber's waste over the duration of an entire climbing trip was judged impractical, so climbers typically collect their waste in CMCs but are permitted to periodically empty that waste into crevasses in all but two particularly sensitive areas: on the high mountain above Camp 5, and within 0.8 km of landing strips at places like Camp 1. This practice constitutes the current waste management plan as of 2011.

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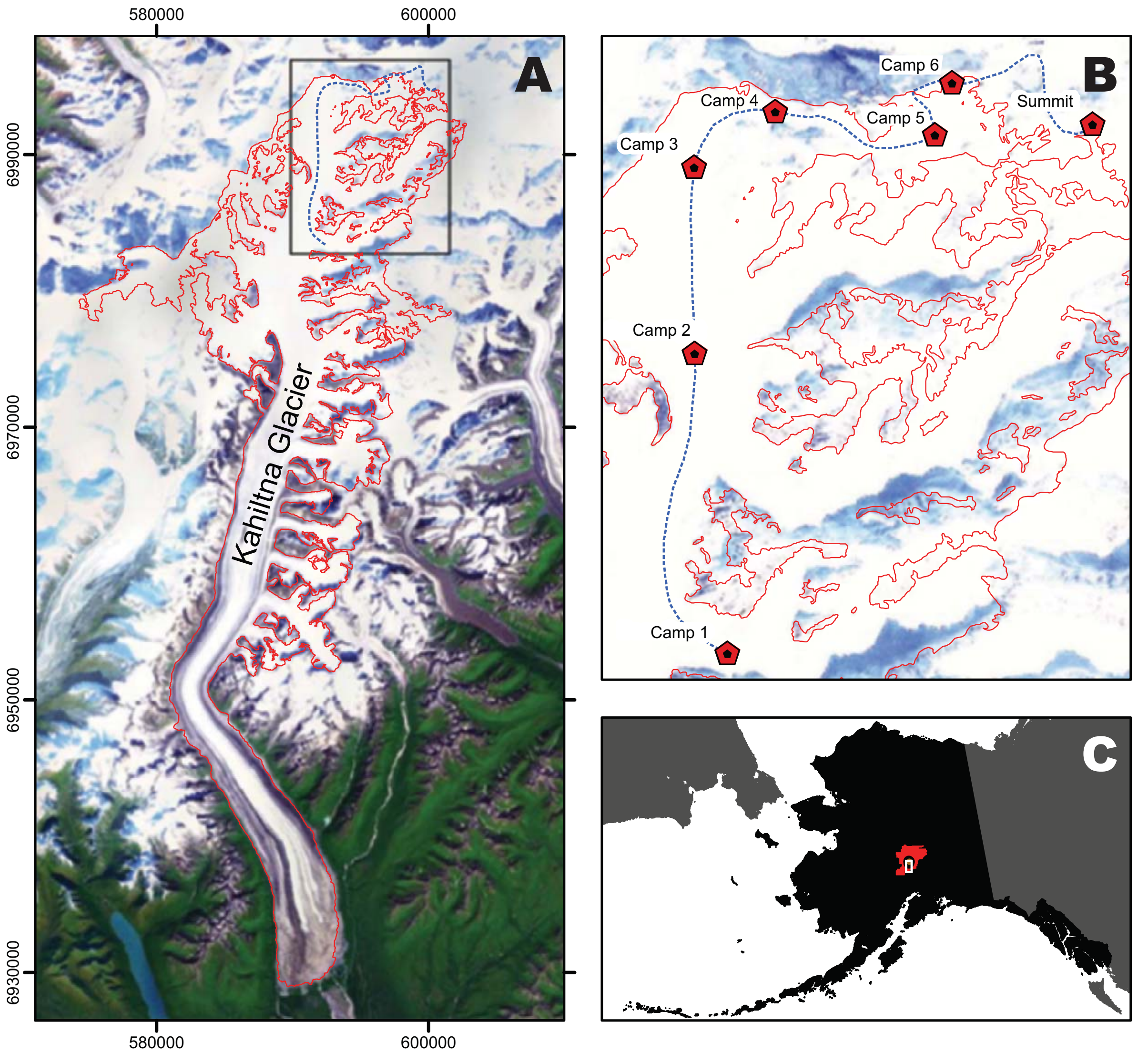

FIGURE 1. Kahiltna Glacier (outlined in panel A) stretches 66 km south from Mt. McKinley. Climbers typically spend 2–3 weeks on the West Buttress climbing route (dashed line). Detail view in B shows approximate locations of Camp 1, other commonly used camps, and the summit. Overview map (C) shows Denali National Park (polygon) and extent of panel A (white rectangle) in Alaska. Grid ticks in meters, UTM Zone 5N.

TABLE 1

Names and elevations of common camps on the West Buttress climbing route with a schedule of typical climber progress. Schedules vary greatly based on weather, climber fitness, acclimatization, etc.

Day of trip	Camp #	Common camp name(s)	Elevation m (ft)	Activity
1–2	1	Base Camp	2200 (7200)	Fly in from Talkeetna, ferry loads
3	2	Seven-Eight	2400 (7800)	Move camp
4	3	Ski Hill	2900 (9500)	Move camp
5–7	4	Eleven Camp	3400 (11,000)	Move camp, rest day, ferry loads
8–12	5	Genet Basin, Fourteen	4300 (14,200)	Move camp, rest days, ferry loads
13–15	6	High Camp, Seventeen	5200 (17,200)	Move camp, attempt summit
16	3	Ski Hill	2900 (9500)	Descent
17–18	1	Base Camp	2200 (7200)	Descent, fly to Talkeetna

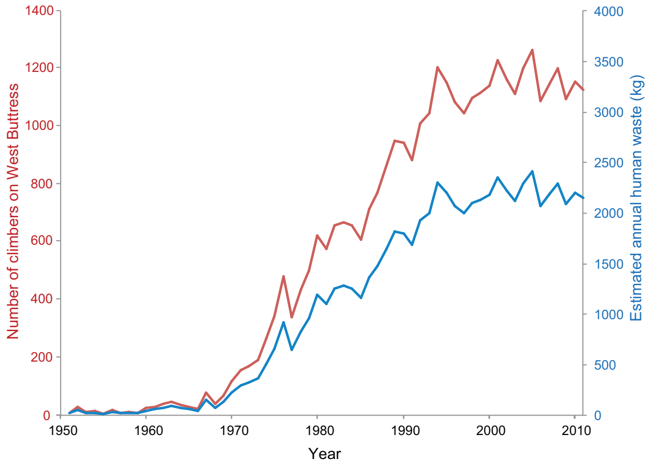

FIGURE 2. Numbers of climbers on Denali's West Buttress climbing route by year (upper line) with an estimate of associated annual human waste generation (lower line). Waste estimate assumes 18 days per climber with 106 g average stool weight per day. In the last decade, climbers have disposed of over 2 metric tons of human waste on the Kahiltna Glacier each year.

Current practice minimizes surface contamination of the Kahiltna Glacier, and climbers experienced on other popular high mountain climbing routes, especially internationally, are generally pleased with the cleanliness of the mountain. Because the climbing route lies completely within the Kahiltna Glacier's accumulation zone, any surface contamination that does occur will be buried by new snow within a year. The vast majority of waste is still left on the mountain, however; it is just deposited in crevasses. Since 1970 over 34,000 persons have attempted to climb Denali via the West Buttress climbing route, leaving behind an estimated 66 metric tons of feces (Fig. 2). NPS managers are therefore right to ask whether fecal pathogens currently contaminate water on the glacier surface, in the glacier ice itself, or downstream in the Kahiltna River. Furthermore, this buried waste will eventually be carried by downglacier flow to the ablation zone where it will melt out at the glacier surface. If we can predict where and when glacially transported waste will emerge again at the glacier surface, will pathogens in that waste still be viable?

There is some evidence to suggest that concerns about fecal pathogens on the Kahiltna Glacier are well-founded. Direct fecal contamination of the climbers' water supply (melted snow) was documented by a 2002 epidemiological study on Denali (McLaughlin, 2005). A survey of 132 climbers revealed that 39% of climbers saw fecal contamination on the snow in or near camps, 78% reported collecting snow for consumption within 10 m of camp, and 29% suffered from acute gastroenteritis within 1–21 days upon arrival on the mountain (McLaughlin, 2005). These conditions were attributed to the inadequate disposal of human waste and poor hygienic practices (McLaughlin, 2005). Similarly, outbreaks of waterborne illness are common on the popular high-altitude climbing route of Mt. Acongagua, Argentina, and were attributed by Carr et al. (2002) to evidence of fecal contamination both in the major campsites as well as along the climbing route. Persistence of fecal contaminants in surface snow was tested in an experiment conducted by Ells (1999) on Mt. Rainier, Washington, where he found that fecal coliform persisted around a human fecal deposit for two weeks, after which contaminants were undetectable. These studies suggest that fecal coliform bacteria are common around well-used

FIGURE 3. Components of recent human waste management practice on Denali. Clean Mountain Cans (CMCs, panel A) are used at most camps on the mountain. Waste from the cans can be emptied into crevasses, except above 4300 m and near airstrips. This light-weight portable toilet measures 30 cm tall and 20 cm in diameter. Straps and a lock tight lid ensure sanitary transport of human waste. Used CMCs containing non-crevassed waste, shown here at Camp 1 along with white plastic bags full of climber garbage (B), are flown back to Talkeetna. Until 2011, a latrine pit was dug each season at Camp 5 and crowned with a plywood outhouse (C).

glacier campsites, and sufficiently persistent in surface snow to pose a health threat to recreational users.

Disappearance of detectable coliform bacteria from the snow surface (in the Ells study, for example) does not, however, demonstrate mortality of those organisms, since many are likely transported down through the snow and firn by meltwater for temporary (days to years) storage within glacier ice before ultimately entering downstream rivers. The potential for contamination of a glacial river by human waste disposal on an upstream glacier was demonstrated by Whiteman et al. (2005), who found that terminus meltwater discharge from the Mont Mine Glacier, Switzerland, contained coliform bacteria. A popular hut sits at the head of the Mont Mine Glacier, which is also traversed by many users of the popular Haute Route. The remaining glaciers in this study showed no fecal contamination and in comparison with Mont Mine were infrequently visited by humans. This study clearly shows that meltwater can carry surface contaminants to downstream rivers, but can contaminants survive long-term exposure to conditions on and within the glacier?

Waste deposited on a glacier will be exposed to multiple freeze-thaw cycles, UV radiation, and deep cold when deposited at the surface. Once buried in firn/ice, it will be exposed to constant near-freezing temperatures and complete darkness. Waste will again experience freeze-thaw cycles and UV light once it emerges at the surface of the ablation zone. We are not aware of any studies that document the survival of fecal coliform bacteria in Denali's harsh and varying environments, but pertinent research from non-glacial environments suggests that freeze-thaw cycles (Adhikari et al., 2007), UV light exposure (Hallmich and Gehr, 2010), and long-term nutrient starvation (Dawes and Senior, 1973) are all potentially fatal conditions for fecal bacteria. Indeed, two studies of historic feces left subaerially exposed for multiple decades showed that coliform bacteria were undetectable in a ~50-year-old sample (Nedwell et al., 1994) and in a 30- to 40-year-old sample (Hughes and Nobbs, 2004). Spore-forming bacteria were found to persist longer in both cases.

In summary, nutrient scarcity, subfreezing temperatures with freeze-thaw cycling, and UV light may limit survival of coliform bacteria in a glacial environment, but the few studies available nonetheless suggest that overall survival may still be sufficient to pose a human health hazard. Here, we report findings from a field study that documents the presence and persistence of fecal indicator bacteria on and downstream of the Kahiltna Glacier, and from a laboratory experiment designed to replicate conditions of both deep and shallow burial on the glacier. We also document Kahiltna Glacier surface velocities and predict the time and place that human waste deposited at various sites along the climbing route will ultimately emerge in the glacier's ablation zone.

Methods

We conducted several field surveys and two experiments between May 2010 and August 2011 to determine the presence and persistence of fecal bacteria in a range of sub-environments associated with the Kahiltna Glacier. First, we document these surveys and experiments and the laboratory procedures involved in testing samples for indicator bacteria. Second, we describe how we used surface velocities on the Kahiltna Glacier, along with generalized estimates of the mass balance profile and equilibrium line altitude, to construct a simple model that predicts emergence times and locations for waste buried at common camps along the climbing route.

FIELD SAMPLES

Water and snow contaminated with feces contain a wide range of bacteria and pathogens. We focus on three indicator bacteria that are abundantly present in the intestines of warm-blooded animals and are common indicators used to test for fecal contaminated water (U.S. Environmental Protection Agency, 2003): total coliform, *Escherichia coli* (*E. coli*), and fecal enterococci. These bacteria may cause illness and are indicators of potential contamination by other pathogens, such as *Giardia lamblia*, that are difficult to detect and less frequently included in standard water quality testing (World Health Organization, 2001). Because the human source of bacterial contamination is self-evident for fecal samples and snow collected from near climber camps, these samples were tested only for total coliform and *E. coli*. Water samples are more susceptible to contamination from other non-human sources, and were therefore tested for a third indicator—fecal enterococci—which when present strengthens the inference of a mammalian (though not definitively human) origin of contamination.

For the purpose of this study, we recognize five sub-environments on and around the Kahiltna Glacier. We distinguish these sub-environments on the basis of physical characteristics that pose distinct challenges to the survival of indicator bacteria, but note also that the potential threat to human health is different in each area (Table 2). Starting at the highest elevations and moving downwards, these sub-environments are (1) windswept glacier surfaces on the highest ridgelines, (2) snow surfaces along the main climbing route, (3) long-term englacial burial, (4) ice surfaces in the ablation zone subject to shallow seasonal burial, and (5) glacial meltwater at the glacier terminus. We summarize the conditions and sampling strategies for each unique sub-environment below. Sample locations are shown in Figure 4 and Table 3.

On high, windswept ridgelines, particularly between Camp 6 and the summit, snow accumulation is minimal and extreme cold prevails year-round. Feces left on the glacier surface can persist for years in a frozen state, exposed to intense UV radiation and continuous below-freezing temperatures that exceed −70 °C (International Arctic Research Center, 2010). To test for the persistence of fecal bacteria that pose a potentially direct threat to the health of climbers melting surface snow and ice for water, a series of sampling kits were sent out with patrolling NPS rangers during summer 2010 to collect any feces left on the surface of the upper climbing route. A single fecal sample was collected by an NPS ranger at 5700 m (18,800 feet; Fig. 4) on 20 May, early enough in the climbing season to infer that the feces had been deposited in the previous climbing season, and had weathered at least 10 full months in that location. This sample was tested for total coliform and *E. coli* only.

Lower on the climbing route, where snow accumulation can occur anytime during the year, fecal contaminants will persist at the surface only a short time (days to weeks) before the material is buried and enters the englacial environment. Most waste in this zone is deposited directly in a crevasse or latrine pit, and so may bypass this environment entirely. We tested for the presence of surface contamination by collecting surface snow samples at the

TABLE 2

Five sub-environments of the Kahiltna Glacier characterized by differing physical characteristics that control pathogen survival and hence affect potential threats to human health. Elevations are approximate.

Elevation (m)	Subenvironment	Physical characteristics	Potential threat
>4300	Windswept ridgelines	Little snow accumulation. Continual below freezing temperatures with seasonally high UV radiation.	Direct contamination of snow or ice melted for water on the main climbing route.
4300–2200	Snow surfaces on climbing route	Briefly exposed to freeze-thaw cycles and UV radiation before burial by year-round snowfalls.	Direct contamination of snow or ice melted for water on the main climbing route.
4300–300	Englacial burial	Firn and ice remain at ~0 °C year-round with no UV radiation.	No direct threat, but may contaminate englacial meltwater discharged into river.
1900–300	Ice surfaces in ablation zone	Daily freeze-thaw cycles and UV radiation except during shallow burial each winter.	Contamination of supraglacial runoff used by rare recreational users of the lower glacier.
<300	Glacial meltwater	Glacial river with suspended sediment and temperatures of 1–5 °C.	Use of contaminated water by downstream users of Kahiltna River.

locations of major climbing camps before (control) and after (treatment) the establishment of camps that are used repeatedly by multiple groups during the main climbing season. Control samples were accessed by helicopter and collected by an NPS ranger on 17 May 2010. At sites S2, S3, and S4 (Fig. 4), a 100-m transect was established and sampled every 10 m near traditional camp locations but on clean snow visibly unaffected by recent climbing or camping activity. We collected a second set of surface snow samples on 28 June 2010, directly adjacent to five established and well-used camps marked by substantial snow walls (Fig. 4). These locations included the three control sites as well as a higher- and lower-elevation site. At each site, one sample was collected at the center of an established camp (within the snow walls) and additional samples were collected every 5 m along each of four 20-m transects that radiated outwards in the four cardinal directions. These samples were tested for total coliform and *E. coli* only.

Whether left in a crevasse, a latrine pit, or on the surface, waste left in all but the most windswept portions of the climbing route will be buried ever more deeply by accumulating snow while being transported downglacier. Over time, snow progresses from firn to glacier ice that remains dark and in most locations (except within <15 m of the glacier surface and in isolated and uncommon patches of colder ice) at the pressure-melting point (~0 °C) year-round. This waste is inaccessible during its slow transport to the ablation zone, where progressive melting will eventually return the waste to the glacier surface. Human bodies recovered from melting glaciers demonstrate that organic materials can survive this englacial transport with only minimal mechanical breakdown (Deem, 2008). Once at the glacier surface, waste would be exposed in summer to freeze-thaw conditions, rainfall, and UV radiation. In winter, it would be buried under <1 to a few meters of snow, partially insulated from freeze-thaw cycles, and free of UV exposure. Our own observations, including aerial surveys focused on sites of likely waste emergence, coupled with observations of climbers, rangers, and researchers familiar with the Kahiltna Glacier, suggest that this emergence has not yet occurred. Later in the paper, we use a simple model to predict when and where this emergence will occur. In the meantime, we did not sample any *in situ* fecal materials from the englacial or ablation zone environments. We addressed the potential fate of such materials with field and lab experiments described in the next section.

Most waste still buried deeply within the ice is exposed seasonally to substantial quantities of glacial meltwater traveling through conduits and pore spaces within the ice and discharging eventually to the Kahiltna River, where it will be transported 114 km downstream to the Susitna River and then an additional 50 km to Cook Inlet, a northern embayment of the Pacific Ocean. The Kahiltna River is ungaged, but the nearby Chulitna River, which is also glaciated and has a comparable basin area, has an average summer discharge of 665 m3 s^{-1} and remains just above freezing year-round (U.S. Geological Survey, 2011). To test for indicator bacteria in the Kahiltna, we collected water samples on 26 August 2010 and 6 June 2011 from several locations where the river exits the glacier terminus (Fig. 4). To address the possibility that any detected contaminants were sourced in non-glacial stream valleys that contribute water to the lower Kahiltna Glacier some distance upstream of the terminus, on those same dates we also collected control samples from such streams adjacent to the glacier margin (Fig. 4). Site access was by helicopter, and samples were collected with sterile 100 mL IDEXX (2008) water vessels. All water samples were tested for all three bacterial indicators.

EXPERIMENTS

Because we were unable to directly test existing *in situ* samples of deposited waste in the englacial or ablation zone environments, we conducted two experiments to simulate those environments. In the first, a field experiment, we buried a single human feces near Camp 1 in June 2010, and returned a year later—in June 2011—to excavate it and test for presence of indicator bacteria. The initial burial was 4.00 m deep (a typical minimum depth for a latrine pit or crevasse disposal) in the wall of a snow pit that was subsequently refilled (Fig. 4). The waste was enclosed in a plastic bag (like most crevassed waste) taped to four Recco reflectors (Atkins, 2011) to assist in relocating the waste the following year. Directly above the waste, at 2 m depth, we buried an additional 4 reflectors and a temperature logger recording hourly measurements.

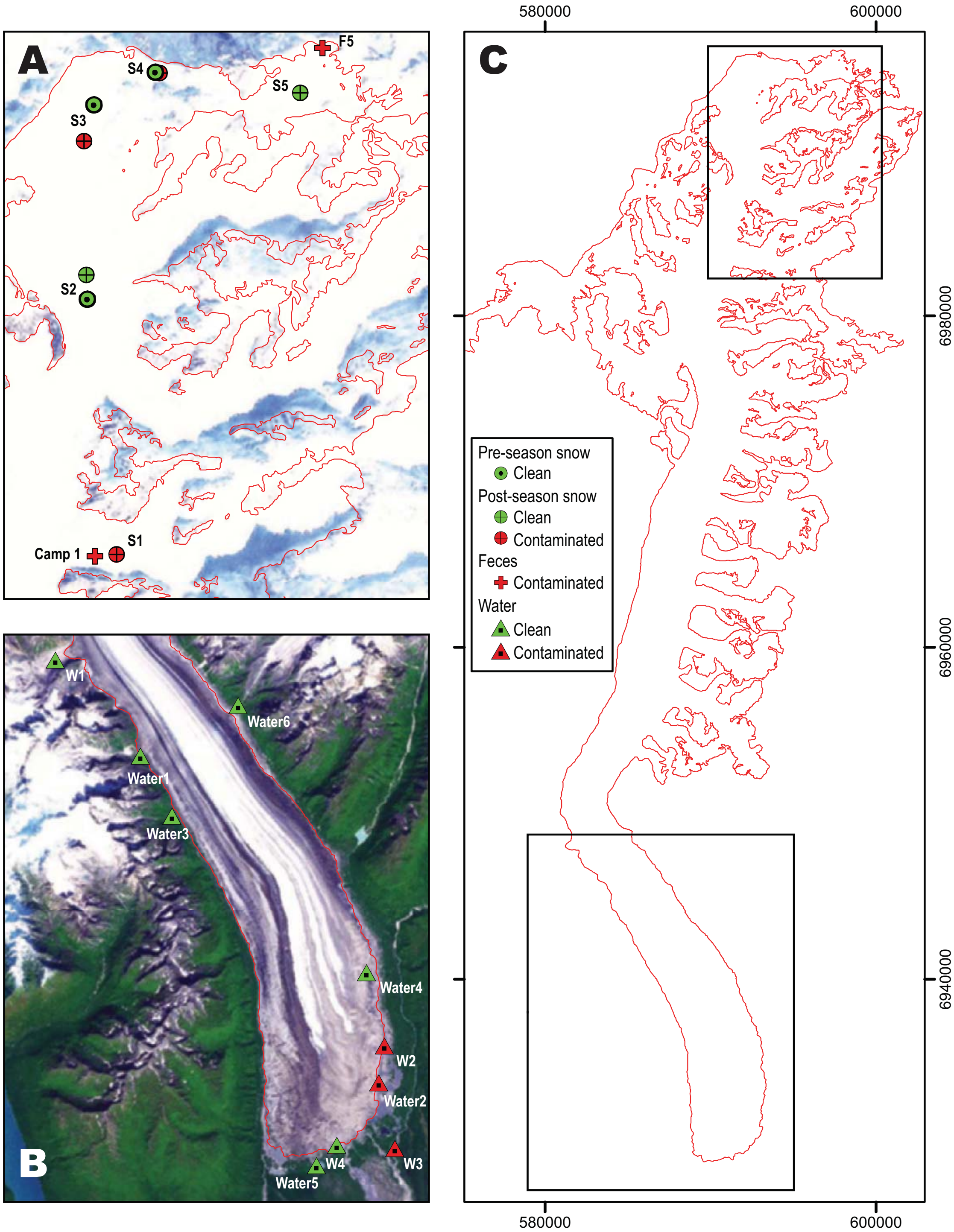

FIGURE 4. Maps depicting locations and general results of field surveys conducted on Kahiltna Glacier. Panel A shows locations of snow and fecal samples on the upper glacier, and panel B shows locations of water samples collected around the glacier terminus. Legend in overview map (C) identifies samples by symbol type and color. Note that post-season snow sample sites identified as ''contaminated'' indicate that a single sample, out of many collected at each site, tested positive for indicator bacteria. See text and Table 3 for details. Grid ticks in meters, UTM Zone 5N.

In June 2011 we returned to Camp 1 with a Recco locator and retrieved the datalogger and fecal sample. The waste was 5.3 m deep at the time of retrieval. The waste was tested for total coliform and *E. coli* only.

In a second experiment, we used laboratory cold chambers to expose fecal samples to four separate treatments that simulated specific englacial and ablation zone environments. One chamber maintained the constant 0 °C temperature expected deep within the glacier while another simulated temperature fluctuations expected during exposure on, or shallow burial near, the glacier surface. In detail, these temperature fluctuations will vary with season and specific location, but for the purposes of the experiment we used

TABLE 3

Sample types, locations, sampling dates, and indicator bacteria results.

Sample type/ID	Longitude*	Latitude*	Date (m/dd/yyyy)	Total coliform	*E. coli*	Enterococci
Feces (1 sample each)						
F-5700m	151°03′54.23″	63°04′44.11″	5/20/2010	>2.42 × 10^8/100 mL	>2.42 × 10^8/100 mL	NA
Base camp	151°11′0.29″	62°58′03.85″	6/06/2011	>2.42 × 10^8/100 mL	>2.42 × 10^8/100 mL	NA
Pre-season snow (11 samples per site)						
S2-2400m	151°11′02.03″	63°01′28.81″	5/17/2010	absent	absent	NA
S3-2900m	151°10′40.77	63°04′3.83″	5/17/2010	absent	absent	NA
S4-3400m	151°08′50.86″	63°04′28.40″	5/17/2010	absent	absent	NA
Post-season snow (17 samples per site)						
S1-2200m	151°10′22.00″	62°58′04.81″	6/28/2010	present-1 sample	absent	NA
S2-2400m	151°11′01.73″	63°01′48.60″	6/28/2010	absent	absent	NA
S3-2900m	151°10′59.40″	63°03′35.27″	6/28/2010	present-1 sample	present-1 sample	NA
S4-3400m	151°08′42.42″	63°04′27.94″	6/28/2010	present-1 sample	absent	NA
S5-4300m	151°04′35.63″	63°04′08.99″	6/28/2010	absent	absent	NA
Terminus stream water (1 sample each)						
W2-West Fork	151°13′24.44″	62°29′04.15″	8/26/2010	2/100 mL	1/100 mL	0/100 mL
W3-East Fork	151°10′50.97″	62°28′58.31″	8/26/2010	8/100 mL	6.3/100 mL	0/100 mL
W4-East Toe Pond	151°11′10.54″	62°31′04.00″	8/26/2010	0/100 mL	0/100 mL	0/100 mL
Water2	151°11′28.61″	62°30′18.94″	6/06/2011	3.1/100 mL	3.1/100 mL	0/100 mL
Water4	151°11′52.94″	62°32′33.54″	6/06/2011	0/100 mL	0/100 mL	0/100 mL
Water5	151°14′18.96″	62°20′38.40″	6/06/2011	0/100 mL	0/100 mL	0/100 mL
Tributary water (1 sample each)						
W1-Control Trib	151°25′16.45″	62°39′04.87″	8/26/2010	0/100 mL	0/100 mL	0/100 mL
Water1	151°21′36.61″	62°37′05.20″	6/06/2011	0/100 mL	0/100 mL	0/100 mL
Water3	151°20′16.73″	62°35′51.00″	6/06/2011	0/100 mL	0/100 mL	0/100 mL
Water6	151°17′13.78″	62°20′38.40″	6/06/2011	0/100 mL	0/100 mL	0/100 mL

* For pre and post-season snow samples, latitude and longitude denote center of sampled points. NA = not applicable.

a diurnal cycle of −5 to +6 °C. This temperature range is narrower than daily and seasonal air temperature variations evident on the Kahiltna Glacier, and reflects in a general way the dampening effects of phase changes between ice and liquid water at the glacier surface. The range would be even narrower in winter, under a layer of insulating snow. The two desired temperature regimes were maintained by a remote computer, linked to temperature sensors in the two cold chambers. To independently test the influence of UV radiation on bacterial persistence, half of the samples in each of the two cold chambers were exposed constantly to a Repti Sun 5.0 26-watt UVA/UVB light that was kept within 0.3 m (12 inches) of all samples; the others remained in total darkness. Fecal samples were collected from multiple volunteers, mixed in a sterile container, and divided into 480 11-g samples. Each sample was placed in a sterile 100 mL vessel, and 120 samples were placed in each of the four treatments. Once the experiment commenced, two 11-g samples were pulled from each of the four treatments every 72 h. One sample from each of the four groups was analyzed for total coliform and *E. coli*; the second sample from each of the four groups was analyzed for fecal enterococci using standard techniques described below. The experiment was concluded after 150 days.

LABORATORY PROCEDURES

Because our focus in this paper is on the potential for human health impacts of fecally contaminated water, preparation and enumeration procedures for all fecal, snow, and water samples collected (including laboratory experiment samples) were conducted according to the Standard Methods for Examination of Water and Wastewater, Part 900 (Rice et al., 2012). All fecal samples and water samples were tested by the Most Probable Number (MPN) method, while snow samples were tested simply for presence/absence. Fecal samples in aqueous suspension typically exceeded the test's maximum count of 2419.6 microorganisms per 100 mL sample, so for these we performed serial dilutions, up to 1/100,000. In such cases, we report MPN as the count times the denominator of the dilution; where MPN exceeded the maximum count even at maximum dilution, we report concentration as >2.42 × 10^8 100 mL^{-1} in accordance with EPA guidelines (U.S. Environmental Protection Agency, 2003).

GLACIER VELOCITIES

How long will crevassed waste or latrine pits remain buried in glacier ice before they emerge in the glacier's ablation zone? The answer depends on several variables, including the speed with which waste is transported downvalley. We documented glacier surface velocities on the valley-confined portion of Kahiltna Glacier from Camp 4 (3400 m) down to the glacier terminus (Fig. 1), ignoring Camp 5 and other areas on the upper mountain from which the glacier, and waste contained therein, spills off high cliffs in spectacular icefalls which defy the simple modeling effort undertaken here.

In the perennially snow-covered accumulation zone of Kahiltna Glacier, where tracking of remotely sensed surface features is difficult, we measured glacier surface velocities during summers 2007 and 2009 with precise re-measurement of stakes embedded in the snow surface. We used a steam drill to vertically insert 3-m PVC stakes at each of 16 sites, and then stake locations were measured at the glacier surface using a Trimble GeoXH GPS unit with Zephyr antenna. Remeasurement intervals on these stakes ranged 17 to 27 days and horizontal measurement errors were all <0.04 m day^{-1} (Table 4). We supplemented these data with measurements, collected using similar techniques, from six stakes measured by A. Bucki (unpublished data, 2002) and J. Young (unpublished data, 2011). Finally, we used data collected by NPS between 1991 and 2011 at the Index Site, a single monitoring site located at ~1930 m near the equilibrium line of the glacier (R. Burrows, unpublished data, 2011). All stake locations are shown in Figure 5 and Table 4.

Below the equilibrium line, we used stake measurements collected by J. Young and remotely sensed data collected by the Advanced Land Observing Satellite (ALOS). The satellite's Phased Array type L-band Synthetic Aperture Radar (PALSAR) was used to track displacements of glacier surface features (like crevasses, rocks, and distinctive topography) that are stable over the interval of measurement. The PALSAR data we used spanned two winter intervals: 17 January to 4 March 2007, and 20 January to 6 March 2008. From these data sets surface displacements were computed using normalized cross-correlation feature tracking, a method well described by Strozzi et al. (2002) and Rott (2009). It is suitable for alpine-style glaciers when they exhibit sufficient surface features that move coherently with the glacier ice. The technique does not, therefore, provide velocities for the more featureless snow-covered portion of the Kahiltna accumulation zone.

Tracking was done on the single-look complex imagery using the maximum resolution of 4.7 m and 3.1 m pixel spacing in slant range geometry. Image pairs were first co-registered to sub-pixel accuracy (standard deviation of co-registration fit <0.25 pixels in range and azimuth) and the local offset was then measured by the maximum correlation peak. The size of tracking windows (64 ×

TABLE 4

Velocities and associated survey information for stakes measured on Kahiltna Glacier between 1991 and 2011 and shown in Figure 6.

Start Date	Days	Stake Name	Northing (m)	Easting (m)	Velocity (m/day)	Error** (m/day)	Bearing	Reference
1-Jun-1991	*	Index Site	6980233.6	589007.1	0.55	—	177.37	Burrows
26-Jun-2002	23	LS1	6983151.6	592214.6	0.34	—	277.24	Bucki
27-Jun-2002	22	LS2	6983241.6	592219.1	0.36	—	260.61	Bucki
27-Jun-2002	22	LS3	6983342.1	592257.4	0.36	—	260.90	Bucki
27-Jun-2002	22	LS4	6983479.1	592284.3	0.34	—	260.91	Bucki
27-Jun-2002	22	LS5	6983574.3	592328.6	0.33	—	262.12	Bucki
27-Jun-2002	22	LS6	6983691.5	592332.9	0.29	—	264.16	Bucki
15-Jun-2007	22	heli long	6983314.0	592858.3	0.38	0.02	264.85	this paper
16-Jun-2007	20	stake 1	6984362.1	591016.7	0.43	0.02	203.40	this paper
16-Jun-2007	20	stake 2	6990008.5	591788.3	0.32	0.03	163.60	this paper
17-Jun-2007	19	stake 3	6992916.8	591667.7	0.25	0.04	188.43	this paper
17-Jun-2007	19	stake 4	6995409.0	592405.6	0.10	0.03	247.10	this paper
18-Jun-2007	17	stake 5	6995280.0	593645.6	0.06	0.03	269.94	this paper
23-May-2009	27	LS#1	6983926.4	591804.3	0.24	0.02	276.29	this paper
23-May-2009	27	LS#2	6983744.5	591758.0	0.31	0.02	268.21	this paper
23-May-2009	27	LS#3	6983629.3	591733.9	0.35	0.01	255.20	this paper
23-May-2009	27	LS#4	6983445.6	591559.2	0.33	0.01	256.91	this paper
23-May-2009	27	LS#5	6983279.8	591659.6	0.40	0.01	253.42	this paper
23-May-2009	27	US#1	6983529.5	593683.0	0.25	0.02	266.61	this paper
23-May-2009	27	US#2	6983396.2	593705.8	0.32	0.02	265.12	this paper
23-May-2009	27	US#3	6983268.8	593703.5	0.23	0.02	213.56	this paper
23-May-2009	27	US#4	6983148.6	593708.1	0.31	0.02	252.03	this paper
23-May-2009	27	US#5	6983026.2	593703.1	0.26	0.02	236.63	this paper
1-May-2010	501	KT3	6955102.5	584823.3	0.65	0.00	211.50	Young
2-May-2010	500	KT5	6947092.1	584248.6	0.61	0.00	138.98	Young
2-May-2010	500	KT4	6950375.1	582440.2	0.63	0.01	164.03	Young
3-May-2010	499	KS2	6957249.2	585829.5	0.58	0.00	201.55	Young
29-Apr-2011	138	KS3	6952755.8	583631.2	0.67	0.00	217.87	Young
30-Apr-2011	137	KT2	6959604.0	586408.1	0.54	0.00	190.63	Young
6-Jun-2011	70	KH1	6995222.2	593179.8	0.12	0.01	297.69	Young
6-Jun-2011	70	KH2	6989920.0	591645.1	0.33	0.00	150.05	Young
6-Jun-2011	100	KT1	6966242.6	587943.7	0.63	0.00	194.40	Young
6-Jun-2011	70	KH3	6984185.4	590384.9	0.45	0.00	196.17	Young
6-Jun-2011	70	KH4	6973560.0	590277.3	1.05	0.00	189.15	Young

* 19 seasonal measurements from 1991 to 2011; stake location, velocity, and bearing varied slightly.

** Based on 95% confidence intervals of horizontal stake positions; '—' indicates error unknown.

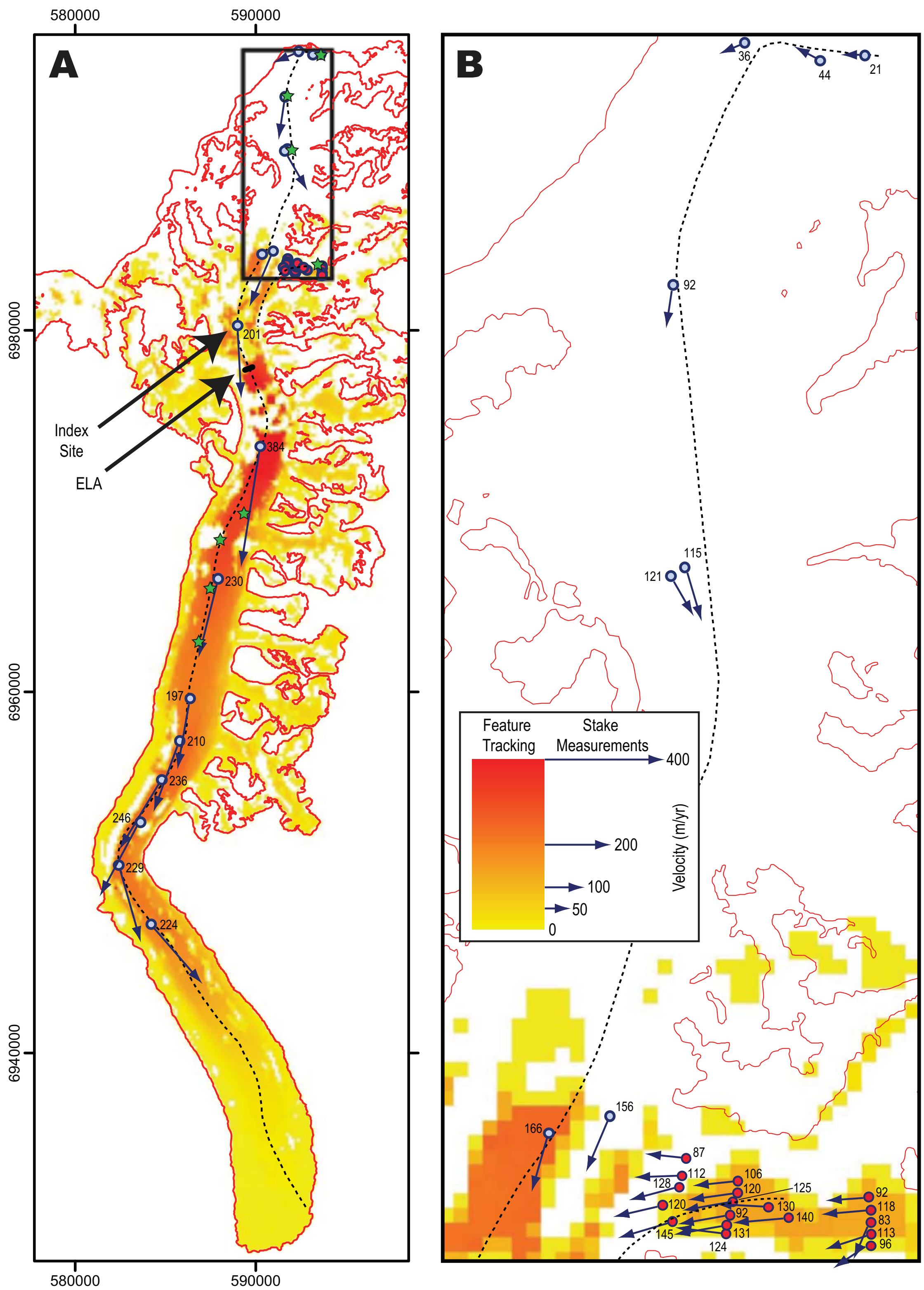

FIGURE 5. Glacier velocities on the Kahiltna Glacier as measured by feature tracking (colored pixels on central and southern portion of glacier) and repeat GPS measurements of stakes (blue dots). Panel A shows the entire glacier, and panel B shows detail of the climbing route and Southeast Fork (Camp 1 and airstrip) area. Color bar indicates feature tracking velocities in m yr^{-1}, and arrows indicate stake velocities (labeled in m yr^{-1}) and bearings. Dashed black lines indicates approximate location of central flowline from Camp 4 to the terminus and also a tributary flowline from the Southeast Fork into the main trunk glacier. Dots with blue centers were used in constructing the velocity profile in Figure 6; red center dots are used to model for the Southeast Fork trajectory. Green triangles indicate starting points (northern 4) and emergence points (southern 4) calculated in our emergence model. Grid ticks in meters, UTM Zone 5N.

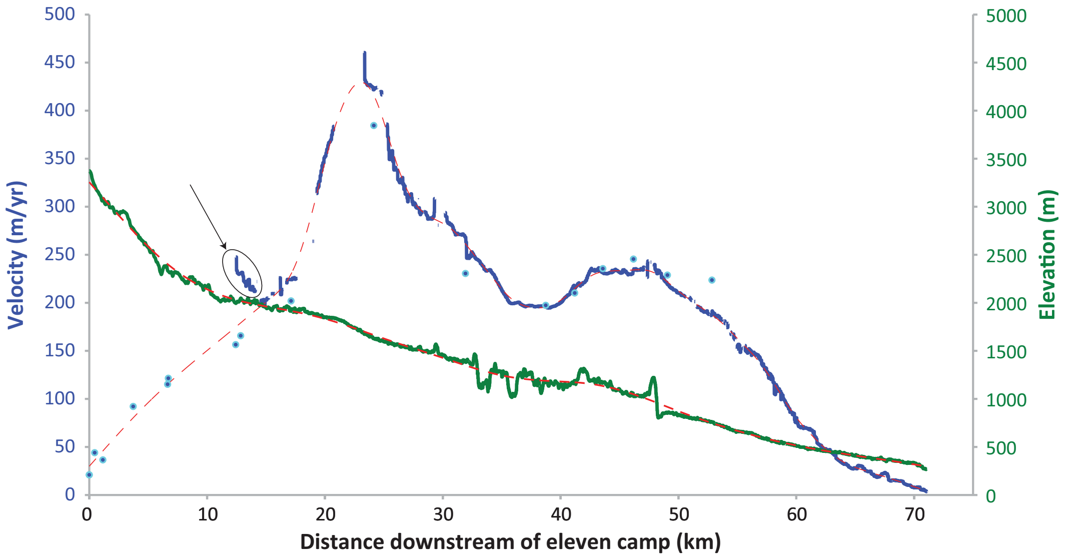

FIGURE 6. Glacier surface elevations and velocities for the Kahiltna Glacier, plotted as a function of distance downstream (along a central flowline) from Camp 4 (see Figure 1). Annual velocities are derived from feature tracking (blue lines) and stake measurements (blue dots). Anomalously high velocities from the uppermost edge of the feature tracking technique's effectiveness (black ellipse and arrow) were excluded when fitting velocities with a spline smoothing function (dashed red line). Elevations from a 2010 ASTER-based GDEM (green line) were sampled along the central flowline and smoothed with a spline smoothing function that eliminates erroneous depressions (dashed red line).

192 pixels) and step size (12 × 36 pixels) were both adapted to the different range and azimuth resolution in order to achieve approximately squared tracking pixels. The velocity fields were then orthorectified to a standard map projection using the U.S. Geological Survey NED digital elevation model. Finally, the two products were resampled to 150-m resolution and then averaged over the two time intervals to produce a spatially explicit map of average velocity. Uncertainties in the final displacement products resulted from co-registration errors and from changes of surface feature over time. The resulting displacement fields were filtered to remove extreme and presumably poor quality offsets. Displacements with a signal-to-noise ratio lower than 7 were discarded. Based on stable targets (e.g. bedrock) we estimate the uncertainty to be approximately ± 10 m yr^{-1}.

EMERGENCE MODEL

As waste is carried downstream by glacier flow, it will be buried by further snow accumulation until it reaches the equilibrium line, at which point surface melt will dominate and eventually lead the waste to emerge at the glacier surface. To estimate the time and distance elapsed before such emergence, we used Matlab to code a simple numerical model that uses glacier velocities and surface mass balance to track yearly changes in the horizontal position and depth (below the glacier surface) of waste. Starting at the four different major camps on the valley-confined portion of Kahiltna Glacier (Fig. 1), the model assumes an initial burial depth of 10 m—a representative depth for a shallow crevasse or deep latrine pit—and then tracks the waste movement down a central flowline (Fig. 5) with known longitudinal profiles of glacier velocity and surface elevation (Fig. 6). Waste buried below the ice surface will travel at velocities slightly lower than the measured surface velocities due to internal deformation, but because such deformation is concentrated near the glacier bed, we ignore this detail for the shallow burial depths in our model. Surface elevations are based on a smoothed profile extracted from an ASTER digital elevation model acquired 6 September 2010 (NASA LP DAAC, 2010). In the case of waste burial at Camp 1, we estimate the trajectory and velocity of the waste from stakes clustered in the Southeast Fork Kahiltna Glacier (Fig. 5) until the waste enters the main trunk glacier 1 km east of the Index Site. Downstream of this point, the Camp 1 waste will follow an independent flowline slightly east of waste from the other sites but we utilize the velocity profile in Figure 6, implicitly making the simplifying assumption of no cross-glacier variations in velocity. At each annual time step, depth of the waste (measured, for convenience, in meters of water equivalent: m w.e.) is adjusted by the surface mass balance (b_{sfc}) at the corresponding elevation. From each starting location, the model tracks waste motion until depth ≥ 0 m.

The mass balance of Kahiltna Glacier is not well known: Mayo (2001) measured an average gradient of 0.0032 (m w.e. m^{-1}, hence unitless) in the four years 1992–1995, but his measurements spanned only a range of several hundred meters near the equilibrium line. Recent research on the Kahiltna (J. Young, personal communication, 2011) found a slightly shallower gradient (0.0026) between the equilibrium line and the glacier terminus; we averaged these five measurements (0.0031) for the ablation zone gradient. Based on NPS measurements at the Index Site between 1991 and 2010, we use an average equilibrium line altitude (ELA) of 1879 m (Mayo, 2001; R. Burrows, unpublished data, 2011; J. Young, personal communication, 2011; Fig. 5). We have less information about the mass balance in the accumulation zone, where gradients typically diminish with elevation (Furbish and Andrews, 1984; Rea, 2009), and used a shallow ice-core-based estimate of 0.8 m w.e. yr^{-1} net balance at 3800 m (Campbell et al., 2012) to calculate a gradient of 0.0007 between the ELA and Camp 4. Better estimates of the glacier's mass-balance profile would improve our emergence model, but in any case we note that mass balance and equilibrium line altitude are very sensitive to ongoing climatic changes and our simple model makes no effort to forecast the effects of such changes on mass balance or glacier geometry.

Results

FIELD SAMPLES

The fecal sample collected from 5700 m (Fig. 4) was frozen solid and wind-desiccated when collected, and had been exposed to extremely cold temperatures for at least 10 months, and perhaps several years. Nonetheless, the sample tested positive for total coliform and *E. coli* with a MPN $>2.42 \times 10^8$ 100 mL^{-1}, the maximum sensitivity of the test (Table 3).

On snow-covered portions of the main climbing route, no fecal contaminants (total coliform or *E. coli*) were detected on clean snow sampled at the beginning of the climbing season, but some indicator bacteria were found on the snow surface late in the climbing season (Fig. 4). These contaminants remained rare: only 3 of the snow samples in this group of 65 post-season samples from 5 sites tested positive for indicator bacteria (Table 3). At S4 and S1, one sample from each site tested positive for total coliform, and at S3 a sample tested positive for both total coliform and *E. coli*. None of the collected snow samples, including those testing positive for indicator bacteria, appeared discolored or contaminated when collected, but we note that all three of the positive samples were collected from locations near (within <1 m) a given camp's designated ''pee-hole,'' where climbers also commonly use their CMCs.

Very low levels of total coliform and *E. coli* were found in some water samples from the Kahiltna River where it exits Kahiltna Glacier's terminus, but no indicator bacteria were found in tributary streams that contribute non-glacial water to the Kahiltna River (Fig. 4; Table 3). Trace levels (MPN 1–8/100 mL) of total coliform and *E. coli* were detected in 3 of 6 samples collected from Kahiltna River in the 2 years; no enterococci were found in any water samples. In the east fork of the Kahiltna River, total coliform was detected at 8/100 mL and *E. coli* at 6.3/100 mL in the 2010 samples; in the 2011 samples total coliform was detected at 3.1/100 mL and *E. coli* at 3.1 mL. No indicator bacteria were detected in the 2010 or 2011 water samples collected from tributaries that drain small unglaciated (or partly glaciated) watersheds on either side of the glacier. These watersheds are the most obvious potential non-human source for the contaminants we found in the downstream Kahiltna River. Of the Kahiltna River samples that showed no sign of bacterial indicators, two (W4-East Toe Pond and Water4) are situated well upstream of the modern terminus where silty waters flow along the east margin of the glacier. We have conservatively grouped these with the other Kahiltna River samples, but it is possible that the clean water sampled at those sites was primarily derived from tributary sources rather than Kahiltna Glacier runoff; this would even more strongly isolate Kahiltna Glacier runoff as the source of bacterial contamination in the terminus stream.

EXPERIMENTS

A single human feces buried in firn (old, compacted snow) at Camp 1 still contained total coliform and *E. coli* levels greater than the maximum sensitivity of our test when re-excavated one year later (Fig. 4; Table 3). The waste, which was enclosed in a plastic bag, was unfrozen (still deformable) when recovered from a depth of 5.3 m. A temperature logger buried 2 m above the sample remained at 0 °C throughout the summer of its first burial and began cooling on 20 September, reaching a minimum of −4.5 °C on 15 January 2011, at which time the datalogger failed. We do not therefore know the minimum temperature the sample was subjected to, but because it was 2 m deeper than the temperature logger it was subject to smaller and slower temperature fluctuations than the logger itself, and based on experience with snowpits in other Alaskan glaciers we conservatively estimate that the sample never exceeded a minimum temperature of −7 °C.

Fecal samples tested in the laboratory cold experiment resulted in no discernible mortality of the indicator bacteria. Importantly, however, the bacterial counts exceeded the sensitivity of the test. We do not, therefore, quantify any mortality that did occur, but rather conclude simply the indicator bacteria we tested are fully capable of surviving 150 days of conditions as severe as modest freeze-thaw cycling with constant UV light exposure.

GLACIER VELOCITIES

Measured glacier surface velocities range from <25 m yr^{-1} at Camp 4 and at the terminus to >400 m yr^{-1} at the large icefall around 25 km downstream of Camp 4 (Fig. 5). Despite the variety of sampling intervals (including summer, winter, and year-round measurements ranging from 1991 to 2011) and the combination of direct stake measurements with remotely sensed feature tracking, the longitudinal pattern of velocities is internally consistent, as shown in a longitudinal plot of velocities along a central flowline (Fig. 6). Small deviations of stake measurements from the feature tracking can be explained by the larger area over which the remote sensing product averages measurements. This apparent temporal consistency is supported by repeat measurements at the Index Site, a stake where NPS has separately measured summer (June–August) and winter velocities nearly continuously since 1991 (Fig. 5). The average summer velocity (0.555 m day^{-1}) there is less than 1% more than the average winter velocity of 0.551 m day^{-1}, and the standard deviation of 29 distinct measurements in that period is only 0.057 m day^{-1}. The northernmost velocities are also generally consistent with independently published velocities for that region (Campbell et al., 2012). Overall, observed velocities are higher on steeper portions of the glacier and generally match the expectation that ice flux, and by inference typical ice velocities, peak near the equilibrium line and taper towards the glacier head and terminus (Anderson et al., 2006).

EMERGENCE MODEL

Our emergence model predicts that waste buried 10 m deep in any of Camps 1 through 4 will emerge at the glacier surface 71 to 206 years later with a constant ELA at 1879 m (Table 5). Camp 1 waste will be the first to emerge, as early as 2025 based on the first use of the airstrip in 1954. Waste buried highest in the accumulation zone will remain encased in glacier ice for the longest time, and emerges the furthest downstream: waste from Camp 4 will travel about 36.5 km before emerging in the ablation zone

TABLE 5

Predicted emergence times and locations for waste buried at an initial depth of 10 m at four commonly used camps on the Kahiltna Glacier.

Burial Camp #	Camp distance* (km)	Camp elevation (m)	Emergence time** (yr)			Emergence elevation (m)	Emergence distance* (km)	Emergence Northing (m)	Emergence Easting (m)
4	0.0	3116	(238)	206	(180)	1214	36.5	6962748	586879
3	3.7	2745	(167)	142	(117)	1331	32.4	6965753	587506
2	6.7	2402	(124)	102	(76)	1439	29.7	6968430	588087
1	NA	2173	(91)	71	(52)	1505	28.0	6969903	589342

* Distances refer to flowline distance below ''Eleven Camp'' on the main trunk of Kahiltna Glacier; Base Camp is not on the main trunk and therefore has no starting distance downstream.
** Emergence times are based upon the average ELA of 1879 m. Numbers in parentheses indicate emergence times for a 10% decrease (left side) or increase (right side) in the ELA.

(Fig. 5). Waste from either the Camp 2 or Camp 1, on the other hand, will travel less than 25 km before emergence. Time and distance to emergence are not sensitive to differing estimates of the balance gradient if climate-induced changes in rates of accumulation and ablation are correlated, but emergence is very sensitive to the position of the equilibrium line. Table 5 shows that the modeled time to emergence varies by between 13% and 28% in response to a 10% change in the altitude of the equilibrium line.

Discussion

In a recent survey of West Buttress climbers, 50% of respondents expressed concern about human waste on the climbing route. One respondent asked, ''How can the NPS still allow people to throw their 'poo' into a deep crevasse? How can that be safe?'' (Kedrowski, 2009). These climbers shared their concerns about the potential effects of buried and emergent waste with NPS managers whose job includes the protection of human health. There are other potentially important impacts of current waste management practices, including the unpleasant aesthetics of human waste emerging in a preserved wilderness parkland, but we have focused here on water quality and public health. From this perspective, we have aimed to answer the following question: Are current management practices safe?

Before discussing the effects of buried and downstream emergent waste, we consider the upper portion of the Kahiltna Glacier. Here, in the accumulation zone of the glacier where West Buttress climbers spend all of their time, current management practices have been only partially successful in minimizing the primary health hazard: contamination of surface snow by human waste and subsequent consumption of that snow as melted drinking water. Most waste is deposited properly, but the concentration of climbers along a single trail and at a small number of camps increases the probability of encountering waste-contaminated snow even if it is very uncommon. Our results confirm that waste deposited at the snow surface will remain biologically active for at least one year whether it sits briefly on the snow surface, ends up shallowly buried, or even remains exposed to extreme temperatures and high UV light exposure at the highest windswept ridgelines. Full compliance with NPS regulations would eliminate this hazard; NPS efforts should therefore be focused on increasing climber compliance with existing policies and on educating climbers regarding best sanitary practices while on the mountain.

The majority of waste generated on Kahiltna Glacier ends up encased within accumulating snow and ice and poses no immediate threat to West Buttress climbers. Such waste will reappear, however, in the ablation zone of the glacier, emerging, according to our model, ~30 km downstream of the burial site in less than 15 years (for the case of waste buried at Camp 1 in 1954). Essentially all of the waste buried on the West Buttress is expected to emerge in a section of the glacier untraveled by West Buttress climbers but traversed occasionally by backcountry users connecting Camp 1 with the popular Little Switzerland climbing area (Fig. 5). Waste emerging in this area will, therefore, be encountered by backcountry travelers in a comparatively remote portion of the park.

The eventual emergence of this waste is certain, but precise times and locations of emergence, as indicated in Table 5, should be interpreted with some caution. A potential source of error in these predictions is the quality of the data sets that are incorporated into the model. The velocity field is generally well-constrained, but may be slightly biased by the predominance of seasonal (rather than year-round) velocity measurements. There is also some error introduced by selecting velocities along a central flowline that is inferred rather than documented by direct and spatially comprehensive measurements of ice trajectory. Glacier surface elevations were smoothed to compensate for obvious errors (noise in Fig. 6) in the satellite-based data set, and will be increasingly biased as the actual surface elevations decline due to ongoing glacier shrinkage. The mass balance profile is based on a small number of measurements over a short time span, and its precise shape could certainly be improved by better spatial distribution of measurements over multiple years. However, the uncertainties in emergence time introduced by all these variables are trivial in comparison with the importance of the equilibrium line altitude. In our model, emergence times vary by 13–28% in response to a 10% change in ELA (Table 5), and ELA is also strongly coupled with climate. With ongoing arctic warming (Richter-Menge et al., 2011), it is very likely the ELA will continue to rise and significantly shorten the times and distances traveled to emergence that are predicted here. Despite the collective uncertainties in our simplistic model, the predicted emergence times are therefore very conservative, and we believe they represent a robust estimate of the maximum time (and thus distance downstream) to waste emergence.

Human waste presently encased in the ice of the Kahiltna Glacier is expected to begin emerging at the glacier surface within no more than 15 years. The human health hazard posed by that waste is dependent upon the viability of fecal pathogens during the decades to centuries of downstream travel. Our results suggest that this waste, though presently buried, is already contaminating the englacial water supply that feeds Kahiltna River and that it will further contaminate supraglacial meltwater once it emerges at the surface.

The widespread presence of fecal contamination on the mountain suggests bacteria are persistent in a glacial environment and may survive for an extended period of time. The short-term (days to years) persistence of fecal bacteria in a variety of glacial microclimates was demonstrated by a fecal sample collected at 5700 m (18,800 feet) after at least one full year of exposure to sometimes extreme negative temperatures and high UV light exposure, by another sample buried experimentally for one full year at Camp 1, by snow samples collected near active camps, and by replicated samples from a half-year-long laboratory experiment. Supporting this argument, we found low concentrations of fecal bacteria in water samples collected over two melt seasons from the Kahiltna River. We cannot guarantee the contamination is in fact from climbing activities upglacier (bacterial concentrations were too low for DNA analysis; ARRI, 2010), but negative results from nearby tributary streams suggest this. We suggest that the bacteria originate from diffuse contact between englacial meltwaters and 'old' waste encased in glacial ice many kilometers upstream from the terminus.

Our results do not confirm the long-term (decades to centuries) persistence of fecal pathogens in a glacial environment, but they are consistent with an argument that bacteria can survive long periods in the englacial environment. A definitive test of long-term persistence will be possible when waste finally emerges in a downglacier location, but anecdotal observations of the lower glacier confirm what our model predicts: such emergence has not yet occurred. We therefore used the laboratory experiment to simulate the conditions of both englacial burial and surface exposure in the ablation. In all cases, we were unable to document any decline in bacterial concentrations for the duration of the experiment (150 days). Importantly, some undetected mortality may have occurred because the bacteria count never got below the maximum reading of the test, even at maximum dilution; a more explicit test of bacterial mortality at high concentrations would be a valuable follow-up to this study.

The particular conditions of englacial burial may be less hostile to fecal pathogens than originally suspected. Under only a few meters of snow and firn, temperatures within the glacier stabilize near the pressure-melting point: it is moderately cold but almost invariably so, and bacteria would be subjected to essentially no freeze-thaw activity. The glacier interior is dark and completely free of UV exposure. The glacial environment is also nutrient poor, but most fecal waste is deposited in communal latrines or marked crevasses near heavily used camps. These become nutrient-rich oases that could conceivably support fecal bacteria without risk of nutrient scarcity for centuries. Documented limits of bacterial persistence in Antarctica, where fecal contaminants were exposed to extremely cold air temperatures and intensive freeze-thaw activity (e.g. Nedwell et al., 1994, Hughes and Nobbs, 2004) may therefore be a poor analog for an Alaskan englacial setting. After emergence at the glacier surface, conditions will become more challenging as UV light exposure and significant temperature variations return, but for the ~half of the year that is coldest, the waste piles will be buried and thus protected from the harshest temperature swings by seasonal snow accumulation. A definitive test awaits emergence of the first West Buttress waste piles, but in the meantime we suggest that these inferred environmental conditions and the persistence of bacteria in our test results collectively argue for a conservative, if tentative, conclusion that at least some fecal bacteria will persist in buried waste until emergence at the glacier surface decades to centuries later.

The hazard posed to downstream users by these contaminants is currently small. In two cases, measured concentrations of total coliform and *E. coli* in the Kahiltna River did exceed drinking water limits, but they were well below the safe limits for recreational waters (U.S. Environmental Protection Agency, 2003). Downstream, dilution will further reduce contaminant concentrations. No towns or cities currently use the Kahiltna River or the Susitna River downstream of its confluence with the Kahiltna for municipal water supplies, and these waters are only occasionally used for recreation. On the other hand, our results suggest that concentrations of indicator bacteria in the Kahiltna River will increase as additional waste is buried in the glacier, as buried waste begins to emerge at the glacier surface to interact with supraglacial meltwaters, and as all the waste flows further downstream towards the terminus. We can only speculate whether these concentrations will be sufficient to pose a health hazard in the Kahiltna River, but we can more confidently assert that recreational travelers on the lower Kahiltna Glacier will in the coming decades need to carefully question the typically ssumed—and celebrated—purity of meltwater encountered on the glacier surface.

Whether NPS should change its existing waste management policy is not immediately obvious. The likely alternative—some sort of packout policy—could have significant costs. These might include higher rates of climber noncompliance, the need for increased education and enforcement programs, and the possibly substantial expense, carbon footprint, and safety hazard associated with increased air traffic hauling collected waste off the mountain. A new management policy requires careful consideration of those costs. Such a policy—based on scientific evidence as well as the values of NPS managers, visitors, and downstream Alaskan residents—could provide a model for managers of high-use glaciated destinations worldwide.

Conclusions

In summary, we conclude that present waste disposal practices on the West Buttress pose a documented health hazard to climbers on the West Buttress climbing route, and pose a limited but growing threat to downstream users of the lower glacier and the Kahiltna River. The direct hazard to climbers is a function primarily of noncompliance with existing policies and poor sanitation practices, but the growing downstream hazard is a direct consequence of existing policy. In the Kahiltna River, the hazard might remain trivial due to low contaminant concentrations and limited human use. On the lower glacier, however, the ultimate emergence of waste piles will pose a greater hazard to occasional recreational users, with potential for significant contaminant concentrations in supraglacial meltwaters and the substantial, though tangential to this study, negative aesthetic impacts of emergent human waste, plastic bags, toilet paper, and associated (though prohibited) trash.

Current NPS management practices on the West Buttress are having a measurable and growing impact on the downglacier and downstream environment. Our evidence suggests, but cannot confirm, that the indicator bacteria we measured can survive long-term burial to remain active in these emergent piles. We have not considered whether other fecal pathogens (e.g. *Giardia lamblia*) have similar survival characteristics in the glacial environment, and further study of this question would valuably extend the conclusions of this study. Regardless, a rarely visited and truly wild portion of Denali National Park and Preserve will be substantially impacted by the eventual emergence of human waste.

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