Journal of Water Resource and Protection, 2020, 12, 577-589
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Spatial Variation of Nutrient Concentrations (NH_4^+ and Cl^-) in the Dudhkoshi River Basin, Sagarmatha National Park, Nepal

Jessique Ghezzi-Haeft[1*], K. Nicholson[1], K. Neumann[1], L. Wood[2], S. Acharya[1], S. Sharma[3]

[1]Environment, Geology and Natural Resources, Ball State University, Muncie, USA
[2]Department of Earth Sciences, Indiana University-Purdue University, Indianapolis, USA
[3]Aquatic Ecology Laboratory, Kathmandu University, Dhulikhel, Nepal
Email: *jhaeft@bsu.edu

How to cite this paper: Ghezzi-Haeft, J., Nicholson, K., Neumann, K., Wood, L., Acharya, S. and Sharma, S. (2020) Spatial Variation of Nutrient Concentrations (NH+ 4 and Cl⁻) in the Dudhkoshi River Basin, Sagarmatha National Park, Nepal. *Journal of Water Resource and Protection*, **12**, 577-589.
https://doi.org/10.4236/jwarp.2020.127035

Received: May 31, 2020
Accepted: July 20 2020
Published: July 23, 2020

Abstract

The Sagarmatha National Park (SNP) in Nepal is home to unique natural beauty and cultural significance. While the SNP has a relatively small local population, it has drawn thousands of visitors since Edmund Hillary and Tenzing Norgay reached the peak of Mt Everest in 1953. Importantly, the tourists and their concurrently generated refuse have caused massive anthropogenic pressure with serious environmental consequences for the unique SNP and SNP Buffer Zone ecosystems. This study aimed to understand the spatial variation of nutrient concentrations in stream water and drinking water (primarily shallow springs) using analyses of nitrogen as NH_4^+ and chlorine (Cl^-) concentrations. Sampling occurred in April 2017 during the pre-monsoon dry season in the upper Dudhkoshi River Basin, SNP. Dissolved inorganic nitrogen (NH_4^+) concentrations in both drinking water and stream water were low with average concentrations in drinking water of 0.016 mg/L (±0.010) and 0.033 mg/L (±0.031) in stream water. Similarly, Cl^- concentrations were also low with average concentrations of 0.185 mg/L (±0.045) and 0.124 mg/L (±0.051) in stream and drinking water, respectively. Importantly, nitrogen in stream waters exhibits a decreasing trend with altitude whereas Cl^- values decrease with altitude in both drinking water and streams. The observed spatial variations of nitrogen and chlorine concentrations are attributed primarily to the significant variations in land use/land cover from the highest portions of the drainage basin to the lowest elevations, which are outside of the SNP boundary and therefore allow more agricultural development. Our results demonstrated that although the quality of stream water in the upper reach of Dudhkoshi River Basin meets WHO standards for drinking water, there is significant surface water contamination in the form of agricultural run-off. These results will provide base-line data for further studies and will help to improve understanding of the relationship between land use/land cover and water quality in the region.

Keywords

Sagarmatha, Nutrients, Nitrogen, LULC, Water Quality, Nepal

1. Introduction

Headwater streams are important sources of nutrients for downstream use, particularly nitrogen, and can have a significant impact on both aquatic ecosystems and water quality in the downstream reaches [1] [2] [3] [4]. The concentrations of nitrogen and chlorine in river systems can be influenced by a variety of natural and anthropogenic factors, the relative influences of which vary spatially and temporally [5]. Recently, several major studies have shown that eutrophication has intensified in downstream systems [6] [7]. However, very little is known about the nutrient concentrations of headwater streams in the high elevation regions of the Nepal Himalaya where anthropogenic factors could have a significant impact downstream. In general, these streams have been considered indicative of a pristine environment; however, major changes in tourism and land use/land cover (LULC) over the past 70 years could be impacting water quality (land use refers to human activity on a piece of land, and land cover refers to its surface features, e.g. [8]).

The Nepal Himalaya region, including the Sagarmatha National Park (SNP) and in particular the Khumbu Valley, is considered a data-poor region, primarily due to the location's geographic remoteness and ruggedness; historically, it has been difficult and expensive to access [9]. Increasing tourism over the past few decades has boosted the local economy and infrastructure, making access to the region for scientific endeavors more feasible, and there has been a marked increase in published research of the region since the turn of the century [10]. In 1964, a total of 20 tourists visited the Khumbu region (what is now the SNP) whereas more than 32,000 tourists visited in 2010 [11]. In all, more than half a million trekkers have visited the Khumbu region since the first successful ascent of Mt. Everest by Tenzing Norgay and Edmund Hillary in 1953 [11]. Despite concerns since the 1970's regarding tourism-related pollution of the region, the first systematic study of drinking water quality in the Khumbu Valley was not undertaken until 2014. In that year, Nicholson *et al.* [12] sampled community water sources with a focus on fecal contamination of drinking water. The study concluded that there were higher counts of *E. coli* and other coliform bacteria associated with fecal contamination in samples collected from lower elevation, higher-population areas, and that surface water was more highly contaminated than springs fed by groundwater. Moving forward, an evaluation of the spatial variation of nitrogen, chlorine, physical parameters and LULC in the upper Dudhkoshi River Basin will establish baseline data and provide key information for understanding the importance of LULC and park management practices in the region.

2. Data and Methods

2.1. Study Site

The Sagarmatha National Park was established in 1976 and designated a World Heritage Site in 1979 [13]. The park and its associated Buffer Zone (here within referred to as the SNP) covers an area of ~1425 km^2 and includes the majority of the Khumbu Valley and Mt. Everest [14]. The region is characteristically high altitude; with 31% of the total land area at elevations of 4000 - 5000 m, and 52% of the total land area at elevations 5000 - 6000 m. This study focuses on the Dudhkosi River Basin (**Figure 1**). The Dudhkosi River is one the highest-elevation river systems in the world [15] and one of the seven tributaries of the Saptakoshi River, which is part of the greater Ganges River System. Within the study area, the Dudhkosi River flows from the Gokyo Lakes region, is joined by the tributaries Imja Khola and Lobuche Rivers, downward to Lukla and then out of the study area.

The Khumbu Valley has a temperate climate characterized by clear seasonality with dry winters as cold at −17˚C and summers as warm as 37˚C [12]. More than 80% of the annual precipitation to the region falls between the months of June and September [10] [16] [17] [18] via the South Asian Monsoon System, which carries warm, moist air out of the south or southwest from the Bay of Bengal across the Indian Subcontinent and delivers precipitation as far north as the Tibetan Plateau [19] [20].

Regional vegetation varies with altitude. The majority of the sampling route falls below the local tree line at c. 4000 m. The landscape is dominated by lush rhododendron forests punctuated by small, terraced, subsistence agricultural fields. Above the tree line, much of the ground is bare, and juniper and other hardy shrubs replace rhododendrons. From c. 5500 - 6000 m, only low-growing mats of cushion plants thrive. The nival zone above c. 6000 m is glaciated or snow-covered for much of the year, and vegetation is extremely limited. Local fauna includes the snow leopard, musk deer, and red panda, all of which are either endangered or threatened species [14] [21].

2.2. Land Use/Land Cover (LULC)

The Khumbu region was first inhabited 500 years ago by the Sherpa people, who emigrated from Eastern Tibet [10] and are still the majority of the permanent residents in the region. Accurate census data for the region are scarce, and estimates place the population of the Khumbu Valley between 3500 m and 6000 m (e.g. [10] [14]). The economy of the Khumbu Valley is based upon tourism and agriculture. Local farmers grow potatoes, barley, and buckwheat, as well as raising yaks and zopkios (a cattle-yak hybrid), for dairy, meat, and as beasts of burden [10].

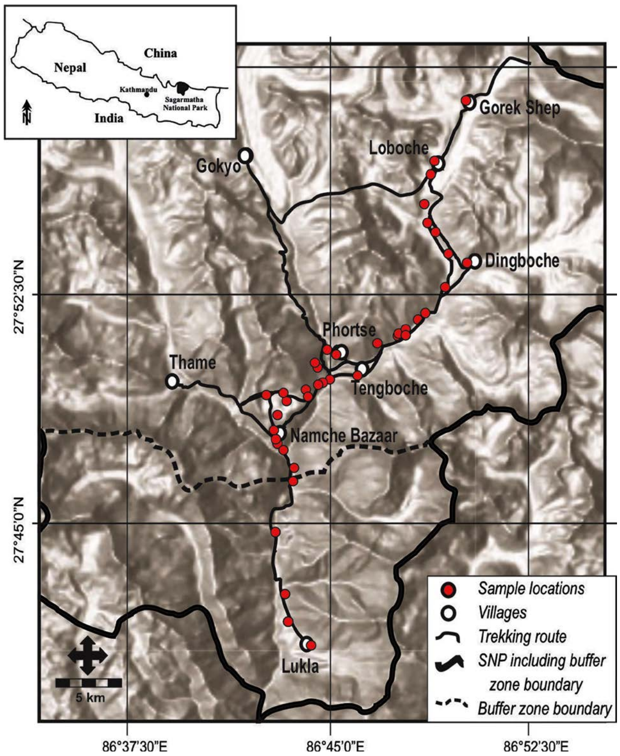

Figure 1. Location map of the SNP with inset showing the relative location of the SNP within Nepal and to China and India. The larger topographic map shows the study area, within the SNP, the main villages and the 2017 sample locations.

Throughout the entire SNP, areas with relatively gentle slopes tend to be extensively cultivated whereas areas with steep topography are generally left as forest and grassland. However, the steady increase in and dependence on tourism has resulted in many changes, for example: the number of lodges grew from 56 in 1989 to over 300 in 2012 [22]. The issue of changes to LULC has been the subject of several recent studies, e.g. [23] [24] [25] [26] [27]. The studies of Humagain [24] and Garrard *et al.* [27] both combined stakeholder perceptions and interviews with remote sensing data. Their results suggest a substantial decrease in the land area covered by snow and ice since 1992 (>24%), with decreases in forests and farmland (>20%) and increases (>40%) in the land area covered by rock and soil [24] [27]. Humagain [24] also found an increase in grazing, settlement and shrubland. Both studies conclude that the lower elevations LULC changes are a direct result of anthropogenic factors (specifically related to increasing tourism and park management) whereas at higher elevations the melting snow and glacial ice are attributed to climate change [24] [27].

2.3. Methods

Sampling and field analysis occurred between April 21 and May 05, 2017, during the dry, pre-monsoon spring season. Sampling was conducted within the Khumbu Valley along the main Everest Base Camp Trekking Route between the town of

Lukla and Everest Base Camp. Sampling locations included large rivers, small streams, natural springs, and numerous community standpipes. Locations were selected to reflect community drinking water sources (primarily standpipes; n = 19) and the waterways that supply them (rivers, tributaries, and springs; n = 9). A study site map with sampling locations is provided in **Figure 1**.

Samples for ion analysis were collected with a sterile syringe, then passed through a 0.45-μm filter into pre-washed 60-mL or 125-mL high-density polyethylene bottles with screw-on polypropylene caps. Bottles were then sealed with paraffin sealing film. Temperature, pH, conductivity, and total dissolved solids (TDS) were measured in the field via Fisher Scientific Accumet AP85 portable waterproof meter. When possible, the instrument probes were inserted directly in the uncollected water for measurements. In case of insufficient flow it was necessary to insert probes into water collected in a plastic 1-L bottle.

For bacteria analyses, samples were collected in a sterile 60 mL syringe and 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 which uses two color producing chemicals, one for the detection of the enzyme glucuronidase (produced by *E. coli* strains but not by general coliforms) and one for the detection of galactosidase (produced by all coliforms, including *E. coli*). The samples were then placed into a portable field incubator and kept as close to 35˚C as possible for ~24 hours. Sample counts were done using a magnifying glass and a 10x geological hand lens. *E. coli* colonies are royal blue/purple and coliform bacteria colonies appear to be light green.

Analysis for cations (including NH_4^+) was conducted at Ball State University via ion chromatography (IC) using a Dionex ICS-2000 with a Dionex AS40 Automated Sampler and processed through Chromeleon Chromatography Data System software. Analysis for anions (including Cl-) was conducted at Ball State University via IC using a Dionex ICS-5000+ with a Dionex EGC for potassium hydroxide eluent generation, a Dionex IonPac AS15 analytical column and an Anion Self-Regenerating Suppressor 300. HCO_3-concentrations were calculated from the charge balance using AquaChem groundwater software. All measured and calculated ion concentrations are reported in μEq/L.

3. Results

3.1. Physical Parameters *E. Coli* and Coliform Bacteria

The overall trend for all samples is decreasing in the case of temperature, total dissolved solids (TDS) and conductivity, and increasing pH with altitude (**Figure 2**, see [28] [29] for complete analyses including household use water). In 2017 average drinking water temperatures were 9.14 (±3.79)˚C: stream water 8.53 (±3.87)˚C, spring water 9.42 (±3.83)˚C. Stream and spring water temperatures consistently decrease with increasing altitude (**Figure 2(b)**). pH (**Figure 2(a)**) shows a steady increase with altitude with an average of 7.07 (±0.47). The average pH of stream water was 7.25 (±0.67) and the average for spring water was 6.99 (±0.33).

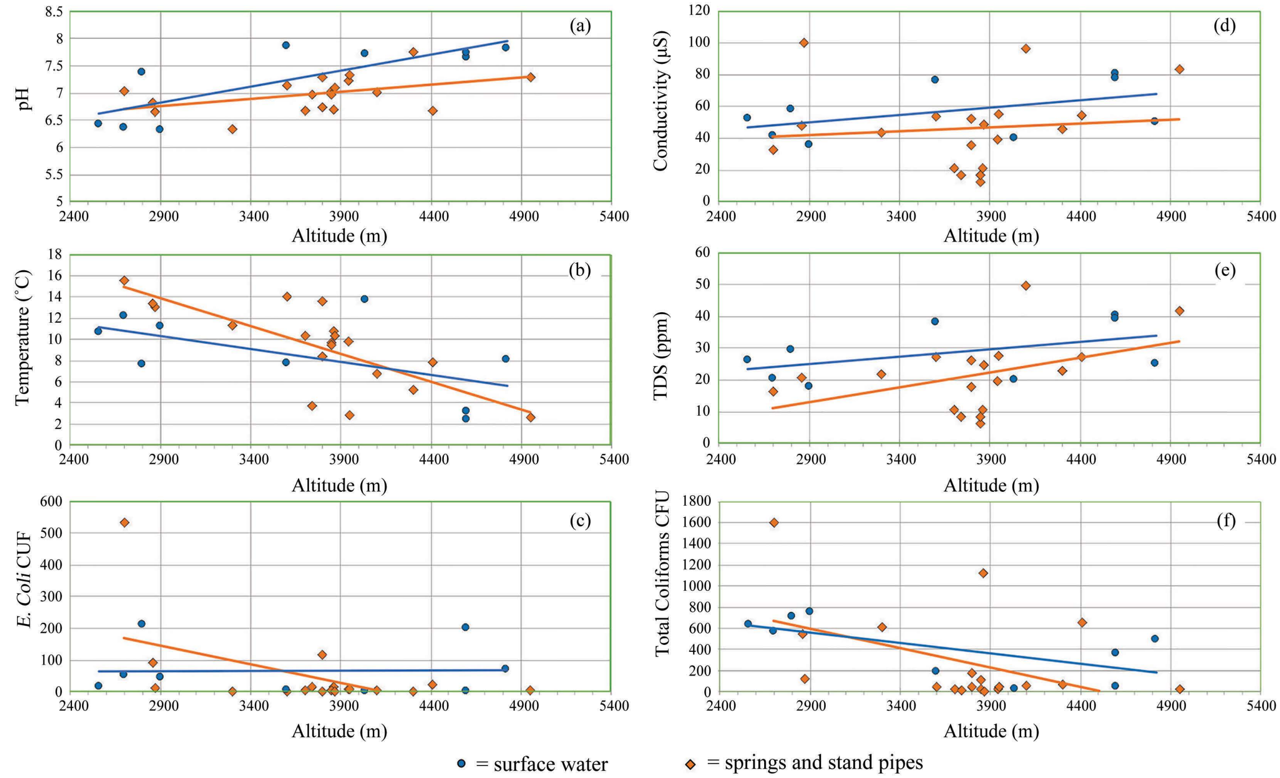

Figure 2. Bivariate plots of physical parameters and bacterial content plotted against altitude. (a) (b) (d) and (e) show that pH, conductivity and TDS consistently increase with altitude, although the trends are weak, and temperature consistently decreases with altitude [12] [28] [29]. (c) and (f) illustrate the weak negative relationship between bacterial content and altitude.

The range in conductivity and TDS in all samples was relatively small with a maximum conductivity of 99.8 µS and a minimum of 12.71 µS, and a range of TDS from 6.29 ppm to 49.60 ppm (Figure 2(d), Figure 2(e)). In general, streams had slightly higher average conductivity and TDS than spring water: springs 46.31 µS ±25.27 and 21.53 ppm ±11.34, stream water 57.0 µS ±17.39 and 28.53 ppm ±8.78. As with pH, conductivity and TDS show a very weak positive correlation with altitude.

All 28 water samples were analyzed for *Escherichia coli* (*E. coli*) and Total Coliform bacteria. The samples contained between 0 and 533 *E. coli* CFU (colony forming units per 100 ml sample; Figure 2(c), Figure 2(f)) with an average of 52 (±110) and between 8 and 1600 CFU Total Coliforms with an average of 325 (±396). Stream water samples had an average of 66 (±88) CFU *E. coli* and 410 (±293) CFU Total Coliforms. Spring water contained an average of 46 (±119) CFU *E. coli* and 291 (±432) CFU Total Coliforms.

The correlation between bacterial content and physical parameters is weak; however, there is a correlation between bacterial content and altitude and, hence, temperature (Figure 2(c), Figure 2(f)).

3.2. Water Types, NH_4^+ and Cl^- Values

Ion analysis revealed domestic water resources in the study area are primarily of the calcium bicarbonate water-type. All samples were undersaturated with respect to any mineral. Ionic strength ranged from 0.14 - 0.91 mM/L with an average of 0.50 mM/L. Both Balestrini *et al.* [21] and Wood *et al.* [30] report ion concentrations for samples within the study area, and both report that the samples are enriched in all species except NH_4^+ compared with precipitation samples from the same study.

On average, NH_4^+ concentrations ranged from 0.007 mg/L to 0.106 mg/L, with an average of 0.22 mg/L, and Cl^- concentrations ranged from 0.064 mg/L to 0.269 mg/L (**Figure 3**, **Figure 4** respectively). Spring water had, on average, lower concentrations of NH_4^+ than water from streams, with springs averaging 0.016 mg/L ±0.010 and streams averaging 0.033 mg/L ±0.031. Similarly, spring water had, on average, lower concentrations of Cl^- than water from streams, with springs averaging 0.124 mg/L ±0.051 and streams averaging 0.185 mg/L ±0.045. The higher NH_4^+ and Cl^- in streams compared to spring water is suggestive of pollution from LULC.

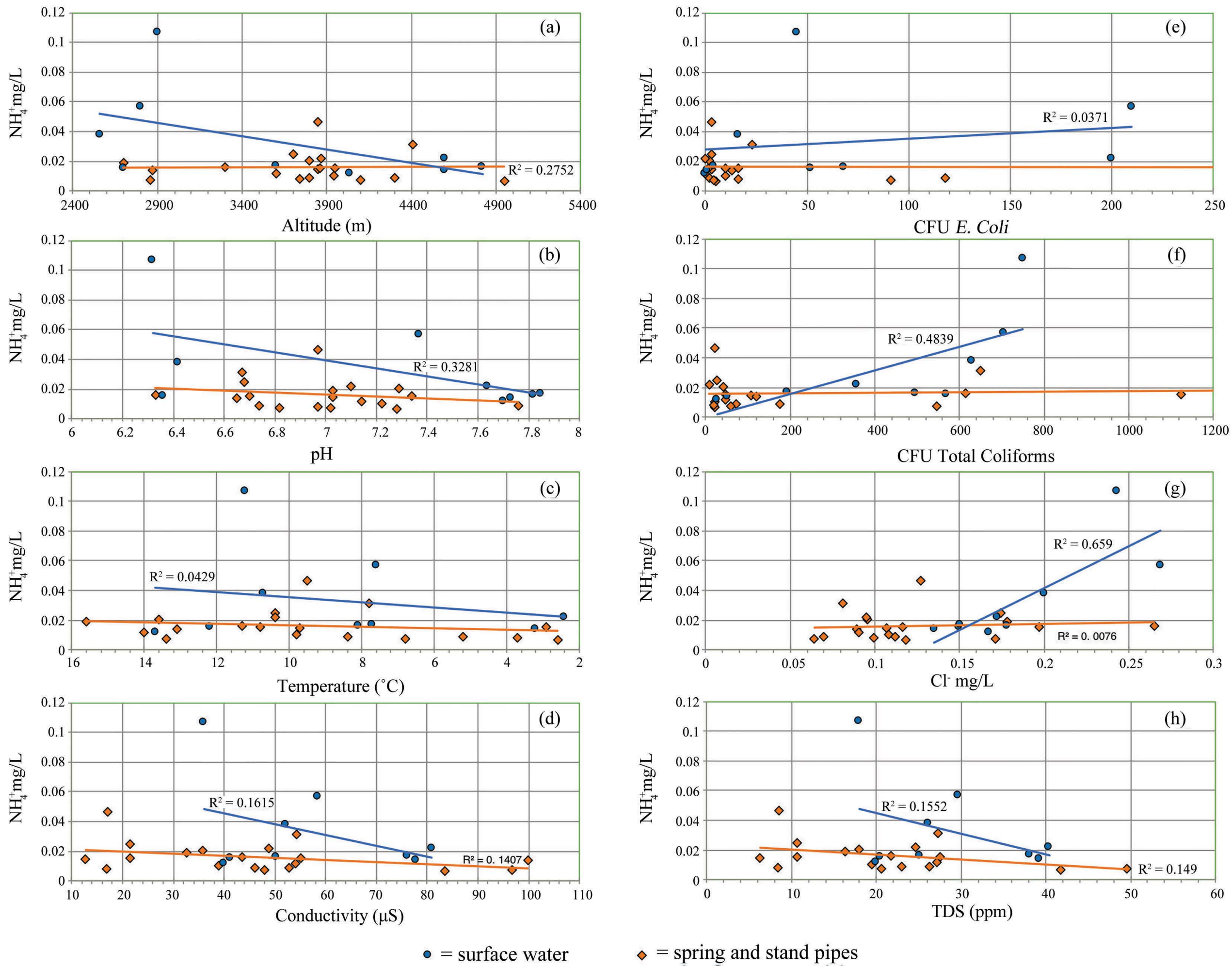

Figure 3. Bivariate plots of NH_4^+ versus altitude (a), physical parameters (b, c, d, h), bacterial content (e, f) and Cl^- (g). Trendlines and R^2 values were calculated using Excel. Of significance is the difference between trends in surface water as opposed to the lack of trends seen in springs and stand pipes.

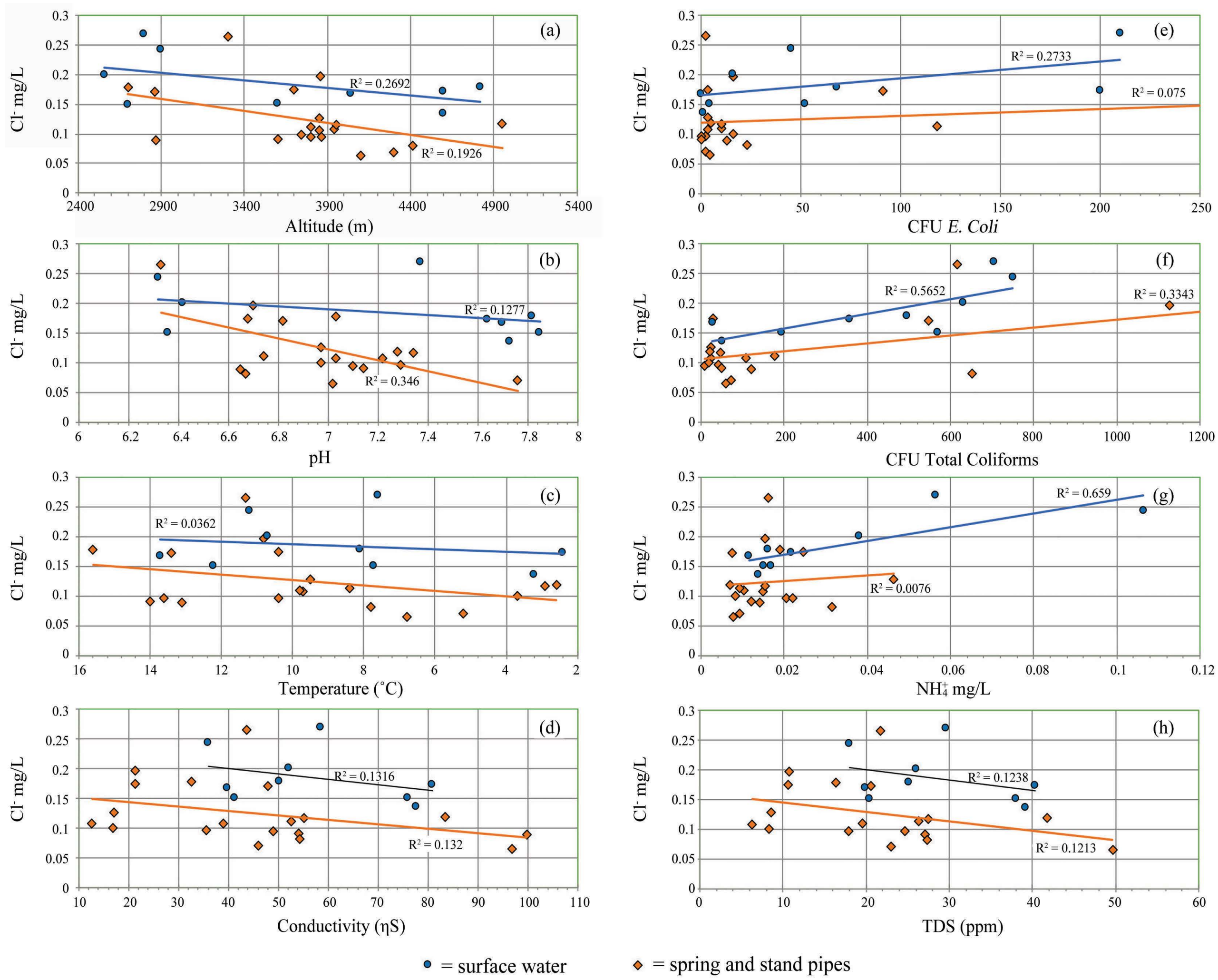

Figure 4. Bivariate plots plots of Cl^- versus altitude (a), physical parameters (b, c, d, h), bacterial content (e, f) and NH_4^+ (g). Trendlines and R^2 values were calculated using Excel. Of significance is the difference similarity between trends in surface water and in springs and stand pipes, as opposed to the trends observed in **Figure 3**.

3.3. Trends

NH_4^+ and Cl^-, particularly in stream water, show distinct correlations with physical parameters and bacterial content (**Figure 3**, **Figure 4**). Notably both NH_4^+ and Cl^- in stream water decreases with altitude, pH, conductivity and TDS but shows only a weak relationship with temperature (**Figure 3**, **Figure 4**). Conversely, NH_4^+ and Cl^- concentrations in stream water both show a positive correlation with bacterial content, particularly Total Coliforms. For stream water samples NH_4^+ and Cl^- themselves correlated positively (**Figure 3**, **Figure 4**).

Trends in the spring water samples show that NH_4^+ concentrations are essentially independent of altitude, physical parameters, bacterial content and Cl^- (**Figure 3**). Cl^- concentrations in spring water, however, do show negative correlation between altitude and physical parameters, with Cl^- decreasing with pH, temperature, conductivity and TDS (**Figure 4**). Additionally, Cl^- shows a strong positive correlation with Total Coliforms (**Figure 4**).

4. Discussion

LULC change is one of the most important forms of environmental change occurring in many of the world's mountain regions [31]. The drivers of LULC change in mountainous regions, such as the SNP, involve complex interlinked environmental, social, and economic impacts, over a range of scales. Multiple methods of analysis are required to understand the drivers and their impact on the environment, landscapes, and rural societies (e.g. [8] [32]). Although changes in LULC in the SNP have been studied over the last 20 years [23] [24] [25] [26] [27], there have been few attempts to understand how LULC impacts water resources in the region. This is noteworthy as the SNP is already experiencing water insecurity due to climate change; hence this knowledge is fundamental to long-range resource management and planning.

When discussing trends in the data it is important to remember the possible sources for NH_4^+ and Cl^- in water samples. Sources of both NH_4^+ and Cl^- in remote high-altitude, mountainous, regions are limited. Balestrini *et al.* [21] concluded that Cl^- in precipitation samples were derived from the long-range transport of sea salt from the Indian Ocean, especially given that the regional precipitation is predominated sourced by the Indian Monsoon. Studies of precipitation in Tibet have come to similar conclusions [33] [34]. Cl^- can also be derived from human and/or animal waste. The most likely source of NH_4^+ is animal (including human) waste and are therefore indicative of LULC (including population growth).

Although there is scatter in the data, the trends observed in spring and stream water Cl^- concentrations are important. Firstly, concentrations of Cl^- in all samples are extremely low. Secondly, the trends observed in both springs and streams with respect to altitude and physical parameters are very similar (*i.e.* the slope of the trend lines is the same) with slightly more Cl^- in springs (average 0.124 ± 0.051 mg/L) versus streams (average 0.185 ± 0.045 mg/L). The decrease in Cl^- with altitude is a result of depletion of the precipitation as it moves further from the ocean and upward [21]. The major difference between spring and stream water is the relationship Cl^-/NH_4^+, whereby stream water shows increasing Cl^- with increasing NH_4^+, whereas spring water does not. A similar relationship is seen between Cl^- and bacteria, whereby the stream water appears to correlate better with increasing bacteria (both *E. coli* and Total Coliforms) than spring water. These trends suggest that surface water in the region derives a small amount of Cl^- from animal waste (including human), whereas spring water does not.

Concentrations of NH_4^+ show very different trends to those observed in Cl^-. NH_4^+ in spring samples are independent of altitude, physical parameters and bacteria. Given that the primary source of NH_4^+ in the region is from human and/or animal waste this suggests that springs contain relatively little (or no) surface water contamination during the pre-monsoon dry season. These results agree with the conclusions of Nicholson *et al.* [28] who suggest that during the pre-monsoon dry season, most village water sources are relatively uncontaminated.

However, surface water (streams) show a different trend. Water samples taken from streams in the region show a negative correlation between NH_4^+ concentrations and altitude and most physical parameters, and a positive correlation with both bacteria content and Cl^- concentration. These results have implications for LULC in the region.

The stream samples were collected from the border of the SNP buffer zone and extend, along the main trekking route and the Dudhkoshi River, into the park itself and uphill towards Mt Everest based camp (**Figure 1**). The buffer zone (below ~2900 m) has a higher population [10], more agriculture and few restrictions on land use. As altitude increases, the population decreases, the number of tourists decreases, and the type of agriculture shifts toward more grazing and less cultivation. Although there does not appear to be a significant relationship between population, LULC and Cl^- concentrations in either spring or stream water samples, there does appear to be a relationship with NH_4^+ concentration in surface water. At lower altitudes there is more NH_4^+ in the streams which is likely a direct result of contamination by human and/or animal waste. Above ~4000 m there appears to be little difference between NH_4^+ in spring and stream water samples, supporting the idea that the impact of cultivation and/or population at the lower altitudes is important. Given that waste is typically used as fertilizer and that open defecation is a problem within the region [10], these conclusions seem reasonable. What remains to be investigated is how changing LULC in the region will impact water quality.

Work by Humagain [24] and Garrard *et al.* [27] show significant changes in LULC in the SNP since 1992. Of particular interest to this study is the fact that there has been an increase in grazing, settlement, and shrubland throughout the region [24], and that the lower elevations LULC changes are a direct result of anthropogenic factors [24] [27]. These changes are bound to impact water quality, particularly surface water, hence a better understanding of the impacts of LULC on spring and stream water is important to park management. Resource and park management strategies must take these factors into account, especially considering the impact of climate change continues, glacial retreat and changing monsoon patters.

5. Conclusion

This study provides an evaluation of the spatial variation of nitrogen, chlorine, physical parameters and LULC in the upper Dudhkoshi River Basin to establish baseline data and provide key information for understanding the importance of LULC and park management practices in the region. Stream samples indicate direct contamination by human and/or animal waste. Higher altitude stream and spring samples support the idea that cultivation and/or population at the lower altitudes is significant. Given that waste is typically used as fertilizer and there is a problem with open defecation in the region, these conclusions seem reasonable. What remains to be investigated is how changing LULC in the region will impact water quality, but this study implies that proper waste management is key to protecting vital water resources.

Acknowledgements

We would like to acknowledge Ball State University for financially supporting this research. We thank the Nepal National Park Service, Kathmandu University, and Ang Nurbu Sherpa of Holiday Namche.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Martí, E., Bowden, W.B., Valett, H.M. and Hershey, A.E. (2001) Control of Nitrogen Export from Watersheds by Headwater Streams. *Science*, **292**, 86-90. https://doi.org/10.1126/science.1056874

[2] Houser, J.N., Mulholland, P.J. and Maloney, K.O. (2006) Upland Disturbance Affects Headwater Stream Nutrients and Suspended Sediments during Baseflow and Stormflow. *Journal of Environmental Quality*, **35**, 352-365. https://doi.org/10.2134/jeq2005.0102

[3] Pringle, C.M. (1990) Nutrient Spatial Heterogeneity: Effects on Community Structure, Physiognomy, and Diversity of Stream Algae. *Ecology*, **71**, 905-920. https://doi.org/10.2307/1937362

[4] Hood, E. and Scott, D. (2008) Riverine Organic Matter and Nutrients in Southeast Alaska Affected by Glacial Coverage. *Nature Geoscience*, **1**, 583-587. https://doi.org/10.1038/ngeo280

[5] Mouri, G., Takizawa, S. and Oki, T. (2011) Spatial and Temporal Variation in Nutrient Parameters in Stream Water in a Rural-Urban Catchment, Shikoku, Japan: Effects of Land Cover and Human Impact. *Journal of Environmental Management*, **92**, 1837-1848. https://doi.org/10.1016/j.jenvman.2011.03.005

[6] Howarth, R.W. and Marino, R. (2006) Nitrogen as the Limiting Nutrient for Eutrophication in Coastal Marine Ecosystems: Evolving Views over Three Decades. *Limnology and Oceanography*, **51**, 364-376. https://doi.org/10.4319/lo.2006.51.1_part_2.0364

[7] Rabalais, N.N., Turner, R.E., Díaz, R.J. and Justić, D. (2009) Global Change and Eutrophication of Coastal Waters. *ICES Journal of Marine Science*, **66**, 1528-1537. https://doi.org/10.1093/icesjms/fsp047

[8] Lambin, E.F. and Meyfroidt, P. (2010) Land Use Transitions: Socio-Ecological Feedback versus Socio-Economic Change. *Land Use Policy*, **27**, 108-118. https://doi.org/10.1016/j.landusepol.2009.09.003

[9] Salerno, F., Viviano, G., Manfredi, E.C., Caroli, P., Thankuri, S. and Tartari, G. (2013) Multiple Carrying Capacities from a Management-Oriented Perspective to Operationalize Sustainable Tourism in Protected Areas. *Journal of Environmental Management*, **128**, 116-125. https://doi.org/10.1016/j.jenvman.2013.04.043

[10] Byers, A. (2005) Contemporary Human Impacts on Alpine Ecosystems in the Sagarmatha (Mt. Everest) National Park, Nepal. *Annals of the Association of American Geographers*, **95**, 112-140. https://doi.org/10.1111/j.1467-8306.2005.00452.x

[11] Ghimire, N.P., Jha, P.K. and Caravello, G. (2013) Physico-Chemical Parameters of High-Altitude Rivers in the Sagarmatha (Everest) National Park, Nepal. *Journal of Water Resource and Protection*, **5**, 761-767. https://doi.org/10.4236/jwarp.2013.58077

[12] Nicholson, K., Hayes, E., Neumann, K., Dowling, C. and Sharma, S. (2016) Drinking Water Quality in the Sagarmatha National Park, Nepal. *Journal of Geoscience and Environment Protection*, **4**, 43-53. https://doi.org/10.4236/gep.2016.44007

[13] Panzeri, D., Caroli, P. and Haack, B. (2013) Sagarmatha Park (Mt Everest) Porter Survey and Analysis. *Tourism Management*, **36**, 26-34. https://doi.org/10.1016/j.tourman.2012.11.003

[14] UNESCO (United Nations Educational, Scientific and Cultural Organization) (2009) Case Studies on Climate Change and World Heritage.

[15] Xiang, Y., Yao, T.D., Gao, Y., Zhang, G.Q., Wang, W.C. and Tian, L. (2018) Retreat Rates of Debris-Covered and Debris-Free glaciers in the Koshi River Basin, central Himalayas, from 1975 to 2010. *Environmental Earth Sciences*, **77**, Article No. 285. https://doi.org/10.1007/s12665-018-7457-8

[16] Barry, R.G. and Chorley, R.J. (1982) Atmosphere, Weather and Climate. 4th Edition, Methuen & Co. Ltd., Methuen.

[17] Mani, A. (1981) The Climate of the Himalaya. In: Lall, R. and Moddie, A.D., Eds., *the Himalaya*: *The Aspects of Change*, Oxford University Press, New Delhi, 3-15.

[18] Salerno, F., Buraschi, E., Bruccoleri, G., Tartari, G. and Smiraglia, C. (2008) Glacier Surface-Area Changes in Sagarmatha National Park, Nepal, in the Second Half of the 20th Century, by Comparison of Historical Maps. *Journal of Glaciology*, **54**, 738-752.

[19] Muller, F. (1980) Present and Late Pleistocene Equilibrium Line Altitudes in the Mt. Everest Region-An Application of the Glacier Inventory. *Proceedings of the Riederalp Workshop*, No. 126, 75-94.

[20] Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E., Cristofanelli, P., Stocchi, P., Agrillo, G., Ma, Y. and Tartari, G. (2015) Weak Precipitation, Warm Winters and Springs Impact Glaciers of South Slopes of Mt. Everest (central Himalaya) in the Last 2 Decades (1994-2013). *Cryosphere*, **9**, 1229-1247. https://doi.org/10.5194/tc-9-1229-2015

[21] Balestrini, R., Polesello, S. and Sacchi, E. (2014) Chemistry and Isotopic Composition of Precipitation and Surface Waters in Khumbu Valley (Nepal Himalaya): N Dynamics of High Elevation Basins. *Science of the Total Environment*, **485-486**, 681-692. https://doi.org/10.1016/j.scitotenv.2014.03.096

[22] Gehrig, R. (2013) Lodge Development in Khumbu, Nepal. MSc. Thesis, Center for Development and Environment, University of Bern, Switzerland.

[23] Bajracharya, B., Uddin, K., Chettri, N., Shrestha, B. and Siddiqui, A.S. (2010) Understanding Land Cover Change Using a Harmonized Classification System in the Himalayas: A Case Study from Sagarmatha National Park, Nepal. *Mountain Research and Development*, **30**, 143-156. https://doi.org/10.1659/MRD-JOURNAL-D-09-00044.1

[24] Humagain, K. (2012) Examining Land Use/Land Cover Change and Potential Causal Factors in the Context of Climate Change in Sagarmatha National Park, Nepal. Ph.D. Thesis, Western Kentucky University, Bowling Green, Kentucky.

[25] Stevens, S.F. (2013) National Parks and ICCAs in the High Himalayan Region of Nepal: Challenges and Opportunities. *Conservation and Society*, **11**, 29-45. https://doi.org/10.4103/0972-4923.110946

[26] Thakuri, S., Salerno, F., Guyennon, N., Viviano, G., Smiraglia, C., D'Agata, C. and Tartari, G. (2013) Glacier Response to Climate Trend and Climate Variability in Mt. Everest Region (Nepal). American Geophysical Meeting Abstracts with Programs.

[27] Garrard, R., Kohler, T., Price, M.F., Byers, A.C., Sherpa, A.R. and Maharjan, G.R. (2016) Land Use and Land Cover Change in Sagarmatha National Park, a World Heritage Site in the Himalayas of Eastern Nepal. *Mountain Research and Development*, **36**, 299-310. https://doi.org/10.1659/MRD-JOURNAL-D-15-00005.1

[28] Nicholson, K.N., Neumann, K. and Sharma, S. (2019) The Impact of Precipitation on Drinking Water Resources in the Sagarmatha National Park (Mt. Everest Region), Nepal. *Journal of Water Resources and Protection*, **11**, 1351-1368. https://doi.org/10.4236/jwarp.2019.1111078

[29] Nicholson, K.N., Neumann, K., Dowling, C., Gruver, J., Sherman, H. and Sharma, S. (2018) An Assessment of Drinking Water Sources in Sagarmatha National Park (Mt Everest Region), Nepal. *Mountain Research and Development*, **38**, 353-364. https://doi.org/10.1659/MRD-JOURNAL-D-17-00024.1

[30] Wood, L., Neumann, K., Nicholson, K., Dowling, C. and Bird, B. (2018) High-Altitude Communities in a Warming World: A Geochemical Analysis of Domestic Water Resources in the Khumbu Valley, Nepal. *GSA Annual Meeting in Indianapolis*, 7 November 2018, Indiana, 271-274.https://doi.org/10.1130/abs/2018AM-319331

[31] Korner, C. and Ohsawa, M. (2005) Mountain Systems. Island Press, Washington DC, USA.

[32] Garrard, R., Kohler, T., Wiesmann, U., Price, F.M., Byers, A.C. and Sherpa, A.R. (2012) Depicting Community Perspectives: Repeat Photography and Participatory Research as Tools for Assessing Environmental Services in Sagarmatha National Park, Nepal. *eco. mont*, **4**, 21-31. https://doi.org/10.1553/eco.mont-4-2s21

[33] Liu, B., Kang, S.C., Sun, J.M., Zhang, Y.L., Xu, R.,Wang, Y.J., Liu, Y.W. and Cong, Z.Y. (2013) Wet Precipitation Chemistry at a High-Altitude Site (3,326 m a.s.l.) in the Southeastern Tibetan Plateau. *Environmental Science and Pollution Research*, **20**, 5013-5027. https://doi.org/10.1007/s11356-012-1379-x

[34] Zhang, Y.L., Kang, S.C., Li, C.L., Cong, Z.Y. and Zhang, Q.G. (2012) Wet Deposition of Precipitation Chemistry during 2005-2009 at a Remote Site (Nam Co Station) in Central Tibetan Plateau. *Journal of Atmospheric Chemistry*, **69**, 187-200. https://doi.org/10.1007/s10874-012-9236-3