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Land Use and Water Quality in Bangladesh and Bhutan

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Abstract
The freshwater systems of Bhutan and Bangladesh offer marked contrasts in anthropogenic disturbance, surrounding land uses, watershed population density, and benthic macroinvertebrate ecology. However, they share a lack of published research on water quality monitoring, specifically in regard to biological monitoring with benthic macroinvertebrates. With their high diversity, high abundance, and spectrum of pollution tolerances, benthic macroinvertebrates are an inexpensive yet powerful tool for monitoring freshwater health. In November of 2015, the Stroud Water Research Center performed physical, chemical, microbiological, and macroinvertebrate sampling at 18 stream sites in western Bhutan, with sites representing a variety of surrounding land uses and disturbance levels. In August of 2016, the author and fellow Penn MES student Naimul Islam performed a second round of sampling at fourteen sites in Bhutan, and a first round of sampling at ten sites in Bangladesh, using both quantitative collection techniques as well as less technical citizen-science techniques. After extraction and identification to the taxonomic level of family, macroinvertebrate taxa were compared across land uses and in relation to collected physico-chemical and microbiological metrics. In Bhutan, significant changes in macroinvertebrate taxa were correlated with changes in upstream versus downstream condition, as well as with monsoon versus postmonsoon sampling times. In Bangladesh, the citizen-science collection technique of leaf packs selected overwhelmingly for Chironomidae and thus could not distinguish between upstream and downstream conditions, necessitating an in-field or lab modification of the technique for future use. Given each country’s direct interests in maintaining clean, functioning freshwater systems, both Bangladesh and Bhutan – and much of South Asia – are ripe for the implementation of both citizen-science and technical biomonitoring techniques that connect communities and public officials to measures of water quality and stream condition.

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LAND USE AND WATER QUALITY IN BANGLADESH AND BHUTAN

Bryan Currinder

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Dr. Sarah Willig
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ABSTRACT

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Dr. Bernard Sweeney

The freshwater systems of Bhutan and Bangladesh offer marked contrasts in anthropogenic disturbance, surrounding land uses, watershed population density, and benthic macroinvertebrate ecology. However, they share a lack of published research on water quality monitoring, specifically in regard to biological monitoring with benthic macroinvertebrates. With their high diversity, high abundance, and spectrum of pollution tolerances, benthic macroinvertebrates are an inexpensive yet powerful tool for monitoring freshwater health. In November of 2015, the Stroud Water Research Center performed physical, chemical, microbiological, and macroinvertebrate sampling at 18 stream sites in western Bhutan, with sites representing a variety of surrounding land uses and disturbance levels. In August of 2016, the author and fellow Penn MES student Naimul Islam performed a second round of sampling at fourteen sites in Bhutan, and a first round of sampling at ten sites in Bangladesh, using both quantitative collection techniques as well as less technical citizen-science techniques. After extraction and identification to the taxonomic level of family, macroinvertebrate taxa were compared across land uses and in relation to collected physico-chemical and microbiological metrics. In Bhutan, significant changes in macroinvertebrate taxa were correlated with changes in upstream versus downstream condition, as well as with monsoon versus post-monsoon sampling times. In Bangladesh, the citizen-science collection technique of leaf packs selected overwhelmingly for Chironomidae and thus could not distinguish between upstream and downstream conditions, necessitating an in-field or lab modification of the technique for future use. Given each country's direct interests in maintaining clean, functioning freshwater systems, both Bangladesh and Bhutan – and much of South Asia – are ripe for the implementation of both citizen-science and technical biomonitoring techniques that connect communities and public officials to measures of water quality and stream condition.
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**Introduction and Background**

The Stroud Water Research Center (SWRC) is an independent, non-advocacy organization whose mission is to advance knowledge and stewardship of freshwater systems through global research, education, and restoration ([http://www.stroudcenter.org/](http://www.stroudcenter.org/)). In 2015, SWRC partnered with the Waterkeeper Alliance (WA) - a non-profit advocacy group also focusing on freshwater issues and ecology - to help with their initiatives in preserving and studying the freshwater systems of Bhutan.

Bhutan, a small country located in the Eastern Himalayas, is home to some of the last pristine waterways in the world. Despite the country’s small population and low population density, significant challenges exist for Bhutan in maintaining adequate water quality, particularly for those living downstream of population centers or agriculture. A primary goal of the partnership is to bring water quality monitoring and stewardship capabilities to the nation of Bhutan by first increasing the scientific understanding of the country’s relatively unstudied waterways. The current lack of knowledge about Bhutan’s freshwater systems is an impediment to understanding the scope of impairment - and therefore the potential threats to public health and ecological integrity - under different types of anthropogenic disturbance. To that end, SWRC’s partnership with the WA looked to investigate the physical, chemical, and biological aspects of Bhutan’s freshwater systems, particularly as they relate to disturbances from different forms of human development.

In November of 2015, the SWRC performed qualitative sampling for aquatic macroinvertebrates at eighteen sites upstream and downstream of varied human development in western Bhutan (in addition to physical and chemical sampling) near the
population centers of Thimphu, Paro, and Punakha (Figure 1). In January of 2016, the author partnered with SWRC to sort and identify this first collection of macroinvertebrates down to the taxonomic level of family. With their high diversity, high abundance, and spectrum of pollution tolerances, aquatic macroinvertebrates are a powerful tool for monitoring freshwater quality upstream and downstream of anthropogenic disturbances (Bonada, 2006). SWRC plans to visit Bhutan at least three more times to obtain a more holistic picture of the nation’s stream ecosystems and impacted water quality, with the visit of the author during this project functioning as the second trip for sampling.

Lying downstream of Bhutan, the country of Bangladesh offers valuable contrasts in land use, population density, water quality, and associated macroinvertebrate fauna within scarcely studied waterways. As one of the most densely populated countries on the planet, undisturbed forest is scarce in Bangladesh, and stream and river health have suffered under pollution from widespread agriculture and urbanization within most watersheds. As an addendum and point of comparison to the ongoing project in Bhutan, the author and SWRC looked to see how land uses and population centers are affecting water quality in a lesser-studied area of Bangladesh.

A primary goal of this capstone project is to bring basic water quality monitoring capabilities to both Bhutan and Bangladesh. A portion of this goal can be achieved through the expansion of SWRC’s Leaf Pack Network (LPN). The LPN is a citizen science objective and online network of citizens, teachers, and students that use basic macroinvertebrate sampling techniques for monitoring water quality within selected stream sites (http://www.leafpacknetwork.org/). The beauty of the LPN as a citizen
science tool lies in its simplicity, low cost, low labor input, and high reproducibility. Participants create a standardized, artificial leaf pack within a mesh bag and place it in a stream for three to four weeks for colonization by macroinvertebrates. After colonization, leaf packs are collected and macroinvertebrates are sorted to a chosen taxonomic level (typically order or family). Macroinvertebrate data can then be shared through the SWRC’s LPN website for comparison and a qualitative indication of water quality within the sampled stream. For both Bhutan and Bangladesh, instituting the LPN will first require calibration, as there is a lack of research on the associated macroinvertebrate fauna represented within upstream-reference and downstream-disturbed sites. Macroinvertebrate samples from leaf packs were also supplemented with basic physical, chemical, and microbiological samples that give a more holistic picture of stream health via nutrient, coliform, and sediment pollution.

Additionally, while this capstone project has been primarily focused on the scientific investigation of stream health and water quality, the project is jointly coordinated with fellow MES student Naimul Islam, whose goals for the project revolve primarily around public involvement and education in the biomonitoring process. Naimul has been heavily involved in the field work and scientific aspects of this project, but is taking more of a lead in the equally crucial endeavor of “getting the word out” for public use of the results. In sum, both Naimul and the author hope that the scientific findings and methods of this project do not remain esoteric and inaccessible, but instead play an important role in helping communities, officials, and biologists monitor stream health and water quality in these lesser-studied areas of South Asia.
Literature Review

The Stream and Its Valley

The vital characteristics and processes of streams are, in many ways, a reflection of the characteristics of their watershed. Stream ecologists have long noted the close connection between streams and their surrounding landscapes (Hynes, 1975; Vannote et al., 1980; Allan, 2004). From a landscape ecology perspective, streams are composed of and influenced by climatic, biologic, geologic, hydrologic, and topographic factors interacting at multiple spatial and temporal scales (Hynes, 1975; Robinson et al., 2002; Allan, 2004; Goetz & Fiske, 2008). In this sense, as noted by Allan (2004), streams and rivers can be thought of as “riverscapes” – collections of habitats continuously being influenced and changed by interacting variables from the surrounding landscape (the same logic applies to low order streams, which can be referred to as “streamscapes;” Fausch et al., 2002; Allan, 2004). The high biodiversity of many stream systems is closely linked to their high heterogeneity of habitats (Townsend, 1989; Robinson et al. 2002; Allan, 2004), with the biodiversity roughly spaced along a changing continuum within the streamscape (Vannote et al., 1980).

Because of the intimate connection between landscapes and the streams that flow through them, any significant structural or functional changes to a landscape result in corresponding changes within that landscape’s streams (Hynes, 1975; Allan, 2004; Allan & Castillo, 2007). Intensive land uses that significantly alter watershed functionality - i.e. deforestation, urban, and/or agricultural land uses - can set off a cascade of changes in a stream system, affecting the many geomorphic processes that maintain a streamscape and, ultimately, water quality (Allan & Castillo, 2007). For example, the natural
hydrology of a stream creates a variety of habitat features within the streamscape – riffles, bars, pools, and islands – that can host a corresponding variety of biota (Townsend, 1989; Wiens, 2002; Allan, 2004). Ultimately, the disruption of the stream’s geomorphic processes results in a loss of habitat heterogeneity and a loss in the corresponding biota – this is the degraded streamscape brought on by an altered landscape (Robinson et al., 2002; Townsend et al., 2003; Allan, 2004).

In addition to altering the geomorphology of stream habitats, human land uses often contribute a wide variety of pollutants that can alter stream system ecology and function (Allan & Castillo, 2007). Non-point source inputs from agricultural areas may include excess nutrients from fertilizer, pesticides, herbicides, and coliform bacteria from livestock (Rosenberg & Resh, 1993; Allan & Castillo, 2007). In addition to more frequent and intense runoff events, urban areas typically contribute a wider variety of non-point source pollutants, with the types of pollutants dependent upon the use of the urban area in question. Common pollutant inputs include excess nutrients, hydrocarbons, heavy metals, and sewage (dependent upon the presence/absence, and capabilities of, sewage systems; Rosenberg & Resh, 1993; Allan, 2004).

Urban Land Use and Stream Condition

Although urban land typically constitutes a low percentage of land within a total watershed, particularly in comparison to agriculture, it can have a disproportionately large effect on stream condition (Paul & Meyer, 2001; Wang et al., 2001; Allan, 2004). The amount of urban land within a watershed is closely linked to serious declines in stream condition (Paul & Meyer 2001; Wang et al. 2001; Allan 2004; Goetz & Fiske,
The principal cause behind stream degradation is the increase in impervious surface cover (ISC) that accompanies urbanization (for the purposes of this study, urban land will also encompass suburban land, as both result in high levels of ISC; Paul & Meyer, 2001; Roy et al., 2003). Increases in ISC affect hydrology by decreasing the infiltration of precipitation, and concomitantly, by increasing the amount of surface runoff, changing the timing and severity of peak flows (Paul & Meyer, 2001; Wang et al., 2001; Roy et al., 2003; Allan 2004). Severe peak flows after precipitation events can alter channel morphology, destroy the variety of habitats, displace sediments, and displace vital organic materials (Paul & Meyer, 2001; Wang et al., 2001; Allan, 2004; Goetz & Fiske, 2008).

Increases in ISC often accompany losses of riparian vegetation, which is particularly troublesome for low order streams (Sweeney, 1993; Allan 2004; Sweeney & Blaine, 2007; Sweeney & Newbold, 2014). Low order streams are largely dependent on allochthonous organic material input from riparian vegetation, most notably the leaves of trees, which form the energy base for the biodiversity of the stream (Sweeney, 1993; Paul & Meyer, 2001; Sweeney & Newbold, 2014). Furthermore, loss of riparian vegetation results in loss of shading, increasing mean water temperature during spring and summer months (Sweeney, 1993; Sponseller et al., 2001; Sweeney & Newbold, 2014). Mean stream water temperature is also affected directly by increases in ISC as runoff is heated on exposed surfaces (Paul & Meyer, 2001; Wang et al., 2001; Allan, 2004).

The chemical integrity of streams is also impaired in urbanized areas as pollutants are collected on impervious surfaces by the increased amount of surface runoff (Paul & Meyer, 2001). The types of pollutants entering streams vary depending on the type of
urban land use, but there are consistently decreases in dissolved oxygen, increases in conductivity, increases in suspended solids, and increases in ammonium, hydrocarbons, and heavy metals (Paul & Meyer, 2001; Allan, 2004; USEPA, 2013). There is also an increase in the amount of available nutrients, particularly nitrogen and phosphorus, from effluent overflows and fertilizers after precipitation events (Paul & Meyer, 2001; Allan, 2004).

Given the direct and indirect connections of ISC to most aspects of stream degradation in the urban landscape, there has been an effort to develop a threshold of ISC within any given watershed at which stream degradation occurs. While the challenges of developing this threshold are complex (Allan, 2004), most thresholds of stream degradation have been associated with an ISC of 10-20% within a watershed (Paul & Meyer, 2001). As the amount of urban land within a watershed begins to cross this threshold, the altering of the natural hydrological regime typically begins to show measurable effects in overall stream health (Paul & Meyer, 2001; Wang et al., 2001; Roy et al., 2003).

**Agriculture and Stream Condition**

While agricultural land use varies by factors like intensity, region, livestock, and crop type, virtually all conventional agricultural land use alters stream condition through modified flows, degraded channel habitat, altered temperature regimes, and high inputs of nutrients, pesticides, and sediments (Watzin & McIntosh, 1999; Allan, 2004). The hydrology of streams in agricultural watersheds typically resembles that of urban areas with high ISC – low base flow combined with higher peak flows that can alter and erode
channel structure. This is often a result of soil compaction (dependent on crop type, rotation, use of heavy machinery, etc.) that decreases soil infiltration capacity and the presence or absence of irrigation (Allan, 2004). Irrigation can either alter stream flows through direct extraction, or potentially alter base flow through groundwater extraction (Allan & Castillo, 2007).

The removal or degradation of natural riparian forest can have a profound impact on stream condition in agricultural watersheds. Intact riparian areas offer allochthonous inputs of leaf litter, maintain cooler water temperatures during the summer (particularly in low order streams), stabilize stream banks, and can intercept runoff containing excess nutrients, pollutants, and sediments (Sweeney, 1993; Stewart et al., 2001; Sweeney & Newbold, 2014). Habitat quality and heterogeneity within the stream channel is significantly affected by all of these variables, and can be further impacted by biological processes like eutrophication resulting from excessive nitrogen and phosphorus inputs (Watzin & McIntosh, 1999; Allan, 2004).

Attempts at finding a threshold of agricultural land cover within a watershed at which stream degradation is significant have been inconsistent in their findings (Allan, 2004). Some studies have shown that 30-50% of a watershed must be converted to agriculture before measured degradation occurs (Quinn & Hickey, 1990; Wang et al., 2003), while other studies have found streams in good condition at up to 80% agricultural cover (Wang et al., 1997; Meador & Goldstein, 2003). With these highly variable findings, it seems the demarcation of an agricultural land cover threshold at which stream degradation occurs is fraught with false assumptions about other underlying variables (variabilities in soil, types and intensities of agriculture, regional peculiarities, etc.).
Additionally, known studies of this nature were mostly performed on watersheds in North America, not South Asia or elsewhere. Nevertheless, the threats to stream condition stemming from agriculture are at least partly a function of the total land cover comprised of agriculture within a watershed, even if thresholds of stream degradation differ by site. In this sense, total agricultural land use within a catchment is still a useful concept for predicting the type and nature of impacts on stream systems.

*Aquatic Macroinvertebrates as Indicators of Stream Condition and Water Quality*

Measuring a stream’s condition involves comparing the stream in question to unimpaired or least-impaired reference sites (Karr & Chu, 1999; Allan, 2004). A key tool in measuring stream condition is biomonitoring – the use of biological variables to survey and assess an environment (Barbour et al., 1999; Bonada, 2006). In stream ecosystems, aquatic macroinvertebrates serve as unique tools for assessing the biological health of a stream because of (a) their intimate connection to the physical, chemical, and biological conditions of a stream, (b) their limited mobility within a habitat, (c) their critical role in a stream’s food web, (d) their huge species richness, with different species offering different environmental responses to a variety of stressors, (e) their compatibility with simple, low-cost sampling techniques, (f) their known pollution tolerances, and (g) their ubiquity (Rosenberg & Resh, 1993; Barbour et al., 1999; Karr & Chu, 1999; Usseglio-Polatera et al., 2000; Bonada, 2006). The macroinvertebrate taxa that are most intolerant of pollution, and therefore most indicative of stream health, are the Ephemeroptera, Plecoptera, and Trichoptera, which are collectively known as the EPT. These taxa are
often pooled in analysis to assess stream health (Rosenberg & Resh, 1993; Bonada, 2006).

In short, biomonitoring with macroinvertebrates gives a window into a longer time frame of pollution and disturbance history within a stream ecosystem, whereas other physical and chemical measures provide only a snapshot in time. However, the use of macroinvertebrates in a biosurvey is still most informative when paired with other measures of habitat quality and water chemistry (Rosenberg & Resh, 1993; Bonada, 2006). It is also worth noting that while macroinvertebrate surveys are a vital part of assessing stream condition, they typically do not allow for claims of direct causation to land uses (Allan, 2004; Bonada, 2006). Certain land use types may be strongly correlated with certain macroinvertebrate assemblages, abundances, and presence/absence of macroinvertebrate groups, but any links of direct causation are notoriously difficult to establish (Karr & Chu, 1999; Allan, 2004).

**Bangladesh**

Bangladesh presents a marquee example of how environment can shape culture, as well as how modern economic and social forces can alter natural systems. In one sense, being Bangladeshi represents one’s strong connection to the country’s abundant freshwater and estuarine resources, knowledge of the diversity and opportunity that lies within them, and an adaptability to the seasonal fluctuations of dry season scarcity and wet season overabundance (Hanchett et al., 2014; Price et al., 2014). Annual floods are a part of the natural seasonal rhythm in Bangladesh – the South Asian monsoon brings most streams to flood stage, spreading vital sediments and nutrients over agricultural
lands that occupy the surrounding floodplains. When streams spill their banks during the wet season, there are little to no geographical barriers to the spread of the floodwaters, and little resistance to migration of the stream channels. The continuous shifting of the country’s many streams, in addition to the numerous wetlands and oxbow lakes, often blurs the line between what might be considered terrestrial versus aquatic. For most rural Bangladeshis, the distinction is largely insignificant, as aquatic and terrestrial systems depend on one another and the Bangladeshi farmer or fisherman depends on this mutual arrangement (Chowdhury et al., 2014; Price et al., 2014; Hanchett et al., 2014; Price & Mittra, 2016). Water produces wealth, but it can also take wealth, or life, away (Hanchett et al., 2014).

Bangladeshis hold reverence towards their abundance of water, but the current state of the country’s surface waters would suggest otherwise (Karn & Harada, 2001; Hanchett et al., 2014). Where did things go wrong? Understanding this begins with addressing the country’s population problem. With ~160 million people crammed into an area roughly the size of Iowa (equal to about 1100 people per square kilometer), natural watersheds are understandably scarce in Bangladesh. As of 2011, 70% of the country was under cultivation, while only 11% remained as or had been converted back to tropical forest, with ~10% of this forest contained exclusively in the Sundarbans mangrove forest along the southwest coast. In upland freshwater watersheds, only about one percent of the land remains as intact forest, with most of it fragmented into small plots. The urban areas, particularly Chittagong, Khulna, and the capital Dhaka, have grown into megalopolises of nightmarish proportions. The Dhaka metro area, already at over 18 million people, adds 500,000 new people each year (most of whom are rural economic migrants) into pockets
of woefully inadequate infrastructure. Development at this scale – both urban and agricultural – has decimated water just as it has decimated the forest.

Urban streams and rivers are essentially channelized human and industrial waste removal systems rather than ecologically functioning entities. The Buriganga river, a major river running through Dhaka, is one of the most compromised and polluted surface water sources in the entire region (Karn & Harada, 2001). Sewage and industrial waste make their way directly into the river or one of its many tributaries upstream (Karn & Harada, 2001). Streams and rivers in agricultural areas retain some ecological capacity, but this has mostly shifted to the base of the trophic pyramid as excess nutrients from fertilizers and livestock are contributed via runoff. The green revolution arrived in Bangladesh in the 1960s, and with it came all the modern agricultural inputs of inorganic fertilizer, pesticides, and modern irrigation techniques (Hanchett et al., 2014). With the option of increased yield, most Bangladeshi farmers have abandoned traditional cultivation techniques. Inorganic fertilizers and pesticides are still prohibitively expensive for most farmers, so neither are typically applied in copious amounts (Sharif Jamil, personal communication, 2016; the reverse is true for most agriculture in North America). However, the complete alteration of entire watersheds – including the removal of riparian areas – leaves little buffer for preventing fertilizers or pesticides from polluting waterways. Productive land is a scarce commodity in Bangladesh – most agriculture and development directly abuts streams and rivers where riparian vegetation previously stood.

The widespread alteration of watersheds has also affected the country’s natural flooding regimes. While flooding is an entirely expected and natural phenomenon for
Bangladeshis, in recent decades the intensity of the country’s flooding has trended towards the unrecognizable. Almost half of the country can be classified as wetlands, many of which have been drained or altered for agriculture or urban development. The loss of forest and wetland areas is suspected to have led to serious deficiencies in the land’s ability to retain and slowly discharge water. Additionally, climate change is believed to be connected to an increasingly intense South Asian monsoon, whose severity is compounded by rivers already swollen from melting Himalayan glaciers upstream (Price & Mittra, 2016). To be sure, not all of Bangladesh’s flood problems can be blamed on climate change or watershed alterations – many decisions about water flow and dam release timing are made in India, whose monopoly on the issue can exacerbate a drought or cause flooding in downstream Bangladesh (Hanchett et al., 2014; Thomas, 2016).

The degradation of Bangladesh’s water resources seems largely a function of modern trends beyond any one community’s control, rather than a degradation of the traditional Bangladeshi reverence towards freshwater resources. If there is to be one critique of Bangladeshi culture’s role in the current state of affairs, it is that traditional culture is well-adapted to the historical conditions of natural systems, but seems slow to mitigate all of the natural consequences that come along with the transition to a burgeoning modern economy (Hanchett et al, 2014; Price et al., 2014; Thomas, 2016). To be fair, this trend – that of intense environmental degradation when modern economics clashes with more traditional cultures and developing economies – is largely true the world over. The nascent pangs of this dynamic are growing sharper in Bangladesh’s upstream neighbor, Bhutan.
Bhutan

Located just 100 kilometers north of Bangladesh through a small sliver of India, Bhutan is, given its proximity, in surprisingly stark contrast to the hot and crowded lowlands of Bangladesh. The population of Bhutan is a sparse 780,000 people, or about 20 people per square kilometer. Virtually all of the country is mountainous, spanning the southern slope of the Himalayas from the Indo-Gangetic plains to the Tibetan plateau. The majority of the population is found in rural areas throughout the low to mid elevations of the southern portion of the country, though the urban proportion of the population has been rapidly increasing in recent decades (RGOB, 2010).

Bhutan’s political and cultural history is characterized by isolation, independence, and a value for its traditional roots in Buddhism, which have allowed the nation to develop its own robust environmental ethos. Under the guidance of the well-renowned Gross National Happiness (GNH) index (an alternative to the Gross Domestic Product (GDP) index), Bhutan has implemented a constitutional mandate to preserve 60 percent of its land under forest cover and to designate at least 25 percent of land as protected areas (RGOB, 2010). As of 2007, 72 percent of the country was preserved as forest, and 43 percent of the country’s land was under protection (RGOB, 2010). The GNH theory of development is rooted in the Buddhist philosophy that nature is a living, interconnected system with inherent value, and therefore calls for a multi-dimensional approach towards sustainable development that maintains harmony between economy, environment, culture, and governance (RGOB, 2010). Since opening its borders to the outside world in the 1960s, the GNH approach to development has largely boded well for preserving the country’s rich environment and resources. Some of this success has derived from learning
what not to do from regional neighbors like Nepal, whose opening to the outside world in the 1950s precipitated widespread environmental degradation and pollution. However, increasing pressures stemming from modernization are putting the GNH philosophy to the test (Wangdi et al., 2013), with Bhutan’s freshwater resources encapsulating this conflict. Despite Bhutan’s small population and low population density, significant challenges exist for Bhutan in maintaining adequate water quality for its population and environment, particularly for those living downstream of population centers, agriculture, or industry. In recent decades, the country has undergone rapid population growth and development, putting the first significant strains on Bhutan’s abundant, but fragile, forests and water resources (Rinzin et al., 2007; Rinzin et al., 2009; Wangdi et al., 2013).

The future of Bhutan’s freshwater resources represents the first major test for the GNH doctrine. Tumbling down from the high Himalayas in the north onto the plains of India in the south (and, eventually, into Bangladesh via the Brahmaputra river), the country’s river systems represent an enormous potential for hydropower. Neighboring India has taken notice and overseen the funding and construction of a spate of recent hydropower projects throughout Bhutan. India imports around 75% of the cheap electricity produced by these projects, which contributes to 25% of Bhutan’s GDP (RGOB, 2010). Under current plans, new and existing hydropower projects will leave no major river basin in the country untouched. The downstream consequences of this arrangement are mostly unknown, but could easily affect the ecological connectivity and integrity of each river’s eventual destination – the Brahmaputra. Construction of the projects – overseen by Indian companies with poor track records elsewhere – has caused excessive damage to previously undeveloped river valleys through deforestation,
excavation, and the triggering of landslides, all of which are expected to have had a commensurate effect on riverine water quality and habitats. At the current rate, the hydropower plans of the Bhutanese government meet the requirements for a growth-obsessed India, but they do not satisfy the underlying tenants of a GNH philosophy.

The majority of Bhutan’s population is rural, with traditional rain-fed and irrigated agriculture constituting the primary modes of livelihood, and also a significant portion of the economy. In recent years, many farmers have begun to transition to more intensive agriculture by utilizing inorganic fertilizers (Dorji et al., 2011). As there is little flat terrain in the country, most agriculture is performed on the steep hillsides of river valleys which are particularly prone to erosion, and thus prone to deposition of sediments and nutrients into streams and rivers (Dorji et al., 2011). The rural majority is dependent on surrounding forested landscapes for a variety of ecosystem services, including water regulation for agriculture (RGOB, 2010; Wangdi et al., 2013). Farmers are well aware that intact forests serve as Bhutan’s “water treatment plants” and “storage towers.” Given that most of Bhutan’s population draws untreated water for consumption directly from stream or river systems, forested watersheds are vital to preserving water quantity and quality for the people of Bhutan, and are thus vital to the goals of the GNH index (RGOB, 2010; Wangdi et al., 2013).

The outlook for the country’s forests is not as optimistic as it was in the 1990s, with harvesting of firewood and construction timber degrading and denuding the hillsides (Wangdi et al., 2013). In response, and with an eye towards alleviating high rates of rural poverty, Bhutan’s government has begun to shift its focus from a top-down, centralized protection scheme to community-centered sustainable use of forest and water resources.
(RGOB, 2010; Wangdi et al., 2013). The sustainable development goals and methods employed under such government programs are viewed favorably by most Bhutanese: the GHN path to sustainable development has special appeal within a Buddhist society as it generally looks to coexist harmoniously with natural systems (Rinzin et al., 2007; Rinzin et al., 2009). Efforts at sustainable utilization of forest resources will be all the more important for preserving water quality and availability as climate change is expected to significantly alter the precipitation and temperature regimes of the Eastern Himalayas in the coming decades (Wangdi et al., 2013).

The recent modernization and growth of urban areas has had the most deleterious effect on streams and rivers (Giri & Singh, 2013). Similar to the situation in Bangladesh (and many other developing countries), a large influx of rural migrants looking for economic opportunity has led to overdevelopment amidst a lack of adequate city planning. Previously small towns and cities in Bhutan now haphazardly span the length of entire river valleys. The effects on river and stream water quality are generally as expected for urban areas – inadequate sewage treatment has allowed waste a direct entry into waterways, and copious runoff from impervious surfaces has contributed pollutants while also altering natural flow regimes (Giri & Singh, 2007). As locals around the capital of Thimphu will tell you, trash-choked waterways are the most apparent indicator that things have begun to go awry. Thus far, one saving grace for Bhutan’s urban water woes seems to have been dilution; the abundance of other surface water resources, most of which are clean or only modestly polluted, have helped dilute the pollution loads flowing from urbanized streams and rivers. However, the combined effects of urbanization, the expansion of intensive agriculture, and a bounty of hydropower projects
does not bode well for the future ecological or aesthetic integrity of Bhutan’s streams and rivers.

A Lack of Research

While Bhutan and Bangladesh offer marked contrasts in population density and levels of anthropogenic disturbance within watersheds, one commonality is a lack of existing and expected future research on their respective freshwater systems. Indeed, a general lack of scientific understanding of freshwater systems – and therefore a lack of knowledge on water quality, levels of impairment, and how biota respond to disturbance – is an unfortunate commonality across much of South Asia (Dudgeon, 2003). From a public health perspective, this is a troubling reality given the region’s high population density and majority rural population that has a direct reliance on clean and functioning freshwater systems (Dudgeon, 2003; Price & Mittra, 2016). From a conservation perspective, South Asian freshwater systems are rich in biodiversity (though much of this ecological information remains incomplete) and the effects of anthropogenic disturbances on freshwater biota remain largely uncategorized (Dudgeon, 2000).

Research in the region using aquatic biota as indicators of water quality is scarce, with most research having taken place outside of Bangladesh or Bhutan. Previous studies in the region have principally been based in the central Himalaya of Nepal or throughout India (Sharma and Moog, 2005; Sharma et al., 2009), or have focused on the East Asian tropics of southeast China, Thailand, and Malaysia (Morse et al., 2007). Korte et al. (2010) are partly an exception to this trend, having developed a multimetric framework for assessing the ecological condition of rivers throughout most of the lowlands of the
Hindu-Kush/Himalayan region (including Bangladesh and Bhutan). However, Korte et al.’s (2010) findings were broad in scope and do not incorporate the mostly pristine highlands of Bhutan for comparison.

In Bangladesh, most knowledge of freshwater systems and water quality is derived from the large rivers that criss-cross the country, focusing principally on the areas surrounding the capital of Dhaka (Karn & Harada, 2001). Given the relatively new utilization of benthic macroinvertebrates as indicators of water quality in combination with the widespread impacts of pollution throughout Bangladesh’s recent history, it is not clear if macroinvertebrates, or any other biota serving as indicators of water quality, have ever been sampled from “pristine” freshwater streams in the country.

In Bhutan, water quality research is limited to only a few recent studies. Pradhan and Mandal (2015) investigated the impairment of three rivers in western Bhutan through the lens of water chemistry, while Giri and Singh (2013) investigated water quality upstream and downstream of the capital Thimphu with multiple metrics, including benthic macroinvertebrates. Governmental studies on water quality are conducted sparingly and have been partly hampered by the lack of ecological information on the country’s benthic macroinvertebrates (NEC, 2005).

While benthic macroinvertebrate monitoring in tropical Asia remains in its infancy, it is also worth noting that all current knowledge is derived from conventional sampling methods - leaf pack sampling remains an unexplored method for use as a community water quality monitoring tool.
Materials and Methods

2015 Sample Sites (Bhutan)

In November of 2015, 18 sites were chosen for physical, chemical, microbiological, and macroinvertebrate sampling in western Bhutan by SWRC (Tables 1-3, Figure 1). Stream sites were chosen primarily if 1) they were accessible for sampling, 2) they presented a gradient of anthropogenic disturbance in which an undisturbed, forested upstream area could be contrasted with an impacted downstream area, or 3) they showed indications of being largely undisturbed, or 4) they showed indications of being disturbed by a categorical land use. As a whole, these sites spanned the Paro Chhu\(^1\) and Thimphu Chhu watersheds within the Paro and Thimphu dzongkhags, as well as the Punat Tsang Chhu watershed within the Punakha dzongkhags.\(^2\)

Field Data Collection

In the field, data collection included 1) measuring location with a Garmin GPSMap 64s Global Positioning System (GPS) handheld unit, 2) collecting macroinvertebrates from the riffle or run areas of streams/rivers with a 500 µm dipnet, 3) measuring water temperature, conductivity, pH, and dissolved oxygen with an Orion 5 star portable meter, 4) measuring water turbidity with a Campbell Scientific OBS3+ turbidity sensor connected to a custom Arduino-based data logger, and 5) recording qualitative site observations in a field notebook.

Field Laboratory Data Collection

\(^1\) Chhu or river.
\(^2\) Dzongkhag or district.
In the field laboratory (i.e. a hotel room), additional data was collected on each site’s nutrient loads as well as levels of *Escherichia coli* and total coliform bacteria. For *E. coli* and total coliform bacteria, stream or river water was collected in sterile Whirl-Pak® bags, transported to the hotel in a cooler, and then stored in a refrigerator. Within 4-24 h, 1.0 ml of water from both a blank (drinking water) and the stream sample were pipetted onto individual 3M Petrifilm E.coli/Coliform Count Plates. Petrifilm® plates were then incubated for 24 h at 35˚C, after which both *E. coli* and total coliform bacteria colony forming units (cfu) were identified by color and trapped gas bubbles and counted. Plates were counted only if associated blank plates did not grow coliform colonies (i.e. remained “blank”). Values were then multiplied by 100 to present data in units more comparable to units of cfu/100 ml typical for water quality criteria. For nutrients, water from the same Whirl-Pak® for *E. coli*/total coliform analysis was used. Within 4-24 h of field collection, 5.0 ml samples were pipetted into four test-tubes and reacted with colorimetric reagents from API-brand Freshwater Test Kits for ammonia, nitrite, nitrate, and phosphorus. After each reaction, nutrient levels were quantified using an open source Arduino-based colorimeter developed by IO-Rodeo.

2016 Sample Sites (Bhutan, Bangladesh)

In August of 2016, 14 of the original 18 sites in western Bhutan were chosen for a second round of sampling by the author and fellow MES student Naimul Islam (Tables 1-3, Figures 2-3).³ For physical, chemical, microbiological, and qualitative data, collection at each site followed the same procedures and used the same equipment as mentioned.

³ Only eleven of the original eighteen sample sites were accessible for a second round of sampling given high flows during the South Asian monsoon.
above for November of 2015 by SWRC. However, macroinvertebrates were collected with quantitative surber samplers rather than qualitatively via dip-net, and were only collected at eleven of the fourteen sample sites.\(^4\) Surber samples encompassed a one square foot sample area and used a 250 \(\mu\)m mesh net, with each site consisting of 16 total surber samples. Working upstream, surber sampling was performed in randomly chosen riffle habitats at each site, though high flows in the main channel sometimes prohibited access to all riffles. If not enough riffle habitats were available at a site, shallow run habitats were sampled. During sampling the surber sampler was placed directly onto the stream bed while facing upstream, and all rocks and woody material within the one square foot area were individually scrubbed with a brush in order to dislodge and collect macroinvertebrates in the net. The exposed stream bed was then disturbed to a depth of 10 cm. For the 16 samples taken at each site, eight were composited into one bucket and eight into another bucket. Each bucket was then transferred to a field splitter and separated into fourths. One of the fourths was randomly chosen and transferred to a marked 200 mL individual container, with two of these fourth subsamples coming from each composite bucket for a total of four composite surber samples per site. Composite samples were then preserved in 70\% isopropyl alcohol and refilled within the next 48 hours to prevent dilution.\(^5\)

In northeastern Bangladesh, ten sites across three different ecoregions were chosen for leaf pack and/or dip-net sampling (Tables 1-3, Figures 2 & 4). The ecoregions

\(^4\) All sites that were visited but not sampled for macroinvertebrates were inaccessible due to high flows, with one exception being BT03 which is a tap along a tourist trail.

\(^5\) While the use of 90-95\% ethyl alcohol is ideal for the preservation and later identification of macroinvertebrates, obtaining large quantities of ethyl alcohol in either Bhutan or Bangladesh was a near impossibility during the trip. Instead, the authors settled for 70\% isopropyl alcohol while in the field, which was still quite difficult to obtain in large quantities.
were not exhaustively characterized but qualitatively differentiated by distance, geology, topography, stream substrates, and surrounding flora. All ten sites followed the same procedures as in Bhutan for the collection of physical, chemical, microbiological, and qualitative data. In the leaf pack sampling method, coarse-mesh bags were filled with a standardized weight (~15 g) of leaf litter collected from the riparian surroundings of the stream. For each site, five leaf packs were spaced equally in riffle areas along a 100 m stream reach and secured to the stream bottom by being tied to large rocks. Leaf packs were then left in the stream for three to four weeks for colonization by macroinvertebrates. After colonization, each leaf pack was collected and thoroughly rinsed with stream water onto a 250 µm sieve to capture macroinvertebrates. Material and macroinvertebrates collected on the sieve were then transferred to marked 200 mL containers, preserved in 70% isopropyl alcohol, and refilled within the next 48 hours to prevent dilution. For most sites, collection of all leaf packs was not possible – some leaf packs were swept onto riparian areas or presumably downstream due to high flows during colonization despite being reasonably secured. For one site (BD08), only two leaf packs were collected after colonization, and so the two leaf pack samples were supplemented with two dip-net samples. For two other sites (BD09 and BD10), four dip-net samples were collected as each site had not been originally targeted for leaf pack sampling. For each dip-net sample, a randomly chosen area within a riffle was targeted for two repetitions of timed one-minute kicks, with the kicked area carefully approximated to be one square foot in size. Each sample’s collected material and macroinvertebrates was then composited in a bucket, poured into a field splitter, and separated into fourths. One of these fourths was randomly chosen, transferred to a marked 200 mL container,
preserved in 70% isopropyl alcohol, and refilled within the next 48 hours to prevent dilution.

In summary, sampling during August of 2016 in Bhutan used only the surber sampler method for collecting macroinvertebrates. In Bangladesh, seven sites were sampled using exclusively the leaf pack method, one site was sampled with a combination of both the leaf pack and dip-net methods, and two sites were sampled exclusively with the dip-net method. All surber, leaf pack, and dip-net samples were transported back to laboratories at the University of Pennsylvania and SWRC for extraction and identification of macroinvertebrates. Extraction of macroinvertebrates involved splitting each sample into initial sub-samples of 1/2, 1/4, 1/8, and two 1/16s. Using stereo microscopes, sub-samples were inspected for all macroinvertebrates until a total of at least 200 specimens was obtained. Once targeted for inspection, each sub-sample was sorted to completion, and all sub-samples inspected for a given sample were recorded. A minority of samples did not contain 200 specimens and so were sorted in their entirety to collect all specimens. Due to time and personnel constraints, only three of the four samples (or sometimes five for leaf-pack sites) were processed for each site. Additionally, only ten of the 11 sites sampled in Bhutan in 2016 were completely sorted (all but BT14), and six of the ten sites in Bangladesh (all but BD03, BD04, BD05, & BD06). Once extracted, insect specimens were identified to the taxonomic level of family according to dichotomous keys compiled in Dudgeon (1999); identifications were

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6 Once macroinvertebrate samples arrived in the United States, the 70% isopropyl alcohol was decanted from each sample and replaced with 95% ethyl alcohol.
7 For accurate statistical analysis of community structure, it is ideal to obtain at least a 200 count of macroinvertebrates from any given replicate sample.
confirmed by SWRC entomologists. Non-insect specimens or specimens too small or damaged for accurate identification to family were instead identified to the level of order.

**Data Analysis**

Each sample’s identified specimens were analyzed using Statistical Analysis System (SAS) software, in which 1000 groupings of 200 macroinvertebrates (or fewer if samples did not reach a 200 count) were pulled randomly from each sample from each of the sites. Thus for each site an average of the total 3000 pulls (three sorted samples per site) was used to determined a suite of metrics indicative of overall stream condition.

Non-metric Multidimensional Scaling (NMS) was used to examine how macroinvertebrate assemblages differed among Bhutanese upstream and downstream sites and sample year using PC-ORD (version 4.37, MjM Software, Gleneden Beach, OR). Analysis was done using Sorenson distance, the step length was set at 0.20, and Monte Carlo was used to determine the optimal number of axes. The first NMS examined log-transformed macroinvertebrate counts of 45 common taxa from 2016 surber samples (taxa were removed if only one individual was collected), coliform counts, and physicochemical variables. This first NMS ran 61 iterations, had an $r^2$ set at 0.50, and a final stress of 9.19. A second NMS was run to compare the presence or absence of 51 macroinvertebrate taxa from 2015 and 2016 sampling (taxa not found at all sites at least twice each year were omitted) and was run with 57 iterations, an $r^2$ set at 0.40, and a final stress of 8.72. The final instability for both NMS was <0.00001.
Results

Bhutan

Stream sample sites, elevations, land use conditions, coliform counts, and associated physico-chemical characteristics for Bhutan are summarized in Tables 1-3. We identified 54 different macroinvertebrate taxa (either families or orders) from hand-picked dip-net samples at eighteen sites in Bhutan in November of 2015. We identified 56 different macroinvertebrate taxa from surber samples taken from ten sites (selected from within the eighteen 2015 sites) in August of 2016. All major aquatic macroinvertebrate groups were represented among the 62 total taxa from both years combined. As a general trend under traditional metrics of stream health and water quality, macroinvertebrate taxa in downstream sites exhibited characteristics of declining stream health when compared with upstream sites (Figures 7-10). Both total richness and EPT richness declined across most downstream versus upstream sites (Figures 7-8). The Plecoptera showed particular declines in abundance and richness downstream and were absent from urban sites altogether (Figure 8).

NMS ordination of log-transformed macroinvertebrate counts, coliform counts, and physico-chemical data for the eleven 2016 sample sites revealed clear differences between upstream and downstream sites (Figure 9). Upstream sites were correlated with macroinvertebrate taxa typically known to be intolerant (EPT taxa and Blephariceridae) or diverse enough to likely contain many intolerant genera (Chironomidae), while downstream sites were correlated with higher levels of total coliform, nitrate, and macroinvertebrate taxa typically characterized as tolerant (Psychodidae, Oligochaeta, and
Simuliidae). However, typically intolerant taxa like Baetidae and Glossosomatidae were also correlated with downstream sites (Figure 9).

In comparing Bhutan sample sites from both 2015 and 2016, NMS ordination of the presence or absence of macroinvertebrate taxa (water chemistry variables excluded) revealed a clustering of sites by upstream, downstream, and sample year (Figure 10). As sample times in each year were differentiated by monsoon (August 2016) or post-monsoon (November 2015) conditions, the clustering by year may be due to differences in seasonal flows, though this is unaccounted for in the ordination. Otherwise, differences in upstream versus downstream sites were distinct for both 2015 and 2016 sampling (Figure 10).

Macroinvertebrate densities in Bhutan did not necessarily decline in downstream sites and were inconsistent across sites, though this may have been partly due to a lack of accessibility to appropriate riffle habitats at some sample sites due to high flows (Figure 11).

**Bangladesh**

Stream sample sites, elevations, land use conditions, coliform counts, and associated physico-chemical characteristics for Bangladesh are summarized in Tables 1-3. We identified 33 macroinvertebrate taxa (either families or orders) in both leaf-pack and dip-net samples from five sites, though leaf packs had a slightly lower overall richness. The leaf pack method selected overwhelmingly for Chironomidae and thus could not distinguish between upstream and downstream sample sites (Figures 12-13). Dip-net samples at one of the leaf pack sites (BD08) and two separate sites (BD09)
revealed a lower percentage of Chironomidae and higher percentages of EPT, as well as a lower percentage of EPT between paired upstream-downstream sites (though this was only for one pair of sites: BD09 & BD10; Figure 13). Densities for leaf pack and dip-net samples were erratic, though they did show some consistency across three different ecoregions in relation to leaf pack or dip-net sampling (though standard error across sites was high; Figure 14).

Discussion

In Bhutan, November of 2015 and August of 2016 sampling revealed that the country’s major urban areas (Thimphu and Paro) are having a significant effect on downstream health and water quality, as in comparison to upstream reference sites within watersheds of protected forest (Figures 7-10). This is of particular concern since Thimphu and Paro are undergoing rapid development and expansion as many rural Bhutanese move into urban areas. Other land uses in Bhutan, such as suburban and agricultural areas, also seemed to exhibit downstream impacts, though the use of macroinvertebrate metrics alone may not tell the whole story. NMS ordinations were distinct in their separation of upstream and downstream sites, as well as their separation of sample years by monsoon or post-monsoon (Figures 9-10). The separation of monsoon and post-monsoon sampling may be attributed to the variations in flow present during each year, but discharge was not measured in the field and thus not considered in the ordination. The separation of these data by season emphasizes the need for further and consistent monitoring in Bhutanese streams and rivers, as well as the inclusion of pre-monsoon sampling. For safety and logistical reasons related to high flows, sampling may
be most realistic in the pre-monsoon and post-monsoon seasons (this is a typical approach in other monsoon systems).

In Bangladesh, the leaf pack method was not able to distinguish between upstream and downstream sites. In North America and elsewhere, leaf packs are known to select disproportionately for Chironomidae even in healthy stream sites, thus potentially skewing traditional metrics of stream health if Chironomidae are included in comparisons of upstream and downstream sites. However, for leaf pack sites in Bangladesh the percentage of Chironomidae per leaf pack was typically too high to even consider other groups (i.e. EPT) that could help determine stream health (Figure 12), despite the protected watersheds of many of the sample sites. Dip-net samples from these same (BD08) or similar sites (BD09 & BD10) revealed a typically healthier profile of macroinvertebrates, specifically in the form of higher percent EPT (Figure 12). In the future, the leaf pack method will require either in-field or lab modification (or both) to reveal meaningful measures of stream health and water quality in Bangladesh. In-field modification could involve filling leaf packs with species containing higher nutrient content from the surrounding riparian areas (bamboo leaves comprised a large proportion of leaf packs) and transporting more leaf pack content out of the field once collected, while lab modifications could involve going beyond a fixed 200 count method in order to capture other macroinvertebrate groups.

While the sampling techniques and protocols used in this project are generally well-established and reproducible, the unique environments of Bangladesh and Bhutan presented varied logistical and technical challenges. The timing of travel (August 2016) of the author and Naimul Islam was during the seasonal south Asian monsoon, which
presented challenges for sampling in the form of high flows. At a few sites in Bhutan, high flows prevented access to the main channel or ideal riffle conditions, which we suspect to have contributed to the inconsistency seen in macroinvertebrate densities across sites (Figure 11). In Bangladesh, leaf packs were sometimes buried or washed downstream (i.e. not collected) as multiple high flows occurred during the three to four week colonization period.

As the country has a long history of intensive landscape modification, it is also unknown whether protected areas in Bangladesh targeted for sampling were pristine or still recovering from past disturbances like deforestation. One protected forest site had non-intensive agriculture (betel leaf production) occurring in its watershed (BD01) and past land uses for most sites were unknown. We observed consistent access to protected sites by surrounding agricultural communities, and high *E. coli* and total coliform counts (Table 3) in protected sites suggested a continued human presence deep within these reserves. In the future, establishing a baseline for streams in the region will be challenging given the unknown land use history and a probable lack of pristine catchments (Harding et al., 1998).

**Conclusions**

Research on the freshwater systems of South Asia is vastly incomplete, but lessons from other regions are clear about the best management strategies for protecting stream and river condition. Best management practices (BMPs) are both structural and non-structural practices for mitigating the deleterious effects that land uses like agriculture or urban areas can have on freshwater systems. The ultimate goal of BMPs is
to have the combined effect of mimicking the conditions of a natural watershed to maintain a natural streamscape. To that end, most BMPs aim to control the amount of sediments and pollutants entering streams through runoff, the timing and velocity of runoff, and water temperature. Sweeney & Blaine (2016) and Sweeney & Newbold (2014) emphasize vegetated riparian buffers as one of the more vital BMPs for stream integrity, with at least 30 m of buffer required for adequate protection of small streams (typically up to 5th order streams). As has been proposed in the United States, BMPs need to be properly incentivized in order to be implemented effectively by many landowners – education and legislation are crucial as well, but not enough (Sweeney & Blaine, 2016). In the case of Bangladesh, the potential loss of production incurred by, say, conversion of 30 m of cultivated riparian area into vegetated buffer would probably necessitate some form of financial compensation or credit, unless the landowner can reap substantial benefits from the riparian area directly. From a public perspective, the indirect societal benefits of BMPs must also be taken into account when considering the potentially prohibitive costs of compensation. For countries like Bangladesh and Bhutan, BMPs could substantially contribute to the public good. Clean freshwater systems make for more productive fisheries, require less investment by downstream water treatment plants, and decrease the potential investment required for tapping groundwater resources amidst polluted surface waters (Hanchett et al., 2014; Price & Mittra, 2016).

A key component of implementing BMPs is ensuring that they actually achieve and maintain their desired effect. If landowners are willing to invest in the continuous monitoring of a BMP in order to confirm its benefits, their behavior should be rewarded more than those who provide no data to back up the effectiveness of their BMP (Sweeney
& Blaine, 2016). The advent of inexpensive, real-time monitoring techniques offers the opportunity to do this on a large scale. No extensive network of this sort currently exists in Bangladesh or Bhutan. Given its inexpensive and straightforward nature, biomonitoring of streams with macroinvertebrates can also fit into this equation as a tool for both public officials and community/citizen science. Within Bangladesh, project partner Naimul Islam and I noticed a consistent lack of knowledge and experience with most aquatic macroinvertebrate groups – even among public officials and professional ecologists – despite their importance in the food chain for many culturally and economically valuable species of fish. The value placed on freshwater fish species in Bangladesh could be a cultural entry point for the adoption of macroinvertebrate biomonitoring techniques in Bangladesh – it seems reasonable to expect that the public would be more receptive to the importance of macroinvertebrates as vital “fish food” rather than for the macroinvertebrates’ own sake.

In Bhutan, the prevalence of Buddhist traditions and values presents a unique opportunity for the use of BMPs and biomonitoring, as they could be viewed as a way to prevent harm to the principal aquatic animal groups of macroinvertebrates and fish. In seeming connection with the Buddhist ethos, a robust urban volunteer community already exists for events like trash pick ups and other data collection measures, which could be tapped for citizen science monitoring and implementation of lower-cost BMPs. The hydrological settings of Bhutan – that of high gradient streams with abundant riffle habitat – also offer the opportunity for use of some of the more established techniques within macroinvertebrate biomonitoring. Additionally, Bhutan’s reputation as an unspoiled “Shangri-La” destination for high-end ecotourism should put the protection of
the country’s waterways as a top priority. Aside from hydroelectric dams, ecotourism is Bhutan’s proverbial cash cow, with the many scenic river valleys acting as premier attractions. Even in a country that has officially shunned traditional measures of economic growth, it must still be shown that conservation pays. Ecotourism in Bhutan certainly does, and maintaining this cash influx will partly depend on how the country manages their waterways and watersheds going forward.

While Bangladesh and Bhutan are particularly distinct in their ecology, topography, and cultural backgrounds, the countries are a microcosm of environmental and freshwater trends occurring throughout other developed and undeveloped portions of South Asia. Modernization, population growth, and recent inclusion into the global economy have brought economic progress (to an extent), but have also taken a severe toll on the ecological integrity of watersheds and, therefore, the streams and rivers that inhabit them. Urban and agricultural areas have come to dominate the watersheds of the vast majority of Bangladesh, while Bhutan’s mostly natural watersheds have only recently come under pressure from urban sprawl, agricultural modernization, and hydroelectric development. The cultural significance of freshwater in each country underscores the opportunities for implementation of BMPs and environmental monitoring of freshwater resources, particularly with established biomonitoring techniques that utilize macroinvertebrates. Undoubtedly, significant challenges exist for the future of freshwater in Bangladesh and Bhutan, but the existing cultural frameworks and emergence of simple monitoring techniques offer opportunities for mitigation and protection.
Works Cited


*Freshwater Biology, 47, 501-15.*
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<tr>
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Table 1. Stream sites sampled in November of 2015 and August of 2016 in Bhutan and August of 2016 in Bangladesh.
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<th>pH</th>
<th>Conductivity (µS/cm)</th>
<th>Dissolved Oxygen (mg/L)</th>
<th>Turbidity (NTU)</th>
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Table 2. Stream sites and water chemistry measured with field meters in August of 2016.
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<th>Land Use/Condition</th>
<th>E. coli (cfu/100 mL)</th>
<th>Total Coliform (cfu/100 mL)</th>
<th>Ammonia (ppm)</th>
<th>Nitrite (ppm)</th>
<th>Nitrrate (ppm)</th>
<th>Phosphate (μM)</th>
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<thead>
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<th>Bangladesh</th>
<th>Land Use/Condition</th>
<th>E. coli (cfu/100 mL)</th>
<th>Total Coliform (cfu/100 mL)</th>
<th>Ammonia (ppm)</th>
<th>Nitrite (ppm)</th>
<th>Nitrrate (ppm)</th>
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Table 3. Stream sites and measurements from field laboratory analyses in August of 2016.
Figures

Figure 1. All 18 sites sampled in western Bhutan in November of 2015 by SWRC. Google Maps.
Figure 2. All 21 sites sampled in both western Bhutan and northeastern Bangladesh in August of 2016. Google Maps.
Figure 3. All 11 sites sampled in western Bhutan in August of 2016. Google Maps.
Figure 4. All 10 sites sampled in northeastern Bangladesh in August of 2016. Google Maps.
Figure 5. Examples of land uses assessed in Bhutan and associated sites pictured: A) Protected forest (BT13 (L) & BT02 (R)), B) Suburban/agriculture (BT08 (L) & BT07(R)), C) Urban (BT14 (L) & BT15 (R))
Figure 6. Examples of land uses assessed in Bangladesh and associated sites pictured: A) Protected forest (BD01 (L) & BD06 (R)), B) Agriculture (BD04 (L) & BD02 (R)), C) Small town/agriculture (BD10)
Figure 7. Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness in relation to three different land use types from 2016 surber sample sites in small streams and large rivers in Bhutan. US = Upstream, DS = Downstream. Error bars are standard error from three surber replicates per site.
Figure 8. Individual richness measures of Ephemeroptera, Plecoptera, and Trichoptera among 2016 surber sample sites in small streams and large rivers in Bhutan. US = Downstream, DS = Downstream. Error bars are standard error from three surber replicates per site.
Figure 9. Non-metric Multidimensional Scaling (NMS) ordination showing similarities and differences among 2016 sample sites in Bhutan in relation to water chemistry variables and log-transformed macroinvertebrate taxa counts ($r^2>0.5$).
Figure 10. NMS ordination showing similarities and differences among 2015 (post-monsoon) and 2016 (monsoon) sample sites in Bhutan in relation to presence/absence of macroinvertebrate taxa ($r^2>0.4$). Taxa that were not found at all sites at least twice each year were omitted (11 of 62 taxa omitted).
Figure 11. Macroinvertebrate densities per square meter at nine sample sites in Bhutan. US = Upstream, DS = Downstream. BT13 was excluded because of particularly low densities, despite having been a protected forest site (due likely to the high degree of difficulty of sampling the site because of the very swift current at the site). Error bars are standard error from three surber replicates per site.
Figure 12. Total macroinvertebrate richness and EPT Richness from six sites in Bangladesh. US = Upstream, DS = Downstream. Ecoregions were not explicitly classified but qualitatively differentiated by their underlying geology, topography, and surrounding flora. Error bars are standard error from three samples per method per site, or two samples for each method in the case of BD08.
Figure 13. Percentages of EPT and Chironomidae within samples from six sites in Bangladesh. US = Upstream, DS = Downstream. Ecoregions were not explicitly classified but qualitatively differentiated by their underlying geology, topography, and surrounding flora. Error bars are standard error from three samples per method per site, or two samples for each method in the case of BD08.
Figure 14. Macroinvertebrate densities per square meter across three different ecoregions from both leaf pack and dip-net samples at six sites in Bangladesh. US = Upstream, DS = Downstream. Ecoregions were not explicitly classified but qualitatively differentiated by their underlying geology, topography, and surrounding flora. Error bars are standard error from three samples per method per site, or two samples for each method in the case of BD08.