Mobilizing Young Researchers, Citizen Scientists, and Mobile Technology to Close Water Data Gaps
Methods Development and Initial Results in the Kathmandu Valley, Nepal

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Dissertation

by

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Dr. ir. M.M. Rutten contributed significantly to the realization of this dissertation.

To my father Grant,
my wife Kristina,
and my late colleague Peter-Jules van Overloop –

all of whom share some responsibility
for getting me into this mess in the first place.

Preface

Water. Every living thing depends on it.

It has the power to both nurture life and to take it. To carve mountains and to cool a sweat stained brow.

From every corner of our wonderful planet, water's awesome power is boldly proclaimed: the breathtaking amphitheaters engraved by glaciers; the staggering canyons carved deep by rivers; the fertile deltas formed by the great floods.

Water has and continues to make its mark.

Like nowhere else on the planet, Nepal showcases water's incredible ability to shape the face of the earth. From the towering Himalayas in the north rising to over 8000 meters, to the southern plains, water affects every facet of life for the people living in these rugged lands.

Now man has slowly been making its own mark on water. Though this time the process is happening quicker and the story does not appear to have a happy ending in sight.

The Kathmandu Valley of Nepal is an example of man's mark on water.

Like many burgeoning cities in the rapidly developing world, extreme population growth has led to extensive stress and degradation of water resources. The animals and plants that rely on water for habitat and food have also been deeply affected.

While the issues are apparent to most in the Kathmandu Valley, the extent of the problems are poorly characterized. The first step to solving any problem is developing a thorough understanding of it. In the context of water, this requires significant amounts of data spread out over both space and time.

This dissertation chronicles the journey of the SmartPhones4Water (S4W) and its first pilot project in Nepal called S4W-Nepal. S4W's goal is to generate the data necessary to support wise water management decisions. We accomplish this with our three pronged approach of Research, Education, and Employment.

Normally water data like rainfall, water flow in streams, groundwater levels, and water quality requires permanent sensors, is expensive, and is easily disrupted by

corruption and vandalism. In many places throughout the world this approach has struggled to produce the data water managers rely on to make good decisions.

S4W mobilizes a combination of (1) young researchers, (2) citizen science, and (3) mobile technology to generate water data. S4W's citizen scientists use an Android smartphone application called Open Data Kit or ODK to collect data about water. Advances in mobile technology like high quality GPS and cameras have improved the accuracy and reliability of citizen science observations. All data collected by S4W are open source and freely available, with the aim of encouraging the next generation of Nepali water managers and researchers to collaboratively rise up and face the water challenges before them.

Many parts of the world have huge issues with sustainable water management.

S4W-Nepal is locally led by an enthusiastic team working to characterize the nation's water problems, so that solutions can be developed and successfully applied.

Projects come and go; movements last. Together, we can build a movement focused on wise stewardship of Nepal's remarkable water resources, so that future generations of Nepal may enjoy the life giving power of *water*.

With a bit of luck, and lots more hard work, S4W might even grow from its humble beginnings in Nepal to a global network of young researchers and citizen scientists sharing a passion for taking better care of the only water we've got. Only time will tell.

Regardless of the outcome, this project has my blood, sweat, passion, and tears all over it. I have learned so much through this adventure and trust that a few others have done the same along the way.

I must also make one practical matter clear. From the very start, S4W has been a team effort. Regardless of whether the collaboration came from my family, colleagues in Nepal, California, The Netherlands, or elsewhere, it always was there. It is safe to say that the project has "our" blood, sweat, and tears all over it. However, since this is my dissertation and I am the sole author of Chapters 1, 7, and 8, I will use the singular first person pronoun "I" as necessary, even though the plural "we" seems more appropriate.

I hope you enjoy reading this dissertation as much as I enjoyed living and writing it.

Jeffrey Colin Davids
Delft, May 2019

Summary

Data gaps as educational opportunities - mobilizing young researchers, citizen scientists, and mobile technology in data and resource scarce areas. This dissertation chronicles these themes through the lessons learned along the fledgling journey of SmartPhones4Water (S4W) and S4W-Nepal, from inception through the first few years of implementation. S4W mobilizes young researchers and citizen scientists with simple field data collection methods, low-cost sensors, and a common mobile data collection platform that can be standardized and scaled. S4W's ultimate goal is to improve lives by strengthening our understanding and management of water. If thoughtfully done, this process of filling data and knowledge gaps in data and resource scarce regions can also serve to improve the quality and applicability of young researchers' and citizen scientists' education. S4W's first pilot project, S4W-Nepal, initially concentrated on the Kathmandu Valley, and is now expanding into other regions of the country. S4W-Nepal facilitates ongoing monitoring of precipitation, stream and groundwater levels and quality, freshwater biodiversity, and several short-term measurement campaigns focused on monsoon precipitation, land use changes, stone spout flow and quality, streamflow, and stream-aquifer interactions. This research contains both methodological components that investigate novel methods for generating hydrometeorological data (Chapters 2 through 4), along with initial applications of these methods to answer specific science questions (Chapters 5 and 6).

Chapter 2 investigates the likely impacts of less frequent citizen science-like observations of streams on estimates of minimum flow, maximum flow, and runoff. The results showed that temporally intermittent observations of stream levels and streamflow can still be informative, especially for estimates of minimum flow and runoff. In general, as watershed flashiness decreases and storage ratio increases, the reliability of minimum flow, maximum flow, and runoff estimates obtained from low frequency observations increases. Considering daily observations from watersheds in California that were most similar to Nepal (n = 31), the mean percent error in runoff estimates was 1.9 %.

Chapter 3 explores whether citizen scientists can perform accurate measurements of streamflow using simple methods and equipment and materials that are both inexpensive and locally available. The results showed that the salt dilution method, compared to the float and Bernoulli methods, consistently yielded the most accurate streamflow data for experts and citizen scientists alike. For citizen scientists, mean absolute percent error was 28 % with a mean percent error (or bias) of 7 %. Recording videos of electrical conductivity (EC) breakthrough curves in Open Data Kit (ODK) provided a simple and flexible interface for capturing high temporal resolution EC data with a range of smartphones and EC meters. Additionally, photographs and GPS coordinates of salt dumping and EC measurement

locations provided sufficient meta data to quality control the observations.

Chapter 4 analyzes S4W's 2018 monsoon measurement campaign, whereby citizen scientists (n = 154) measured precipitation with low-cost S4W soda bottle precipitation gauges. The analysis included a collocated evaluation of the low-cost S4W gauge, a comparison of the effectiveness of different recruitment and motivational methods, the performance of citizen scientists, and the resulting costs per observation. The year-long collocated comparison found that the low-cost gauge errors were relatively small (i.e. -2.9 %) compared to the standard 203 mm (8-inch) Department of Hydrology and Meteorology (DHM) gauge used in Nepal. Citizen scientists recruited via random site visits, social media, and outreach programs (listed in decreasing order) took significantly more measurements than those recruited via personal connections. Payment was the only categorization (i.e. not gender, education level, or age) that caused a statistically significant difference in the number of measurements per citizen scientist, and was therefore an effective motivational method. Analyzing photographs of each observation revealed that 91 % of citizen scientists' observations were accurate, and the remaining 9 % required correction. Importantly, it was the inclusion of photographs along with citizen scientist observations that enabled characterization and correction of these human errors. Measurements could be performed for as low as 0.07 and 0.30 USD for volunteers and paid citizen scientists, respectively. Median cost per observation was 0.47 USD for both volunteers and paid citizen scientists.

Chapter 5 looks at the impacts of land-use on water quality in the Kathmandu Valley. The methods leveraged the same synergies between young researchers and mobile technology. Land-use maps were generated with a combination of insitu and remotely sensed observations. Deteriorations in water quality, as determined by an integrated sensory and macroinvertebrate approach (i.e. Rapid Stream Assessment or RSA), correlated most strongly with increases in built land-uses. Upstream locations of six of the nine watersheds investigated had near natural status (i.e., river quality class (RQC) 1), however, downstream RSA measurements for all nine watersheds had RQC 5 (i.e., most highly impaired). RSA results showed statistically significant correlations with measurements of electrical conductivity and dissolved oxygen. Insitu land-use observations have now been repeated four times by S4W-Nepal citizen scientist campaigns. One recommendation, explored in greater detail in Section 7.3.3, is to evaluate the feasibility of developing a simplified RSA approach for citizen scientists.

Chapter 6 explores pre- and post-monsoon stream and shallow groundwater levels and water quality to understand stream-aquifer interactions in the Kathmandu Valley. The data suggested that streams transition from predominantly losing in the pre-monsoon (88 % of sites) to predominantly gaining in the post-monsoon (69 % of sites). Preliminary results suggested that streams transition back to losing relatively quickly after monsoon ends. Stream and shallow groundwater quality had statistically significant positive correlations, suggesting that poor stream water quality negatively impacted shallow groundwater quality. Spatially, stream and shallow groundwater quality deteriorated from upstream to downstream (in agreement with Chapter 5); this relationship was stronger in pre-monsoon compared to

post-monsoon.

Chapter 7 sketches a road map of next steps in case anyone decides to pick these questions and ideas up and push them a bit further along the way. The reality was, as is the case in much of life, that the answers to the questions posed in Chapters 2 through 6 often led to more new questions. This chapter, therefore, serves as a compilation of research ideas and questions specific to the Kathmandu Valley relating to either further analyses of data already collected, or new data collection activities. For each question, there is a brief reflections on background and context, followed by a statement of the key research question(s). Preliminary reflections are also offered on data and methodology that could be used to address each question. The hope is that these questions will ultimately lead someone to pick them up, dust them off, and get to work.

The results of this dissertation suggest that young researchers and citizen scientists can and should be systematically mobilized with a common mobile data collection platform to help close water data gaps. Leveraging smartphones to generate appropriate meta data for each observation (e.g. photographs) and consistently using these meta data to make corrections to raw measurements are keys to ensuring high quality observations. Importantly, all data generated by young researchers and citizen scientists should be openly shared. Some significant challenges include the identification of sustainable funding, ensuring sufficient data quality, and long term continuity of data records. Despite these challenges, there appears to be much potential for turning data gaps into educational opportunities.

Moving these ideas from concept to reality will require broad support and collaboration from (1) water managers and researchers (key consumers of data) and (2) science educators and young researchers (key producers of data). Practically, this means that every science educator should consider systematically recording the data generated by young researchers as part of their academic training and coursework. Also, water managers should consider the un-leveraged potential of young researchers to generate significant amounts of water data. Cross-cutting organizations facilitating such efforts (e.g. S4W) can help to link young water-related researchers across a swath of academic institutions related to environmental science, agriculture, engineering, forestry, economics, sociology, urban planning, etc., thereby encouraging young researchers to contribute to relevant and multidisciplinary research topics. Ultimately, these young researchers can then become the champions of engaging citizen scientists in the communities where they grew up, live, research, and work. Currently, S4W continues to develop and refine these ideas in Nepal, in addition to launching new projects in the Netherlands (S4W-NL) and California (S4W-CA) in 2019 to further evaluate and scale this approach.

Contents

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Introduction

The first essential step in the
Direction of learning any subject
Is to find principles of numerical reckoning
And practicable methods for measuring
Some quality connected with it.

Lord Kelvin

Data gaps as educational opportunities - mobilizing young researchers, citizen scientists, and mobile technology in data and resource scarce areas. This dissertation chronicles these themes through the lessons learned along the fledgling journey of SmartPhones-4Water (S4W) and S4W-Nepal, from inception through the first few years of implementation. S4W focuses on mobilizing young researchers and citizen scientists with simple field data collection methods, low-cost sensors, and a mobile data collection platform that can be standardized and scaled. The ultimate goal is to improve our understanding and management of water through filling data and knowledge gaps in resource and data scarce regions, while improving the quality and applicability of young researchers' efforts. S4W's first pilot project, S4W-Nepal, initially concentrated on the Kathmandu Valley, and is now expanding into other regions of the country. S4W-Nepal facilitates ongoing monitoring of precipitation, stream and groundwater levels and quality, freshwater biodiversity, and several short-term measurement campaigns focused on monsoon precipitation, land use changes, stone spout flow and quality, streamflow, and stream-aquifer interactions. This research was quite applied in nature, in that it was performed from the very start with the goal of improving our understanding of the Kathmandu Valley water balance.

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1.1. Water Data Gaps

Lord Kelvin was right. We cannot understand, much less manage, the things we do not measure. When it comes to our world's precious and finite natural resources, if we aim to wisely steward them, we must first learn to measure them. Despite growing demand, the amount of water data actually being collected continues to decline in several parts of the world, especially in Africa, Latin America, Asia, and even North America ([1], [2], [3], [4]). Specifically, there is an acute shortage of water data in headwater catchments [5] and developing regions [6]. The reasons for this trend are various, but the situation is perpetuated by a lack of understanding among policy makers and citizens alike regarding the importance of water data, which leads to persistent funding challenges ([7], [8]). This is further compounded by the reality that the hydrological sciences research community has focused much of its efforts in recent decades on advancing modeling techniques, while innovation in methods for generating the data these models depend on has been relegated to a lower priority [9]. We have some significant water data gaps on our hands.

1.2. Data Gaps As Educational Opportunities

Professional scientists working to understand and manage water resources are often faced with significant shortages of data in both space and time. While they often know what, where, when, and how to generate these data, they lack the resources (human, economic, etc.) to close water data gaps. The world round, millions of young researchers (generally students ranging from secondary levels through graduate school) also need data for their education and research work, and gain important experience in the field by being the ones to collect it. In contrast, however, these young researchers have capacity to generate data, but often lack the necessary understanding of what, where, when, and how to contribute. Moreover, scientists and young researchers alike struggle with issues of data generation, management, quality control, data sharing, and ownership.

There are essentially two fundamental and related issues here. First, water managers and scientists find it increasingly more difficult to rightfully perform their tasks because of growing or persistent data gaps. Second, young researchers, because of a disconnectedness from practicing managers and scientists, do not progress in their practical learning and research as they might otherwise. Is it possible that these data gaps could be turned into educational and research opportunities, thereby helping to solve both issues simultaneously? Moreover, can this collaboration between scientists and young researchers be carried out in a way that increasingly involves the general public as well? These are the motivating questions of this dissertation.

1.3. Citizen Science

Citizen science (or CS) - a rapidly growing global movement - has the potential to link these themes of scientists, young researchers, and participation of the general

public. Most broadly, citizen science can be defined as the general public actively participating in scientific research [10]. Citizen science can involve communities defining research questions and methodologies to performing monitoring, analyzing data, interpreting results, and modifying management practices and policies. Citizen science can include community based monitoring [11] and or community based management [12]. Citizen science is on the rise in the USA [11], Canada [13], and in many other areas around the world ([14], [15]). Ongoing developments in sensing and mobile technology, data processing and analysis, and methods of data and knowledge communication continue to open novel opportunities for citizen science ([16], [4]). In particular, recent advances make smartphones a perfect tool for citizen science ([17], [18]). GPS and high resolution camera technology embedded in smartphones can be used to collect verifiable records in the field, and cellular networks can be leveraged to transmit collected data to a central repository.

1.4. SmartPhones4Water

1.4.1. Young Researchers + Citizen Scientists + Mobile Technology

With these themes in mind, SmartPhones4Water (S4W) was created in 2013 to mobilize young researchers, citizen science, and mobile technology to improve lives by strengthening our understanding and management of water. S4W focuses on simple field data collection methods and low-cost sensors that can be standardized and scaled so that young researchers and citizen scientists can help fill data gaps in data scarce regions, while improving the quality and applicability of local water related research. In an effort to generate the data water managers need and strengthen education for young researchers, SmartPhones4Water (S4W; [19], [20], [21], [22]) aims to link young researchers with scientists, and the relevant data gaps they delineate. S4W does this by providing a collaboration space and technology platform that links the respective strengths of scientists (i.e. know how) and young researchers (i.e. time and enthusiasm), respectively. The process can be embedded at the community scale by leveraging citizen science. Once young researchers incorporate hydrometric observations into their own education and research, they can in turn champion the involvement of community members as citizen scientists in their respective local contexts. To support long term data collection, it is also critical that academic institutions responsible for development of curricula and outputs for these young researchers be fully supportive of, and integrated into, this approach.

1.4.2. SmartPhones4Water-Nepal

In order to ground-truth these concepts, S4W launched its first project in Nepal - SmartPhones4Water-Nepal (S4W-Nepal) - in 2016. In many ways, this dissertation explores the lessons learned from S4W-Nepal's journey, from inception through the first few years of implementation in Nepal. S4W-Nepal is a young researcher led effort generating open access data about the quantity and quality of Nepal's water resources. S4W-Nepal facilitates ongoing monitoring of precipitation, stream and groundwater levels and quality, freshwater biodiversity, and several short-

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term measurement campaigns focused on monsoon precipitation, land use changes, stone spout (Nepali: dhunge dhara) flow and quality, and now streamflow. Starting in the Kathmandu Valley, S4W-Nepal has engaged over 50 young researchers and nearly 400 citizen scientists in order to generate and analyze data to improve our understanding and management of water. These young researchers have joined S4W-Nepal by being a part of short research campaigns during school breaks, as part of their educational curricula, in order to fulfill the research requirements of their degrees, or out of sheer interest, wonder, and appreciation of their country's remarkable water resources.

1.4.3. The S4W-Nepal Team

Through S4W-Nepal, this dissertation has involved hundreds of young researchers and citizen scientists. Our core team of passionate young researchers carries out the day to day activities of recruiting and motivating citizen scientists, quality controlling data, exploring sustainable business models, developing local partnerships, disseminating research findings in locally relevant and accessible ways, managing and developing S4W-Nepal's technology platform, and guiding other young researchers along the way. Currently (spring of 2019), this core team is organized into seven groups:

1. Streamflow and environmental stream health assessment (Flow-ESHA) led by Ms. Anusha Pandey;

2. Groundwater led by Mr. Rajaram Prajapati;

3. Precipitation, land use change, and evapotranspiration (Precip-LUC-ET) co-led by Mr. Amber Bahadur Thapa and Ms. Anusha Pandey;

4. Technology platform development led by Mr. Saujan Maka;

5. Citizen scientist management and data quality control (CS-Mgmt-Data-QC) led by Mr. Eliyah Moktan;

6. Education and outreach led by Mr. Anurag Gyawali; and

7. Strategic planning and networking led by Mr. Rajaram Prajapati.

S4W-Nepal has the pleasure of working with two promising interns: Ms. Surabhi Upadhyay and Pratik Shrestha. Together, this team continues to dream about, implement, and refine how S4W's vision can be applied to Nepal's benefit. While their hard work and enthusiasm immediately benefits Nepal, and all the citizen scientists and young researchers they are working with, it is also provides a model and template for the benefit of other similar data and resource scarce settings, along with the broader citizen science community.

1.5. The Kathmandu Valley

1.5.1. Overview

While S4W-Nepal's activities have slowly started to expand, the majority of the work described in this dissertation focuses on the Kathmandu Valley (Valley; Figure 1.1) of Nepal. As such, S4W-Nepal's methods have focused on generating data that will help answer some of the Valley's pressing water management questions. The Valley is a small intermontane basin roughly 25 km in diameter with a total land area of 587 km^2 in the Central Region of Nepal. Population in the Valley has increased significantly in the last 25 years [23], with official estimates of somewhere between 2.2 and 2.5 million people living in one of the three major districts of Kathmandu, Lalitpur, and Bhaktapur ([24], [25], [26]). Once a lacustrine environment, the Valley floor has a generally mild southerly slope and contains relatively deep and fertile deposits of gravels, sands, silts, and clays, from north to south ([27], [28]). These soils, and increasingly the underlying groundwater system, support wide-scale agriculture within the Valley, consisting primarily of rice, corn, vegetables, and other cereals.

1.5.2. Hydrology

The Valley is principally drained by the Bagmati River, whose headwaters originate at the perennial springs on the southeastern slopes of Shivapuri Peak (Figure 1.1. Nine other historically perennial tributaries join the Bagmati River, prior to it exiting the southwestern edge of the Valley near Chobar. Elevations in the Valley range from 1260 m near Chobar, to 2780 m at Phulchowki Peak, the headwaters of the Godawari River. Precipitation patterns are dominated by the South Asian monsoon, with 80 % of precipitation occurring between June and September [29]. Due to the topography of the Valley, and the strong south to north monsoonal air movement, there are large precipitation gradients from rain shadow and orographic effects on the southern and northern portions of the Valley, respectively (Insert reference from Soda Bottle Science). The hydrogeologic setting of the Valley is discussed in Section 6.1.2.

1.5.3. Water Crisis

Climate change is expected to have a substantial impact on the Himalayan region, however, the magnitude and extent of these impacts are still poorly understood [31]. Within the Ganges watershed, uncertainty in future precipitation and growth in population and economic activities are anticipated to have the largest affects on future water availability [32].

Due in part to uncontrolled population growth and a lack of integrated land-use and water resources planning, the Kathmandu Valley currently suffers from both water quantity and quality crises. Ongoing rural to urban migration coupled with uncontrolled urban expansion into the fringes surrounding the historically populated areas is increasing demand for water, intensifying discharge of untreated wastewater discharged to streams, and reducing recharge potential for the progressively stressed underlying aquifer system [28]. These rapid land use changes are having
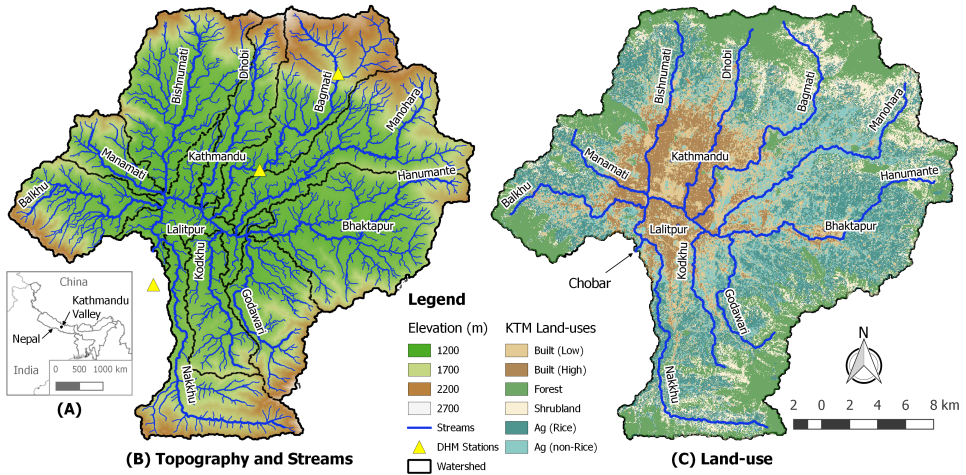
Figure 1.1: Map showing (A) location of Nepal and Kathmandu, (B) topography of the Kathmandu Valley from a Shuttle Research Telemetry Mission [30] Digital Elevation Model (DEM) and resulting stream network [20], and (C) land-use. Approximate locations of the three metropolitan areas labeled (i.e. Kathmandu, Lalitpur, and Bhaktapur). Locations of the three Department of Hydrology and Meteorology (DHM) stations in the Valley shown along with the point where the Bagmati River exists the Valley (Chobar). Names of the 10 historically perennial watersheds are labeled.

large impacts on the Valley's hydrology and water supply [33]).

In the Kathmandu Valley (Valley), groundwater provides a critical source of water for domestic, industrial, agricultural, and environmental uses [28]. Shrestha et al. [28] estimate that groundwater provides roughly 50 % of the Valley's water supply during the monsoon, and roughly 60 to 70 % during the subsequent dry period [34]. The recent rates of population growth in the Valley have far outpaced the ability of the public-private partnership (PPP) Kathmandu Upatyaka Khanepani Limited (KUKL) to design, construct, and maintain adequate water and sanitation infrastructure. Additionally, even where KUKL drinking water service is available, the frequency of availability and water quality is often poor. For example, some parts of the KUKL service area only receive water for an hour or two each week. Starting in earnest in the 1980s, as an alternative to KUKL water service, many companies and private parties drilled both shallow and deep wells, and now rely on groundwater as their primary water source [28]. Additionally, groundwater has the benefit of always being accessible, assuming an energy source for abstraction is available, and short-term well yields within the Valley are generally sufficient to meet pumping demands.

1.5.4. Unsustainable Groundwater Use

Groundwater, at both regional and global scales, is an increasingly mismanaged resource [35]. This has been confirmed by insitu measurements, remotely sensed observations, and numerical models ([36], [37], [38], [39]). Geographically, groundwater overdraft is often concentrated in areas with intensive irrigated agriculture

or dense urban and industrial land uses ([40], [41]). Unsustainable groundwater development can lead to several undesirable results including: chronic lowering of groundwater levels, reductions in groundwater availability, intrusion of saline water, degradation of water quality, land subsidence, and depletions of interconnected surface waters such as springs, lakes, and streams [42].

In the Kathmandu Valley, before large scale extraction from the groundwater system began, the shallow aquifer was full, and streams were predominantly gaining throughout the Valley floor. This led to historically higher streamflow, especially during the eight month dry season (i.e. October), as infiltrated monsoon rainwater discharged slowly discharged back to the stream in a sustaining annual cycle. Initially, as groundwater withdrawals began, water was removed from shallow aquifer storage. As pumping intensified, capture of groundwater discharge to streams increased. At some point, all of groundwater discharge to streams was captured, and Δh transitioned from positive to negative, so that pumping started to induce recharge from streams (i.e. artificially losing streams). This sequence of impacts from increased groundwater pumping - from storage removal, to captured discharge, to induced recharge - was first outlined by Theis [43]. Now, though the Valley's streams appear to be gaining for at least a portion of the monsoon and post-monsoon, the majority of the year pumping captures all historical discharge to streams and now induces additional recharge from streams. This coupled with the facts that (1) monsoonal recharge has been reduced by hardscaping and (2) most streams are fully diverted for water supply when they transition from natural to agricultural or built land uses has led to the extensive occurrence of artificially ephemeral streams in the Valley. During the dry season, these dry streams often don't start flowing again until untreated wastewater is discharged back into the stream. Unfortunately, many of these undesirable results of unsustainable groundwater use are already being observed in the Kathmandu Valley.

The reality of mismanaged groundwater on a global scale, the critical nature of groundwater resources as a freshwater supply to Nepal, and the Kathmandu Valley's extreme dependence on groundwater for urban, agricultural, and industrial uses, all serve to underscore the importance of improving our understanding of the various fluxes and stores of water in the Valley. While many of the data necessary to help answer these questions was developed during this dissertation, the main focus was an exploration of the potential roles of young researchers, citizen science, and mobile technology in the data generation and interpretation process.

1.6. Data Generation Efforts

1.6.1. Mobile Data Collection Platform

Through this work, S4W developed an open source technology platform leveraging Open Data Kit (ODK) Collect, ODK Aggregate, MongoDB, and Python to collect, store, quality control, and disseminate water data collected by young researchers and citizen scientists (Figure 1.2). ODK Collect runs on nearly any Android based smartphone. Smartphones - which become more ubiquitous each day, even in the most rural corners of Nepal - provide a suite of tools that can greatly improve

the reliability of data collected in the field. GPS sensors can be used to know where measurements are from. High resolution cameras can be used to provide transparent and auditable records of observations. GSM or CDMA radios can be used to transmit information to a central location in near real-time.

Data are collected in the field by young researchers and citizen scientists using ODK Collect. Blank and completed ODK Collect forms are downloaded from, and submitted to, ODK Aggregate (running on Google App Engine), respectively. When ODK Aggregate receives a new submission it processes the data, stores it in a Google Cloud Datastore, and publishes it to a JSON server. The published JSON data are received by a custom Python web application (webapp) running on a Google Cloud Compute instance. The webapp contains (1) structured MySQL meta data about sites, projects, users, and citizen scientists; (2) raw collections of ODK form submissions organized into form groups, and (3) processed and quality controlled data that contains updated information about the site and citizen scientist that collected the data. Additionally, the webapp has a number of Python functions that are called automatically by a chrono loop that moves data from the raw to processed collections and performs other important updates. The general public (and young researchers and citizen scientists) can interact with and download the data via the public webapp (data.smartphones4water.org). S4W staff can quality control and manage the data, manage workflow, and generate customized reports via a private password protected portion of the webapp (admin.smartphones4water.org). All ODK forms used during the S4W-Nepal project can be accessed here: https://github.com/jcdavids/s4w-nepal-odk.git. The ODK community maintains excellent documentation and a lively forum accessible here: https://docs.opendatakit.org/ and here: https://forum.opendatakit.org/, respectively.

1.6.2. Overview of Data Collection

S4W-Nepal identified six key areas for data collection (Figure 1.3). The focus of data collection was on developing repeatable methods for application in other contexts, while at the same time generating useful data for local research and management purposes. All of our methods had an emphasis on young researchers, citizen science, low-cost sensors, and mobile technology. S4W-Nepal's data collection activities are organized into both (1) ongoing monitoring efforts and (2) short-term measurement campaigns.

Measurement Campaigns

S4W-Nepal organized several different focused measurement campaigns repeated at different frequencies. From May through September (2017 and 2018), annual monsoon measurement campaigns with a focus on the Kathmandu and Pokhara Valleys were facilitated. S4W-Nepal plans to expand monitoring into other areas of Nepal in future monsoons. Chapter 4 provides additional details about S4W-Nepal's monsoon rainfall measurement campaign in 2018. S4W-Nepal organized three measurement campaigns bi-annually (twice a year) in the pre- and post-monsoon in coordination with local colleges and universities. First, citizen science streamflow
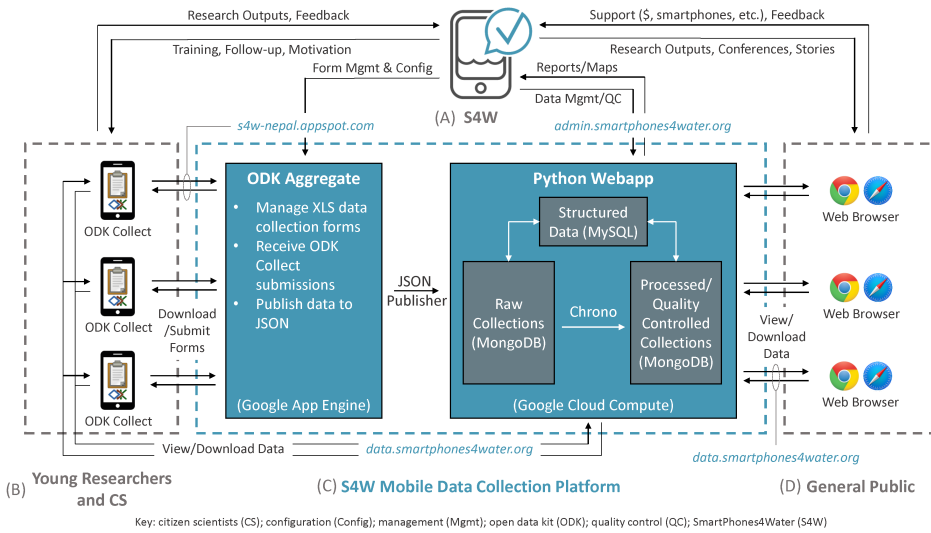
Figure 1.2: Diagram of S4W mobile data collection platform including four basic components: (A) S4W (including S4W-Nepal), (B) Young Researchers and Citizen Scientists, (C) S4W's Mobile Data Collection Platform, and (D) the General Public. The thicker dashed lines represent components (B), (C), and (D), respectively. Arrows represent the direction of interactions between components and text describes their nature.
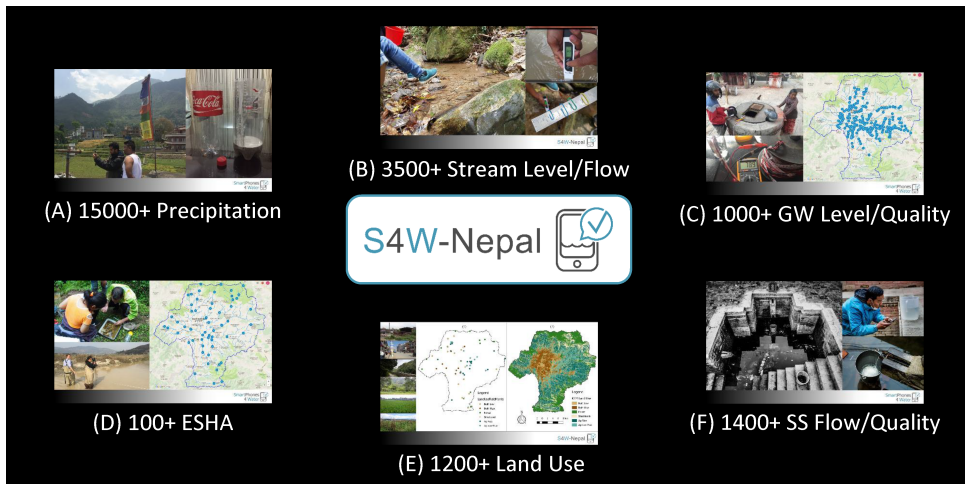
Figure 1.3: Summary of S4W-Nepal data collection activities, including: (A) precipitation; (B) stream flow, level, and quality; (C) groundwater level and quality; (D) environmental stream health assessment (ESHA); (E) land cover and land use; and (F) stone spout flow and quality. ESHA is based on the Rapid Stream Assessment (RSA) protocol discussed in Chapter 5. Stone spouts - an ancient water supply source for inhabitants of the Kathmandu Valley - are an important feature of the Kathmandu Valley from both a water supply and cultural perspective.

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(CS Flow) started in 2018 pre-monsoon, and focused on generating high resolution stream and spring flow data in the headwater catchments of Nepal, starting with the Kathmandu Valley. Second, in pre-monsoon 2017 S4W-Nepal launched a stone spout (dhunge dhara or 2D) campaign focusing on measuring flow and electrical conductivity of stone spouts within the Kathmandu Valley. Finally, S4W-Nepal organized a bi-annual land use change (LUC) campaign in order to generate georeferenced ground based observations of land use and land cover. These data were then combined with remotely sensed images to develop pixel based coverages to improve understanding of how land use and land cover is changing over space and time, especially within the Kathmandu Valley due to population growth and ongoing industrialization.

Ongoing Observations
S4W-Nepal facilitates, and in some cases performs, several ongoing data collection efforts. Within the Kathmandu Valley, S4W-Nepal directly performs the following measurements: daily precipitation at five sites, monthly streamflow at 15 sites, monthly biomonitoring at 5 sites, and quarterly stream-aquifer water level and quality at stream sites with adjacent hand-dug shallow wells. Additionally, within the Valley S4W-Nepal facilitates citizen scientists to continue the following ongoing measurements: daily precipitation at 10 sites, weekly water levels at 10 sites, and monthly groundwater levels at 30 sites.

1.7. S4W-Nepal Citizen Scientists
1.7.1. Summary
As of the spring 2019, there were 370 participants in the S4W-Nepal database, comprised of 72 % volunteers and 28 % paid citizen scientists. 10 % of the participants were less than or equal to 18 years old, while the remaining 71 % and 16 % were between 19 and 25, and over 25 years old, respectively. Regarding education level, 23 % of the participants had the equivalent of a high school degree or less, 66 % were working towards or have obtained a Bachelor's degree, and 9 % have finished or were enrolled in graduate studies. This reflects the fact that most effort was invested into recruiting Bachelor's aged students. This also reflected the relatively high education rates of S4W-Nepal participants, and highlights the challenges of involving citizens with less education and overall low science proficiency in citizen science projects. Out of the 370 citizen scientists, 61 % were male and 39 % were female. Occupationally, 81 % were students, 2 % were involved in full-time agriculture, and 14 % had other occupations.

1.7.2. Recruitment Methods
Citizen science projects rely on citizens. As such, the success of any citizen science project relies at least partly on successful citizen recruitment and engagement efforts. Citizen scientists were recruited for the monitoring campaigns with a variety of methods including:

1. Leveraging personal relationships;

2. Posts on social media;

3. Outreach programs at schools and colleges; and

4. Random site visits.

While discussed in greater detail in Chapter 4 in the context of our 2018 monsoon expedition, these same recruitment methods were used more broadly to recruit citizen scientists and young researchers to join the S4W-Nepal project.

1.7.3. Motivation Methods
Once a citizen scientist has been successfully recruited it is critical to motivate their continued involvement. Previous studies have shown that appropriate and timely feedback is a key motivation factor for sustaining citizen science ([44], [16], [45], [46]). S4W-Nepal motivated citizen scientists with a variety of actions including:

1. Personal follow-ups via SMS, phone, and site visit;

2. Bulk SMS messages personalized for each citizen scientist;

3. Workshops;

4. Use of the data;

5. Lucky draws;

6. Certificates of involvement; and

7. Payment in certain cases.

The way these motivations were applied depended on the specific parameter being observed and the context of the respective citizen scientists. However, two basic combinations of motivations for (1) young researchers (motivations 1 through 6) and (2) rural citizen scientists (motivations 1, 2, and 7) were used. These motivations are discussed in greater detail in Chapter 4; although the original context is 2018 monsoon expedition monitoring, these same motivation efforts were used more broadly throughout the S4W-Nepal project.

1.8. Aims and Goals
The overall goal of this thesis was to explore the opportunities to fill water data gaps by mobilizing young researchers and citizen scientists along with mobile technology and low-cost sensors. Filling data gaps is a critical step towards systematizing water data in support of improved integrated water resources management [47]. This goal was carried out in the context of desiring to leverage underutilized sources of information to constrain the water budget of the Kathmandu Valley. Chapters 2, 3, and 4 focus on the development, evaluation, and implementation of new data collection methods and low-cost sensors for measuring streamflow and precipitation (Figure 1.3). Chapters 5 and 6, however, focus on answering specific science questions

relating to the influence of land-use on water quality and stream-aquifer interactions (Figure 1.4) using methods similar to those explored in the earlier chapters. While the data generated in these earlier - more methodologically focused - chapters are likely helpful for improving our understanding of the Kathmandu Valley's water situation, the analysis and documentation of these findings will be explored in subsequent work. For example, see Chapter 7 for an outline of key next steps that could be taken to generate meaningful outputs for the Kathmandu Valley from these data.
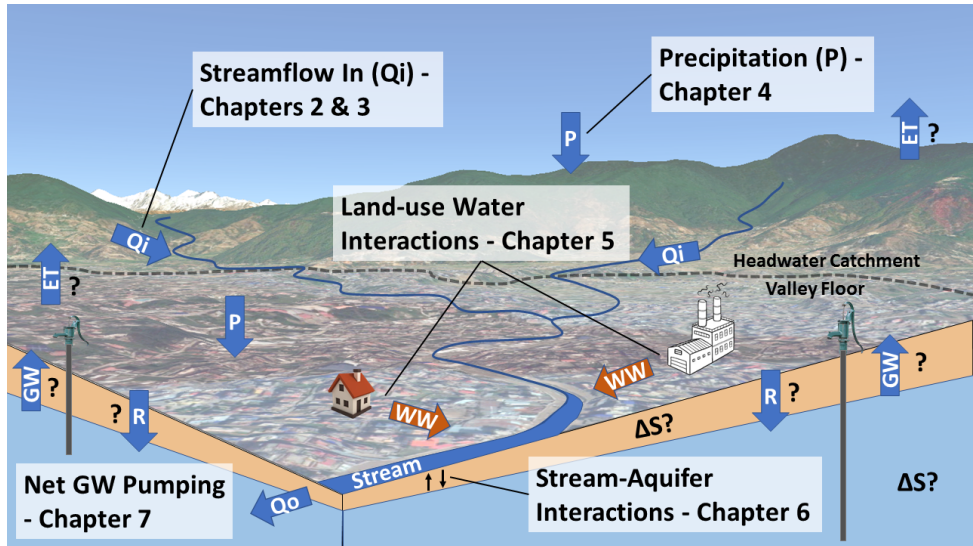
Figure 1.4: Schematic of Kathmandu Valley water balance fluxes and interactions explored in this dissertation. Streamflow in and out of the Valley floor (Qi and Qo, respectively) are explored in Chapters 2 and 3. Precipitation (P) is explored in Chapter 4. The linkages between land-use and water, including waste water return flows (WW) from urban and industrial land-uses (shown with brown arrows) are discussed in Chapter 5. Stream-aquifer interactions are characterized in Chapter 6. A suggested methodology for quantifying net groundwater pumping is described in Sections 7.2.2 and 7.2.3. Evapotranspiration (ET) was not explicitly explored, but is strongly driven by land use, which is discussed in Chapter 5. Recharge (R) was also not directly explored, however, future S4W-Nepal campaigns should focus on characterizing infiltration rates of different land uses. The unsaturated zone is shown in tan with the saturated aquifer shown in blue below. Change in storage terms (ΔS) are included for the unsaturated zone and the aquifer. The delineation between the headwater catchment areas, which contain most of the natural land-uses (see Figure 1.1), and the Valley floor, which is predominantly urbanized, is indicated with a dashed gray line. The base image was obtained from Google Earth Pro. The snow capped mountains in the background are the Ganesh Himal to the northwest of the Valley.

The following summarizes the context and main research questions addressed in Chapters 2 through 6.

- Chapter 2 - Streams and springs provide essential water for people and the environment. To manage these systems, we need data (e.g. water level and streamflow) to understand how these streams change over both space and time. Can citizen science observations of these streams be useful for gener-

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ating the data water managers need to make good decisions? Specifically, how does the temporally intermittent nature of citizen science observations impact our understanding of basic streamflow statistics like minimum flow, maximum flow, and runoff?

- Chapter 3 - Measuring streamflow is a difficult task. Typically streamflow measurements involve expensive equipment used by highly trained staff, which often limits the spatial extent of data collection. Understandably, investments are generally focused on larger streams, often to the neglect of headwater catchments. The resulting data often cannot address smaller scale water management questions, such as how spring flows are changing in response to natural or anthropogenic stressors. Therefore, can citizen scientists perform streamflow measurements themselves using simple methods and inexpensive and readily available materials and equipment? If so, what is the anticipated accuracy of these measurements? Moreover, what are the challenges associated with applying these methods at a larger scale?

- Chapter 4 - Precipitation is the main source of terrestrial freshwater. Precipitation intensity and duration can vary sharply over short distances and time periods, especially in mountainous areas dominated by orographic and convective precipitation mechanisms. In contexts like these, it is difficult to have a monitoring network with sufficient spatial density to capture these small scale heterogeneities. Therefore, can usable precipitation data be collected by citizen scientists using gauges made from recycled materials and open source technology? If so, how can we motivate citizens to start and continue taking measurements? Finally, what are the quality and costs of citizen science measurements?

- Chapter 5 - Land development without thoughtful water supply planning can lead to unsustainability. In practice, management of our lands and waters is often unintegrated. Can water quantity, water quality, ecological stream health, and land use data be collected by young researchers to improve understanding of the longitudinal (i.e. upstream to downstream) linkages between land-use and water quality and quantity? Specifically, how does land use impact water quality and quantity during the monsoon and pre-monsoon periods in the Kathmandu Valley? Additionally, is there scope for these data collection activities to be repeated by young researchers in partnership with their academic institutions and citizen scientists?

- Chapter 6 - Depending primarily on geology and the groundwater table, streams can either be gaining (i.e. increasing flow moving downstream) or losing (i.e. decreasing flow moving downstream). These gains and losses impact water quality interactions between the streams and the underlying groundwater system. Therefore, understanding stream-aquifer interactions is critical for sustainable management of groundwater resources. In the Kathmandu Valley, It is especially important to understand this linkage because (1) the streams are used as the primary sewage conveyance system and (2) groundwater is

the primary water supply. Specifically, what is the nature of stream-aquifer interactions in the Kathmandu Valley, and how does this change over space and time? Moreover, can young researchers kick-start stream and groundwater level and quality data measurements with methods that can be continued by citizen scientists?

- Chapter 7 - The reality was, as is the case in much of life, that the answer to one question often led to two new questions. This chapter, therefore, serves as a compilation of research ideas and questions specific to the Kathmandu Valley. Importantly, much of the data necessary to support the exploration of these questions has already been generated. For each question, there is a brief reflections on background and context, followed by a statement of the key research question(s). Preliminary reflections are also offered on data and methodology that could be used to address each question. The hope is that these questions will ultimately lead someone to pick them up, dust them off, and get to work. With any luck, S4W-Nepal (and maybe other instances of S4W) will still be around when this happens to lend a helping hand.

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2

Continuity vs. The Crowd

An experiment is a question
Which science poses to Nature,
And a measurement is the recording
Of Nature's answer.

Max Planck

Hydrologic data has traditionally been collected with permanent installations of sophisticated and accurate but expensive monitoring equipment at limited numbers of sites. Consequently, observation frequency and costs are high, but spatial coverage of the data is limited. Citizen science can possibly overcome these challenges by leveraging easily scaled mobile technology and local residents to collect hydrologic data at many sites. However, understanding of how decreased observational frequency impacts the accuracy of key streamflow statistics such as minimum flow, maximum flow, and runoff is limited. To evaluate this impact, we randomly selected 50 active USGS streamflow gauges in California. We used 7 years of historical 15-minute flow data from 2008 through 2014 to develop minimum flow, maximum flow, and runoff values for each gauge. To mimic lower frequency citizen science observations, we developed a bootstrap randomized subsampling with replacement procedure. We calculated the same statistics, and their respective distributions, from 50 subsample iterations with four different subsampling frequencies ranging from daily to monthly. Minimum flows were estimated within 10 % for half of the subsample iterations at 39 (daily) and 23 (monthly)

of the 50 sites. However, maximum flows were estimated within 10 % at only 7 (daily) and 0 (monthly) sites. Runoff volumes were estimated within 10 % for half of the iterations at 44 (daily) and 12 (monthly) sites. Watershed flashiness most strongly impacted accuracy of minimum flow, maximum flow, and runoff estimates from subsampled data. Depending on the questions being asked, lower frequency citizen science observations can provide useful hydrologic information.

2.1. Background and Introduction

Natural resource managers rely on timely and accurate data to make management decisions. Though water resources for human purposes is one of the most fundamental ecosystem services [2], fundamental data required to adequately manage water resources is often lacking both spatially and temporally ([3], [4], [5], and others). Remarkably, despite the multiple benefits of long term hydrologic records, the amount of river flow data being collected is actually declining in many parts of the world, especially in Africa, Latin America, Asia, and even North America ([6], [7]). The factors leading to this decline are diverse, but include a lack of understanding of the importance of long-term streamflow data, and persistent funding challenges [8]. This lack of information makes it difficult to know how our water systems are changing over time and space due to natural or human activities and to decide what management actions should be taken to either avoid or mitigate undesirable conditions in the present and future. In addition to remotely sensed stream stage and flow measurement techniques ([9]; currently applicable to large rivers only), Citizen Science appears to be a promising methodology for filling these data gaps ([10], [11]).

Citizen Science is the process of involving citizens in the scientific process as researchers [12]. Citizen Science can include community based monitoring [13] and/or community based management [14]. Citizen Science is on the rise in the USA [13], Canada [15], and many other areas around the world ([16], [17]). New developments in sensing technologies, data processing and analysis techniques, and methods of knowledge communication are opening novel opportunities for Citizen Science [2]. In particular, recent advances in mobile technologies make smartphones a perfect tool for Citizen Science. Global Positioning Systems (GPS) and high resolution camera technology embedded in smartphones can be leveraged to collect verifiable records in the field. Cellular networks and the internet can be used to transmit collected data to a central repository.

Conventional methods for collecting hydrologic data depend on fixed deployments of advanced, highly accurate, but costly monitoring equipment installed at limited numbers of monitoring locations [18]. Therefore, observational frequency and expenses are high, but spatial extent of the resulting data is limited. Achieving adequate maintenance of sophisticated equipment can be costly [19], and in developing countries often exceeds local technical and resource capacity. Experience has shown that permanently deployed monitoring equipment is susceptible to corrosion, vandalism, and theft [20].

Applying citizen science to hydrologic data collection (i.e. citizen hydrology) has the potential to overcome these limitations. Fienen and Lowry [11] demonstrated that citizen science water level measurements using text message based reporting can have acceptable errors. Mazzoleni et al. [19] showed that crowdsourced streamflow observations can be integrated into hydrological models to improve flood predictions, and found the accuracy of individual measurements impacted results more than the irregularities in observation assimilation. Rather than using expensive installations at a few points, citizen science leverages mobile technology to gather data at many sites, in a manner that is highly scalable, enabling the produc-

tion of significantly more data than an individual organization possibly could [21]. One of the tradeoffs for increased spatial resolution, however, is reduced temporal resolution.

We were interested in how decreased observation frequency associated with citizen science observations affects the ability to accurately characterize critical streamflow metrics (e.g. runoff). Based on our review of the literature using search terms of streamflow, citizen science/hydrology, subsampling, and sample frequency, we could not identify other previous works addressing this particular theme. While Moss and Tasker [22] used subsampling to evaluate two different hydrological network design technologies in order to maximize regional stream gauge information with limited funding and monitoring period, their subsampling was based on selecting subsets of sites and site-years of data (the entire year) to develop regressions for ungauged basins. Thoreson et al. [23] investigated the relationship between different sampling intervals and water volume calculations, but in the context of irrigation canal systems, where flows are artificially managed to meet irrigation water requirements. One possible explanation for why this theme has not been explored is that existing literature assumes traditional streamflow monitoring approaches will be used, whereby permanent water level or water velocity sensing devices are installed and used to collect samples every 15 minutes (if not more frequently). Perhaps, therefore, it is often implicitly assumed that high frequency data records will be available if one is interested in monitoring streamflow.

An immediate application of this research is to inform monitoring plans for a citizen science campaign in Nepal called SmartPhones4Water-Nepal (S4W-Nepal). At streamflow monitoring locations, low-cost staff gauges are installed, and water level data is collected by local residents with smartphones using an open source Android data collection platform called Open Data Kit (ODK) Collect [24]. Within ODK Collect, each water level observation requires the citizen scientists to enter the water level reading, save the current date, time, GPS coordinates, and take a photograph of the observation. The data are automatically transmitted to a centralized Google Cloud database via ODK Aggregate (see Section 1.6.1 for details). Stage-discharge curves for the selected sites are developed from monthly to bi-monthly observations of discharge with a SonTek FlowTracker Acoustic Doppler Velocimeter (ADV) performed by young researchers (local BSc and MSc science and engineering students). Chapter 3 explores the accuracy of citizen scientist streamflow measurements in greater detail. In addition to the various technical challenges, onsite training, frequent communication, and effective incentivization must also play a central role for the campaign to be successful and sustainable.

The goal of this paper is to evaluate the impacts of decreased observational frequency, which is a primary tradeoff of citizen science observations, on estimates of minimum flow, maximum flow, and runoff. We attempt to meet this goal by performing a subsampling analysis on seven years of data from 50 randomly selected United States Geological Survey (USGS) stream gauges in California. The three hypotheses we further evaluate are: (1) decreased observational frequency will negatively impact accuracy of flow and runoff estimates, (2) the nature of this impact will differ depending on the parameter in question, and (3) there will be

correlations between accuracy of flow and runoff estimates and latitude, water-shed area, Richards-Baker Flashiness Index (R-B Index), and storage ratio (see Section 2.2.3 for details). The following analysis assumed (1) subsampled water level observations were as precise and accurate as continuous USGS records and (2) an equally accurate stage-discharge curve was available for converting water levels to flows. While not addressed in this paper, these simplifying assumptions highlight two important areas where further research is required if citizen science is to help fill the globally widening hydrologic data gap.

2.2. Materials and Methods

2.2.1. Streamflow Data

We compiled an inventory of the 403 streamflow gauging stations (gauges or sites) in the state of California operated and maintained by the United States Geological Survey (USGS) with 15-minute water level and flow data from January 1st 2008 through December 31st 2014. From this inventory, 50 streamflow gauges were randomly selected. For these 50 gauges, we compiled 15 minute records and station metadata including the name, location, and elevation of the gauging station. Figure 2.1 shows the location of the 50 gauging stations labeled by the USGS Station ID or SiteID. Basic information about the 50 gauges is provided as supplemental material to this paper.

2.2.2. Subsampling Procedure

To mimic citizen science observations at a lower observation frequency than the continuous record, we developed a bootstrap randomized subsampling with re-placement procedure to generate randomized subsample datasets from each gauge record. The subsample datasets were randomly selected from the continuous record at average subsample intervals of once a day, every three days, weekly, and monthly. The subsampling procedure was similar to that used by Jones et al. [25] to assess the influence of sampling frequency on total phosphorus and total suspended solid loads. The subsampling algorithms detailed in Equations 2.1 through 2.3 were implemented to develop multiple subsample iterations via sampling with replacement. The subsampling procedure was coded in Python [26], and is available at GitHub at https://github.com/jcdavids/CAFlowSubsample. This procedure was then repeated for 50 iterations to provide additional information about the distributions of the resulting statistics. The following is a description of the subsampling process.

Suppose the original 15-minute time series data set is given by the formula:

$$q_y = [q_y(1), q_y(2), \ldots q_y(r)], \qquad (2.1)$$

where q_y is a vector (i.e. one dimensional matrix) containing records of flow rate for gauging station y from records 1 through r; r is the total number of records in the 15-minute time series for each station. Now suppose that we randomly sample from q_y based on the formula:
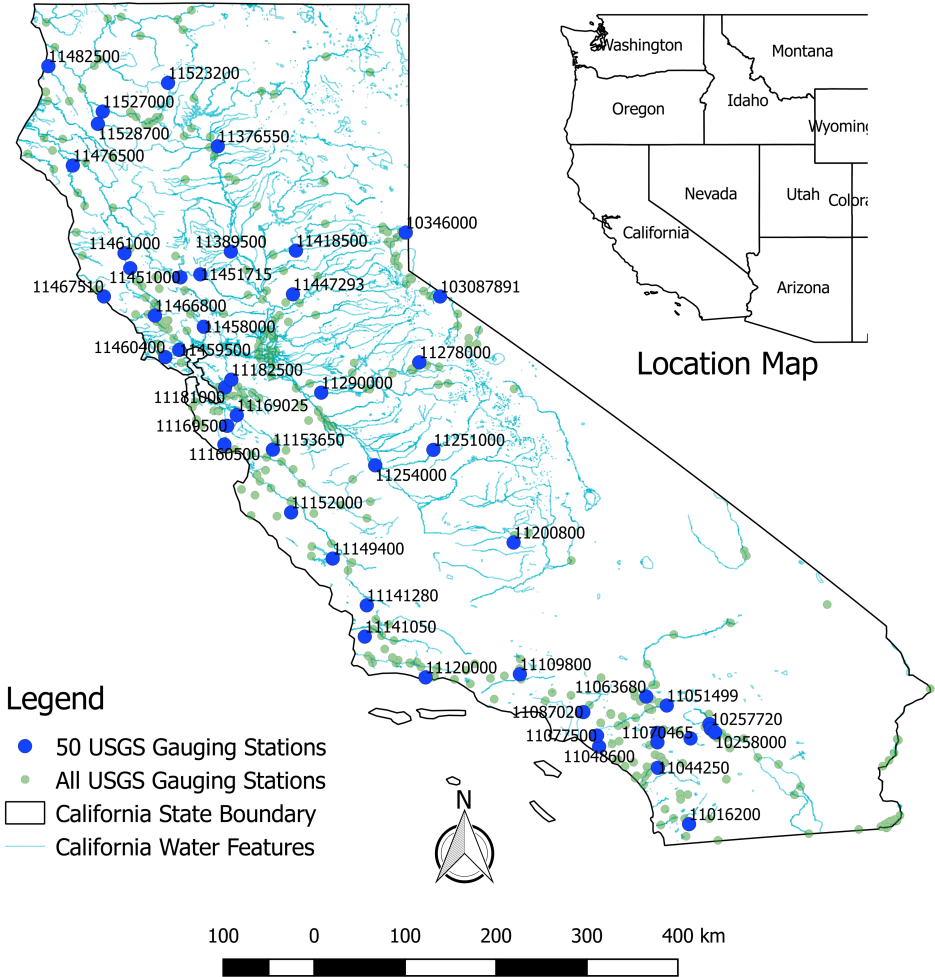
Figure 2.1: Map of California showing 50 randomly selected USGS stream gauging sites. All major waterways in the state are shown in light blue. A location map of the West Coast of the U.S. is also shown on the top right. Subsampled hydrograph results shown in Section 2.3.1 are for the Truckee River Near Farad (SiteID 10346000), which is the northern most site on the California-Nevada border.

$$\mathbf{qss}_{(y,i)} = [q_y(\mathbf{rss}(y,i)[0]), q_y(\mathbf{rss}_{(y,i)}[1]), \dots, q_y(\mathbf{qss}_{(y,i)}[N])], \qquad (2.2)$$

where $\mathbf{qss}_{y,i}$ is the subsample flow vector containing all subsampled records for gauging station y and iteration i. Because we require the subsample to be a random selection with on average even spacing between subsamples, we define the records that should be used for the subsamples used to develop $\mathbf{qss}_{y,i}$ with the formula

where $\mathbf{rss}_{y,i}$ is the subsample record vector containing the randomly selected

records used to develop the subsample flow vector $\mathbf{qss}_{y,i}$. S is the average subsample interval (an even integer) and n is the subsample number ranging from 0 to N. The value of N is given by the formula:

$$N = int(floor(r/S)) - 1. \tag{2.3}$$

The functions int() and floor() select the nearest integer below r/S. For example, if r/S was 83.94, then the combined functions would return 83. RI is a random integer ranging from -S/2 to S/2. Offsetting S/2+n*S by RI ensures that each subsample will be somewhere within the range of S centered about S/2+n*S. In our case, S was set to 96 (daily), 288 (three day), 672 (weekly), and 2922 (monthly). Per the minimum recommended number of bootstrap samples by Efron and Tibshirani [27], 50 iterations (i) of $\mathbf{rss}_{y,i}$ were developed for each gauging station (y) to assess the resulting distributions for minimum flow, maximum flow, and runoff volume.

To summarize the subsampling process: first, we developed subsample record vectors using Equation 2.3 for each gauging station and iteration, and second, we developed subsample flow vectors using Equation 2.2. In total, we developed 2500 subsamples (i.e. y sites times i subsamples, or 50 times 50) for each of the four subsample intervals S, for a total of 10000 subsamples. The average size of each resulting subsample was 2571, 857, 367, and 84 records for daily, three day, weekly, and monthly subsampling intervals, respectively. A sample result of the subsampling procedure is presented in Section 2.3.1 for the Truckee River near Farad (SiteID 10346000).

2.2.3. Comparison Statistics

We compiled the 50 original 15-minute data sets and the 10000 subsamples into Microsoft Access SQL databases. SQL queries were developed to compute normalized statistical comparisons (see Section 2.2.3) for the 15-minute records and subsampled data. In all cases, the flow ratios were aggregated over the entire 7-year period (period) from the beginning of 2008 through the end of 2014. For purposes of comparison and normalization, the actual period minimum flow, maximum flow, and runoff volume for each station was determined from the 15-minute data. As previously stated, each individual subsample observation was assumed to have the same flow measurement accuracy as the original 15 minute observations.

Flow Ratios

A normalized minimum flow ratio between minimum flow obtained from subsampled data for each gauging station (y) and iteration (i) (i.e. $Qmin_{y,i}$) and actual minimum flow from 15 minute record (i.e. $Qmin_a$) expressed as a fraction (i.e. $Qmin_a$ / $Qmin_{y,i}$) was used for comparison purposes. The actual minimum is placed in the numerator so that the minimum flow ratio ranges from 0 to 1.

A normalized maximum flow ratio between maximum flow obtained from subsampled data for each gauging station (y) and iteration (i) (i.e. $Qmax_{y,i}$) and actual maximum flow from 15 minute record (i.e. $Qmax_a$) expressed as a fraction (i.e.

Qmax$_{y,i}$ / Qmax$_a$) was used for comparison purposes. Maximum flow ratio ranges from 0 to 1.

A normalized runoff ratio between runoff calculated from subsampled data for each gauging station (y) and iteration (i) (i.e. $V_{y,i}$) and actual runoff from 15 minute record (i.e. V_a) expressed as a fraction (i.e. $V_{y,i}$ / V_a) was used for comparison purposes. Runoff ratio ranges from 0 to infinity.

In all cases, if the denominator was 0, a value of 1 was returned. Ratios closer to 1 represent better agreement between subsampled data and the original 15 minute records.

Correlation Analysis

A correlation analysis was performed to assess relationships between minimum flow, maximum flow, and runoff ratios and the following variables: (1) latitude, (2) watershed area, (3) the Richards-Baker Flashiness Index and (4) storage ratio. The first three variables were chosen to explore possible geographic, spatial scale, and temporal/magnitude based dependencies, respectively. Storage ratio was selected because of the intuitive relationship between the "flattening" of the hydrograph discussed by Vörösmarty and Sahagian [28] and the flow ratios being investigated. The results of the correlation analysis are presented in Section 2.3.3. Note that there are mathematical dependencies between some variables; Runoff Ratio, R-B Index, and Storage Ratio are each normalized by runoff (further discussed in Section 2.3.3).

The Richards-Baker Flashiness Index (R-B Index) is a unitless value used to quantify the flashiness of a watershed [29]. The R-B Index normalizes fluctuations in flow by the total flow over a given period, so that flashiness between watersheds can be compared. The entire 7-year study period was used for calculating the R-B Index.

Storage ratio is a unitless value calculated as the total usable reservoir water storage upstream of the gauging station divided by average annual runoff measured at the gauging station for the 7-year study period [28]. Usable reservoir water storage was calculated as the sum of the difference between maximum storage volume and dead pool volume for all reservoirs upstream of each gauging station. Storage potential of upstream soils, groundwater systems, and floodplains were not included in the storage ratio. The storage ratio attempts to normalize storage upstream of each gauging station, so that the impacts of reservoir storage can be quantitatively determined and compared among all gauging stations. Note that three storage ratios (SiteIDs 11051499, 11077500, and 11109800) are marked with an asterisk (*). For these three sites, artificially imported water is stored in upstream reservoirs, so the amount of storage available is large compared to natural annual runoff. These three sites are not used in correlation analyses involving storage ratio.

2.2.4. Hypotheses, Visualization Methods, and Evaluation Criteria

Table 2.1 provides a summary of the five visualization methods used in Sections 2.3.2 and 2.3.3, organized by three hypotheses being evaluated. Criteria for eval-

uating each visualization method are provided in the right column.

Table 2.1: Summary of the three hypotheses and five visualization methods used in Sections 2.3.2 and 2.3.3, along with evaluation criteria for each. Additional details for the third (3) hypothesis are presented in the text.

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Hypotheses	Visualization of Results	Evaluation Criteria
(1) Decreased observational frequency will negatively impact agreement between flow ratios computed from subsampled data and the continuous record.	Tabular summary of sites with 50 % of subsamples within ±10 % and ±20 % of actual flow ratios as a function of subsample interval (Table 2.2)	Closer to 50 indicates subsampled data better matches continuous records
	Quad box plots showing flow ratio distributions for all 50 sites for all subsample intervals (Figures 2.3, 2.5, and 2.7)	Closer to 1 indicates subsampled data better matches continuous records
(2) The nature of this impact will be different for each ratio.	Histograms of flow ratios showing site-subsample distributions organized by subsample interval (Figures 2.4, 2.6, and 2.8)	Closer to 1 indicates subsampled data better matches continuous records
(3) There will be statistically significant correlations between the different flow ratios and latitude, watershed area, R-B Index, and storage ratio. *	Tabular summary of Pearson's r values as a function of subsample interval (Table 2.3)	Farther from 0 (i.e. closer to 1 or -1) indicates stronger correlation
	Quad scatter plots of flow ratios as a function of latitude, watershed area, R-B Index, and storage ratio for daily subsample interval only (Figures 2.10 through 2.12)	Visual interpretation for observable trends required

The following are additional sub-hypotheses related to the third (3) hypothesis in Table 2.1.

- Increasing latitude will improve estimates of maximum flow and runoff, but will worsen estimates of minimum flow.

- Increasing watershed area will improve estimates of minimum flow, maximum flow, and runoff.

- Increasing R-B Index will improve estimates of minimum flow, but will worsen estimates of maximum flow and runoff.

- Increasing storage ratio will improve estimates of minimum flow, maximum flow, and runoff.

2.3. Results

2.3.1. Example Subsampled Hydrographs

The subsampling selections and resulting hydrographs for daily, three day, weekly, and monthly subsample intervals are shown on Figure 2.2 for the Truckee River near

Farad (SiteID 10346000) near the California-Nevada state border for May 2010. Shown on each of the graphs (a through d) are (1) the original 15-minute hydrograph (dark blue), (2) the subsampled hydrograph resulting from iteration 1 (red), and (3) the bootstrap randomized subsamples with replacement for each of the 50 iterations (light blue dots). The hydrograph represents a typical spring runoff superimposed with spring precipitation events in the Sierra Nevada mountains. The shorter scale temporal dynamics of the 15-minute hydrograph are progressively lost as the subsample frequency decreases from daily to monthly. For example, the daily subsampled hydrograph shown by the red trace in Figure 2.2 (a) follows the general trends of the 15-minute hydrograph shown in blue. However, the monthly subsampled hydrograph shown by the red trace in Figure 2.2 (d) almost completely misses the peaks and troughs shown in the 15-minute hydrograph.

Each hydrograph can be constructed by (1) selecting a horizontal gridline representing a subsample iteration, and then (2) moving vertically from each light blue dot on the selected subsample iteration gridline until the 15-minute hydrograph is reached. The random distribution of the roughly 1500, 500, 200, and 50 light blue dots respectively, illustrates that the subsampling method described in Section 2.2.2 is providing good subsample randomization.

2.3.2. Flow Ratio Results

Table 2.2 provides a summary of the number of sites that had at least half of the iterations of subsampled flow ratios within ± 10 % and ± 20 % of actual flow ratios for the four subsample intervals evaluated.

Table 2.2: Summary of the number of sites out of the 50 selected with at least half of the iterations (i.e. between the first and third quartile) with subsampled Flow Ratios within ±10 % and ±20 % of actual Flow Ratios for the four subsample intervals evaluated.

Ratio	Subsample Interval (S)	Daily	Three Day	Weekly	Monthly
Min Flow Ratio	Number of Sites Within ±10 %	39	35	31	23
	Number of Sites Within ±20 %	42	38	36	25
Max Flow Ratio	Number of Sites Within ±10 %	7	5	3	0
	Number of Sites Within ±20 %	7	6	6	2
Runoff Ratio	Number of Sites Within ±10 %	44	39	27	12
	Number of Sites Within ±20 %	49	46	43	22

For minimum flow ratio with a daily subsample interval, 39 and 42 of the 50 sites had a 50 % chance that subsampled minimum flows were within ± 10 % and ± 20 % of the actual minimum, respectively. For the monthly subsample interval, 23 and 25 of the 50 sites had a 50 % chance that subsampled minimum flows were within ± 10 % and ± 20 % of the actual minimum, respectively.

For maximum flow ratio with a daily subsample interval, only seven of the 50 sites had subsampled maximum flow within ± 10 % and ± 20 % of the actual maximum. None of the 50 sites had monthly subsampled maximum flows within ± 10 %, and only two were within ± 20 % of actual maximum flows.

For runoff ratio with a daily subsample interval, 44 and 49 of the 50 sites had a
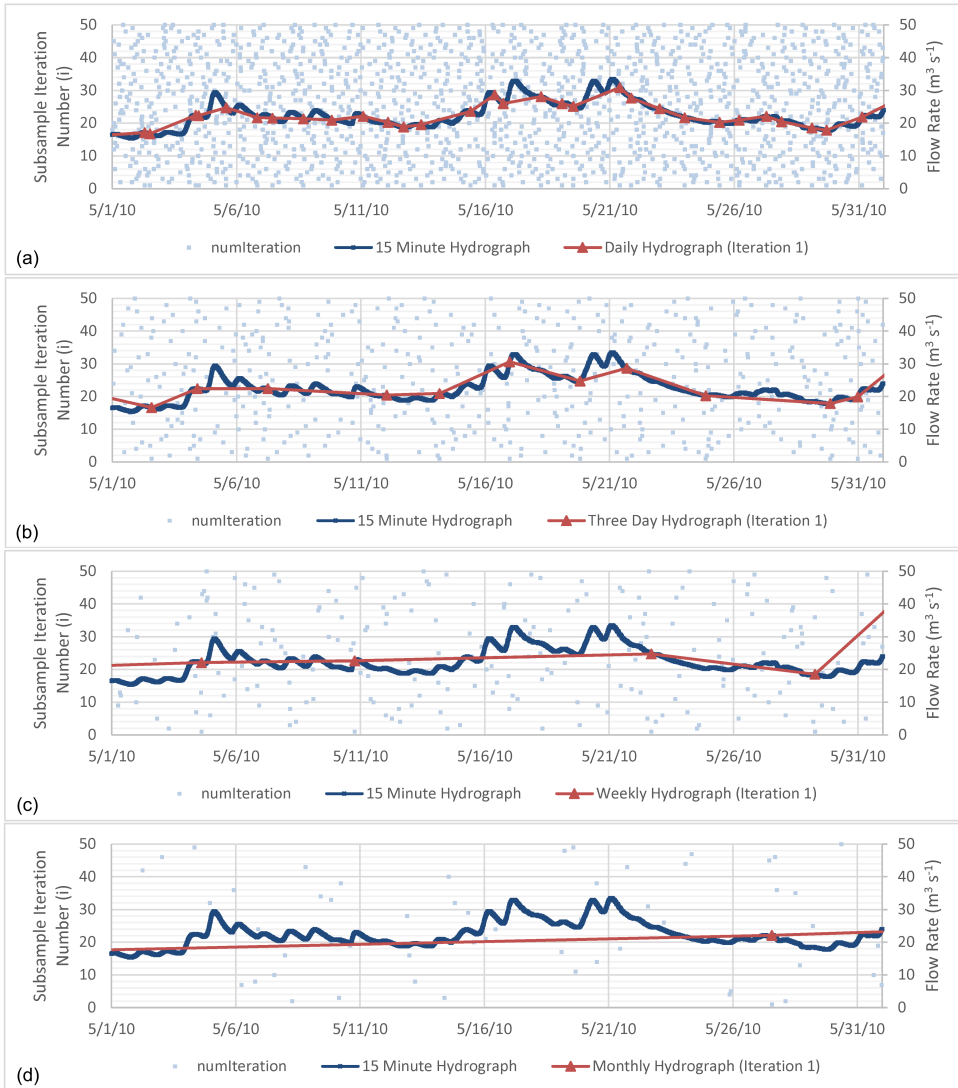
Figure 2.2: Example bootstrap randomized subsamples with replacement for each of the 50 iterations (light blue dots), original 15-minute hydrograph (dark blue), and hydrograph from subsample iteration 1 (red) for the Truckee River near Farad. The horizontal axis displays time, in this case the month of May from 2010. The primary (left) vertical axis displays subsample iteration number (i), and the secondary (right) vertical axis displays flow rate. Each horizontal gridline represents a single subsample iteration from 1 to 50. Each light blue square on the horizontal gridlines represents a datetime selected for the respective subsample iteration. The 30 subsamples that make up the hydrograph for iteration 1 shown as red triangles coincide horizontally, that is with respect to time, with the 30 light blue squares on the first horizontal gridline above the x-axis (i.e. subsample iteration number 1). The data shown is for the (a) daily, (b) three day, (c) weekly, and (d) monthly subsample intervals.

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50 % chance that subsampled minimum flows were within ± 10 % and ± 20 % of the actual runoff, respectively. For the monthly subsample interval, 12 and 22 of the 50 sites had a 50 % chance that subsampled runoff values were within ± 10 % and ± 20 % of actual runoff, respectively.

Minimum Flow Results

Results for minimum flows are shown in Figures 2.3 and 2.4. The distribution of minimum flow ratios, shown as box plots in Figure 2.3, moves progressively towards zero on the vertical axis as the subsample frequency decreases. Notice that the median (interface between light and dark red) minimum flow ratios moved progressively towards zero as the subsample frequency decreased. The closer the points are to 1 on the vertical axis, the better the subsampled data characterizes minimum flows.

A histogram of minimum flow ratios for daily, three day, weekly, and monthly subsample intervals (Figure 2.4) shows non-normal distributions for all subsample intervals. The distributions for all subsample intervals were similar and were more heavily weighted towards the right, but increasingly less so as the subsample interval increases. Nearly 72 % of the site-subsamples pairs (site-subsamples) had a minimum flow ratio greater than or equal to 0.9.

Maximum Flow Results

Results for maximum flows are shown in Figures 2.5 and 2.6. Figure 2.5 shows box plots of the maximum flow ratios. The closer the points are to 1.00 on the vertical axis, the better the maximum flow was characterized. The median (interface between light and dark red), along with the distribution, moved progressively closer to 0 as the subsample frequency decreased. Even with a daily subsample interval, the median maximum flow ratios still ranged between 0.2 and 1.0, with an average of 0.67. This suggests that maximum flows were substantially underestimated, even with daily observations.

Figure 2.6 shows a histogram of maximum flow ratios for daily, three day, weekly, and monthly subsample intervals. The distributions for all subsample intervals were non-normal. The daily subsample distribution was more heavily weighted to the right, with 0.9 to 0.95 and 0.95 to 1.00 containing the highest number of site-subsamples (n = 617 or roughly 25 %). In contrast, the monthly subsample distribution was more heavily weighted to the left, with 0.0 to 0.05 and 0.05 to 0.1 containing the highest number of site-subsamples (n = 915 or roughly 37 %).

Runoff Results

Results for the runoff (volume) are shown in Figures 2.7 and 2.8. Figure 2.7 shows box plots of runoff ratios. The vertical axis scale is locked from 0 to 2, however, for subsample intervals greater than daily, some of the maximum runoff ratios (maximum error bars) were above 2 and are therefore not shown on the plot. The data move progressively farther from 1 as the subsample frequency decreases, indicating that runoff volume estimates became more uncertain as observation frequency
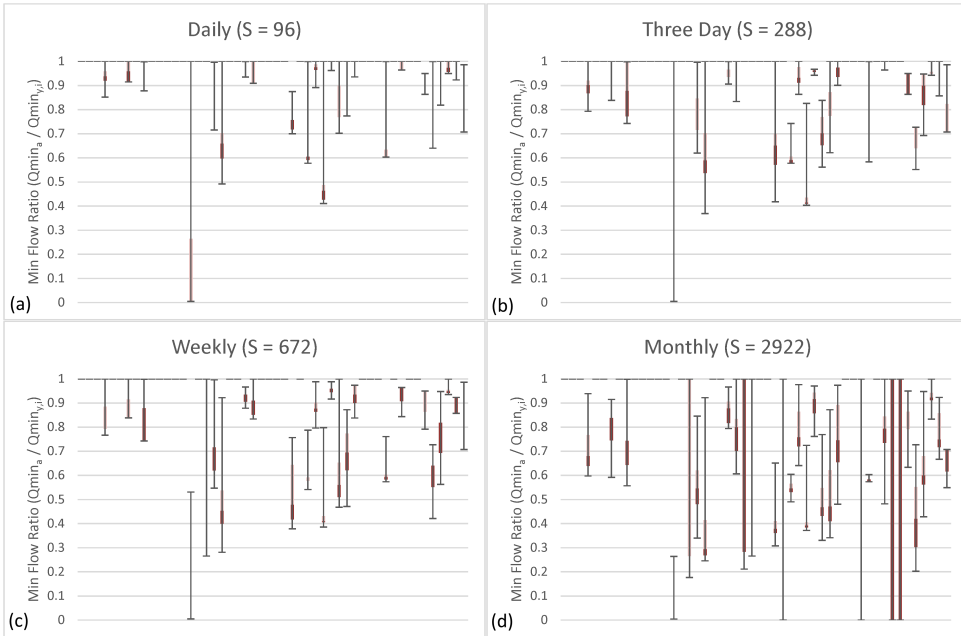
Figure 2.3: Minimum flow ratio between actual minimum flow from the 15 minute record (i.e. $Qmin_a$) and minimum flow calculated from subsampled data for each gauging station (y) and iteration (i) (i.e. $Qmin_{y,i}$) and expressed as a fraction (i.e. $Qmin_a / Qmin_{y,i}$). All minimum flow ratios were calculated for the 7-year period from 2008 to 2014. Data for all four subsample intervals are shown starting from the top left. Each of the four subplots includes box plots for all 50 sites containing the median (Q2; interface between light and dark red), the 1st and 3rd quartiles (Q1 and Q3; bottom of dark red and top of light red respectively), and the minimum and maximum (negative and positive error bars respectively). Note that sites with minimum, Q1, Q2, Q3, and maximum flow ratios equal to 1 are simply shown as a dash at the top of each graph. In cases where either Q1 and Q2, or Q2 and Q3 are coincident, no light or dark red rectangles are visible, respectively. Sites are sorted in ascending order by SiteID.

decreased. The median values (interface between light and dark red) moved increasingly downwards from 1 as the subsample frequency decreased, representing an amplified negative bias in runoff estimates.

There was a systematic negative bias in the runoff estimates, as evidenced by the greater number of sites below 1 than above 1 for all subsample intervals. Runoff was underestimated for 54 %, 54 %, 55 %, and 61 % of site-subsamples for daily, three day, weekly, and monthly subsample intervals respectively. This indicates that the negative bias was stronger as the subsample frequency decreased. This trend is also illustrated by the median being consistently below the 1 runoff ratio line in Figure 2.8, especially as the subsample frequency decreased to weekly and monthly.

Figure 2.9 presents a geographic summary of the subsampling results for runoff. At each location there are four concentric and scaled circles. Daily, three day, weekly, and monthly subsample intervals are shown in light to dark red respectively. The size of the circle corresponds to the maximum from all 50 iterations

	Daily	Three Day	Weekly	Monthly
Mean	0.94	0.91	0.89	0.84
Median	1.00	1.00	1.00	1.00
Stdev	0.12	0.15	0.17	0.21
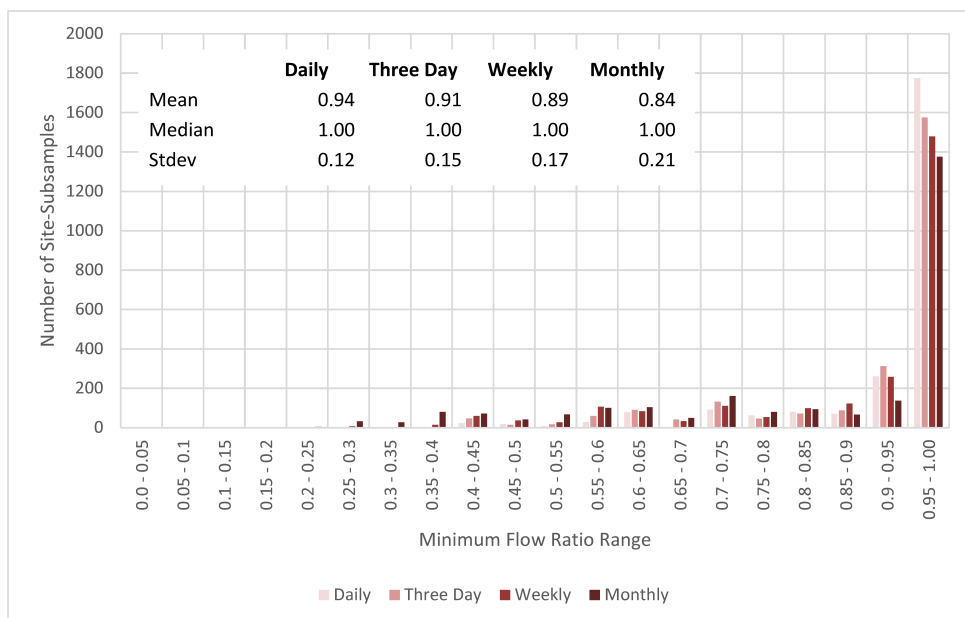
Figure 2.4: Histogram and basic statistics of minimum flow ratios for all four subsample intervals.

of the absolute value of the runoff ratio minus one for the 1st and 3rd quartiles. In other words, there is a 50 % chance that a runoff estimate would be within the displayed fraction of the actual runoff. For example, daily and monthly sub-samples for Atascadero Creek near Goleta (SiteID 11120000) have a 50 % chance of having runoff estimates within 16.8 % (i.e. 0.168) and 76.4 % (i.e. 0.764) of actual runoff respectively. In general, watersheds in the San Francisco Bay Area (e.g. SiteIDs 11182500 and 11181000) and watersheds in Southern California (e.g. SiteIDs 11077500, 11070270, and 11070465) had the highest runoff ratio residuals for all subsample intervals. These watersheds also tend to exhibit greater flashi-ness, as indicated by higher R-B Index values.

2.3.3. Correlation Analysis Results

Figures 2.10 through 2.12 show scatter plots between minimum flow, maximum flow, and runoff ratios, and (1) latitude, (2) watershed area, (3) R-B Index, and (4) storage ratio, respectively. Data are shown for daily sampling frequencies only. The dark red points are average values for each of the 50 sites. The light red points show the 50 iterations for each of the 50 sites. Table 2.3 shows Pearson's r values between average flow ratios (i.e. one value per site; total of 50) and (1) latitude, (2) watershed area, (3) R-B Index, and (4) storage ratio. Pearson's r values were tested for significance with a two-tailed p-value hypothesis test (n = 50, p = 0.05; Table 2.3); statistically significant values are shown with bold and italic font (i.e. Pearson's r > 0.28). Values shown in dark red had mathematical

Figure 2.5: Maximum flow ratio between maximum flow calculated from subsampled data for each gauging station (y) and iteration (i) (i.e. $Qmax_{y,i}$) and actual minimum flow from the 15 minute record (i.e. $Qmax_a$) expressed as a fraction (i.e. $Qmax_{y,i}$ / $Qmax_a$). All maximum flow ratios were calculated for the 7-year period from 2008 to 2014. Data for all four subsample intervals are shown. Each plot contains the median (Q2; interface between light red and dark red), the 1st and 3rd quartiles (Q1 and Q3; bottom of dark red and top of light red respectively), and the minimum and maximum (negative and positive error bars respectively). In cases where either Q1 and Q2, or Q2 and Q3 are coincident, no light or dark red rectangles are visible, respectively. Sites are sorted in ascending order by SiteID.

dependencies between variables (see note under Table 2.3); therefore, significance tests are non-valid, so values have regular font styles.

There were statistically significant correlations between subsampled average minimum flow ratios and latitude and R-B Index; no significant correlations were seen with watershed area and Storage Ratio (Table 2.3 and Figure 2.10). In general, this indicated that minimum flow estimates became more accurate as latitude decreased and as flashiness increased. The strength of the statistically significant correlations increased as the subsample frequency decreased.

There were statistically significant correlations between subsampled average maximum flow ratios and latitude, watershed area, R-B Index, and storage ratio (Table 2.3 and Figure 2.11). In general, this indicated that maximum flow estimates became more accurate as latitude, watershed area, and Storage Ratio increased, and R-B Index decreased. The strength of the watershed area, R-B Index and Storage ratio correlations increased as subsample frequency decreased. In contrast, the strength of the correlation with latitude decreased as subsample frequency decreased.
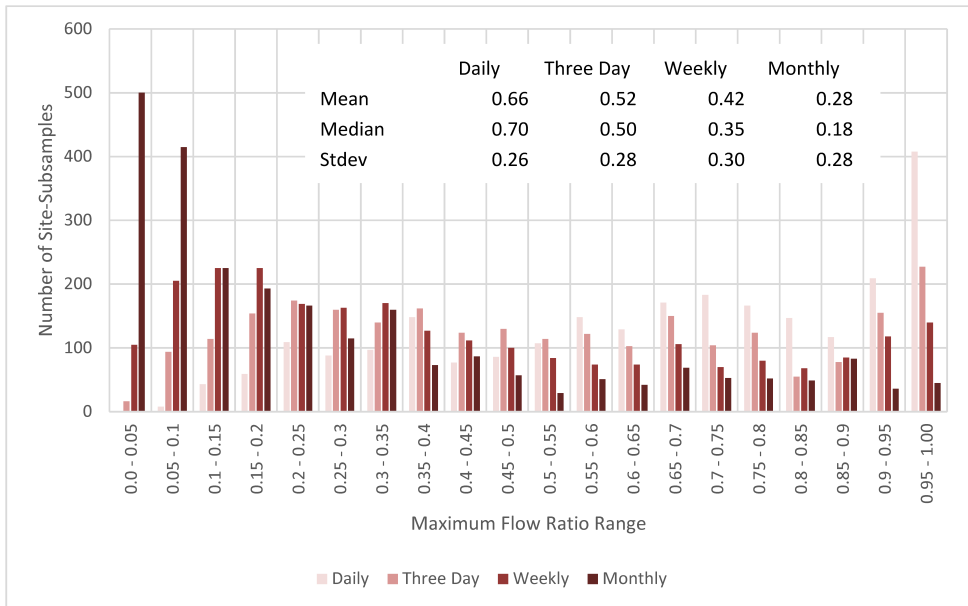
Figure 2.6: Histogram and basic statistics of maximum flow ratios for all four subsample intervals.

There were statistically significant correlations between subsampled average runoff ratio and latitude (Table 2.3 and Figure 2.12; see note below Table 2.3). In general, this indicated that runoff estimates became more accurate as latitude increased. The strength of this correlations was relatively unaffected by decreased subsample frequency.

2.4. Discussion

Accurate streamflow statistics of minimum flow, maximum flow, and runoff often form the basis of sound water resource management and planning. Assuming (1) subsampled water level observations are as precise and accurate as continuous observations and (2) an equally accurate stage-discharge curve is available for converting water levels to flows, this analysis indicates that lower frequency observations of stream stage and flow can be useful, and could play a role in hydrologic data generation. The utility of lower frequency data depends largely on what the ultimate use(s) of the data are. Table 2.4 provides a summary of the discussion organized by the hypotheses presented in Table 2.1.

One limitation of our approach was the assumption that citizen science spot measurements of water level or stage could be converted to flow with the same accuracy as 15 minute continuous USGS records. Much of the challenge of streamflow monitoring lies precisely in the conversion from stage to flow, or the development of the stage-discharge rating curve [30]. For example, many of the USGS rating curves implicitly utilized in this analysis were developed by trained hydrometric pro-
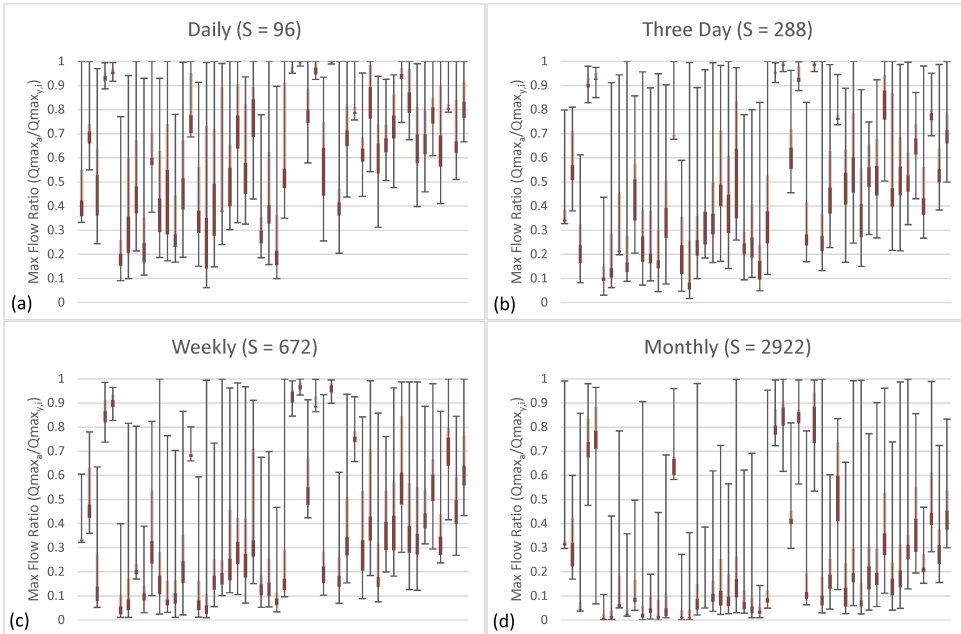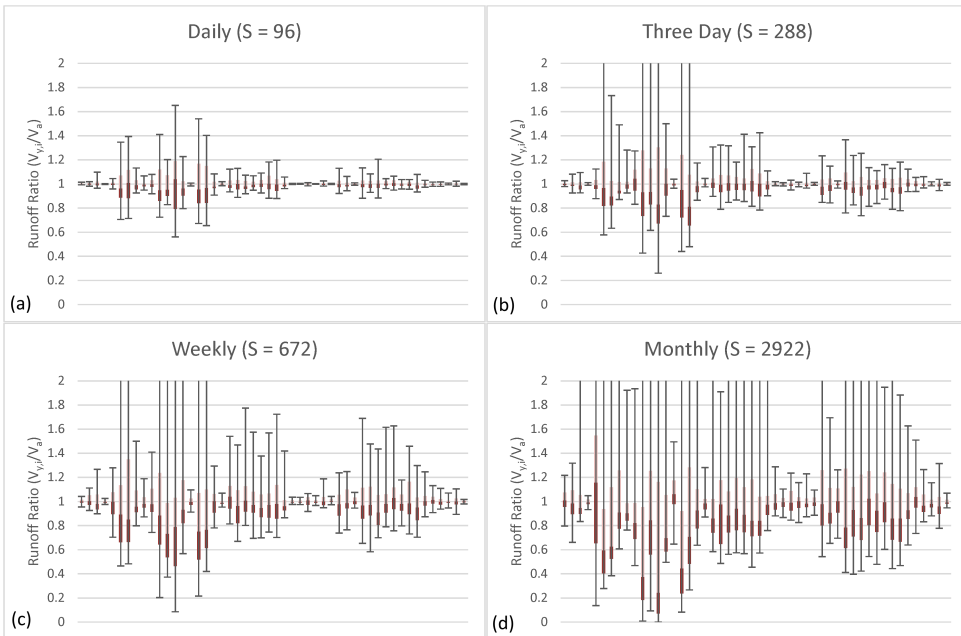
Figure 2.7: Runoff ratio between runoff calculated from subsampled data for each gauging station (y) and iteration (i) (i.e. $V_{y,i}$) and actual runoff from 15 minute record (i.e. V_a) expressed as a fraction (i.e. $V_{y,i} / V_a$). Both runoff values are calculated for the 7-year period from 2008 to 2014. Data for all four subsample intervals are shown. Each plot contains the median (Q2; interface between light and dark red), the 1st and 3rd quartiles (Q1 and Q3; bottom of dark red and top of light red respectively), and the minimum and maximum (negative and positive error bars respectively). Sites are sorted in ascending order by SiteID.

fessionals using sophisticated and expensive equipment over the course of several decades. In addition to uncertainties in water level observations, the discussion about citizen science should also focus on understanding uncertainties in rating curves ([31], [32], [33], and others), focusing on those developed from infrequent observations, or on new methods for citizen scientists to accurately observe streamflow directly. The associated uncertainties with these new methods will need to be assessed to capture the comprehensive uncertainties of citizen science data.

2.4.1. Minimum Flow

Estimates of minimum flow discussed in Section 2.3.2, as compared to maximum flow and runoff (Sections 2.3.2 and 2.3.2 respectively), were the least sensitive to changes in subsample intervals. Because minimum flows tend to persist for longer timescales, they were estimated within 10 % for half of the subsample iterations at 39 (daily) and 23 (monthly) of the 50 sites. There were statistically significant correlations between subsampled average minimum flow ratios and latitude and R-B Index. Precipitation in California has a positive correlation with latitude. We suggest that the observed negative correlation between latitude was due to north-to-south
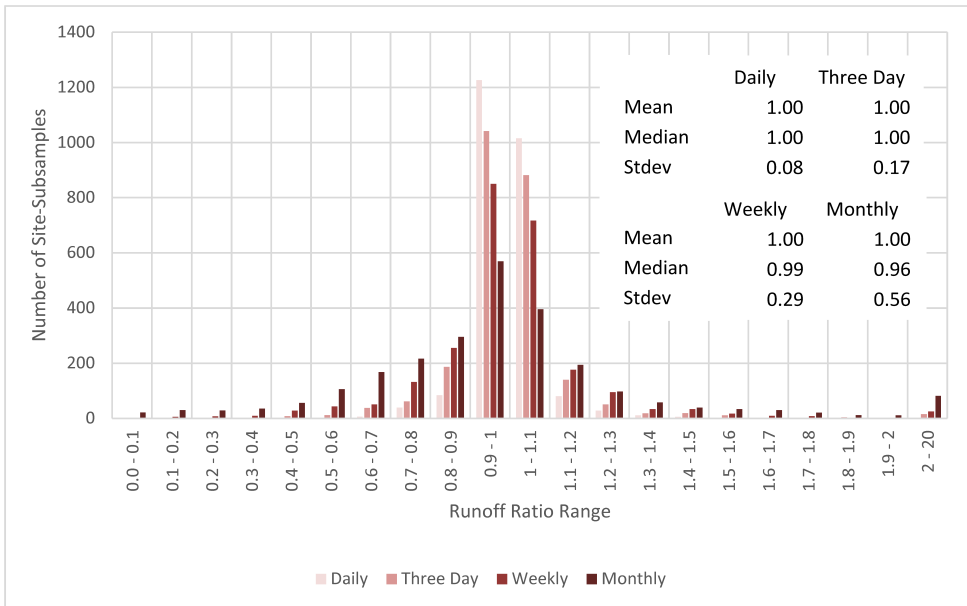
Figure 2.8: Histogram and basic statistics of runoff ratios for all four subsample intervals.

trends in precipitation, resulting in fewer ephemeral streams and more variable minimum flows as latitude increases. Subsampled measurements are most likely to characterize minimum flows for ephemeral streams, or streams that normally go dry for at least certain parts of the year. Streams that run dry also typically have a higher flashiness index.

2.4.2. Maximum Flow

Because maximum flows occur only briefly, it is unlikely that reliable maximum flow estimates (Section 2.3.2) will be obtained from subsampled measurements with average observation intervals of daily or greater. For example, maximum flows were estimated within 10 % for half of the subsample iterations at only 7 (daily) and 0 (monthly) sites. This is consistent with Cheviron et al. [34] who found that only observation intervals that are smaller than the characteristic time period of fluctuations in the variable of interest tend to ensure reliable approximations. Therefore, if the primary monitoring objective is developing data for water resources infrastructure design, whereby maximum flows are required as design criteria, we suggested either (1) variable observation frequency based citizen science (e.g. it is raining so go take measurements; see Section 2.4.4) or traditional continuous stream gauging methods. Our results also indicate that a simple mechanical maximum level gauge with a manual reset similar to that discussed by Bragg et al. [35] could be an important addition to citizen science flow monitoring sites if maximum water levels and flows need to be assessed. There were statistically significant correlations between subsampled maximum flow ratios and latitude, watershed area, R-B Index,
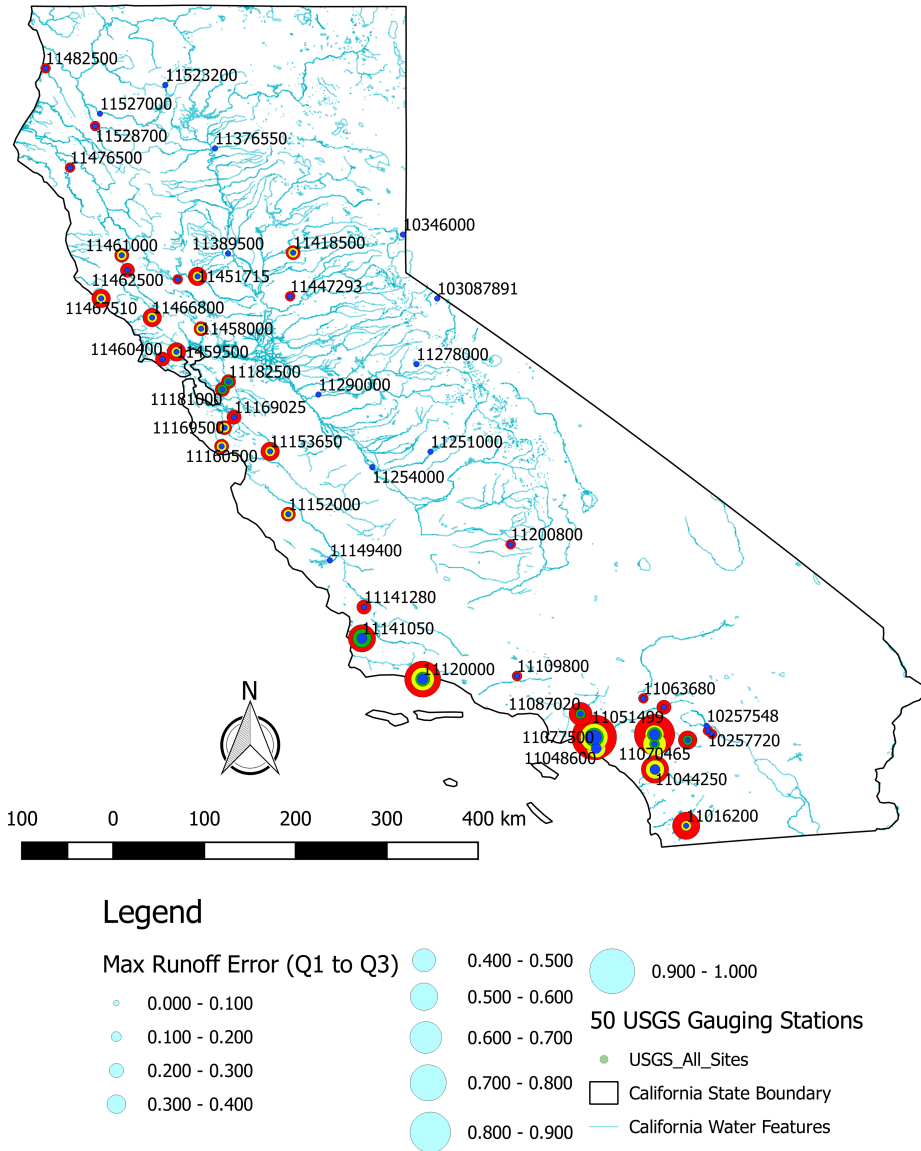
Figure 2.9: Map figure of 50 USGS stream gauges labeled with USGS Station ID. At each location, there are four concentric and scaled circles. The circles are scaled by maximum runoff error (i.e. maximum of the runoff ratio residuals) within the 1st and 3rd quartiles from the 50 subsample iterations. Daily, three day, weekly, and monthly subsample intervals are shown in blue, green, yellow, and red respectively.

and storage ratio (Table 2.3 and Figure 2.11). The strongest correlations were be-

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Table 2.3: Pearson's r values (i.e. correlation coefficients) between average flow ratios and (1) Latitude (decimal degrees), (2) Watershed Area (km^2), (3) R-B Index (unitless), and (4) Storage Ratio (unitless). Data used from all 50 sites for all four subsample intervals. Statistically significant (two tailed; p = 0.05) Pearson's r values shown in **bold** font. * Values shown in *italics* have mathematical dependencies between variables; Runoff Ratio, R-B Index, and Storage ratio are each normalized by runoff. Therefore, *italic* values cannot be compared to non-italic values, but can be compared in a relative sense to other *italic* values. Note that statistical significance is also impacted by this dependency.

Ratio	Subsample Interval	Latitude	Watershed Area	R-B Index *	Storage Ratio *
Min Flow Ratio	Daily	**-0.36**	0.03	**0.33**	-0.01
	Three Day	**-0.37**	0.04	**0.36**	-0.02
	Weekly	**-0.37**	0.04	**0.37**	-0.06
	Monthly	**-0.42**	0.01	**0.41**	-0.08
Max Flow Ratio	Daily	**0.47**	**0.41**	**-0.58**	**0.43**
	Three Day	**0.42**	**0.49**	**-0.59**	**0.53**
	Weekly	**0.37**	**0.52**	**-0.62**	**0.54**
	Monthly	**0.30**	**0.55**	**-0.62**	**0.54**
Runoff Ratio *	Daily	**-0.51**	-0.21	*0.90*	*-0.30*
	Three Day	**-0.49**	-0.21	*0.92*	*-0.28*
	Weekly	**-0.49**	-0.23	*0.91*	*-0.28*
	Monthly	**-0.52**	-0.26	*0.93*	*-0.20*

Table 2.4: Summary of discussion organized by hypotheses.

Hypotheses	Discussion of Results
(1) Decreased observational frequency will negatively impact agreement between flow ratios computed from subsampled data and the continuous record.	Decreased observational frequency negatively impacted minimum flow, maximum flow, and runoff ratios calculated from the subsampled data as compared to the original 15 minute USGS record (Table 2.2 and Figures 2.3 through 2.8).
(2) The nature of this impact will be different for each ratio.	The nature of this impact was different depending on the flow ratio in question. Maximum flow ratio was least sensitive to changes in observational frequency, whereas runoff ratio was most sensitive, with minimum flow ratio being moderately sensitive (Table 2.2 and Figures 2.3 through 2.8).
(3) There will be statistically significant correlations between the different flow ratios and latitude, watershed area, R-B Index, and storage ratio.	There were statistically significant correlations between some average flow ratios and latitude, watershed area, R-B Index, and storage ratio, with R-B Index having the most significant correlation with maximum flow (Table 2.3 and Figures 2.10 through 2.12).

tween maximum flow ratios and R-B Index, followed closely by storage ratio and watershed area. One of the strongest controls on the timescales of the rainfall-runoff relationship is watershed area. All else being equal, larger watersheds have more temporally damped runoff responses, and vice versa. Additionally, significant reservoir water storage (i.e. high storage ratio) can drastically affect stream hydrographs, with one of the significant impacts being a "flattening" of the hydrograph [28]. This "flattening" of the hydrograph increases chances of characterizing maximum flows with lower frequency observations, especially as observation frequency
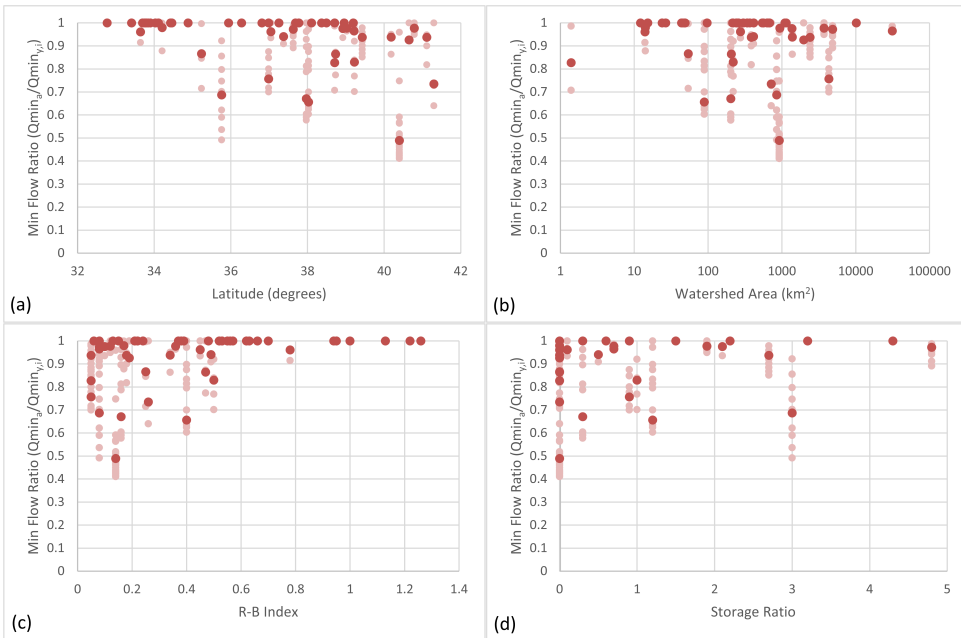
Figure 2.10: Scatter plots of Minimum Flow Ratio as a function of (a) Latitude (decimal degrees), (b) Watershed Area (km^2), (c) Richards-Baker Flashiness Index (R-B Index), and (d) Storage Ratio. Average data for all 50 sites shown in dark red; data for all 50 iterations shown in light red. Storage Ratio calculated as the upstream usable reservoir storage divided by the mean annual runoff for the study period. Data shown for the daily subsample interval only.

decreases. Therefore, these results were congruent with our intuitions, and are similar to those discussed by Horowitz et al. [36].

2.4.3. Runoff

Runoff volumes were estimated within 10 % for half of the iterations at 44 (daily) and 12 (monthly) of the 50 sites. The systematic negative bias in runoff estimates that increased as the subsample frequency decreased is congruent with the findings of Coynel et al. [37]. Data assimilation could be helpful to correct for these biases (see Section 2.4.5). For daily observations on streams with average flows greater than 0.2 m3 s-1, or storage ratios greater than one, runoff was estimated within 20 % (except for one site) and 10 % respectively for half of the subsample itera-tions. There were statistically significant correlations between subsampled runoff residuals and latitude and watershed area (Table 2.3 and Figure 2.12). There are mathematical dependencies between runoff ratio and R-B Index and storage ratio, because each are normalized by runoff. Therefore, Pearson's r for these relation-ships should not be directly compared to other Pearson's r values. Additionally, statistical significance is also impacted by this dependency. Since runoff residuals closer to zero indicate more accurate characterizations of runoff, negative corre-lations with latitude, watershed area, and storage ratio suggest runoff estimates
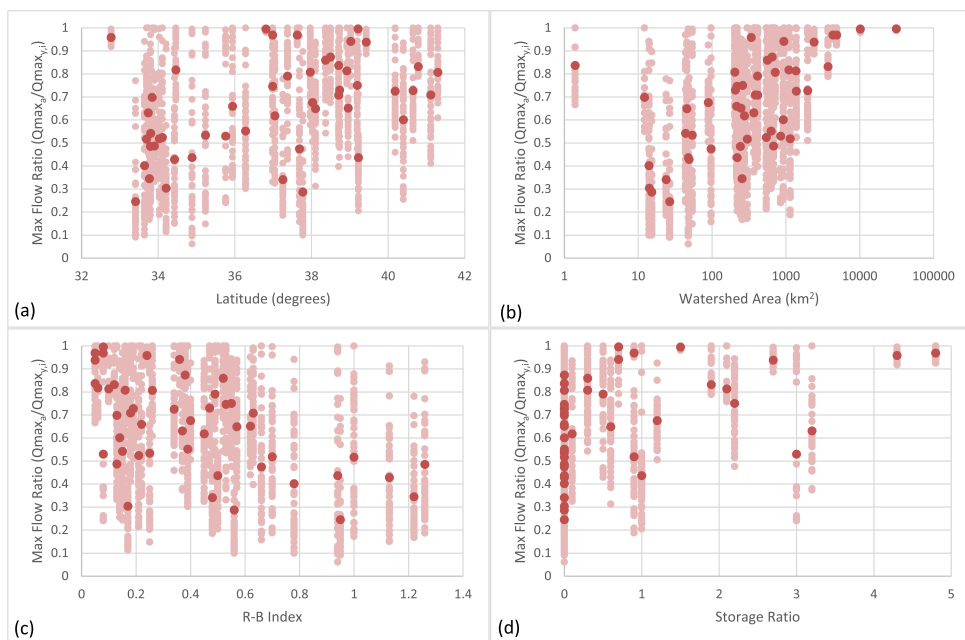
Figure 2.11: Scatter plots of Maximum Flow Ratio as a function of (a) Latitude (decimal degrees), (b) Watershed Area (km^2), (c) Richards-Baker Flashiness Index (R-B Index), and (d) Storage Ratio. Average data for all 50 sites shown in dark red; data for all 50 iterations shown in light red. Storage Ratio calculated as the upstream usable reservoir storage divided by the mean annual runoff for the study period. Data shown for the daily subsample interval only.

improve as these variables increase. Congruent with intuition, the positive correlation between runoff ratio and R-B Index indicates that runoff can be more accurately estimated from low frequency observations in watersheds with low flashiness (and vice versa). Short period runoff events in flashy ephemeral streams often contribute significant percentages of total runoff. It is more likely that lower frequency measurements will produce less accurate runoff results, because critical portions of the hydrograph can be completely missed as the observation frequency increases.

2.4.4. Variable Observation Frequencies

While the subsampling procedure used in this paper produced somewhat regularly spaced readings, actual citizen science observations will likely consist of an irregular mixture of observation frequencies. Thoughtfully varied observation frequencies, however, are a potential strength of citizen science. We envision that, at a minimum, monitoring frequencies could be varied based on (1) typical seasonal hydrologic patterns and (2) individual rainfall-runoff events. In Nepal, for example, where our field work is being completed, it rains for roughly four months during the monsoon season (June through September), and is relatively dry for the remaining eight months. Hydrographs during the monsoon season are quite dynamic, and therefore more frequent observations are desired. During the dry period, the hydrograph
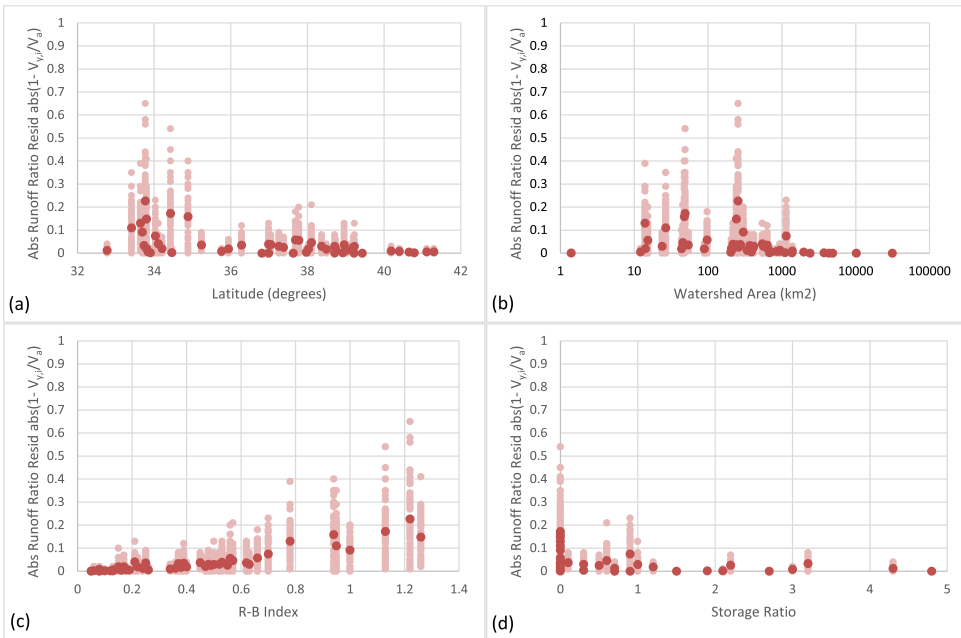
Figure 2.12: Scatter plots of the absolute value of the Runoff Ratio residual (i.e. $1 - V_{y,i} / V_a$) as a function of (a) Latitude (decimal degrees), (b) Watershed Area (km^2), (c) Richards-Baker Flashiness Index (R-B Index), and (d) Storage Ratio. Average data for all 50 sites shown in dark red; data for all 50 iterations shown in light red. Storage Ratio calculated as the upstream usable reservoir storage divided by the mean annual runoff for the study period. Data shown for the daily subsample interval only.

mainly undergoes a long recession, so less observations are needed, especially towards the end of the recession prior to the next monsoon. Additionally, depending on rainfall-runoff response timescales, observation frequencies could be altered depending on rainfall duration and intensity, or more simply by if it is raining or not. Therefore, future work should explore how variable observation frequencies, or adaptive monitoring, could lower uncertainty in citizen science data.

2.4.5. Data Assimilation

We suggest that data assimilation (briefly mentioned in Section 2.4.3), or a systematic combination of modeling and observations, could be promising methodology for adding value to, and improving accuracy of, citizen science observations. For example, higher frequency observations of rainfall collected by a permanently installed sensor could be combined with lower frequency observations of stream stage and flow performed by citizen scientists. Then, in the context of a rainfall-runoff model, these data could be combined to help "fill in the gaps" of the hydrograph. Data assimilation has the possibility to improve minimum flow, maximum flow, and runoff estimates based on lower frequency observations, and should be the focus of future citizen science research.

2

2.4.6. Relevance for Data Poor Regions

The results of this research are most meaningful if the watersheds chosen for sub-sampling from the "data rich" region(s) are similar to those of the "data poor" region(s) targeted for applications of citizen science. For our purpose of designing a citizen science monitoring campaign in Nepal, we specifically chose stream gauges from California for subsampling because of (1) the abundance of high quality stream gauging stations and (2) the topographic and climate similarities with Nepal. For example, both California and Nepal have well defined four to five month long wet periods when the majority of precipitation occurs (i.e. November through March and June through September, respectively), followed by prolonged dry periods. During the wet periods, both California and Nepal have significant precipitation events that occur due to the strong winter Pacific jet stream [38] and the Asian Summer Monsoon [39], respectively. Additionally, both California and Nepal have significant topographic variations in a direction perpendicular to the predominant direction of the jet stream. In the case of California, low pressure systems from the Pacific Ocean typically move to the east, and are forced over the Sierra Nevada mountains which predominantly run north to south. In Nepal, the South Asian monsoon moves to the north, while the Himalayas predominantly run east to west. While results from this analysis can be used to inform citizen science efforts in "data poor" regions with dissimilar hydrologic contexts to that of California, it is suggested that the subsampling procedures discussed herein be repeated for hydrologically similar "data rich" regions.

As a sample 'data poor 'region application, we are using citizen science observations to estimate runoff in several sub-watersheds (10 km^2 to 587 km^2) of the Bagmati River watershed in the Kathmandu Valley. Precipitation patterns and amounts for the Kathmandu Valley are similar to those in Northern California (i.e. above a latitude of roughly 36 north). There are 31 watersheds with a latitude above 36 included in this study ranging in size from 1 km^2 to 31313 km^2. The highest R-B Index observed for these 31 sites was 0.66 for SiteID 11181000. For daily observation frequencies, out of a total of 1550 site-subsamples (i.e. 31 sites times 50 subsamples), only 28 site-subsamples had runoff errors greater than 10 %, and only one site-subsample exceeded 20 %; the average runoff error was 1.9 %. With the assumptions previously stated at the end of the Section 2.1 in mind (i.e. regarding water level observation accuracy and stage-discharge curve availability), these results give us reasonable confidence that runoff estimates based on daily citizen science observations should be within 10 % of actual runoff, if not better.

2.5. Summary and Conclusions

The goal of this paper was to investigate the impacts of lower frequency observations (i.e. daily, three day, weekly, and monthly), similar to those that could be produced by citizen science, on the accuracy of basic streamflow statistics like minimum flow, maximum flow, and runoff. To answer this question, we performed a subsampling analysis on seven years of streamflow data from 50 USGS gauging stations in California. Depending on the questions being asked, and the charac-

teristics of the watershed(s) in question, lower frequency observations, such as those produced from citizen science, can provide useful hydrologic information. In general, as watershed flashiness decreases and storage ratio increases, the reliability of minimum flow, maximum flow, and runoff estimates obtained from low frequency observations increases. Also, as latitude increases, which for California is a reasonable proxy for precipitation, the reliability of runoff estimates based on low frequency observations increases. Interestingly, watershed size seems to play a less prominent role than latitude (i.e. precipitation), R-B Index, and storage ratio in determining reliability of low frequency observation based runoff estimates.

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2

3

Citizen Science Flow

No man ever steps in the same river twice,
For it is not the same river, And he is not the same man.

Heraclitus

Wise management of water resources requires data. Nevertheless, the amount of streamflow data being collected globally continues to decline. Generating hydrologic data together with citizen scientists can help fill this growing hydrological data gap. Our aim herein was to (1) perform an initial evaluation of three simple streamflow measurement methods (i.e. float, salt dilution, and Bernoulli run-up), (2) evaluate the same three methods with citizen scientists, and (3) apply the preferred method at more sites with more people. For computing errors, we used mid-section measurements from an acoustic Doppler velocimeter as reference flows. First, we performed 20 evaluation measurements in headwater catchments of the Kathmandu Valley, Nepal. Reference flows ranged from 6.4 to 240 L s^{-1}. Mean absolute percentage errors (MAPEs) were 23, 15, and 37 % with mean percentage errors (MPEs or biases) of 8, 6, and 26 % for float, salt dilution, and Bernoulli methods, respectively. Second, we evaluated the same three methods at 15 sites in two watersheds within the Kathmandu Valley with 10 groups of citizen scientists (three to four members each) and one "expert" group (three authors). At each site, each group performed three simple methods; "experts" also performed SonTek FlowTracker mid-section reference measurements (ranging from 4.2

to 896 L s^{-1}). For float, salt dilution, and Bernoulli methods, MAPEs averaged 41, 21, and 43 % for "experts" and 63, 28, and 131 % for citizen scientists, while biases averaged 41, 19, and 40 % for "experts" and 52, 7, and 127 % for citizen scientists, respectively. Based on these results, we selected salt dilution as the preferred method. Finally, we performed larger scale pilot testing in week-long pre- and post-monsoon Citizen Science Flow campaigns involving 25 and 37 citizen scientists, respectively. Observed flows (n = 131 pre-monsoon; n = 133 post-monsoon) were distributed among the 10 headwater catchments of the Kathmandu Valley, and ranged from 0.4 to 425 L s^{-1} and 1.1 to 1804 L s^{-1} in pre- and post-monsoon, respectively. Future work should further evaluate uncertainties of citizen science salt dilution measurements, the feasibility of their application to larger regions, and the information content of additional streamflow data.

3

3.1. Introduction

3.1.1. Background

The importance of measuring streamflow is underpinned by the reality that it is the only truly integrated representation of the entire catchment that we can plainly observe [2]. Traditional streamflow measurement approaches relying on sophisticated sensors (e.g. pressure transducers, acoustic doppler devices, etc.), site improvements (e.g. installation of weirs or stable cross-sections, etc.), and discharge measurements performed by specialists are often necessary at key observation points. However, these approaches require significant funding, equipment, and expertise, and are often difficult to maintain, and even more so to scale [3]. Consequently, despite growing demand, the amount of streamflow data being collected continues to decline in several parts of the world, especially in Africa, Latin America, Asia, and even North America ([4], [5], [6], [7]). Specifically, there is an acute shortage of streamflow data in headwater catchments [8] and developing regions [9]. This data gap is perpetuated by a lack of understanding among policy makers and citizens alike regarding the importance of streamflow data, which leads to persistent funding challenges ([10], [11]). This is further compounded by the reality that the hydrological sciences research community has focused much of its efforts in recent decades on advancing modeling techniques, while innovation in methods for generating the data these models depend on has been relegated to a lower priority ([12], [13]), even though these data form the foundation of hydrology [14].

Considering these challenges, alternative methods for generating streamflow and other hydrological data are being explored [7]. For example, developments in using remote sensing to estimate streamflow are being made ([15], [16]), but applications in small headwater streams are expected to remain problematic [7]. Utilizing cameras for measuring streamflow is also a growing field of research ([17], [18], [19], [20]), but it is doubtful that these methods will be broadly applied in headwater catchments in developing regions soon because of high costs, lacking technical capacity, and potential for vandalism. In these cases, however, involving citizen scientists to generate hydrologic data can potentially help fill the growing global hydrological data gap ([21], [22], [23], [3], [24], [25]).

Kruger and Shannon [26] define citizen science as the process of involving citizens in the scientific process as researchers. Citizen science often uses mobile technology (e.g. smartphones) to obtain georeferenced digital data at many sites, in a manner that has the potential to be easily scaled [27]. Turner and Richter [28] partnered with citizen scientists to map the presence or absence of flow in ephemeral streams. Fienen and Lowry [21] showed that water level measurements from fixed staff gauges reported by passing citizens via a text message system can have acceptable errors. Mazzoleni et al. [29] showed that flood predictions can be improved by assimilating citizen science water level observations into hydrological models. Le Coz et al. [30] used citizen scientist photographs to improve the understanding and modeling of flood hazards. Davids et al. [3] showed that lower frequency observations of water level and discharge like those produced by citizen scientists can provide meaningful hydrologic information. Van Meerveld et al. [24]

showed that citizen science observations of stream level class can be informative for deriving model-based streamflow time series of ungauged basins.

While the previously referenced studies focus mainly on involving citizen scientists for observing stream levels, we were primarily concerned with the possibility of enabling citizen scientists to take direct measurements of streamflow. Using keyword searches using combinations of "citizen science", "citizen hydrology", "community monitoring", "streamflow monitoring", "streamflow measurements", "smartphone streamflow measurement", and "discharge measurements," we found that research on using smartphone video processing methods for streamflow measurement has been ongoing for nearly five years ([31], [32]). Despite the promising nature of these technologies, we could not find any specific studies evaluating the strengths and weaknesses of citizen scientists applying these technologies directly in the field themselves.

Etter et al. [33] evaluated the error structure of simple "stick method" streamflow estimates (similar to what we later refer to as the float method) from 136 participants from four streams in Switzerland. Participants estimated cross-sectional area with visual estimates of stream width and depth. Floating sticks were used to measure surface velocity, which was scaled by 0.8 to estimate average velocity. Besides this study, we could not find other evaluations of simple streamflow measurement techniques that citizen scientists could possibly use. Therefore, in addition to the "stick method," we turned to the vast body of general knowledge about observing streamflow to develop a list of potential simple citizen science streamflow measurement methods to evaluate further (see Section 3.2.1 for details).

3.1.2. Research Questions

Our aims in this paper were to (1) perform an initial evaluation of selected potential simple streamflow measurement methods, (2) evaluate these potential methods with actual citizen scientists, and (3) apply the preferred method at a larger scale. Our research questions were:

- Which simple streamflow measurement method provides the most accurate results when performed by "experts"?

- Which simple streamflow measurement method provides the most accurate results when performed by citizen scientists?

- What are citizen scientists' perceptions of the required training, cost, accuracy, etc. of the evaluated simple streamflow measurement methods?

- Can citizen scientists apply the selected streamflow measurement method at a larger scale?

3.1.3. Limitations

While identifying and refining methods for citizen scientists to measure streamflow may be an important step towards generating more streamflow data, these types of citizen science applications are not without challenges of their own. For example,

citizen science often struggles with the perception (and possible reality) of poor data quality [34] and the intermittent nature of data collection [35]. Additionally, there are other non-citizen science based streamflow measurement methods (e.g. permanently installed cameras) that may undergo rapid development and transfer of technology, and thus make a significant contribution towards closing the stream-flow data gap.

Additionally, the use of "citizen scientist" herein is restricted to only student citizen scientists, which is a narrow but important subset of potential citizen scientists. Our vision was to partner with student citizen scientists first to develop and evaluate streamflow measurement methodologies. Once methodologies are refined in coordination with students, we aim to partner with community members and students in the rural hills of Nepal to improve the availability of quantitative stream and spring flow data.

3.2. Materials and Methods

3.2.1. Simple Streamflow Measurement Methods Considered

Streamflow measurement techniques suggested in the United States Bureau of Reclamation Water Measurement Manual [36] that seemed potentially applicable for citizen scientists included: deflection velocity meters; the Manning-Strickler slope area method; and pitot tubes for measuring velocity heads. The float, current meter, and salt dilution methods described by several authors also seemed applicable ([37], [38], [39], [40], [41], [42], [43]). Finally, Church and Kellerhals [44] introduced the velocity head rod, or what we later refer to as the Bernoulli run-up (or just Bernoulli) method. Table 3.1 provides a summary of these eight simple measurement methods. For the categories of (1) inapplicability in Nepal (specifically to headwater catchments), (2) cost, (3) required training, and (4) complexity of the measurement procedure, a rank of either 1, 2, or 3 was given by the authors, with 1 being most favorable and 3 being least favorable. Theses ranks were then summed, and the three methods with the lowest ranks (i.e. Bernoulli, float, and salt dilution (slug)) were selected for additional evaluation in the field.

3

Table 3.1: Summary of simple streamflow measurement methods considered for further evaluation. Integer ranks of 1, 2, or 3 for inapplicability in Nepal (especially for smaller headwater catchments), cost, required training, and complexity were given to each method, with 1 being most favorable and 3 being least favorable. The three methods with the lowest rank were selected for further evaluation. Smartphones are not included in equipment needs because it was assumed that citizen scientists would provide these themselves.

#	Method	Brief Description	Equipment Needs	Range of Applicability	In-applicability in Nepal	Cost	Req-uired Training	Com-plexity	Total Rank (4 to 12)	Selec-ted (yes/no)
1	Bernoulli	Velocity-area method. Thin flat plate (e.g. measuring scale) used to measure velocity head. Repeated at multiple stations.	Measuring scale	Higher velocities with parallel flow lines preferred	1	1	2	1	5	yes
2	Current Meter	Velocity-area method. Current meter (e.g. bucket wheel, propeller, acoustic, etc.) used to measure velocity. Repeated at multiple stations.	Current meter, measuring scale	Less turbulent, parallel flow lines	2	3	3	2	10	no
3	Deflection Rod	Velocity-area method. Shaped vanes projecting into the flow along with a method to measure deflection, and thereby computing velocity. Repeated at multiple stations.	Deflection rod, measuring scale	Less turbulent, parallel flow lines	3	2	2	2	9	no
4	Float	Velocity-area method. Time for floating object to travel known distance used to determine water velocity. Repeated at multiple stations.	Measuring scale, timer	Less turbulent, parallel flow lines	2	1	2	1	6	yes
5	Manning-Strickler	Slope area method. Slope of the water surface elevation combined with estimates of channel roughness and channel geometry to determine flow using the Manning-Strickler equation.	Auto level (or water level), measuring scale	Uniform flow, no pool and drop	2	2	2	3	9	no
6	Pitot Tube	Velocity-area method. Pitot tube used to measure velocity. Repeated at multiple stations.	Pitot tube, measuring scale	Higher velocities with parallel flow lines preferred	2	2	2	2	8	no
7	Salt Dilution (Constant-rate Injection)	Constant rate of known concentration of salt injected into stream. Background and steady state electrical conductivity values measured after full mixing. Flow is proportional to rate of salt injection and change in EC.	EC meter, mixing containers	Turbulent, well mixed flow	1	2	3	3	9	no
8	Salt Dilution (Slug)	Known volume and concentration of salt injected as a single slug. EC of breakthrough curve measured. Flow is proportional to integration of breakthrough curve and volume of tracer introduced.	EC meter, mixing containers	Turbulent, well mixed flow	1	2	2	2	7	yes

3.2.2. Expanded Description of Selected Simple Streamflow Measurement Methods

Float Method

The float method is based on the velocity-area principle, whereby the channel cross-section is defined by measuring depth and width of n sub-sections, and the velocity is found by the time it takes a floating object to travel a known distance which is then corrected for friction losses. In some cases, a single float near the middle of the channel (often repeated to obtain an average value) is used to determine surface velocity [45]. In this study, surface velocity was measured at each of the n sub-sections. Total streamflow (Q) in liters per second (L s^{-1}) is calculated with Equation 3.1:

$$Q = 1000 * \sum_{i=1}^{n} *C * V_{F_i} * d_i * w_i \tag{3.1}$$

where 1000 is a conversion factor from m^3 s^{-1} to L s^{-1}, C is a unitless coefficient to account for the fact that surface velocity is typically higher than average velocity (typically in the range of 0.66 to 0.80 depending on depth; [36]) due to friction from the channel bed and banks, V_{F_i} is surface velocity from float in meters per second (m s^{-1}), d_i is depth (m), and w_i is width (m) of each sub-section ($i = 1$ to n, where n is the number of stations). A coefficient of 0.8 was used for all float method measurements in this study. Surface velocity for each sub-section was determined by measuring the amount of time it takes for a floating object to move a certain distance. For floats we used sticks found on site. Sticks are widely available (i.e. easiest for citizen scientists), generally float (except for the densest varieties of wood), and depending on their density, are between 40 and 80 % submerged, which minimizes wind effects. An additional challenge with floats is that they can get stuck in eddies, pools, or overhanging vegetation.

Float method streamflow measurements involve the following steps:

1. Select stream reach with straight and uniform flow

2. Divide cross-section into several sub-sections (n, typically between 5 and 20)

3. For each sub-section, measure and record

   (a) The depth in the middle of the sub-section
   (b) The width of the sub-section
   (c) The time it takes a floating object to move a known distance downstream (typically 1 or 2 m) in the middle of the sub-section

4. Solve for streamflow (Q) with Equation 3.1

Distances of 1 or 2 m were necessary to measure surface velocity for each sub-section since it was unlikely that a float would stay in a single sub-section for 10 or 20 m. These shorter distances ensured that surface velocity measurements were

representative of their respective sub-sections and associated areas. One benefit of this approach was that the measured surface velocities were cross-sectional area weighted. This area weighting was more important as surface velocity differences between the center and the sides of the channel increased. Since these velocity differences vary from site to site, using a single float with a single coefficient (e.g. 0.8) would have ignored these differences among sites.

Salt Dilution Method

There are two basic types of salt dilution flow measurements: slug (previously known as instantaneous) and continuous rate ([41], [42]). Salt dilution measurements are based on the principle of the conservation of mass. In the case of the slug method, a single known volume of high concentration salt solution is introduced to a stream and the electrical conductivity (EC) is measured over time at a location sufficiently downstream to allow good mixing [42]. An approximation of the integral of EC as a function of time is combined with the volume of tracer and a calibration constant (Equation 3.2) to determine discharge. In contrast, continuous rate salt dilution method involves introducing a known flow rate of salt solution into a stream [41]. Slug method salt dilution measurements are broadly applicable in streams with flows up to 10 m^3 s^{-1} with steep gradients and low background EC levels [42]. For the sake of citizen scientist repeatability, we chose to only investigate the slug method, because of the added complexity of measuring the flow rate of the salt solution for the continuous rate method. Some limitations of the salt dilution method include: (1) inadequate vertical and horizontal mixing of the tracer in the stream, (2) trapping of the tracer in slow moving pools of the stream, and (3) incomplete dilution of salt within the stream water prior to injection. The first two limitations can be addressed with proper site selection (i.e. well mixed reach with little slow-moving bank storage), while incomplete dilution can be avoided by proper training of the personnel performing the measurement.

Streamflow (Q; L s^{-1}) is solved for using Equation 3.2 ([38], [42]):

$$Q = \frac{V}{k * \sum_{i=1}^{n}(\sigma(t) - \sigma_{BG}) * \Delta t} \tag{3.2}$$

where V is the total volume of tracer introduced into the stream (L), k is the calibration constant in centimeters per microsiemens (cm μS^{-1}), n is the number of measurements taken during the breakthrough curve (unitless), $\sigma(t)$ is the EC at time t (μS cm^{-1}), σ_{BG} is the background EC (μS cm^{-1}), and Δt is the change in time between EC measurements (s).

Salt dilution method streamflow measurements involve the following steps:

1. Select stream reach with turbulence to facilitate vertical and horizontal mixing

2. Determine upstream point for introducing the salt solution and a downstream point for measuring EC

    (a) A rule of thumb in the literature is to separate these locations roughly 25 stream widths apart ([46], [47], [42])

3. Estimate flow either performing a "simplified float measurement (i.e. only a few sub-sections)" or by visually estimating width, average depth, and average velocity

4. Prepare salt solution based on the following guidelines (approximate average of dosage recommendations from previous studies cited by Moore [42])

   (a) 10000 ml of stream water for every 1 m^3 s^{-1} of estimated streamflow

   (b) 1667 g of salt for every 1 m^3 s^{-1} of estimated streamflow

   (c) Thoroughly mix salt and water until all salt is dissolved

   (d) Following these guidelines ensure a homogenous salt solution with 1 to 6 salt to water ratio by mass

5. Establish the calibration curve relating EC values to actual salt concentrations [41] to determine calibration constant (k) relating changes in EC values in micro Siemens per centimeter (μS cm^{-1}) in the stream to relative concentration of introduced salt solution (RC; see Section 3.2.3 for details)

6. Dump salt solution at upstream location

7. Measure EC at downstream location during salinity breakthrough until values return to background EC

   (a) Record a video of the EC meter screen at the downstream location and later digitize the values using the time from the video and the EC values from the meter

Bernoulli Run-up Method

Like the float method, Bernoulli run-up (or Bernoulli) is based on the velocity-area principle. The basic principle is that "run-up" on a flat plate inserted perpendicular to flow is proportional to velocity based on the solution to Bernoulli's equation. Bernoulli run-up is also referred to as the "velocity head rod" by Church and Kellerhals [44], Carufel [48], and Fonstad et al. [49], and is similar to the "weir stick" discussed by USBR [36]. The velocity measurement theory of Bernoulli is similar to using a pitot tube [50], without the associated challenges of (1) using and transporting potentially bulky and fragile equipment and (2) clogging from sediment or trash [51]. However, the accuracy and precision of Bernoulli method velocity head measurements are likely lower than pitot measurements. Total streamflow (Q; L s^{-1}) is calculated with Equation 3.3:

$$Q = 1000 * \sum_{i=1}^{n} *V_{B_i} * d_{1_i} * w_i \tag{3.3}$$

where 1000 is a conversion factor from m^3 s^{-1} to L s^{-1}, V_{B_i} is velocity from Bernoulli run-up (m s^{-1}), d_{1_i} is depth (m), and w_i is width (m) of each sub-section ($i = 1$ to n). Area for each sub-section is the product of the width and the depth

in the middle of each sub-section. Velocity for each sub-section (V_{B_i}) was deter-
mined by measuring the "run-up" or change in water level on a thin meter stick
(or "flat plate;" dimensions: 1 m long, by 34 mm wide, by 1.5 mm thick used in
this study) from when the flat plate was inserted parallel and then perpendicular
to the direction of flow. The parallel depth measurement represents static head,
while the perpendicular represents total head. Velocity (V_{B_i}; m s^{-1}) is calculated
from Bernoulli's principle with Equation 3.4:

$$V_{B_i} = \sqrt{2g * (d_{2_i} - d_{1_i})} \tag{3.4}$$

where g is the gravitational constant (m s^{-2}) and d_{2_i} and d_{1_i} are the water
depths (m) when the flat plate was perpendicular and parallel to the direction of
flow, respectively.

Bernoulli method streamflow measurements involve the following steps:

1. Select constricted stream section with elevated velocity to increase the differ-
   ence between d_{1_i} and d_{2_i}

2. Divide cross-section into several sub-sections (n, typically between 5 and 20)

3. For each sub-section, measure and record

   (a) The depth with a flat plate held perpendicular to flow (d_{2_i} or the "Run-up"
       depth)

   (b) The depth with a flat plate held parallel to flow (d_{1_i} or the actual water
       depth)

   (c) The width of the sub-section

4. Solve for streamflow (Q) with Equations 3.3 and 3.4

3.2.3. General Items

Types of Streams Evaluated

Streams evaluated during this investigation (Phases 1, 2, and 3) were a mixture of
pool and riffle, pool and drop, and run stream types. Streamflows ranged from 0.4
to 1804 L s^{-1}. Stream widths and average depths ranged from 0.1 to 6.0 m and
0.0040 and 0.97 m, respectively. Streambed materials ranged from cobles, gravels,
and sands in the upper portions of watershed to sands, silts, and sometimes man-
made concrete streambeds and side retaining walls in the lower portions. During
pre-monsoon, sediment loads were generally low, while during post-monsoon, in-
creased water velocities led to increased sediment loads (both suspended and bed).
Slopes (based on Phase 2 data) ranged from 0.020 to 0.148 m m^{-1}. Additional de-
tails about the measurement sites are provided in Tables 3.4 and 3.5. Since roughly
80 % of Nepal's precipitation occurs during the summer monsoon [52], pre- and
post-monsoon represent periods of relatively low and high streamflows, respec-
tively. Therefore, we consistently use pre-monsoon and post-monsoon to refer to
the general seasons that Phase 1, 2, and 3 activities were performed in.

Reference Flows

To evaluate different simple citizen science flow measurement methods, reference (or actual) flows for each site were needed. We used a SonTek FlowTracker acoustic Doppler velocimeter (ADV) to determine reference flows. The United States Geological Survey (USGS) mid-section method was used, following guidelines from USGS Water Supply Paper 2175 [38], along with instrument specific recommendations from SonTek's FlowTracker manual [53]. Stream depths were shallow enough that a single vertical 0.6 depth velocity measurement (i.e. 40 % up from the channel bottom) was used to measure average velocity for each sub-section [38]. While there is uncertainty in using the 0.6 depth as representative of average velocity, Rantz [38] states that "actual observation and mathematical theory have shown that the 0.6 depth method gives reliable results" for depths less than 0.76 m; multipoint methods are not recommended for depths less than 0.76 m, so this is the recommended USGS approach. Depending on the total width of the channel, the number of sub-sections ranged from 8 to 30. The FlowTracker ADV has a stated velocity measurement accuracy of within one percent [53]. Based on an ISO discharge uncertainty calculation within the SonTek FlowTracker software, the uncertainties in reference flows for Phase 1 and 2 ranged from 2.5 to 8.2 %, with a mean of 4.2 %. Based on the literature ([38], [54], [43]), these uncertainties in reference flows are towards the lower end of the expected range for field measurements of streamflow. Therefore, we do not think that any systematic biases or uncertainties in our data change the results of this paper. A compilation of the measurement reports generated by the FlowTracker ADV, including summaries of measurement uncertainty, are included as supplementary material.

Salt Dilution Calibration Coefficient (k)

Our experience was that the most complicated portion of a salt dilution measurement was performing the dilution test to determine the calibration coefficient k. The calibration coefficient k relates changes in EC values in micro Siemens per centimeter ($\mu S\ cm^{-1}$) in the stream to relative concentrations of introduced salt solution (RC). During Phases 1 and 2, we determined k using a calibrated GHM 3431 [GHM-Greisinger] EC meter with the procedure recommended by Moore ([41], additional details included as supplementary materials).

Due to the challenges of measuring k in the field, especially for citizen scientists who are the ultimate target for performing these streamflow measurements, average k values were used to determine salt dilution streamflows. For Phase 1, an average k of 2.79E-06 (n = 10) was used for all 20 measurement sites (Table 3.4). For Phase 2, an average k of 2.95E-06 (n = 15) was used for all 15 sites (Table 3.5). For Phase 3, the Phase 2 average k of 2.95E-06 was used to calculate streamflows for all salt dilution measurements. The impact of using average k values on salt dilution measurements is discussed in Section 3.4.1. Moore [42] suggests that k is a function of (1) the ratio of salt and water in the tracer solution and (2) the chemical composition of the stream water. To minimize variability in k due to changes in salt concentration, a fixed ratio of salt to water (i.e. 1 to 6 by mass) was used to prepare tracer solutions for all phases of this investigation.

Inexpensive EC Meters

For Phases 2 and 3, ten inexpensive (i.e. $15) Water Quality Testers [HoneForest] were used to measure EC for salt dilution measurements. To evaluate the accuracy of these meters, we performed a six-point comparison test with reference EC values of 20, 107, 224, 542, 1003, and 1517 μS cm^{-1}, as determined by a calibrated GHM 3431 [GHM-Greisinger] EC meter. EC measurements were performed from low EC to high EC (for all six points) and were repeated three times for each meter. Because EC is used to compute the integral of the breakthrough curve (Equation 3.2), the percent difference (i.e. error) in EC changes between the six points (i.e. five intervals) from the inexpensive meters were compared to reference EC intervals (Figure 3.1). Based on this analysis, the inexpensive meters had a positive median bias of roughly 5 % (ranging from -14 to 21 %) for EC value changes between 20 and 542 μS cm^{-1} (i.e. D1, D2, and D3). A nearly zero median bias (ranging from -5 to 5 %) for EC value changes between 542 and 1003 μS cm^{-1} (i.e. D4) was present. Finally, there was a negative median bias of roughly -9 % (ranging from -18 to 6 %) for EC value changes between 1003 and 1517 μS cm^{-1} (i.e. D5). No corrections were made to EC measurements collected with inexpensive [HoneForest] EC meters.
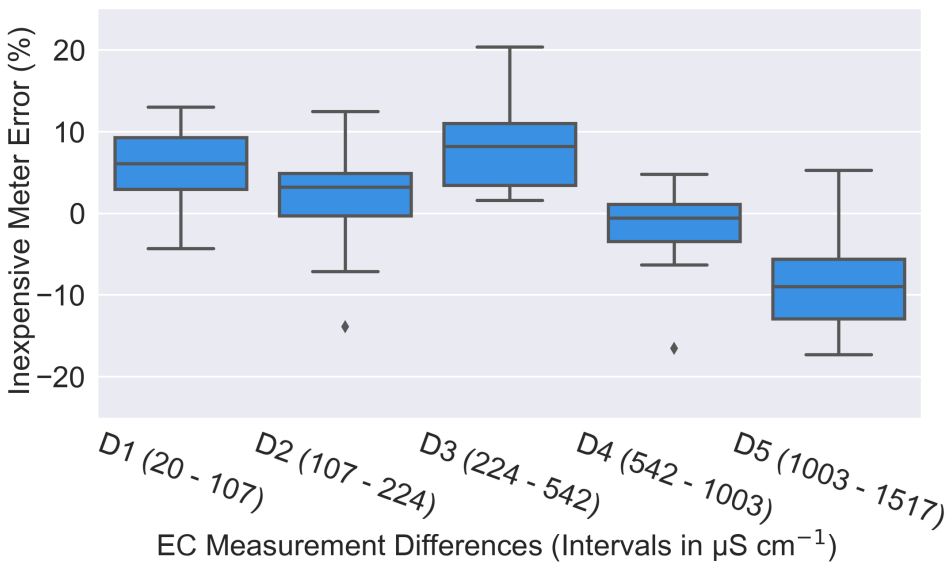
Figure 3.1: Box plots of inexpensive Water Quality Testers [HoneForest] errors for five different intervals (i.e. D1 to D5). The range of EC values from reference EC measurements (determined by a calibrated GHM 3431 [GHM-Greisinger] EC meter) are shown in parentheses in μS cm^{-1}. Boxes show the interquartile range between the first and third quartiles of the dataset, while whiskers extend to show minimum and maximum values of the distribution, except for points that are determined to be "outliers" (shown as diamonds), which are more than 1.5 times the interquartile range away from the first or third quartiles.

Table 3.2: Brief descriptions of three data collection phases including who performed the field data collection, and what period and season the data were collected in.

#	Phase	Description	Performed by	Period	Season
1	Initial Evaluation	Initial evaluation of three simple flow measurement methods (i.e. float, salt dilution, and Bernoulli) along with Flow-Tracker ADV reference flow measurements at 20 sites within the Kathmandu Valley. Reference flows ranged from 6.4 to 240 L s^{-1}.	Authors	March/ April 2017	Pre-monsoon
2	Citizen Scientist Evaluation	Citizen Scientist evaluation of three simple flow measurement methods (i.e. float, salt dilution, and Bernoulli) along "expert" and FlowTracker ADV reference flow measurements at 15 sites within the Kathmandu Valley. Reference flows ranged from 4.2 to 896 L s^{-1}.	Authors for "expert" and reference flows plus 10 Citizen Science Flow groups for simple methods	September 2018	Post-monsoon
3	Citizen Scientist Application	Salt dilution measurements at roughly 130 sites in the 10 perennial watersheds of the Kathmandu Valley. Float measurements with a small number of sub-sections (e.g. 3 to 5) performed at each site to determine salt dosage. Observed flows ranged between 0.4 to 425 and 1.1 to 1804 L s^{-1} in pre- and post-monsoon, respectively.	18 Citizen Science Flow groups (8 from April and 10 from September)	April and September 2018	Pre- and Post-Monsoon

3.2.4. Phases of the Investigation

This investigation was carried out in three distinct phases including: Phase 1 - initial evaluation; Phase 2 - citizen scientist evaluation; and Phase 3 - citizen scientist application (Table 3.2).

Initial Evaluation (Phase 1)

For Phase 1 evaluation of the three simple streamflow measurement methods, we (three authors) performed sets of measurements at 20 sites within the Kathmandu Valley, Nepal (Figure 3.2.a and 3.2.b). The Kathmandu Valley is a small intermontane basin roughly 25 km in diameter with a total area of 587 km^2 in the Central Region of Nepal, and encompasses most of Kathmandu, Bhaktapur, and Lalitpur districts. Figure 3.2.c is a photograph of the typical types of relatively steep pool and drop stream systems included in Phase 1. Sites were chosen to represent a typical range of stream types, slopes, and flow rates. At each site, we performed float, salt dilution, and Bernoulli measurements, in addition to reference flow measurements with the FlowTracker ADV per the descriptions in Sections 3.2.2 and 3.2.3, respectively. All Phase 1 salt dilution EC measurements were taken with a calibrated GHM 3431 [GHM-Greisinger] EC meter.

At each site, measurements were performed consecutively, and took roughly one to two hours to perform, depending on the size of the stream and the resulting number of sub-sections for float, Bernoulli, and reference flow measurements. Measurements were performed during steady state conditions in the stream; if runoff generating precipitation occurred during measurements at a site, the measurements were stopped, and repeated after streamflows stabilized at pre-event
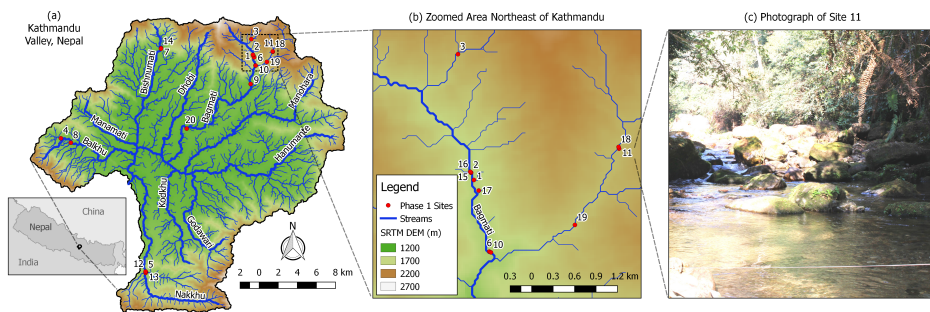
Figure 3.2: Map showing topography of the Kathmandu Valley from a Shuttle Research Telemetry Mission [55] Digital Elevation Model (DEM), resulting stream network [56], and locations of phase 1 measurement sites (a). Names of the ten historically perennial tributaries are shown. Panel (b) shows an enlarged view of the area where 11 of the 20 measurements were taken. Panel (c) is a photograph of site 11, a pool and riffle sequence flowing at roughly 100 L s^{-1}. Measurement sites are labelled with Phase 1 Site IDs.

levels. As previously described, salt dilution calibration coefficient k was determined at 10 of the 20 sites. Field notes for float, salt dilution, and Bernoulli were taken manually and later digitized into a spreadsheet (included as supplementary material). Results from Phase 1 are summarized in tabular form (Table 3.4). To understand relative (normalized) errors, we calculated percent differences in relation to reference flow for each method. Mean absolute percentage errors (MAPEs), mean percentage errors (MPEs or biases), and standard deviations of percentage errors were used as metrics to compare results among methods and between Phase 1 and 2.

Citizen Scientist Evaluation (Phase 2)

To evaluate the same three streamflow measurement methods with actual citizen scientists, we recruited 37 student volunteers from Khwopa College of Engineering in Bhaktapur, Nepal for our Citizen Science Flow (CS Flow) evaluation. 10 CS Flow evaluation groups of either three or four members were formed. Citizen scientists were second and third-year civil engineering Bachelors' students ranging in age from 21 to 25; 12 were female and 25 were male. Phase 2 citizen scientist evaluations (Figure 3.3) were performed at seven sites in the Dhobi watershed in the north (Figure 3.3.b; D1 to D7) and eight sites in the Nakkhu watershed in the south (Figure 3.3.c; N1 to N8). Sites were chosen to represent a typical range of stream types, slopes, and flow rates found within the headwater catchments of the Kathmandu Valley, and to minimize travel time between locations.

Phase 2 started on 17 September (2018) with a four-hour theoretical training on the float, salt dilution, and Bernoulli streamflow measurement methods per Section 3.2.2. The theoretical training also introduced citizen scientists to Open Data Kit (ODK; [57]), a freely available open-source software for collecting and managing data in low-resource settings. ODK was used with the specific streamflow measurement workflow described below.
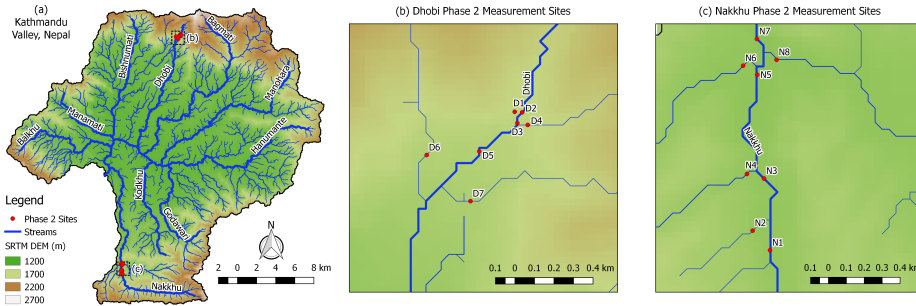
Figure 3.3: Map showing topography of the Kathmandu Valley, stream network, and locations of phase 2 measurement sites (a). Names of the ten historically perennial tributaries are shown. Panel (b) shows an enlarged view of the upper Dhobi watershed where Phase 2 measurements D1 through D7 were performed. Panel (c) shows an enlarged view of the middle Nakkhu watershed where Phase 2 measurements N1 through N8 were performed. Measurement sites are labelled with Phase 2 Site IDs.

Based on our initial experiences and results from Phase 1, we developed an ODK form to facilitate the collection of float, salt dilution, Bernoulli, and reference streamflow measurement data. After installing ODK on an Android smartphone, and downloading the necessary form from S4W-Nepal's ODK Aggregate server on the Google Cloud App Engine, the general workflow is included as supplementary material.

Training was continued on 18 September with a two-hour field demonstration session in the Dhobi watershed located in the north of the Kathmandu Valley. During this field training, we worked with three to four groups at a time, and together performed float, salt dilution, and Bernoulli measurements at site D3.

Following the field training, a Google My Map with the 15 sites was provided to the citizen scientists. Groups were strictly instructed to not discuss details regarding the selection of measurement reaches or the results of the streamflow measurements with other groups. For the remainder of 18 September and all of 19 September, the 10 CS Flow groups rotated between the seven sites in the Dhobi watershed. To ensure that measurements could be compared with each other, four S4W-Nepal interns travelled between sites to verify that CS Flow groups performed measurements on the same streams in the same general locations. All eight measurements on the Nakkhu watershed were performed in similar fashion on 20 September.

Using the same schedule of the CS Flow groups, the "expert" group (three authors) visited the same 15 sites. At each site, in addition to performing float, salt dilution, and Bernoulli measurements, the "expert" group performed (1) reference flow measurements per Section 3.2.3, (2) salt dilution calibration coefficient k dilution measurements per Section 3.2.3, and (3) an auto-level survey to determine average stream slope. At each site, auto-level surveys included topographical surveys of stream water surface elevations with a AT-B4 24X Auto-Level [Topcon] at five locations including: 10 times and 5 times the stream width upstream of the reference flow measurement site (reference site), at the reference site, and 5 and

Table 3.3: Summary of Phase 2 survey questions and the meanings of ranks, respectively.

#	Question	Rank 1 Meaning	Rank 3 Meaning
Q1	Required training for each method	Least	Most
Q2	Cost of equipment for each method	Least	Most
Q3	Number of citizen scientists required for each method	Least	Most
Q4	Data recording requirements for each method	Least	Most
Q5	Complexity of procedure for each method	Least	Most
Q6	Enjoyability of measurement method	Most	Least
Q7	Safety of each method	Most	Least
Q8	Accuracy of each method	Most	Least

10 times the stream width downstream of the reference site. For each site, stream slope was taken as the average of the four slopes computed from the five water surface elevations measured.

All CS Flow and "expert" measurements were conducted under steady state conditions. Based on two S4W-Nepal citizen scientists' precipitation measurements (official government records aren't available until the subsequent year) nearby the Dhobi sites (i.e. roughly 3 km to the west and east), no measurable precipitation occurred during 18 and 19 September. Water level measurements from a staff gauge installed at site D3 taken at the beginning and end of 18 and 19 September confirmed that water levels (and therefore flows) remained steady. On 20 September, 7 mm of precipitation was recorded by a S4W-Nepal citizen scientist in Tikabhairab which is roughly 1 km north of the eight measurement sites in the Nakkhu watershed. Based on field observations of the "expert" group, rain didn't start until 15:30 LT, and all CS Flow group measurements were completed before 15:30 LT. Three "expert" measurement sites were completed after 15:30 LT, but most rain was concentrated downstream (to the north) of these sites (i.e. N1, N2, and N3). Based on water level measurements performed at the beginning, middle, and end of measurements at these sites, no changes in water levels (and therefore flows) were observed. We also don't see any systematic impacts to the resulting comparison data for these sites (Table 3.5 and Figure 3.4).

Once ODK forms from all 15 sites were finalized and submitted to the ODK Aggregate server, CS Flow and "expert" groups digitized breakthrough curves (i.e. time and EC) from EC videos in shared Google Sheet salt dilution flow calculators. Digitizations for all measurements were then reviewed for accuracy and completeness by the authors.

After the completion of Phase 2 field work, a Google Form survey was completed by 33 of the Phase 2 citizen scientists (Table 3.3). The purpose of the survey was to evaluate citizen scientists' perceptions of the three simple streamflow measurement methods. The survey questions forced participants to rank each method from 1 to 3. Questions were worded so that in all cases, a rank of 1 was most favourable and 3 was least favourable.

A tabular summary of the 15 Phase 2 measurement locations was developed (Table 3.5). To understand relative (normalized) errors, we calculated percent dif-

ferences in relation to reference flow for each method. Mean absolute percentage errors (MAPEs), mean percentage errors (MPEs or biases), and standard deviations of percentage errors were used as metrics to compare results among methods and between Phase 1 and 2. Box plots showing the distribution of CS Flow group measurement errors along with "expert" measurement errors for each method were developed (Figure 3.4). To visualize the results of the citizen scientists' perception survey, a stacked horizontal bar plot grouped by streamflow measurement methods was developed (Figure 3.5).

3

Citizen Scientist Application (Phase 3)

From 15 to 21 April (2018; pre-monsoon) and 21 to 25 September (2018; post-monsoon), 25 and 37 second and third-year engineering Bachelors' student citizen scientists, respectively, from Khwopa College of Engineering in Bhaktapur, Nepal joined S4W-Nepal's Citizen Science Flow (CS Flow) campaign. Citizen scientists formed 8 pre-monsoon and 10 post-monsoon CS Flow groups of three or four people each, respectively. Ages of pre-monsoon citizen scientists ranged from 21 to 25; 7 were female and 18 were male (post-monsoon group composition is described in Section 3.2.4).

Post-monsoon Phase 3 measurements were performed by the same 10 CS Flow groups that performed Phase 2 citizen scientist evaluations. Therefore, additional training for these groups was not necessary. Training for pre-monsoon CS Flow groups included a four-hour theoretical training on 15 April about the float and salt dilution streamflow measurement methods per Section 3.2.2. The theoretical training also introduced citizen scientists to ODK Android data collection application. For both pre- and post-monsoon Phase 3 measurements, the workflow was similar to that described in Section 3.2.4 (see supplementary material for details), with the exceptions of (1) skipping collection of Bernoulli data, and (2) only performing a "simplified" float measurement involving only two or three sub-sections in order to have a flow estimate for calculating the recommended salt dose. Training was continued on the afternoon of 15 April with a two-hour field demonstration session in the Hanumante watershed located in the southwestern portion of the Kathmandu Valley (Figure 3.6). During this field training, we worked with four groups at a time, and together performed "simplified" float and Bernoulli measurements at two sites.

After training was completed, citizen scientists were sent to the field to perform streamflow measurements as described above in all 10 headwater catchments of the Kathmandu Valley (Figure 3.6). All Phase 3 salt dilution EC breakthrough curve measurements were performed with inexpensive [HoneForest] meters. Once ODK forms from all Phase 3 measurements were finalized and submitted to the ODK Aggregate server, CS Flow groups digitized breakthrough curves (i.e. time and EC) from EC videos in shared Google Sheet salt dilution flow calculators. Digitizations for all measurements were then reviewed for accuracy and completeness by the authors. While not included in this paper, it is important to note that students analyzed the collected flow data and finally presented oral and written summaries of their quality-controlled results to their faculty and peers at Khwopa College of Engineering.

While subsequent work will highlight the knowledge about spring and stream-flows gained from these data, the purpose herein is more a proof of concept showing that the salt dilution method can be successfully applied at more sites with more people. As such, a simple map figure is used to show the spatial distribution of measurements. The three streamflow gauging stations within the Kathmandu Valley (only one in a headwater catchment) operated by the official government agency responsible for streamflow measurements (i.e. the Department of Hydrology and Meteorology or DHM) are also included. Additionally, histograms of flow and EC for pre- and post-monsoon are also shown. While measurements in pre- and post-monsoon were not all taken in the same locations, histograms can still be used to see seasonal changes in distributions.

3.3. Results

The following results section is organized into the same three phases included in the methodology (Section 3.2.4): initial evaluation (Phase 1), citizen scientist evaluation (Phase 2), and citizen scientist flow application (Phase 3).

3.3.1. Initial Evaluation Results (Phase 1)

Reference flows evaluated in Phase 1 ranged from 6.4 to 240 L s^{-1} (Table 3.4; sorted in ascending order by reference flow). Elevations of measurements ranged from 1313 to 1905 meters above mean sea level. Salt dilution calibration coefficients (k) averaged 2.79E-06 and ranged from 2.57E-06 to 3.02E-06. MAPEs with respect to reference flows averaged 23, 15, and 37 %, while biases for all methods were positive, averaging 8, 6, and 26 % for float, salt dilution, and Bernoulli methods, respectively. Standard deviations of percentage errors were 29, 19, and 62 % for float, salt dilution, and Bernoulli methods, respectively. The largest salt dilution errors occurred for reference flows of 21 L s^{-1} or less (i.e. sites 1 through 7), while float and Bernoulli errors were more evenly distributed throughout the range of observed flows. Field notes from Bernoulli flow measurements for two measurements (Site IDs 9 and 19) were destroyed by water damage, so Bernoulli flow and percent difference data were not available for these sites. Detailed reports for reference flow measurements along with calculations for each simplified streamflow measurement method are included as supplementary material.

3.3.2. Citizen Scientist Evaluation Results (Phase 2)

Reference flows evaluated in Phase 2 ranged from 4.2 to 896 L s^{-1} (Table 3.5). MAPEs for "expert" measurements averaged 41, 21, and 43 %, while biases for all methods were positive, averaging 41, 19, and 40 % for float, salt dilution, and Bernoulli methods, respectively (Table 3.5 and Figure 3.4). Standard deviations of "expert" percentage errors were 34, 26, and 51 % for float, salt dilution, and Bernoulli methods, respectively. Salt dilution calibration coefficients (k) averaged 2.95E-06 and ranged from 2.62E-06 to 3.42E-06. Measurement sites in the Dhobi watershed were pool and drop stream types, with slopes ranging from 0.076 to 0.148 m m-1. Streambeds for these sites were predominantly cobles, gravels, and

3

Table 3.4: Summary of initial evaluation (Phase 1) measurement comparison data. Records sorted in ascending order by reference flow (Q Reference). Latitude and longitude in reference to the WGS84 datum. All flow values shown are shown in L s^{-1} rounded to the nearest integer for values greater than or equal to 10 and to the nearest tenth place for values less than 10. Percent differences (errors) calculated using Q Reference (FlowTracker) as the actual flow. Data summarized at the bottom with average, minimum (min), maximum (max), and standard deviation (std dev). Note that averages (avg *) shown in the summary area near the bottom for the last three columns (i.e. percent errors) indicate biases with MAPEs shown in parentheses. Null (empty) cells indicate that data for that site and parameter were either damaged (i.e. Q Bernoulli for SiteIDs 9 and 19) or not collected in the field (i.e. missing k values). Average k (2.79E-06) was used to compute Q Salt for all Phase 1 sites.

Site ID	Date	Lat- itude	Long- itude	Ele- vation (m)	k (cm µS^{-1})	Q Ref- erence (L s^{-1})	Q Float (L s^{-1})	Q Salt (L s^{-1})	Q Ber- noulli (L s^{-1})	% Error Float	% Error Salt	% Error Ber- noulli
1	02/03/17	27.78065	85.42426	1649		6.4	7.4	4.3	8.8	16	-34	37
2	18/04/17	27.78158	85.42385	1659		6.9	8.0	7.5	10	15	9	45
3	10/03/17	27.79649	85.42177	1905	2.76E-06	11	7.8	12	8.8	-28	10	-19
4	24/04/17	27.70026	85.22077	1406		17	19	19	18	11	13	5
5	22/03/17	27.57487	85.31314	1482	2.80E-06	18	20	24	19	12	38	5
6	19/04/17	27.77164	85.42657	1609		19	28	28	22	48	49	16
7	30/03/17	27.78691	85.32589	1364	2.57E-06	21	26	27	48	27	32	132
8	24/04/17	27.69620	85.23142	1382		23	9.5	25	6.3	-59	7	-73
9	19/04/17	27.75406	85.42170	1355		34	51	34		52	0	
10	19/04/17	27.77154	85.42680	1609		41	41	48	63	0	16	53
11	01/03/17	27.78483	85.44480	1877		104	111	85	101	7	-18	-3
12	22/03/17	27.57542	85.31268	1477	2.67E-06	111	106	115	116	-4	4	5
13	22/03/17	27.57410	85.31277	1481	2.83E-06	117	81	128	102	-31	10	-13
14	30/03/17	27.78627	85.32583	1356	2.74E-06	153	208	141	470	37	-7	208
15	02/03/17	27.78156	85.42383	1659		155	248	130	161	59	-16	4
16	18/04/17	27.78168	85.42373	1663		156	140	144	210	-10	-8	34
17	10/03/17	27.77932	85.42496	1653	2.80E-06	159	183	155	228	15	-2	43
18	11/03/17	27.78505	85.44473	1877	2.91E-06	208	221	216	150	7	4	-28
19	11/03/17	27.77514	85.43867	1806	3.02E-06	230	188	237		-18	3	
20	20/04/17	27.71106	85.35432	1313	2.78E-06	240	246	267	264	3	12	10
			avg * ->	1579	2.79E-06	92	97	92	111	8 (23)	6 (15)	26 (37)
			min ->	1313	2.57E-06	6.4	7.4	4.3	6.3	-59	-34	-73
			max ->	1905	3.02E-06	240	248	267	470	59	49	208
			std dev ->	190	1.22E-07	81	89	82	122	29	19	62

Table 3.5: Summary of (Phase 2) measurement comparison sites including salt dilution calibration co-efficient (k), resulting reference flows (Q Reference), "expert" streamflow measurement method flows (Q Float, Q Salt, and Q Bernoulli), and corresponding "expert" measurement errors. Date and time associated with "expert" measurements, and represent the time that the expert ODK form was started in the field. Latitude and longitude in reference to the WGS84 datum. All flow values shown are shown in L s^{-1} rounded to the nearest integer for values greater than or equal to 10 and to the nearest tenth place for values less than 10. Percent differences (errors) calculated using Q Reference (FlowTracker) as the actual flow. Data summarized at the bottom with average, minimum (min), maximum (max), and standard deviation (std dev). Note that averages (avg *) shown in the summary area near the bottom for the last three columns (i.e. percent errors) indicate biases with MAPEs shown in parentheses. Average k (2.95E-06) was used to compute Q salt for all Phase 2 and 3 sites.

Site ID	Date	Time	Latitude	Longitude	k (cm µS^{-1})	Slope (m m^{-1})	Q Reference (L s^{-1})	Expert Q Float (L s^{-1})	Expert Q Salt (L s^{-1})	Expert Q Bernoulli (L s^{-1})	Expert % Error Float	Expert % Error Salt	Expert % Error Bernoulli
D1	18/09/18	14:42	27.79246	85.37166	2.76E-06	0.099	137	150	134	122	10	-2	-11
D2	18/09/18	15:46	27.79263	85.37158	2.70E-06	0.091	253	364	258	356	44	2	41
D3	18/09/18	13:41	27.79213	85.37136	2.62E-06	0.076	417	551	500	396	32	20	-5
D4	18/09/18	12:44	27.79189	85.37162	2.69E-06	0.139	78	77	84	81	-1	7	3
D5	19/09/18	10:18	27.79071	85.36966	2.80E-06	0.148	184	243	207	287	32	12	56
D6	19/09/18	11:52	27.79052	85.36695	3.42E-06	0.134	36	84	47	88	132	30	146
D7	19/09/18	13:11	27.78791	85.36912	2.87E-06	0.126	55	60	86	52	10	56	-6
N1	20/09/18	17:35	27.56525	85.31356	2.90E-06	0.025	437	699	548	540	60	25	24
N2	20/09/18	16:59	27.56615	85.31214	3.37E-06	0.105	4.2	7.3	4.0	11	73	-5	158
N3	20/09/18	16:02	27.56935	85.31277	2.93E-06	0.075	340	392	548	445	15	61	31
N4	20/09/18	15:21	27.56916	85.31200	2.71E-06	0.091	25	40	27	33	61	8	33
N5	20/09/18	12:56	27.57328	85.31263	3.08E-06	0.022	407	607	700	545	49	72	34
N6	20/09/18	13:33	27.57408	85.31226	2.95E-06	0.055	105	151	103	136	44	-2	30
N7	20/09/18	11:50	27.57558	85.31269	3.35E-06	0.044	896	944	814	839	5	-9	-6
N8	20/09/18	10:59	27.57516	85.31345	3.11E-06	0.020	270	382	284	453	41	5	68
				avg * ->	2.95E-06	0.083	243	317	290	292	41 (41)	19 (21)	40 (43)
				min ->	2.62E-06	0.020	4.2	7.3	4.0	10.8	-1	-9	-11
				max ->	3.42E-06	0.148	896	944	814	839	132	72	158
				std dev ->	2.62E-07	0.043	235	281	265	244	34	26	51

sands. Smaller tributaries measured in the Nakkhu watershed (N2, N4, and N6) were also pool and drop stream types with slopes of 0.105, 0.091, and 0.055 m m-1, respectively. The remainder of the sites in the Nakkhu watershed were pool and riffle stream types with slopes ranging from 0.020 to 0.075 m m-1.

Box plots of CS Flow group errors combined with "expert" measurement errors for float (a), salt dilution (b), and Bernoulli (c) methods show that errors, for both "expert" and CS Flow groups, are least for the salt dilution method (Figure 3.4). The number of CS Flow group measurements used to develop individual box plots ranged from 6 to 12 for each site and totalled 117 for all 15 sites. Two groups measured site D3 twice, so even though there were only 10 groups, there were 12 measurements available for comparison for this site. For the remainder of sites (except N5), problems with either capturing, compressing, uploading, or interpreting the video of EC used for determining salt dilution flow limited the number of usable measurements to less than the number of groups (i.e. 10). MAPEs for CS Flow group measurements averaged 63, 28, and 131 %, while biases for all methods were positive, averaging 52, 7, and 127 % for float, salt dilution, and Bernoulli methods, respectively. Standard deviations of CS Flow group percentage errors were 82, 36, and 225 % for float, salt dilution, and Bernoulli methods, respectively.

For the float method (Figure 3.4.a), 13 median CS Flow group errors were pos-

itive, while two sites (i.e. D3 and N7) were negative. Float "expert" errors (i.e. red circles) were within the interquartile range (IQR; blue boxes between the first and third quartile) of CS Flow group errors for 10 out of 15 sites. One float "expert" error and 21 CS Flow group errors were over 100 %. Float error medians and distributions were more variable in the Dhobi watershed than the Nakkhu watershed. For the salt dilution method (Figure 3.4.b), seven median CS Flow group errors were positive, while eight were negative. Salt dilution "expert" errors (i.e. red circles) were within the IQR of CS Flow group errors for 7 out of 15 sites. Zero salt dilution "expert" errors and two CS Flow group errors were over 100 %. Salt dilution error distributions were more compact for the Dhobi watershed compared to the Nakkhu watershed. For the Bernoulli method (Figure 3.4.c), all 15 median CS Flow group errors were positive. Bernoulli "expert" errors (i.e. red circles) were within the IQR of CS Flow group errors for 3 out of 15 sites. Two Bernoulli "expert" errors and 50 CS Flow group errors were over 100 %. Similar to float results, Bernoulli error medians and distributions were more variable in the Dhobi watershed than the Nakkhu watershed.

Overall, citizen scientists ranked the float method most favourably (43.2 % of Rank 1 selections; average of blue bars) compared to Bernoulli and salt dilution methods, at 30.3 and 26.5 %, respectively (Figure 3.5). In contrast, citizen scientists ranked the salt dilution method least favourably (64.0 % of Rank 3 selections; average of tan bars) compared to Bernoulli and float methods, at 18.6 and 17.4 %, respectively. Most citizen scientists (72.7 %) thought the float method required the least amount of training (Q1), followed by the Bernoulli and salt dilution methods. Citizen scientists thought the Bernoulli method required the smallest investment in equipment (45.5 %; Q2), the fewest number of citizen scientists (54.5 %; Q3), and least amount of data recording (42.4 %; Q4). Additionally, citizen scientists found the float method to be the least complex (48.5 %; Q5), most enjoyable (60.6 %; Q6), and safest (42.4 %; Q7) method. Finally, most citizen scientists (75.8 %) thought the salt dilution method was most accurate (Q8), followed by the float and Bernoulli methods. The complete results from the survey are included as supplementary material.

3.3.3. Citizen Scientist Application Results (Phase 3)

Observed flows from the CS Flow campaign (n = 131 pre-monsoon; n = 133 post-monsoon) were distributed among the 10 perennial headwater catchments of the Kathmandu Valley and ranged from 0.4 to 425 L s^{-1} and 1.1 to 1804 L s^{-1} in the pre- and post-monsoon, respectively (Figures 3.6.a and 3.6.b). The three locations in the Kathmandu Valley where the Nepal Department of Hydrology and Meteorology (DHM) measures either water levels or flows (gauges) are included on Figures 3.6.a and 3.6.b to illustrate the difference in spatial resolutions between the two datasets. Note that only one of the three DHM gauging stations is in a headwater catchment (i.e. Bagmati). Histograms of flow (Fig 6.c and 6.d) and EC (Figures 3.6.e and 3.6.f) show the increase in flows and the expected decrease in EC from pre- to post-monsoon.
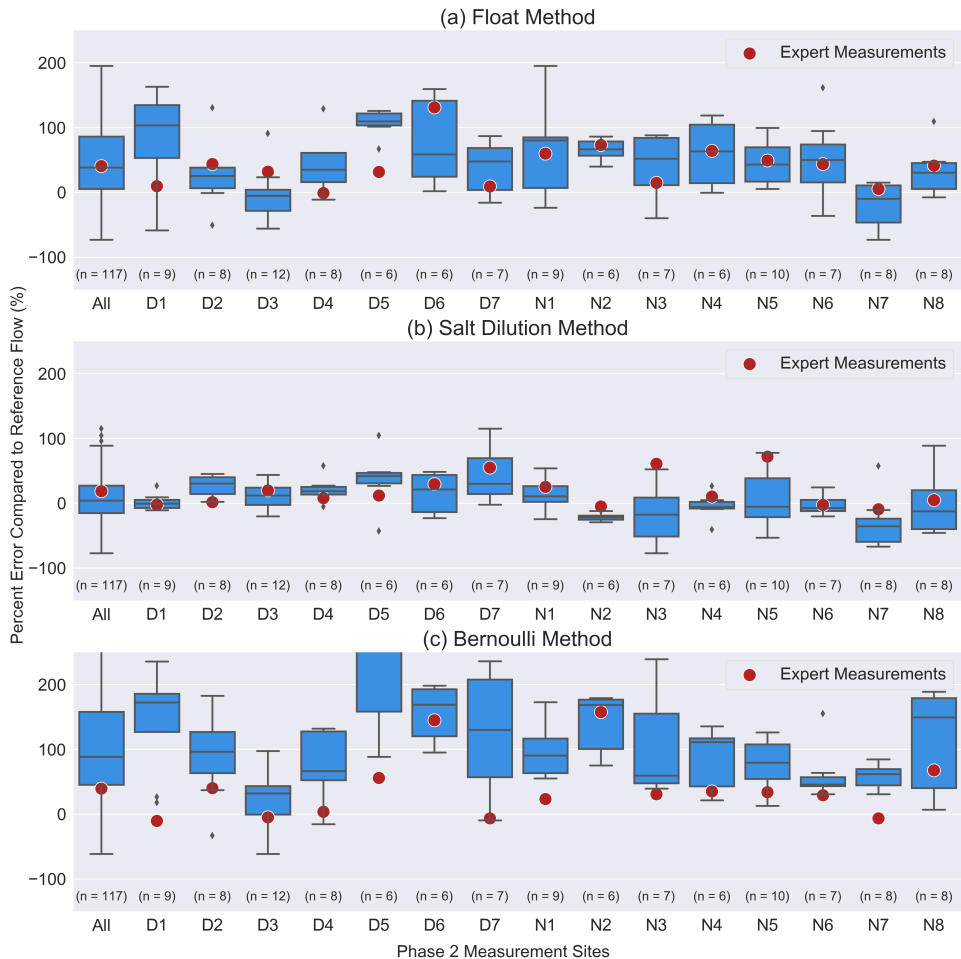
Figure 3.4: Box plots showing distribution of CS Flow group percent errors compared to reference flows for (a) float, (b) salt dilution, and (c) Bernoulli streamflow measurement methods. A summary of "All" measurements followed by the 15 Phase 2 measurement sites (i.e. D1 to D7 in the Dhobi watershed and N1 to N8 in the Nakkhu watershed) are shown on the horizontal axes. Percent errors for "expert" measurements for each site and method are shown as red circles. The "expert" measurements shown for "All" are the mean of all "expert" measurements for each method. Sample sizes for each method and each site are shown in parentheses above each site label. Boxes show the interquartile range between the first and third quartiles of the dataset, while whiskers extend to show minimum and maximum values of the distribution, except for points that are determined to be "outliers" (shown as diamonds), which are more than 1.5 times the interquartile range away from the first or third quartiles. To facilitate comparison between sub-panels, vertical axes are fixed from -150 to 250 percent. In certain cases, portions of the error distribution are outside of the fixed range (e.g. Site D5 for (c) Bernoulli method).

3.4. Discussion

Of the simple streamflow measurement methods evaluated in this paper, salt dilution provides the most accurate streamflow measurements for both "experts" and
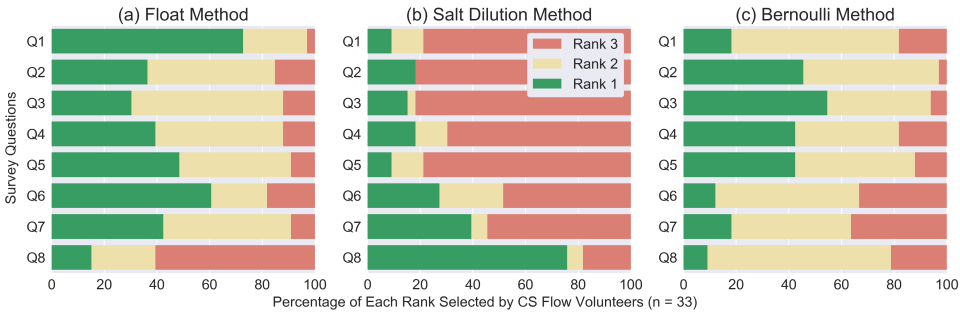
Figure 3.5: Results of the CS Flow group perception questions for (a) float, (b) salt dilution, and (c) Bernoulli methods. Questions Q1 through Q8 are shown on the vertical axis. Percentage of each rank selected by CS Flow citizen scientists (n = 33) are shown on the horizontal axis. Questions were worded so that in all cases, a rank of 1 was most favourable and 3 was least favourable. Questions are as follows (also included in Table 3.3): Q1 - Required training (1 least and 3 most); Q2 - Cost of equipment (1 least and 3 most); Q3 - Number of citizen scientists required (1 least and 3 most); Q4 - Data recording requirements (1 least and 3 most); Q5 - Complexity of procedure (1 least and 3 most); Q6 - Enjoyability of measurement (1 most enjoyable and 3 least enjoyable); Q7 - Safety (1 safest and 3 least safe); Q8 - Accuracy (1 most accurate and 3 least accurate).

Table 3.6: Summary of mean absolute percentage errors (MAPEs), mean percentage errors (MPEs), and standard deviations of percentage errors (Std Dev % Error) for Phase 1 and 2 measurements. All values shown as percentages rounded to the nearest integer.

Phase	Performed by	Metric	Float Method	Salt Dilution Method	Bernoulli Method
1	Authors	MAPE (%)	23	15	37
		MPE (%)	8	6	26
		Std Dev % Error (%)	29	19	62
2	"Expert" (Authors)	MAPE (%)	41	21	43
		MPE	41	19	40
		Std Dev % Error (%)	34	26	51
2	CS Flow Groups	MAPE (%)	63	28	131
		MPE	52	7	127
		Std Dev % Error (%)	82	36	225

citizen scientists alike. In both Phases 1 and 2, salt dilution method resulted in the lowest MAPEs and MPEs (or biases; Table 3.6) compared to float and Bernoulli methods.

3.4.1. Initial Evaluation Discussion (Phase 1)

Our first research question was: *Which simple streamflow measurement method provides the most accurate results when performed by "experts?"* Based on Phase 1 "expert measurements, we found that salt dilution had the lowest MAPE (i.e. 15 %), compared to float (i.e. 23 %) and Bernoulli (i.e. 37 %) methods, respectively (Table 3.4).

The largest salt dilution errors occurred for reference flows of 21 L s^{-1} or less, while float and Bernoulli errors appeared to be more evenly distributed through
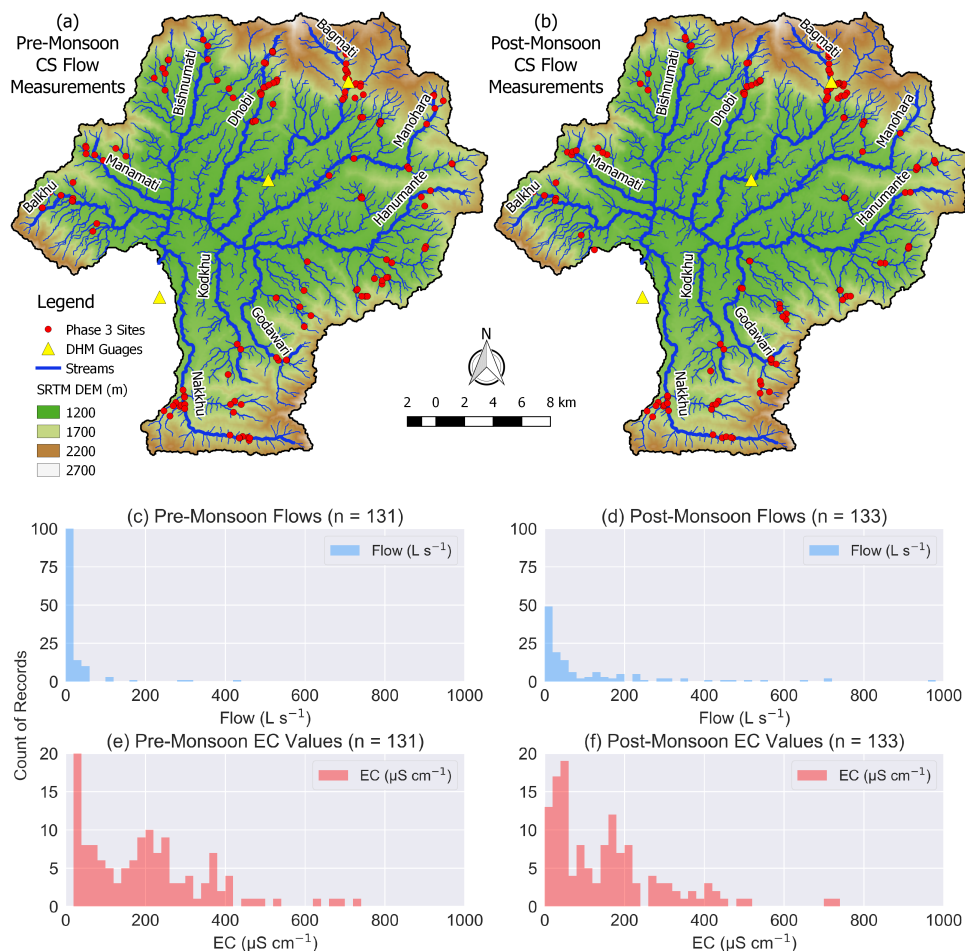
Figure 3.6: CS Flow campaign measurement locations (n = 131 pre-monsoon; n = 133 post-monsoon) within the Kathmandu Valley for (a) pre- and (b) post-monsoon. Histograms show distributions of measured flows in L s^{-1} ((c) and (d)) and EC in µS cm^{-1} ((e) and (f)). Bins are set to 20 units wide for both flow and EC. Three flow measurements for the post-monsoon (d) that were above 1000 L s^{-1} are not shown: 1059, 1287, and 1804. Three Department of Hydrology and Meteorology (DHM) gauging stations shown as yellow triangles.

the range of observed flows. Because salt dilution measurements of low flows require less salt and water, it is possible that larger relative measurement errors caused while measuring these small quantities led to larger overall measurement errors. However, this is not substantiated in Phase 2 results, so additional research is required in this area.

Our experience in the field was that float velocity measurements in slow moving and shallow areas were difficult to perform. The combination of turbulence and boundary layer impacts from the streambed and the overlying air mass often made

floating objects on the surface travel in non-linear paths, adding uncertainty to distance and time measurements. In the literature, challenges with applying the float method in shallow depths is supported by USBR [36] and Escurra [40], who showed that uncertainty in surface velocity coefficients (i.e. the ratio of surface velocity to actual mean velocity of the underlying water column; C from Equation 3.1) increased as depth decreased, especially below 0.3 m. The impacts of shallow depths on surface velocity coefficient C should be the focus on additional research.

A primary challenge we experienced with Bernoulli measurements was keeping the flat plate at the same vertical location while rotating the plate from parallel to perpendicular to the flow direction (Section 3.2.2). This was usually due to the bottom of the flat plate being set on a streambed consisting of sands and gravels that could be easily disturbed during rotation. Slow water velocities, and correspondingly small changes in Bernoulli depths (Equation 3.4) further compounded this issue. Adding a circular metal plate to the bottom of the flat plate used for Bernoulli depth measurements could help minimize these uncertainties.

Based on the ten measured k values in Phase 1, using an average k for all salt dilution measurements caused the largest percent difference in salt dilution flow (Equation 3.2) for site 7 (8.6 % increase in flow) followed by site 19 (7.6 % decrease in flow). For Phase 2, using average k values for all salt dilution measurements caused the largest percent difference in salt dilution flow (Equation 3.2) for site D6 (13.7 % decrease in flow) followed by site D3 (12.6 % increase in flow). Because observed MAPE distributions from Phase 1, and especially Phase 2, are larger than percent errors introduced by using average k values (sometimes by more than an order of magnitude), we do not think our overall findings are negatively impacted by using average k values. However, because of the sensitivity of salt dilution measurements to k (Equation 3.2), future work should focus on improving understanding of the variables affecting k. Specifically, spatial and temporal variability in k due to changes in stream water chemistry should be investigated prior to applying the salt dilution methodology described in this paper in other areas. For citizen science projects in other areas, we recommend that locally appropriate average k values be determined from measurements at multiple sites to understand spatial variability. Additional k measurements should also be repeated in different seasons to understand temporal variability.

3.4.2. Citizen Scientist Evaluation Discussion (Phase 2)

Our second research question was: *Which simple streamflow measurement method provides the most accurate results when performed by citizen scientists?* Based on Phase 2 citizen scientist measurements, we found that salt dilution had the lowest MAPE (i.e. 28 %) compared to float (i.e. 63 %) and Bernoulli (i.e. 131 %) methods, respectively (Figure 3.4 and Table 3.6).

While MAPE distributions for citizen scientists followed the same trend to that of "expert" measurements, the relative increases in errors for float (41 to 63 %; increase of 54 %) and Bernoulli (43 to 131 %; increase of 205 %) were larger than that of salt dilution (21 to 28 %; increase of 33 %). This could be due in part to the fact that salt dilution measurement errors may be less sensitive to a lack of field

data collection experience. For example, as long as turbulent mixing conditions are present (which can be controlled by proper site selection during the experimental design phase), citizen scientists can primarily introduce errors into salt dilution measurements by (1) making mistakes in measurement or recording of amounts of salt and/or water used to prepare tracer solutions, (2) not thoroughly mixing tracer solution until all salt is dissolved, (3) not providing enough distance between salt injection and EC measurement points (recommended as 25 stream widths by Day [46], Butterworth et al. [47], and Moore [42]), or (4) recording videos of EC changes that are difficult to read. Each of these sources of error can be minimized by implementing relatively easy to follow protocols like "be sure to mix the salt and water until you can't see the salt any longer." In contrast, while performing float and Bernoulli measurements, citizen scientists need to accurately characterize (1) average stream depth, (2) stream width, and (3) average water velocity. Characterizing average depth and velocity requires several individual measurements, each coming with the chance of introducing measurement errors. Additionally, selecting the number of sub-sections required, and selected representative locations for each of these sub-sections can be difficult, even for people with extensive streamflow data collection experience. These factors may help explain the wider error distributions observed in float and Bernoulli methods compared to salt dilution (Figure 3.4). Additional training might also help to close the observed differences between salt dilution error distributions and that of float and Bernoulli methods.

Our third research question was: *What are citizen scientists' perceptions of the required training, cost, accuracy, etc. of the evaluated simple streamflow measurement methods?* Based on a survey of 33 citizen scientists, we found that volunteers ranked the float method most favourably (43.2 % of Rank 1 selections) compared to Bernoulli and salt dilution methods, at 30.3 and 26.5 %, respectively (Figure 3.5).

Regarding question number 4 from the perception survey (i.e. data recording requirements), it is interesting to note that salt dilution received the least favourable ranking, meaning that citizen scientists perceived salt dilution to require the greatest amount of data. Our perception was that salt dilution, in terms of individual pieces of information, requires the least amount of data recording. This ranking may be explained by either (1) the amount of meta data collected about salt dilution measurements (i.e. GPS and photos of salt injection and EC measurement locations; see Section 3.2.4 and supplementary material for details) or by (2) citizen scientists' perception of using a digital EC meter and smartphone video as recording lots of individual pieces of data, when in some ways a video can be thought of as a single observation. Whereas results from float and Bernoulli method measurements are available immediately in the ODK from, the post processing requirements of EC breakthrough curve data to solve for salt dilution flow may also lead to the perception that salt dilution measurements have higher data recording requirements.

Citizen scientists ranked float method safest, followed by salt dilution, and finally Bernoulli. We found this result to be somewhat counter intuitive, because salt dilution is the only method that can be performed without entering the stream, whereas for float and Bernoulli measurements the entire stream must be waded across to

get depth and velocity data. Because the perception survey was performed after Phase 2 evaluations where all three methods were performed consecutively, it may not have been obvious to citizen scientists that salt doses could be obtained without entering the stream from visual estimates of channel width, depth, and water velocity.

In terms of perceived measurement accuracy (question 8), 75.8 % of citizen scientists ranked salt dilution as the most accurate method. This ranking was performed before any quantitative results were reviewed. Our experience is that reading a value from a digital meter often gives an unfounded sense of measurement accuracy. Salt dilutions' perceived accuracy may be due to it being the only method that directly involves a digital measurement device (i.e. EC meter).

"Expert" MAPEs for float, salt dilution, and Bernoulli increased from 23, 15, and 37 % in Phase 1 to 41, 21, and 43 % in Phase 2. For the float method, this increase in error may be partially explained by the overall increase in flows from pre-monsoon (Phase 1; average reference flow of 92 L s^{-1}) to post-monsoon (Phase 2; average reference flow of 243 L s^{-1}). Our experience was that increased flow and velocity in high gradient headwater streams made it more difficult to perform float measurements. This was mostly due to an increase in turbulence resulting in more non-linear flow lines and increased relative measurement uncertainty for shorter float times (assuming distances were held constant). For the Bernoulli method however, our hypothesis was that increased velocities would on average reduce measurement errors, because of decreased relative measurement uncertainty for larger Bernoulli depth changes. This hypothesis however was not supported by the data. The challenge of pulsing flows which require citizen scientists to visually average short period (i.e. seconds or less) water level fluctuations may also counteract the otherwise larger Bernoulli depth changes. We do not have any explanations for the overall increase in salt dilution method MAPE from 15 to 21 % from Phase 1 to Phase 2. Unlike the Phase 1 results, we also do not see a concentration of larger errors at the lower reference flows in Phase 2.

3.4.3. Citizen Scientist Application Discussion (Phase 3)

To proceed with Phase 3, we had to select a preferred simple streamflow measurement method. Based on the results from Phases 1 and 2, the salt dilution method had the lowest MAPEs, biases, and standard deviations of percentage errors for both "experts" and citizen scientists. Therefore, from an accuracy perspective, salt dilution was the preferred approach. However, the results of our perception survey showed that citizen scientists thought the float method was most enjoyable (Q6) and required the least amount of training (Q1). Another important consideration was that salt dilution is the only method that does not require citizen scientists to enter and cross the stream, and therefore can be safely performed over a broader range of flow conditions. While the enjoyment of measurements is an important motivational factor for citizen scientists, we concluded that accuracy and safety were ultimately more important. Considering all these factors, we selected the salt dilution method as the preferred approach.

Finally, our fourth research question was: *Can citizen scientists apply the se-*

lected streamflow measurement method at a larger scale? Based on measurements from pre- (n = 131) and post-monsoon (n = 133) in the Kathmandu Valley, citizen scientists can apply salt dilution streamflow measurements at a larger scale; however, challenges of recruiting, training, and motivating citizen scientists, along with data management issues require further investigation.

The CS Flow campaigns provided us with a unique opportunity to evaluate the preferred salt dilution streamflow measurement method with more people at more sites. In addition to the valuable streamflow data that will help us characterize the water supply situation in the Kathmandu Valley with greater precision for pre- and post-monsoon periods, we also learned several practical lessons about how to scale citizen science-based streamflow measurements. For example, our experience was that digitizing breakthrough curves from ODK captured EC videos took roughly 15 to 30 minutes per site, depending on video length and quality. Additionally, managing EC change videos can be a significant challenge if videos are recorded at a smartphones' native resolution. In some cases, each minute of high definition video can be nearly 100 MB. Uploading such large files, and subsequently storing and accessing them can be challenging and costly. These difficulties can be solved by improved training and protocols regarding video collection settings and, when necessary, video compression.

3.5. Conclusions and Future Work

Compared to float and Bernoulli, the salt dilution method consistently yielded the most accurate streamflow measurement results for authors and citizen scientists alike. Given ongoing global declines in the amount of streamflow data being collected by traditional entities, salt dilution measurements performed by young researchers and citizen scientists could play an important role in closing this data gap. While globally applicable, this is especially true for headwater catchments in low resource settings.

With regards to young researchers (i.e. science and engineering minded students from primary through graduate school ages), performing salt dilution streamflow measurements has the benefits of (1) filling data gaps and (2) improving the quality and applicability of students' educational experience. We suggest that science and engineering educators should make smartphone-based data collection activities a core component of their curricula. Moreover, these data should be collected together with globally active partners to ensure standardization and open access to data.

As a step in this direction, S4W and S4W-Nepal in partnership with local educators are working towards broader applications of salt dilution streamflow measurements in Nepal and beyond. Importantly, variability in the calibration coefficient (k) should be evaluated over larger ranges of time, geology, and water quality. Another practical challenge requiring specific attention is the transfer, management, and digitization of break through curve video files. The information content of additional headwater streamflow data should be explored, especially regarding the trade-offs between observation density and accuracy. Efforts should focus on how to effectively recruit and motivate young researchers and citizen scientists to par-

ticipate in citizen science streamflow measurements. Lastly, emphasis should be placed on exploring these and other citizen science related questions in the relatively unexplored Asian context.

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4

Soda Bottle Science

Come on with the rain
I've a smile on my face
I'll walk down the lane
With a happy refrain
Just singin'
Singin' in the rain

Don Lockwood

Citizen science, as a compliment to ground-based and remotely-sensed precipitation measurements, is a promising approach for improving precipitation observations. During the 2018 monsoon (May to September), Smart-Phones4Water (S4W) Nepal - a young researcher-led water monitoring network - partnered with 154 citizen scientists to generate 6,656 precipitation measurements in Nepal with low-cost (< 1 USD) S4W gauges constructed from repurposed soda bottles, concrete, and rulers. Measurements were recorded with Android-based smartphones using Open Data Kit Collect and included GPS-generated coordinates, observation date and time, photographs, and observer-reported readings. A year-long S4W gauge intercomparison revealed a -2.9 % error compared to the standard 203 mm (8-inch) gauge used by the Department of Hydrology and Meteorology (DHM), Nepal. We analyzed three sources of S4W gauge errors: evaporation, concrete soaking, and condensation, which were 0.5 mm day^{-1} (n = 33), 0.8 mm (n = 99), and 0.3 mm

(n = 49), respectively. We recruited citizen scientists by leveraging personal relationships, outreach programs at schools/colleges, social media, and random site visits. We motivated ongoing participation with personal follow-ups via SMS, phone, and site visit; bulk SMS; educational workshops; opportunities to use data; lucky draws; certificates of involvement; and in certain cases, payment. The average citizen scientist took 42 measurements (min = 1, max = 148, stdev = 39). Paid citizen scientists (n = 37) took significantly more measurements per week (i.e. 54) than volunteers (i.e. 39; alpha level = 0.01). By comparing actual values (determined by photographs) with citizen science observations, we identified three categories of observational errors (n = 592; 9 % of total measurements): unit (n = 50; 8 % of errors; readings in centimeters instead of millimeters); meniscus (n = 346; 58 % of errors; readings of capillary rise), and unknown (n = 196; 33 % of errors). A cost per observation analysis revealed that measurements could be performed for as little as 0.07 and 0.30 USD for volunteers and paid citizen scientists, respectively. Our results confirm that citizen science precipitation monitoring with low-cost gauges can help fill precipitation data gaps in Nepal and other data scarce regions.

4

4.1. Introduction

Precipitation is the main terrestrial input of the global water cycle; without it, our springs, streams, lakes, and communities would gradually disappear. Understanding spatial and temporal distributions of precipitation is therefore critical for characterizing water and energy balances, water resources planning, irrigation management, flood forecasting, and several other resource management and planning activities [2]. However, observing, and moreover understanding, precipitation variability over space and time is fraught with difficulty and uncertainty. Because of these challenges, there are persistent, but spatially heterogeneous, precipitation data gaps that need to be addressed [3].

Accuracy is a primary concern, even for common precipitation measurement methods ([4], [5]) including: manual and automatic gauges, radar, and satellite remote sensing. Manual and automatic gauges are expensive to maintain and thus generally do not lead to adequate spatial representations of precipitation (e.g. [6]). For example, the total area of all the rain gauges in the world is less than half a football field [3], or 0.000000002 % of the global terrestrial landscape. Precipitation radars can provide meaningful data between gauges, but are subject to errors from beam blockage, range effects, and imperfect relationships between rainfall and backscatter [3]. Additionally, radars are expensive and operate by line of sight, so spatial cover of radar in mountainous terrains like Nepal can be limited. Satellite remotely sensed precipitation products have the benefit of global coverage, but can be impacted by random errors and bias (e.g. [7]) arising from the indirect linkage between the observed parameters and precipitation and imperfect algorithms [8]. Clearly, there remain precipitation data gaps and uncertainties that need to be filled.

Low-cost sensors and consumer electronics can play a role in closing these data gaps ([9], [10]). In general, the potential of low-cost sensors to improve understanding of a process depends on the interplay between (1) the spatial heterogeneity of the process being observed, (2) the impacts on accuracy of the low-cost sensor, and (3) the observational cost savings. The need for higher density observations increases as the spatial heterogeneity of the process being observed increases. So, if (1) the observed process has high spatial heterogeneity, and (2) the low-cost sensor provides high accuracy, with (3) high cost savings, the potential of the low-cost sensor to improve understanding of the process is considered high. Alternatively, if (1) the observed process has low spatial heterogeneity, and (2) the low-cost sensor has low accuracy measurements, with (3) small cost savings, the potential of the low-cost sensor to improve understanding of the process is considered low.

Citizen science has emerged as a promising tool to help fill data gaps. At the same time, citizen science can improve overall scientific literacy and reconnect people with their natural resources. McKinley et al. [11] define citizen science as "the practice of engaging the public in a scientific project." They go on to clarify that crowdsourcing is another way for public participation in science through "... large numbers of people processing and analyzing data." Notable examples of citizen science precipitation monitoring include: the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS: www.cocorahs.org); Weather

Underground (www.wunderground.com); Met Office Weather Observation Website (WOW: wow.metoffice.gov.uk/); UK Citizen Rainfall Network [12]; the NOAA Citizen Weather Observer Program (CWOP: wxqa.com); and an internet-connected amateur weather station network called Netatmo (www.netatmo.com, [13]) [3]. The following paragraphs describe CoCoRaHS and the history of citizen science based precipitation monitoring efforts in Nepal in greater detail.

Launched in the spring of 1998 by the Colorado Climate Center at Colorado State University, CoCoRaHS is a volunteer-led precipitation monitoring effort [14]. Volunteers measure daily precipitation with a standardized 102 mm (4-inch) gauge [15] and report their data via an online system. While CoCoRaHS was established in response to small scale flash floods, it has grown into the world's largest volunteer precipitation monitoring network, with over 20,000 active observers in the United States, Canada, the U.S. Virgin Islands, the Bahamas, and Puerto Rico [16].

In Nepal, three specific attempts have been made to launch citizen science precipitation measurement campaigns. The first was a single year effort in 1998 initiated by Nepali scientists Ajaya Dixit and Dipak Gyawali who partnered with community members to measure rainfall in the Rohini River watershed, a tributary to the Ganges, in south-central Nepal. The second was launched by Recham Consulting in 2003, and included 17 gauges similar to US National Weather Service 203 mm (8-inch) gauges in the Kathmandu Valley. However, the project stalled after only a few years of data collection. The third, Community Based Rainfall Measurement Nepal (CORAM-Nepal), was launched in 2015 with seven high schools in the Kathmandu Valley [17]. CORAM's approach to obtain rainfall data is to partner with local high school science teachers and students, but other community members were also welcome to participate. CORAM-Nepal uses standard 102 mm (4-inch) CoCoRaHS gauges and collects data from schools monthly by phone call or site visits. All of these previous efforts grappled with the challenges of sustainable (1) funding, (2) human resources, and (3) technological issues related to data collection, quality control, data storage, analysis, and dissemination of precipitation data.

What is needed is a sustained effort to monitor precipitation via citizen scientists. To achieve sustainability, such an effort needs to be both accurate and cost effective. The latter part may be attainable through leveraging low-tech MacGyver-type solutions - but only if they lead to accurate and reproducible observations. This paper focuses on S4W-Nepal's 2018 monsoon (May through September) precipitation monitoring efforts using decidedly low-tech gauges (in contrast to high-tech approaches like Netatmo). All of S4W's efforts, including the research herein, have a focus on low-cost MacGyver-type sensors and field data collection methods that can be standardized, and cost effectively scaled, so that young researchers and citizen scientists alike can help fill water data gaps in data scarce regions.

Our research questions can be organized into two primary categories: (1) low-cost S4W precipitation gauge analyses and (2) citizen scientist involvement.

1. **S4W precipitation gauge analyses**

    (a) What are the types and magnitudes of errors for S4W's low-cost precipitation gauge?

(b) How do precipitation measurements from S4W's low-cost gauge compare to other commonly used gauges, including the Department of Hydrology and Meteorology (DHM), Nepal standard gauge?

2. **Citizen scientist involvement**

(a) How effective were our methods of recruiting citizens to join the monsoon precipitation monitoring campaign?

(b) How effective were our methods of motivating citizens to continue taking daily precipitation measurements?

(c) What were the types and frequencies of common citizen scientist observation errors?

(d) What were the average costs per observation for citizen scientists, and did this relate to citizen scientist performance?

4.2. Context and Study Area

To answer our research questions, S4W-Nepal launched a 2018 monsoon precipitation monitoring campaign; 154 citizen scientists generated 6,656 precipitation measurements using low-cost (< 1 USD) S4W gauges constructed from repurposed soda bottles, concrete, and rulers. Measurements were recorded with smartphones using an Android-based application called Open Data Kit (ODK; https://opendatakit.org/) Collect, and included GPS-generated coordinates, observation date and time, photographs, and citizen scientist reported readings. Measurements were primarily in the Kathmandu Valley and Kaski District of Nepal (Figure 4.1).
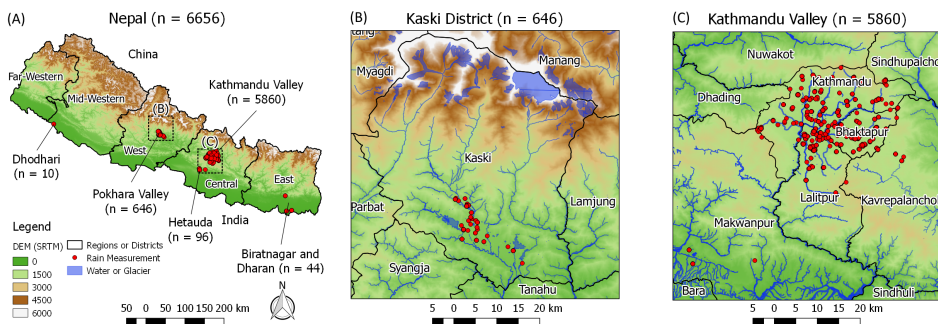
Figure 4.1: Map showing locations of 2018 Monsoon (May to September) precipitation measurements with the number of measurements shown in parentheses for (A) Nepal, with enlarged views of (B) the Kaski District, including the Pokhara Valley, and (C) the Kathmandu Valley. Topography shown from a Shuttle Radar Telemetry Mission (SRTM) 90-m digital elevation model (DEM) [18].

Precipitation in Nepal is highly heterogeneous, both spatially and temporally. Spatial variability of precipitation in Nepal is driven by (1) strong convection and (2) orographic effects [19]. Temporal fluctuations are mostly due to the South Asian summer monsoon (June to September) - a south to north moisture movement perpendicular to the Himalayas (Figure 4.1) along the southern rim of the

Tibetan Plateau ([20], [21]). Roughly 80 % of Nepal's (and South Asia's in general) precipitation occurs during the summer monsoon ([22], [23]). Annual precipitation in Nepal varies spatially by more than an order of magnitude, ranging from 250 mm on the northern (leeward) slopes of the Himalayas to over 3000 mm around Pokhara in the Kaski District [22]. In general, both (1) the percentage of annual rainfall occurring during the summer monsoon rainfall and (2) total annual precipitation decrease from the center of the country westward. About 88 % of our 2018 monsoon measurements were performed in Nepal's Kathmandu Valley. Within the Kathmandu Valley, average monsoon precipitation (42-year average) is 1040 mm [17], with average annual precipitation being roughly 1300 mm at Tribhuvan International Airport. Thapa et al. [24] state that average annual precipitation ranges from roughly 1500 mm in the Valley floor to 1800 mm in the surrounding hills.

4.3. Methods and Materials

4.3.1. S4W Rain Gauge

Construction and Use

S4W gauges were constructed from of recycled clear plastic bottles (e.g. 2.2-liter Coke or Fanta bottles in Nepal) with 100 mm diameters, concrete, rulers, and glue (Figure 4.2A). A tutorial video describing how to construct an S4W rain gauge is available on S4W's YouTube channel (https://bit.ly/2sItFTh; Nepali language only). The clear plastic bottles had uniform diameters for at least 200 mm from near the base towards the top; bottles with non-uniform cross sections were not used. Concrete was placed in the bottom of the bottle up to the point where the uniform cross section begins. The concrete provided a level reference surface for precipitation measurements. The additional weight from the concrete also helped to keep the gauge upright during windy conditions. Bottle lids were cut off at the point towards the top of the bottle where the inward taper begins. This lid was then inverted and placed on top of the gauge in an attempt to minimize evaporation losses - which can be a major source of rain gauge error [25]. A simple measuring ruler of sufficient length with millimeter graduations was glued vertically onto the side of the bottle. The ruler was placed with the zero mark at precisely the same level as the surface of the concrete. In order to minimize variability and possible introduction of errors, all gauges used in this investigation were constructed by S4W-Nepal. Each S4W gauge costs less than one USD in terms of materials and takes roughly 15 minutes to make (assuming a minimum of 10 gauges are constructed at a time).

S4W gauge design is similar to what Hendriks [26] proposed as a low-budget rain gauge, except that the addition of a solid base and measuring scale enabled direct measurements of precipitation depths, thus eliminating the need to measure water volumes. Similar low-cost funnel-type gauges have also been used extensively in rainfall partitioning studies ([27], [28], [29], [30]).

Precipitation measurements were performed by citizen scientists using an Android smartphone application called Open Data Kit Collection (ODK Collect; [31]). Video tutorials of how to install and use ODK and perform S4W precipitation measurements are available on S4W's YouTube channel (https://bit.ly/2Rdtadx; Nepali

Figure 4.2: (A) Repurposed plastic bottle after placement of concrete, ruler, and inverted lid. (B) S4W gauge installed on the roof of a house in the Balkhu watershed (western Kathmandu Valley). The S4W-Nepal young researcher (dark jacket) is training the citizen scientist (white shirt) to take a precipitation measurement. After selecting the parameter to measure, the citizen scientist (C) entered their observation of precipitation (mm) and (D) took a picture of the water level in the S4W rain gauge before emptying it. Each record was reviewed by S4W-Nepal staff to ensure that the numeric entry from the citizen scientist (C) matches the photographic record of the observation (D). Any observed discrepancies were corrected, and records of edits were maintained.

language only). Citizen scientists collected the precipitation data presented in this paper by performing the following steps:

1. S4W gauges were installed in locations with open views of the sky (e.g. Figure 4.2B)

    (a) Gauge heights above ground surface ranged from 1 meter (m) in rural areas to over 20 m (on rooftops) in densely populated urban areas

2. An inverted lid without a cap (i.e. Cap1; see Section 4.3.1 below) was used to minimize evaporation losses Measurements were performed as often as daily but sometimes less frequently

3. ODK was used to record date, time, and GPS coordinates

4. Gauges were removed from their stands and placed on a level surface

5. Precipitation readings were taken as the height of the lower meniscus of the water level within the bottle with the gauge placed on a level surface

6. A numeric reading of precipitation level was entered into ODK in millimeters (mm; Figure 4.2C)

7. ODK was used to record a photograph of the water level with the smartphone camera level to the water surface (Figure 4.2D)

8. Water was quickly dumped from the gauge to ensure that all ponded water above the concrete surface was removed but moisture within the concrete was retained

9. The measurement was saved locally to smartphone memory and sent to the S4W-Nepal ODK Aggregate server running on Google App Engine

    (a) ODK was designed to work offline (i.e. without cellular connection) and can be configured to automatically or manually send data after connection is restored

Error Analysis

The World Meteorological Organization [32] identified the following primary error sources for precipitation measurements (estimated magnitudes in parentheses): evaporation (0 to 4 %), wetting (1 to 15 %), wind (2 to 10 % for rain), splashing in or out of the gauge (1 to 2 %), and random observational and instrument errors. The first three sources of errors are all systematic and negative [32]. Because of the S4W gauge design, we separated wetting into concrete soaking and condensation on the clear plastic walls. The resulting categories of S4W gauge errors included: (1) evaporation, (2) concrete soaking, (3) condensation, and (4) other. Unlike some observation errors, which can be identified and corrected from photographs, gauge related errors must be understood and, if possible, systematically corrected. The following sections provide additional details regarding the first three sources of gauge errors related to the S4W gauge being low-cost and nonstandard in nature. While all gauge errors were originally measured by differences in mass, all errors were converted to an equivalent depth (mm) for comparison. It should be noted that other rainfall gauge related errors, such as errors in construction of the gauge, errors related to placement of the gauge (e.g. a gauge installed too close to a building or below vegetation), or errors related to maintenance of the gauge (e.g. clogging) were not analyzed but are described in more detail below.

Evaporation Errors

For manually read gauges, evaporation errors occur when precipitation evaporates from the rain gauge prior to taking a reading. Gauge design, weather, and the duration between precipitation events and gauge readings all impact the magnitude of the evaporation errors. To assess evaporation errors for S4W gauges, we performed evaporation tests between June 5th and August 23rd, 2018. We evaluated the impact of the following three rain gauge cover configurations on evaporation losses: (a) Open (i.e. no lid), (b) Cap1 (i.e. lid without cap), and (c) Cap2 (i.e. lid with cap and 7 mm hole; Figure 3). We randomly selected three gauges for each of these cover configurations for a total of nine gauges. With these nine gauges, we performed eleven sets of 24-hour evaporation measurements yielding a total of 99 evaporation observations (i.e. 33 for each cover configuration).

We performed an initial investigation to see if the depth of water in the gauge had a noticeable impact on evaporation losses. We investigated two water depths (i.e. 10 mm and 30 mm) that corresponded to commonly observed rainfall events
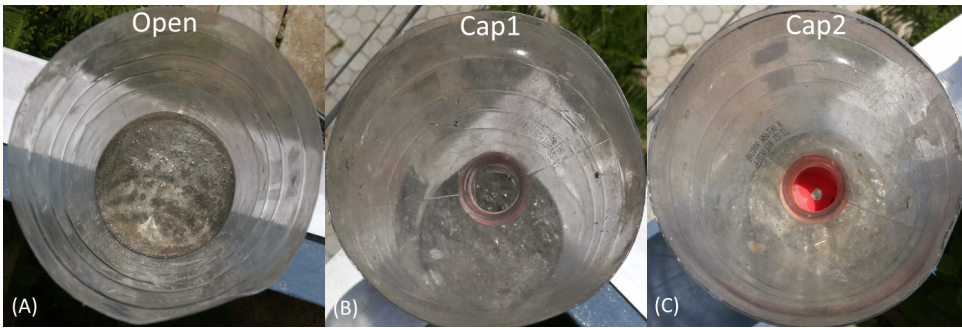
Figure 4.3: Three different rain gauge cover configurations for evaporation measurements. Open (A) is completely open to the atmosphere. Cap1 (B) has the original top of the bottle inverted and placed back on top of the gauge. Cap2 (C) has the same cover but also includes the original soda bottle cap with a 7 mm punched or drilled hole in the center to allow precipitation to enter the gauge. The resulting areas open to evaporation were roughly 7850, 530, and 40 mm^2 for Open, Cap1, and Cap2 covers, respectively. The diameters of the cover and the lower portion of the gauge are the same, but the thickness of the plastic material causes a tight connection between the cover and the gauge.

in the Kathmandu Valley. Our initial results showed that evaporation losses were not noticeably different between the 10 mm and 30 mm depths, so we used 30 mm depths for the remainder of the tests.

During each 24-hour period, all nine gauges were set on the roof of the S4W-Nepal office in Thasikhel, Lalitpur (https://goo.gl/maps/oq81TwPAZnk) in a place with full exposure to the sun and wind. If precipitation occurred during the 24-hour period, the experiment was cancelled and restarted the following day. We used an EK1051 [Camry] electronic weighing scale (accuracy $\pm$ 1 g $\approx$ $\pm$ 0.08 mm) to determine evaporation losses by measuring the mass of the gauges before and after each successful (i.e. no precipitation) 24-hour period.

Concrete Soaking Errors

As previously described, S4W gauges have a concrete base. As a semi-porous media, concrete requires a certain amount of moisture prior to saturation and subsequent ponding or accumulation of water above the concrete surface. The amount of water absorbed prior to ponding is a function of the concrete mixture (e.g. type and ratio of materials, etc.), the volume of concrete, and the initial moisture content of the concrete. The depth of precipitation read from S4W gauges represents only precipitation that accumulates above the concrete surface. Any precipitation that soaks into the concrete itself was not included in gauge readings. Therefore, concrete soaking represented a systematic negative error.

To evaluate soaking, we used an EK1051 [Camry] electronic weighing scale to measure the mass of the nine gauges used in the evaporation tests in both dry and saturated conditions. For the first set of measurements, the concrete had cured and dried for 30 days and no additional water beyond the amount initially needed for making the concrete mixture had been introduced to the gauge. To saturate the concrete, approximately 100 mm of water was added to the gauge and left for

a period of 24 hours. Subsequent soaking measurements were performed after drying the gauges in sunlight for periods ranging between one and three days.

Condensation Errors

For S4W gauges with Cap1 and Cap2 covers, condensation accumulated on the clear plastics sides of the rain gauge. Because we used weight as a measurement to quantify evaporation losses, condensation was not included as a loss; only water that fully exited the rain gauge was considered an evaporation loss. However, water that evaporates and subsequently condenses on the gauge walls causes a lowering of the ponded water level, or the amount of moisture within the concrete if no ponded water is present. Therefore, condensation constitutes a systematic negative error in S4W gauge readings.

To evaluate condensation, we filled the same nine gauges with roughly 5 mm of water and covered them with a Cap2 cover. The gauges were placed in the sun for approximately two hours to allow condensation to develop. Condensation was removed from gauges by wiping the inside of each gauge completely dry with a paper towel, ensuring that any remaining ponded water at the bottom was avoided. We determined condensation with an EHA501 [Camry] electronic weighing scale (accuracy $\pm$ 0.1 g $\approx$ $\pm$ 0.008 mm) by measuring the mass difference between each saturated and dry paper towel.

Other Errors Not Included in this Analysis

Differences in gauge installation can impact precipitation measurements. For example, gauge height can influence systematically negative wind-induced errors [33], or cause splash into the gauge. Wind-induced errors average between 2 and 10 % and increase with decreasing rainfall rate, increasing wind speed, and smaller drop size distributions [34]. Gauges that are not installed level will also cause an undercatch. The suitability of all gauge installation locations used in this paper were evaluated by S4W-Nepal staff by reviewing pictures of each gauge installation. Any issues identified from pictures were communicated directly to citizen scientists via personal communication (SMS, phone call, or site visit) and corrective actions were taken. However, installation errors are not the focus of this work and the data collected to date were insufficient to characterize these errors; therefore, gauge installation errors were not analyzed.

Gauge construction quality can also introduce errors. If future studies use gauges constructed by citizen scientists themselves (not the case in this study), the errors related to differences in construction quality should be considered.

Other possible maintenance or observation errors that may impact citizen scientists' measurements include: clogging of gauge inlets, incomplete emptying of gauges, and taking readings on unlevel surfaces. Effective training and follow-up is likely the key to minimizing such errors, so future work should explore different training approaches and their efficacy for various audiences. Training approaches should also consider scalability; for example, site visits become impractical if there are 1000 participants.

Comparison to Standard Rain Gauges

To evaluate the accuracy of S4W gauges, a comparison with three other gauges (within 5 meters) was performed in Bhaisepati, Lalitpur, Nepal from May 1st, 2017 to April 30th, 2018 (Figure 4.4). Measurements were generally taken within 12 hours of the end of each precipitation event, and in the morning or evening to minimize condensation errors. Other gauges included an Onset Computer Corporation Hobo Tipping Bucket RG3-M Rain Gauge (Onset), a manually read Community Collaborative Rain, Hail, and Snow Network standard gauge (CoCoRaHS), and a manually read standard 203 mm (8-inch) diameter Nepali Department of Hydrology and Meteorology gauge (DHM; similar to US National Weather Service 203 mm (8-inch) gauges). The Onset gauge measured the date and time of every 0.2 mm of precipitation from June 3rd to November 23rd, 2017.
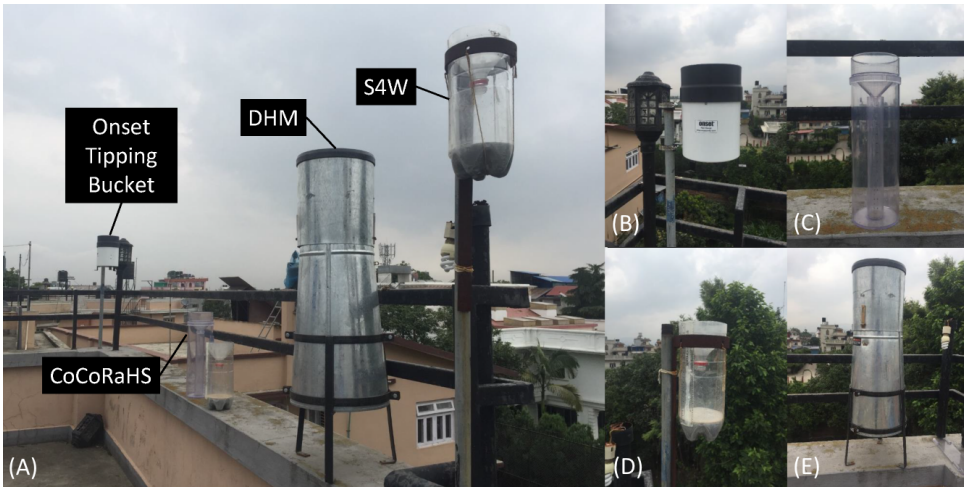
Figure 4.4: Comparison between (A) four different gauges including: (B) Onset Computer Corporation Hobo tipping bucket, (C) Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) standard 102 mm (4-inch) diameter gauge, (D) S4W gauge, and (E) the Nepali Department of Hydrology and Meteorology (DHM) standard 203 mm (8-inch) diameter gauge (similar to US National Weather Service 203 mm (8-inch) gauge).

We used DHM gauge measurements as the reference or actual value of precipitation. Because Onset data were not available for the entire year period (i.e. May 1st, 2017 to April 30th), cumulative errors for the Onset gauge are not presented. Only fully overlapping data sets between DHM and Onset are used. Based on DHM measurements, we filtered data into three precipitation event ranges (i.e. 0 to 5 mm, 0 to 25 mm, and 0 to 100 mm), yielding a total of nine scatter plots between DHM measurements and S4W, CoCoRaHS, and Onset measurements. The different precipitation ranges were used to understand gauge errors at different measurement scales.

4.3.2. Recruiting and Motivating Citizen Scientists

Citizen science projects rely on citizens. As such, the success of any citizen science project relies at least partly on successful citizen recruitment and engagement efforts. We decided to focus monitoring on a five-month period from May through the end of September in 2018. Even though the monsoon usually does not start until the middle of June [35], starting the campaign in May provided time to ramp up interest and participation. Interested and motivated citizen scientists were encouraged to continue measurements after the campaign. We recruited citizen scientists for the monitoring campaign with a variety of methods (the number of citizen scientists recruited with each method is shown in parentheses):

- **R1: Leveraging personal relationships (n = 53)** - At the time of the 2018 monsoon expedition, the S4W-Nepal team was comprised of nine young researchers (i.e. BSc, MSc, and PhD researchers or recent graduates). Our first round of citizen science recruiting started with our personal connections. Each of us asked our family, friends, and colleagues to consider joining the S4W-Nepal monsoon monitoring campaign.

- **R2: Social media posts (n = 11)** - We made posts on S4W's Facebook page (https://www.facebook.com/SmartPhones4Water) in order to explain the monsoon monitoring campaign and invite interested individuals to join as citizen scientists. S4W-Nepal's 2018 monsoon monitoring expedition titled "Count the Drops Before It Stops" included the main themes of "Join, Measure, and Change the way water is understood and managed in Nepal."

- **R3: Outreach programs at schools/colleges (n = 61)** - In order to reach larger groups of possible citizen scientists, we organized outreach events at four secondary schools and five colleges during the spring of 2018. The outreach programs typically included presentations about the global water cycle, the Asian South Monsoon, the Kathmandu Valley water crisis, the importance of measuring resources we are trying to manage, and how the S4W-Nepal project is trying to quantitatively "tell the story" of the Valley's water problems to citizens and policy makers alike, with the aim to improve understanding and management in the future. Outreach programs generally ended with a call for volunteers, practical training on how to measure precipitation, and the distribution of S4W gauges to interested individuals. In the case of secondary schools, S4W gauges were provided to the schools directly, along with large pre-printed canvas graphs for plotting both daily precipitation amounts and cumulative monsoon precipitation totals.

- **R4: Random site visits (n = 29)** - The recruiting methods above mainly reached people living in the core urban areas of the Valley. However, our goal was to maximize the spatial distribution of our precipitation monitoring network, so it was important to include sites in the surrounding rural areas as well. In order to recruit citizen scientists in these areas, we made random site visits to strategic areas lacking citizen scientists. Sometimes during these random site visits, we would first talk to local community members to explain

the vision and importance of the S4W-Nepal project. If community members responded positively, we would ask for references of individuals with a general interest in science and technology who had working Android smartphones. At other times, we started dialogues directly with people we thought might be interested. In either case, once an individual with a working Android smartphone showed interest, we would together install an S4W gauge and perform initial training, including taking a first measurement together. In roughly 10 cases, we provided donated Android smartphones to individuals who were keenly interested in participating, but did not have a working smartphone.

To visualize recruitment progress, we developed a heatmap of the number of measurements performed showing time by week on the horizontal axis and (A) citizen scientists, (B) recruitment method, and (C) motivational method on the vertical axis. When computing grouped averages, zeroes were used for citizen scientists who did not take measurements in the respective weeks. We used the Mann-Whitney U test [36] for the entire 22-week period to determine if a significantly different number of measurements were taken for all possible pairs of recruitment methods and between paid (see motivation M7 below for details on payments) and volunteer citizen scientists. Citizen scientist composition was defined by four categories including: (A) volunteer or paid, (B) gender, (C) age, and (D) education. For education, citizen scientists were classified based on the highest level of education they had either completed or were currently enrolled in.

Once a citizen scientist has been successfully recruited it is critical to motivate their continued involvement. Previous studies have shown that appropriate and timely feedback is a key motivation factor for sustaining citizen science ([37], [38], [39], [14]). Essentially, there were two different combinations of motivations for the volunteers (n = 117) and paid (n = 37) citizen scientists, respectively. Motivations M1 through M6 were applied to all volunteers; whereas, M1, M2, and M7 were applied to paid citizen scientists.

- **M1: Personal follow-ups** - At the end of each week, we reviewed the performance of each citizen scientist and developed plans for personal follow-ups for the subsequent week. Follow-ups focused on citizen scientists who had taken measurements in the last month but had not taken a measurement in the last five days, or on citizen scientists making either unit or meniscus errors (Section 4.3.3). Personal follow-ups included (a) SMS messages, (b) phone calls, and (c) site visits. Roughly 20 site visits were made each week, amounting to an average of two visits per volunteer, and five (i.e. monthly) visits per paid citizen scientists during the five-month campaign. During personal follow-ups, S4W staff reiterated the importance of the work the citizen scientists were doing, and the difference that their measurements were making. Another purpose was to develop stronger personal relationships and develop a sense of being part of a larger community of people who are passionate about improving the way water resources are stewarded in Nepal.

- **M2: Bulk SMS messages** - At the end of each week we provided personalized bulk SMS messages to all citizen scientists who had taken mea-

surements during the 2018 monsoon campaigns. The goals of the messages were to acknowledge the citizen scientists' contributions, to summarize their measurements in a meaningful way, and to reinforce that their data was making a difference. The personalized message read: "Hello from S4W-Nepal! From StartDate to EndDate you have taken NumberOfMeasurements totaling AmountOfPrecipitation mm. Your data is making a difference! https://bit.ly/2Rb15Uo" where StartDate was the beginning of the monsoon campaign, EndDate was the date of the citizen scientists' most recent measurement, NumberOfMeasurements is the number of measurements taken and AmountOfPrecipitation is the cumulative depth of presentation between StartDate and EndDate. The link at the end of the message was to S4W's Facebook page.

- **M3: Outreach and workshops** - Because Nepal is a collectivist or group society, we thought it was important to gather as an entire group at least once a year for a post-monsoon celebration. At this celebration, preliminary results from our efforts were presented and stories from the citizen scientists were shared. We also performed follow-up outreaches to schools that were measuring precipitation.

- **M4: Use of the data** - S4W's aim is to share all of the data we generate, but our data portal isn't completed yet. We encouraged citizen scientists to continue their participation by providing them with all the data generated by the monsoon monitoring campaign.

- **M5: Lucky draws** - We held a total of nine lucky draws (i.e. raffles) for gift hampers that included earphones, study lamp, wallet, movie ticket, and mobile balance credits. Only citizen scientists taking regular measurements (i.e. at least 50 % of the time) were entered into the lucky draw.

- **M6: Certificates of involvement** - Especially for high school, undergraduate, and graduate students, certificates are important motivational factors because companies or organizations looking for new hires consider participation and employment certificates an important part of a candidate's resume. In order to get a certificate, citizen scientists had to take measurements for at least 50 % of the days during the monsoon.

- **M7: Payments** - In some cases, especially in rural areas with limited employment opportunities, where the need for data was high, and the number of possible volunteers was low, S4W-Nepal compensated citizen scientists for measurements. For these citizen scientists, S4W-Nepal provided a small per observation transfer to their mobile phone account. Precipitation observations earned 25 Nepali Rupees (NPR; roughly 0.22 USD).

We used the number of measurements per citizen scientists as a simple indicator of the effectiveness of motivational efforts. For each group in each citizen scientist characteristic (i.e. volunteer or paid, gender, age, and education level),

we used the Kruskal-Wallis *H* test [40] to see if there were statistically significant differences (alpha level = 0.01) between the number of measurements taken by citizen scientists per group in each category during the entire five-month period. For example, for age, we tested if more measurements per month were taken by <=18 compared to both 19-25 and >25, and so forth.

4.3.3. Performance of Citizen Scientists

Using a custom Python web application, we manually reviewed pictures from every precipitation observation to ensure that values entered by citizen scientists (Figure 4.2C) matched photographic records (Figure 4.2D). Any observed discrepancies were corrected, and records of edits were maintained. Through this process we identified three categories of citizen science observation errors: unit, meniscus, and unknown errors. Unit errors caused order of magnitude differences between original citizen scientist values and edited values due to citizen scientists taking readings in centimeters instead of millimeters. Meniscus errors were caused by citizen scientists taking readings of capillary rise instead of the lower portion of the meniscus. We observed the capillary rise to be as much as 3 mm in some cases. Unknown observation errors were errors caused by unknown factors.

The combination of edit ratio and edit distance was used to determine the type of error represented by each corrected record. Edit ratio was calculated with Equation 4.1:

$$ER_i = \frac{OV_i}{EV_i} \qquad (4.1)$$

where ER_i is the error ratio, OV_i is the original precipitation value, and EV_i is the edited precipitation value for record i. Unit errors were defined as records with edit ratios between 8 and 12. Edit distance was calculated with Equation 4.2:

$$ED_i = OV_i - EV_i \qquad (4.2)$$

where ED_i is edit distance for record i. Meniscus errors were defined as records with edit ratios less than 8 and edit distances between 0 and 3. The remaining edited records (neither unit nor meniscus errors) were classified as unknown observation errors.

On a weekly interval, we performed additional training and follow up (via SMS, phone, or in person) with citizen scientists who had made measurement errors during the prior week. Performance ratio was used to evaluate individual and group performance and was calculated with Equation 4.3:

$$PR_{CS,t} = \frac{TNM_{CS,t} - NCM_{CS,t}}{TNM_{CS,t}} * 100\% \qquad (4.3)$$

where $PR_{CS,t}$ is the performance ratio for one or more citizen scientists (CS) during time period (t), $NCM_{CS,t}$ is the number of corrected measurements, and $TNM_{CS,t}$ is the total number of measurements for the same citizen scientist(s) (CS)

and time period (t). Performance ratio (%) ranges from 0 to 100 with 100 % being ideal.

We used the Mann-Whitney U test [36] to evaluate if the interquartile range (IQR) of citizen scientists (in terms of the number of measurements they took) had worse performance ratios (PRs). After dividing citizen scientists into two groups based on the number of measurements they took during the five-month campaign (i.e. (1) the IQR and (2) the remainder), we calculated the Mann-Whitney U on the PRs (alpha level = 0.01).

4.3.4. Cost Per Observation

In order to evaluate the cost effectiveness of our approach, and any relationships between cost and citizen science performance, we performed a reconnaissance-level cost per observation (CPO) analysis. For each citizen scientist, average CPO was calculated with Equation 4.4:

$$CPO_{CS,t} = \frac{EC_{CS,t} + RC_{CS,t} + MC_{CS,t}}{TNM_{CS,t}} \qquad (4.4)$$

where EC is equipment costs, RC is recruiting costs, MC is motivational costs, and TNM is the total number of measurements, for each citizen scientist (CS) and time period (t). In this case, the time period was the five-months period from May through September 2018. The following general assumptions were used for the CPO analysis:

- All costs (Table 4.1) are in Nepali rupees (NRP); an exchange rate of 114.3 NPR (November 22nd, 2018) was used for conversion into one United States dollar (USD)

- All costs assume an hourly labor rate of 50 NPR per hour

- The full study period of 22 weeks was used for calculating costs unless stated otherwise

In order to evaluate CPOs, it is important to have a general sense of the economic context in Nepal. Nepal's per capita gross domestic product (GDP) in 2018 was 1,004 USD or 114,800 NPR [41]. Assuming 2,080 working hours per year (i.e. 40-hour work week for 52 weeks), the average hourly rate for 2018 was 0.48 USD or 55 NPR per hour.

All citizen scientists used the S4W gauge, so equipment costs were constant. RC was different for citizen scientists depending on which recruitment strategy (R1 through R4) was applied; we assumed that only one recruitment strategy was ultimately responsible for each citizen scientists' participation (recruitment methods per citizen scientists are included as supplementary material). Table 4.1 details the assumptions used to develop recruitment and motivational costs.

Motivational costs (MCs) for volunteers (MCVol) were entirely fixed, and were solved for using Equation 5. For paid citizen scientists, MCs were a combination

Table 4.1: Assumptions and resulting costs for each recruitment and motivational category. See Section 4.3.2 for more detailed descriptions of each category.

CPO Category	Sub Category	Assumptions	Cost (NPR)	Cost (USD)
R1		Leveraging personal relationships took four staff 10 hours per week for two weeks, for a total of 4000 NPR. Since 53 citizen scientists were recruited with this method, the cost was 75 NPR per citizen scientist recruited.	75	0.66
R2		For social media, an investment of two hours per week at 50 NPR was made. Since 11 citizen scientists were recruited with this method, the cost was 200 NPR per citizen scientist recruited.	200	1.75
R3		Workshops and outreaches were organized at a total of four schools and five colleges/universities. Workshops at schools and colleges/universities were estimated to cost 2500 and 5000 NPR, respectively. Since 61 CS were recruited with this method, the cost was 574 NPR per citizen scientist recruited.	574	5.02
R4		Random site visits were used to recruit 29 citizen scientists in rural areas. Assuming a two-person team, working for eight hours, plus 40 km traveled per day, a daily subsistence allowance of 200 NPR/person, and recruitment of 5 citizen scientists per day, the average cost was 280 NPR per citizen scientist recruited.	280	2.45
M1		There are three types of personal follow ups: SMS (M1a), phone calls (M1b), and site visits (M1cV and M1cP).		
M1	M1a	For SMS, we assumed that each citizen scientist received eight SMS messages during the monsoon, and that each message cost 10 NPR, for a total of 80 NPR.	80	0.70
M1	M1b	For phone calls, we assumed that each citizen scientist received eight phone calls, and that each call cost 15 NPR, for a total of 120 NPR.	120	1.05
M1	M1c	Assuming a two-person team, working for eight hours, plus 40 km traveled per day, a daily subsistence allowance of 200 NPR/person, and visits of 10 citizen scientists per day, the average cost was 140 NPR per citizen scientist site visit.		
M1	M1cV	For site visits, we assumed that each volunteer citizen scientist received two site visits, for a total of 280 NPR per volunteer citizen scientist.	280	2.45
M1	M1cP	For site visits, we assumed that each paid citizen scientist received five site visits, for a total of 700 NPR per paid citizen scientist.	700	6.12
M2		Bulk SMS messages were sent weekly, and cost roughly 3 NPR per message including the time to generate and load the necessary report(s), for a total of 66 NPR per citizen scientist.	66	0.58
M3		Outreach workshops focused on motivating volunteer citizen scientists, at an estimated cost of 40,000 NPR total, or with 117 volunteer citizen scientists, 342 NPR per volunteer.	342	2.99
M4		The motivation of data use was considered to have negligible cost, because of existing infrastructure necessary for other purposes.	0	0.00
M5		Lucky draws were used as a motivation for volunteer citizen scientists. A total of nine lucky draws were performed, with an estimated cost of 1200 NPR each for 117 volunteers, or 92 NPR per volunteer.	92	0.80
M6		Certificates were used to motivate volunteer citizen scientists, and cost 25 NPR each.	25	0.22
M7		Payments were used to motivate paid citizen scientists, and cost 25 NPR per observation.	25	0.22

Table 4.2: Summary of results from evaporation, soaking, and condensation experiments (error type) including configuration, unit, sample size (n), mean, minimum (min), maximum (max), and standard deviation (stdev).

Error Type	Configuration	Unit	n	Mean	Min	Max	Stdev
	Open	mm day^{-1}	33	3.7	2.1	5.8	1.0
Evaporation	Cap1	mm day^{-1}	33	0.5	0.1	1.0	0.2
	Cap2	mm day^{-1}	33	0.3	0.1	1.3	0.3
Soaking	Initial (post cure)	mm	9	3.9	2.0	4.7	0.9
	Subsequent	mm	99	0.8	0.4	1.9	0.5
Condensation	-	mm	49	0.31	0.04	0.51	0.11

of fixed (MCPaid; Equation 5) and variable costs (M7; Equation 6). MCs were calculated with the following equation:

$$MC_{CS,t} = \begin{cases} M1_a + M1_b + M1_cV + M2 + M3 + M4 + M5 + M6 & (CS = Volunteer) \\ M1_a + M1_b + M1_cP + M2 + M7_{CS,t} & (CS = Paid) \end{cases} \quad (4.5)$$

where the variables are defined above, with the exception of $M7_{CS,t}$ for paid citizen scientists. $M7_{CS,t}$ was calculated as:

$$M7_{CS,t} = TNM_{CS,t} * R_{Precip} \quad (4.6)$$

where R_{Precip} is the payment rate for each precipitation measurement. $TNM_{CS,t}$ was limited to a maximum of one measurement per day.

4.4. Results

4.4.1. S4W Rain Gauge

Of the S4W gauge errors investigated (Table 4.2), initial (post cure) concrete soaking errors (n = 9) and evaporation without lids (Open; n = 33) were the largest, averaging 3.9 mm and 3.7 mm day^{-1}, respectively. Subsequent concrete soaking requirements (n = 99) averaged 0.8 mm, or roughly five times smaller than the initial soaking requirement. S4W gauge evaporation was reduced from Open by an average of 86 % (0.5 mm day^{-1}) and 92 % (0.3 mm day^{-1}) for Cap1 and Cap2 configurations, respectively. Condensation errors were similar to Cap2 evaporation, and averaged 0.31 mm (n = 49).

For the co-located gauges in Bhaisipati, cumulative precipitation amounts for the one year of data collected were 900, 930, and 927 mm for the S4W, CoCoRaHS, and DHM gauges, respectively. Using DHM as the reference for the entire year of data, cumulative gauge error was -2.9 % for S4W and 0.3 % for CoCoRaHS. Measured precipitation amounts were linearly correlated for the three precipitation ranges, but the correlation decreased in strength as total precipitation decreased (Figure 4.5). Points near the horizontal axis of Figure 4.5A (n = 9) indicate that some small rain events (n = 5 for DHM less than 0.8 mm; n = 4 for DHM between 0.8 and 2 mm) were completely missed by the S4W gauge.
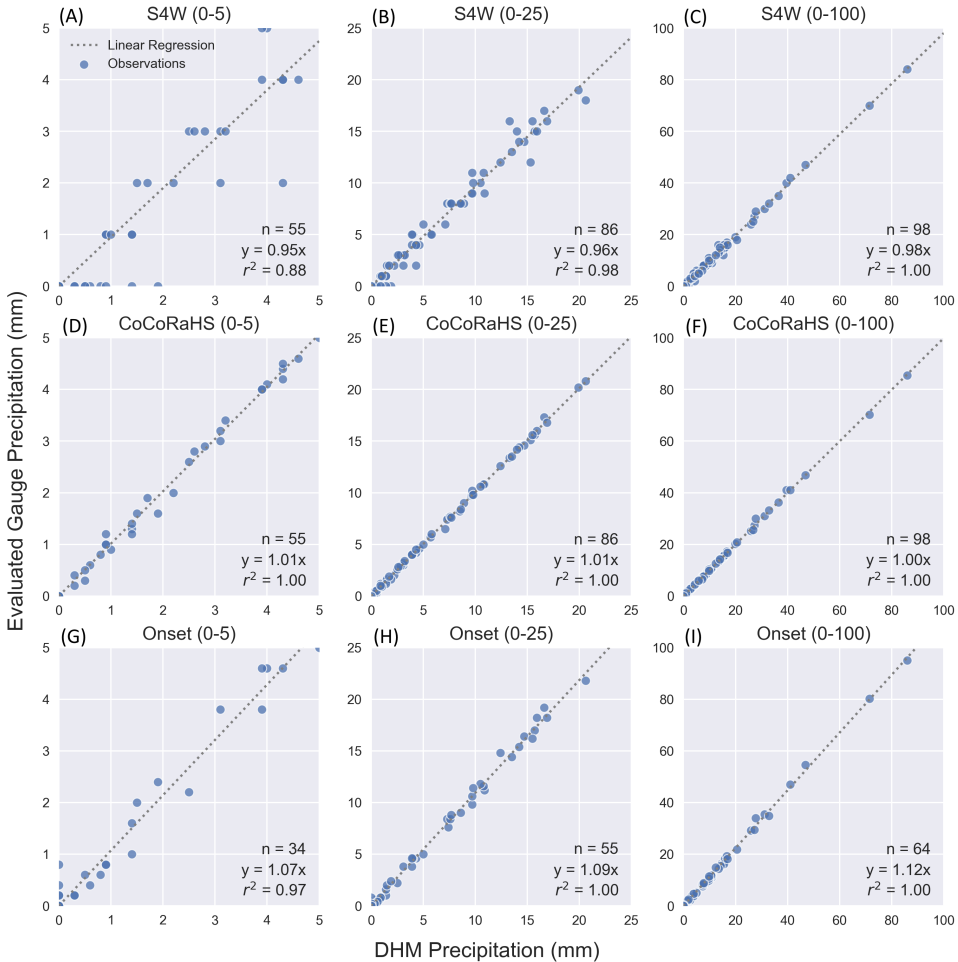
Figure 4.5: Comparison of precipitation data from S4W, CoCoRaHS, and Onset gauges using DHM observations as the reference (i.e. horizontal axis) from the co-located gauges in Bhaisipati. Per reference DHM measurements, data was filtered into three precipitation event ranges: 0 to 5 mm (i.e. panels (A), (D), and (G)), 0 to 25 mm (i.e. panels (B), (E), and (H)), and 0 to 100 mm (i.e. panels (C), (F), and (I)). No precipitation events above 100 mm were recorded. Data shown are from May 1st, 2017 through April 30th, 2018. The period of record for the Onset gauge was June 3rd, 2017 to November 27th, 2018; only fully overlapping data between Onset and DHM were used, resulting in decreased sample sizes for panels (G) through (I).

For S4W, the magnitude of the systematic underestimation increased for smaller measurements (Figures 4.5A, through 4.5C). For example, for precipitation measurements between 0 and 5 mm (Figure 4.5A), the S4W gauge linear regression coefficient was 0.95 indicating that measurements are on average -5 % from the DHM gauge. In contrast, linear regression coefficients for 0 to 25 and 0 to 100 mm ranges were 0.96 (-4 %) and 0.98 (-2 %), respectively. Measurements from

Table 4.3: Summary of results from evaporation, soaking, and condensation experiments (error type) including configuration, unit, sample size (n), mean, minimum (min), maximum (max), and standard deviation (stdev).

Year-Month	Active CS	Paid	Volun-teer	Female	Male	<=18	19-25	>25	<Bach-elors	Bach-elors	>Bach-elors
2018-05	121	21	100	47	74	11	87	23	21	92	8
2018-06	106	26	80	39	67	11	76	19	20	79	7
2018-07	96	30	66	38	58	12	63	21	21	65	10
2018-08	93	30	63	35	58	11	64	18	21	63	9
2018-09	64	20	44	26	38	10	43	11	15	43	6

the CoCoRaHS gauge were strongly correlated with the measurements from the DHM gauge for all ranges with small biases (linear regression coefficients between 1.00 and 1.01; Figures 4.5D through 4.5F). For Onset, the magnitude of systematic overestimation increased for larger events (Figures 4.5G through 4.5I), from 1.07 (7 %) at 0 to 5 mm, and up to 1.09 (9 %) and 1.12 (12 %) at 0 to 25 and 0 to 100 mm ranges, respectively.

4.4.2. Recruiting and Motivating Citizen Scientists

A heatmap of citizen scientists' precipitation measurements per week illustrates the rate of recruitment along with the continuity of their measurements (Figure 4.6A). "Citizen science heroes" can be seen as the persistent dark blue rows (e.g. the second row down from the top). In contrast, inconsistent citizen scientists can be seen as the rows with large variations in blue (e.g. fifth and sixth rows down from the top). Unfortunately, several citizen scientists took only a few measurements during their first week, especially towards the end of the second week (e.g. 2018-19). At a 0.05 alpha level, the average number of measurements per week was significantly higher for citizen scientists recruited via social media (R2) versus personal relationships (R1; Figure 4.6B; p = 0.018), recruited via outreach programs (R3) versus personal relationships (R1; Figure 4.6B; p = 0.033), and motivated with payments versus volunteers (Figure 4.6C; p = 0.013). At an alpha level of 0.01, the average number of measurements per week was significantly higher for recruitment by random site visits (R4) versus personal connections (R1; Figure 4.6B; p = 0.003). No other statistically significant differences (alpha level = 0.05) were observed between the remaining possible pairs of recruitment methods.

The number of active citizen scientists peaked in May (n = 121) and decreased through the campaign until September (n = 64; Table 4.3). The ratio of female to male citizen scientists remained relatively stable throughout the period (mean = 63 %). From May to September, the number of volunteer citizen scientists decreased by 66 %, whereas the number of paid citizen scientists only decreased by 5 %. The most stable age group was <=18, followed by 19-25, and finally >25. In terms of education, <Bachelors and >Bachelors were more stable than Bachelors, which decreased by 53 %.

From May through September 2018, the average citizen scientist took 42 measurements (min = 1, max = 148, std = 39). Sixteen citizen scientists took only one measurement. Based on results from Kruskal-Wallis H tests, paid citizen scientists
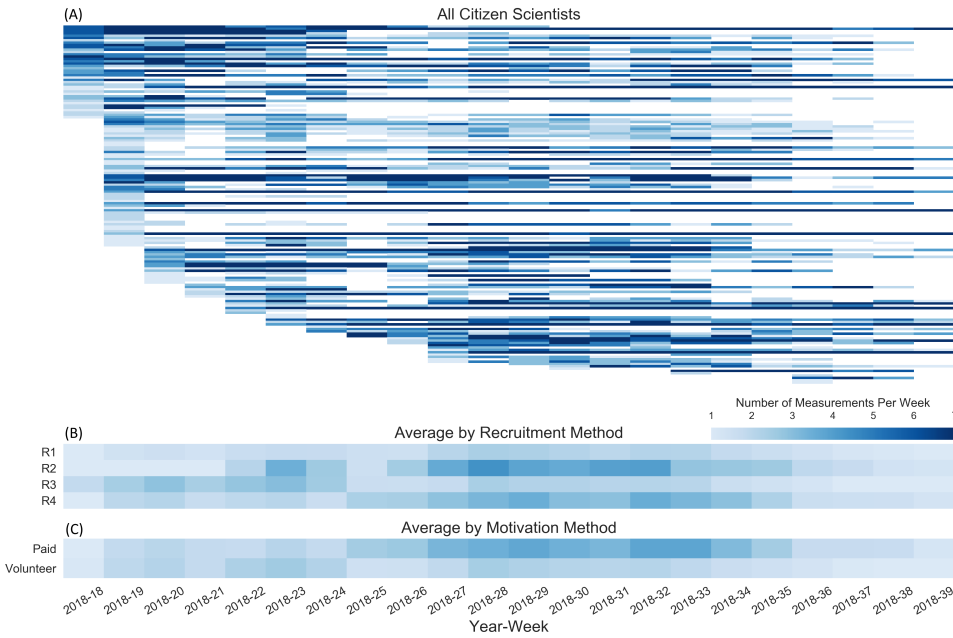
Figure 4.6: Heatmap of the number of measurements per year-week for a 22-week period from the first week of May (i.e. 2018-18) through the end of September (i.e. 2018-39). Each column of pixels represents a single week. Each row of pixels represents (A) an individual citizen scientist, (B) averages from the four recruitment methods (i.e. R1: Leveraging personal relationships (n = 53); R2: Social media (n = 11); R3: Outreach programs (n = 61); R4: Random site visits (n = 29)), or (C) motivation method group (i.e. paid (n = 37) or volunteer (n = 117)); see Section 4.3.2 and 4.4.2 for details). The color of each pixel represents the number of measurements performed each week. Light and dark blue represent one and seven measurements, respectively; white means zero measurements were performed that week. For panel (A) citizen scientists are sorted vertically in reverse chronological order by the date of their first measurement; the rate of recruitment is shown by the slope of the left edge of pixels in the heatmap - larger negative slopes (i.e. 2018-18 and 2018-19) represent higher recruitment rates. When computing grouped averages for panels (B) and (C), zeroes were used for citizen scientists that did not perform measurements in the respective weeks.

took significantly more measurements than volunteers (Figure 4.7; alpha level = 0.01; p = 0.005). No other statistically significant differences in contributions were observed.

There were statistically significant correlations between the number of measurements taken and mean daily precipitation for the same day (Figure 4.8A; r = 0.60; r critical = 0.21; alpha level = 0.01) and the previous day (Figure 4.8B; r = 0.38; r critical = 0.21; alpha level = 0.01), but the strength of the same day correlation was stronger, explaining 36 % of the variance, while the previous day precipitation explained only 14 %. This suggests that the harder it rains the more likely citizen scientists are to take a measurement that same day (and the next but less so).
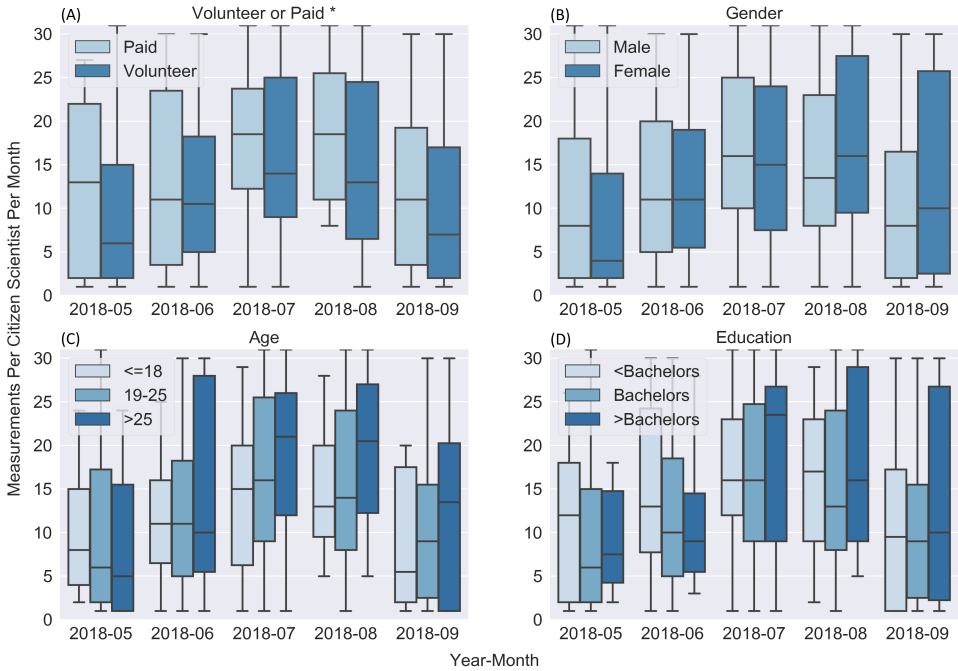
Figure 4.7: Grouped box plots showing the medians and distributions of the number of citizen scientist precipitation observations per month. Box plot groups are shown for four different categories: (A) volunteer or paid; (B) gender, (C) age, and (D) education. For education, citizen scientists were classified into the highest education level that they had either completed or were currently enrolled in. An asterisk (*) in the subplot title indicates statistically significant differences (alpha level = 0.01) between the number of measurements performed by each group within that category during the entire five-month period.

4.4.3. Performance of Citizen Scientists

Citizen scientist observation errors were found for 9 % (n = 592) of the total measurements (n = 6656). Meniscus errors (n = 346) (Figure 4.9; light blue area) accounted for 58 % of observation errors. Unit errors (n = 50) (Figure 4.9; light red sector) comprised 8 % of the errors. Finally, unknown errors (n = 196) accounted for the remaining 33 % of observational errors.

Only six citizen scientists had Unit, Meniscus, and Unknown errors. 41 citizen scientists had both Meniscus and Unknown errors; 10 had both Meniscus and Unit errors; and 8 had Unit and Unknown errors. The largest number of errors for a citizen scientist was 32, or 22 % of their 143 records. The mean citizen scientist performance ratio (PR) was 93 % (Figure 4.10). Stated alternatively, on average, there were errors on 7 % of the measurements from citizen scientists. There were a total of 63 citizen scientists with perfect PRs (100 %); 10 of these recorded more than the median number of measurements and 53 less (38 below Q1). Citizen scientists who took a moderate number of measurements (i.e. interquartile range (IQR) between Q1 and Q3; middle 50 %) were significantly more likely to have a
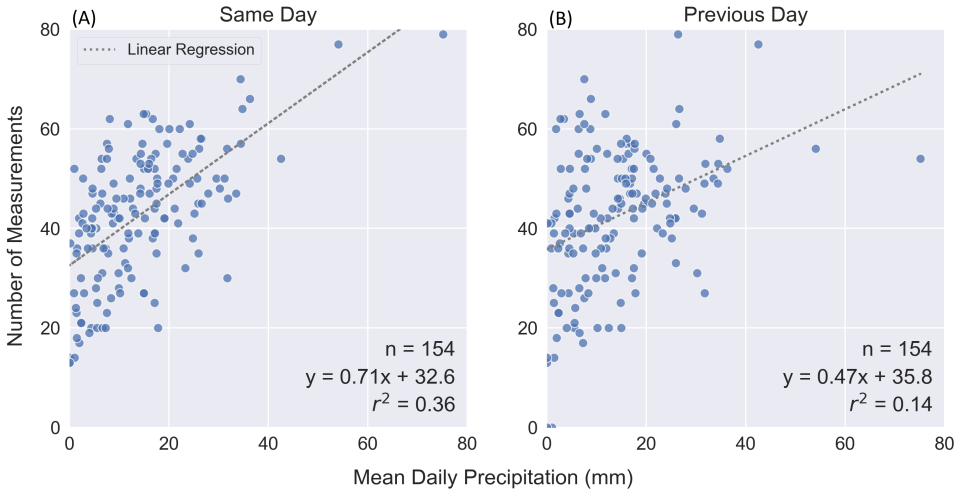
Figure 4.8: Scatter plot of the number of measurements per day as a function of mean daily precipitation for the (A) same day and (B) previous day. Mean daily precipitation was taken as the average of all citizen scientists' measurements. There were statistically significant correlations (Pearson's r) for the (A) same day (r = 0.60; r critical = 0.21; alpha level = 0.01) and the previous day (r = 0.38; r critical = 0.21; alpha level = 0.01).
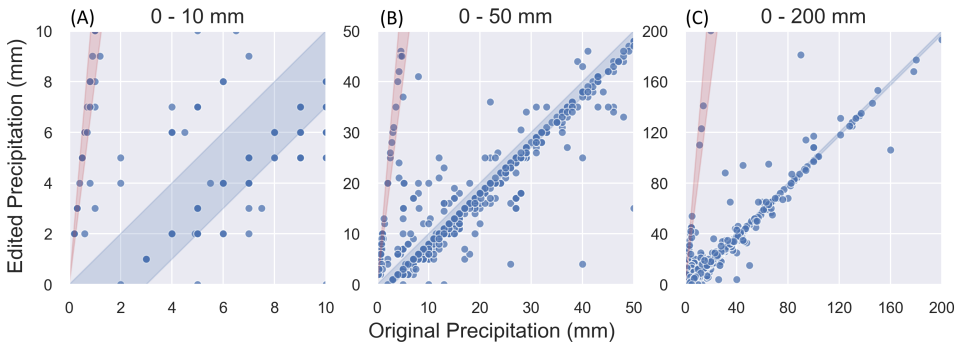
Figure 4.9: Scatter plot of corrected records (n = 592) with original (i.e. raw) precipitation entries on the horizontal axis and edited (i.e. after quality control) values on the vertical axis. Data is shown for three different scales: (A) 0 - 10 mm, (B) 0 - 50 mm, and (C) 0 - 200 mm. Meniscus error range (n = 346) is shown as light blue area, while Unit error range (n = 50) is shown as light red sector. Points outside of the light blue and light red areas are unknown errors (n = 196).

worse PR than those outside of the interquartile range (Figure 4.10; alpha level = 0.01; p = 0.0001).

4.4.4. Cost Per Observation

Fixed costs for equipment (S4W gauge) were 0.87 USD. Fixed costs for recruiting ranged from 0.66 to 5.02 USD, while for motivation they were 8.79 and 8.45 USD

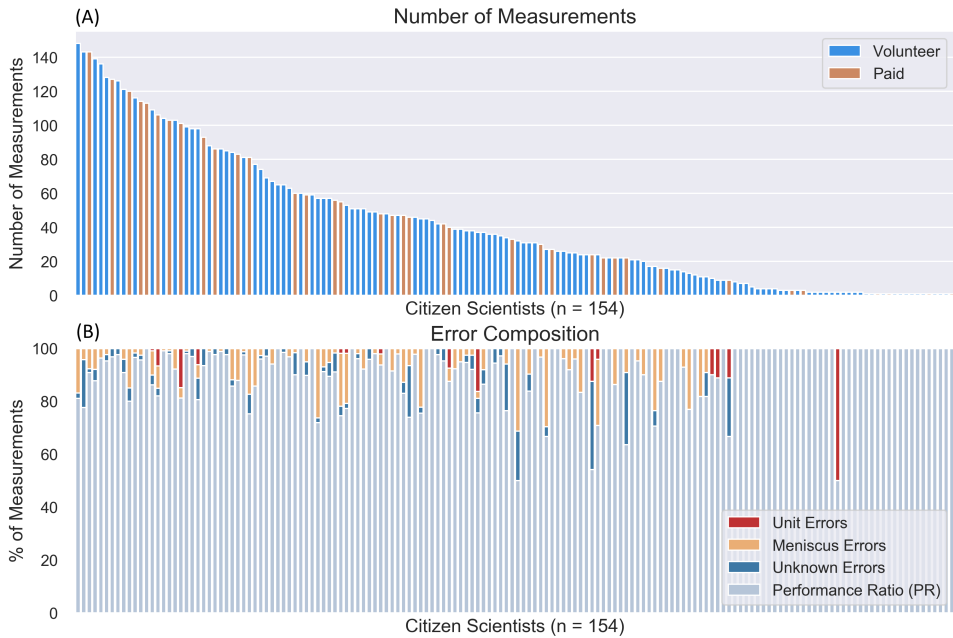Figure 4.10: Summary of (A) the number of measurements collected from May through September with volunteer and paid citizen scientists distinguished and (B) the corresponding error composition for all 154 citizen scientists. Citizen scientists sorted in descending order by their total number of measurements. Performance ratio (PR) becomes less informative as the total number of measurements for each citizen scientist decreases, especially at or below two.

for volunteer and paid citizen scientists, respectively (Table 4.4; see Table 4.1 for details). Variable costs were only applicable for paid citizen scientists, and were 0.22 USD per observation. Outreach programs recruited the largest number of citizen scientists (n = 61), but were also the most expensive recruitment method (5.02 USD per citizen scientists recruited). Leveraging personal relationships was the second most effective (n = 53) and cheapest approach (0.66 USD). Random site visits recruited 29 citizen scientists, of whom 27 were paid, and cost roughly 2.45 USD per recruited citizen scientist. Only 11 citizen scientists joined the monitoring campaign purely through social media, for a cost of 1.75 USD per recruited citizen scientist.

Estimated average costs per observation (CPO) for all citizen scientists ranged from 0.07 to 14.68 USD and 0.30 to 11.99 USD for volunteer and paid citizen scientists, respectively (Figure 4.11). Median CPOs where 0.47 USD for both volunteer and paid citizen scientists. Because all costs for volunteers are fixed, the number of observations per citizen scientist had the largest impact on CPOs. For example, volunteer citizen scientists (recruited with outreach programs) that took only one measurement had CPOs of 14.68 USD (Figure 4.11A). For paid citizen scientists, fixed costs were lower, but an additional variable cost of 0.22 USD (25 NPR) was

Table 4.4: Summary of results from evaporation, soaking, and condensation experiments (error type) including configuration, unit, sample size (n), mean, minimum (min), maximum (max), and standard deviation (stdev).

Cost Type	Description	Number of Citizen Scientists	Per Citizen Scientist Fix Costs (USD)	Per Observation Variable Costs (USD)
Equipment	S4W Gauge	154	0.87	-
Recruitment	R1: Personal relationships	53	0.66	-
	R2: Social media	11	1.75	-
	R3: Outreach programs	61	5.02	-
	R4: Random site visits	29	2.45	-
Motivation	MVolSum: Volunteer Motivations	117	8.79	-
	MPaidSum: Paid Motivations	37	8.45	0.22

added due to per observation payments. This resulted in a smaller range of CPOs, where (1) minimum CPOs approached per observation payment amount as the number of observations performed increased and (2) maximum CPOs approached fixed costs for paid citizen scientists as the number of measurements approached one (Figures 4.11C and 4.11D). Performance ratio (PR) did not appear to be related with CPO, nor was there a clear difference in PR for volunteer and paid citizen scientists (Figures 4.11A and 4.11B).
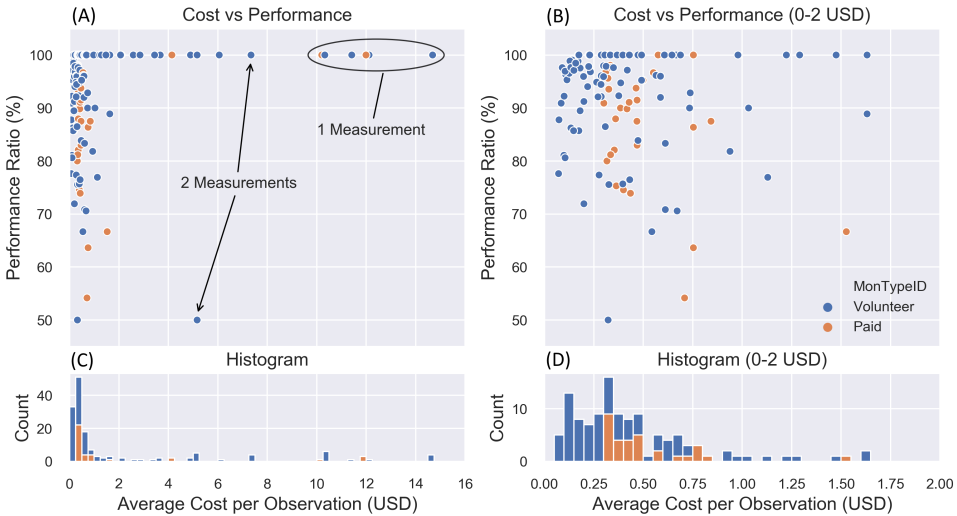
Figure 4.11: Scatter plots of performance ratio (PR) as a function of average cost per observation for costs from (A) 0-16 USD and (B) 0-2 USD ranges, respectively. Each point represents the performance ratio and average cost per observation for a single citizen scientist. Histograms below show the total number of citizen scientists in each cost bin for (C) 0-16 USD and (D) 0-2 USD ranges, respectively.

Gauge cost had a large impact on fixed costs for all citizen scientists. For example, increasing gauge cost from 0.87 USD (S4W gauge) to 31.50 USD (CoCoRaHS gauge) increased median CPOs from 0.47 to 1.57 and 1.12 USD for volunteer and

paid citizen scientists, respectively. Using DHM gauges, which cost 65.60 USD, increases median CPOs to 2.88 and 1.85 USD for volunteer and paid citizen scientists, respectively. This analysis was limited to five months, however, since the estimated lifespan of all three gauges is well over five months (perhaps five years or longer), CPOs will decrease as more measurements are taken. As gauge lifespan increases, CPOs approach the sum of annually recurring fixed costs plus per observation variable costs.

4.5. Discussion

4.5.1. S4W Rain Gauge

In the context of wind induced errors arising from using (or not using) wind shields or differences in gauge heights, which can be as large as 10 % for precipitation gauges of the same type [15], the S4W gauge errors related to evaporation, soaking, and condensation are relatively small. Nevertheless, our findings highlight the importance of (1) using covers to minimize evaporation (regardless of cap type), in addition to (2) effective training on how to properly install covers to minimize air gaps and evaporation losses. Since evaporation can be limited by the amount of time that ponded water is stored in the gauge, citizen scientists should be encouraged to take measurements as quickly as possible after precipitation events. Citizen scientists should also be specifically guided to minimize the "other" errors discussed in Section 4.3.1 by: (1) keeping gauge inlets free of clogging hazards, (2) fully emptying gauges after measurements, and (3) taking readings on level surfaces.

Average S4W gauge evaporation losses with Cap1 (mean = 0.5 mm day^{-1}) and Cap2 (mean = 0.3 mm day^{-1}) compared favorably with Tretyakov gauge summer evaporation losses in reported by [42], which ranged from 0.3 to 0.8 mm day^{-1}. Interestingly, Golubev et al. [43] found evaporation losses from US National Weather Service 203 mm (8-inch) gauges (similar to the DHM gauge used in this investigation) to be "negligible" (e.g. 0.2 mm day^{-1}). While variability in evaporation can be partially explained by differences in solar radiation, wind speed, temperature, and relative humidity [15], it is also possible that small differences in cover installation could also explain part of the observed variability in evaporation losses. For example, if a cover is installed at an angle, or not firmly pressed down, a small opening between the lid and the inside of the gauge can remain. These small openings could account for some of the high evaporation rates observed with Cap1 (max = 1.0 mm day^{-1}) and Cap2 (max = 1.3 mm day^{-1}) cover configurations (Table 4.2).

S4W gauges should be manually saturated prior to data collection to avoid the first roughly 3.9 mm of rain going to concrete saturation (Table 4.2). While subsequent saturation took only 0.8 mm, if not corrected for, this could introduce systematic negative bias into S4W gauge measurements. In order to reduce the need for corrections, alternative lower-porosity materials for filling the bottom of S4W gauges should be investigated.

Citizen scientists should be encouraged to take measurements at a consistent time in the morning (e.g. 07:00 LT; [14]) to minimize condensation errors and to

simplify data processing. S4W gauge condensation averaged 0.31 mm, which is 61 % of observed average daily Cap1 evaporation rates (0.5 mm day^{-1}) and 39 % of concrete saturation requirements (0.8 mm). While percentage-wise, condensation errors were smaller than evaporation and concrete saturation, taking measurements in the morning (or evening) when condensation accumulations are low can reduce these errors. A correction for condensation errors could be added if the time of a measurement is during peak daylight hours.

While S4W gauge error was relatively small (-2.9 %) compared to the DHM standard, it is still possible to apply corrections for the systematic S4W gauge errors. We suggest that corrections could be based on either an (1) error correction factor (ECF) or (2) evaporation (EVAP). The ECF uses cumulative precipitation values for S4W and DHM gauges to develop a constant correction, which is our case was 1.03. After adjusting S4W gauge records with the ECF approach, corrected cumulative S4W precipitation matched the DHM total of 927 mm. Alternatively, the EVAP approach is based on average daily evaporation (i.e. 0.5 mm) with soaking requirements (i.e. 0.8 mm) as an upper limit. After applying the EVAP approach, corrected cumulative S4W precipitation was 943 mm, or roughly 1.8 % higher than DHM. Additional details regarding both of these approaches are included as supplementary material to Davids et al. [1].

It is also important to note that gauge errors, or systematic measurement differences, arising from differences in gauge installations were not evaluated. While standardizing gauge installation criteria like gauge height could help to minimize these differences, it may not be practical to apply such standards to citizen science projects in urban areas. For example, in the densely populated mid-rise core urban areas of Kathmandu, installing precipitation gauges at 1 m would only be possible in large courtyards. In these cases, it is likely more practical (and accurate) to install rain gauges on roof tops.

S4W gauge evaluation results should be considered the likely errors for "ideal" citizen scientists. Other possible errors that may impact citizen scientists' measurements include: (1) clogging of gauge inlets, (2) incomplete emptying of gauges, (3) improper gauge installation, and (4) taking readings on unlevel surfaces. Because we performed gauge intercomparison measurements ourselves with focused attention on avoiding these issues, they are not reflected in our results. Future work should consider the impacts of these potential error sources on citizen scientist measurements. Since it is likely that effective training and follow-up is the key to minimizing such errors, future work should also explore the effectiveness of different training approaches on different audiences.

4.5.2. Recruiting and Motivating Citizen Scientists

Our results showed that citizen scientists recruited via random site visits (R4; alpha = 0.01), social media (R2; alpha = 0.05), and outreach programs (R3; alpha = 0.05) on average took significantly more measurements than those recruited from personal connections (R1). Since all but two citizen scientists recruited from random site visits were also paid, it is not clear if the greater number of measurements was due to the recruitment method or payment, or a combination of the two. Citizen

scientists who were recruited via social media had to take several self-initiated steps to move from (1) initially seeing something about S4W-Nepal on social media to (2) collecting precipitation data during the 2018 monsoon. In contrast, the barrier to entry for other recruitment methods was lower, and was externally initiated through interpersonal interactions. Therefore, the initial investment and motivation level of citizen scientists who joined the monitoring campaign through social media is relatively higher.

A survival analysis of volunteers in CoCoRaHS, the longest running large scale citizen science-based precipitation monitoring effort, found that retirement aged participants (i.e. ages 60 and above) were most likely to continue taking measurements [44]. This suggests that older citizen scientists are most easily motivated, at least in a western context. While we did not have any retirement aged participants, our oldest age group (>25) actually had the largest attrition rates (52 %). Future citizen science projects in Asia should focus on involving older citizen scientists to test the validity of this finding in the context of Nepal or other Asian settings.

Since payment appears to be an effective motivation, future work should explore how payment can be used as an effective means of recruitment. Also, per the subsequent motivation discussion, recruitment of citizen scientists should be expanded to focus on retirement age groups and on clear communication of the usefulness of generated precipitation data.

While we only observed statistically significant differences in citizen science performance due to payment, roughly half of the bachelor's students involved in the project continued their involvement in the project (attrition rate was 53 % for the five-month campaign) without monetary motivations (no bachelor's students received payments). This suggests that students can be motivated to participate in citizen science projects with incentives like (1) the opportunity to use data for their research projects (e.g. bachelor's theses), (2) lucky draws (i.e. raffles or giveaways), and (3) by receiving certificates of involvement. However, these student-focused incentives often lead to data collection in urban areas, and may not be effective at generating data in rural areas with limited student populations and relatively low scientific literacy levels. In such areas, payments may be the most effective near-term incentive.

Survey results from CoCoRaHS volunteers have shown that a significant motivational factor is the knowledge that the data they are providing is useful [14]. Therefore, a key component of any citizen science project should be "closing the loop" back to citizen scientists by clearly communicating the usefulness of their data, along with easy to understand examples. Our experience has shown that the difficulty of "closing the loop" increases as the citizen scientists' scientific literacy decreases. Therefore, in places like rural Nepal with, on average, relatively low scientific literacy rates, additional efforts must be made to properly contextualize and connect abstract concepts like data collection and fact-based decision making to the daily lives of community members. Payments might also be an important intermediate solution to motivate involvement while generational improvements in scientific literacy are realized.

Finally, even though we specifically reinforced the value of measuring zeros

during training, our results suggested that the magnitude of precipitation was an important motivator for citizen scientists. However, there was some noise in this relationship because for the citizen scientists who did not take measurements, it was unknown whether this occurred because (1) there was no measurable precipitation in their gauge that day, or (2) they simply did not take a measurement. Regardless, this suggests that it may be difficult to motivate people to continue taking regular measurements outside the monsoon season, so focused monsoon monitoring campaigns are a good solution.

4.5.3. Performance of Citizen Scientists

Our findings reinforce the importance of including photographic records so that citizen science observations can be quality controlled and corrected if necessary. In our five-month campaign, 9 % of measurements required corrections; if not for photographic records, these errors may have been more difficult to detect, or may have gone unnoticed. It is important to note that the feedback we provided to citizen scientists about their errors during the campaign most likely led to fewer errors than there would have been without feedback. Future work should explore the opportunity to automate the quality control process by leveraging machine learning techniques to automatically retrieve correct values from photographs of measurements. Meniscus errors were more difficult to identify and correct from photographic records. Training citizen scientists to read the lower meniscus was at times a difficult task, because of the small variations in readings, often on the order of only a few millimeters.

4.5.4. Cost Per Observation

Median CPOs of 0.47 USD for both volunteer and paid citizen scientists were roughly equivalent to one hour of labor at nationally averaged rates (0.48 USD per hour; see Section 4.3.4 for details). The cost per observation analysis revealed well over an order of magnitude difference between minimum and maximum average CPO for both volunteer and paid citizen scientists; this demonstrates the sensitivity of CPO to the number of observations. Our initial findings suggest that personal relationships and social media are the most cost-effective means of recruitment. A limitation of this study is that only two different groups of motivations were applied to volunteer and paid citizen scientists, respectively.

There was no increase in data accuracy with increases in CPO, thus efforts to minimize CPO do not appear to systematically lower PR. An important part of sustaining citizen science efforts is funding, and all efforts to minimize CPO while maintaining data quality will lead to lower funding requirements and greater chances of sustainability.

Since it is difficult to predict how citizen scientists will respond to recruitment and motivational efforts, returns on investments (as partially quantified by CPO) in citizen science monitoring efforts are uncertain and difficult to predict. Improved characterization of the effectiveness of different recruitment and motivational strategies will facilitate better understanding of the returns from citizen science-based precipitation monitoring investments.

4.5.5. Outlook

While leveraging personal relationships was a cost-effective means of citizen scientist recruitment, relying on this method poses challenges to scalability. Future efforts should focus on development and refinement of more scalable approaches. We see young researchers (grade 8 through graduate school) as potential catalysts towards expanding and sustaining citizen science-based monitoring efforts. Future work should explore how sustainable measurements of precipitation (and other parameters) can be achieved by linking standard measurement goals and methods developed by professional scientists with (1) young researchers, (2) citizen science at the community, and (3) a common technology platform including low-cost sensors (not necessarily electronic). Involving young researchers in this process has the potential benefits of both improving the quality of their education and level of practical experience, while simultaneously providing valuable data to support fact-based decision making. As previously mentioned (see Section 4.5.2), the potential role of retired aged participants (i.e. ages 60 and above) in Asian citizen science projects should also be investigated.

Finally, future efforts should explore the potential for cross-cutting organizations to facilitate and catalyze this process by linking young water-related researchers across a range of academic institutions related to water including: natural sciences, agriculture, engineering, forestry, economics, sociology, urban planning, etc. Desired outcomes of these links would be to (1) encourage young researchers to focus their efforts on relevant and multidisciplinary research topics and (2) encourage academic institutions to integrate participatory monitoring into their curricula and academic requirements [45]. Ultimately, these young researchers can then become the champions of engaging citizen scientists in the communities where they grew up, live, research, and work.

4.6. Conclusions and Outlook

Our results illustrate the potential role of citizen science and low-cost precipitation sensors (e.g. repurposed soda bottles) in filling globally growing precipitation data gaps, especially in resource constrained environments like Nepal. Regardless of how simple low-cost gauges may be, it is critical to perform detailed error analyses in order to understand and correct, when possible, low-cost gauge errors. In this study, we analyzed three types of S4W gauge errors: evaporation (0.5 mm day^{-1}), concrete soaking (3.9 mm initial and 0.8 mm subsequent), and condensation (0.31 mm). Compared to standard DHM gauges, S4W and CoCoRaHS cumulative gauge errors were -2.9 and 0.3 %, respectively, and were relatively small given the magnitude of other errors (e.g. wind induced) that affect all "catch" type gauges.

In total, 154 citizen scientists participated in the project, and on average performed 42 measurements during the five-month campaign from May to September 2018. Citizen scientists recruited via random site visits, social media, and outreach programs (listed in decreasing order) took significantly more measurements than those recruited via personal connections. Payment was the only categorization (i.e. not gender, education level, or age) that caused a statistically significant difference in the number of measurements per citizen scientist, and was therefore an effective

motivational method. We identified three categories of citizen science observation errors (n = 592; 9 % of total measurements): unit (n = 50; 8 % of errors), meniscus (n = 346; 58 % of errors), and unknown (n = 196; 33 % of errors). Our results illustrate how simple smartphone-based metadata like GPS-generated coordinates, date and time, and photographs are essential for citizen science projects. Estimated average costs per observation (CPO) was highly dependent on the number of measurements taken by each participant and ranged from 0.07 to 14.68 USD and 0.30 to 11.99 USD for volunteer and paid citizen scientists, respectively, and. Median CPOs were 0.47 USD for both volunteer and paid citizen scientists. There was no increase in data accuracy with increases in CPO, thus efforts to minimize CPO do not appear to systematically lower citizen scientist performance.

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5

Land-use and Water Linkages

Water and air,
The two essential fluids on which all life depends,
Have become global garbage cans.

Jacques-Yves Cousteau

Land development without thoughtful water supply planning can lead to un-
sustainability. In practice, management of our lands and waters is often
unintegrated. We present new land-use, ecological stream health, water
quality, and streamflow data from nine perennial watersheds in the Kath-
mandu Valley, Nepal in the 2016 monsoon (i.e. August and September) and
2017 pre-monsoon (i.e. April and May) periods. Our goal was to improve un-
derstanding of the longitudinal linkages between land-use and water. At
a total of 38 locations the Rapid Stream Assessment (RSA) protocol was
used to characterize stream ecology, basic water quality parameters were
collected with a handheld WTW multi-parameter meter, and stream flow was
measured with a SonTek FlowTracker Acoustic Doppler Velocimeter. A pixel
based supervised classification method was used to create a 30-meter grid-
ded land use coverage from a Landsat 8 image scene captured in the fall of
2015. Our results indicated that land-use had a statistically significant im-
pact on water quality, with built land-uses (high and low) having the greatest
influence. Upstream locations of six of the nine watersheds investigated had
near natural status (i.e. River Quality Class (RQC) 1) and water could be used

for all purposes (after standard treatments as required). However, down-stream RSA measurements for all nine watersheds had RQC 5 (i.e. most highly impaired). Generally, water quality deteriorated from monsoon 2016 to pre-monsoon 2017. Our findings reinforce the importance of integrated land and water management, and highlight the urgency of addressing waste management issues in the Kathmandu Valley.

5

5.1. Background and Introduction

5.1.1. Land-use - Water Linkages

Many studies have highlighted the strong linkages between land-use and water resources, from both process and planning perspectives ([2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], and others). Yet, in many parts of the world, land-use planning and water resources management continue to be implemented in an unintegrated fashion [14]. This situation is frequently exacerbated in developing countries by a combination of weak political and financial institutions, deficient physical infrastructure, and limited understanding of the physical processes that link the two. The resulting sum of a series of economically or politically sensible land-use planning decisions often leads to intractable water management predicaments ([15], [16], [17]). Additionally, the data necessary to analyze changes in both land-use and water quality and quantity over space and time are often not available ([18], [19], [20], [21]).

Several examples exist the world round, of rapid and largely unplanned urban growth completely outpacing necessary freshwater delivery and waste water treatment infrastructures ([22], [23], [24], [25], [26]). This eventually leads to degradation of surface and groundwater, including dependent ecosystem services ([27], [28], [29]). The primary factors leading to this degradation include direct discharge of untreated urban and industrial effluents (nitrogen, solvents, fecal contaminants, etc.) and uncontrolled agricultural waste discharges (e.g. nitrogen, phosphorus, pesticides, salt, etc.).

5.1.2. Kathmandu Valley

Due in part to a lack of integrated land-use and water resources planning, the Kathmandu Valley currently suffers from both water quantity and quality crises. Uncontrolled urban expansion into the fringes surrounding the historically populated areas is increasing demand for water, intensifying discharge of untreated wastewater discharged to streams, and reducing recharge potential for the progressively stressed underlying aquifer system [20]. We searched for pertinent literature that characterizes these issues using Google Scholar and the key search terms land-use, water, management, quality, quantity, and Kathmandu.

Regarding land-use, Rimal [30] found that the area of built land (i.e. urban, industrial, etc.) within the core of the Kathmandu Metropolitan area increased nearly four-fold (i.e. 395 %) in just over three decades from 1976 to 2009. Within the hill regions of Nepal, Paudel et al. [31] found that urban land uses were increasing rapidly in the Kathmandu and Pokhara Valleys. Uddin et al. [32] developed a land cover map for the entire country of Nepal for 2010. However, possible land-use changes between 2010 and 2016 (i.e. when the field work was performed) reinforced the need for an updated land-use coverage focus on the Kathmandu Valley.

Several studies have highlighted the degradation of water quality in the Valley, with many of them focusing on groundwater quality, since it is a critical water supply ([33], [34], [35], [36], [37], [38], [39], [20], [40], [41], [42]). Shrestha et al. [43] mapped the water quality of the Bagmati River in the Kathmandu Valley and

found that water quality was extremely poor in rivers sections inside built areas, fair in agricultural dominated areas, and good in most upper stretches of the rivers which are generally forested and inside protected areas. In the meantime, biological methods have been developed and evaluated for integrated measurement of the status of water quality in rivers (e.g., [44], [45]). Shah and Shah [25] presented benthic macroinvertebrate assemblage as an indicator of ecological status along the Bagmati River and a few tributaries in the Kathmandu Valley. While they did not quantify tributary land-use composition, they did conclude that benthic macroinvertebrate assemblages reflected the actual ecological status and they observed changes between seasons at the studied sites. Finally, by performing a baseline study along the Bagmati to collect physical, chemical, and biological indicator data regarding water quality and water pollution, Milner et al. [46] found that pollution originating from the Kathmandu Valley persisted to 75 km downstream from Chobar (i.e. the outlet of the Bagmati River from the Kathmandu Valley).

While our literature review showed that several studies have focused on land-use changes or water quality in the Kathmandu Valley, we could not identify any quantitative assessments of the impacts of land-use on water quality and quantity. Therefore, the goal of this paper is to improve understanding of the longitudinal (i.e. upstream to downstream) linkages between land-use and water quality and quantity for both monsoon and pre-monsoon periods in the Kathmandu Valley. We do this by collecting, analyzing, and presenting new land-use, ecological stream health, water quality, and streamflow data from the perennial tributaries to the Bagmati River in the Kathmandu Valley (Valley), Nepal.

5.2. Materials and Methods

To better understand the impacts of land-use on water in the pre-monsoon and monsoon periods, we first delineated the locations of streams in the Kathmandu Valley. Next, we collected new field data including streamflow, basic water quality, rapid stream assessments, and land-use ground observations. Then we developed a land-use coverage and watershed delineations for each of our stream measurement locations. We then used the combination of these field and derived geospatial data to visually represent how water quality and quantity changed as a function of land-use. Finally, we performed a correlation analysis to quantify these relationships.

5.2.1. Stream Network Generation

Using Quantum Geographic Information System (QGIS) as a user interface, we used the Geographic Resources Analysis Support System (GRASS) modules r.watershed to develop a stream network for the Kathmandu Valley. First, a Shuttle Radar Telemetry Mission (SRTM) 30-meter digital elevation model (DEM) was used to create a raster coverage of drainage directions between each pixel and the surrounding eight pixels [47]. Then, an accumulation raster was developed, where the number of upstream pixels draining to each pixel was quantified. Finally, thresholds of 100 and 600 upstream pixels were used to create both a fine and course scale stream network raster, which was converted to a vector coverage. These and other Python

scripts can be found in the following GitHub repository:

https://github.com/jcdavids/KathmanduLandUseWater.

5.2.2. Field Data Collection

For each of the nine perennial watersheds in the Valley, we identified between three and seven locations for performing the field data collection activities described below. Emphasis was placed on performing upstream measurements prior to considerable non-natural land-uses, and downstream measurements near the confluence with other tributaries. All field measurements were collected digitally in the field with an Android application called Open Data Kit or ODK [48]. ODK was used to record GPS coordinates and take photographic documentation for all observations.

Field data collection was performed in two different periods to characterize both monsoon and pre-monsoon conditions. Monsoon sampling was performed from the 5th to the 30th of September 2016. Except for one measurement (i.e. BA00; see Figure 5.2 for details), pre-monsoon sampling was performed between the 18th of April and the 17th of May 2017. Efforts were made to use the same personnel and equipment for both monsoon and pre-monsoon assessment to ensure data compatibility. Additionally, during pre-monsoon sampling, care was taken to avoid sampling during or after precipitation events, to ensure that measurements were representative of baseflow or near baseflow conditions. In practice this meant that field work was stopped if runoff generating rainfall events occurred. Sampling was later resumed when water levels returned to pre-event levels.

Streamflow Measurements

We measured streamflow at all locations with a SonTek FlowTracker Acoustic Doppler Velocimeter (ADV) using the United States Geological Survey (USGS) mid-section discharge method [49].

Basic Water Quality

We used a MultiLine® Multi 3630 IDS [WTW Germany] multiparameter meter to perform in-situ measurements of temperature (T), electrical conductivity (EC), dissolved oxygen (DO), and (pH). Due to equipment problems, 2017 pre-monsoon pH measurements were not performed and approximately half of the pre-monsoon dissolved oxygen measurements were analyzed at ENPHO labs in Kathmandu.

Rapid Stream Assessment

We used the Rapid Stream Assessment (RSA) for Himalayan streams ([44], [25]) to assess ecological stream health at each sampling location. RSA has been used as an integrated and robust method to assess ecological stream health for over 5 years. RSA utilizes four primary classification categories including: (1) sensory, (2) ferro-sulfide reduction, (3) bacteria, fungi, and periphyton, and (4) macro-invertebrate composition. Sensory features evaluated include smell, non-natural debris and turbidity. Ferro-sulfide reduction is used as a proxy for high organic loadings associated with high biological oxygen demand (BOD) and the associated reduction of

dissolved oxygen (DO). Certain bacteria, fungi, and periphyton are indicators of the presence and/or absence of certain pollutants. Finally, macroinvertebrates' richness and dominance of sensitive or tolerant organisms serve as a robust and integrated indicator of ecological stream health.

The output of the RSA process is a river quality class (RQC), ranging from one (1) to five (5), representing the best and worst quality rivers, respectively. RQC 1 represents natural to near natural waters suitable for all municipal, industrial, agricultural, and environmental purposes (after standard treatments as required). RQC 5, however, is most strongly impaired, with waters not suitable for any purposes. For each site, an RSA form was completed, georeferenced, and photographed via ODK.

Land-use Ground Observations
We used ODK to collect georeferenced photographic observations of land-uses at and around each RSA monitoring location. Land-use classes were based on the National Land Cover Database 1992 (NLCD92) introduced by the USGS Land Cover Institute [50]. Six land-uses classes were selected to represent the land-uses in the Kathmandu Valley: Forest; Shrubland, Agriculture Rice; Agriculture Non-Rice; Built Low; and Built High (Table 5.1). The sum of Forest and Shrubland are considered Natural land-uses; Agriculture Rice and Agriculture Non-Rice are collectively considered Agricultural land-uses; and Built Low and Built High are together consider Built land-uses. A total of 141 ground observations were recorded.

5.2.3. Land-use Map and Watershed Delineations
Land-use Map
We used the QGIS GRASS modules i.gensig and i.maxlik to assign per pixel a maximum likelihood for each land-use class. We performed this semi-supervised pixel based land-use classification on a cloud free Landsat 8 scene captured on October 7th, 2015 [51]. Two thirds of the 141 ground observations were used as training points for the spectral analysis algorithms, while one third were subsequently used as validation points of the resulting land-use map.

We assumed that land-use remained constant from the fall of 2015, when the Landsat image was taken, through the spring of 2017, when the pre-monsoon measurements were performed. Pre-monsoon sampling was performed prior to the planting of rice. Therefore, what was classified as rice in the October 2015 Landsat scene, was either weeds or bare earth being prepared for rice seedlings. Rice is usually planted roughly 2 to 4 weeks after when 2017 pre-monsoon sampling was completed.

Watershed Delineations
With the drainage direction raster developed during the stream network generation process, we used r.water.outlet to determine the watershed delineation for each RSA monitoring point. Using the watershed delineations, the land-use coverage, and QGIS GRASS zonal statistics, we calculated the area of each land-use within each RSA watershed. We developed Python scripts with Matplotlib library to develop stacked area land-use proportion summaries with RQC, water quality, and

Table 5.1: Description of land-use classes.

Class	Classification Criteria	Sample Picture
Forest	Trees (either evergreen or deciduous) cover greater than 25 %.	
Shrubland	Natural vegetation less than 6 meters tall and shrubs cover greater than 25 %.	
Ag Rice	Greater than 75 % rice.	
Ag Non-Rice	Greater than 75 % agriculture non-rice. This also includes non-natural grassy fields.	
Built Low	Between 25 % and 80 % built features (e.g. roads, houses, etc.).	
Built High	Greater than 80 % built features (e.g. roads, houses, etc.).	

water flow data plotted on the secondary vertical axes. These and other Python scripts can be found in the following GitHub repository:

https://github.com/jcdavids/KathmanduLandUseWater.

5.2.4. Correlation Analysis

We used Pearson's correlation coefficient r values [52] to characterize relationships between land-use and water quality and flow for 2016 monsoon and 2017 pre-monsoon data. The Pearson's r values were tested for significance with a two-tailed p-value hypothesis test.

5.3. Results for the Kathmandu Valley

5.3.1. Stream Network, Monitoring Locations, and Sub Watershed Delineations

Figure 5.1 shows the original SRTM 30-meter DEM (1) and the resulting stream network (2). The lighter and thinner blue lines represent streams with at least 100 upstream pixels. The darker and thicker blue lines represent streams with at least 600 upstream pixels. The Kathmandu Valley watershed boundary is shown, and uses Chobar as the pour point.
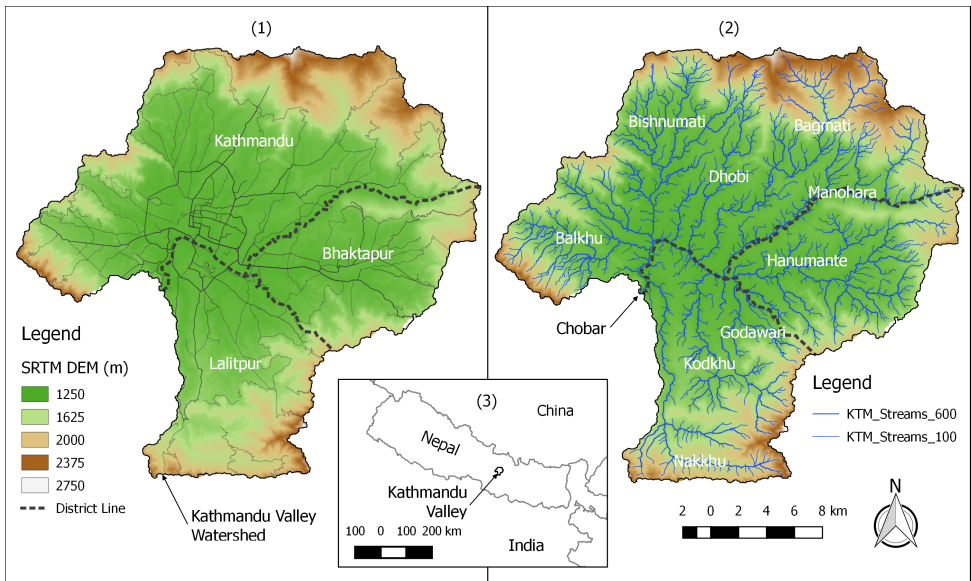
Figure 5.1: Kathmandu Valley Watershed with roads, district boundaries, and SRTM DEM at 30-meter resolution (1), stream network with nine perennial streams labeled (2), and location map of Nepal and the Kathmandu Valley (3). The Kathmandu Valley Watershed shown uses Chobar as the pour point.

Figure 5.2 shows the 38 monitoring locations (1) and the resulting upstream watershed delineations for each location (2). A single color was chosen for each of

the 9 tributaries, and the opacity was decreased from upstream to downstream. A tabular summary of the collected data is included in the supplementary data.
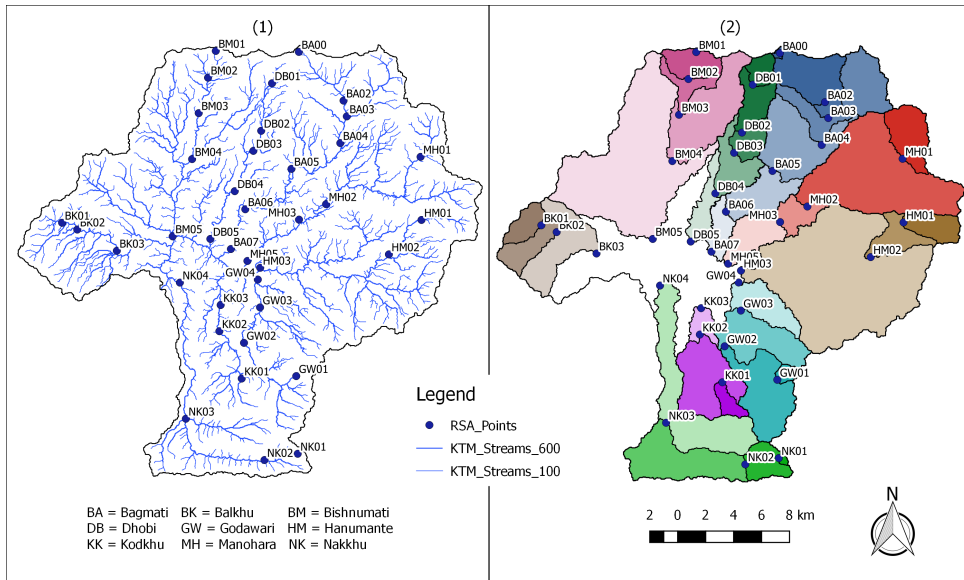

Figure 5.2: 38 measurement locations within the Kathmandu Valley (1) and resulting upstream watersheds for each location (2).

5.3.2. Land-use Coverage and Land-use Change Figures

Figure 5.3 presents the locations of our 141 land-use observation points (1) and the resulting 30-meter land-use raster coverage (2). 33 % of the Valley was classified as natural land-uses comprised of 22 % Forest and 11 % Shrublands. 41 % was classified as agriculture, with 24 % Agriculture Rice and 17 % Agriculture Non-Rice. The remaining 26 % was classified as Built, with 16 % low density, and 10 % high density. There was an 88 % agreement between the resulting land-use coverage and the land-use observations used for validation. For the remaining 12 %, the disagreement was either small and explainable (i.e. a mix-up between high and low developed areas or between rice and non-rice agriculture), or was at points where the land-use classification on the ground was also in doubt. Detailed information about resulting land-use statistics can be found in the supplemental material.

Figure 5.4 presents a map-based display of both the 2016 monsoon (1) and 2017 pre-monsoon (2) data. In both the monsoon and pre-monsoon data, locations with better ecological stream health were seen around the periphery of the Valley, with declining stream health moving towards the densely populated urban areas near the center of the Valley (shown in dark and light brown). Except for the Balkhu watershed to the west, the most upstream measurement of each watershed was either RQC 1 or 2 (i.e. blue or green). A noticeable upstream shift in RQC 4 and 5 (i.e. orange and red) was seen on the streams originating from the northern,
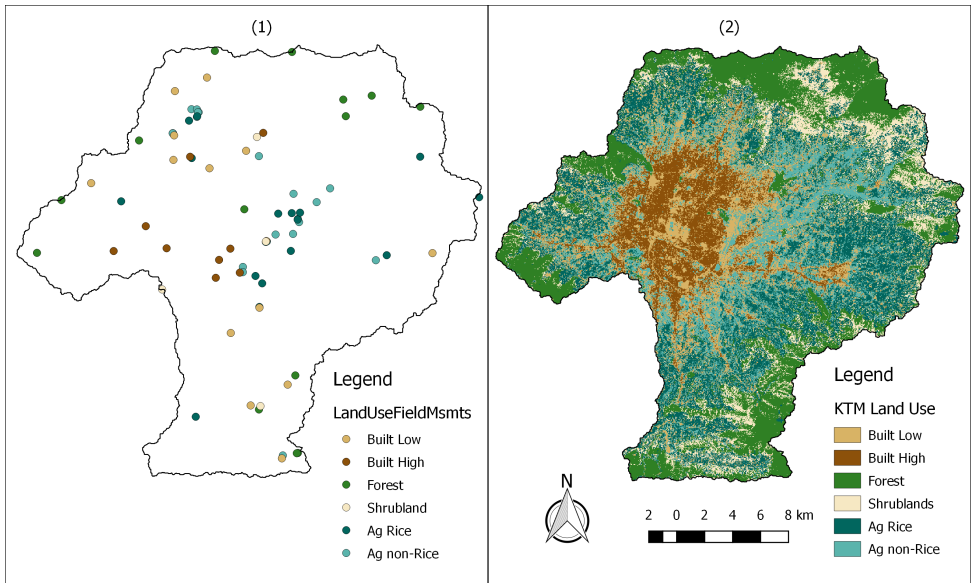
Figure 5.3: 141 land-use observation points (1) and resulting 30-meter resolution land-use classification map (2).

eastern, and southern portions of the Valley. The Balkhu watershed to the west has the lowest overall ecological stream health for all three monitoring locations.

For the Bagmati River, RQC was determined at seven sites during the 2016 monsoon and 2017 pre-monsoon (Figure 5.5; see supplemental materials for underlying data). The two upstream-most measurement sites were RQC 1 in both monsoon and pre-monsoon periods. RQC for the third through sixth sites diverges for monsoon and pre-monsoon. A deterioration in ecological stream health, illustrated by an increase in RQC, occurs from monsoon to pre-monsoon at all four of these sites. The fourth, fifth, and sixth sites showed a decline of two classes. The seventh and last site was RQC 5 for both the monsoon and pre-monsoon measurements.

Figures 5.6 through 5.9 present three by three arrays of the land-use proportion and water quality and flow data for the nine perennial streams in the Kathmandu Valley. The data are presented in the same way as the Bagmati River watershed data (Figure 5.5). RQC and EC data are plotted with the secondary (right) vertical axes reversed so that values that move vertically downward on the plot areas represent a decline in ecological stream health or water quality.

RQC had deteriorating trends from upstream to downstream for all nine watersheds (Figure 5.6). The steepest declines in ecological stream health occurred in the Dhobi (1), Bishnumati (4), and Hanumante (6) watersheds. These watersheds had the largest and upstream most occurring proportions of built (low and high) uses. A deterioration in ecological stream health from 2016 monsoon to 2017 pre-monsoon periods was observed at the Dhobi (1), Bagmati (2), and Godawari (3) watersheds (Figure 5.6). The largest improvement in ecological stream health from
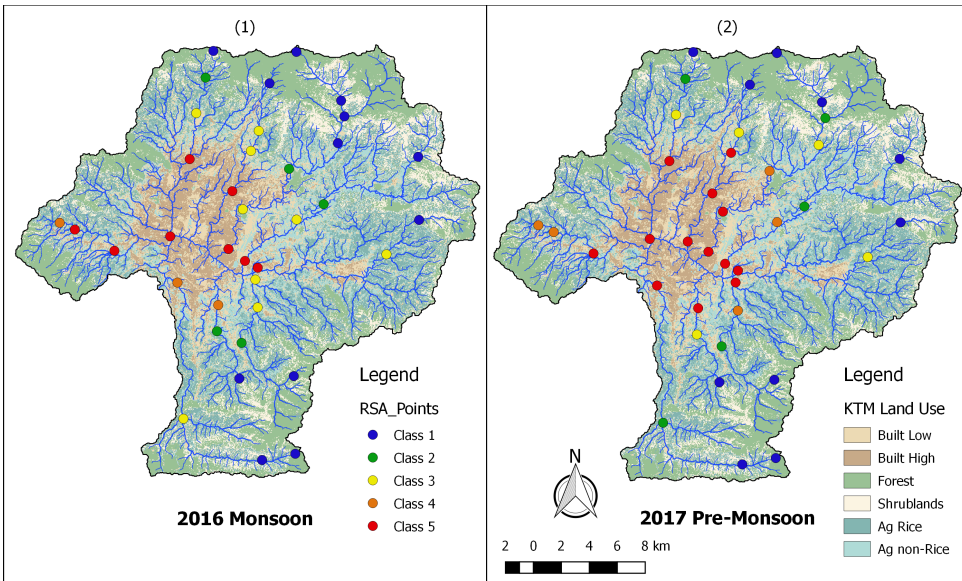
Figure 5.4: Map based approach for both the 2016 monsoon (1) and 2017 pre-monsoon (2) data. Land-use colors are shown with 50 % transparency to make RQC more viewable. Standard colors for RQC are used [44].

monsoon to pre-monsoon was one RQC, while the largest deterioration was two RQC. All watersheds during 2017 pre-monsoon had RQC 5 at the most downstream measurement site. During the 2016 monsoon, the Kodkhu (5), Nakkhu (8), and the Godawari (9) had RQC of 4, 4, and 3, respectively.

Both EC and DO showed similar deteriorating trends from upstream to downstream for all nine watersheds (Figures 5.7 and 5.8). An increase in EC was observed at eight out of the nine watersheds from 2016 monsoon to 2017 pre-monsoon; EC levels decreased slightly at the Nakkhu watershed. The largest changes in EC were observed at the Dhobi (1), Bagmati (2), Bishnumati (4), and Hanumante (6) (Figure 5.7). The largest declines in DO were observed at the Dhobi (1), Bagmati (2), Bishnumati (4), and Balkhu (7) watersheds (Figure 5.8). During 2017 pre-monsoon, the Dhobi (1), Bagmati (2), Manohara (3), Bishnumati (4), Hanumante (6), and Balkhu (7) watersheds all had DO values below 2 mg l^{-1}.

Flows showed increasing trends from upstream to downstream for all watersheds in the 2016 monsoon and 2017 pre-monsoon periods (Figure 5.9). All flows during the 2017 pre-monsoon were less than 2016 monsoon. On average, flows during the pre-monsoon were 11 % of monsoon values (min = 0.6 %; max = 49 %; SD = 12 %). During the pre-monsoon period, precipitation and runoff are low. Even still, we observed steady increases in streamflow from upstream to downstream, especially in areas with Built Low and High land-uses. Our hypothesis is that this increase in flow is due to wastewater return flows from either surface water or groundwater sources. A subsequent publication will explore the possibility of
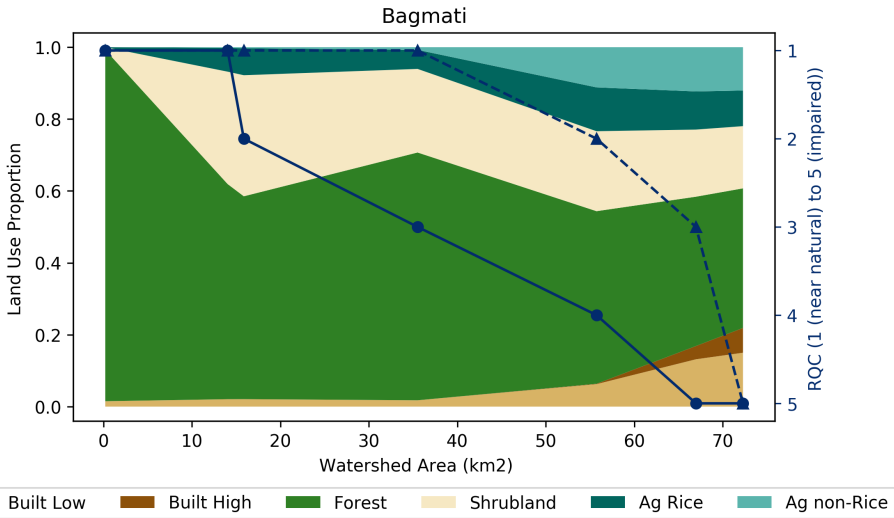
Figure 5.5: Land-use proportions and river quality class (RQC) for the Bagmati River in the Kathmandu Valley. Land-use proportions shown for six land-uses classes with reference to the primary (left) vertical axes. RQC shown for 2016 monsoon (dashed line with triangles) and 2017 pre-monsoon (solid line with circles) periods with reference to the secondary (right) vertical axes. The x-axis represents areas of the watersheds upstream of each measurement point, moving upstream to downstream (left to right). Watershed areas range from 0.2 to 72.3 km². The six colors on the figure correspond with the six land-use classifications (Figure 5.3). The relative vertical proportion of each color at each monitoring location represents the upstream proportion of each land-use (with reference to the primary (left) axis).

solving for net groundwater pumping from stream reach water balance analyses in the pre-monsoon period.

5.3.3. Correlation Analyses

Pearson's r values between variables for both 2016 monsoon and 2017 pre-monsoon are shown in Table 5.2 (n = 38, p = 0.01, r > 0.430). For the 2016 monsoon period, 21 out of the possible 28 correlations (i.e. all except flow) were statistically significant. During the 2017 pre-monsoon period, 24 out of 28 correlations were statistically significant. For both monsoon and pre-monsoon data, RQC had significant correlations with all three land-use groups. RQC had a positive correlation with Built and Ag land-uses, meaning that ecological stream health deteriorated as the proportions of Built and Ag lands increased. In contrast, RQC was negatively correlated with Natural lands. Both temperature and EC increased, while DO decreased, as proportions of built and agricultural land-uses increased. Natural lands had the exact opposite impact. Temperature and EC decreased, while DO increased, as proportions of natural lands increased.
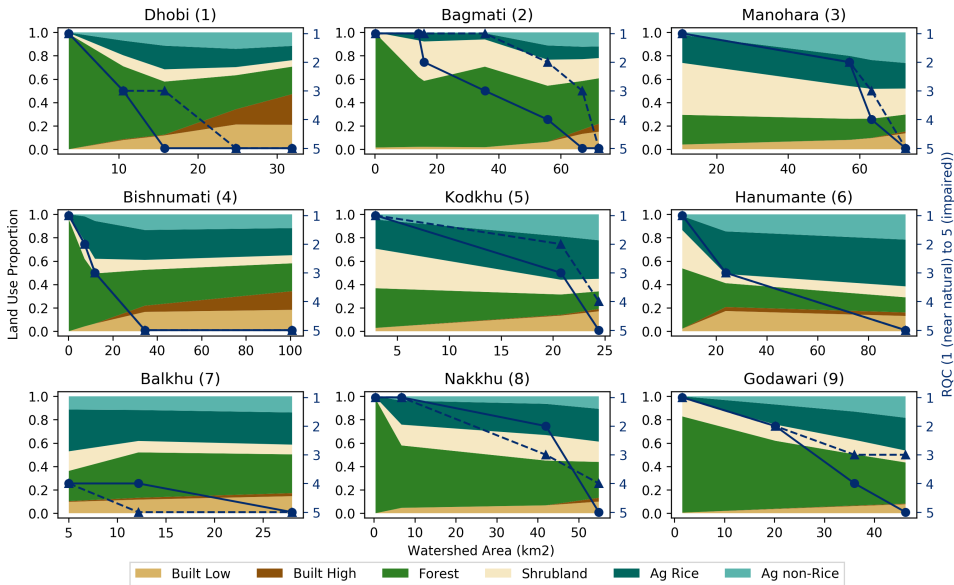
Figure 5.6: Land-use proportions and river quality class (RQC) for the nine perennial streams in the Kathmandu Valley. Land-use proportions shown for six land-uses classes with reference to the primary (left) vertical axes. RQC shown for 2016 monsoon (dashed line with triangles) and 2017 pre-monsoon (solid line with circles) periods with reference to the secondary (right) vertical axes.

5.4. Conclusions and Discussion

Headwater land-uses were dominated by natural (i.e. Forest and Shrublands) land-uses (Figures 5.3 and 5.6). Moving downstream, land-uses transitioned to agriculture (i.e. Ag Rice and Ag Non-Rice) and then to built (high and low density; Figures 5.3 and 5.6). Due mostly to mild topography and a lack of legal protections, some watersheds (i.e. Manohara, Kodkhu and Balkhu; Figures 5.6.3, 5.6.5 and 5.6.7) do not have large percentages of natural land-uses upstream of the first RSA monitoring points. This results in the most upstream RQC and water quality values being already impaired. These upstream to downstream land-use trends are a function of topography, historical population areas, and protected areas. The hills surrounding the Kathmandu Valley have steeper slopes than the Valley floor, which constrains agricultural and built land-uses. There are also several protected areas and community forests in the surrounding hills inhibit agricultural and built expansion.

Spatially, RQC increased (i.e. deteriorated in quality) moving radially inward toward the center of the Valley where Built land-uses dominated (Figure 5.4). Similar trends for EC and DO were observed (Figures 5.7 and 5.8). Correlation analyses showed that Built land-uses had the strongest impact on RQC, EC, and DO (Table 5.2).

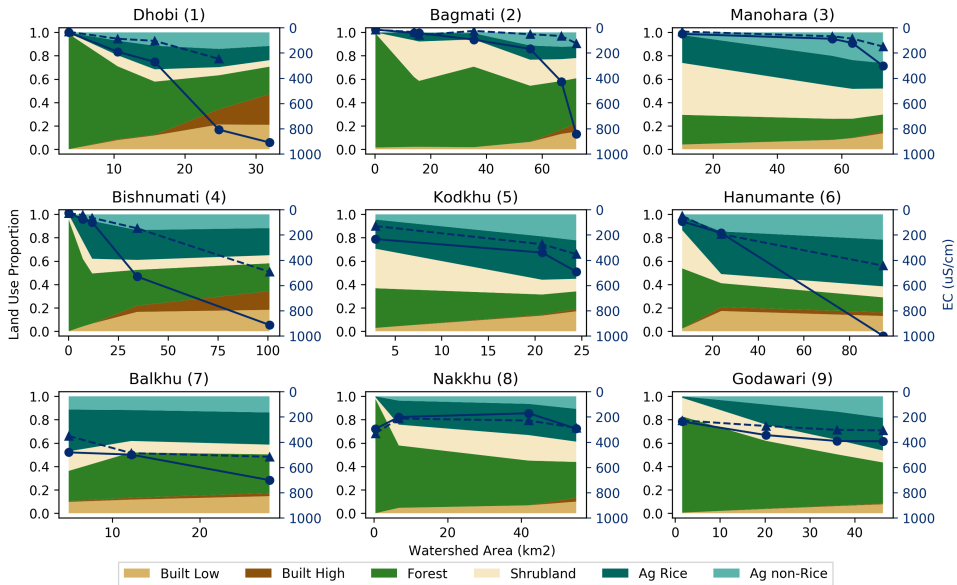Temporally, RQC mostly stayed the same or deteriorated from 2016 monsoon

Figure 5.7: Land-use proportions and electrical conductivity (EC) results for the nine perennial streams in the Kathmandu Valley. Land-use proportions shown for six land-uses classes with reference to the primary (left) vertical axes. EC results in micro siemens per centimeter (μS cm^{-1}) shown for 2016 monsoon (dashed line with triangles) and 2017 pre-monsoon (solid line with circles) periods with reference to the secondary (right) vertical axes.

to 2017 pre-monsoon (Figure 5.6). Deviations from this trend were observed at the middle sites of the Balkhu (7) and Nakkhu (8). In general, DO and EC both deteriorated (i.e. DO decreased and EC increased) from monsoon to pre-monsoon (Figures 5.7 and 5.8). Only the Nakkhu (8) had higher EC values in the 2017 monsoon compared to 2016 pre-monsoon values. Regarding DO, only upstream sites from the Bagmati (2), Bishnumati (4), and Nakkhu (8), and the midstream measurement from the Kodkhu, deviated from this trend with higher DO during 2017 pre-monsoon measurements.

5.4.1. Discussion

Our results are supported by a previous study of the Bagmati River basin [25]. Shah and Shah [25] indicated that nutrient like chloride and ortho phosphate, and the physicochemical parameters temperature and conductivity increased as rivers flowed through urban areas. Built land-uses include both urban and industrial activities. A lack of water treatment facilities leads to direct discharge of wastewater into streams ([25], [46]). The organic and nutrient loads of these wastewaters caused the statistically significant correlations observed [25]. In built areas, stressors related to effluents, activities and facilities, and solid wastes mainly contribute to deteriorating water quality of rivers ([43], [25]). However, certain watersheds (i.e. Manohara, Nakkhu, and Godawari) had natural and agricultural land-uses that
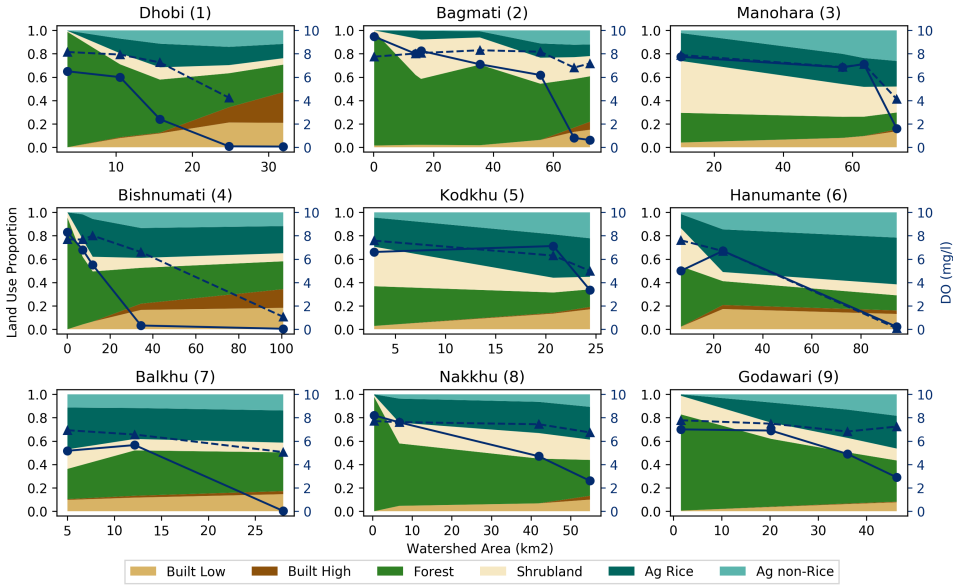
Figure 5.8: Land-use proportions and dissolved oxygen (DO) results for the nine perennial streams in the Kathmandu Valley. Land-use proportions shown for six land-uses classes with reference to the primary (left) vertical axes. DO results in milligrams per liter (mg l^{-1}) shown for 2016 monsoon (dashed line with triangles) and 2017 pre-monsoon (solid line with circles) periods with reference to the secondary (right) vertical axes.

persisted at higher relative proportions farther downstream relative to other watersheds within the Valley. This helped to maintain ecological stream health over longer stream reaches (Figures 5.6.3, 5.6.8, and 5.6.9). Therefore, land-use managers should place higher priority on actively managing and protecting lands within the upstream portions of these tributaries.

For the Balkhu (7), the upstream RQC was 4, whereas all other upstream measurements were RQC 1 or 2. Based on discussions with local residents during field work, many of the springs originating in the higher elevations of the southern portion of the watershed are diverted for water supply. The remaining drainage areas are relatively low in elevation and receive less precipitation in relation to other areas of the Valley because of rain shadow effects. We suggest that these two factors, combined with the low proportion of natural land-uses (Figure 5.6.7) in the watershed, cause the observed low quality.

Shah and Shah [25] also found that pre-monsoon is the most critical season for ecological condition of the river. They observed that ecological river quality was worst in pre-monsoon compared to post-monsoon season because the amounts of stressors are similar throughout the year, while discharge dramatically reduces during the pre-monsoon. River stretches flowing through built areas had mainly sludge as river substrates with assemblages of nil to few numbers of highly tolerant macroinvertebrates like red Chiromidae and Syrphidae. Since flows during the pre-
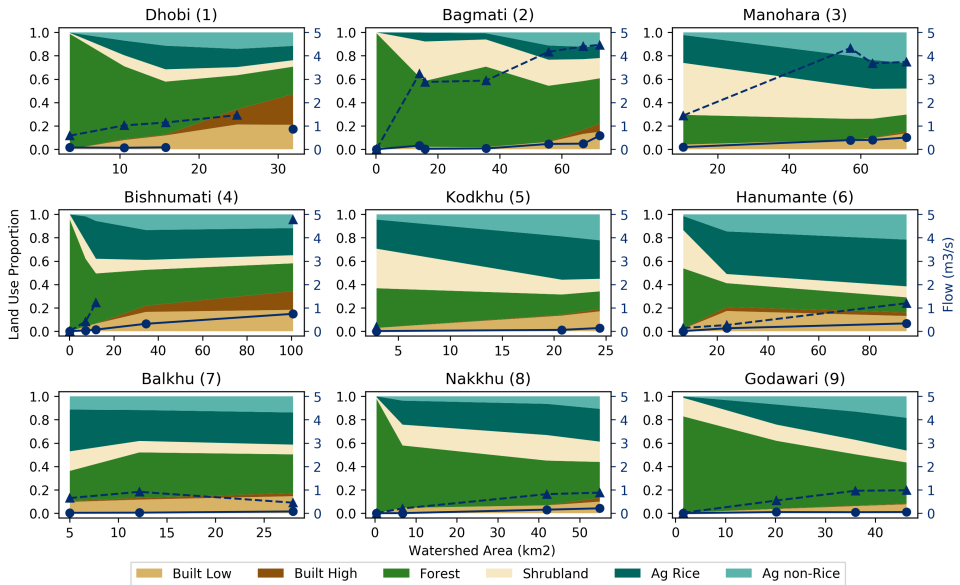
Figure 5.9: Land-use proportions and flow results for the nine perennial streams in the Kathmandu Valley. Land-use proportions shown for six land-uses classes with reference to the primary (left) vertical axes. Flow results in cubic meters per second (m3 s^{-1}) shown for 2016 monsoon (dashed line with triangles) and 2017 pre-monsoon (solid line with circles) periods with reference to the secondary (right) vertical axes.

monsoon are less than the monsoon (on average 11 %; Figure 5.9), this trend is likely due to the adage that "dilution is the solution to pollution."

We suggest that our three different visualization techniques (i.e. map based, graphical, and correlation matrixes) can be used to "tell the story" in these land-use and water quality data to a wide audience of citizens, scientists, and policy makers. The map based and graphical approaches for visually presenting the relationships between land-use and water quality and quantity provide a framework for communicating these data to a wide audience. The correlation analyses quantify these relationships in a concise way. Additional work should focus on evaluating the effectiveness of these techniques on crucial stakeholders and decision makers.

5.4.2. Sources of Uncertainty

Two land-use assumptions stated earlier are worth revisiting. First, we assumed that land-use was stationary between the image capture date in October 2015, monsoon monitoring in 2016, and pre-monsoon monitoring in 2017. Because of the 18-month interval between the 2015 image capture date and 2017 pre-monsoon monitoring, it is likely that there were some changes to land-uses during this period. While efforts are currently underway to collect additional land-use observations to create an updated land-use map, the results are not yet available. Therefore, there is currently no way to quantify the extent of the land-use changes within the period

Table 5.2: Pearson's r values between RQC, Built (i.e. sum of Built Low and High), Natural (i.e. sum of Forest and Shrubland), Ag (i.e. sum of Ag Rice and Ag non-Rice), temperature (Temp), electrical conductivity (EC), dissolved oxygen (DO), and streamflow (FLOW). Statistically significant values (n = 38, p = 0.01, r > 0.430) shown in **bold** font.

	RSA	Built	Natural	Ag	Temp	EC	DO	Flow
2016 Monsoon								
RSA	1							
Built	**0.84**	1						
Natural	**-0.82**	**-0.76**	1					
Ag	**0.68**	**0.44**	**-0.92**	1				
Temp	**0.56**	**0.53**	**-0.81**	**0.82**	1			
EC	**0.60**	**0.49**	**-0.56**	**0.51**	**0.46**	1		
DO	**-0.68**	**-0.71**	**0.68**	**-0.56**	**-0.46**	**-0.64**	1	
Flow	0.26	0.39	-0.27	0.16	0.34	-0.17	-0.23	1
2017 Pre-Monsoon								
RSA	1							
Built	**0.73**	1						
Natural	**-0.78**	**-0.76**	1					
Ag	**0.63**	**0.44**	**-0.92**	1				
Temp	**0.51**	**0.52**	**-0.63**	**0.55**	1			
EC	**0.72**	**0.81**	**-0.66**	0.42	0.36	1		
DO	**-0.84**	**-0.78**	**0.67**	**-0.45**	**-0.46**	**-0.83**	1	
Flow	**0.55**	**0.81**	**-0.54**	0.28	0.39	**0.61**	**-0.64**	1

of this study. We anticipate, however, that any observed changes will be less than a few percentage points. Second, we assumed that the inter-annual variations in actual land cover within the Agriculture Rice land-use had a negligible impact on our results. While it is likely that these seasonal changes have an impact on evapotranspiration and soil moisture storage, it is unlikely that stream water quality was affected. This is because rainfall, and therefore recharge and runoff were low during the 2017 pre-monsoon sampling period.

Uncertainty in land-use classification ends up directly propagating to uncertainty in the resulting understanding of the impacts of land-use on water quality and flow. Our pixel based classification methodology is based on probabilities derived from training, so inherently there is a chance of misclassification. Our validation process indicated that roughly 88 % of the pixels checked were correctly classified. The incorrect classifications were either mistakes between the density (i.e. low or high) of built land-uses, or between the type of agriculture (i.e. rice or non-rice). While built low or high (or agriculture rice or non-rice) are likely to have different impacts on ecological stream health, the magnitude of these differences is poorly understood. To improve confidence in the land-use classification, we suggest that it be updated every 2 to 5 years, and that additional ground truthing observations be performed. This will decrease uncertainty in the classification probabilities, and will increase the size of the validation data set. Despite these uncertainties in land-use classification, we do not observe any systematic biases that would change the primary findings of this investigation.

Additionally, uncertainty in field measurements (e.g. RQC, EC, DO, and Flow) ends up affecting uncertainty in our understanding of the impacts of land-use on water quality and flow. RSA measurements, including (1) sensory, (2) ferro-sulfide reduction, (3) bacteria, fungi, and periphyton, and (4) macro-invertebrate composition observations, are likely the most subjective measurement included in this analysis. Despite the semi-subjective nature of the sensory observations in particular, we suggest that using the same person to perform RSA measurements, as was done for this study, is the best way to remove this source of uncertainty. This is because the same person is most likely to consistently repeat sensory observations using the same standards. EC and DO were measured with a MultiLine® Multi 3630 IDS [WTW Germany] with a stated accuracy of ±0.5 % of the actual value. Based on an ISO discharge uncertainty calculation within the SonTek FlowTracker software, the average uncertainty in flow was 4.9 %. Despite these uncertainties in field observations of RQC, EC, DO, and flow we do not observe any systematic biases that would change the main conclusions of this paper.

5.5. Summary

We collected water flow and quality data from 38 locations within the Kathmandu Valley during 2016 monsoon and 2017 pre-monsoon periods. By combining these data with a newly generated land-use coverage, we were able to quantify the impacts of land-use on water quality and flow. There was a statistically significant impact ($p = 0.01$) of land-use on water quality (i.e. RQC, DO, and EC), with built land-uses (both low and high density) having the strongest impact. Our findings emphasize the need to integrate land-use planning and water resource management in general, while specifically underscoring the critically impaired status of the perennial tributaries to the Bagmati River in the Kathmandu Valley.

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6

Streams, Sewage, and Shallow Groundwater

*It's like mixing cow manure and ice cream -
It doesn't mess the cow manure up too bad,
But it sure ruins the ice cream.*

Shane Claiborne

Due to rapid urbanization and insufficient water resource planning and waste water management, the Kathmandu Valley (Valley) is facing both a water quantity and quality crisis. Annually, groundwater extractions in the Valley exceed recharge rates, resulting in groundwater table declines. Even though streams often are an important linkage between surface water and ground-water systems, from both a quantity and quality perspective, understanding of stream-aquifer interactions in the Valley is limited. To improve this understanding, we performed topographic surveys of water levels, and measured water quality, in streams and adjacent hand dug wells (shallow aquifer). In pre-monsoon 2018 (three watersheds, 16 stream-well pairs), we found 88 % of water levels in wells lower than adjacent streams, indicating a loss of stream water to the aquifer. However, in post-monsoon 2018 (eight water-sheds, 35 stream-well pairs), 69 % of wells had water levels higher than adjacent streams, indicating that monsoon rainfall had at least temporarily recharged the shallow aquifer, causing streams to transition from losing to gaining. No recurring longitudinal trends (upstream to downstream) in water level differences were seen. Concentrations of all water quality parameters (electrical conductivity, ammonia, chloride, hardness, alkalinity, and hard-ness) were higher in the pre-monsoon compared to the post-monsoon. Stream

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water quality showed relatively larger differences in distributions from pre- to post-monsoon, while well differences were generally smaller (with the exception of hardness). Stream and groundwater quality in adjacent wells depleted longitudinally from upstream to downstream. Our findings highlight the importance of managing streams and aquifers as a single integrated resource. In the Kathmandu Valley, groundwater is currently the primary way that large amounts of monsoon rain water are stored for use in the subsequent eight month dry period. While we clearly observed seasonal refilling of the shallow aquifer, the timing and extent of this process, and the role of the deep aquifer in seasonal storage processes deserve future research attention. In the meantime, Kathmandu's incessant growth is steadily paving over the "inlet" to its essential water storage "tank," while its lack of wastewater management is gradually contaminating the water that still makes it in.

6

6.1. Introduction

6.1.1. Stream-Aquifer Interactions

Surface water and groundwater are often treated as two different resources. However, almost all surface waters interact with groundwater [1]. An understanding of these interactions is crucial when managing water resources. Exchange between streams and aquifers may happen in three different ways: the stream is either (1) losing - stream water infiltrates into the aquifer, (2) gaining - groundwater flows into the stream, or (3) disconnected - losing stream that is disconnected from the aquifer by an unsaturated zone [1]. Water availability is decreasing due to pollution [2]. Intuitively, when a losing stream is polluted, the quality of the stream affects the quality of the surrounding groundwater. Therefore, the poor water quality in the Kathmandu Valley's streams ([3], [4], [5]) illustrates the relevance of this study. Knowledge of stream-aquifer interactions is crucial component of developing effective and sustainable water management plans that integrate both water quantity and quality issues [6].

6.1.2. Kathmandu Valley Hydrogeology

The Kathmandu Valley (Valley) and its surrounding hills consist of 400 million years old basement rock (Precambrian to Devonian age). This layer is covered with unconsolidated to partly consolidated Pliocene and Quaternary sediments [7]. The thickness of this unconsolidated layer ranges from 10 m at the edges of the Valley to 500 m near the center, and consists of fine texture sediment in the center and coarser sediment around it [8]. The Japan International Cooperation Agency (JICA; [9]) divided the Kathmandu Valley into three groundwater districts (Figure 6.1). The Northern Groundwater District has high recharge potential and consists of unconsolidated and highly permeable sand and gravel, this forms the main aquifer in the Valley. The upper layer of the Central Groundwater District consists of very thick stiff black clay (Kalimati clay), unconsolidated low permeable coarse sediment is found under this layer. This confined aquifer is stagnant and is not directly rechargeable vertically from above. The Southern Groundwater District consists of thick impermeable clay and only along the Bagmati River between Chobhar and Pharping is there an alluvial aquifer. An important implication for areas with thick layers of Kalimati clay is that vertical groundwater flow to the deep aquifer is likely low. However, it should be noted that the Kalimati clay layer does not cover the entire Valley floor, so active recharge of the deep aquifer may be possible, especially in the Northern Groundwater District. However, the shallow aquifer does have the potential to be recharged, which is confirmed by the yearly fluctuating levels during the monsoon. Natural recharge of the shallow aquifer (and perhaps deep as well) is declining due to the increased sealing (hardscaping) of the surface by urbanization which prohibits rainwater infiltration [8].

Deposits within the Valley contain multiple sand and gravel beds which form the principal aquifers in the northern and northeastern part of the Valley. In the central and southwestern parts of the Valley these layers are overlain by a thick lacustrine clay layer that acts as aquitard. The south and southeastern part of
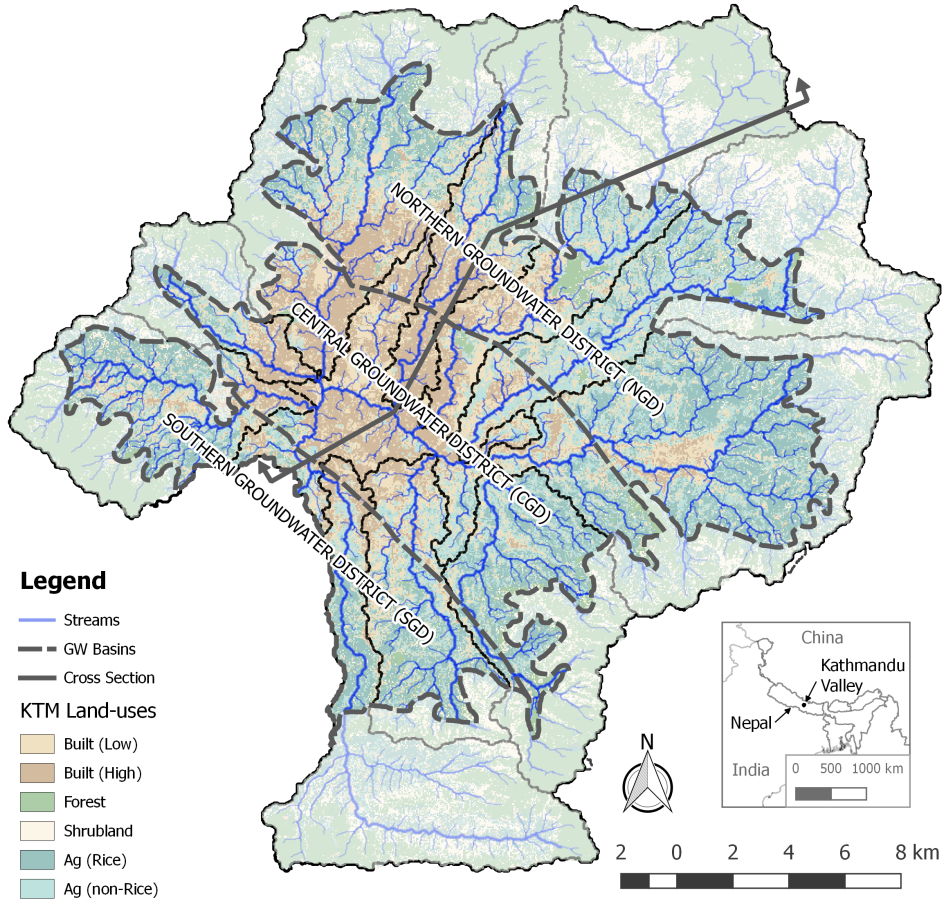
Figure 6.1: Kathmandu Valley watershed showing land use, stream network, and the geologic cross-section location shown in Figure 6.2. The three groundwater zones delineated by JICA [9] are also shown. The Kathmandu Valley watershed delineation, land use, and stream network are described in greater detail in Chapter 5.

the Valley consist of carbonate rocks which are classified as lower permeability aquifers. Figure 6.2 provides a cross-sectional view of the subsurface geology and hydrogeological system [8].

6.1.3. Kathmandu Valley Water Situation

The Kathmandu Valley finds itself in a water quantity and quality crisis. Surface water supplies in the Valley can be unpredictable, scarce, and polluted. Therefore, depending on the time of year, groundwater meets between 50 and 75 % of the residential, industrial, and agricultural water demands in the Valley [11]. Rapid ur-

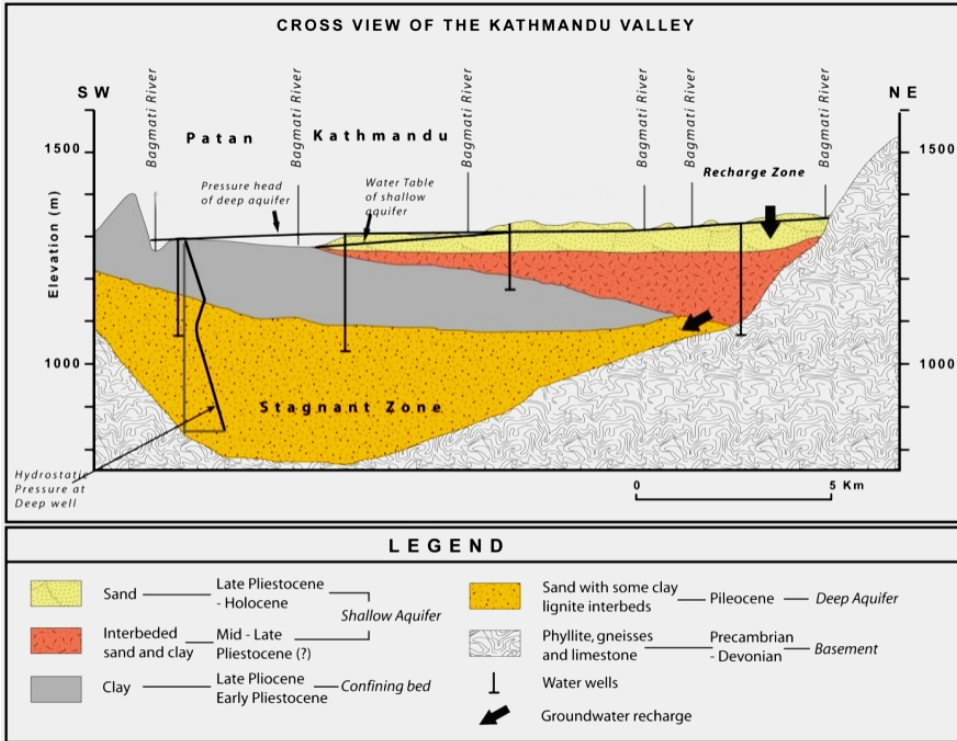Figure 6.2: Conceptual cross-section through the Kathmandu Valley Basin groundwater system. Edited from "A first Estimate of groundwater ages for the deep aquifer of the Kathmandu Basin, Nepal, Using the Radioisotope Chlorine-36" by Cresswell et al. 2001 retrieved from [10]. Copyright by Cresswell et al., 2001. Reprinted with permission. Cross-section line shown in Figure 6.1.

banization, inadequate infrastructure, and changing lifestyles and socioeconomics continue to increase demand for water, increase discharge of untreated wastewater into the rivers, and reduce groundwater recharge [8]. During monsoon, regular precipitation events create opportunities for refilling depleted soil moisture and subsequent refilling of the aquifer(s), however, recent hardscaping (i.e. decreasing the permiability of surfaces) has decreased infiltration capacity and increased runoff [12]. A lack of institutional responsibility in groundwater management intensifies the problem [13]. Understanding stream-aquifer interactions, therefore, is critical for sustainable management of both water quantity and quality.

Currently, groundwater in the Valley is extracted from both the shallow and deep aquifers, which are separated by interbedded layers of clay with varying thicknesses [14]. Before the 1970s, the shallow aquifer was the only source of groundwater production. Subsequently, mechanized extraction from the deep aquifer was started for municipal supplies, industry, and the private sector. Due to the long timescales of interactions with surficial processes, water in the deeper aquifer is more slowly affected by human activities [8]. Extraction rates from the deep aquifer have con-

tinued to increase [15]. Since rates of groundwater withdrawal are estimated to be in excess of capturable discharge, groundwater levels has been declining since the 1980s ([14], [12], [8]). However, spatial distribution of impacts between the shallow and deep aquifer are poorly understood. Anecdotal evidence of progressively more stone spouts and shallow wells going dry each year supports the conclusion that the shallow aquifer is being negatively impacted by over extraction [15].

In addition to over extraction, anthropogenic activities are also degrading water quality [12]. Various studies have shown declines in groundwater quality over time [16], [17], [18], [14], [19]). The shallow aquifer, to varying degrees, is predominantly contaminated by nitrates and Escherichia coli (E. coli) ([20], [15]).

While many studies have highlighted deterioration of water quality of groundwater and surface water in the Valley independently, only Bajracharya et al. [21] quantified interactions between streams and the underlying aquifer(s) and its implications. Using chemical parameters and stable water isotopes, they found that interactions affecting both surface water and groundwater exist near river channels, and the direction of interactions varies by location. They also found that the rivers in the Valley deteriorate from upstream to downstream. The monsoon overall improves chemical ion concentrations, with values decreasing nearly by one half compared to pre-monsoon values. The study concludes by recommending collection of more water quality samples from wells and streams, in addition to data on groundwater levels and adjacent surface water levels.

6.1.4. Objectives

The aims of this paper were to (1) understand stream-aquifer interactions in the Valley, with a specific focus on the northern tributaries, (2) compare these interactions between pre- and post-monsoon periods, and (3) investigate the impact of these interactions on water quality. This research focused on answering the following questions:

1. What is the nature of pre- and post-monsoon stream-aquifer interactions in the primary tributaries to the Bagmati River within the Kathmandu Valley?

2. How do these interactions change longitudinally from upstream to downstream?

3. How do pre- and post-monsoon interactions impact stream and groundwater quality?

6.2. Methods and Materials

6.2.1. Monitoring Locations

We performed measurements in three watersheds in the pre-monsoon, and in eight watersheds in the post-monsoon of 2018 (Figure 6.3). Pre-monsoon measurements were performed at 16 (red) sites from 6 April to 10 April 2018. The initial pre-monsoon measurements focused on streams overlying the highly permeable Northern Groundwater District, and therefore included the Bishnumati, Dhobi, and

Bagmati River watersheds. Post-monsoon measurements were performed between 6 September and 29 September 2018 at 35 (red and blue) sites. In the post-monsoon, we added five other watersheds including the Manohara, Hanumante, Godawari, Nakkhu, and Balkhu. The additional watersheds were added to improve the spatial distribution of observations and to investigate the impact of different geology, hydrology, and land-use on stream-aquifer interactions.

For each watershed, three to ten monitoring locations were chosen for field data collection (Figure 6.3). Locations were chosen based on (1) the availability of dug wells in the shallow aquifer located close (i.e. within 100 m) to the selected streams, and (2) the desire to distribute sites from upstream to downstream as much as possible. Upstream measurement locations along the Bagmati are not equidistant because BA05 (between BA04 and BA06; not shown in Figure 6.3), which was measured during the pre-monsoon season, was inaccessible during the post-monsoon measurement campaign. Therefore, it was removed from our analyses.

In the case of BA06, GD04, and BK03, abandoned wells nearby the stream were used for water level measurements, but an adjacent well with some amount of production was used for water quality measurements. This helped to ensure that the groundwater sample was representative of conditions in the shallow groundwater, and not simply surface contamination introduced into an used well. In all cases, wells were located as close to the stream as possible, and within the fluvial plain, since topographic conditions of a site influence groundwater levels [23]. Sites with a steep and elevated surroundings were likely have higher groundwater levels, so in steeper areas we tried to select wells with similar elevations as the streams.

6.2.2. Data Collection and Analyses

All measurements were recorded in the field using an Android application called Open Data Kit (ODK) Collect [24]. ODK Collect supports recording GPS locations, taking photographs of measurements, entering text and numerical data in the field. S4W developed and uses a custom Python webapp for quality controlling and managing data collected by citizen scientists and young researchers (see Section 1.6.1 for details). The same equipment and measurement methodology were used pre- and post-monsoon. Measurements in the pre-monsoon were performed by one of the authors along with S4W-Nepal staff, while in the post-monsoon they were performed by five of the authors. Care was taken to avoid sampling during rainfall events so that measurements represented near base flow conditions. Measurements were postponed during heavy rainfall events and where resumed after streams returned to pre-event water levels.

We developed Python scripts with Matplotlib extensions to create Figures 6.6 through 6.10 showing water level differences, water quality parameters, and correlations using both pre- and post-monsoon data. Trendlines have been made using the Numpy polyfit function (Least squares polynomial fit). Box plots have been made using the pyplot Box plots function. Pearson correlation values are calculated using the Numpy correlation coefficient function corrcoeff. All used scripts can be found here: https://github.com/jcdavids/KTMStreamAquiferInteractions.
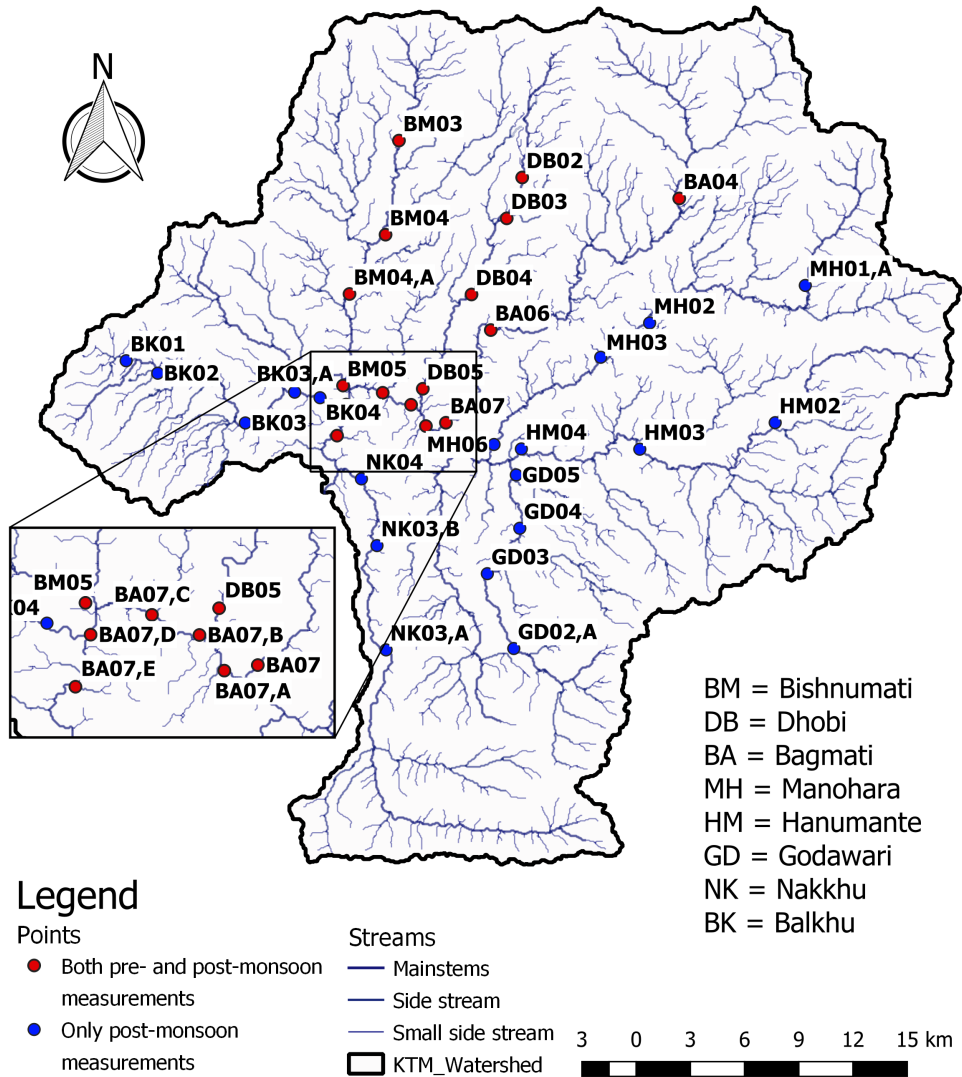
Figure 6.3: Measurement locations in the Kathmandu Valley with the network of the nine perennial streams used as a base map [22]. Monitoring sites (n = 35) that were measured in both the pre- and post-monsoon 2018 (n = 16) are shown as red circles; blue circles were only measured during the post-monsoon 2018 (n = 19). Measurements at each site included a water level and quality measurement in the stream in addition to a water level and quality measurement in an adjacent shallow (i.e. hand dug) monitoring well.

6.2.3. Water Level Measurements

All wells included in this investigation were hand-dug shallow wells with concrete ring casings and rock bottoms. Depths of shallow wells ranged from 2.2 to 10.5

m. Well diameters ranged from 0.67 to 1.21 m. Groundwater extraction from monitoring wells was either non-existent (i.e. abandoned) or limited, due to manual methods of water production with a bucket and rope. We made efforts to avoid taking groundwater level measurements within a few hours of groundwater withdrawals. Because of the limited depths of these wells, the lack of penetration into potentially confined aquifer units, and the generally low production rates, we considered groundwater level measurements in wells to be representative of shallow groundwater table conditions adjacent to the well.

To calculate stream-aquifer water level difference (Δh), topographic surveys of water levels in streams and adjacent wells was performed with a Topcon AT-B series 24x Automatic Level [Topcon] (Figure 6.4). Topographic surveys and stream level and groundwater level measurements involved the following steps:

1. Selected shallow groundwater wells and stream water level measurement locations.

2. Identified, marked, and took pictures of reference points (RPs) on wells and benchmarks (BMs) near stream banks.

    (a) RPs were generally the top of the concrete rings used as the well casings.

    (b) BMs were usually the top of retaining walls or the deck of bridges.

3. Performed topographic survey to measure the difference in elevation between BMs and RPs (RP_BM).

    (a) In most cases, this involved a single tripod setup without any turning points.

    (b) When sites required multiple setups, a closed loop survey was performed and resulting errors were distributed between surveyed points.

4. Measured distance from BM to water surface elevation (BM_WSE).

    (a) Performed by lowering a measuring tape from the BM until it touched the water surface. By convention, these measurements were considered negative.

    (b) Some sites were equipped with 1 m fiberglass staff gauges. In this case, water level readings were recorded and the 0 mark of the staff gauge was surveyed as the BM. By convention, these measurements were considered positive.

    (c) In either case, photographs of BM to WSE measurements were taken in ODK Collect to provide quality control of data entry.

5. Measured distance from RP to groundwater WSE (RP_GWSE).

    (a) Performed by lowering a measuring tape from the RP until it touched the GWSE.

(b) Took photographs of RP to GWSE measurements were taken in ODK Collect to provide quality control of data entry.

(c) By convention, RP to GWSE measurements were positive.

After performing the field measurements detailed above, we calculated RP to BM with Equation 6.1:

$$RP\_BM = RP_{Elev} - BM_{Elev} \tag{6.1}$$

Where RP_{Elev} and BM_{Elev} are the elevations of the reference point and benchmark, respectively, from the topographic survey. We calculated the difference in stream and groundwater levels with Equation 6.2:

$$\Delta h = RP\_BM - BM\_WSE - RP\_GWSE \tag{6.2}$$

Where BM_WSE is the distance from benchmark to water surface elevation in the stream, and RP_GWSE is the distance from reference point to groundwater surface elevation. Using previously mentioned sign conventions, Δh was negative for losing streams and positive for gaining streams. For example, the stream in Figure 6.4 is losing, so Δh would be negative.

Since we only took single observations in the pre- and post-monsoon, our measurements of stream and groundwater levels were "snapshots" in time. These data were not sufficient to capture smaller timescale dynamics, perhaps associated with individual rainfall events or extraction of groundwater from a well, or longer temporal trends. To improve our understanding of these variations and trends, we performed regular water level difference measurements at BM05, BA07, and DB05 between 7 September and 26 October 2018. These measurement locations cover a range of different types of wells: rare use (BM05), occasional (domestic) use (BA07), and moderate (industrial) use (DB05). Each of these sites were equipped with staff gauges to make ongoing water level measurements easy and accurate.

6.2.4. Water Quality Measurements

We measured water quality parameters of both wells and streams to better understand spatial and temporal water quality changes. Water quality also provided an additional and independent line of evidence for assessing stream-aquifer interactions. In both the pre- and post-monsoon, we measured the following: electrical conductivity (EC), ammonia, phosphorus, hardness, chloride, alkalinity, and E. coli. For general reference, the concentration limit set by the Government of Nepal and the World Health Organization (WHO) of each parameter is stated in Table 6.1. No health based concentration limits for alkalinity and phosphorus are defined by both the Government of Nepal or WHO, and are therefore excluded from the table.

EC is an important water quality parameter because it shows a significant correlation with ten water quality parameters including alkalinity, hardness, and chloride [26]. Previous research on pollution in the Kathmandu Valley also indicates that EC covaries with several water quality parameters ([27], [22]). Hardness is the result of aqueous compounds of calcium and magnesium and is expressed in terms of
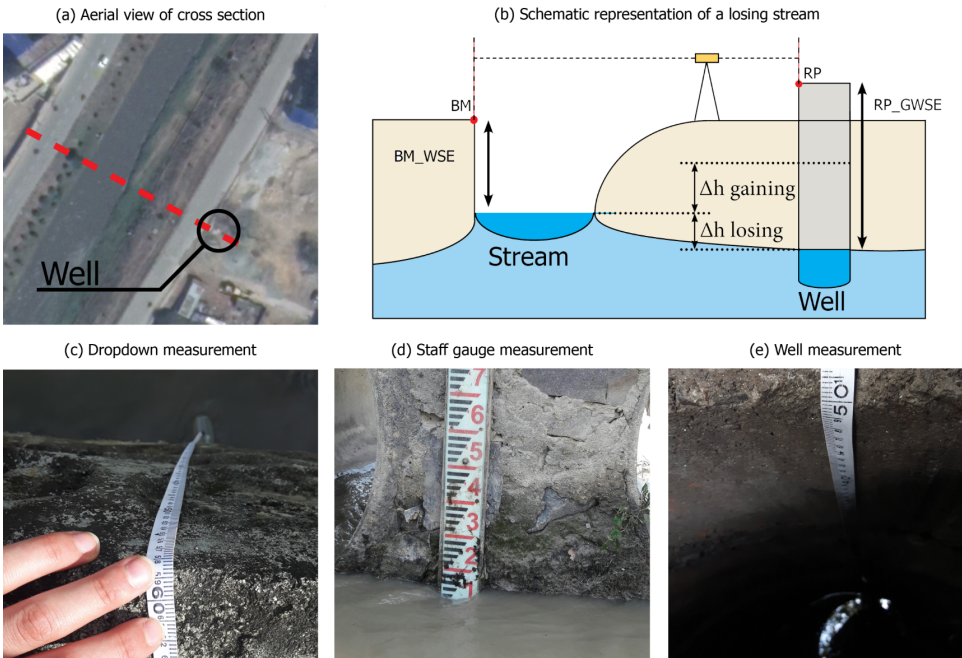
Figure 6.4: Summary of stream-aquifer water level difference (Δh) measurements. Reference point (RP) and benchmark (BM) are indicated with red dots. Sub-panels include (a) aerial view of measurement site, (b) cross-sectional schematic, (c) sample measurement from BM to stream water surface elevation (WSE) as a dropdown measurement, (d) sample measurement from BM to stream WSE measurement with a staff gauge (note that the benchmark (BM) was considered the staff gauge zero mark), and (e) reference point (RP) to groundwater surface elevation (GWSE) measurement in a well. Automatic level surveys were conducted to determine elevation differences between RP and BM.

equivalent quantities of calcium carbonate. High concentrations of chloride indicate sewage pollution and give undesirable taste [28]. Phosphorus is found in natural rocks, domestic sewage, and decaying organic matter. In excess amounts, it can induce eutrophication in water bodies. Alkalinity is the water's capacity to resist changes in pH that would make the water more acidic.

We used a portable water quality test kit from the Environment and Public Health Organization (ENPHO) to measure ammonia, phosphates, hardness, and chloride. Water quality test strips from Baldwin Meadows were used to measure total alkalinity. At most sites, water quality testing was done in-situ. For the sites where in-situ testing was not possible, samples were taken to the S4W-Nepal office in polyethylene bottles to perform measurements later the same day. Polyethylene bottles were cleaned thoroughly before use and rinsed with sample water prior to sampling.

A calibrated GHM 3431 [GHM-Greisinger] EC meter was used to measure in-situ EC and temperature. 3M™ Petrifilm™ E. coli/Coliform Count Plates [3M] were used to enumerate E. coli and total coliform. Sterile droppers were used for each

Table 6.1: Drinking water quality concentration limits for electrical conductivity (EC), ammonia, hardness, and chloride as set by the Government of Nepal and the World Health Organization [25].

Parameter	Unit	GNP	WHO
EC	$\mu S\ cm^{-1}$	1500	2500
Ammonia	ppm	1.5	1.5
Hardness	ppm	500	500
Chloride	ppm	250	250

plate and sample water was drawn directly from the well where possible to avoid contamination. Inoculated petrifilm count plates were stored for incubation at room temperature for 48-72 hours to allow full sample development.

Pearson's r (correlation coefficient; [29]) was used to describe the strength of linear relationships between water quality parameters in streams and wells in pre- and post-monsoon season. Significance for correlations was tested with two-tailed p value hypothesis tests using an alpha level of 0.01.

6.3. Results

6.3.1. Water Level Results

Stream-aquifer water level differences (Δh) ranged between -4.29 m and 1.10 m in the pre-monsoon, and between -1.34 m and 2.24 m in the post-monsoon (Figure 6.5). The average pre- and post-monsoon stream-aquifer Δh was -0.82 m and 0.44 m, respectively. During pre-monsoon 2018, 14 out of 16 sites (88 %) were losing water to the aquifer (negative Δh), and the remaining two (12 %) were gaining (positive Δh). In contrast, during post-monsoon 2018, only 11 out of 35 (31 %) were losing, and the remaining 24 (69 %) were gaining. Twelve of the fourteen sites that were losing in pre-monsoon transitioned to gaining in the post-monsoon. In every case, groundwater levels increased from pre-monsoon to post monsoon; the average increase from the 16 wells monitored in both seasons was 1.99 m (see supplementary materials for additional details).

Consistent longitudinal (upstream to downstream) trends among streams in pre- or post-monsoon were not observed (Figure 6.6). The Nakkhu, Hanumante, and Balkhu rivers each showed decreasing trends in Δh from upstream to downstream, while the Manohara, Godawari, and Dhobi showed the opposite, to varying extents. With the exception of BM05, Δh was higher in post-monsoon than pre-monsoon (see Discussion for additional information about BM05). The Bagmati River showed a full transition from completely losing in pre-monsoon to completely gaining in post-monsoon. All losing sites in the post-monsoon were either located in (1) the hilly regions surrounding the Valley floor or (2) the lower permeability southern groundwater district. The Nakkhu was completely losing in the post-monsoon. Additional measurement details are included as supplementary material.

Regular measurements at BM05, BA07, and DB05 were performed to improve the understanding of short-term variations and trends in stream-aquifer water level
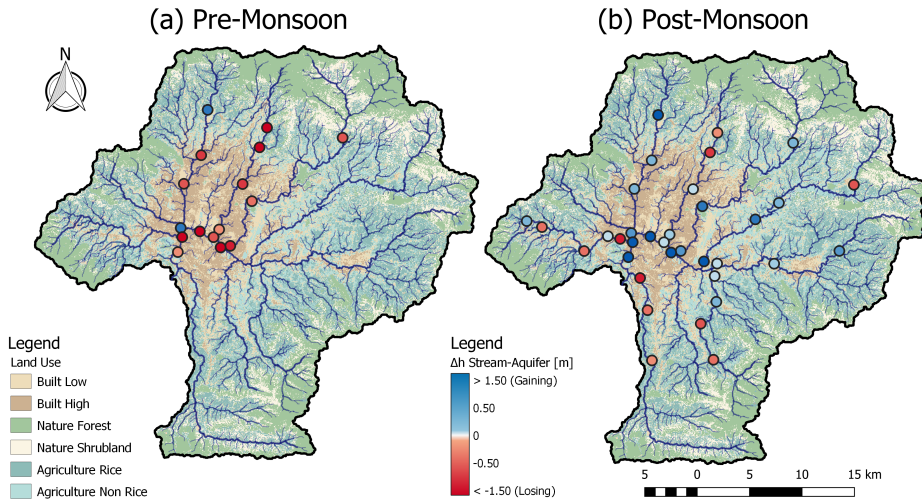
Figure 6.5: Stream-aquifer water level differences in meters for (a) pre-monsoon (n = 16) and (b) post-monsoon (n = 35) in the Kathmandu Valley. land-use and stream network data are used as a base map [22]. Gaining stream locations are indicated with blue gradient circles (n = 2 pre-monsoon, n = 24 post monsoon), while losing stream locations are indicated with red gradient circles (n = 14 pre-monsoon, n = 11 post-monsoon). Darker colors represent a larger absolute value of water level differences, either gaining or losing.

differences (Figure 6.7). All sites showed linear trends in stream-aquifer water level difference (Figure 6.7.a), with two decreasing (BA07 and DB05) and one increasing (BM05). Groundwater level changes contribute most to the temporal variations of the water level difference, with the exception of the second half of October for BM05 (Figure 6.7.b). For example, groundwater levels decreased by 0.9 m and 1.0 m, while stream water levels decreased by 0.3 m and 0.1 m for BM07 and DB05, respectively (Figure 6.7.b). These measurements showed that DB05 had already transitioned from gaining to losing in early October. Extrapolation of BA07's linear trend indicated that this site most likely also transition from gaining to losing by the end of October. In contrast to BA07 and DB05, stream-aquifer water level differences at BM05 increased during the period of ongoing monitoring (Figure 6.7.a). Viewing stream and groundwater levels separately for BM05 (Figure 6.7.b) showed that stream levels declined as expected during the post-monsoon hydrograph recession period; however, groundwater levels unexpectedly increased, especially from the middle of October onward.

6.3.2. Water Quality Results

Concentrations of all water quality parameters were higher in the pre-monsoon compared to the post-monsoon (Figure 6.8). Streams showed relatively larger differences in distributions from pre- to post-monsoon, while well differences were generally smaller (with the exception of hardness). Measured EC values ranged
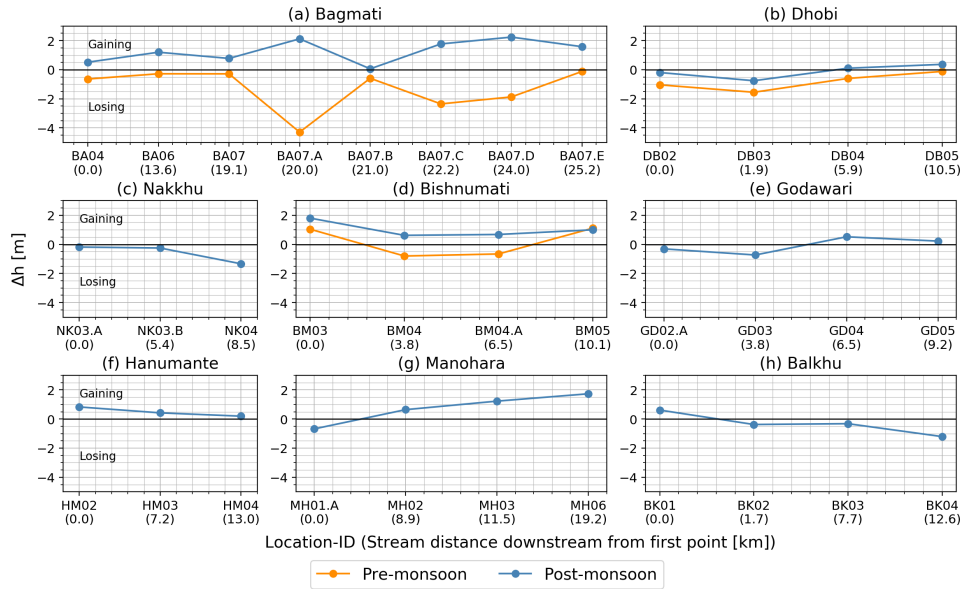
Figure 6.6: Pre-monsoon (orange) and post-monsoon (blue) water level differences for the selected eight watersheds. For Bagmati (a), Dhobi (b), and Bishnumati (d) both pre- and post-monsoon data is available. On horizontal axes, measurement locations are labeled, and the distance in kilometers from the most upstream location are shown in parentheses. Vertical axes show stream-aquifer water level differences using the adjacent stream level as the reference (i.e. zero on the y-axis). The y-axes are all uniformly fixed at -4.5 to +3.0 m.

from 17 to 2200 µS cm^{-1}, while ammonia levels ranged from 0.0 to 3.0 ppm. It should be noted that the range of the equipment used to measure ammonia was limited to 3.0 ppm (mentioned further in Discussion). Chloride and phosphorus values ranged from 0 to 212 ppm and 0 and 1 ppm, respectively. Alkalinity and hardness ranged from 0 to 240 ppm and 0 to 456 ppm, respectively.

In general, water quality deteriorates in pre- and post-monsoon from upstream to downstream for both streams and wells (Figure 6.9; specifically focused on EC). Similar trends were observed for other water quality parameters (see supplemental materials for water quality data). As observed in Figure 6.9, pre- and post-monsoon differences in stream EC (solid lines) are larger than differences in well EC (dashed lines). In pre-monsoon, stream and well EC were similar. In post-monsoon season, well EC generally exceeded stream EC at the same monitoring location. However, EC values from BM05 do not follow these general trends. BM05 also differed from generally observed trends in water levels (Section 6.3.1).

E. coli was found in all stream water samples for both pre- and post-monsoon, indicating a high likelihood of fecal contamination due to untreated waste disposal. Considering only wells with pre- and post-monsoon data (n = 16), E. coli was found in 75 % of wells (12 out of 16) and 63 % of wells (10 out of 16) in the pre- and post-monsoon, respectively. For all post-monsoon wells, E. coli was present in 41
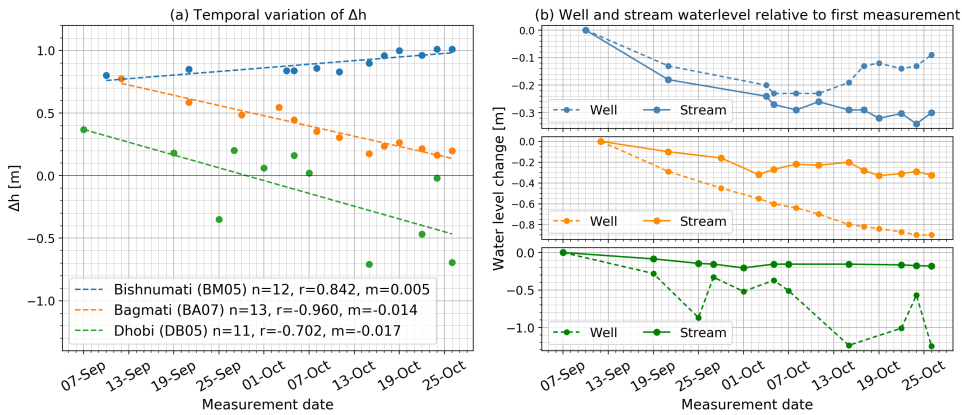
Figure 6.7: Graphs showing temporal variation of the stream-aquifer water level difference (a) and water level changes for both wells and streams (b) at Dhobi (DB05; blue), Bagmati (BA07; orange), and Bishnumati (BM05; green). In the left graph (a), measurements are indicated as points. Dashed lines represent linear trendlines, with the indicated sample sizes, slopes (m) and Pearson's r values. For the right graph, the vertical axis represents the water level difference (m) relative to each sites' initial measurement from early September.

% of wells (14 out of 35). In general, E. coli counts increased from upstream to downstream. Additional E. coli data is available as supplementary material.

Most parameters - 25 out of 36 possible pairs - have a statistically significant correlations between streams and wells (Table 6.2). However, phosphorus in wells appears to be uncorrelated with concentrations in streams. Similarly, alkalinity in streams seems to be uncorrelated with all well water quality parameters except groundwater alkalinity.

Focusing on the diagonal of the correlation matrix (Table 6.2), we observed seasonal (pre- to post-monsoon) shifts in the relationships between EC and chloride in streams and wells (Figures 6.10.a and 6.10.b). The linear correlations between

Table 6.2: Pearson's r (correlation coefficients) for the water quality parameters measured in streams and wells. Values are calculated using combined pre- and post-monsoon data. Statistically significant values are shown in bold. For all correlations with alkalinity (only post-monsoon data available): n = 34, p = 0.01, r critical = 0.44. For other correlations with chloride: n = 49, p = 0.01, r critical = 0.47. For correlations with EC, ammonia, hardness, and phosphorus: n = 50, p = 0.01, r critical = 0.36.

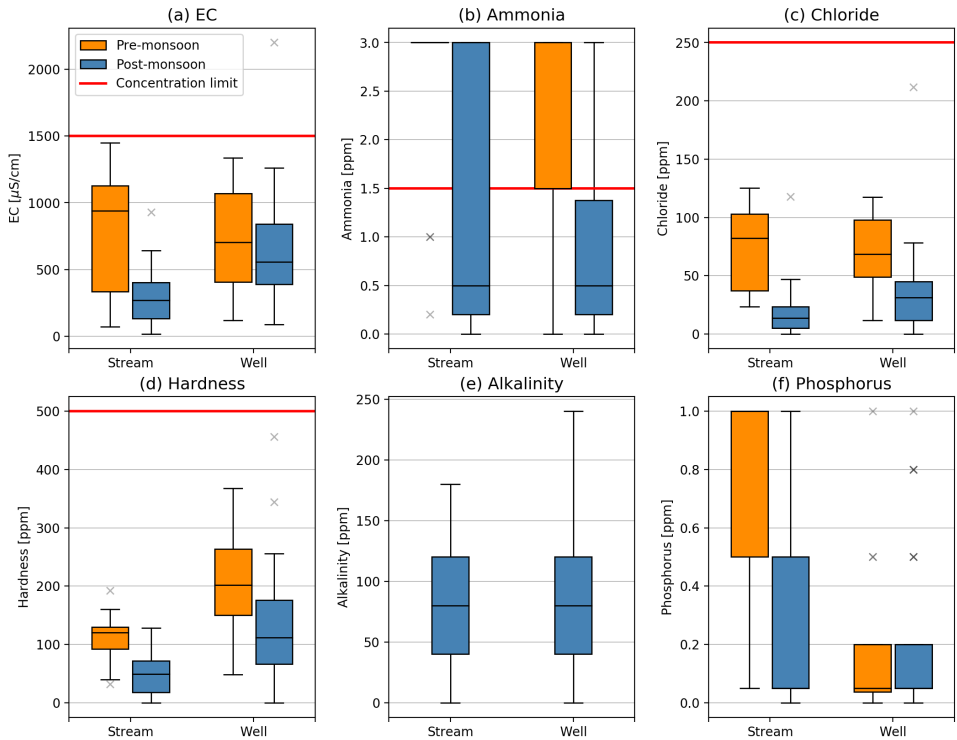|		Stream					
		EC	Ammonia	Chloride	Hardness	Alka-linity	Phos-phorus
Well	**EC**	**0.62**	**0.58**	**0.60**	**0.48**	0.28	**0.65**
	Ammonia	**0.67**	**0.53**	**0.66**	**0.56**	0.22	**0.60**
	Chloride	**0.73**	**0.62**	**0.79**	**0.54**	0.22	**0.71**
	Hardness	**0.69**	**0.67**	**0.68**	**0.59**	0.21	**0.73**
	Alkalinity	**0.57**	**0.57**	**0.46**	0.42	**0.61**	**0.59**
	Phosphorus	0.08	0.08	0.08	0.08	0.17	0.13

Figure 6.8: Box plots showing the distribution of water quality parameter values for streams and wells for all sites in the pre- (orange) and post-monsoon (blue) 2018. For general reference, the Government of Nepal concentration limit is shown as a red line for EC, ammonia, chloride, and hardness (Government of Nepal, 2005). Boxes show the interquartile range between the first and third quartiles of the dataset, while whiskers extend to show minimum and maximum values of the distribution, except for points that are determined to be "outliers," which are more than 1.5 times the interquartile range away from the first or third quartiles. Outliers, shown as grey x-marks, have been made partially transparent to show the presence of identical values.

EC and chloride were statistically significant in both pre- and post-monsoon. In the pre-monsoon, well EC was on average lower than stream EC, leading to a trendline slope of less than one (m = 0.73). In the post-monsoon, however, well EC was on average higher than stream EC, leading to a trendline slope of greater than one (m = 1.37). Chloride shows a similar temporal pattern. The remaining water quality parameters did not show the same seasonal shifts.

6.4. Discussion and Recommendations

6.4.1. Water Level Discussion

Our first research question was: *What is the nature of pre- and post-monsoon stream-aquifer interactions in the primary tributaries to the Bagmati River within the Kathmandu Valley?* In general, streams were losing water (88 %) to the shal-
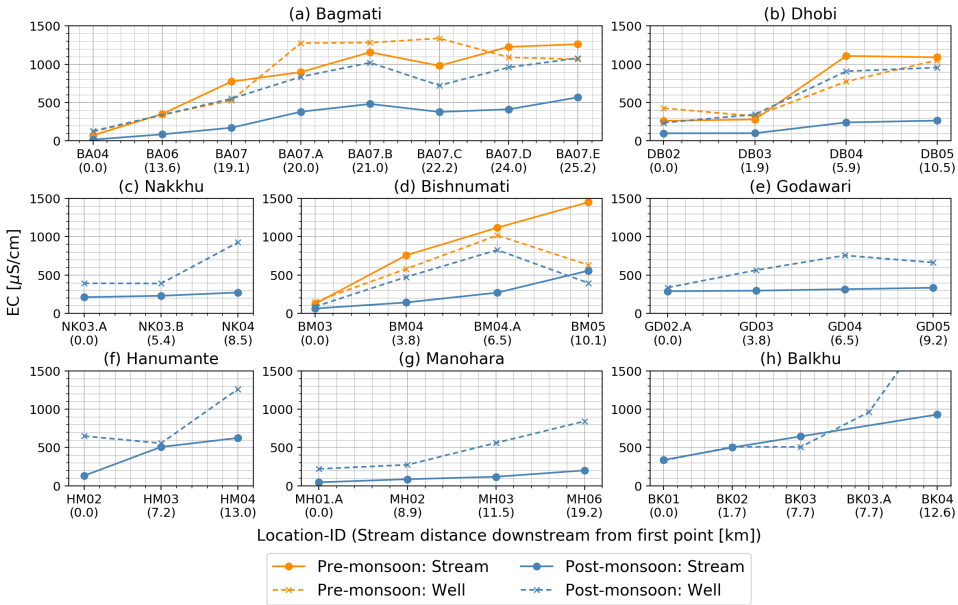
Figure 6.9: Electrical conductivity (EC) of streams (solid lines) and wells (dashed lines) in pre- (orange) and post-monsoon (blue). For Bagmati (a), Dhobi (b), and Bishnumati (d) both pre- and post-monsoon data is available. On horizontal axes, measurement locations are labeled, and the distance in kilometers from the most upstream location are shown in parentheses. Vertical axes show EC and are all fixed from 0 to 1500 µS cm^{-1}. Post-monsoon well EC at BK04 was 2200 µS cm^{-1}.

low aquifer during pre-monsoon and were gaining water (69 %) from the shallow aquifer in the post-monsoon (Figures 6.5 and 6.6).

Our second research question was: *How do these interactions change longitudinally from upstream to downstream?* Pre-monsoon, no recurring trend in water level difference was seen longitudinally from upstream to downstream. Post-monsoon, most losing monitoring locations were upstream, away from the valley floor and most gaining locations were in the Valley floor (Figure 6.6).

Due to groundwater extraction and minimal recharge, groundwater levels in the shallow aquifer decrease in the pre-monsoon season. Monsoon rainfall recharges the shallow aquifer, increasing groundwater levels in the shallow aquifer. This impact is predominantly visible in the Valley floor. This seasonal dynamic is less apparent in upstream sites, which still tend to be losing year round, indicating a continuous recharge of the shallow (and potentially deep) aquifer(s). For example, in the Northern Groundwater District, an area of highly permeable sands and gravels [8], three monitoring sites (DB02, DB03, and MH01.A) were losing water to the aquifer in post-monsoon.

All monitoring locations on the Nakkhu watershed (NK03.A, NK03.B and NK04) were losing water to the aquifer in post-monsoon. Along the stream corridor of the Nakkhu, there are relatively high permeability alluvial deposits of sand and gravel
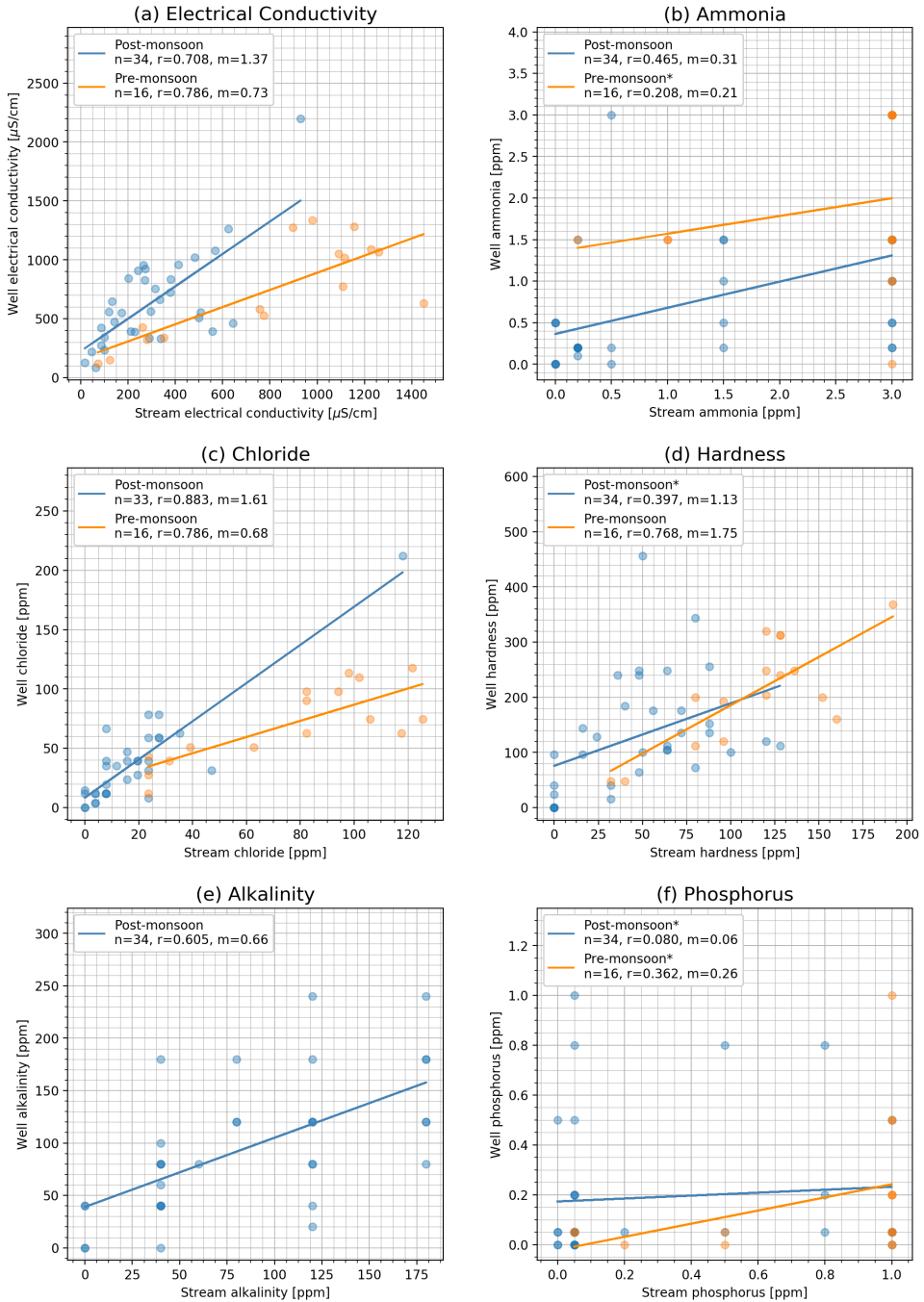
Figure 6.10: Pre- and post-monsoon scatterplots of stream and well water quality results for EC, ammonia, chloride, hardness, alkalinity, and phosphorus. The water quality value of the stream and well are shown on the horizontal and the vertical axes, respectively. The number of measurements (n), correlation coefficient (r), and the slope of the trendline (m) per parameter and season are shown in the legends. Markers are partially transparent to show the presence of overlapping (identical) values. Labels marked with an asterisk * are correlations that are not statistically significant at an alpha level of 0.01. All other correlations are statistically significant. The following critical values were used: n = 16, critical r = 0.62; n = 33, critical r = 0.43; n = 34, critical r = 0.44.

overlaying lower permeability metamorphic formations of the Southern Groundwater District. These narrow alluvial deposits support growing groundwater extractions for municipal, industrial, and agricultural uses, while at the same time the surrounding watershed is undergoing rapid urbanization and hardscaping. While the Nakkhu River used to flow perennially and support populations of fish and recreational swimming, it now goes dry upstream of the confluence with the Bagmati near Nakkhu. Since shallow groundwater levels indicate that the Nakkhu is now losing even in post-monsoon, the river now dries when runoff from the rainfall or inflows from the upper catchment cease.

Repeated stream-aquifer water level measurements at DB05 and BA07 revealed that the transition to gaining did not persist for long (Figure 6.7). DB05 already transitioned from gaining to losing by early October. Extrapolation of the linear trend in levels for BA07 (r = 0.96) indicated that this site most likely also transitioned from gaining to losing by the end of October. This suggests that it may only be a short term mounding of shallow aquifer levels along the stream alignments that seasonally recharges due to high streamflows from monsoon rains. High flows also could scour the streambed, causing potentially order of magnitude increases in streambed hydraulic conductivity. This theory could be tested by performing (1) lateral groundwater level transects running perpendicular to stream alignments and (2) precision Real-time Kinematic (RTK) GPS surveys of reference points and benchmarks. The combination of these datasets will allow construction of a three dimensional groundwater surface model and the computation of groundwater flow directions. These data could also be used to refine a numerical groundwater flow model. Also, future stream-aquifer measurements should be repeated more frequently (e.g. weekly) after monsoon rains end to try and capture the temporal and spatial dynamics of the transition from gaining to losing streams.

Repeated stream and groundwater level measurements at BM05 (Figure 6.7) show an increase in groundwater levels in late October. Due to these unexpected results, we performed EC measurements in four wells surrounding the initial well, which all indicated much higher EC values similar to other values from the Valley floor. While we do not have sufficient information to understand the mechanisms for this discrepancy, our working hypothesis is that there must be a source of groundwater recharge other than precipitation nearby this well. Potential sources include leaky water distribution or sewage pipes. However, the reasons for the timing of these observed increases in shallow groundwater levels are unknown.

Although the methods used gave a good insight in the direction of interactions (i.e. gaining or losing), understanding their magnitude has not been possible with the current methodology. Including a survey on the hydraulic conductivity (K) of the streambed and aquifer at the different monitoring locations would lead to information about the specific discharge between the stream and the aquifer. Eventually this information would be key to setting up a water balance. However, the determination of hydraulic conductivity is generally characterized by large uncertainties, due to the fact that the outcomes may vary over some order of magnitudes and are highly variable in space and time [30]. The K value changes in time due to scour from high flows, deposition, and degree of saturation of the soil, therefore

long-term monitoring would be needed [30]. Also the anisotropy of the soil has to be taken into account as the vertical (K_V) and horizontal (K_H) hydraulic conductivity may differ if the soil not structure-less [31]. Previous research has shown that the K value in the shallow aquifer differs from 12.5 to 44.9 m day^{-1} in the Kathmandu Valley [12]. Taking into account the vertical component in groundwater flow would give additional information about the interactions between the stream and the aquifer. To construct a flow field map, a piezometer nest will have to be installed with two or more piezometers installed at the same location at different depths [30].

Streambed hydraulic conductivity (K_S), an important parameter for aspect in quantifying stream-aquifer exchanges. K_S can be estimated using two piezometers, installed above and below the semi-permeable streambed. Based on this pressure difference and the depth of the layer between the piezometers, a good estimation for the streambed hydraulic conductivity can be made. Also, a more common and practical method is the field standpipe permeameter test [32].

6.4.2. Water Quality Discussion

Our third research question was: *How do pre- and post-monsoon interactions impact stream and groundwater quality?* Stream and shallow groundwater quality in the Kathmandu Valley deteriorated longitudinally from upstream to downstream. In pre-monsoon, most monitoring locations were losing and observed shallow groundwater quality was similar to stream water quality. In post-monsoon, most monitoring locations had transitioned to gaining and stream water quality was better than shallow groundwater quality. Intuitively, groundwater quality improvements from pre- to post-monsoon were not as large as stream water quality improvements (Figures 6.8 through 6.10).

In pre-monsoon, our results suggest that polluted stream water infiltrates into the shallow aquifer. In post-monsoon, stream water quality improves more than shallow groundwater water quality. During the monsoon, streamflow is diluted by relatively high quality water, thus improving water quality. Measurements were performed during baseflow conditions (avoiding rainfall events), so increased streamflow is likely caused by increased groundwater discharge from the upper catchments, not by run-off from the Valley urbanized Valley floor. There is a significant difference in water quality entering the Valley floor from headwater catchments with natural land-uses [22]. The shallow groundwater quality does not improve as quickly because the amount of groundwater in storage is high and groundwater flow velocities are low which leads to a slower rate of improvement. It is also possible that shallow aquifer recharge in the Valley floor is of lower quality because of extensive overlying build land-uses.

Even though groundwater quality is a complex issue influenced by a range of factors, the dynamic linkage we observed between streams and shallow groundwater should not be neglected when managing water sources in the Kathmandu Valley. Upstream sites tend to be losing year-round, so effort should focus first on protecting and improve water quality in headwater catchment areas. Since Davids et al. [22] showed that land-use is one of the main reasons for the deteriorating

stream water quality longitudinally, establishing protections for natural and agricultural land uses should be a top priority for water managers. For the same reason, when building a sewage collection system, we suggest starting upstream and moving downstream.

6.4.3. Limitations

It is important to highlight that these results are only applicable to the shallow aquifer within the corridors nearby the streams we measured. Seasonal refilling of the shallow aquifer in these observed areas should not be misconstrued to suggest that the deeper aquifer does (or does not) undergo similar seasonal refilling. Instead, in order to address questions about the deep aquifer, and intermediate confining beds of Kalimati clay, observations from monitoring wells penetrating these units are needed. Additionally, vertical gradients between different aquifer layers cannot be quantified with our methodology. Instead, vertical fluxes should be assessed with measurements of piezometric surfaces from carefully constructed multi-completion monitoring wells with discretely screened piezometers in the respective aquifer and aquitard zones of interest.

Despite our efforts to capture baseflow conditions and avoid measurements during rainfall, an important limitation of our research methods was that the measurements represent a specific point or "snapshot" in time. When considering water level difference measurements, vertical components of groundwater flow were not considered, since this would require that a piezometer nest (or multi-completion well) would be necessary [30]. This was well beyond the scope and budget of this investigation which leveraged existing hand dug wells. This research is limited by the availability of dug wells penetrating into the shallow aquifer. For some watersheds (e.g. Manohara), it was difficult to find suitable wells located relatively even distances (longitudinally) from each other along the streams.

Additionally, water level differences merely indicate the driving potential for groundwater flow, but an understanding of streambed hydraulic conductivities is necessary to translate potential into an actual flux. In this study, we did not measure streambed hydraulic conductivities, so it is not possible to perform this analysis at this time. Future research should evaluate different methods for quantifying these conductivities, and applying selected the preferred approach through our study area. Because of low flow (pre-monsoon) deposition of fine particles and algaes, and high flow (monsoon) erosion and scour events, streambed conductivities are likely to vary in time. Therefore, it is also important to repeat these measurements at least pre- and post-monsoon.

ENPHO Water Test Kit measured ammonia on a scale from 0 to 3 ppm. We found that ammonium concentrations at downstream sites often exceeded 3 ppm. This made it impossible to see any variation in concentration beyond the 3 ppm upper threshold, which introduced uncertainty in our correlation analysis. This threshold has a larger impact on downstream values, because upstream values were usually below 3 ppm. Alkalinity measurements were performed with Baldwin Meadow strips where values are measured in increments of 40 ppm. These large increments provide low resolution alkalinity data and result in more similar value between streams

and groundwater. The values from the ENPHO water test kit are an approximate estimation of drinking water quality and can be used as an indicator for stream-aquifer interactions. For more accurate analysis on the drinking water quality laboratory analysis is required.

6.5. Conclusion and Outlook

While several studies have highlighted extensive overdraft in the Kathmandu Valley, our results suggest that despite increased groundwater extraction and urbanization, seasonal (monsoon) refilling of the shallow aquifer still occurs within stream corridors. This seasonal refilling leads to most streams (i.e. 69 % of sites) being gaining in the immediate post-monsoon. However, after a currently unknown period after post-monsoon, the streams we measured (i.e. 88 % of sites) transition, so that by pre-monsoon they are once again losing. Our preliminary findings from repeated measurements at two sites suggest that the transition from gaining to losing after monsoon rains end happens relatively quickly, perhaps by early to mid-October.

Our research also shows a clear connection between water quality of streams and shallow groundwater. Therefore, untreated sewage being directly discharged into the Valley's rivers negatively impact not only the streams themselves, but also the underlying shallow groundwater system. Unfortunately, our results also indicate that the "flushing" effect of monsoon rains that dramatically - albeit temporarily - improves stream water quality, is not as effective at "flushing" out the increasingly contaminated shallow groundwater system.

Since this research only represents two "snapshots" in time, it is critical that measurements be continued at these (and possibly other) sites on a regular basis. Only after a time series of two, five, and ten years is available will a more robust understanding of stream-aquifer interactions - and how these are changing in space and time - be possible. With this in mind, we developed the methodology to be as simple as possible. Now that the topographic survey is complete, only stream and groundwater levels are necessary to determine gradients. We suggest that a mixture of young researchers and citizen scientists with a shared mobile data collection platform provides a path towards sustainable data collection. S4W-Nepal is currently working towards identifying key academic partner(s) who will commit to providing young researchers to facilitate ongoing measurements. In this arrangement, S4W-Nepal could provide the mobile data collection platform, all previous data and reports, and any necessary training to young researchers. We suggest that young researchers should be tasked with implementing a citizen science based approach of involving well owners and other community members in the processes of (1) data collection, (2) interpretation and outreach, and (3) decision making.

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7

Outlook

It's the job that's never started
That takes longest to finish.

J.R.R. Tolkien

Getting things moving in Nepal was a lot of work. Our stay in Nepal over-lapped with some significant challenges in Nepal's history. In the spring of 2015, just months before arriving, two massive earthquakes shook the Himalayas and caused significant damage to life and property. Later that year, after a 10-year struggle to draft a new constitution, Nepal suffered a debilitating six-month border blockade with India. These events, together with load-shedding from insufficient power production and incessant road construction and widening, combined to form a challenging working environment. It also took time to learn the language, culture, context, and to develop a network of friends and professional connections. Despite these challenges, we were able to learn a lot about how to mobilize young researchers and cit-izen scientists with the aim of filling water related data gaps. The reality was, as is the case in much of life, that the answer to one question often led to two new questions. Therefore, the goal of this chapter is to sketch a road map of next steps in case anyone decides to pick these questions and ideas up and push them a bit further along the way.

7.1. Introduction

This chapter is a compilation of ideas and questions that arose along the way that never made it too far beyond these pages. These ideas may have originated during a chat over chana and milk tea at Sarsoti Didi's tea shop, or perhaps as a shouting match on the back of our favorite (and only) form of personal transportation in Nepal (other than walking which we did a lot of also) - the motorcycle. Regardless, this chapter stores them away, not unlike a squirrel does with his nuts before winter, hoping that at the right time an enthusiastic young researcher might find them. If all goes well, might they grab whichever nut looks best, blow off the dust, and get to work. With any luck, S4W-Nepal will still be around to lend a helping hand. One important globally applicable note, as discussed in greater detail in Chapter 8, is that all data generated by these efforts should be freely available to all interested parties.

The ideas are organized into two basic categories: additional analyses and additional data collection. The co-equal goals of the additional analyses are to (1) improve the understanding of the Kathmandu Valley water balance and (2) to analyze the effectiveness of the data collection methodologies utilized within this dissertation. These additional analyses can be completed with data that has already been generated. Additional data collection provides recommendations for additional data collection activities that can further reduce uncertainty in the Kathmandu Valley water balance or improve upon the methods developed in this dissertation.

7.2. Additional Analyses

7.2.1. Quantifying Baseflow Contributions to Kathmandu Valley Water Supplies

Background

As discussed in greater detail in Chapter 3, springs are a critical dry season source of water to support the environment and various human uses. One of the primary unknowns in the Kathmandu Valley water balance is the pre-monsoon baseflow contributions of spring and streams. Therefore, the principal interest in this investigation is to improve understanding of headwater baseflow contributions to the overall water supply of the Kathmandu Valley, with a specific focus on the pre-monsoon period. Starting in the spring of 2017, S4W-Nepal started collecting monthly flow measurements at strategic locations along nine perennial tributaries to the Bagmati River (see Chapter 5).

This effort will leverage these flow measurements, 30 x 30 meter resolution land cover and land use data [1], precipitation ([2], [3]), exposure, geology, etc. to develop a regression model between baseflow and these aforementioned independent variables. The regression model will then be applied to extrapolate our observations to the remainder of the ungauged baseflow generating areas (UBGAs). UBGAs will likely be limited to unmeasured natural land covers (i.e. forest and shrubland) or perhaps natural and agricultural land uses within the Valley. Improved understanding of baseflow contributions to the Valley's pre- and post-monsoon water supply is critical to further constrain (1) our understanding of the temporal and spatial

mismatches between water supply and demand and (2) our ability to estimate net groundwater extractions for urban, industrial, and agricultural purposes.

Research Question(s)
- How do pre- and post-monsoon baseflow contributions to water supplies in the Kathmandu Valley vary with (1) precipitation, (2) land cover and land use, and (3) geology?

- What implications does this have on the spatial and temporal mismatch between supply and demand in the Kathmandu Valley?

- How can an improved understanding of baseflow further constrain our understanding of net groundwater extraction in the Kathmandu Valley?

Methodology
- Select flow measurement locations that have a sufficient number of records (e.g. monthly for one year) and are above any known diversion (or sites that have diversions that can be estimated).

  - Selected sites should be distributed around the Valley as much as possible.
  - The initial round of analyses should focus on S4W-Nepal FlowTracker measurement sites. Subsequent efforts can include salt dilution measurements from CS Flow groups.

- Quality control the data and review raw FlowTracker files to ensure proper measurement protocols were followed when collecting the data. Also, leverage pictures from the ODK records.

- Delineate upstream watersheds for selected locations.

- Select and quantify relevant statistics that will be used to estimate baseflow contributions from ungauged watersheds.

  - Statistics should include: elevation, aspect (at a minimum leeward and windward to catch orography and rain shadow), land-use (all 6 land uses, but likely this can be collapsed to just agriculture and natural), precipitation, etc.
  - For precipitation, an evaluation of DHM and S4W-Nepal data should be made to determine which product should be used. The MoChWo poster [3] which computed monthly normalized deviations from the mean should be considered.

- Develop regression model that fits observed baseflows at the selected locations to some or all of these statistics.

  - This analysis should start first with developing an understanding of which variables have the largest impact on baseflow.

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- Develop methodology for applying the preferred regression model to the remaining ungauged areas in the Kathmandu Valley.

  – Consider using the assumption that baseflow is only generated by natural or perhaps natural and agricultural lands.

  – For each of the 10 perennial watersheds in the Kathmandu Valley (see Chapter 5 for details), calculate the difference in baseflow generating for the entire watershed and the baseflow generating area within the catchment of the selected measurement locations. This area will be considered the ungauged baseflow area (UGBA); each of the 10 watersheds will have an associated UGBA. For a watershed without any selected measurement locations, the UGBA would be for the entire watershed.

  – For each watershed UGBA, calculate the same variables selected for the baseflow regression analyses at the measured locations.

- Apply the developed baseflow estimation methodology to each watershed UGBA.

  – The critical period for developing baseflow estimates is in the pre-monsoon, but the same approach could potentially be used at a monthly time step.

- Feed this number into a pre-monsoon monthly water budget. See Section 7.2.2 for details on the Kathmandu Valley water balance structure and key fluxes and storage changes.

7.2.2. Constraining the Kathmandu Valley Water Balance with Underutilized Sources of Information

Background

Water balances are foundational to characterizing competing interests in water-energy-food systems, and should form the quantitative basis of water management decisions. Many water balance fluxes, like evapotranspiration, precipitation, and groundwater extraction, are difficult and expensive to measure on the ground with adequate spatial resolution. Therefore, remotely sensed observations are increasingly used to make estimates of water balance fluxes and changes in storage ([4], [5], [6]). Remotely sensed observations can generally benefit from accurate and accessible ground-truth data, which unfortunately are often not available. However, new developments in sensing technologies, data processing and analysis techniques, and methods of knowledge communication are opening novel opportunities for Citizen Science [7]. Therefore, to what extent can water balances be further constrained by well-conceived citizen science observations of fluxes (e.g. stream flow, precipitation, etc.) and/or parameters strongly influencing the estimation of fluxes (e.g. temperature, land use, etc.)? Further, how do water balance results compare when using the following three sets of data: (1) remotely sensed (RS) data only, (2) remotely sensed plus available "official" data from DHM or otherwise, and (3) remotely sensed plus official plus citizen science data generated by S4W-Nepal.

Research Question(s)
- How can citizen science and remotely sensed data be combined to improve our understanding of individual water balance fluxes, and the entire water budget in the Kathmandu Valley?

Methodology
- Perform the Kathmandu Valley water balance with remote sensing only.

  - Considering using evaluating CHIRPS, GPM, and TRMM for possible use.
  - Evapotranspiration (ET) should be computed from one of the existing "operational" ET datasets available.
    - SEBS (5 km x 5 km)
    - GLEAM (25 km x 25 km)
    - SSEBop (1 km x 1 km)
  - Runoff will need to be computed with a rainfall runoff model.

- Perform the Kathmandu Valley water balance with remote sensing and previously available ground observations.

  - Use similar remotely sensed products as discussed above, but this time constrain these observations with ground-based data available from the Department of Hydrology and Meteorology (DHM) or otherwise.

- Re-perform the Kathmandu Valley water balance with remote sensing, previously available ground observations, and S4W-Nepal citizen science data.

  - Using similar methods developed for the previous two water balances, calculate a third version using remotely sensed data, previously existing ground data, and newly generated S4W-Nepal data discussed in previous chapters of this dissertation, and other data sources discussed in this chapter.

- Evaluate the different water balance results from the three different levels of analysis: (1) remotely sensed only, (2) remotely sensed with existing ground data, and (3) remotely sensed, existing ground, and S4W-Nepal citizen science data.

- Specifically focus attention on the resulting improvements in understanding of net groundwater extraction.

7.2.3. Sub-watershed Water Balances to Determine Spatial Distribution of Groundwater Pumping in the Kathmandu Valley

Background

While performing the analyses detailed in Section 7.2.2 will provide a lumped estimate of net groundwater pumping, the following analyses can help distribute this spatially among the different sub-watersheds of the Kathmandu Valley.

Even though Chapter 6 documents that the streams in the Kathmandu Valley in the pre-monsoon are predominately losing (i.e. groundwater is flowing from the stream to the shallow aquifer), streamflows are observed to increase from upstream to downstream (see streamflow data from Chapter 5), even when the incremental watershed areas are completely built and there is no precipitation and runoff. Rather, based on visual observations of influent waste water, and extensive documentation of the same, these increases in streamflow are predominantly from inflowing waste water. Waste water in the Valley is generally a combination of surface water and groundwater. Especially in the headwater regions close to the sources of the perennial stream, water demands are predominantly met with diversions from springs and streams. Section 7.2.1 describes a suggested methodology for quantifying baseflow contributions to Kathmandu water supplies, especially in the pre-monsoon. To the extent that observed increases in streamflow are larger than baseflow contributions less evapotranspiration, groundwater pumping must be making up for the additional water. Therefore, these longitudinally distributed (i.e. upstream to downstream) observations of streamflow in the pre-monsoon can be used to develop spatially distributed estimates of net groundwater pumping. The term "net groundwater pumping" is used, because some of baseflow and pumped groundwater returns back to the groundwater system, so the water balance closure term does not represent gross groundwater pumping, but rather net. As an additional resource, this presentation (https://bit.ly/2D28EYx) from S4W-Nepal's 2017 groundwater symposium can be used as a reference.

Research Question(s)

- How can longitudinally distributed measurements of streamflow in the pre-monsoon be combined with other S4W-Nepal data, such as baseflow (Section 7.2.1), land use (Section 7.2.5), etc. to determine net groundwater pumping, and its spatial distribution at the watershed level in the Kathmandu Valley?

- How does per capita net groundwater pumping vary spatially within the Valley?

Methodology

- Perform stream-reach water balance analysis can then be performed on the tributaries to provide spatial resolution to changes in flows along the alignment of tributaries during pre-monsoon conditions.

- Refine and validate assumption that once tributaries enter the Valley floor the flows will increase moving downstream because of waste water return flows and agricultural runoff. The source of these two inflows are either perennial spring discharges from the upper watershed or groundwater pumping.

  – Note that both of these are ultimately from the groundwater system, pointing to the importance of groundwater in the Kathmandu Valley.

- Estimate monthly evapotranspiration fluxes for different watersheds.

- Perform monthly root-zone water balance to estimate portion of evapotranspiration coming from changes in soil moisture storage.

- Develop maps of estimated groundwater pumping based on estimates from stream reach water balances.

- Develop best estimate of spatially distributed population data in the Valley.

    - The possibility of using dynamic population estimates from mobile phone data (see http://www.flowminder.org for details) should be explored.

- Use best available population estimates to determine average net per capita groundwater pumping rates.

- Disseminate data, results, and conclusions to relevant stakeholders.

7.2.4. Synergies Between Citizen Science and Remotely Sensed Precipitation Data

Background

Precipitation is the only way that water currently enters the Kathmandu Valley (this will change once the inter-basin Melamchi water project is completed). Therefore, it is critical to accurately quantify this water source, including how it varies in space and time. Citizen science observations of precipitation, like those explored in Chapter 4, can improve our understanding, in part due to the potentially high spatial resolution. However, citizen scientists' measurements can be temporally discrete and irregular. Traditional ground based precipitation measurements (e.g. tipping bucket) are usually accurate but expensive. Remotely sensed precipitation data have coarse spatial resolution and, especially in mountainous environments, have large chances of systematic biases and random errors. With all this in mind, can these data be combined in a way that leverages their respective strengths and overcomes their individual weaknesses?

Research Question(s)

- What are the synergies between citizen science and remotely sensed precipitation estimates in the Kathmandu Valley?

- How can remotely sensed precipitation data be spatially downscaled and/or bias corrected with citizen science precipitation data?

- How can citizen science data be temporally downscaled with remotely sensed precipitation data?

Methodology

- Collect tipping bucket rainfall data in the Valley near the center of remotely sensed (RS) pixels (e.g. GPM).

- Use tipping bucket and high temporal resolution RS data to determine how RS observations characterize the presence/absence of rain.

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- If RS presence/absence data is sufficiently reliable, it could be used to temporally downscale citizen science observations of bulk rainfall.

  – In other words, if a citizen scientist measured 20 mm of rain over a 24 hour period, and the RS data said it only rained from 2 hours, an time series of precipitation could be developed with citizen science based quantities but RS derived temporal distribution.

  – The temporal resolution could only be as fine as the original RS data.

- Evaluated the additional information gained from fusing RS and citizen science precipitation data.

7.2.5. Characterizing Land Use in the Kathmandu Valley with Citizen Science and Remote Sensing

Background

Understanding land use and land cover (LULC) is critical to several resource management efforts, not least water resources management. LULC largely drives partitioning of precipitation between interception, infiltration, and runoff. Under the constant pressure of population growth, LULC in the Kathmandu Valley continues to be in a state of rapid change. It is critical that these changes be quantified so that decision makers and citizens have the chance of making informed decisions. While young researchers and citizen scientists can be mobilized to collect land use ground truth observations, these data must be combined with remote sensing to generate a continuous LULC coverage. In the fall of 2016, a multi-disciplinary team of MSc students from Delft University of Technology generated a 30 x 30 meter coverage of LULC based on roughly 100 ground truth observations and Landsat 8 images. Since then, S4W-Nepal has organized bi-annual (i.e. twice a year) land use change (LUC) campaigns with local universities. S4W-Nepal is working to develop a standard process for making annual LULC maps from the post-monsoon citizen science data. Overall, S4W-Nepal has generated over 900 additional LULC observations.

Research Question(s)

- How reliable are land cover and land use maps developed with citizen scientists and remotely sensed images?

- How has land cover and land use changed from 2016 to 2018?

- Based on this changes, what are the implications on water supply and security in the Kathmandu Valley?

- Based on the observed rates of land cover and land use changes, what is the projected future situation of the Kathmandu Valley in 10, 25, and 100 years?

Methodology

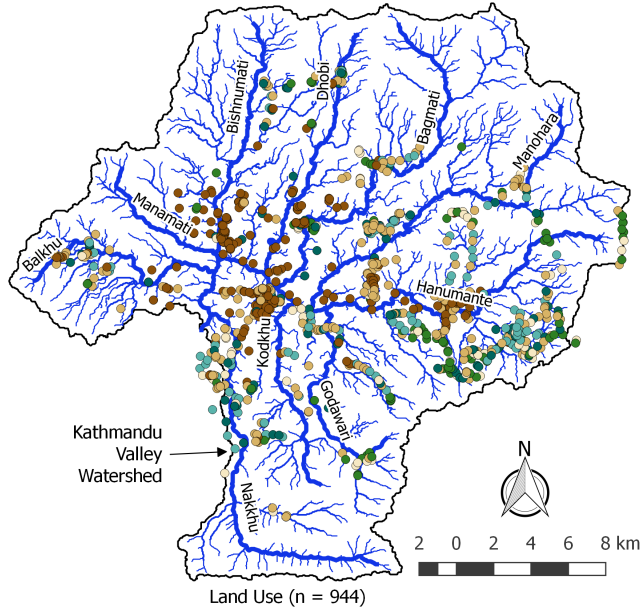- Create updated post-monsoon land use maps for the fall of 2017 and 2018.

Figure 7.1: Location of land use measurements since January 1st, 2017.

- See Chapter 6 and [8] for details on the process of using Quantum GIS and GRASS to develop LULC maps.

- Perform per pixel time series analyses to understand LULC changes.

- Develop creative methods for dissemination of the data.

7.3. Additional Data Collection

7.3.1. Citizen Science Groundwater Monitoring

Background

As mentioned in Chapter 6, shallow groundwater provides critical dry season water to the Kathmandu Valley. Initially, shallow groundwater was accessed via dhunge dhara, or stone spouts, which are publicly accessible ancient water supplies that in some cases are hydrogeologically similar to an improved spring source. In these cases, lowering water tables and contamination of the shallow groundwater can have profound impacts on the flow and quality of stone spouts. As demand for water increased - in quantity and spread out spatially - community and private hand dug wells were constructed to access shallow groundwater. Further increases in demand led companies and private parties to tap deeper aquifer layers in search of higher yielding geologic units with better quality water. Anecdotally, the combined impact of the vast (and unknown) number of shallow and deep wells in the Kathmandu

Valley is severe. However, water level and quality data for both the shallow and deep aquifers are either difficult to obtain, irregular, or simply not available.

In light of this data and accessibility gap, S4W-Nepal began systematically collecting shallow groundwater level and quality data in the spring (pre-monsoon) of 2017. Since then, S4W-Nepal has trained and equipped local well owners to become citizen scientists, and together we have collected over 1200 shallow groundwater level and quality measurements. Groundwater levels are measured with a simple meter tape and flashlight as necessary to view the groundwater level. Photographs are used to quality control all observations. Groundwater quality observations include monthly electrical conductivity and temperature measurements (performed with similar inexpensive meters as discussed in Chapter 3), and seasonal measurements of pH, iron, ammonia, chloride, nitrate, total hardness, E. coli, alkalinity, phosphate, and residual chlorine.
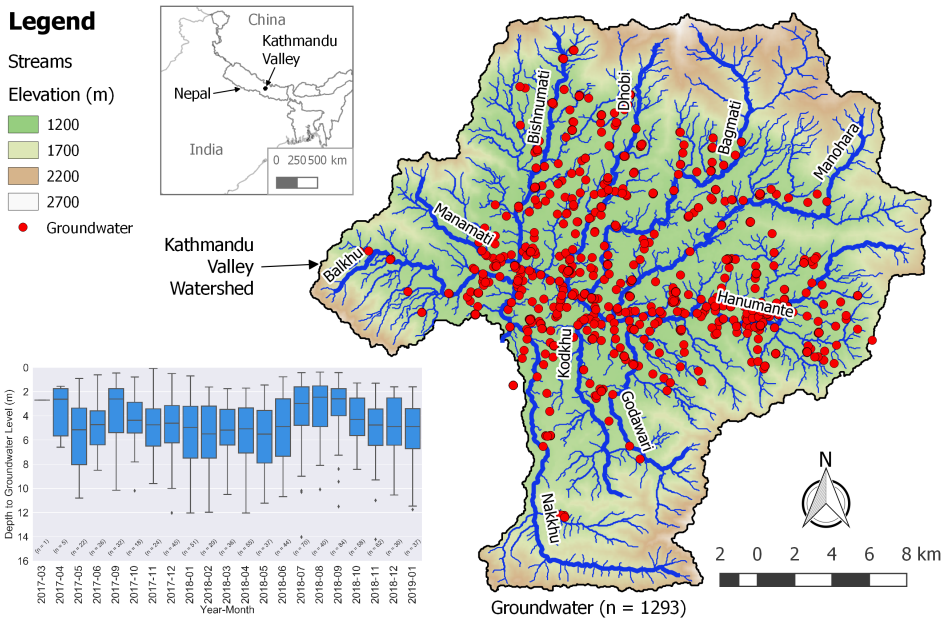
Figure 7.2: Location of all S4W-Nepal groundwater level measurements since January 1st, 2017. Box plot on the lower left shows monthly distribution of depth to groundwater level.

Research Question(s)

- How effective were our methods of recruiting and motivating private well owners in Nepal to start and continue taking groundwater level and quality measurements?

- How accurate and consistent were citizen science based groundwater level and quality measurements?

- What spatial and temporal conclusions about shallow groundwater levels can be made based on monthly citizen science observations?

- What spatial and temporal conclusions about shallow groundwater quality can be made based on monthly citizen science observations?

The following is a list of suggested tasks to move this analysis forward in the Kathmandu Valley:

- Analyze amount of corrected records during the quality control review of pictures to determine accuracy of citizen science observations. Chapter 4 can be used as a template.

- Characterize the frequency of citizen science observations and interpret the effectiveness of different recruitment and motivational efforts.

- Perform time series analysis on nearly 2 years of monthly measurements to determine trends for different spatial scales (e.g. whole Valley, by watershed, individual site, etc.).

- Using Real-time Kinematic (RTK) GPS with sub-meter accuracy, survey reference points of all monitoring wells.

- Perform spatial analysis to characterize trends and develop interpolated depth to groundwater maps.

- Create estimated flow direction maps based on RTK GPS reference point surveys and citizen science groundwater level measurements.

- Develop estimates of specific yield for shallow groundwater system from existing literature and additional data collection.

- Estimate annual shallow groundwater level storage changes from low (pre-monsoon) to high (post-monsoon) measurements.

7.3.2. On the Brink of Extinction: Quantifying the Stories of Stone Spouts in the Kathmandu Valley

Background

Stone spouts (Dhunge Dhara in Nepali) are ancient public water supply points in the Kathmandu Valley with critical cultural significance. Water from stone spouts originates from either ancient canals, springs, or more recently from modern municipal water supply lines. Unfortunately, due to a combination of land use changes, drying of adjacent ponds, and groundwater depletion (among other factors), discharge from stone spouts has been steadily decreasing. In many cases, stone spouts have completely dried and/or been destroyed. S4W-Nepal has been measuring discharge from over 200 stone spouts in the pre- and post-monsoon periods of 2017 and 2018. The purpose of this investigation is to improve understanding of how stone spout discharge and water quality is changing in space and time, and what factors most strongly drive these changes.
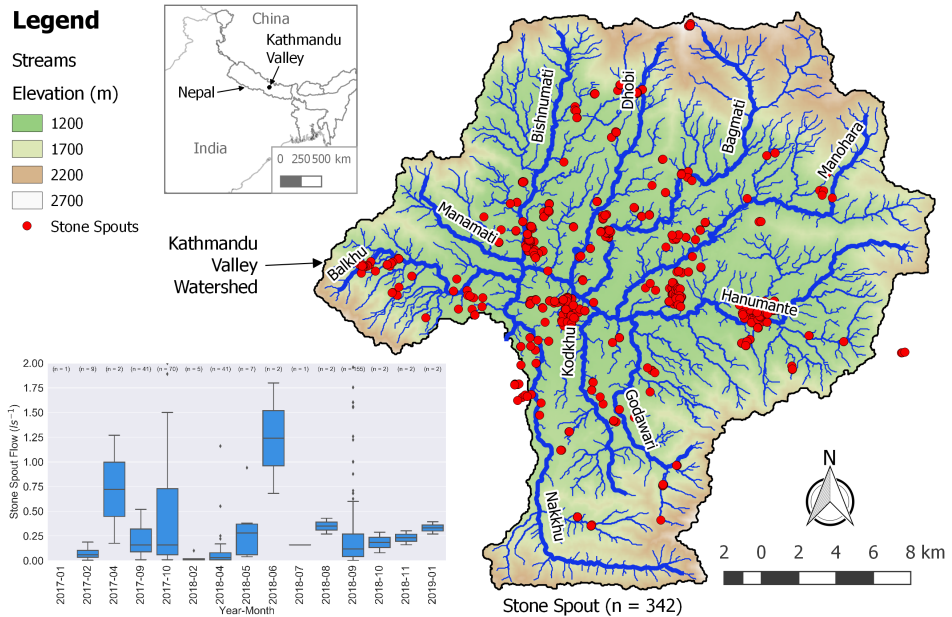
Figure 7.3: Location of stone spout measurements. Boxplot on the lower left shows the distribution of monthly flows in liters per second.

Research Question(s)

- How effective (e.g. cost, worth of data, educational value for students, etc.) are S4W-Nepal's bi-annual stone spout campaigns?

- What is the spatial and temporal extent of variations in stone spout discharge and water quality?

- What factors appear to most strongly influence stone spout discharge?

- What are the implications of these data on water security in the Kathmandu Valley?

Methodology

- Interview S4W-Nepal staff and campaign participants.

- Perform cost benefit analysis to determine return on investment.

- Develop methodology to determine the source of water (e.g. ancient canals, springs, municipal water supply lines, etc.) for each stone spout.

- Implement methods of determining stone spout water source.

- Review images from all measurements to ensure that sites are correctly assigned, and multiple measurements from single sites are accurately represented.

- Determine representative land use (based on land use data from Chapter 6) for each stone spout site.

- Perform spatial and temporal analyses to identify important trends and stories in the data.

7.3.3. Citizen Science Based Rapid Stream Assessments

Background

River water quality assessments have shifted from physico-chemical to biological assessments in recent years due to their cost-effectiveness and reliability in assessing the integrated effects of a range of environmental parameters on river health. Benthic macro-invertebrates are ideal for monitoring river health due to their abundance, diversity, habitat range, limited mobility, relatively long life cycle, and sensitivity to pollution and disturbances. In Chapter 5, Quantifying the Connections, we used the rapid stream assessment (RSA) for Himalayan streams to characterize ecological stream health or river water quality class (RQC; [9], [10]). RSA has been used as an integrated and robust method to assess ecological stream health for over 5 years. RSA uses four classification categories including: (1) sensory, (2) ferro-sulfide reduction, (3) bacteria, fungi, and periphyton, and (4) macro-invertebrate composition. One benefit of RSA is that it does not require any electronic sensing equipment, and instead relies completely on human sensory capabilities.

For these reasons, biomonitoring is an excellent candidate for possible integration with citizen science based water quality monitoring efforts. However, the macro-invertebrate identification process for RSA requires expert knowledge and is time consuming. Therefore, the standard RSA approach needs to be simplified before citizen scientists can be expected to independently use it. The proposed work includes developing a simplified RSA protocol, testing this protocol against experts performing the full RSA, applying the simplified citizen science approach to a larger area, and analyzing and reporting the findings to relevant stakeholders. These citizen science based approaches should be complimented by the standardized collection of samples and physical characterization of riparian and in-stream habitat. Additionally, S4W's mobile data collection platform should be used to capture simplified RSA data in the field, along with GPS coordinates, pictures, and other relevant meta data to improve the quality and reliability of observations.

Research Question(s)

- Can the Rapid Stream Assessment (RSA) protocol be simplified so that citizen scientists can reliably repeat it?

- How do simplified citizen science RSA and expert RSA measurements compare?

- How can citizens be recruited and motivated to participate in RSA campaigns?

- What science questions be addressed with these new data?

Methodology
- Develop RSA protocols for citizen scientists.

- Develop ODK form for field data collection of RSA data that automatically calculates the resulting RSA score without manual calculations.

  - The RSA workflow described in Chapter 5 can be used as a template.
  - Prepare basic taxonomic keys (each for five different water quality classes) and provide to citizen scientists as a field guide to identify macro-invertebrates to order level. Ideally, a key component of this effort would be selecting the most informative indicator species (e.g. 10 species) that can be readily identified by citizen scientists.
  - This simplified ODK from should also include physical characterization protocol to document in-stream and riparian habitat conditions.

- Identify schools, universities, community groups, etc. as project partners.

- Co-design reoccurring (e.g. annually or quarterly) RSA monitoring campaigns (e.g. StreamBio-KTM). Opportunities to partner with local community members surrounding monitoring sites should be explored.

- Host training(s) for roughly 30 citizen scientists representing a range of ages, gender, and education levels.

- Form teams of three to four citizen scientists for RSA field measurements.

- Perform RSA measurements (citizen scientists and "expert" aquatic ecologists), focusing on established monitoring sites discussed in Chapter 5.

- Collect (citizen scientists and "experts") multi-habitat samples stored in 70 % ethanol solution with proper labeling.

- Compare results (i.e. river quality classes (RQCs) and community structures of macro-invertebrates) between "expert" and citizen scientist measurements for the complete range of RQCs. Differences in Taxon richness, Shanon-Wiener Diversity Score, and GRS-BIOS/ASPT index scores should also be explored.

- Evaluate the performance of citizen scientists from based on age, gender, education level, etc.

- Refine methods of citizen science recruitment, training, and motivation.

- Perform spatial and temporal analyses of generated data to characterize patterns and trends.

- Disseminate information in collaboration with project partners (e.g. schools) to relevant stakeholders.

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8

Discussion and Conclusions

I have made this longer than usual
Because I have not had time to make it shorter.

Blaise Pascal

This dissertation explores novel methods for generating hydrometeorological data (Chapters 2 through 4), along with a few initial applications of these methods (Chapters 5 and 6). Chapter 2 showed that lower frequency citizen science-like streamflow observations can be informative for estimating minimum flow and runoff, but are less informative for maximum flow. Chapter 3 illustrated that citizen scientists can use the salt dilution method to take streamflow measurements with an average absolute error or 28 % with an average 7 % bias. Chapter 4 showed that citizen scientists (n = 154) could be recruited and motivated to measure monsoon rainfall with simple soda bottle rain gauges and smartphones, and that low-cost gauge errors were relatively low (on the order of -3 %). Chapter 5 highlighted the indelible influence that land-use has on water in the Kathmandu Valley, showing that the river quality class (RQC) for most perennial tributaries to the Bagmati River transitions from best (i.e. 1) near their headwaters to worst (i.e 5) near their confluence with the Bagmati River. Finally, Chapter 6 explored the connections between streams and the shallow aquifer, and found that streams are mostly gaining in the early post-monsoon (69 %) and mostly losing in the pre-monsoon (88 %).

These results suggest that young researchers and citizen scientists can and should be systematically mobilized with a common mobile data collection platform to help close water data gaps. Moving these ideas from concept to reality will require broad support and collaboration from (1) water researchers

and managers (key consumers of data) and (2) science educators and young researchers (key producers of data). Some significant challenges include the identification of sustainable funding, ensuring high data quality, and long term continuity of data records. Leveraging smartphones to generate appropriate meta data for each observation (e.g. photographs) and consistently using these meta data to make corrections to raw measurements are keys to ensuring high quality observations. Despite these challenges, there appears to be much potential for turning data gaps into educational opportunities.

Importantly, all data generated should be openly shared, in the spirit of "…data of the people, by the people, for the people." [1]

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8.1. Summary of Findings

This dissertation has both (1) developed and evaluated new methods of hydrome-teorological data collection, and (2) applied these methods to generate new water quantity and quality data (mostly) about the Kathmandu Valley. Chapters 2, 3, and 4 focused on the development and evaluation of new data collection methods that leverage the synergies between young researchers, citizen scientists, and mobile technology. Chapters 5 and 6, however, focus on answering science questions using methods similar to those explored in the earlier chapters. While the data generated in these earlier - more methodologically focused - chapters are likely helpful for improving our understanding of the Kathmandu Valley's water situation, the analysis and documentation of these findings will be explored elsewhere. For example, see Chapter 7 for an outline of key next steps that should be taken to generate meaningful research outputs from these data. The following summarizes the key conclusions from Chapters 2 through 6.

- Chapter 2 showed that temporally intermittent observations of stream levels and streamflow, similar to those expected from citizen scientists, can still be informative. In general, as watershed flashiness decreases and storage ratio increases, the reliability of minimum flow, maximum flow, and runoff estimates obtained from low frequency observations increases. Considering daily observations from watersheds in California that were most similar to Nepal (n = 31), the mean percent error in runoff estimates was 1.9 %.

- Chapter 3 explored whether citizen scientists can perform accurate measure-ments of streamflow using simple methods and equipment and materials that are both inexpensive and locally available. The results showed that the salt dilution method, compared to the float and Bernoulli methods, consistently yielded the most accurate streamflow data for experts and citizen scientists alike. For citizen scientists, mean absolute percent error was 28 % with a mean percent error (or bias) of 7 %. Recording videos of electrical conductiv-ity (EC) breakthrough curves in Open Data Kit (ODK) provided a simple and flexible interface for capturing high temporal resolution EC data with a range of smartphones and EC meters. Additionally, photographs and GPS coordi-nates of salt dumping and EC measurement locations provided sufficient meta data to quality control the observations.

- Chapter 4 evaluated the accuracy of a low-cost S4W soda bottle precipitation gauge, and compared the effectiveness of different recruitment and motiva-tional methods, the performance of citizen scientists, and the resulting cost per observation. A year-long collocated comparison found that the lost-cost gauge errors were relatively small (i.e. -2.9 %) compared to the standard 203 mm (8-inch) Department of Hydrology and Meteorology (DHM) gauge used in Nepal. Citizen scientists recruited via social media and random site visits, and motivated with payments took more measurements than other classifications. Analyzing photographs of each observation revealed that 91 % of citizen scientists' observations were accurate, and the remaining 9 %

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required correction. Importantly, it was the inclusion of photographs along with citizen scientist observations that enabled characterization and correction of these human errors. Measurements could be performed for as low as 0.07 and 0.30 USD for volunteers and paid citizen scientists, respectively. Median cost per observation was 0.47 USD for both volunteers and paid citizen scientists.

- Chapter 5 looked at the impacts of land-use on water quality in the Kathmandu Valley. The methods explored the same synergies between young researchers and mobile technology. Land-use maps were generated with a combination of insitu and remotely sensed observations. Deteriorations in water quality, as determined by an integrated sensory and macroinvertebrate approach (i.e. Rapid Stream Assessment or RSA), correlated most strongly with increases in built land-uses. Upstream locations of six of the nine watersheds investigated had near natural status (i.e., river quality class (RQC) 1), however, downstream RSA measurements for all nine watersheds had RQC 5 (i.e., most highly impaired). RSA results show statistically significant correlations with measurements of electrical conductivity and dissolved oxygen. Insitu land-use observations have now been repeated four times by S4W-Nepal citizen scientist campaigns. One recommendation, expanded on in Section 7.3.3 of Chapter 7, is to evaluate the feasibility of developing a simplified RSA approach for citizen scientists.

- Chapter 6 explored pre- and post-monsoon stream and shallow groundwater levels and water quality to understand stream-aquifer interactions in the Kathmandu Valley. The data suggest that streams transition from losing in the pre-monsoon to gaining in the post-monsoon. Preliminary results suggest that streams transition back to losing relatively quickly after monsoon ends. Poor water quality in streams is having a negative impact on shallow groundwater quality. Spatially, stream and shallow groundwater quality deteriorate from upstream to downstream (in agreement with Chapter 5); this relationship is stronger in pre-monsoon compared to post-monsoon.

8.2. Broader Implications

With these general conclusions in mind, the following sections present additional conclusions along with broader implications and recommendations at relevant spatial scales and for different vocational activities.

8.2.1. Kathmandu Valley

Chapter 2 showed that daily observations of streams can be informative, especially for estimates of runoff. Therefore, citizen science observations of streamflow (Chapter 3) and water levels (as described in Chapter 6) can be used to cost effectively improve understanding of watershed yield, especially for springs and headwater catchments. These data can be used to improve water balance calculations and associated water management planning activities. Results in Chapter 2, how-

ever, indicated that infrequent observations are unlikely to capture peak events. Therefore, for flood early warning systems where these peak events are key, the operational value of citizen science data is questionable. Nevertheless, infrequent citizen science data can still play an important role in calibrating models, which can then be used with real-time inputs (e.g. precipitation) to make actionable predictions of streamflows and inundation levels.

Chapter 5 indicated that land-use had a statistically significant impact on water quality, with built land-uses (high and low) having the greatest influence. These findings reinforce the importance of integrated land and water management, and highlight the urgency of addressing waste management issues in the Kathmandu Valley. Specifically, the results suggest that land-use management and conservation efforts in the Kathmandu Valley should focus on watersheds that still have large proportions of natural land uses. For example, specific attention should be given to protecting the upper Bagmati, Manohara, Godawari, and Nakkhu watersheds from further land-use changes. The large areas of natural and agricultural land-uses in these watersheds are under immense development pressures. If these pressures are yielded to, it is likely that there will be severe ecological and water management ramifications.

Chapter 6 explored stream-aquifer interactions in the Valley. In pre-monsoon 2018, 88 % of stream sites investigated were losing water to the shallow aquifer. However, in post-monsoon 2018, 69 % of stream sites had transitioned from losing to gaining. These findings highlight the importance of managing streams and aquifers as a single integrated resource. In the Kathmandu Valley, groundwater is currently the primary way that large amounts of monsoon rain water are stored for use in the subsequent eight month dry period. While seasonal refilling of the shallow aquifer was observed, the timing and spatial extent of this process, and the role of the deep aquifer in seasonal storage changes deserves future research attention. In the meantime, Kathmandu's incessant growth is steadily paving over the "inlet" to its essential water storage "tank," while its lack of wastewater management is gradually contaminating the water that still makes its way in.

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Since measuring extraction rates from the thousands of wells now operating in the Kathmandu Valley is unlikely in the near future, improved measurements of (1) baseflow contributions from headwater catchments, together with (2) accurate measurements of Bagmati River outflow from the Valley, are suggested to improve estimates of net groundwater pumping. Further, net groundwater pumping can be spatially distributed using additional streamflow measurements distributed longitudinally (i.e. upstream to downstream) along the perennial tributaries to the Kathmandu Valley. These regionally distributed net groundwater pumping values can be converted to per capita pumping rates using best available spatially distributed population data (see Section 7.2.3 for details). Improved estimates of net groundwater pumping can sharpen our understanding of groundwater overdraft in the Valley, which will support the analyses and designs of water supply solutions (e.g. Melamchi Water Supply Project [2]).

8.2.2. Other Data Scarce Regions

While most of this research was performed in the Kathmandu Valley, many of the lessons learned here could be helpful to other data scarce regions. With S4W-Nepal as a pilot case, the main barriers to replication in other areas include: (1) identifying key champions with the region (ideally within the local educational system), (2) working with S4W to create another project instance along with the associated ODK collect forms, (3) establishing partnerships with academic institutions who are interested to incorporate data collection and analysis activities into their science curricula, (4) designing effective methods of recruiting and motivating citizen scientists, and (5) identifying locally appropriate ways of closing the loop between S4W and citizen scientists (e.g. SMS messages, emails, etc.).

8.2.3. Remote Sensing and Citizen Science Practitioners

As discussed, remote sensing is a critically important source of timely, spatially distributed, and objective data useful for a range of water management purposes ([3], [4], [5]). However, there will always be a need to link these data with in-situ observations, whether it be for bias corrections, validation, or downscaling. In fact, some argue that more remote sensing data demands more in-situ measurements [6]. Looking at it in the other direction, remote sensing can add significant value to citizen science observations (e.g. Chapter 5). For these reasons, it seems important to explicitly link these two areas of research, starting at the moment of project design, in order to maximize the potential synergies between remote sensing and citizen science. Most likely, an important step in this direction is for both research communities to remember that neither solution is the end all "silver bullet" for filling these data gaps.

It is important to also note that there are several significant barriers to widespread use of remotely sensed data in resource constrained settings like Nepal. First, there are practical challenges of accessing these large data sets with slow internet resources. Platforms like Google Earth Engine can help alleviate the need to move significant amounts of data, however, relatively fast internet connections are still needed to use these types of cloud based applications. Perhaps an even more persistent challenge, assuming internet connectivity improves into the future, is the lack of capacity that is often found in places like Nepal for analyzing, visualizing, and interpreting large geospatial data sets. Therefore, realizing the use of remote sensing data in conjunction with citizen science data in resource constrained environments will take a concerted effort to build both awareness of available remotely sensed data products, but also the capacity to effectively analyze these data. During these training efforts, the role of open source tools like Quantum GIS and Python and their associated plugins and modules should be highlighted.

8.2.4. Science Educators

Experiences gained through this dissertation have shown that young researchers (i.e. students) are a significant and largely untapped resource that can be leveraged to help close growing water data gaps. One key to releasing the potential of young researchers is to facilitate a collaboration space that links them to (1) scientists with

a sense how and what to measure and (2) an open source technology platform that facilitates collaborative data collection and sharing. Young researchers can provide critical citizen science "beach heads" in regions with relatively low levels of scientific literacy.

Young researchers should be explored as an important component of future citizen science efforts in Nepal. This is perhaps especially true in places that do not have large retired populations with sufficient scientific literacy to be intrinsically motivated to participate in citizen science projects. Mobilizing large numbers of young researchers (grade 8 through graduate school) into the data scarce regions of the world equipped with commonly developed vision, methodology, and a shared data collection platform can have several benefits. First, there is always a consistent supply of young researchers that need research questions and field experience to fulfill the requirements of their degrees. Second, providing a digital, consistent, and accessible platform for generating water-related data helps to maintain quality and consistency, while ensuring that past research is not lost, and future research builds on previous efforts. Finally, cross-cutting organizations facilitating such efforts can help to link young water-related researchers across a swath of academic institutions related to environmental science, agriculture, engineering, forestry, economics, sociology, urban planning, etc., thereby encouraging young researchers to contribute to relevant and multidisciplinary research topics. Ultimately, these young researchers can then become the champions of engaging citizen scientists in the communities where they grew up, live, research, and work. Future work should evaluate the effectiveness of recruitment strategies on a wider range of possible citizen scientists (e.g. retirement age). This will help provide the necessary context for understanding the relative importance of young researchers in citizen science efforts.

8.2.5. Low-cost Sensors

The potential of a low-cost sensor to improve understanding of a process depends on the interplay between (1) the spatial heterogeneity of the process being observed, (2) the changes in accuracy when using a low-cost sensor, and (3) the observational cost savings. The need for higher density observations increases as the spatial heterogeneity of the process being observed increases. So, if (1) the observed process has high spatial heterogeneity, and (2) the low-cost sensor has high accuracy measurements, with (3) high cost savings, the potential of the low-cost sensor to improve understanding of the process is considered high. Alternatively, if (1) the observed process has low spatial heterogeneity, and (2) the low-cost sensor has low accuracy measurements, with (3) small cost savings, the potential of the low-cost sensor to improve understanding of the process is considered low. In areas with extreme topographic diversity and strong convective processes (e.g. Nepal), precipitation can vary substantially over short distances. For example, a low-cost sensor like the S4W gauge that offers large cost savings (Section 4.4.4) and high accuracy (Section 4.4.1; average -2.9 % error without correction) has a high potential to improve process understanding. More generally, this framework can be used to prioritize investments in water-related citizen science projects and low-cost

sensor development; focus should be on efforts related to water-related processes with high spatial heterogeneities, high sensing accuracy, and high potential for cost savings. However, it is critical to consider the interplay between citizen scientists and low-cost sensors.

There is often a tension in citizen science efforts regarding the role of the citizen in the scientific observation, interpretation, or communication. Some efforts focus more on the technology and automation side, and this can often lead to the participants feeling obsolete or underutilized. In contrast to this, the experience with S4W-Nepal has been that participants of all ages, genders, and educational backgrounds are capable of making reliable water observations, and validating others' observations to ensure their quality and completeness. Including humans in these tasks can be an intrinsic motivation for participating in citizen science projects. Therefore, future citizen science projects should think carefully about the human role in observation, validation, and communication of data, with a strong consideration of keeping a "human in the loop" with these tasks, rather than attempting to partially or wholly automate them.

8.3. Challenges and Limitations

Some of the primary challenges in implementing S4W's vision include (1) securing sustainable funding, (2) maintaining high quality data, and (3) ensuring long term records.

8.3.1. Sustainable Funding

Securing sustainable funding for baseline hydrometeorological monitoring is one of the key ingredients for sustainable application of the ideas in this dissertation. The following paragraphs detail four possible funding concepts ranging greatly in complexity, uncertainty, and ambition, including: (1) non-profit donation based model, (2) small business model, (3) Water Funds, and (4) an environmental tax.

Sustainable funding for motivation of paid citizen scientists could come from an "adopt a citizen scientist" program, whereby classrooms in more affluent countries, who are perhaps learning about the water cycle or other related topic, could raise funds. Sufficient funds to support one rural citizen scientists for a monsoon could be raised if each student in a classroom of 30 raised roughly 1 USD. Such a program could be modeled after similar efforts such as the Trans-African Hydro-Meteorological Observatory (TAHMO) school-to-school program [7], even though many of the details of the TAHMO project are still in flux and have not been completely ground-truthed.

Alternatively, the technology platform developed and used by citizen scientists for collecting, quality controlling, storing, and disseminating observations could be monetized with a software as a service (SaaS) type business model in support of data collection efforts by governments, researchers, or private sector organizations in more developed countries. Part of a SaaS model could be "human in the loop" quality control review of relevant metadata (e.g. pictures, videos, etc.) to validate observations that are difficult to automatically validate with computers. These

tasks could be performed in developing (data scarce) regions to leverage economic gradients, and profits could be used to support and expand citizen science efforts.

The concept of embedding and sustaining citizen science as part of Water Funds should be explored. Water Funds - an approach successfully used in much of Latin America - are collaborative change systems aimed at improving water security in urbanized areas by mobilizing beneficiaries of water-related ecosystem services to support conservation and restoration activities that protect these benefits into the future (payments for ecosystem services (PES); [8], [9]). Citizen science could play a key role in the design, implementation, and monitoring of these conservation and restoration activities [10]. Therefore, a small amount of the fund could be invested in citizen science projects that provide long-term benefits to the Water Funds.

It is possible that a globally administered environmental tax should be administer to build the environmental management capacities of producers in low resource settings. Globally connected free markets link the production and consumption of goods and services across significant spatial scales. Economic leverage (i.e. profit) can be maximized by producing in low resource areas (i.e. least developed countries) while focusing consumption in high resource areas (i.e. most developed countries). One of the undesirable consequences, however unintended, is that the environmental impacts of production become spatially concentrated in low resource areas. This concentration can rapidly lead to acute environmental impacts, in part because low resource settings are often least prepared to manage and mitigate environmental impacts from increased economic production. This lack of mitigation capacity can be caused by a combination of weak economies, insufficient institutional structures and capacity, and inadequate physical infrastructures. As efficient as "the market" is in many contexts, it is unlikely that market forces will coalesce towards solutions to these acute environmental challenges. Instead, such a tax would ensure that financial obligations for capacity building efforts aimed at producers would come from consumers. Many questions, however, remain about this approach, not least how and who would administer such a tax among sovereign nations.

Regardless of the funding mechanism, there will be an ongoing need to identify and characterize water related environmental challenges at different spatial scales. Towards this end, baseline hydrometeorological monitoring could be performed by non-profit research institutions (e.g. S4W) in partnership with regional academic institutions, young researchers, and citizen scientists with a common mobile data collection platform. Investing limited monitoring resources in this way has the following potential benefits, each of which should be the focus of future research efforts:

- Lower cost per observation compared to traditional data collection approaches

- Improved spatial and temporal density of observations

- Increased measurement transparency with photographic meta data for quality control and GPS coordinates for location validation

- Increased capacity and experience for young researchers

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  • Employment and educational opportunities at the community scale

  • Development of contextualized and (potentially) transferable data collection
    methods and low-cost sensors

  • Open access to data

8.3.2. Data Quality

A consistent challenge that citizen science projects face, especially from established
data generating institutions, is data quality. While Bonney et al. ([11]) state that
citizen scientists can generate data with equal quality to those generated by ex-
perts, this is a valid and important concern that will likely persist. Issues of data
quality can be organized into the following categories: accuracy, precision, repre-
sentativeness, completeness, and comparability [12]. A few important factors for
addressing these concerns are (1) leveraging mobile technology to generate ap-
propriate meta data for each observation, (2) consistently using these meta data
to make corrections to raw measurements, and (3) freely sharing data with all in-
terested parties. Reviewing the meta data, and making any necessary corrections
will help with the accuracy, precision, and completeness issues. For representative-
ness and comparability, adequate training and well designed mobile data collection
workflows are critical. Ideally, data review processes could be performed by young
researchers as volunteers, or as a crowd-sourced or gamified process. Otherwise,
continuity in funding becomes critically important to ensuring the sustainability of
data quality. It is critical to quickly "close the loop" between errors observed during
the quality control process and the citizen scientists making the errors during data
collection by providing customized feedback and training.

  Additionally, Zheng et al. [13] provide a useful summary of eight methods to
assure the quality of crowdsourced or citizen science data. These methods include
the following:

  1. Comparison with an expert or gold standard data set

  2. Comparison against an alternative source of data

  3. Combining multiple observations

  4. Crowdsourced peer review

  5. Automated checking

  6. Methods from different disciplines

  7. Measures of credibility of the information and users

  8. Quantification of uncertainty of data and model predictions

8.3.3. Long Term Records

In addition to data quality, ensuring continuity of records is also a challenge most citizen science projects face. For example, focusing on young researchers may ensure a continuous and reliable supply of participants, but there may be high turnover rates leading to lots of short term (i.e. less than one year) data sets. In light of this challenge, it may be helpful to establish a certain number of longer-term commitments with a subset of the most motivated citizen scientists. As scientific literacy improves in data and resource scarce regions, especially among older populations, it is likely that retirement aged citizen scientists will play a critical role in this [14]. The goal would be to have a sufficient number of core sites that could be used to help "stitch" together the remaining shorter records. These core stations would also be important for assessing the impacts of long-term trends due to climate change, or other longer time scale phenomena. Importantly, utilizing free and open source tools, and developing systems that operate with little or no maintenance, are important factors to ensure ongoing data collection.

Another idea for optimizing the use of temporally intermittent citizen science water data, such as those discussed in this dissertation, is to assimilate these data into reanalysis frameworks similar to those used for climate data ([15], [16], [17]). Such framework(s) could include climate reanalysis data, remotely sensed products, traditional ground based observations, and citizen science data (and others). The combination of these data could be used as inputs for both (1) hydrological model(s) and (2) error model(s). The resulting data product(s) could be combinations of the various parameters and the uncertainty of each respective parameter as quantified by the error model(s).

8.4. Call To Action

Despite these challenges, there appears to be much potential for turning water data gaps into water related educational opportunities. Mobilizing young researchers and citizen scientists with a shared mobile data collection platform is a critical first step towards realizing this potential. The reality is that the limiting factors for implementation are likely not (1) water related challenges, (2) data gaps, (3) young researchers, or (4) mobile technology. Rather, the main limiting factor is likely our vision and passion (or lack there of) to realize these synergies. Practically, this means that every water related science and engineering educator should consider systematically recording the data generated by young researchers as part of their academic training and coursework (note that potential applications extend well beyond just water related studies). Also, water managers and researchers should consider the un-leveraged potential of young researchers to generate significant amounts of water data. Cross-cutting organizations facilitating such efforts (e.g. S4W) can help to link young water-related researchers across a swath of academic institutions related to environmental science, agriculture, engineering, forestry, economics, sociology, urban planning, etc., thereby encouraging young researchers to contribute to relevant and multidisciplinary research topics. Currently, S4W continues to develop and refine these ideas in Nepal, in addition to launching new projects in the Netherlands (S4W-NL) and California (S4W-CA) in

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2019 to further scale this approach. Ultimately, these young researchers can then become the champions of engaging community members as citizen scientists in the places where they grew up, live, research, and work.

One significant benefit of in-situ measurements performed by young researchers and citizen scientists is they can be made open access. Open access data is increasingly recognized as foundational to modern scientific research [18]. Moreover, open access data has the potential to boost the economy, spur economic growth, and increase the rate of discovery [19]. Over time, these systematically collected and quality controlled data have the potential to accumulate into a rich, accessible, and potentially transformative data source.

To borrow (and slightly modify) a quote from one of the great U.S. presidents, let us move towards creating:

"...data of the people, by the people, for the people." [1]

Consider this a call to action; there is much work to be done.

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It was nearly six years ago that I had my first heated discussion (perhaps argument) with the late Dr. Peter Jules (PJ) van Overloop. We were at a US Committee on Irrigation and Drainage conference in Phoenix, Arizona. Each of us thought our inventions were going to save the world. Turns out, we were both wrong. We enjoyed the argument so much, though, that we decided to try our hand at working together. Roughly a year later, I had the pleasure of working with PJ on a short assignment at IJmuiden, where the North Sea Canal empties into the North Sea. A few days into the project, after learning that the site isn't pronounced i-jee-moo-ee-den, I was awoken with the thought of extending PJ's work on using smartphones for improving water management into resource constrained settings like Nepal. I have an affinity for Nepal, smartphones are increasingly ubiquitous there, and the Kathmandu Valley has some serious water problems. Thus, SmartPhones4Water was born. Thanks PJ for being a brilliant friend, even if only for a short time. I was looking forward to a long future of friendship and collaboration with you.

I pitched the idea for SmartPhones4Water to PJ while we inspected the huge venturi meters and sluice gates at IJmuiden. I still don't know if we were supposed to climb down into those vaults, but PJ assured me that it wouldn't earn me the opportunity to learn about the Dutch penal system. He must have liked the idea, because the next morning we were in his boss' office at Delft University of Technology (TU Delft), making the same pitch. This was my first meeting with professor Nick van de Giesen, and I was pretty sure he would call my bluff and send me away packing. Thankfully, perhaps even mystically, he also liked the idea. Nick - you are definitely one of the most clever people I know. These days, I now understand most of what you say (though I still had to Google what the difference between slow and fast neutrons was), but how your English vocabulary got to be twice the size of mine will probably remain a mystery. Thanks for your support and positive spirit that helped carry me through the dull drums. I appreciate all the lessons I've learned from you along the way, and I look forward to passing them on to the next generation.

I left the meeting with Nick with the refrain "shoot, what should I do now?" echoing in my head. I've got a wife, three kids, and I'm 10 years into a consulting career in California. Now I've got an opportunity to get a PhD with TU Delft while

living in Nepal and giving our kids a cross-cultural experience. Of course, I did the only sensible and prudent thing given the circumstances. We sold most everything we had, packed our lives into 10 boxes (okay maybe it was 14), and bought five one-way tickets to Kathmandu. In reality, there was a bit more to the transition then that.

In order to give a bit of official structure and weight to our efforts, we registered SmartPhones4Water, Inc, a California based 501(c)(3) non-profit organization before leaving for Nepal. S4W's mission is to mobilize young researchers, citizen scientists, and mobile technology to improve lives by strengthening our understanding and management of water. I lead this organization as president, along with my dear colleagues and friends Joshua Otto, Matthew Thiede, Joshua Payne, and Brandon Ertis. S4W Board - thanks for your thoughtful support and refining vision for S4W. I look forward to many more years of dreaming together with you all.

2015 started with some significant challenges and sad news. First, we deeply grieved the sudden loss of our friend PJ. Then we cried with the survivors of two catastrophic earthquakes in Nepal which killed over 8,000 people. After losing PJ, there was real uncertainty about how things at TU Delft would continue. After a few nervous emails, Nick assured me that he would make things work, and recommended Dr. Martine Rutten as my new daily supervisor. It turned out that Martine and Nick were both in California in the early summer of 2015, just a few months before our scheduled departure. I drove down to Sacramento to meet them and was immediately impressed by Martine's selection of a Thai restaurant for lunch. Check. We both love Thai food. Martine - thanks for all your support and advice along the way. Your knowledge of math and statistics, your passion for citizen science, along with a few (okay, maybe many) tips and tricks for getting my writing into publishable shape were life savers. Martine's efforts have been complimented more recently by Dr. Thom Bogaard's excellent and timely insights. Thom - thanks for your support and guidance of the various multi-disciplinary groups that joined our project in Nepal, and thank you for helping me wrap things up! I look forward to working with both of you in the coming years.

With things at TU Delft ironed out, we got on the plane to Kathmandu. I'll never forget that first night. After landing at Tribhuvan airport, our dear friend Prajwal Adhikary and three young Nepali men helped load our 14 boxes into an oversized bus that Prajwal had rented. Our kids were wide eyed as we sped through the deserted streets of late-night Kathmandu. It was 2 a.m. by the time we put on the bed sheets and found our tooth brushes. That's when the tears started - I mean a real family-wide tear fest. Prajwal and Debbie - thanks for being such faithful friends. You helped us through those first difficult days by opening your lives and your home to us. We have learned so much from you and look forward to more adventures in Nepal in the coming years!

Some sense of normalcy did finally set in, though I can't recall exactly how long it took. It is an understatement to say that our dear friend and surrogate mother Kamala Tamang, and her daughter Sheela, and son Eliyah played a big role in that. Kamala didi is one of the toughest women I have ever met. She can also cook what I consider some of the best dhal bhat in Nepal, as everyone in the S4W-Nepal

family can attest. Kamala - you loved us so well during our time in Nepal. Thanks for your faithful friendship and support.

I first met Dr. Deep Narayan Shah at my favorite tea and sweet shop in Jawalakhel only a few months after our arrival. Some of my close colleagues at Son-Tek in San Diego had recently donated a FlowTracker acoustic Doppler velocimeter for the Bagmati River expedition. The FlowTracker ended up at Deep and his wife Dr. Ram Devi Tachamo Shah's house, and I ended up with an email in my inbox from Deep stating that "we should meet up some time." Deep's warm laugh, extensive knowledge, and sensible concern for Nepal's rivers won me over immediately. We discussed a sketch of ideas explored in this dissertation, and decided to "throw a few of them at the wall," hoping that a few of them would stick. Practically, this entailed me joining Deep and some of his BSc students on monthly field trips to Shivapuri Nagarjun National Park (SNNP). Deep and Ram Devi had recently initiated and self-financed long term bio-monitoring at five sites within SNNP. Deep and Ram Devi - thanks for your passion for educating Nepal's youth and protecting Nepal's waters. Without your enthusiasm, guidance, and previous work, much of S4W-Nepal's success would not have been possible.

After nearly dying on my first ascent to BA01, Deep and Ram Devi's highest monitoring site near the headwaters of the Bagmati River, I met Sumina Shrestha and Sabina Tamang. Sumina and Sabina are two wonderful and tough young women living with their families within SNNP. Sumina was S4W-Nepal's first citizen scientist, followed shortly by Sabina. We didn't have a crystal-clear plan at the time, but figured there was no use waiting around. We installed staff gauges nearby their homes in the Bagmati and Nagmati rivers and asked them to take and email pictures of the gauges whenever they were in the area. I recall we also rigged up some MacGyver-ish rain gauges that were nearly impossible to use. Sumina and Sabina - thanks for faithfully partnering with S4W-Nepal. You helped us worked out so many kinks and issues, and we owe a lot to you for that. I should also say thanks to Sumina for sharing the best kakaro khursani (cucumber and chili) I've ever eaten, and thanks Sabina for the countless servings of the best aloo tarkari (potato curry) in all of Okhreni.

While our initial data collection methods with Sumina and Sabina were easy to get off the ground, they had little (okay zero) potential for future scalability. Luckily, Tyler Erickson from Google introduced me to Open Data Kit (ODK) at the 2016 European Geophysical Union annual meeting (many thanks Tyler!). The ODK community produces free and open-source software for collecting, managing, and using data in resource-constrained environments. Yaw Anokwa, one of the key founders of ODK, and the rest of the community have built a super solid mobile data collection platform that even a dense civil engineer like me can figure out how to use. That is quite a feat. Thanks to everyone in the ODK community for your development and ongoing support of these tools. I look forward to giving back in whatever small ways I can moving forward.

With our first ODK system operational, and some of the bumps in the road smoothed out thanks to Sumina and Sabina, it was time to scale things a bit. At the time, Deep and Ram Devi both were teaching environmental science courses

at Nami College. They suggested that we hire a couple of third year BSc students from Nami, since their entire year was dedicated to practical internships. A few weeks later, I was in a Nami college room with Deep and Ram Devi interviewing students for the positions. Nischal Devkota was technically competent, outgoing, and bursting with confidence. Anusha Pandey was sharp as a tack, good at writing, and painfully quiet. "Sounds like a perfect match," we thought, so we hired them both. After asking Eliyah Moktan to help with operations, we later added Rajaram Prajapati as CEO, along with Anurag Gyawali, Saujan Maka, Sanam Tamang, Anu Grace Rai, Surabhi Upadhyay, Amber Bahadur Thapa, Pratik Shrestha, and Sugam Dahal into the mix. S4W-Nepal family - thanks for being the best group of young researchers ever. Seriously, we have learned so much together, gotten a lot done, and had a lot of fun doing it. I am forever grateful for the blood, sweat, and tears you invested, and continue to invest, in S4W-Nepal. I look forward to watching you all become the leaders that Nepal so desperately needs.

Having a larger team, along with a few reminders from my wife from time to time, impressed upon me of the importance of finding some financial partners. Since I already had a draft proposal compiled with colleagues from the Nepali Groundwater Resources Development Board (thanks Surendra Raj Shrestha!) and IWMI-Nepal (thanks Dr. Romulus Okoth Okwany!), Nick recommended that I connect with Professor Steve Lyon at Stockholm University. Steve was immediately enthusiastic about the ideas. We quickly modified the existing proposal to beat a Swedish International Development Agency (SIDA) application deadline for their Swedish Links Research Grants program. Steve - thanks for your enthusiasm and mentorship along the way. I'll never forget our workshop at Okhreni middle school, followed by our night march to Chisopani. I look forward to more adventures in the future! Thanks to Steve, by the start of 2017, we had received the good news that SIDA had selected our proposal. Now S4W-Nepal had a talented and growing group of young researchers and a bit of money to invest.

At this point you are probably in one of two camps: (1) when is this guy going to stop talking? or (2) where does the story go from here? If you are in the first camp, my sincerest apologies (see the quote at the beginning of Chapter 8 for further explanation). If the latter, then I guess you've got some more reading to do. Chapters 1, 3, and 4 in this dissertation are probably the best places to start. You might also be interested in this short documentary (thanks to the amazing Deepak Adhikary): https://www.youtube.com/watch?v=30f38L-reTY. However, before launching into the academic "fluff," the following paragraphs highlight the last few groups of folks who have played an instrumental role in this dissertation, or my life in general.

One of the beautiful things about research and academia is the natural link to a steady stream of energetic and talented young researchers. It has been an honor and a pleasure to work with and supervise students from Nepal, the Netherlands, California, Alaska, Mexico, Canada, Greece, and Germany. Thanks to the 2016 TU Delft Multi-disciplinary (MDP) team (Felipe Gonzales, Petra Izeboud, Sven Veldhuis, Vera Knook, and Clemens Gronau) for their tireless efforts to understand the Kathmandu Hydrology and land-use (Chapter 5). Thanks to Annette van Loosen and Wessel David van Oyen for their efforts in understanding citizen science mo-

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It was over 13 years ago (April 2006) that I first landed at Tribhuvan airport in Kathmandu with my wife Kristi, and her father Mitch Cook. Nepal was in what turned out to be the final throes of a decade long civil war with a Maoist insurgency. It was a memorable trip to say the least. Things intensified during our two week stay, to the extent that our exit from the country was in a UN bus filled with terrified tourists escorted by a couple of jeeps with turret mounted machine guns. Thankfully the conflict ended about as peacefully as it could have about a week after we left. Mitch and Barbara - thanks for raising such an amazing daughter and for infecting us with your love for the beautiful people of Nepal.

Thanks to my parents, Grant and Joni, and my brother John. From my earliest memories in Sri Lanka, to the hours of swimming, fishing, and exploring the Sierra Nevadas, you have taught me to love and appreciate water and the life that it brings. Dad - you taught me to work hard, think clearly, and write succinctly. While I might have the first of that list down (working hard), it is clear I've got a long way to go with the next two. Mom - you are the most caring and gracious human being I know. You taught me how to lead by example and how to care for all colors, shapes, and sizes of people on this good earth we share. John - you have always been someone I deeply respect and admire. You taught me to be brave, confident, and face the world with a full head of steam.

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Finally, it is good and right to give thanks to the One who made this wonderful world, along with the beautiful laws that keep it ticking along. It's these wonders us scientists and engineers have the pleasure of gazing towards, marveling, and dissecting. While much is yet undone, thanks that this One is slowly, and at times mysteriously, 'putting all things to rights.'

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Curriculum Vitæ

Jeffrey Colin Davids

27-01-1982   Born in Healdsburg, California, USA.

Education

2000–2004   BSc in General Engineering
California Polytechnic State University, San Luis Obispo, California, USA

2008–2011   MSc in Geosciences & Hydrogeology, Graduation with Distinction
California State University Chico, Chico, California, USA

2015–2019   PhD in Water Management
Faculty of Civil Engineering and Geosciences
Delft University of Technology, Delft, Netherlands

Introduction

Jeff's educational background, broad consulting experience, and dedication to the development of human resources from diverse backgrounds demonstrate his commitment to improved and sustainable management of the Earth's limited natural resources through education, research, and appropriate application of technology. Jeff is Founder and President of SmartPhones4Water and H2oTech, a Ph.D. candidate in Civil Engineering, Water Management, with Delft University of Technology (TU Delft), a Water Resources Consultant for the Food and Agriculture Organization of the United Nations (UN-FAO), and a Water Resources Engineer with Davids Engineering. Jeff also served as a lecturer at California State University, Chico teaching and providing guest lectures in the Civil Engineering department for five years from 2011 to 2015. As a Water Resources Consultant to the UN-FAO, Mr. Davids is tasked with the design and implementation of a series of training packages on Water Accounting and Water Productivity. Jeff is a licensed Professional Engineer in the State of California, has a M.Sc. from California State University, Chico in Geosciences and Hydrogeology, and a B.Sc. in General Engineering from California Polytechnic State University, San Luis Obispo. Jeff's interests focus on how sustainable management of water, energy, and food are supported by education, integrated systems thinking, innovative sources of data, modeling tools, social

engagement, and outreach. Most recently, with SmartPhones4Water and TU Delft, he has been investigating how young researchers, citizen science, mobile technologies, and remote sensing can be leveraged to develop foundational hydrologic datasets in data scarce regions. Prior to moving to Nepal, Jeff provided professional engineering services to a variety of clients in the Western United States and abroad for over 10 years. He has successfully launched various entrepreneurial endeavors, including the RemoteTracker (2011) - an innovative new flow measurement device currently in use on over 150,000 acres of farm land in the Western US; SmartPhones4Water (2013) - a non-profit organization; FLOW (2015) - an online water data portal; and S4W-Nepal (2017) - a Nepal based non-profit research organization. Jeff has utilized various technologies to accurately quantify water flows in a variety of settings including natural streams and rivers, open-channel agricultural conveyance systems, and pipelines over a broad range of materials and sizes. Jeff has extensive experience performing hydrologic and hydrogeologic field measurements used to characterize groundwater and surface water quantity and quality. Jeff has managed diverse international teams and large projects, including the design, installation, calibration, and maintenance of several large flow measurement and data acquisition networks in the US and abroad.

Online Materials

- https://www.linkedin.com/in/jeffdavids
- http://www.davidsengineering.com/meet-the-staff/jeffrey-c-davids/
- http://www.h2otechonline.com/about/
- http://www.smartphones4water.org/our-team/

In The News

- Humans at TU Delft: Jeff Davids, PhD Candidate (TU Delft Delta)
- I Think I'm Going to Kathmandu: Citizen Science for Freshwater in Nepal (The Nature Conservancy Blog)
- Nonprofit Kick-Starts Water Data Gathering In Nepal Valley (Environmental Monitor)
- Citizens Collect Water Data With Smartphones in Nepal Valley (VPdelft)
- Three Generations Near the Banks of the Bagmati (Onset)
- In Pursuit of Data (Forester Magazine)
- SmartPhones4Water Hopes To Fill Water Management Data Gaps for Developing Nations (Environmental Monitor)
- S4W-Nepal Introduction Video (SmartPhones4Water)
- S4W-Nepal Tutorial Videos (SmartPhones4Water)

Selected Work Experience

Food and Agriculture Organization of the United Nations
Water Accounting Training Program, Kabul, Afghanistan and Nay Pyi Taw, Myanmar
Since the spring of 2017, Mr. Davids has served as the lead Water Resources Consultant for the development of materials and conduction of a series of trainings on water account for water managers and educators in Afghan and Myanmar. In total, the training on water accounting will include eight sessions, each involving between three and ten-day intensive sessions comprised of lectures, hands on case studies, and learning activities. Water resources management is a global challenge. Several factors continue to increase water scarcity, which in turn escalates water related social, economic, and environmental challenges. The world's human population is growing, and with it the demands for food and fiber. At the same time, deforestation, water quality degradation, urbanization, climate change and other factors threaten and increase competition for the world's finite freshwater resources. As water demands increase, managing limited freshwater supplies becomes critically important, yet the widespread lack of water related data hinders development of appropriate water management policies, practices, and infrastructure. A common system of water accounting has for the most part been missing in the emerging debate of global water governance. Into this context, the Food and Agriculture Organization of the United Nations (FAO) initiated a capacity development program in water accounting.

Swedish International Development Agency
SmartPhones4Water-Nepal (S4W-Nepal), Kathmandu, Nepal
Mr. Davids founded SmartPhones4Water (S4W) in 2013. S4W is a US-based non-profit organization that leverages the power of young researchers, mobile technology, and citizen science to improve lives by strengthening our understanding and management of water. S4W accomplishes this with a three-pronged approach of Research, Education, and Employment. Starting in 2015, Mr. Davids moved to Kathmandu to lead the design and launch of S4W-Nepal. S4W-Nepal mobilizes young researchers by providing a collaboration space and open source technology platform that links their research interests to pressing water management questions and data gaps in Nepal. S4W-Nepal is a collaboration between SmartPhones4Water (S4W); Himalayan Biodiversity and Climate Center (HimBioCliC), Nepal; Kathmandu Institute of Applied Sciences (KIAS), Nepal; Delft University of Technology, Netherlands; the Swedish International Development Agency (SIDA), Sweden; and Institute of Engineering (IOE), Tribhuvan University, Nepal. Mr. Davids guides S4W-Nepal's core staff team of 10 scientists and engineers, who in turn are engaged with over 50 young researchers and over 300 citizen scientists.

H2oTech
RemoteTracker, California, USA
Mr. Davids served as the lead developer for the RemoteTracker farm-gate delivery measurement project spearheaded by H2oTech, a water technology specialty com-

pany based out of Chico, CA. The RemoteTracker system is an integrated turnout flow measurement, data management and volumetric accounting system developed by H2oTech specifically for agricultural water providers. The RemoteTracker system is comprised of (1) a wirelessly controlled water velocity sensor, (2) a ruggedized tablet PC in the operator's vehicle and (3) a database running on a file server connected to the internet. The user interface on the tablet PC enables operators to view real time flow data from the wirelessly controlled water velocity sensor via a Bluetooth radio connection while adjusting flows at the turnout gate. Data is automatically transferred over a wireless wide area network (WWAN) to the centralized file server at the District headquarters where it is automatically loaded into a custom database application. The database performs quality control and quality assurance procedures on the data and then develops daily volumes for each delivery point with the District. The RemoteTracker is used to measure agricultural water deliveries to over 60,000 hectares in Northern California.

California State University Chico
Fluids Mechanics and Guest Lectures, California, USA
Jeff served as an assistant faculty member at California State University Chico teaching the fluid mechanics laboratory section for five years from 2011 to 2015. Mr. Davids received high marks in both student and peer evaluations as an instructor. Jeff also provided guest lectures for upper division Water Resources and Hydrogeology courses.

Hydraulics Control
North Sea Canal IJmuiden Sluice Gate Flow Measurement Improvements, IJmuiden, Netherlands
The North Sea and Amsterdam-Rhine Canals are the main water supply and drainage facilities for a significant portion of The Netherlands surrounding the greater Amsterdam area. The water surface elevation of the North Sea Canal is predominantly controlled by six lift pumps and seven sluice gates operating in parallel at the IJmuiden control complex. Mr. Davids analyzed existing flow measurement and data management practices, and developed a data collection plan to improve the accuracy of flow measurements through the seven sluice gates. The data collection included the use of advanced hydroacoustic methods to qualitatively detect reversed flow (i.e. from the North Sea into the Canal), and to quantitatively determine flow rates through the sluice structures as compared to the Venturi methods currently being utilized.

Yuba Water Agency
Measurement Improvement Plan Development and Implementation, California, USA
The Yuba Water Agency (YWA) developed an agricultural water management plan (AWMP) in 2012 as required by the Water Conservation Act of 2009. As part of the larger AWMP effort, Mr. Davids led the development of a Measurement Improvement Plan to improve customer delivery measurement and quantification of key

boundary inflows and outflows. Development of the Measurement Improvement Plan included an inventory and inspection of existing open channel and pipe flow measurement sites, in addition to development of designs and cost estimates for improvements required to ensure that YWA is compliant with the Agricultural Water Measurement Regulation (CCR §597). Jeff is currently working with YWA to implement the Measurement Improvement Plan, with the goal of being fully compliant with the accuracy requirements of CCR §597 by the end of 2015.

Shasta Valley Resource Conservation District
Stream-Aquifer Data Collection Program Development, California, USA
Recognizing that the hydrogeology of the Shasta Valley is both complex and poorly understood, the Shasta Valley Resource Conservation District (RCD), with technical assistance by Davids Engineering, developed the Stream-Aquifer Data Collection Program (Program) described in this document. The RCD's goal was to develop foundational knowledge of the basin's groundwater system and the nature of its interaction with surface water bodies. Mr. Davids was the primary author of the Program, and helped design the different monitoring actions that would lead to improved characterization of stream-aquifer interactions within the Shasta Valley.

Joint Water District Board
Joint Board SCADA System Development and Implementation, California, USA
Mr. Davids led the development and implementation of Supervisory Control and Data Acquisition (SCADA) system for the Joint Water District Board. The SCADA uses MODBUS RTU communication protocols between a central ClearSCADA server and the remote sites. The system is comprised of seven Remote Terminal Units (RTUs): five Acoustic Doppler Flow Metering Stations and two critical flow gaging stations. A user friendly Human Machine Interface (HMI) was developed for use by District staff.

Turlock Irrigation District
Customer Delivery Measurement Plan Development, California, USA
Mr. Davids supported the development and implementation of a Customer Delivery Measurement Plan (Plan) for the Turlock Irrigation District (TID). The goals of the Plan are (1) to provide cost-effective service to customers; (2) generate improved operational records for planning and analysis, and; (3) comply with recently passed California legislation (SBx7-7). As part of this effort, Jeff has designed a range of flow measurement approaches for TID involving permanent flow measurement devices and gate/parcel specific flow ratings. Mr. Davids also participated in the development of customized procedures for gate/parcel specific ratings, in addition to the field testing of acoustic Doppler devices.

South San Joaquin Irrigation District
Flow Measurement Plan Development and Implementation, California, USA

Mr. Davids supported the development and implementation of a Flow Measurement Plan (Plan) for the South San Joaquin Irrigation District (SSJID). The goals of the Plan are (1) to provide cost-effective service to customers; (2) generate improved operational records for planning and analysis, and; (3) comply with recently passed California legislation (SBx7-7). As part of this effort, Jeff has designed a range of flow measurement methodologies and site improvements for SSJID involving standard critical depth structures (e.g. flumes and weirs) and acoustic Doppler flow measurement devices. Mr. Davids also participated in the field testing of acoustic Doppler devices.

Reclamation District No. 108
Flow Measurement Pilot Project, California, USA
Reclamation District No. 108 retained Mr. Davids to pilot test alternative measurement methods that are potentially capable of achieving heightening regulatory standards, including: existing orifice gates, weirs set in precast boxes, and a recently introduced portable acoustic Doppler flow measurement device. The pilot program includes (1) customization of the portable measurement device for District needs, (2) selection and inventory of a test reach, (3) calibration of upstream and downstream measurement devices, (4) development of an automated data transfer process and (5) development of a Water Information System for billing and accounting.

Petra Partners Co., Ltd
Water Supply Plan, Chiang Mai, Thailand
Petra Partners is a privately held consumer goods company located in Chiang Mai, Thailand. The Thai holding company is operated by a team of business men and women from around the world. Petra Partners runs socially responsible businesses focused on improving the livelihood of their partner farmers and returning a profit to their investment body. Mr. Davids developed a water supply plan for one of the company's Biodiesel and coffee production facility in Mae Lai Village. The water supply plan involved (1) assessment of the coffee plantation's water demand, (2) quantification of potential spring yields, (3) pump testing of supply wells and (4) conceptual design of a water storage and distribution system.

Wilsey Ham
Civil Design and Site Improvement Plan Preparation, California, USA
Wilsey Ham is a civil engineering firm offering land development, transportation, surveying and mapping services. As an employee of Wilsey Ham, Mr. Davids designed and prepared plans for various improvement projects using AutoCAD. Project elements included gravity pipeline design, retention pond design, grading and drainage and roadway design.

List of Publications

Publications

- **Davids, J.C.**, Devkota, N., Pandey, A., Prajapati, R., Ertis, B.A., Rutten, M. M., Lyon, S.W., Bogaard, T.A., and van de Giesen, N., 2019. Soda bottle science - citizen science monsoon precipitation monitoring in Nepal, *Frontiers in Earth Science, Hydrosphere*, 7, 46(20).

- **Davids, J.C.**, Rutten, M. M., Pandey, A., Devkota, N., van Oyen, W. D., Prajapati, R., and van de Giesen, N., 2019. *Citizen science flow – an assessment of simple streamflow measurement methods*, *Hydrology and Earth System Sciences*, 23, 1045-1065.

- **Davids, J.C.**, Rutten, M.M., Shah, R.D.T., Shah, D.N., Devkota, N., Izeboud, P., Pandey, A. and van de Giesen, N., 2018. *Quantifying the connections - linkages between land-use and water in the Kathmandu Valley, Nepal*, *Environmental management*, 60(1), pp.12-29.

- **Davids, J.C.**, van de Giesen, N. and Rutten, M., 2017. *Continuity vs. the Crowd - Tradeoffs Between Continuous and Intermittent Citizen Hydrology Streamflow Observations*, *Environmental monitoring and assessment*, 190, pp.1-17.

- **Davids, J.C.** and Mehl, S.W., 2015. *Sustainable capture: Concepts for managing stream-aquifer systems. Groundwater*, 53(6), pp.851-858.

- **Davids, J.C.**, 2011. *Spatial and temporal analysis of stream restoration efforts in depleted aquifer systems*, *Master's thesis, California State University, Chico, USA.*

Abstracts and Conference Proceedings

- **Davids, J.C.**, Pandey, A., Prajapati, R., Devkota, N., Rutten, M.M., van de Giesen, N., 2018. *Scalable Methods for Citizens to Measure Spring Discharge - a Canary in a Coal Mine for Changing Hydrological Systems*, *American Geophysical Union Fall Meeting*, Washington D.C., USA.

- **Davids, J.C.**, Pandey, A., Prajapati, R., Devkota, N., Rutten, M.M., van de Giesen, N., 2018. *A Recipe for Sustainable Water Data Collection: Young Researchers + Citizen Science + Mobile Technology*, *American Geophysical Union Fall Meeting*, Washington D.C., USA.

- Sijapati, S., Khanal, P.R. and **Davids, J.C.**, 2018. *Irrigation Modernization by Enhancing Water Productivity through Water Accounting*, *8th International Committee on Irrigation and Drainage (ICID) Asian Regional Conference (8ARC) - Irrigation in Support of Evergreen Revolution*, Kathmandu, Nepal.

- **Davids, J.C.**, 2017. *Leveraging Citizen Science and Mobile Technology for Sustainable Water Management, CREEW 8th National Symposium on Groundwater Resources in Nepal*, Kathmandu, Nepal.

- **Davids, J.C.**, Rutten, M.M. and van de Giesen, N. 2016. *Can Low Frequency Measurements be Good Enough - A Statistical Assessment of Citizen Hydrology Streamflow Observations*, *American Geophysical Union Fall Meeting*, San Francisco, USA.

- **Davids, J.C.**, 2016. *Citizen Science for Sustainable Water Management, NAMI University Conference on Conservation Practices and Trends in Nepal*, Kathmandu, Nepal.

- **Davids, J.C.**, 2016. *Citizen Hydrology - Tradeoffs between Traditional Continuous Approaches and Temporally Discrete Hydrologic Monitoring*, *European Geophysical Union General Assembly*, Vienna, Austria.

- **Davids, J.C.**, 2016. *Groundwater Management in California - A Century of Scientific and Legal Disconnect and the 2014 Sustainable Groundwater Management Act (SGMA), CREEW 7th National Symposium on Groundwater Resources in Nepal*, Kathmandu, Nepal.

- Mehl, S.W. and **Davids, J.C.**, 2015. *Groundwater Storage vs. Surface Water Storage – Why Sustainability Requires a Different Management Framework*, *American Geophysical Union Fall Meeting*, San Francisco, USA.

- **Davids, J.C.**, Norris, J., Mehl, S.W., 2015. *Tradeoffs Between Continuous and Temporally Discrete Hydrologic Observations, U.S. Committee on Irrigation and Drainage, Sustainable Basin Water Management, Eighth International Conference on Irrigation and Drainage*, Reno, USA.

- **Davids, J.C.** and Mehl, S.W., 2015. *Metrics for Sustainable Groundwater Management, California Water Environmental Monitoring Forum (CWEMF) Annual Meeting*, Sacramento, USA.

- **Davids, J.C.**, Mehl, S.W., 2014. *Sustainable Capture Fractions, Sustainable Capture Thresholds, Capture Efficiency, and Sustainable Groundwater Storage: Concepts for Managing Stream-Aquifer Systems, California Groundwater Resource Association Annual Meeting*, Sacramento, USA.

- van Overloop, P.J., Maestre, J.M. **Davids, J.C.**, Hashemy, S.M., Sadowska, A.D., Camacho, E.F., 2014. *Human in the Loop Control of Dez Main Canal,' U.S. Committee on Irrigation and Drainage, Planning, Operation, and Automation of Irrigation Delivery Systems, USCID Water Management Conference*, Phoenix, USA.

- **Davids, J.C.**, Mehl, S.W. and Davids, G.G., 2014. *Sustainable Capture Fractions, Sustainable Capture Thresholds, Capture Efficiency, and Sustainable Groundwater Storage: Concepts for Managing Stream-Aquifer Systems, U.S. Committee on Irrigation and Drainage, Groundwater Issues and Water Management, USCID Water Management Conference*, Sacramento, USA.

- **Davids, J.C.**, van Overloop, P.J. and Vierstra, M., 2014. *Mobile Monitoring Technologies: The MobileTracker and RemoteTracker, U.S. Committee on Irrigation and Drainage, Groundwater Issues and Water Management, USCID Water Management Conference*, Sacramento, USA.

- **Davids, J.C.** and Davids, G.G., 2013. *Canaries and Coal Mines: Monitoring Key Indicators of a Heterogeneous Aquifer in the Shasta Valley, California Groundwater Resource Association Annual Meeting, California's Groundwater in the Balance*, Sacramento, USA.

- **Davids, J.C.** and Mehl, S.W., 2013. *Defining Capture Thresholds for Sustainable Groundwater Management of Interconnected Stream-Aquifer Systems, International Groundwater Modeling Center, MODFLOW and More 2013*, Boulder, USA.

- **Davids, J.C.**, Ertis, B.A., Bair, L.E. and Earley, S.P., 2013. *"Spot" Measurements of Flow Can Be "Good Enough" for California's Heightening Agricultural Measurement Requirements, U.S. Committee on Irrigation and Drainage, Using 21st Century Technology to Better Manage Irrigation Water Supplies, USCID Water Management Conference*, Phoenix, USA.

- **Davids, J.C.**, Davids, G.G., Bair, L.E. and Miller, E.A., 2012. *Creative, Accurate and Cost-Effective Farm-Gate Delivery Measurement Approaches, U.S. Committee on Irrigation and Drainage, Managing Irrigation Systems in Today's Environment, USCID Water Management Conference*, Reno, USA.

- **Davids, J.C.** and Thiede, M.V., 2012. *Evaluation of Weir Boxes and Orifice Gates for Farm-Gate Delivery Measurement, U.S. Committee on Irrigation and Drainage, Managing Irrigation Systems in Today's Environment, USCID Water Management Conference*, Reno, USA.

- **Davids, J.C.**, Davids, G.G. and Bair, L.E., 2011. *Performance of Existing Submerged Orifice Gates for Farm Delivery Measurement in Reclamation District No. 108 Relative to Pending Measurement Accuracy Standards, U.S. Committee on Irrigation and Drainage, 6th Annual Conference on Irrigation and Drainage*, San Diego, USA.

- **Davids, J.C.**, Davids, G.G. and Loy, K., 2011. *Evaluation of stream-aquifer interactions on the Little Shasta River, CA, Groundwater Resource Association of California, Groundwater-Surface Water Interactions Symposium, California's Scientific and Legal Disconnect*, Sacramento, USA.

- **Davids, J.C.** and Mehl, S.W., 2011. *Stream Restoration and Aquifer Recovery – A Significant Nexus?, Groundwater Resource Association of California, Groundwater-Surface Water Interactions Symposium, California's Scientific and Legal Disconnect*, Sacramento, USA.

- **Davids, J.C.** and Mehl, S.W., 2011. *Analysis of stream restoration efforts in depleted aquifer systems, International Groundwater Modeling Center, MODFLOW and More 2011*, Boulder, USA.

- **Davids, J.C.** and Mehl, S.W., 2010. *The timing, spatial extent and magnitude of fishery benefits obtained from re-watering interconnected stream-aquifer systems depleted by historical diversions and pumping – A case study in the Shasta Valley, CA, American Geophysical Union, Fall Meeting 2010*, San Francisco, USA.

Speaking and Teaching Engagements

- **Davids, J.C.**, 2019. *Introduction to Water Accounting and Water Productivity*, Water Accounting 301-302, Water Resources Consultant for the United Nations Food and Agriculture Organization (UN-FAO), Nay Pyi Taw, Myanmar.

- **Davids, J.C.**, 2019. *Open Data Kit - Powerful Platform for Smartphone Based Data Collection*, Delft University of Technology Short Course, Delft, Netherlands.

- **Davids, J.C.**, 2019. *Citizen Science and Smartphones - Synergy for Geospatial Data Generation, Delft University of Technology GIS and Remote Sensing MSc Course*, Delft, Netherlands.

- **Davids, J.C.**, 2019. *Young Researchers and Data Gaps - Challenges to Opportunities, Rotterdam University of Applied Sciences, Rotterdam*, Netherlands.

- **Davids, J.C.**, 2018. *Introduction to Water Accounting Plus (WA+), Water Accounting 307, Water Resources Consultant for the International Center for Biosaline Agriculture*, Dubai, UAE.

- **Davids, J.C.**, 2018. *Data: 'S4W = Young Researchers + Mobile Technology + Citizen Science, Invited Speaker for WaterMappers' Summer Challenge, Climate-KIC and Delft University of Technology*, Delft, Netherlands.

- **Davids, J.C.**, 2018. *Two Years of SmartPhones4Water-Nepal, Delft University of Technology Water Management Colloquium*, Delft, Netherlands.

- **Davids, J.C.**, 2018. *Linkages Between Land-use and Water in the Kathmandu Valley, Invited Speaker for Citizen Science for Sustainable Water Management Workshop, Tribhuvan University Institute of Engineering - Paschimanchal Campus*, Pokhara, Nepal.

- **Davids, J.C.**, 2018. *SmartPhones4Water-Nepal Citizen Science Flow Campaign, Invited Speaker for Khwopa Engineering College Symposium*, Bhaktapur, Nepal.

- **Davids, J.C.**, 2018. *Introduction to Water Productivity, Water Resources Consultant for the Food and Agriculture Organization of the United Nations (FAO)*, Kabul, Afghanistan.

- **Davids, J.C.**, 2018. *SmartPhones4Water-Nepal: Looking Back and Looking Forward, Invited Speaker for SonTek-A Xylem Brand*, Escondido, USA.

- **Davids, J.C.**, 2017. *Practical Lessons on Water Accounting, Water Resources Consultant for the Food and Agriculture Organization of the United Nations (FAO)*, Kabul, Afghanistan.

- **Davids, J.C.**, 2017. *Basic Training on Water Accounting, Water Resources Consultant for the Food and Agriculture Organization of the United Nations (FAO)*, Kabul, Afghanistan.

- **Davids, J.C.**, 2017. *Leveraging Citizen Science and Mobile Technology for Sustainable Water Management, Invited Speaker for 8th National Symposium on Groundwater Resources in Nepal*, Kathmandu, Nepal.

- **Davids, J.C.**, 2017. *SmartPhones4Water - Leveraging Citizen Science and Mobile Technology for Sustainable Water Management, Hydrologic Sciences Graduate Group Seminar Series, University of California Davis*, Davis, USA.

- **Davids, J.C.**, 2017. *SmartPhones4Water - Leveraging Citizen Science and Mobile Technology for Sustainable Water Management, Engineers Without Borders Keynote Speaker, California State University San Luis Obispo*, San Luis Obispo, USA.

- **Davids, J.C.**, 2016. *Citizen Science for Sustainable Water Management, Invited Speaker for Conservation Practices and Trends in Nepal, NAMI University*, Kathmandu, Nepal.

- **Davids, J.C.**, 2016. *Stream-Aquifer Interactions, Invited Speaker for Freshwater Biodiversity Monitoring Training, Tribhuvan University Central Department of Environmental Science*, Kathmandu, Nepal.

- **Davids, J.C.**, 2016. *Groundwater Management in California - A Century of Scientific and Legal Disconnect and the 2014 Sustainable Groundwater Management Act (SGMA), Invited Speaker for 7th National Symposium on Groundwater Resources in Nepal*, Kathmandu, Nepal.

- **Davids, J.C.**, 2014. *Sacramento Valley Groundwater: A Brief Overview, Invited Speaker for the Water Education Foundation's California Groundwater Tour*, Chico, USA.
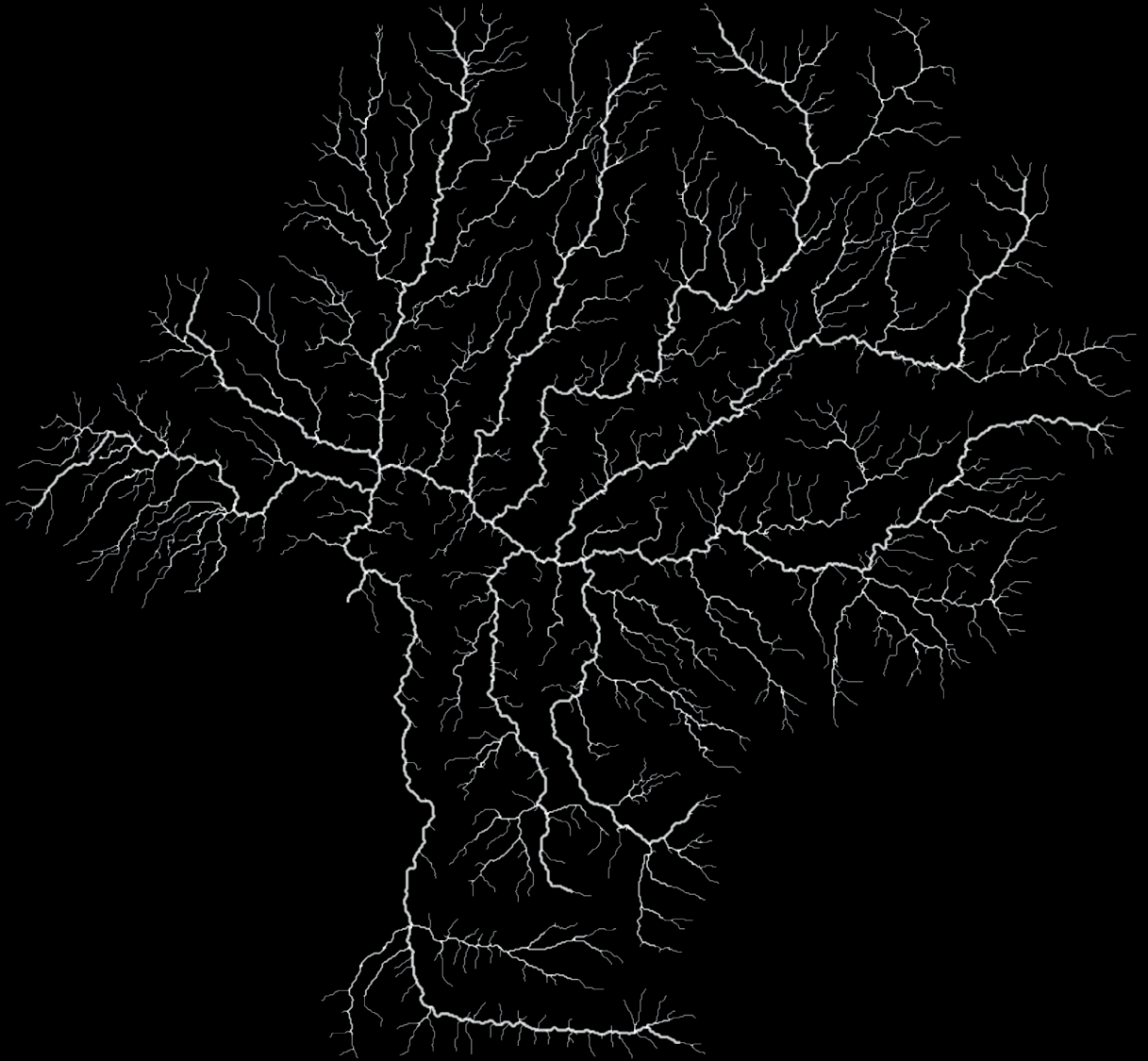
Data gaps as educational opportunities - mobilizing young researchers, citizen scientists, and mobile technology in data and resource scarce areas. This dissertation chronicles these themes through the lessons learned along the fledgling journey of SmartPhones4Water (S4W) and S4W-Nepal, from inception through the first few years of implementation. S4W mobilizes young researchers and citizen scientists with simple field data collection methods, low-cost sensors, and a common mobile data collection platform that can be standardized and scaled.

S4W-Nepal facilitates ongoing monitoring of precipitation, stream and groundwater levels and quality, freshwater biodiversity, and several short-term measurement campaigns focused on monsoon precipitation, land use changes, stone spout flow and quality, streamflow, and stream-aquifer interactions. This research contains both methodological components that investigate novel methods for generating hydrometeorological data (Chapters 2 through 4), along with initial applications of these methods to answer specific science questions (Chapters 5 and 6).