THESIS

ETHIOPIAN SOCIO-HYDROLOGY: GEOGRAPHIES OF DEVELOPMENT AND CHANGE IN THE WATER TOWER OF AFRICA

Submitted by

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ABSTRACT

ETHIOPIAN SOCIO-HYDROLOGY: GEOGRAPHIES OF DEVELOPMENT AND CHANGE IN THE WATER TOWER OF AFRICA

Water access, sanitation, and security remain key foci of international aid and development initiatives. However, the increasing interconnectedness of hydrologic and social systems can cause such initiatives to have unexpected and cascading effects across geographic scales. This presents new challenges for meeting ever-growing demand, as distant and complex socioeconomic and environmental relationships, or “telecouplings,” may significantly influence the outcomes and sustainability of development projects. Predicting future water scenarios thus requires both integrative and basic research into the structure and function of socio-hydrological systems. I explored these emerging concepts in Ethiopia, which is the source of water for much of the Horn of Africa and receives over half of its annual budget from foreign development aid. I analyzed the geography of water in Ethiopia from two perspectives. First, I used examples from the literature to identify water development initiatives in rural and urban settings and at local and national scales. I then situated these initiatives within the telecoupling framework to reveal underlying socio-hydrological relationships. My results indicate that water development is linking Ethiopia’s hydrology with geographically distant communities and markets and creating new and often unexpected flows of people, material, and capital. This is resulting in cross-scale feedbacks among urbanization, geopolitics, and the food-energy-water nexus in Ethiopia. Second, I conducted basic research into alpine wetland dynamics in the Bale Mountains, which provide the only perennial source of water to highland communities and 12 million downstream water users in East Africa. I found that wetlands more than double in extent between dry and wet seasons, and that just 4% of the alpine zone is saturated year-round. I found evidence of a hydrological continuum based on geologic and glacial legacies, which suggests that geology is a principal control on alpine wetland hydrology in Bale. I used this to develop a typology of wetland function, which provides a baseline for future research into climate change impacts and surface-groundwater connectivity.

ACKNOWLEDGEMENTS

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PREFACE

Water is central to many of the key sustainability challenges for the Anthropocene. More than 2 billion people live in water stressed countries, making management and access to safe water one of the key Sustainable Development Goals. However, water can be simultaneously categorized as both a human resource and as part of a natural process, and these aspects must be analyzed in tandem in order to predict future water scenarios and adaptations to climate change. Socio-hydrologic frameworks are particularly important for understanding upstream–downstream dynamics in mountains systems. Moreover, the increasing complexities of the factors driving land change means that system to system relationships can occur over vast distances, creating dynamic, "telecoupled" flows and feedbacks. As a discipline, geography is well-positioned to contribute to this type of integrative research. In addition to the core role of spatial analysis within the discipline, this is in part due to the rapid advances in Geographic Information Systems (GIS) and remote sensing, which enable both the creation and integration of disparate types of data. This thesis applies these emerging theoretical and methodological approaches to understanding the socio-hydrology of Ethiopia. The thesis is organized in two chapters:

Chapter 1 is a synthesis which adapts the telecoupling framework to ask: What water development activities are occurring in Ethiopia, and how are they impacting existing social-hydrological systems? To do this, I compile information on the county's rural, urban, and national-scale water development initiatives and identify the linkages and feedbacks created as a result of their implementation. This work currently exists as a chapter in *Geoscience for the Public Good and Global Development: Toward a Sustainable Future* (Wessell and Greenberg, eds., 2016), published by the Geological Society of America, who also own the copyright. The publisher's manuscript can be found at the following URL: https://pubs.geoscienceworld.org/books/book/688/chapter/3808555/Telecoupling-urbanization-and-the-unintended

Chapter 2 consists of basic research on the hydrology of the Bale Mountains in South-central Ethiopia. Specifically, I use remote sensing and modeling techniques to develop the first seasonal maps of alpine wetland extent. I interpret these results using a hydrogeomorphic approach to develop a typology of wetland function. Finally, I propose a conceptual flow model for the regional hydrologic system, and discuss how this can be used to support integrative research and holistic management. The Appendix is specific to Chapter 2, and provides additional information on data collection, preparation, analysis, and results.

CHAPTER 1

TELECOUPLING, URBANIZATION, AND THE UNINTEDED CONSEQUENCES OF WATER DEVELOPMENT AID IN ETHIOPIA

Introduction

Consequent to the conclusion of the Millennium Development Goals in 2015, the United Nations (UN) set a new 15-year agenda with the introduction of the Sustainable Development Goals (Sachs, 2012). The Sustainable Development Goals differ from their predecessors in that they seek to couple the mission to reduce poverty with the need for global environmental sustainability. This perspective emerges from the recognition that humans are altering the environment in ways that could undermine development gains (Griggs et al., 2013). This is particularly important with regard to water resources, as human demand and political priorities are interwoven throughout the hydrologic cycle (Sternlieb and Laituri, 2009; Swyngedouw, 2009; Hastrup, 2013; Sivapalan et al., 2014).

This intersection presents significant challenges to geoscientists working in water and sanitation development. The failure to properly acknowledge or address the recursive relationship between hydrology and society can result in unexpected and undesirable consequences when an existing “social-hydrological” system is altered through development intervention. There is thus a consensus on the need for and implementation of participatory approaches to water development that address the cultural context of local communities (Bessette, 2006; Laituri, 2011; Kreamer, this volume). However, myriad overlapping factors associated with global markets and urbanization influence the execution and efficacy of development initiatives. As a result, projects that successfully understand local contexts might still overlook key determinants of sustainability that exist at broader scales. The aims of the Sustainable Development Goals therefore demand new frameworks that are able to integrate both the physical and nonphysical aspects of water aid and development across multiple spatial and temporal scales (Seitzinger et al., 2012; Bury et al., 2013).

In meteorology, the term “teleconnections” is defined as “any transmission of a coherent effect beyond the location at which a forcing occurred” (Chase et al., 2006, p. 1). However, the convergence of research in the fields of political ecology, economics, and land change science has led scholars to adapt the “teleconnections” concept to understanding the complex linkages between local and global systems (Meyfroidt et al., 2013). Friis and Nielsen (2014, p. 7) explain:

> “As captured in the prefix ‘tele,’ the teleconnection concept implicitly invokes a sense of geographical and spatial distance between the systems that are interacting to produce the connection. Common for many of the studies currently employing the concept is also an occupation with international trade flows or flows in market information, which are used as analytical proxies for understanding these connections ‘at a distance.’”

In this vein, Seto et al. (2012, p. 1) proposed the concept of urban-land “teleconnections,” which refers to “…the distal flows and connections of people, economic goods and services, and land use change processes that drive and respond to urbanization.” In doing so, they showed that exploration of the dynamic interactions and linkages between urban and nonurban places at local, regional, and global scales can be used to address how multiple or single urban areas can drive change in multiple or single nonurban areas (Seto et al., 2012; Güneralp et al., 2013).

The emerging concept of “telecoupling” (Liu et al., 2013, 2014; Eakin et al., 2014) builds on the idea of teleconnections, but it is less unidirectional and places a greater emphasis on feedbacks between social processes and environmental systems (Friis and Nielsen, 2014). Telecoupling focuses on interactions in one social-ecological system influencing another distant social-ecological system assumed to be disconnected and governed independently (Eakin et al., 2014). A telecoupling perspective accounts for and integrates cross-scale interactions between multiple “sending” and “receiving” systems (Figure 1.1), as well as cascading impacts to intermediate, or “spillover” systems (Liu et al., 2015). This concept has been applied in a number of contexts including global agricultural trade (Liu et al., 2013), land concessions in Southeast Asia (Baird and Fox, 2015), and urban water imports in China (Deines et al., 2016).

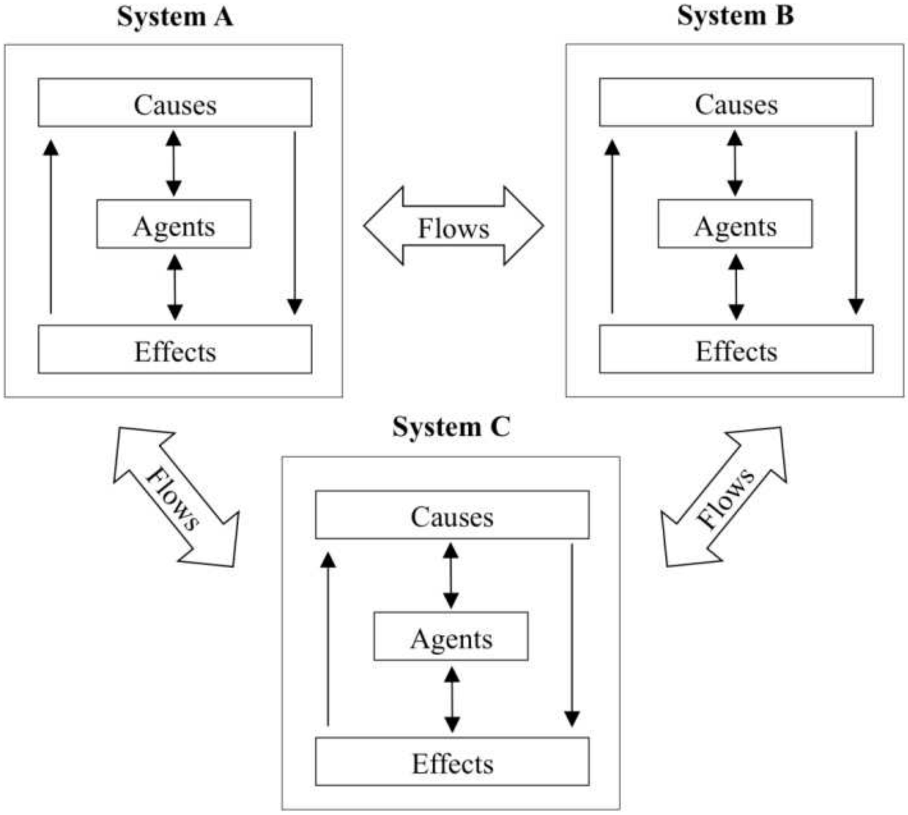

Figure 1.1: Conceptual model of the telecoupling framework as proposed by Liu et al. (2014). Each system is composed of agents, causes, and effects, the interactions of which generate flows between distant systems. Systems can be simultaneously sending, receiving, or spillover systems, depending on the flow in question. Figure is after Liu et al. (2014, their Figure 7.1); Seto, Karen C., and Reenberg, Anette, eds., Rethinking Global Land Use in an Urban Era, figure 7.1, © 2014 Massachusetts Institute of Technology and Frankfurt Institute of Advanced Studies, by permission of The MIT Press.

What might a telecoupling approach reveal about water-related aid and development? How can such a perspective inform the planning and long-term sustainability of water initiatives? I explore these questions through a case study in Ethiopia, a nation experiencing rapid population and environmental change, and a major recipient of international aid. My goal is to operationalize the telecoupling framework for understanding how these activities are connected in unexpected ways. I begin with a brief overview of Ethiopia and its water-related development challenges. Using this as a guide, I summarize current water aid initiatives at the rural, urban, and national settings, and identify key flows of material, people, and capital generated as a result of their implementation. I then situate these systems within the telecoupling framework to reveal cross-scale linkages and feedbacks. Finally, I discuss the strengths, limitations, and potential of the telecoupling framework for researchers and development practitioners working in the international water sector.

Ethiopia case study

Ethiopia is one of the poorest countries in the world, ranked 211 of 228 in gross domestic product (GDP) per capita (CIA, 2015). More than 88% of Ethiopians live in multidimensional poverty, an index that identifies overlapping deprivations in health, education, and standard of living (CIA, 2015; UNDP, 2013). Ethiopia is classified as one of the world's least-developed nations, ranked 173 of 187 by the UN Human Development Index (UNDP, 2013). Agriculture—which is almost entirely rain-fed—is the dominant driver of the country's GDP, accounting for 52% of national income and 80% of employment (Hanjra et al., 2009). However, precipitation (848 mm/yr) is sporadic and unevenly distributed across the country, effectively tying Ethiopia's economy to the rains (Grey and Sadoff, 2007; World Bank, 2015). While nearly 20% of Ethiopia's 96.5 million people resided in cities in 2014 (World Bank, 2015), the nation remains one of the least urbanized nations in the world. Nevertheless, a consistent urban growth rate (5% each year since 2010; World Bank, 2015), in conjunction with limited baseline infrastructure, makes urbanization one of Ethiopia's most pressing development issues.

Government aid agencies, nongovernmental organizations (NGOs), and development banks have invested heavily in Ethiopia since the mid–twentieth century. The country is consistently one of the world's top recipients of international aid, having received more than US$3 billion (~50%–60% of its annual budget) in aid assistance each year since 2010 (World Bank, 2015). Despite water resource development being a major focus of these investments, just 62% of the population has access to improved water sources (UNICEF, 2013). In 2014, more than half (52.1%) of Ethiopians used unimproved sanitation facilities (Beyene et al., 2015). Moreover, access to water is unequally distributed throughout the population, as poorer households tend to use more contaminated sources (Yang et al., 2013), and the urban poor have less access and pay high prices to water vendors in urban centers such as Addis Ababa (Woldemariam and Narsiah, 2014; Kidanie, 2015). These conditions contribute to high morbidity and child mortality rates, as 6.8% of Ethiopian children die before the age of five (UNDP, 2013), and make improving access to potable water and sanitation a top development goal for the Ethiopian government (MoWE, 2015).

Rural water development

Local-scale water, sanitation, and hygiene (WASH) projects in rural settings constitute a major portion of water development initiatives in Ethiopia. Activities range from the implementation of catchment cisterns, hand-dug wells, and bio-sand filters, to more elaborate projects such as machine-drilled wells and the harnessing of spring water for village-scale gravity-fed systems. Many of these initiatives are conducted by NGOs, both Ethiopian and foreign. These range in size and character, from local and regional groups to international coalitions of foreign development and aid organizations (e.g., the Millennium Water Alliance, 2013). In addition to NGOs, Ethiopia's rural water development has had significant investment from government aid agencies and international development banks. The World Bank has played a major role, approving a total US$180 million in financing for rural water development in the past decade, which has seen support from the UN Development Program and the government aid agencies of Japan, Ireland, and Finland (World Bank, 2010).

While monitoring and assessment of these projects are limited, there is evidence that their implementation is creating telecoupled interactions between distant places. A 15-year study of 1,280 households across five rural Ethiopian villages investigated the impacts of a water development initiative that installed village-level taps in communities to the south of the city of Adama (Gibson and Gurmu, 2012). In rural Ethiopia, it is traditionally the case that most daily tasks such as cooking, childcare, and the collection of water fall under the responsibility of women (Gibson and Mace, 2006). The study found that the installation of taps inside or in close proximity to homes enabled women to spend more time and energy on childcare. This additional time for childcare, in conjunction with the reduction of waterborne diseases (especially in young children), resulted in lower child mortality rates and significant population growth.

However, these intended and positive outcomes eventually led to increased competition between young adults for limited education, food, land, and spouses. This brought the population of these subsistence communities beyond their carrying capacity for social services, forcing many young adults to migrate to urban centers in search of employment opportunities (Gibson and Lawson, 2011; Gibson and Gurmu, 2012). Gibson and Gurmu (2012, p. 5) state that "…the arrival of development intervention was associated with increased odds of out-migration for young adults. A young adult with access to taps was three times more likely to migrate to an urban centre compared to a young adult without access to taps in any given season."

Although many migrants were unable to find sufficient opportunities in the city and eventually returned home, the study points to the creation of an unexpected telecoupling driven by water development. Flows of money and technology into the villages played a significant role in rural-urban migration, creating stronger linkages between rural communities and distant cities through outflows of people and labor. It is likely that this process is being repeated in other parts of the country, as the same factors that catalyzed its creation in the Gibson and Gurmu (2012) study (i.e., clean water development, land and resource scarcity) are present throughout rural Ethiopia.

Urban water development

The migration of rural poor to urban areas is currently overwhelming urban services in Ethiopia, including water and electricity (Atnafu et al., 2014). This rapid and unplanned growth also exacerbates existing problems related to inadequate sewage systems and chronic surface-water contamination (Gebremichael et al., 2014). To address these issues, both development banks and NGOs have promoted the installation of communal water points, mobile toilets, and wastewater management systems throughout Addis Ababa and Ethiopia's secondary cities. In 2007, the World Bank launched its Urban Water and Sanitation Services Project, with the goal of improving access to potable water and sanitation in Addis Ababa and the cities of Gonder, Awasa, Jimma, Mek'ele, and Dire Dawa (Figure 1.2). Projects focused on the expansion and increased efficiency of water distribution networks, drilling of wells, construction of communal and household latrines, and training in basic hygiene. The World Bank states that over 1 million people were helped as a result of this project. In 2012, the World Bank approved a US$150 million additional loan for the continuation of such initiatives (World Bank, 2012).

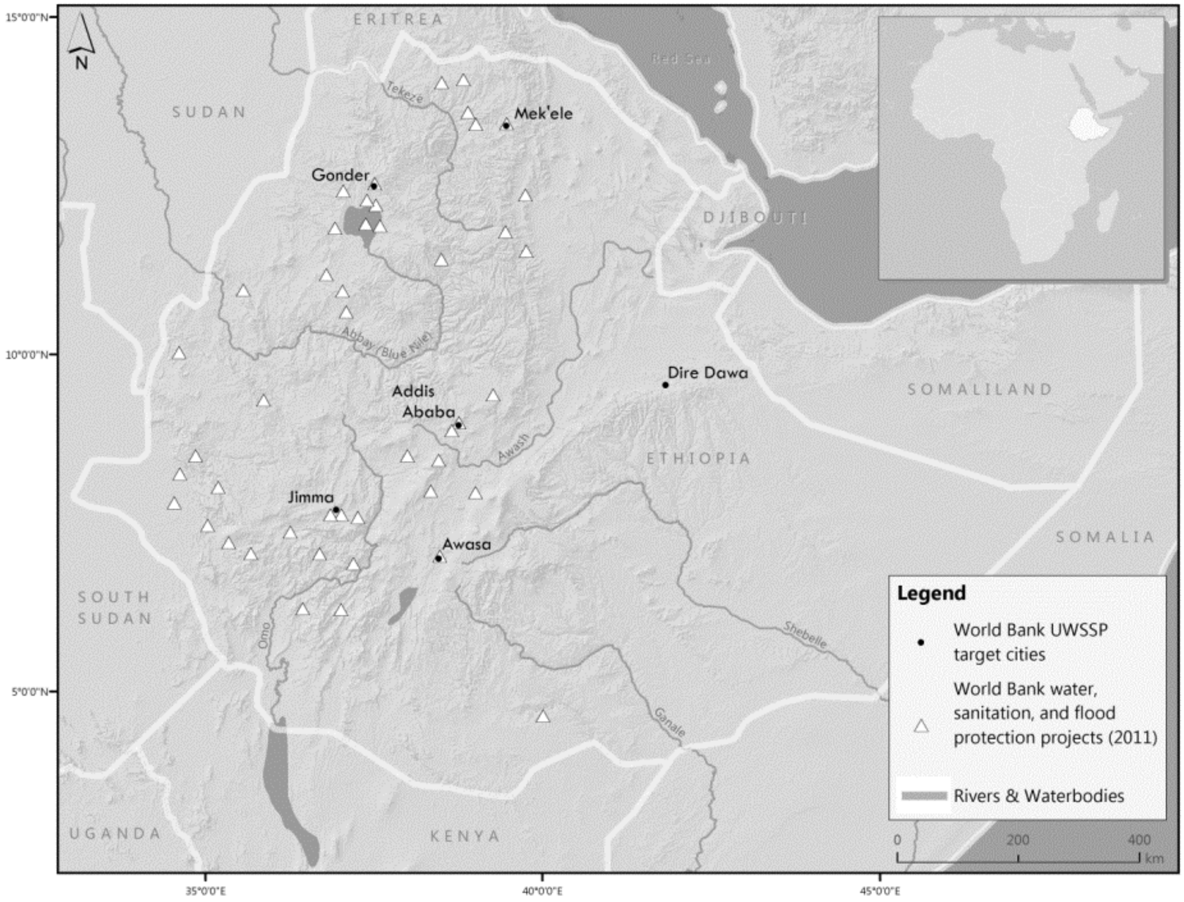

Figure 1.2: Map of Ethiopia and the surrounding region. Locations of World Bank-funded water projects (2011) are shown, as are cities targeted by the World Bank Urban Water and Sanitation Services Project (UWSSP). Topography, country boundaries, and selected transnational rivers are included for reference. Map created by the authors. Data sources: World Bank Mapping for Results Initiative (last updated 2011), Natural Earth, The National Aeronautics and Space Administration, and the Consortium for Spatial Information–Shuttle Radar Topography Mission (SRTM) v.4.

The impacts of these activities are complex and can have cascading effects on both nearby and distant ecosystems and communities. For example, Addis Ababa relies solely on upstream reservoirs and wells in the surrounding rural areas for its water supply. In 2009, the city used the entire available volume (210,000 m3 d–1), with demands 40%–50% beyond the supply (Van Rooijen and Taddesse, 2009). However, the pace and scale of development to upgrade facilities in the city led to an increase in overall water use and wastewater volumes, threatening the quantity and quality of water for the more than 400 ha of surrounding and downstream peri-urban agriculture that relies on urban drainage for irrigation (Van Rooijen and Taddesse, 2009; Van Rooijen et al., 2010). This not only impacts farmers' livelihoods, but could in turn impact food security and drive up imports, as 30% of the city's vegetables and 60%–70% of its milk are provided by urban and peri-urban agriculture (CSA, 2007; Duressa, 2007; Gebremichael et al., 2014).

These downstream effects are mirrored by the creation of new linkages with upstream rural areas. To meet the demands of the capital city, two additional dams have been planned in the nearby Abbay Basin, which would increase water supply to the city from 0.2 million m^3 d^{-1} to 0.8 million m^3 d^{-1} by 2016 (Van Rooijen and Taddesse, 2009). Developments and land-use change in upstream catchments can alter runoff and erosion characteristics, and may threaten water quality and reliability of reservoir inflows (Van Rooijen and Taddesse, 2009). This would result in additional water supply and quality issues for urban and peri-urban farmers. These cascading upstream-downstream impacts demonstrate the telecoupling results of water development aid on Ethiopia's growing cities, peri-urban farmers, and neighboring rural catchments.

National water development

The mounting demand for electricity in Ethiopia's urban centers—in conjunction with the call for additional water storage—is currently driving the construction of major hydroelectric dams across the country. The nation has the second greatest hydropower potential in Africa (the Democratic Republic of Congo has the first; WEC, 2010), of which only 4% has been developed (IJHD, 2013; Verhoeven, 2013). Ethiopia currently has 11 large dams in operation, with three more under construction (IJHD, 2013). These activities are strongly supported by the Ethiopian government, which is emerging as the dominant geopolitical power in East Africa, and which considers water resource development as vital to achieving this goal (Verhoeven, 2013; Gebreluel, 2014).

The dams along the Omo River comprise one of Ethiopia's most significant hydropower efforts. The Gibe I was commissioned in 2004, and the Gibe II was commissioned in 2010. Both dams received funds from the World Bank, European Investment Bank, and the Italian government (CRBM and CEE, 2008). The much larger Gibe III dam is currently under construction and entirely funded by the Ethiopian government. Another hydropower project, the Grand Ethiopian Renaissance Dam, is scheduled for completion in 2017 (Stokstad, 2016) and straddles a section of the Blue Nile near the Ethiopia-Sudan border. The dam has a proposed output of 6000 megawatts (MW), making it the largest hydropower plant in Africa. The estimated final cost of US$4.8 billion is ~60% of the country's annual budget. The Ethiopian government is funding its construction through taxes and the sale of government bonds to its citizens and foreign governments such as Djibouti, which recently purchased US$1 million in bonds (International Rivers, 2013a). Political conflict with downstream Egypt and Sudan has prevented international development banks from investing in the dams. However, Ethiopian, Egyptian, and Sudanese experts appear to be nearing a cooperative agreement on the project (allAfrica, 2013b; MacDiarmid, 2015; Stokstad, 2016). Such an agreement would present lending opportunities for foreign development organizations such as the World Bank.

The flow of money, material, and technology from foreign sources to dam Ethiopia's rivers is creating a host of telecoupling effects. The reservoir created by the Gibe I displaced thousands of people (Yewhalaw et al., 2009), and the construction of the Gibe III is expected to have devastating impacts on downstream ecosystems and the livelihoods of ~200,000 subsistence farmers who rely on seasonal flooding of the Omo's banks (Mousseau and Moore, 2013). The Grand Ethiopian Renaissance Dam is estimated to displace 20,000 people—mostly Gumuz, an ethnic minority—to the edges of the resultant reservoir (Veilleux, 2014). These outcomes will inevitably lead to new distal flows of people as displaced farmers migrate or are relocated to villages and the nation's cities (Ezra and Kiros, 2001; Gebeyehu, 2014).

Ethiopia's dam development also has cascading impacts on regional and global agricultural trade systems. The subsequent availability of irrigation water incentivizes the leasing of "unused" land to grow export crops for profit. This large-scale "land grabbing" is a highly controversial practice in which cross-border land deals are carried out between transnational corporations or initiated by foreign governments, most often for the production of food for export to finance-rich, resource-poor countries (Zoomers, 2010). These often involve the loss of livelihood and forced resettlement of people who lived on the land prior to its concession. Ethiopia has become known as a hotspot for land grabs (Lavers, 2012; International Rivers, 2013b), which are facilitated through the dual forces of the Ethiopian land tenure system, which does not allow for land ownership, and the desire of the national government to increase its influence over the rural peripheries of the country (Verhoeven, 2013). The Omo dams are an example of this practice; in 2011, Ethiopia's prime minister announced plans to take more than 150,000 ha of the Omo Valley for state-owned sugarcane plantations and reserve an additional 200,000 ha for private Ethiopian and foreign firms (Hurd, 2013). This represents a sociopolitical telecoupling whereby the demands of the global market drive the creation of new linkages among foreign companies, the central government in Addis Ababa, and rural livelihood systems.

The electricity generated from Ethiopia's hydropower plants is creating additional domestic and international flows. The Ethiopian government views Ethiopia as the "powerhouse of Africa" and plans to export electricity to neighboring countries in the coming decades (allAfrica, 2013a). In 2012, the World Bank approved a US$684 million loan to finance the construction of 1045 km of 500 kilovolt (kV) transmission lines to export electricity from the Gibe hydropower stations to Kenya (International Rivers, 2012; WorldBank, 2013). The World Bank and the African Development Bank have also provided loans to export hydropower into Djibouti and Sudan (World Bank, 2007; allAfrica, 2008), which will be used to power those countries' major urban areas (Figure 1.3). These activities demonstrate the role of development in the creation of new linkages between regional hydrologic systems and East Africa's growing urban economies. The outflows of electricity meet demands of domestic and foreign cities, while counterflows of capital to Addis Ababa consolidate geopolitical power with the present Ethiopian government (Abbink, 2012; Verhoeven, 2013).

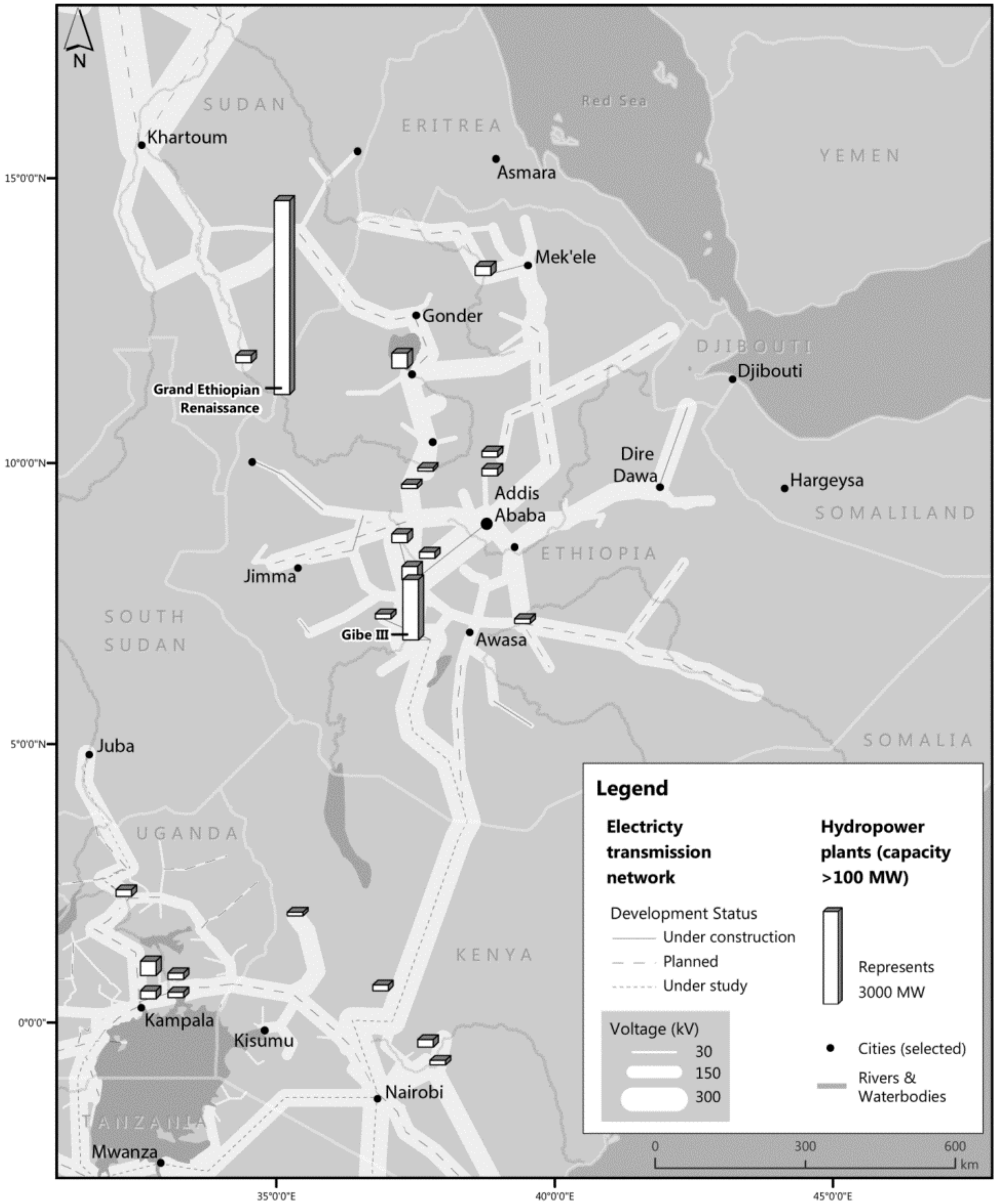

Figure 1.3: Map showing coupling of distant urban centers through Ethiopia's hydropower development. Locations and capacities of major hydropower plants are overlaid by the region's electricity transmission network. Existing lines are symbolized solely by their voltage in kilovolts (kV); lines currently under development also include indication of their status. Selected cities and hydropower plants are also labeled. Map created by the authors. Data sources: African Development Bank Group (2015), Natural Earth.

Summary and synthesis

Situating the identified linkages within the telecoupling framework can aid in interpretation and reveal underlying relationships. Liu et al. (2013) classified telecoupling components into systems (sending, receiving, spillover), flows (commodities, water, people, influence), agents (governments, organizations, individuals), drivers ("causes"), and outcomes ("effects"). Table 1.1 shows this approach applied to the Ethiopia case study.

Table 1.1: Components of telecoupled systems of water development aid in Ethiopia.

Systems	Sending	US/UN international aid and development sector NGOs
	Receiving	Rural/traditional livelihood systems Urban water and sanitation services Hydropower production systems
	Spillover	Peri-urban agriculture Large land concessions/Land grabbing Traditional livelihood systems
Flows	Material	Water Crops/goods Electricity
	Socio-cultural	People Capital Political/cultural influence Technology
Agents	Organizations (Government)	Foreign aid agencies Ethiopian ministries Development banks
	Organizations (Non-government)	Companies (Ethiopian and foreign) Development NGOs Faith-based organizations
	Individuals	Farmers/pastoralists Urban poor Economists Politicians Geoscientists/Development Practitioners

Drivers (Causes)	Economic	Push and pull of global markets Need for increased water/food security
	Socio-cultural	Humanitarian goals Ethiopian government's consolidation of political power Ethiopians' desire to modernize
Outcomes (Effects)	Intended (positive)	Economic development Access to improved water Expansion of Ethiopia's regional and international geopolitical influence Lower infant mortality Competition for land/resources
	Unintended (negative)	Rural-urban/rural-rural migration Displacement Land grabbing Loss of traditional culture and subsistence livelihoods

The classification presented in Table 1.1 distills and organizes the vast amount of information comprising water development aid in Ethiopia. This facilitates the consideration of social, economic, and natural processes that are rarely juxtaposed. However, the tabular structure of the format highlights neither the connectedness nor the complexities inherent in multi-scale, multi-system analyses. For example, I chose to list foreign development organizations as sending systems, and rural, urban, and national systems as receiving systems. Yet each of these systems can simultaneously function as sending, receiving, and/or spillover, depending on the flow and scale in question. Investments flow into these from abroad, but in other cases, they are the origins of material and socio-cultural flows. The same is true for the systems we classified as spillover. To mitigate these classification issues, one can also operationalize the box and arrow model of the telecoupling framework proposed by Liu et al. (2014) and previously presented in Figure 1.1. By populating the model with key components listed in Table 1.1, it is possible to represent the bidirectionality, simultaneity, and feedbacks among the systems and their components (Figure 1.4).

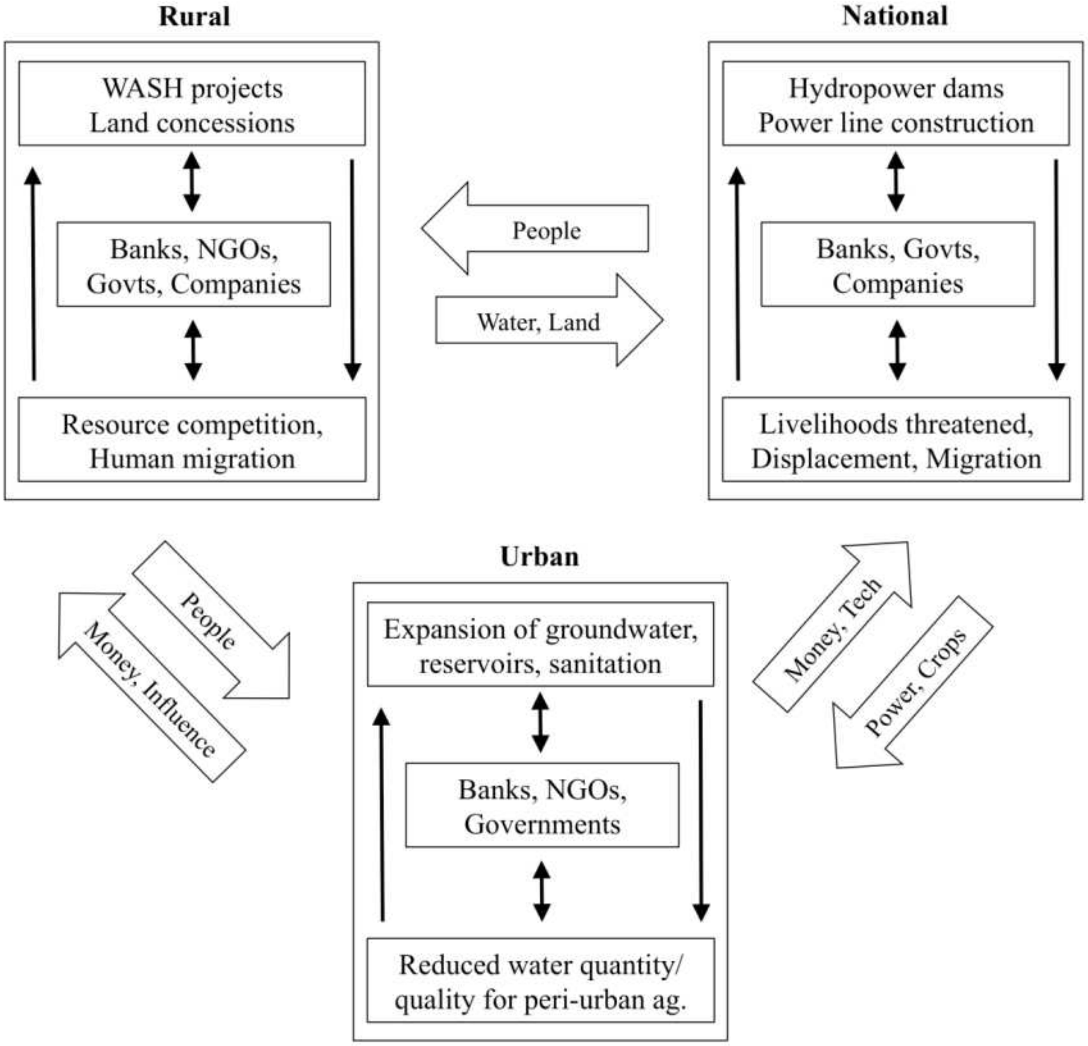

Figure 1.4: **Conceptual model of the telecoupling related to water aid development in Ethiopia. Figure is modified from Liu et al. (2014), previously described in Figure 1.1. Rural, urban, and national systems are represented by the three large rectangles. Each system contains three smaller rectangles: agents (middle), causes (top), and effects (bottom), the interactions of which generate cross-scale flows to other systems. Key flows and their directionality are represented by large block arrows. For interpretability, not all systems, components, or interactions are represented. Flows from foreign development groups are excluded, as are individual agents and communities that may be involved. However, it may be desirable and beneficial to include these components in practice. WASH—water, sanitation, and hygiene; NGO—nongovernmental organization.**

This can significantly facilitate interpretation and analysis. For example, water access and sanitation projects carried out by development organizations in rural villages can bring subsistence communities to carrying capacity and drive out-migration to urban centers (Figure 1.4). As municipal services in urban areas cope with the resulting pressures and unplanned growth, development organizations work to expand water supply and sanitation systems. The subsequent reduction in downstream flows and increase in wastewater contamination threaten the viability of irrigation-dependent peri-urban agriculture. This may ultimately lead cities to invest in and increase food imports from distant regions. The increased demand for water and electricity in urban centers drives the construction of hydropower dams along the nation's rivers. Hydropower is used domestically and exported across borders (via the power lines financed by development banks), coupling distant cities such as Nairobi, Khartoum, and Djibouti to the "powerhouse of Africa" and the geopolitical ambitions of Ethiopia's present government. The dams' reduction in downstream flows displaces thousands of rural people in both Ethiopia and downstream countries (e.g., the Omo Valley and Lake Turkana, Kenya), while upstream communities are displaced by newly created reservoirs. The availability of irrigation water from these reservoirs—in conjunction with global economies and the urban demand for crops—incentivizes foreign and domestic land grabs in rural areas. The thousands of people displaced or forcibly removed as a result of these activities increase competition for scarce land and resources in rural areas. This eventually leads to additional rural-urban migration in search of new livelihoods. This process creates a feedback loop representative of the food-energy-water nexus in East Africa (Laituri, 2014): Dams result in greater economic growth, which in turn drives urbanization, which demands more irrigated agriculture and hydropower, which causes additional rural-urban migration. This contributes to observed inequalities between the poor and wealthy, as well as the disproportionate influence of urban decision makers over rural populations.

Discussion and conclusions

The telecoupling concept is ambitious in the scope of information it integrates. Classifying systems into individual components helps to control for complexity, as does bounding analyses by geographic scale and setting. However, this rigidity may not be appropriate in all situations, and more flexible approaches to operationalizing the framework have been successfully demonstrated by others (Eakin et al., 2014; Baird and Fox, 2015). While a comprehensive understanding of all components is unreasonable and perhaps impossible at certain scales (Challies et al., 2014), thinking about social-hydrological telecoupling can be a useful heuristic device for geoscientists in both planning and implementation of water development aid. The framework fosters an acknowledgment that development actions are not isolated. It recognizes that geoscientists themselves form new linkages and flows, which may lead to cascading effects within and beyond the areas in which they operate. This perspective contributes to the sustainability of water development projects because it encourages cross-scale collaboration among organizations, villages, and governments that might otherwise be overlooked. Practitioners seeking to operationalize the framework in the field could use the structure provided by Table 1.1 and Figure 1.4 as a basis for participatory sessions with communities to better understand the social-hydrological processes at work in a potential project location. This brings the knowledge and concerns of local people to the forefront and—if combined with analysis and review of the existing literature—could identify potential linkages and feedbacks among distal communities and systems.

I found the telecoupling framework to be a useful entry point to understanding water, urbanization, and development in Ethiopia. Future work should explore the utility of novel data collection, analysis, and modeling techniques. Network analysis and agent-based modeling have significant potential for giving predictive power to conceptual models of telecoupled systems (Seto et al., 2012; Liu et al., 2013). The former have been successfully applied to analysis of the global virtual water trade (Konar et al., 2011) and could be used to derive quantitative measures of connectivity among systems of water aid and development. These techniques are becoming increasingly accessible and underscore the need for additional geophysical, economic, and cultural data related to social-hydrological systems. This would enable pairing of development-based field methods like participatory influence network mapping (Schiffer and Hauck, 2010) with geographic information systems and remote sensing data, leading to the development of spatially explicit models of telecoupling. This combination of high-tech and low-tech analyses would enable policy makers, human rights groups, and NGOs to better plan for and react to future water scenarios.

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CHAPTER 2

MAPPING SEASONAL EXTENT AND FUNCTION OF TROPICAL ALPINE WETLANDS IN THE BALE MOUNTAINS, ETHIOPIA

Introduction

Humid tropical alpine environments provide critical environmental services at local, regional, and global scales (Célleri and Feyen, 2009; Buytaert et al., 2011). Distributed across the Andes of South America, the East African alpine belt, and the highlands of Papua New Guinea, these areas support extremely high rates of biodiversity, endemism, and carbon sequestration (Buytaert et al., 2011). They also provide important water resources for mountain ecosystems and communities through precipitation stored in glaciers, wetlands, and soils (Kaltenborn et al., 2010; Buytaert et al., 2011; Mosquera et al., 2015). As most tropical alpine regions do not possess persistent snowpack throughout the year, this hydrologic attenuation makes them "water towers" for large downstream populations and ecosystems, often in arid and semi-arid environments (Buytaert et al., 2006; Viviroli et al., 2007; Buytaert et al., 2011; Mills-Novoa et al., 2017). The resulting mutual dependence makes mountain water towers sites where upstream and downstream actions are intimately connected (Mills-Novoa et al., 2017), entangling hydrologic process with sociocultural and political issues (Zimmerer et al., 2017).

Alpine wetlands represent key components of these coupled systems. Filtration through wetland vegetation and soils regulates the movement of water from the headwaters to lower elevations (Fonkén, 2014; Mosquera et al., 2015). This helps to prevent erosion and set the biogeochemical state for downstream flows (Buytaert et al., 2011). Mountain wetlands also provide drinking water, building materials, and have cultural significance for many highland communities, while providing crucial water sources for livestock and habitat for wildlife during dry months (Bragg, 2015). The vast majority of research on tropical alpine hydrology has focused on Andean wetlands (Buytaert et al., 2006; Carey et al., 2014; Borrelli et al., 2015; Buytaert and Beven, 2011; Mosquera et al., 2015; Polk et al., 2017). By contrast, the mountain wetlands of Africa are poorly studied and lack even baseline inventories of their distribution (Deil et al., 2016; Grundling and Grootjans, 2016).

The Bale Mountains of south-central Ethiopia contain the largest contiguous area of alpine habitat in Africa (commonly referred to as "Afroalpine"). An internationally recognized biodiversity hotspot, the region supports many mountain communities and a host of endemic and endangered wildlife found nowhere else in the world (Kidane et al., 2012; Evangelista et al., 2012). The geography of the region results in large amounts of orographic precipitation that falls as rain and snow across its alpine plateau. This water collects in numerous alpine lakes and wetlands (Figure 2.1), which are thought to perform a range of functions including regulation of water quality, nutrient cycling, groundwater recharge, and discharge timing throughout the dry season (Frankfurt Zoological Society, 2007). The area also serves as the headwaters of five major rivers that flow across the arid lowlands of eastern Ethiopia and into Somalia and northern Kenya . Together, these comprise the Wabe Shebelle River basin, which is the only perennial source of water for approximately 12 million downstream users. This water is used for irrigation, livestock, industry, and human consumption, as well as vast ecosystems and wildlife habitat (Hillman, 1988; Nelson, 2011).

Figure 2.1: Afroalpine habitat of the Bale Mountains, Ethiopia. Photograph by the author, May 2014.

Preservation of this hydrologic system was a primary reason for the establishment of Bale Mountains National Park (BMNP) in 1969 (Nelson, 2011). However, government villagization programs in the 1960s and 1970s have since contributed to increasing settlement and cultivation, and in 2003 it was estimated that 40,000 people live within the park boundaries (Frankfurt Zoological Society, 2007). The park also saw the construction of a hydro-electric dam and road, which led to significant increases in travel and tourism (Hillman, 1988). During the same time period, the development of large-scale mechanized agriculture in the surrounding region has forced thousands of lowland pastoralists into the mountains, and grazing now occurs year-round on the Bale plateau. Competition for land and natural resources has resulted in past conflicts between local people and park management, which considers human activities the single most important cross-cutting issue for the BMNP (Nelson, 2011). There is concern that overgrazing of the alpine vegetation will increase erosion and impact nutrient loading, biogeochemical states, and connectivity of water and sediment (Frankfurt Zoological Society, 2007; Dullo et al., 2015). However, little work exists on the hydrogeology of the Bale Mountains (Kebede, 2013). Although wetland seasonal dynamics and function have been a top research priority of management by the national park for over a decade (Frankfurt Zoological Society, 2007), I am not aware of any studies that address this.

In this study, I conduct basic research on the alpine wetland hydrology in the Bale Mountains. I begin with an overview of the natural and human history of the plateau and surrounding region. Combining field data, remote sensing, and machine learning techniques, I map the extent of perennial and ephemeral wetlands across the alpine zone. I interpret these results using field observations, ancillary data, and the literature to develop a typology of wetland function. For wetland studies to be useful for conservation or management purposes, it is critical to determine the origin of the water supply and whether it is hydrologically connected to other wetlands or water bodies (Fonkén, 2014). I therefore propose a conceptual flow model of the hydrologic system and discuss its implications for future research and management.

Methods

Study area

The Bale Mountains (Figure 2.2) are the remnants of a massive shield volcano, comprised of horizontally bedded basalt and trachytic lava flows from the late Neogene period (Berhe et al., 1987; Hillman, 1988). This created a large plateau that was separated from the western highlands of Ethiopia by the formation of the Rift Valley (Hillman, 1988). The uppermost elevations of the plateau form a low-relief surface interspersed with numerous volcanic plugs and cinder cones. Many of these peaks are the product of recent eruptions, such as Mt. Batu, which has been dated at just 2.5 million years old (Williams, 2016). The dominant peaks occur in the central Sanetti region, with the highest summit being Tullu Deemtu (4,389 m asl).

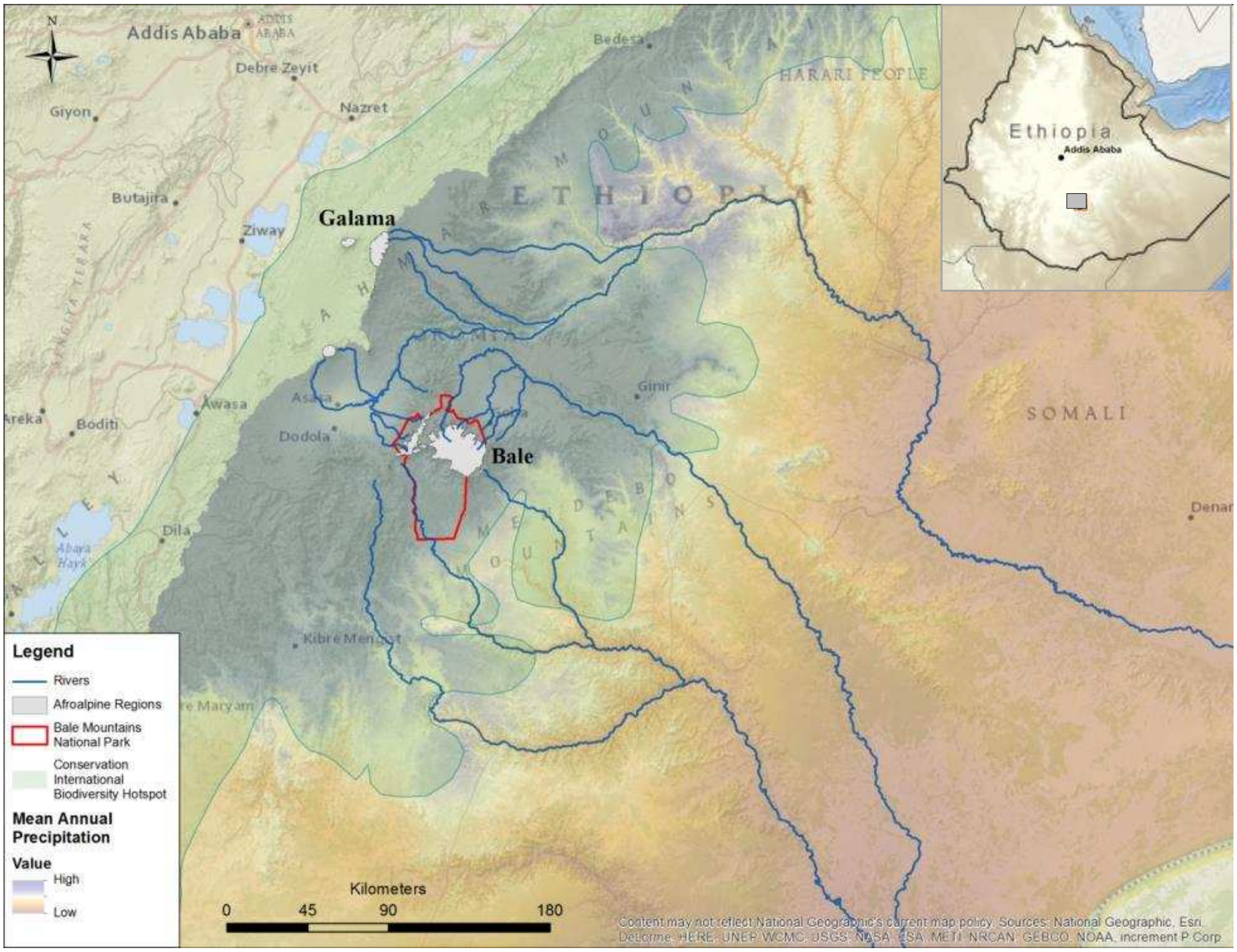

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Figure 2.2. Map of the south-central Ethiopian highlands. Conservation International biodiversity hotspot, Bale Mountains National Park boundary, major rivers, and precipitation of the Eastern lowlands included for reference. Inset shows the topography of the Bale region and the extent of the Afroalpine study area.

Methods

The climate on the plateau is unimodal (8 month wet season). This transitions to a bi-modal climate in lower elevations, with a short wet season from March to May and a longer wet season from July to October (Buytaert et al., 2011; Hillman, 1988). Rainfall is high (approx.

1,150 mm/year) on the northern slopes, but decreases as one moves south toward the central plateau (Hillman, 1988). Moisture increases again at the southern escarpment, where regular clouds and mists support the Horenna forest (Hillman, 1988; Woldu et al., 1989). Like many tropical mountains, the Bale Mountains show clear ecological zonation based on elevation (Woldu et al., 1989). The highest of these, the Afroalpine zone, comprises all areas above 3,500 m asl. Temperature records show considerable diurnal variability, particularly in the highest altitudes during the dry season (Shimelis, 2011). Variations between day and night can be more extreme than variations between seasons, and ground freezing does occur in diurnal freeze-thaw patterns during the colder months above 3600 m (Grab, 2002).

Snow is common across the plateau, and elevations above 4,000 m asl can form packs that persist for days (Miehe and Miehe, 1994). Paleoclimatic and geomorphic studies show evidence of at least two glaciations, the most recent occurring as little as 2,000 years ago (Bale Mountains National Park, 2017). Glaciation took place in two forms: a 30 km^2 ice cap centered over the summit of Tullu Deemtu, and a number of valley glaciers descending down the northern slopes of the plateau (Osmaston et al., 2005). In total 180 km^2 are estimated to have been ice-covered, making the Bale Mountains the most extensively glaciated mountains in Africa during the last glacial maximum (Messerli et al., 1977).

Evidence from pollen and peat records shows a shift in the climate at the end of the Pleistocene which initiated the retreat of these glaciers (Mohammed and Bonnefille, 1998). However, their legacy remains in a variety of glacial and periglacial landforms across the plateau (Grab, 2002; Osmaston et al., 2005). To the south of Tullu Deemtu, patterned ground including stone circles and sorted stone stripes show visible evidence of frost heave cycles. Nearby, disrupted drainage patterns form a series of channels that run north-south along the plateau. To the east of the central summits, kettles created during glacier recession host numerous lakes and wetlands. These form in depressions just 1-2 meters lower than the average surrounding elevation (Eggermont et al., 2011). The small size, shallow depth, and dependence on orographic rainfall of these wetlands contributes to their high inter- and intra-annual variability in moisture and extent (Eggermont et al., 2011). Riparian areas and marshes form in the valleys that descend north and northwest from the central plateau, while deep wetlands occur along parts of the southern escarpment (Tallents and Macdonald, 2011). The lakes, wetlands, rivers and springs ("horas" in the local Oromifa language) comprise the principle components of the hydrologic system of the Bale Mountains (Frankfurt Zoological Society, 2007). Vegetation in moist regions includes the sedge *Carex monostachya*, which occurs as tussocks in the wettest areas (Dullo et al., 2015) as well as wetland species such as *Haplocarpha rueppellii* and *Ranunculus sp*. Cushion plants, *Eriocaulon schimperi* are also abundant (Dullo et al., 2015). Upland Afroalpine vegetation is characterized by grasses, shrubs, *Lobelia rhynchopetalum*, and the occasional isolated *Erica* shrub.

Pastoralists and their livestock have inhabited the Bale region for centuries(Huntingford, 1955; Haberland et al., 1963; Flintan et al., 2008), and it is possible that glacial meltwater provided a reliable source of water for prehistoric people and wildlife at the onset of the Holocene. At an unknown date, people began using fire to improve pasture and extend the Afroalpine habitat (Johansson, 2013). Burning of the ericaceous band (3,000 - 3,500 m asl) is thought to have been practiced for at least 5,000 years and continues today, despite being outlawed since the 1970s (Miehe and Miehe, 1994). It is possible that regular anthropogenic fire is the reason the Afroalpine habitat has not decreased in Bale as would be expected with rising temperatures since the last glacial maximum. Historically, most pastoralists in Bale have managed their livestock under the customary Godantu system. Godantu is a vertical transhumance system involving seasonal journeys to the plateau from the surrounding region to allow animals to graze the Afroalpine vegetation, drink at mineral springs (hora), and access salt (licks) (Flintan et al., 2008). In addition to being key resources during the wet and dry seasons, these springs—as well as those that occur in the Harenna forest to the south—hold significant cultural and spiritual meaning to local people (Chiodi and Pinard, 2011). Peak livestock numbers occur in the Afroalpine in the wetter months, from April to August, when livestock are moved from lower pastures where agricultural crops are being grown (Flintan et al., 2008).

Workflow overview

Wetlands comprise a mixture of water, soil, and plant communities with spectral characteristics that tend to vary considerably over space and time. As a result, they are "moving targets" from a remote sensing perspective, representing more of a moisture regime than a land cover class (Gallant, 2015). These issues are further complicated in Bale, which experiences near-constant cloud cover during the wet seasons. Even in the rare event of a cloud-free image, the saturated surface of the plateau makes accurate spectral separation of wetland versus upland pixels extremely difficult. To address these issues, I used data collected in the dry season to develop a correlative model of wetland distribution. This approach involves training a classifier to predict the likelihood of a response variable given a set of predictor variables and sample data. It enables the integration of variables from a variety of data sources and allows the user to focus on a single class of interest. Specifically, I adapted a presence-background technique designed for mapping wetlands in heterogeneous landscapes of the Rocky Mountains (Chignell et al., 2017). Presence-background modeling estimates the relative likelihood of occurrence of a given response by comparing the environmental characteristics at sites where the response is known to exist (presence) with those throughout the study region (background) (Guillera-Arroita et al., 2015). The technique is useful for modeling rare classes using limited presence data that is dependable but not perfectly random (Pearce and Boyce, 2006). This is accomplished through the use of pseudo-absence points (Barbet-Massin et al., 2012) which are created by sampling the "background" of the modeling space. The output is a raster map showing the relative likelihood of occurrence of the response variable across the landscape. Because it is continuous, this output has been shown to accurately depict the natural moisture gradient of wetland and riparian systems (Maxwell et al., 2016; Chignell et al., 2017). Moreover, discrete maps can be created simply by applying a threshold. I used the random forests technique (Breiman, 2001) for all modeling. Random forests is a widely used ensemble classifier that generates numerous regression trees that are then aggregated to produce a more accurate classification. It is well suited for presence-background modeling with small sample sizes (Williams et al., 2009) and high dimensional, multi-source data sets (Belgiu and Drăguţ, 2016; Chan et al., 2012). The modeling procedure is best summarized in three phases: model inputs, model development, and model evaluation (Figure 2.3). It is an iterative process in which an initial model is run, its outputs are evaluated and interpreted, and variables are added or removed for a subsequent model run. This helps to refine the model by enabling multiple variables to be tested before a final selection is made.

The final step in the workflow involved a hydrogeomorphic characterization and the development of a conceptual flow model (Figure 2.3). Historically, vegetation was used as the primary way to distinguish different types of wetlands (Cowardin et al., 1979). However, in the 1990s there was a recognition that wetland plant communities are largely determined by abiotic factors such as hydrologic regime and geomorphic setting, and that these characteristics relate not only to the distribution of wetlands, but also to their function on the landscape (Brinson, 1993a, 1993b). This concept led to the development of the hydrogeomorphic classification system (Brinson, 1993a; Smith et al., 1995), which focuses on describing wetlands by their water source, hydrodynamics, and geomorphic setting. In this way the HGM seeks to identify “reference” wetlands that are representative of a particular function and can thus be monitored for signs of change. The HGM approach has since been adapted to develop wetland classifications at local, regional, and national scales (Nielsen et al., 2005; Brooks et al., 2011; Van Deventer et al., 2014). It has also led to the development of the Landscape Position, Landform, Water Flow Path, and Waterbody (LLWW) system (Tiner, 2014) which operationalizes the HGM concept for creating inventories of wetland function using GIS and remote sensing. To apply this approach to the Bale Mountains, I adapted HGM and LLWW terminology to describe the wetlands predicted by the final distribution model. I used field observations, ancillary spatial data, and the literature to identify a suite of hydrogeomorphic characteristics and develop a typology of wetland function. I then used this typology to create a conceptual flow model for the overarching hydrologic system.

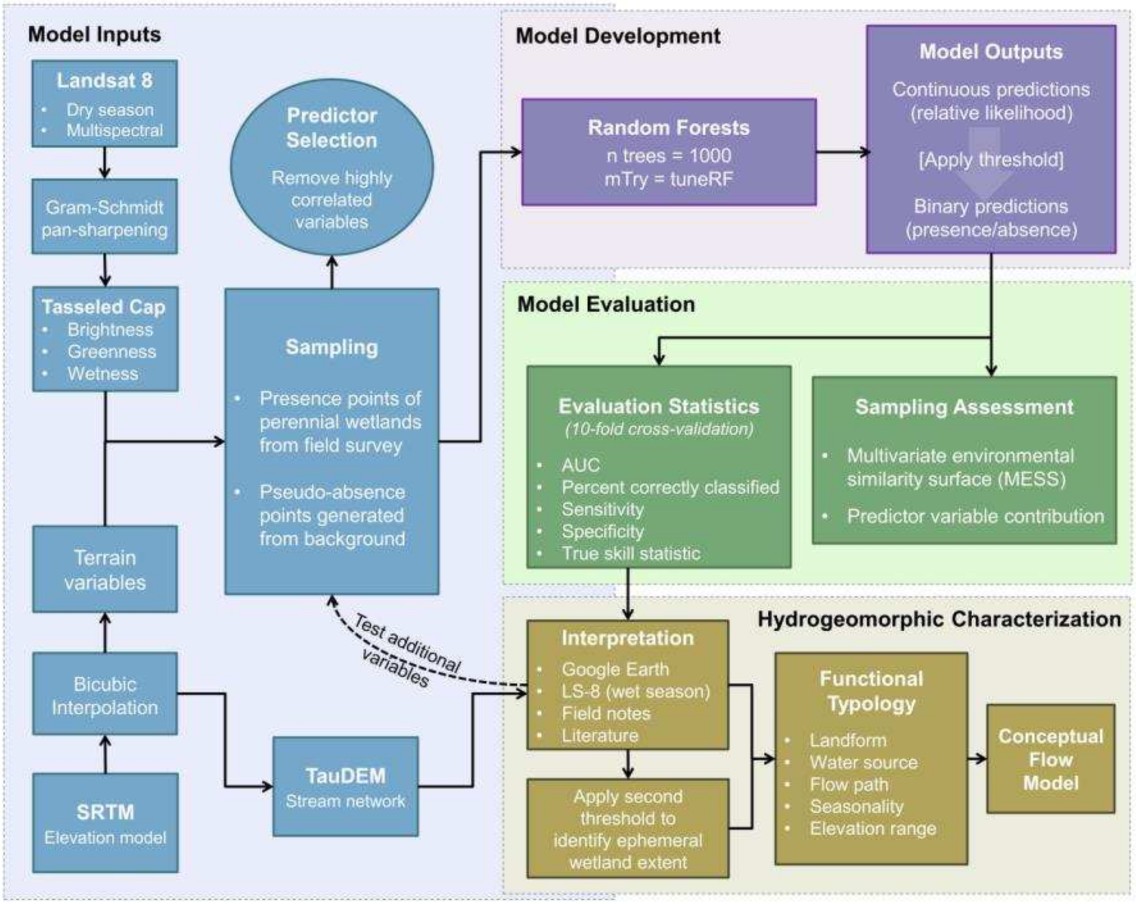


Figure 2.3: Workflow showing the different phases of the study methodology. Figure adapted from Chignell et al. (2017), their Figure 2. SRTM, Shuttle Radar Topography Mission; TauDEM, Terrain Analysis Using Digital Elevation Models; LS-8, Landsat 8.

Model inputs

I used a combination of field data and remote sensing data throughout this study (Table 2.1). These include GPS point data, geo-tagged photographs, Landsat 8 imagery, digital elevation data, and high-resolution imagery from Google Earth. I derived a number of derivative data products from these sources. The following sections describe the acquisition and processing of each of these data sets.

Table 2.1: Summary of data types and sources.

Data Type	Details	Date	Source
Wetland/upland point occurence	Latitude/longitude, photographs, presence/absence of moisture	2015	Field survey
Landsat 8 imagery (wet and dry seasons)	7-band multispectral	2015	U.S. Geological Survey
Shuttle Radar Topography Mission digital elevation model	1 arc-second spatial resolution	2000	U.S. Geological Survey (via Google Earth Engine)
DigitalGlobe imagery (multiple dry seasons)	Visible bands. <1 m spatial resolution.	2003-2017	Google Earth Pro

Field data

I carried out a scoping trip to the plateau in May 2014 (wet season), followed by a field survey in February 28 – March 2, 2015 (dry season). The survey was conducted the end of the dry season when any wetlands with flowing water are assumed to be perennial. Sampling was opportunistic but targeted, guided by prior examination of near-coincident Landsat imagery as well as high-resolution imagery from Google Earth. I sought to capture the variety of wetlands that occur across the plateau, as well as the variety of surrounding upland cover types. At each site, I recorded latitude and longitude, the presence or absence of moisture at the surface, and photographs (Appendix 5) in each of the cardinal directions (n=146). When recording geographic coordinates, I stood within homogenous patches of land cover. With the exception of the summits, the survey covered the entire elevation gradient of the Afroalpine zone, from the uppermost Sanetti region to the southern escarpment (Figure 2.4). Due to time and travel limitations, the survey did not cover the western half of the plateau.

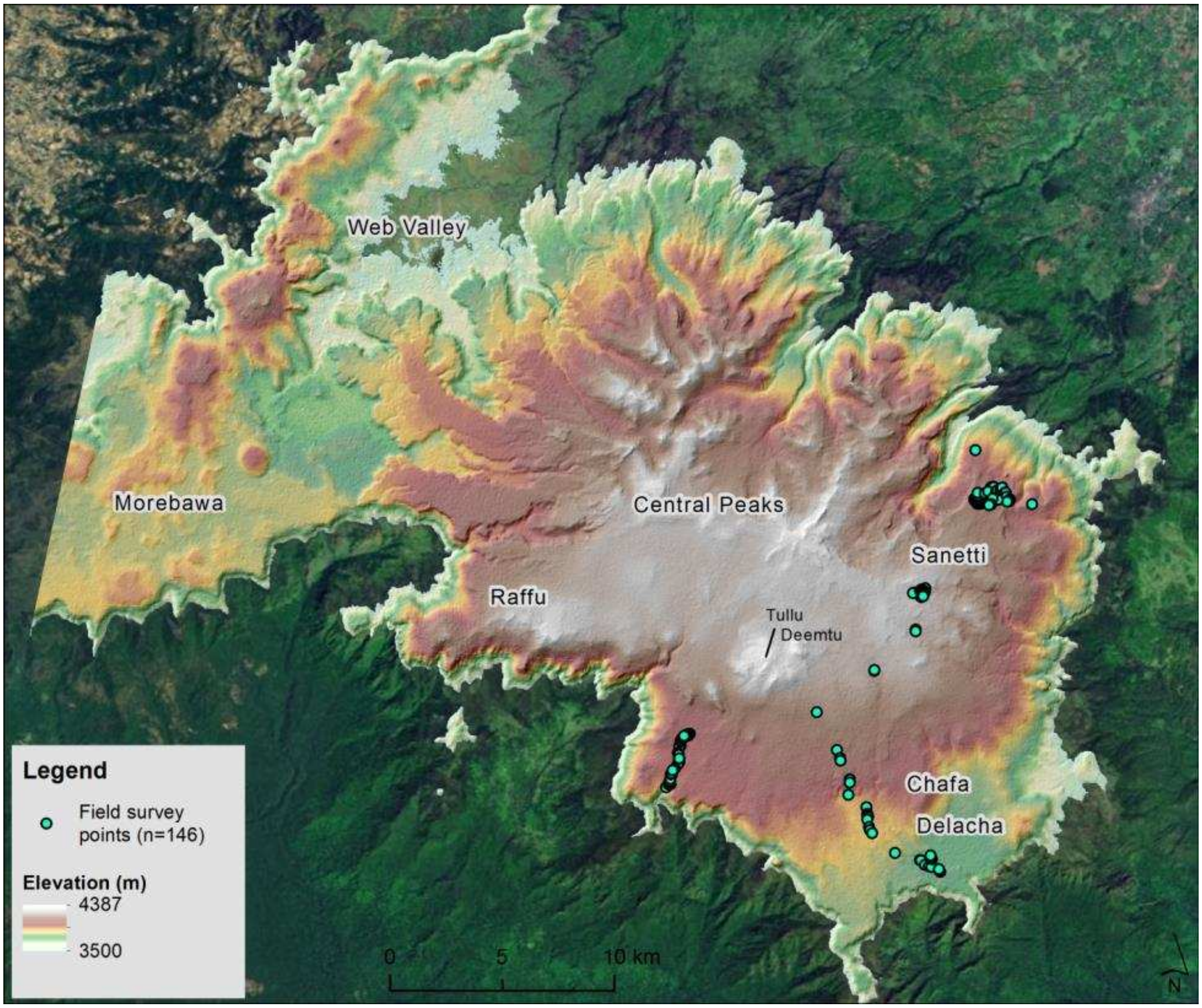


Figure 2.4: Map of the Bale plateau, showing field survey points and the elevation gradient of the Afroalpine zone. Tullu Deemtu and regional names are included for reference.

The upper portion of the plateau was dry, with the exception of a handful of kettle lakes that contained shallow standing water. In addition to the Sanetti region, I walked longitudinal transects along two spring-fed streams that had low flows at the time of the survey. The first is a channel that forms from a spring at the base of a cinder cone outcrop near Tullu Deemtu. This is eventually joined by the Mireta and Hambala streams and flows south toward the escarpment in the Chafa Delacha region. The second is the Sida stream that that emerges from a slope breaks at the base of a cinder cone in the Sanetti region. I followed both channels downstream until they reached the southern escarpment. For wider stream reaches with deeper channels, I marked coordinates along the vegetated stream bank. For narrower reaches with shallow channels, I stood in the thalweg in order to avoid spectral mixing with upland vegetation outside the wetted margin. I recorded all points at least 30 m apart to prevent multiple sampling in the same cell during subsequent model development.

Satellite imagery

I acquired a L1T terrain-corrected Landsat 8 image for path 187, row 42 from the US Geological Survey Earth Explorer data portal. This image was captured on March 3, 2015, which represents late dry season conditions and is nearly coincident with the dates of the field survey. I used ENVI v5.1 to perform a radiometric calibration, converting digital numbers to top-of-atmosphere reflectance. Because the study does not span multiple dates and scenes, I did not perform further corrections so as to avoid unnecessarily injecting error into the spectral values (Young et al., 2017). I also acquired a Landsat 8 scene from November 11, 2014, which was one of the only wet season images in the Landsat archive to show large parts of the plateau without cloud cover. I used this image to aid evaluation and interpretation of the final model results.

For correlative species distribution models to be accurate and useful, they need to use environmental predictors that match the resolution and spatial context of the phenomenon being modeled (Jarnevich et al., 2015). To capture the small depressions and narrow riparian zones of the plateau, I pan-sharpened the 30 m multispectral (MS) bands with the 15 m panchromatic band using the Gram-Schmidt (GS) method (Laben and Brower, 2000) in ENVI. With this data fusion approach, a 30 m panchromatic band is simulated from the multispectral bands, and a GS transformation is applied to merge this simulated band with the multispectral bands. The actual panchromatic band is swapped with the first GS band, and an inverse GS transform is applied to the entire dataset to produce a set of pan-sharpened multispectral bands (Laben and Brower, 2000). The GS method has been shown to be highly effective at preserving the spectral and spatial fidelity of the original multispectral data (Karathanassi et al., 2007; Kumar et al., 2014; Sarp, 2014), and has been used to enable mapping of small (≥ 0.20 ha) wetlands using Landsat imagery (Frohn et al., 2009, 2012). I assessed the quality of the GS pan-sharpening using both qualitative and qualitative approaches. For the qualitative assessment, I used a variety of band combinations to highlight known features on the landscape (e.g., field-validated wetlands, roads, vegetation communities), and visually assessed how well their spectral and spatial characteristics were preserved between the original and pan-sharpened data. The pan-sharpening process clearly improved the minimum mapping unit of the image, providing spectral and spatial nuances of the landscape not visible in the original data (Appendix 1). For the quantitative assessment, I resampled the 15 m pan-sharpened data to 30 m (bilinear interpolation) and calculated band-by-band Pearson's correlation coefficient (CC) and root mean square error (RMSE) between the sharpened data and the original 30 m data. Pearson's CC and RSME are commonly used to assess the level of agreement between the original and sharpened spectral data (Gangkofner et al., 2008; Ashraf et al., 2012; Ai et al., 2016). Pearson's CC measures the linear relationship between the original and fused images, with values ranging from -1 (perfect negative agreement) to +1 (perfect positive agreement). The RMSE measures the standard error between the original and fused images, and is able to identify differences not captures by the CC (Gangkofner et al., 2008; Ashraf et al., 2012). The value range is determined by the data being compared, but RMSE scores closer to 0 indicate better agreement. I made the CC and RMSE calculations at the “global” level (single calculation for each pair of bands, rather than for each pair of pixels). I limited the analysis to pixels within the study area in order to avoid spurious results from the rest of the Landsat scene. Pearsons’ CC scores ranged from 0.84 – 0.99 and RMSE scores ranged from 0.015 – 0.037, indicating strong agreement between the pan-sharpened and original multispectral data (Appendix 1).

Following the assessment, I applied a tasseled cap (TCAP) transformation to the pan-sharpened multispectral bands (Baig et al., 2014). The tasseled cap is a commonly used technique that employs band-specific coefficients to orthogonally transform raw spectral values into a new set of uncorrelated bands (Crist and Cicone, 1984; Crist, 1985). This removes redundant information among raw Landsat bands and increases computational efficiency. The TCAP is particularly useful when developing correlative statistical models with small training data sets, as it reduces the number of predictors while retaining the vast majority of unique information in the data set. The TCAP bands 1, 2, and 3 are commonly associated with brightness, greenness, and wetness on the landscape (Baig et al., 2014). This is important, as modeling with ecologically-meaningful variables significantly enhances the interpretability of model outputs.

Digital terrain data

Topography is a major control on wetland formation—particularly in mountain regions--and numerous studies have shown the importance of terrain variables for modeling wetland distribution (Chignell et al., 2017). To capture these characteristics, I acquired a 1 arc-second (approximately 30 m at the equator) Shuttle Radar Topography Mission DEM (NASA, 2013) for the study site from Google Earth Engine (Google Earth Engine Team, 2015). To match the spatial resolution of the pan-sharpened Landsat data, I used a bicubic interpolation to resample the DEM to a cell size of 15 m. The bicubic algorithm calculates the value of each interpolated cell by fitting a smooth curve based on the surrounding 16 pixels, and has been shown to be able to interpolate DEMs to finer spatial resolutions with minimal error propagation (Rees, 2000; Kidner, 2003; Shi et al., 2005). Following this step, I used ArcMap and the 15 m DEM to derive a slope map and a number of geomorphometric indices (Evans et al., 2014). These included dissection (Evans, 1972), landform (Bolstad et al., 1998), and roughness (Blaszczynski, 1997; Riley et al., 1999). Each of these metrics is scalable, and I chose to create them in increments of five cells from 5 to 40 to account for the variation in sizes of geomorphic features on the plateau. I used a circular moving window to minimize the impact of minor striping associated with SRTM DEM data. Periglacial landscapes leave a hydrologic legacy that can be different from predicted flow paths. I therefore explicitly avoided using predictor variables such as the compound topographic index or "distance to streams" in order to avoid biasing predictions toward idealized flow lines and thus miss relict features and emergent wetlands (Chignell et al., 2017). However, I did used the DEM to generate a stream network (Appendix 2) with the Terrain Analysis Using Digital Elevation Models (TauDEM) ArcGIS tool (Tarboton, 2016). I used this to support the hydrogeomorphic interpretation of the final model predictions.

Model development

I conducted all wetland modeling using the Software for Assisted Habitat Modeling (SAHM) (Morisette et al., 2013). This free software developed by the U.S. Geological Survey streamlines the modeling workflow by linking together a number of data processing tools and R code packages together in a modular user interface. The SAHM is also optimized to run presence-absence models using pseudo-absences, which facilitates presence-background modeling. As described previously, I used the random forests technique to generate the model predictions. To parameterize the model, I set *n tress* = 1,000 and used the tuneRF function to determine the *mTry* value.

Developing models within homogenous landscapes helps to reduce landscape variability (Kassawmar et al., 2016), which is important for distinguishing complex wetland signatures from surrounding features. This is particularly necessary in the Bale Mountains, as the cloud forest on the surrounding escarpment would likely confound the model and be misclassified as wetlands. To prevent this, I used the DEM to create a geographic boundary of Afroalpine area (>3500 m asl) (Frankfurt Zoological Society, 2007). I used this layer to clip all predictor variables using the *Projection, Aggregation, Resampling, and Clipping* module within SAHM. For presence data, I used the wetland locations identified as perennial during the field survey (n = 34) (Appendix 5). For background locations, I followed the recommendations of (Barbet-Massin et al., 2012) and (Phillips and Dudík, 2008) and randomly generated 10,000 background points within the geographic boundary of the Afroalpine zone. I did this in order to limit sampling within a geographic and environmental-based stratum (Barbet-Massin et al., 2012). I used the *MDS Builder* module to extract the values of each predictor variable at the locations of each of the presence and background points. I input these values into the *Covariate Correlation and Selection* module to generate a correlation matrix showing the correlation between each pair of predictor variables (Appendix 3). To prevent issues related to multicollinearity (Jarnevich et al., 2015; Millard and Richardson, 2013), I retained only one of each pair of correlated predictors with a Spearman, Pearson, or Kendal correlation coefficient $|r| \geq 0.70$ (Dormann et al., 2013) for use in developing the final models. I made these selections based on the percent deviance explained from a univariate generalized additive model for each variable and our knowledge of wetland ecology and in each zone. I used an iterative approach to select predictors for use in the final model (Jarnevich et al., 2015; West et al., 2017), examining the correlation between potential predictor variables and comparing evaluation scores and outputs of initial model runs. Through this process, I gradually refined the results before selecting the final set of predictors (Table 2.2) and most eco-plausible model (Jarnevich et al., 2015), based off of the response curves and my observations in the field. Interestingly, TCAP brightness was highly correlated with wetness, which is likely a result of the low albedo of moist areas. After comparing results with each, I chose to keep brightness because it accounts for the most variability in the image (Baig et al., 2014) and appeared to be less susceptible to confusion with *Erica* shrub on the margins of the plateau. The dissection, landform, and roughness variables were highly correlated at most scales. Dissection and roughness appeared to confuse artifacts in the DEM with depressions, especially at smaller scales (radius < 15). For the final model, I used landform at 40 cell radius based on its percent deviance explained and its demonstrated ability to highlight hydrogeomorphic features of wetlands in other landscapes (Van Deventer et al., 2014).

Table 2.2: Summary of predictor variables used to develop the model, as well as their associated environmental characteristic, source data, and key references.

Variable	Landscape characteristic	Reference	Included in final model
Brightness	Albedo	Baig et al., (2014)	Yes
Greenness	Photosynthetic activity	Baig et al., (2014)	Yes
Wetness	Soil and plant moisture	Baig et al., (2014)	Removed because of correlation with brightness
Slope	Slope	N/A	Yes
Dissection	Dissection of the landscape	Evans (1972)	Removed because of correlation with landform
Landform	Curvature/Convexity	Bolstad et al., (2008)	Yes

Roughness	Terrain complexity/variance	Blaszczynski (1997); Riley et al., (1999)	Removed because of correlation with landform

The primary model output comprises a continuous raster surface with cell values that represent the relative likelihood of occurrence of a perennial wetland or riparian zone. Within SAHM, I used this surface to generate a binary map by applying a statistically determined threshold; in this case, the value that maximized the sum of sensitivity and specificity (sensitivity + specificity/2). This is an objective threshold optimization method recommended for use with models developed without true absences (Liu et al., 2013). To create a map of ephemeral wetlands, I manually selected a threshold by comparing the probability surface to high-resolution Google Earth imagery and the field survey locations that had wetland vegetation and geomorphic characteristics but were lacking in moisture.

Model evaluation

I conducted a 10-fold cross-validation using the *Model Selection Cross Validation* module in SAHM. Cross-validation is repeated data splitting, in which multiple models are developed and tested with results averaged over the repetitions (Hastie et al., 2009). This approach is useful with small training data sets, as it makes use of all of the data points for both training and testing, and is therefore more robust to spurious results that can occur from simple data splitting (Jarnevich et al., 2015). I used this to calculate a variety of evaluation statistics, which enables a better overall assessment than is possible with a single statistic (Lobo et al., 2008; Jarnevich et al., 2015). The first, area under the receiving operator curve (AUC), is a threshold-independent metric representing the likelihood of a presence location having a higher predicted value than an absence location (Fielding and Bell, 1997; Pearce and Ferrier, 2000).

AUC values have a range of 0 to 1 (value of 1 represents a perfectly performing model) and are independent of prevalence (ratio of presence to absence locations). The practical range is 0.5 to 1, as a value of ≤0.5 would indicate model predictions no better than random. Another evaluation statistic, percent correctly classified (PCC) is the proportion of cross-validated presence and background points correctly classified by the binary map that results from the probability threshold. It is important to note that AUC and PCC weight omission and commission errors equally and their values should therefore be interpreted cautiously when using background points (Lobo et al., 2008; Jiménez-Valverde, 2012; Jarnevich et al., 2015).

To supplement these metrics, I also calculated sensitivity, and specificity, and the true skill statistic (TSS). Sensitivity is the proportion of positive pixels predicted (1- omission error rate) and specificity is the proportion of negative pixels predicted (1 - commission error rate). Sensitivity and specificity both have a value range of 0 to 1 (a value of 1 represents perfect performance). The TSS (sensitivity + specificity -1) is a simple and intuitive metric for assessing the predictive performance of distribution models from presence/absence maps (Allouche et al., 2006). Similar to the Kappa statistic, TSS is a prevalence-independent measure of performance useful for assessing model predictions expressed as presence-absence maps (Allouche et al., 2006). TSS has values that range from -1 to +1, with +1 indicating perfect agreement and ≤0 indicating a performance no better than random. In addition to these statistics, I used SAHM to generate a multivariate environmental similarity surface (MESS) to measure degree and location of extrapolation and interpolation across the study area (Elith et al., 2010; Stohlgren et al., 2011). This indicates whether the variability present in the predictor variables has been adequately captured by the sample data set.

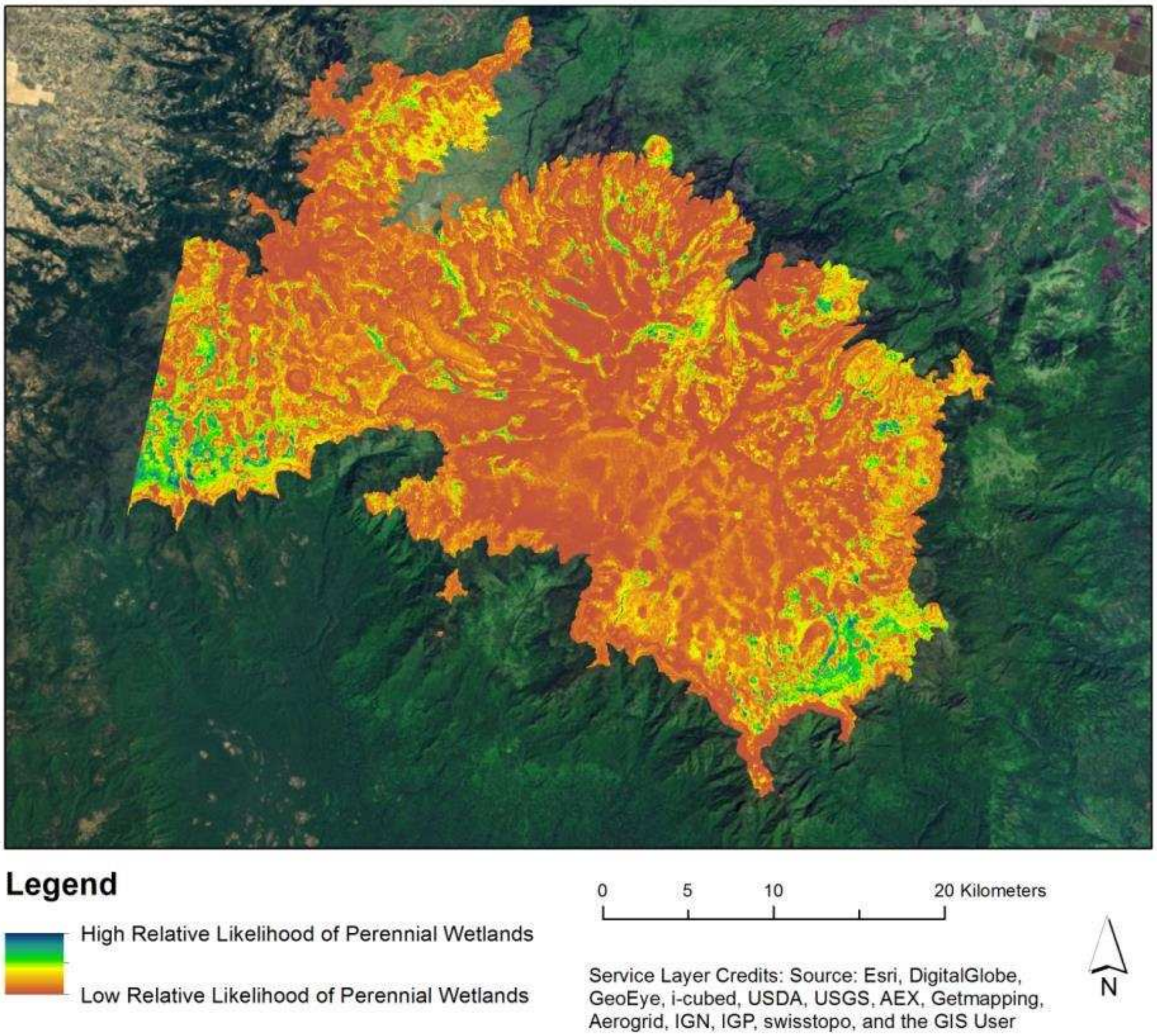
Model results

The model achieved test AUC, PCC, and specificity scores of 0.99. However, because these evaluation statistics weight presence and background points evenly, these values are likely inflated and should be interpreted cautiously (Jarnevich et al., 2015). Still, the results of the prevalence-independent statistics such as sensitivity (0.80), specificity (0.99), and TSS (0.80) indicate high predictive performance. Predictor importance was fairly even among the five variables (Appendix 3). TCAP greenness was the most influential, showing a 33% decrease in model accuracy upon removal. Landform, elevation, slope, and TCAP brightness ranged from 21-25% mean decrease in accuracy upon removal. This suggests that the model captured both biotic and abiotic controls on wetland distribution in the area**.** Table 2.3 shows that wetland and riparian zones occupy 17% (175 km^2) of the total Afroalpine area of the Bale Mountains (4% perennial and 13% ephemeral). Just 23% (41 km^2) of all wetlands are perennial and 77% (134 km^2) are ephemeral. This indicates a change of 53% (93 km^2) in wetland extent between wet and dry seasons.

Table 2.3. Summary statistics of Afroalpine wetland and upland area in the Bale Mountains.

Cover type	Area (m^2)	Area (km^2)	% Total wetland area	% Total Afroalpine area
Perennial	40,926,150	40.92	23.4%	3.9%
Ephemeral	133,812,450	133.81	76.6%	12.8%
Upland	867,442,500	867.44	0%	83.2%
	Total	**1042.18**	**100%**	**100.0%**

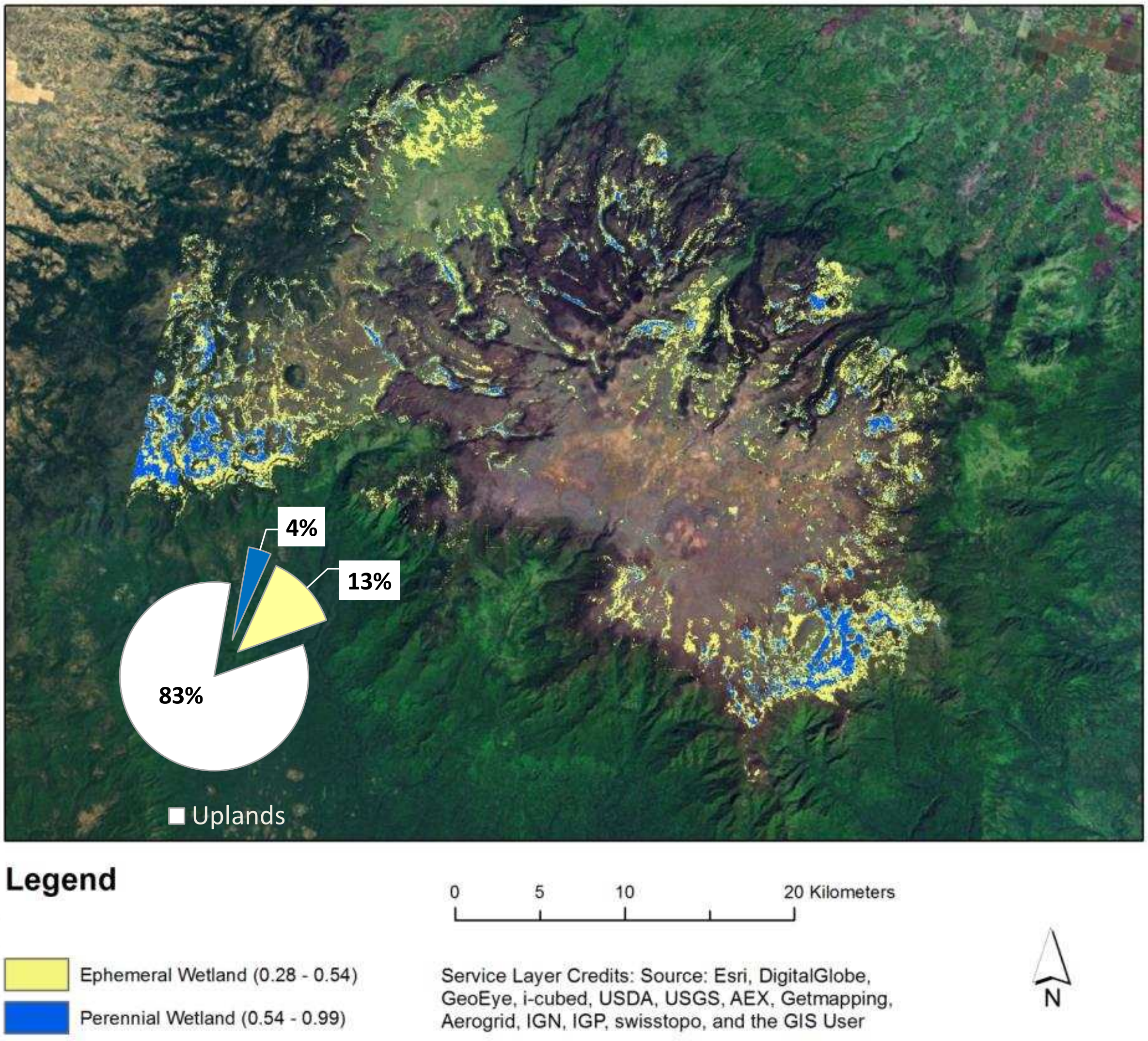
My results reveal a perennial-ephemeral continuum across the elevation gradient of the Bale plateau (Figure 2.5; Figure 2.6). The uppermost elevations of the central Sanetti region are predominantly ephemeral, with the exception of a few perennial wetlands on the summits. The intermediate elevations show the emergence of small streams and riparian zones that feed into large perennial basins near the southern escarpment. This continuum also occurs within individual wetland complexes which show core perennial patches surrounded by increasingly ephemeral margins. This corroborates the intra-wetland variability described by (Dullo et al., 2015), who conducted a detailed dry season study of a fen in the Sanetti region of the plateau.



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User

Figure 2.5: Map showing relative likelihood of perennial wetlands and riparian zones in the Afroalpine region of the Bale Mountains. Model predictions are overlaid on false-color (6-5-4) Landsat 8 image captured March 3, 2015. The map indicates a moisture continuum

along the elevation gradient, with the highest central plateau being almost entirely ephemeral, the middle elevations producing seeps and riparian zones, and the southeast and southwestern edges collecting this water in large perennial basin wetlands.



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User

Figure 2.6: Map showing predicted distribution of ephemeral and perennial wetlands in the Afroalpine area of the Bale Mountains. Each discrete class was generated by applying numerical thresholds (listed in legend) to the continuous relative likelihood map. Model predictions are overlaid on false-color (6-5-4) Landsat 8 image captured March 3, 2015.

Hydrogeomorphic characterization

Using the model results, ancillary satellite imagery, field observations, and the literature, I defined five wetland types for the Bale plateau (Table 2.4). I determined these using the following criteria: 1) Landform setting, 2) Water Source, 3) Flow Path, and 4) Seasonality. I also assigned an elevation range to each wetland type. While there is some overlap, the classification seeks to capture the primary hydrogeomorphic descriptors and function of each type. In the following sections, I present evidence for each grouping, starting at the central peaks and moving to the edge of the plateau.

Table 2.4: Hydrogeomorphic characteristics and funtional types for the Afroalpine wetlands of the Bale Mountains. Approximate elevation range is also listed.

Type	Landform	Water Source	Flow Path	Seasonality	Elevation (m)
Seep	Slope	Groundwater, Snowmelt	Outflow	Perennial	3,900 - 4,200
Lake	Kettle, Fringe	Precipitation	Vertical, Outflow	Ephemeral	4,000 - 4,150
Fen	Kettle, Slope	Precipitation, Surface flow, Shallow groundwater	Throughflow, Outflow	Ephemeral	3,900 - 4,150
Riparian	Channel fringe	Groundwater (spring), Overland flow	Throughflow	Perennial	3,500 - 3,900
Marsh	Basin	Groundwater, Precipitation	Throughflow, Vertical	Perennial	3,500 - 3,800

Cinder cone seepage slopes (3,900 – 4,200 m)

My model results indicate that the highest-elevation wetlands of the Bale plateau are seep wetlands that occur on the cinder cones of Tullu Deemtu and the central summits (Figure 2.7). This can be explained by the fact that cinder cones form during the post-shield stage of shield volcano development, during which the lava chemistry changes and produces highly viscous flows. Due to their viscosity, the aquifers that form in post-shield rocks generally have lower permeability than underlying shield-stage lava flows. This increases residence time and can serve as important groundwater resources in tropical volcanic regions such as the Hawaiian islands (U.S. Geological Survey, 2013). In Bale, post-shield cinder cones comprise nearly all areas above 4,000 m on the plateau. These are the only elevations at which significant snow packs develop, reaching depths of up to 20 cm and remaining for up to three days (Miehe and Miehe, 1994). Snow melts due to diurnal and seasonal changes in temperature, the meltwater infiltrates into the underlying rock until it emerges from the flank of the cone or at the foot of scree slopes. These slopes are likely remnants of colder periods, produced from frost weathering of south-facing rock faces with long-lying snow packs (French 1996) (Ruiz-Fernández and Oliva, 2016) (Harris, 2013). It is also possible that some of these scree slopes are the remnants of ancient gelifluction, as most exist within the boundary of the glacier cap and remain largely vegetated. While the existence of relict buried ice is unlikely, ancient frost debris were found in a soil profile above Rira (3,500 m asl) (Miehe and Miehe, 1994), and periglacial processes still occur in the upper elevations, particularly in moist areas. The seeps that emerge from the cinder cones tend to form saturated areas, most with small outflow channels that follow the local topographic gradient. These represent the vast majority of perennially saturated wetlands in the upper elevations of the plateau, a product of the wet season snowpack and lower hydraulic conductivity of the source rock. Some of these channels become tributaries of small channels such as Sida stream. Others contribute flow to more ephemeral channels or—in rare cases—feed directly into nearby kettle lakes, allowing them to persist well into the dry season.

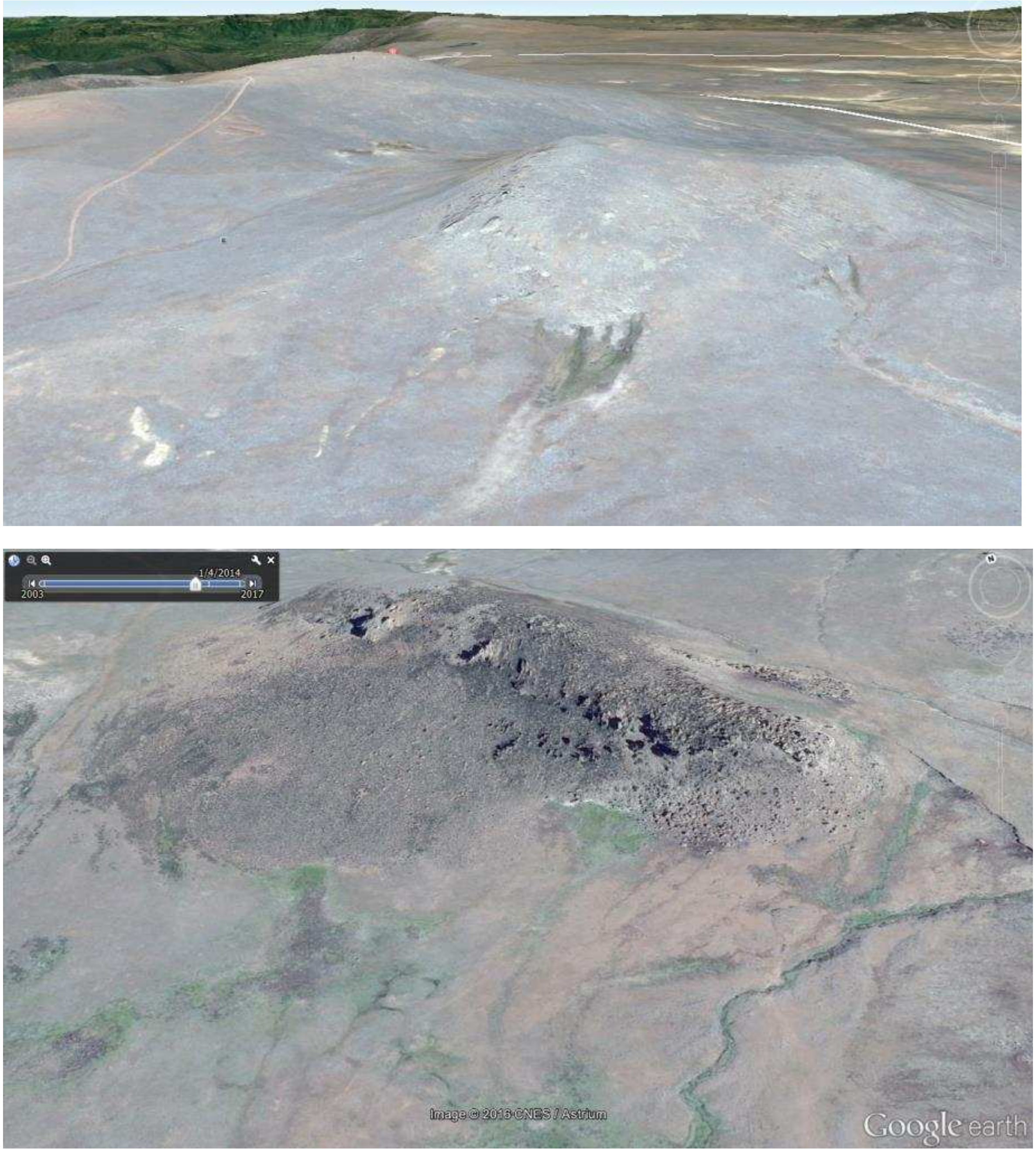


Figure 2.7: Top: Perennial seepage slope wetland emerging from the summit of a trachytic cinder cone east of Tullu Deemtu (visible in background). Some of the outflow channels feed directly into kettle lakes. Bottom: weathered cinder cone summit in the Sanetti region. Numerous seep wetlands are visible emerging from frost-weathered scree slopes and form small channels and wetlands in relict periglacial cracks and polygons.

These conclusions are also supported by relict periglacial landforms near some of the volcanic plugs that lie beyond the limits of the glacier cap estimated by Osmaston et al., (2005).

In addition to localized scree slopes (Hendrickx et al., 2015), a number of sorted stripes and stone circles are visible at the base of these plugs (Appendix 4). The cryoturbation processes that produce these landforms are more intense in moist areas, which tend to be at the foot of slopes with long-lying snow patches (Ruiz-Fernández and Oliva, 2016). This would have been the scenario in the past, when the climate was cooler and more humid. These landforms are visible near the two plugs to the south of Tullu Deemtu, as well as the large plug in the southwestern region of Morebawa. Those near Tullu Deemtu are much more pronounced than in Morebawa, likely due to their higher elevation and close proximity to the glacier cap, which would have resulted in more intense freeze-thaw processes for longer durations. The absence of such features near lower elevation plugs further supports this, as these areas are beyond the lower limit for periglacial processes on the plateau (3,800 m asl).

Kettle lakes and fens (3,800 – 4,100)

Immediately below the cinder cone seeps, a complex of terrene lakes and wetlands begins at the base of Tullu Deemtu and extends northeast to elevations of approximately 3,900 m asl. Nearly all of these lakes exist within the boundary of the probable limits of ice during the last glacial maximum, and were either formed or affected by glacial activity (Eggermont et al., 2011). With the exception of Garba Guracha, many of the lakes have been filled up with sediment and are shallow and temporal (Eggermont et al., 2011). Other depressions have been completely filled up, forming the flats nearest to the north and northeast of the base of Tullu Deemtu. This is supported by the proximity of these areas to the glacier cap (all are within the possible limits of the last glacial maximum estimated by (Osmaston et al., 2005), and the higher availability of glacial till for infilling. Their position in the upper elevations of the plateau and their highly variable water levels—many are completely dry by then end of the dry season—

strongly suggest that they are ombrotrophic. While the majority of these lakes have no perennial surface outlet (Miehe and Miehe, 1994; Osmaston et al., 2005), observations from (Dullo et al., 2015) and Google Earth (Figure 2.8) reveal that many do possess an ephemeral outflow channel. These are likely the product of "fill-and-spill" dynamics in which the lake level rises until the water spills over the edge and is conveyed downhill in the ephemeral channels. This process is common in geographically isolated wetlands, and represents episodic surface connectivity (Cohen et al., 2016). The lakes also support vegetated wetlands on their margins, which are inundated after rain events and subsequently dry up as water infiltrates and the wetted edge recedes. Downslope and adjacent to the lakes are numerous peat-forming, minerotrophic fens that receive inputs from shallow groundwater flows as well as precipitation (Kebede, 2013; Dullo et al., 2015). Some of these fens are connected by visible surface channels to upstream lakes, which convey overflow water during the wettest months. Together, these lakes, fringe wetlands, and peat fens make up a highly dynamic wetland complex on the central plateau.

Figure 2.8: Series of three dry season images of the Sanetti kettle lakes and fens (Google Earth). Kidney Lake (left) is at the highest elevation and has a small outlet; water is lost to

vertical and lateral infiltration, as well as the fill-and-spill process once the lake reaches the height of the outlet. This conveys water to the wetland immediately downslope, near the Sanetti campsite. Both lakes in the center have outlets to ephemeral streams, but the outlet of the left lake is at a lower elevation. The left lake supports a vegetation community when full, but as the outlet empties the lake this water is transferred to the minerotrophic fen immediately downstream, past the road, which is the same fen that was studied by Dullo et al. (2015). Once the outflow lake empties, the fen also begins to dry, evidenced by the gradual shrinking and disappearance of its pools.

Perennial riparian areas and marshes (3500 – 3800 m)

The model results show that the majority of perennial wetlands occur below 3,800-3,900 m asl. Interestingly, this corresponds to the toe of the uppermost lava flow on the plateau and its intersection with the underlying basal unit. Multiple field observations in these areas revealed significant springs emerging from fractured basalt columns at the end of the dry season (Figure 2.9). Young volcanic landscapes are highly porous at the surface and subsurface, which results in high precipitation infiltration rates and exceptionally high hydraulic conductivities (Tague and Grant, 2004). This layer-cake stratigraphy often plays an important role for subsurface flow, as the geometry of lava flows can be a strong control on groundwater movement (McGuire et al., 2005; Jefferson et al., 2006; U.S. Geological Survey, 2013). In Bale, it is likely that water from the upper elevations infiltrates vertically into the uppermost lava flow until it meets the older underlying flow unit. It then moves laterally through the interflow zone, following the topographic gradient, until it emerges as springs at outcrops at dykes and toes of the lava flow. This process is similar to other mafic volcanic regions such as the Pacific Northwest (Jefferson et al., 2006; Tolan et al., 2009), Hawaii (U.S. Geological Survey, 2013), and the Simien Mountains of northwest Ethiopia (Kebede, 2013). Moreover, the response curve for the elevation predictor variable shows a sharp increase in perennial wetland probability at the 3,800 m asl mark (Figure

2.10); this corresponds to the lower limits of the upper lava flow unit and the emergence of springs from the interflow zone at weathered outcrops.

Figure 2.9: Perennial toe-of-slope seep wetland emerging from the interflow zone between the uppermost lava flow and the underlying unit. A small outflow stream and riparian area is visible flowing southward. Smoke is the result of anthropogenic fire on the southern escarpment. Photo by the author, March 1, 2015.

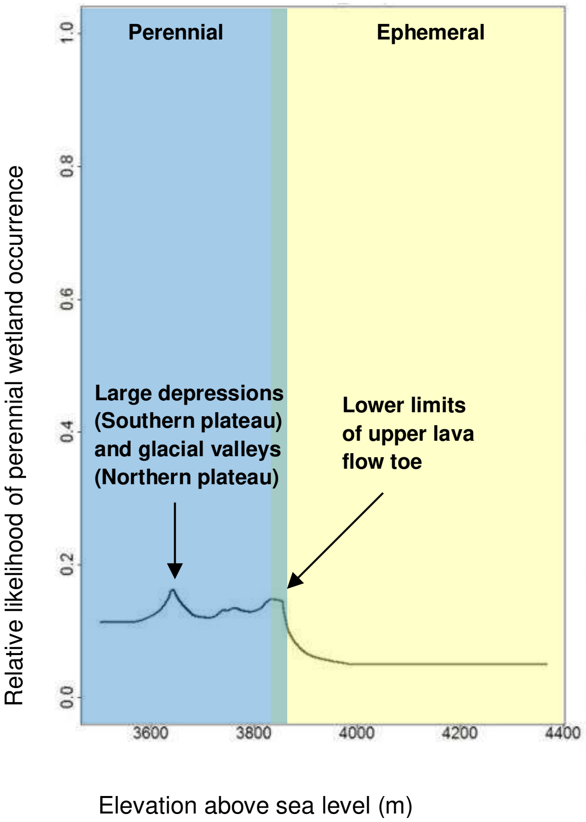


Figure 2.10. Response curve for elevation in the wetland model. Arrows denote the clear transition from perennial to ephemeral wetlands at 3,800 – 3,900 m asl. This corresponds with the lower limits of the upper lava flow unit and the emergence of springs from the interflow zone at weathered outcrops.

Conceptual flow model

I propose the following conceptual flow model for the Bale Mountains (Figure 2.11): During the wet season, precipitation falls as rain and snow across the plateau. This builds snowpack on the cinder cones summits and provides ombrotrophic inputs to the surrounding kettle lakes. As diurnal temperature fluxes melt the snow pack, much of the meltwater infiltrates into the dense post-stage rock of the cinder cones. Since most of the kettle lakes do not have perennial outflows (Miehe and Miehe, 1994; Osmaston et al., 2005), the lake water infiltrates vertically through the lake beds. Eventually the lake edge expands into the surrounding lentic wetland vegetation until it fills the rim of the kettle. Continued input eventually causes the water to spill out into first order streams. This is conveyed to lower elevation wetlands through ephemeral channels which are at first losing streams but eventually become gaining streams as the soil is saturated and the water table rises (Winter, 1998). As precipitation wanes in the dry season, the ephemeral lakes and streams dry out, but the long residence time of the cinder cones results in seeps that continue to contribute flow throughout the dry season. As lake levels drop, kettles shift to purely vertical flow until they dry out. A handful of particularly deep kettles—as well as those that receive inputs from cinder cone seeps—may stay wet throughout the dry season. Water infiltrates through the uppermost flow unit, and is transported laterally downslope through the interflow zone. Some of this water emerges as springs at the edge of the uppermost lava flow (approximately 3,800 - 3,900 m), while some infiltrates into deeper lava flow units through dykes and fractures (Tewodros, 2005; Kebede, 2013). The former source the small riparian channels that provide perennial flows to the large basin wetlands in Chafa Delacha and Morebawa, as well as the rivers on the northern declivities and the Web Valley. The latter infiltrates deeper into the region's aquifer or emerges as horas in the Harenna forest escarpment (Chiodi and Pinard, 2011). This processes results in a hydrologic continuum in the Afroalpine zone; higher elevations tend to be ephemeral (with the exception of the cinder cone seeps) and lower elevations tend to be perennial, with the transition being the lower limits of the upper trachyte flow (approximately 3,800 m asl). This altitudinal zonation has been observed in similar regions, including northwest Ethiopia, and suggested for the Bale massif (Kebede, 2013).

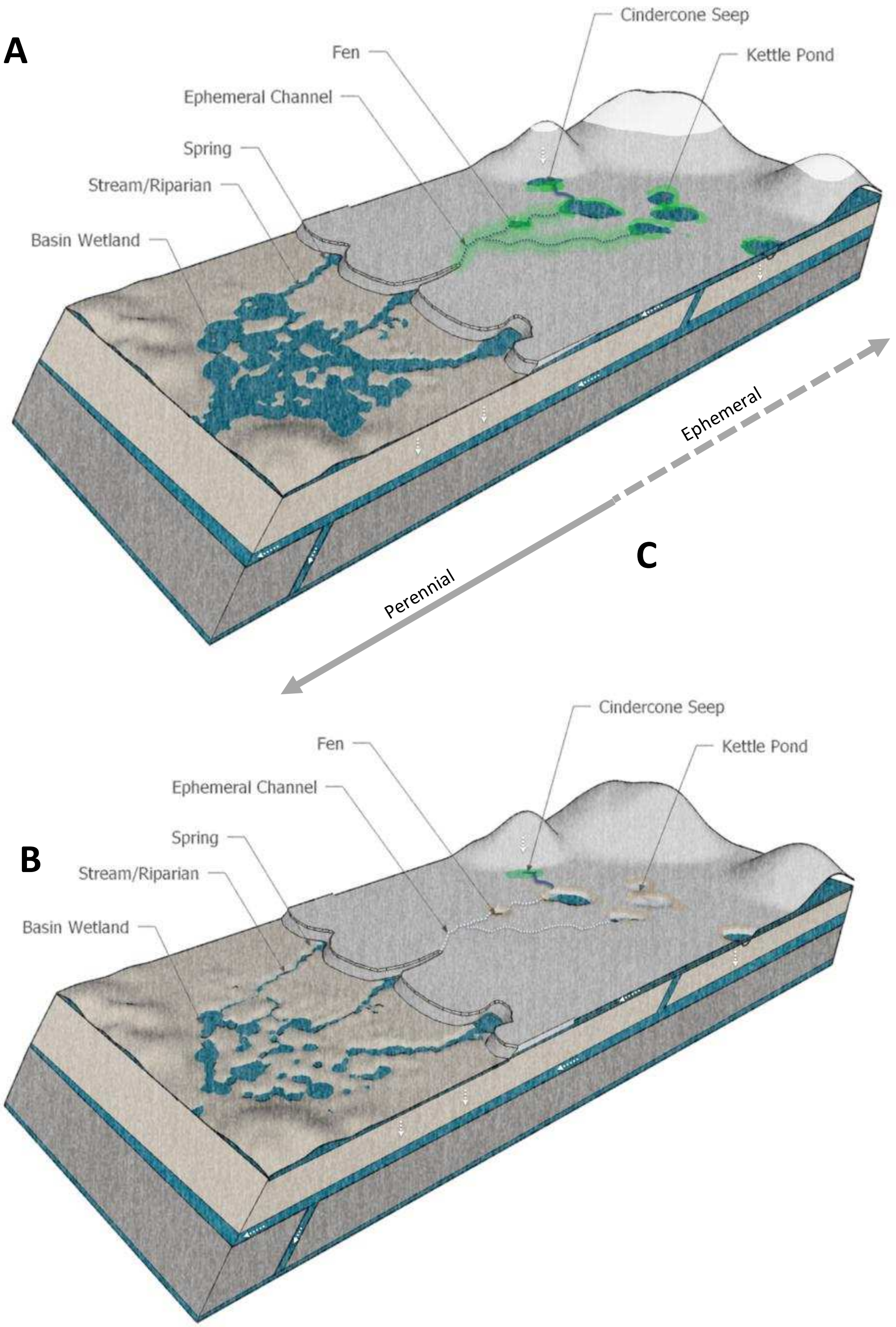


Figure 2.11: Conceptual flow model of the seasonal dynamics of Afroalpine wetlands in the Bale Mountains. A) Wet season conditions; heavy precipitation saturates the plateau, with

small snow packs developing on the summits and infiltrating into the dense post-shield cinder cone. Some kettle lakes lose water to vertical infiltration (white arrows). Ephemeral outflow channels form from overland flow and the fill-and-spill cycle of the kettles. Groundwater moving through fractured lava and the uppermost interflow zone emerges as springs at the fractured toe of the uppermost lava flow. This forms small perennial channels with narrow riparian zones that convey water to the basins and valleys in the lower limits of the Afroalpine area. Some groundwater infiltrates into deeper strata via dykes, and some emerges as spring and river recharge on the escarpment and the surrounding region. B) Dry season conditions; with the exception of those connected to higher-elevation outflow channels from cinder cone seeps, the vast majority of kettle lakes and ponds dry as they lose water to vertical infiltration. As the water level recedes the adjacent wetland vegetation and small outflow channels also dry. C) Arrows illustrating the hydrologic continuum along the elevation gradient; wetlands below the toe of the uppermost lava flow unit (3,800 – 3,900 m asl) receive groundwater throughout the dry season, while wetlands and channels above this line dry out.

Discussion

The results of predictive distribution models should be treated as hypotheses to be tested with further field data collection, experimentation, and modeling (Jarnevich et al., 2015). My study provides a foundation for building a deeper understanding of the Bale Mountains. Future work should include monitoring of horas and seep wetlands, as such springs represent "windows" into the sub-surface, and the chemistry of the emerging water reveals important clues about the timescales, pathways, and storage volumes of water at the landscape scale (Grant et al., 2010). Water isotopes of springs can be used to identify recharge elevations and delineate cryptic flow paths that do not necessarily obey topographic divides (Jefferson et al., 2006). This has important implications for management, as inter-annual variability in discharge from springs can be used to interpret landscape memory and sensitivity to climate variation.

Future research should use the results of this study to guide field assessments and identify reference wetlands that can be used to monitor change and thus the efficacy of proposed conservation zones. Regular measurements of stage and discharge in each wetland type would provide insights into fill and spill dynamics, water conveyance, and hydrologic attenuation. These data would enable GIS modeling of longitudinal stream connectivity at the reach scale (Wohl et al., 2016), and how this might change with wetland degradation or shifts in hydrologic regime. The increasing availability of multi-spectral data from Sentinel-2 could provide enough temporal coverage to capture multiple cloud-free images of the plateau each year. Integrating this imagery with gauge locations would enable regular modeling of wetland distribution and moisture. Much of this process could be streamlined or even automated with the rapidly improving suite of remote sensing data products and freely available software.

While additional data collection is important, the future preservation and functioning of the Bale Mountains ultimately depends on understanding its social systems. The upstream-downstream pressures from population growth and climate change in East Africa are intensifying; in March, 2017, heavy water consumption by agriculture in upstream reaches of the Wabe Shabelle river reduced water levels in the Somalian city of Jowhar to less than a third of typical levels for that time of year, with some ground reports indicating the river was completely dry (United Nations Office for the Coordination of Humanitarian Affairs, 2017). Increasing conflict over land and water access may further exacerbate recent conflicts between Oromo and Somalis (Beyene, 2017; BBC News, 2017). This speaks to the need for data collection on the physical environment to be collected alongside engagement with local people. Where and how do communities interact with the hydrologic system? Which wetlands are most important and why? Can cultural and livelihood services, such as livestock watering at horas, be maintained with limited impact to the functioning of the larger hydrologic system? What changes to the system have been observed? Moreover, if—as my results suggest—local geology is a primary control on wetland distribution and function, could it also serve to buffer the impacts of wetland degradation due to grazing? Integrating this information with my conceptual flow model would be a powerful tool for understanding the resilience of the headwaters and downstream systems to shocks. This could be accomplished through interviews, social network mapping, and participatory GIS, which would help to situate current wetland functions within the context of current and past human activities. Another outcome would be the rebuilding of trust between local people and park managers, provided they are fully involved in the decision making process. This could be done alongside calls for a forest and fire management plan (Johansson, 2013) that is co-developed with local people and takes into account their needs and knowledge of the landscape (Tadesse et al., 2011).

Connections to other tropical alpine landscapes

Connectivity between land change and hydrologic processes are not well understood in tropical mountain regions (Polk et al., 2017). There is an urgent need to move beyond conceptualizations of tropical mountains as remote canaries in the coal mine for climate change (Zimmerer et al., 2017). Just as insights from the volcanoes of Hawaii and Oregon inform research in the Bale Mountains, the Bale Mountains may inform processes in Kilimanjaro and the Andes, which are currently undergoing deglaciation. While these systems are distinct, there are striking similarities in vegetation, including cushion plants in wetlands and bogs among the Andes, Bale, and New Guinea (Dullo et al., 2015). Better understanding of the processes in Bale could serve as a foreshadowing and provide information for prediction and mitigation of impacts to the hydrology and communities in these areas. Such studies are often hindered by physical and political hurdles which make fieldwork difficult and expensive. There is thus a need for straightforward approaches to modeling in tropical alpine environments that can extract the most amount of information from scarce data (Buytaert et al., 2011). My methodological approach may help to address these gaps, as it requires only free and globally available remote sensing data and limited amount of field data.

Conclusions

I conducted the first study of Afroalpine wetland seasonal dynamics and geomorphic function in the Bale Mountains, Ethiopia. My results show that perennial wetlands occupy just 4% of the Afroalpine area, and that these more than double in extent between the dry and wet season. Furthermore, the majority of the perennially saturated areas are sustained by groundwater from upstream springs and seepage slopes. Results also indicate the existence of a functional continuum based on geologic and glacial legacies, with higher elevations being largely ephemeral and lower elevations largely perennial. This typology serves as a starting point for much needed studies on surface-groundwater connectivity, and can be used to target conservation, field assessments, and monitoring of change.

I also demonstrated how correlative distribution modeling approaches can be used to gain insights into ungauged, often inaccessible tropical alpine environments. Coupling these efforts with hydrogeomorphic assessments can produce understanding that goes beyond what is possible with traditional land cover mapping. I also demonstrate the utility of using dry season imagery for such research, which is necessary in tropical alpine environments because of the persistent cloud cover and saturation in the wet season. This speaks to the value of timing field data collection with coincident satellite image acquisition, which adds confidence and interpretability to resulting predictions.

My results underscore the fact that the current hydrologic system of the Bale plateau is the product of multiple legacies that overlap in space and time. The first is the geologic history, which largely influences when and where water flows throughout the dry season. The second is the landforms left by glacial and periglacial processes, which determine wetland hydrogeomorphic setting and function. The final, and perhaps most pertinent, are the social legacies, which include those of prehistoric human inhabitants as well as those from recent and ongoing development. The pressures on the Bale Mountains are not simply a product of population growth; they are in part the legacy of government policies that displace lowland communities and drive them into higher elevations. This continues today with large-scale hydropower projects and land concessions that feed urban markets at the expense of rural livelihoods (Chignell and Laituri, 2016). Sustainable and equitable management policies for socio-hydrological systems must consider cross-scale and cascading feedbacks through time and space (Carey et al., 2014; Polk et al., 2017). This will require not only additional data collection and monitoring, but conscious effort to develop research and management frameworks that are holistic and inclusive of multiple perspectives. This combination of deductive, data-driven, and community-led approaches will help to guard against defaulting to catastrophic narratives and one-sided management prescriptions.

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APPENDIX 1 – PAN-SHARPENING ASSESSMENT

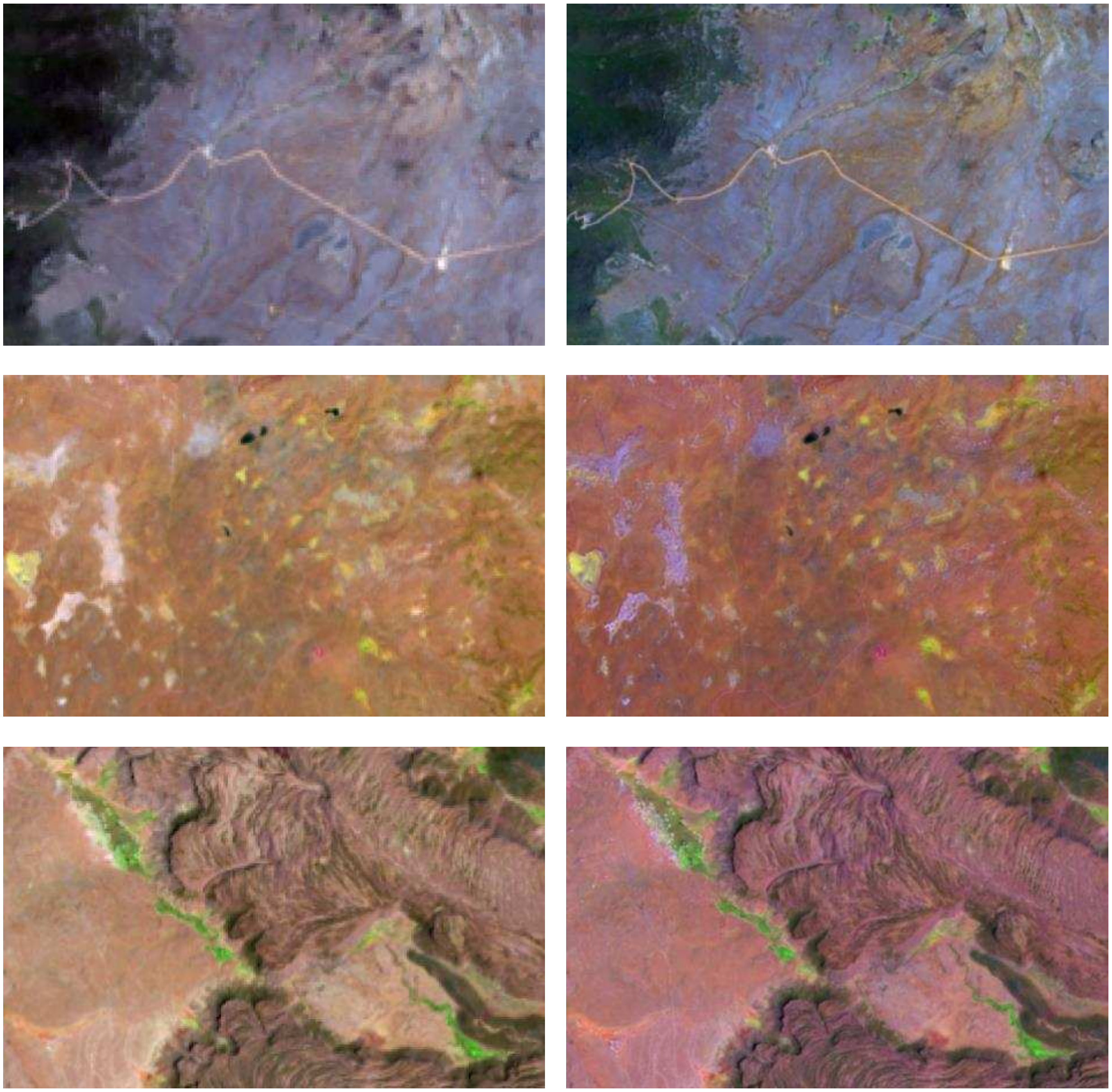


Figure A1: Qualitative evaluation of Gram-Schmidt pan-sharpening. Top row: Sharpening of linear features such as the riparian area and road (true color). Middle row: Enhancement of kettle lake edges in the central plateau (6-5-4 false color). Bottom row: Increased detail of lava flow toe and emerging wetlands near Morobowa region.

Table A1: Quantitative evaluation Gram-Schmidt pan-sharpening. Pearson's correlation coefficient and Global Root Mean Square Error (RMSE) indicate the level of agreement between the bands of the original 30 m resolution multispectral image and the pan-sharpened 15m image (downsampled to 30 m to enable pixel-to-pixel comparison). For correlation, a value of 1 indicates perfect agreement. For RMSE, values closer to 0 indicate better agreement.

	Deep Blue (B1)	Blue (B2)	Green (B3)	Red (B4)	NIR (B5)	SWIR 1 (B6)	SWIR 2 (B7)
Correlation	0.28	0.84	0.97	0.99	0.91	0.98	0.98
RMSE	0.015	0.015	0.016	0.021	0.032	0.037	0.027

Note: Deep Blue (B1) is not used in the tasseled cap transformation; thus its low correlation score does not influence any subsequent analyses in the modeling workflow.

APPENDIX 2 – STREAM NETWORK MODELING

I used TauDEM v5.3 software and its associated ArcGIS toolbox to model the Afroalpine hydrography of the plateau. I prepared the clipped DEM using the *Pit Remove* tool to fill, which ensures that subsequent algorithms are able to solve for downstream flow direction. I then computed *D8 Flow Directions* and *D8 Contributing Area*, which produce a raster model of the accumulation of flow from each cell down the landscape. Conventional hydrologic modeling requires a user-defined threshold for flow accumulation, representing the point at which flow initiates the creation of a stream channel. However, TauDEM is able to determine this threshold objectively using the drop analysis approach developed by Tarboton, et al. (1991, 1992), and Tarboton and Ames (2001). To do so, I used the *Peuker Douglas* tool to identify upwardly-curved cells from the D8 contributing area using the method developed by Peuker Douglas (1975) and further explained by Band (1986). This results in a raster layer resembling a proto-channel network which I used as input in the *Peuker Douglas Stream Delineation* tool. This conducts a drop analysis to determine the most appropriate threshold to apply to the Peuker Douglas results and D8 contributing area raster grid. I converted the output of this tool to vector-based stream network and watershed boundaries using the *Stream Reach and Watershed* and *Watershed Grid to Shapefile* tools.

APPENDIX 3 – MODEL EVALUATION

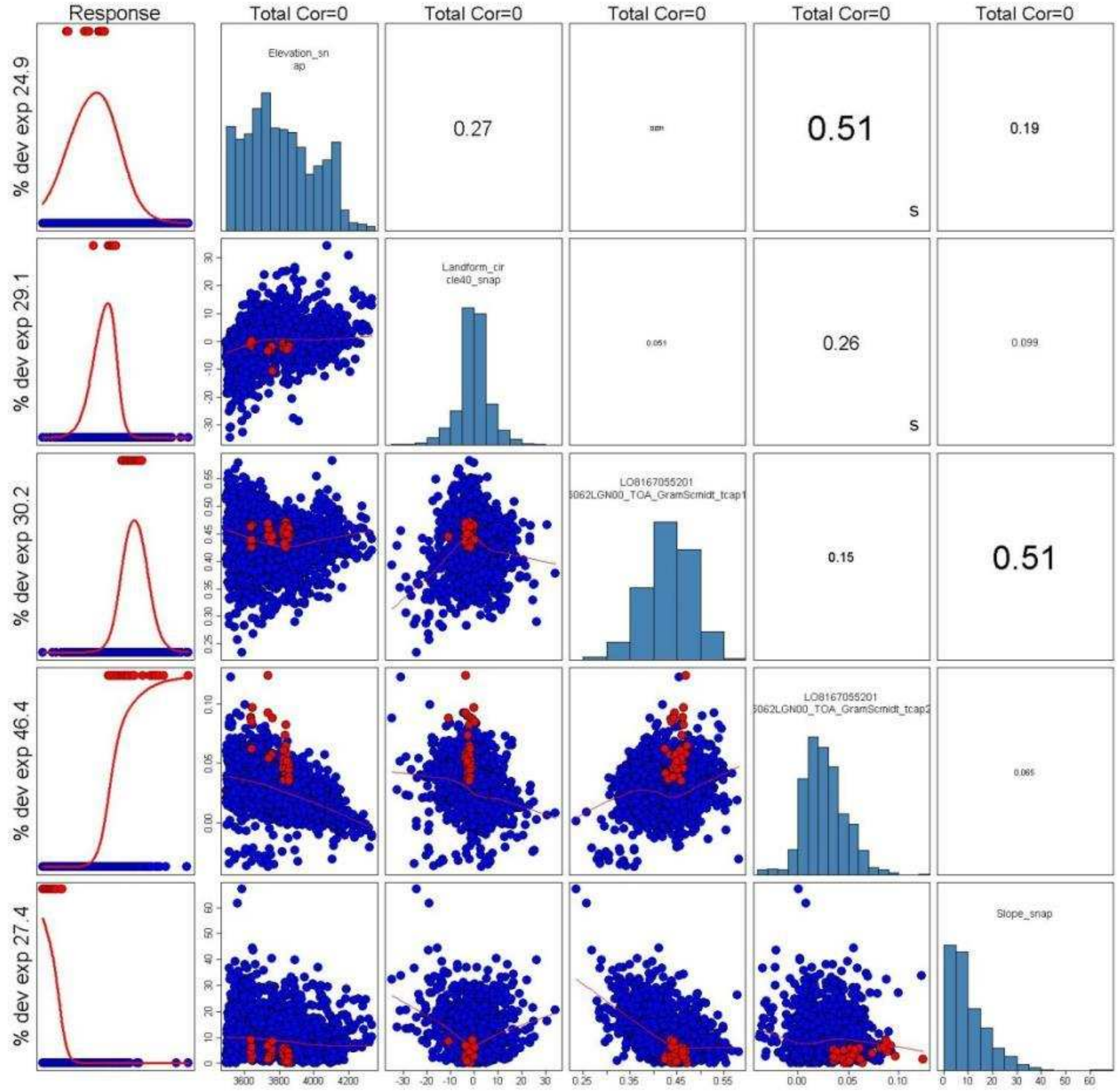
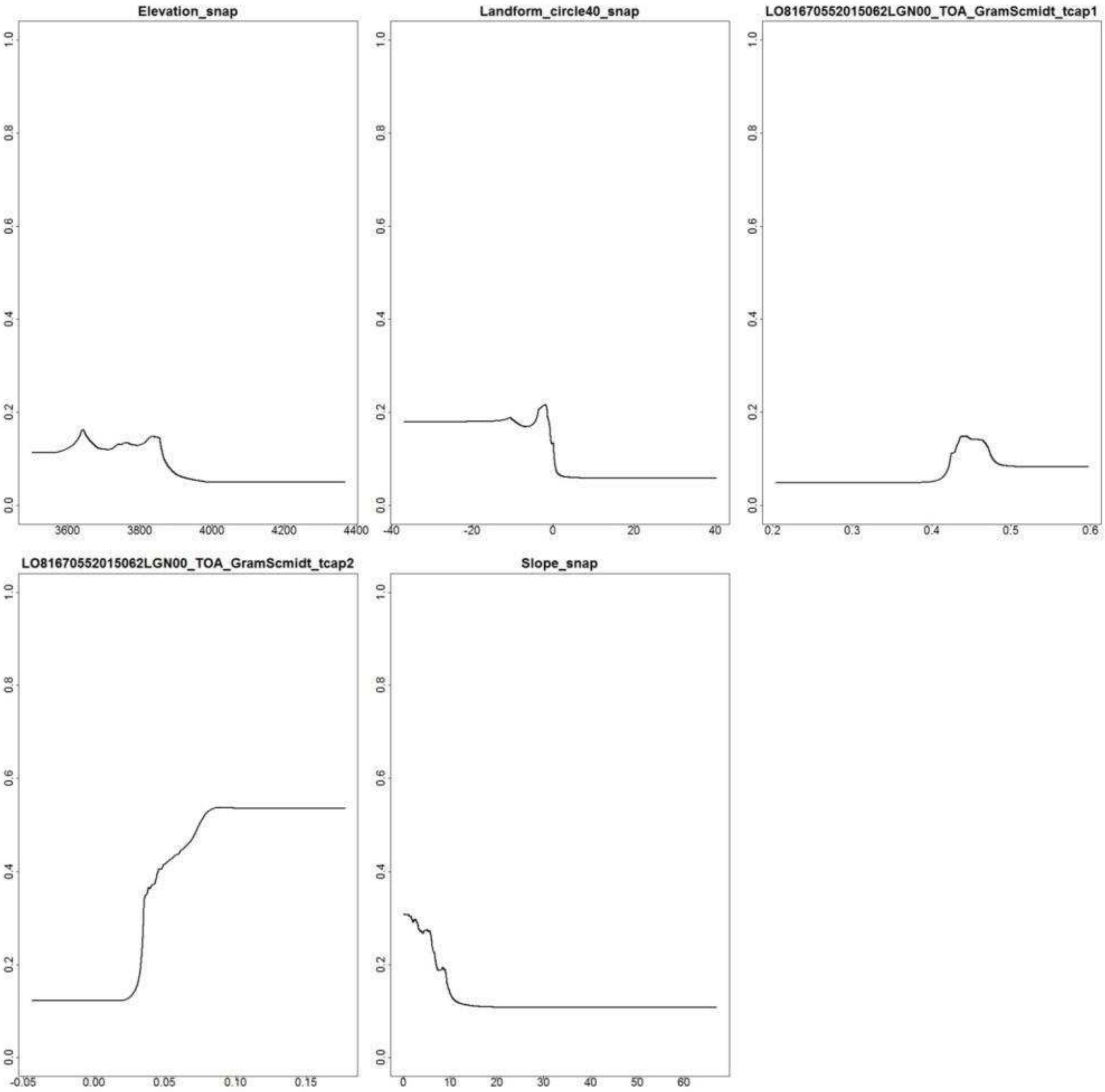


Figure A2: Covariate Correlation and Selection Matrix from SAHM.



Elevation_snap

Landform_circle40_snap

LO81670552015062LGN00_TOA_GramScmidt_tcap1

LO81670552015062LGN00_TOA_GramScmidt_tcap2

Slope_snap

Figure A3: Predictor variable response curves

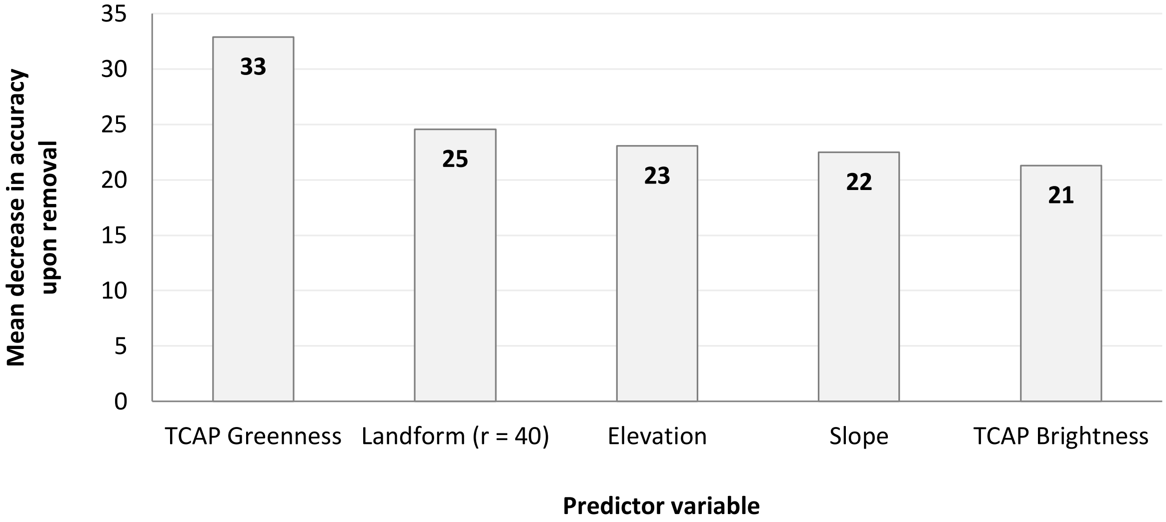


Figure A4. Final predictor variables used to develop the model and the mean decrease in model accuracy upon their removal.

APPENDIX 4 – SUPPLEMENTARY RESULTS FIGURES

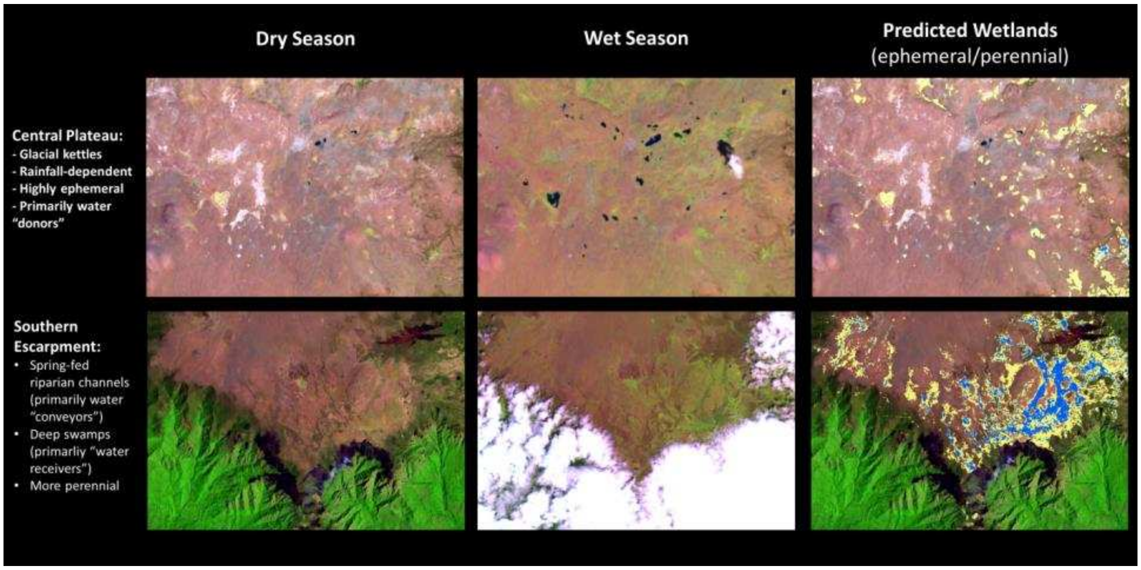


Figure A5: Dry and wet season comparison of Landsat 8 images and model predictions.

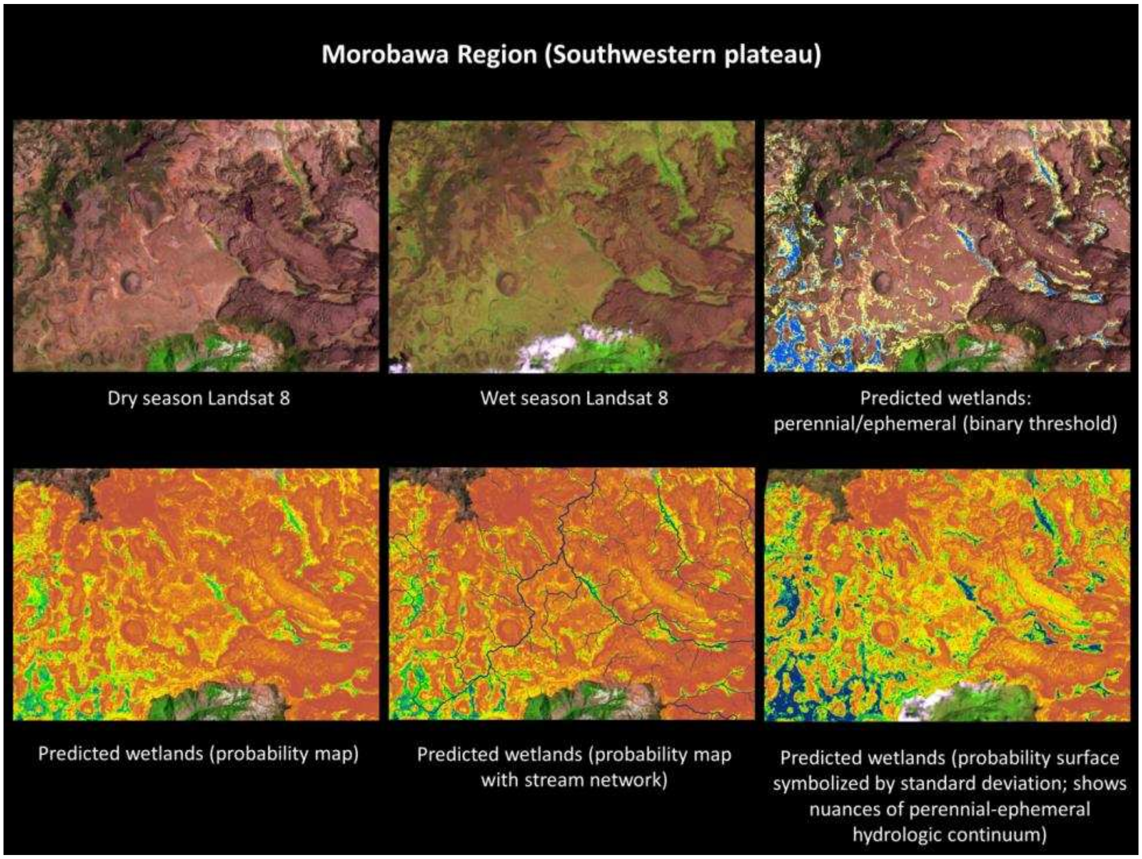


Figure A6: Model results in the Morobawa region on the Southwestern edge of the plateau.

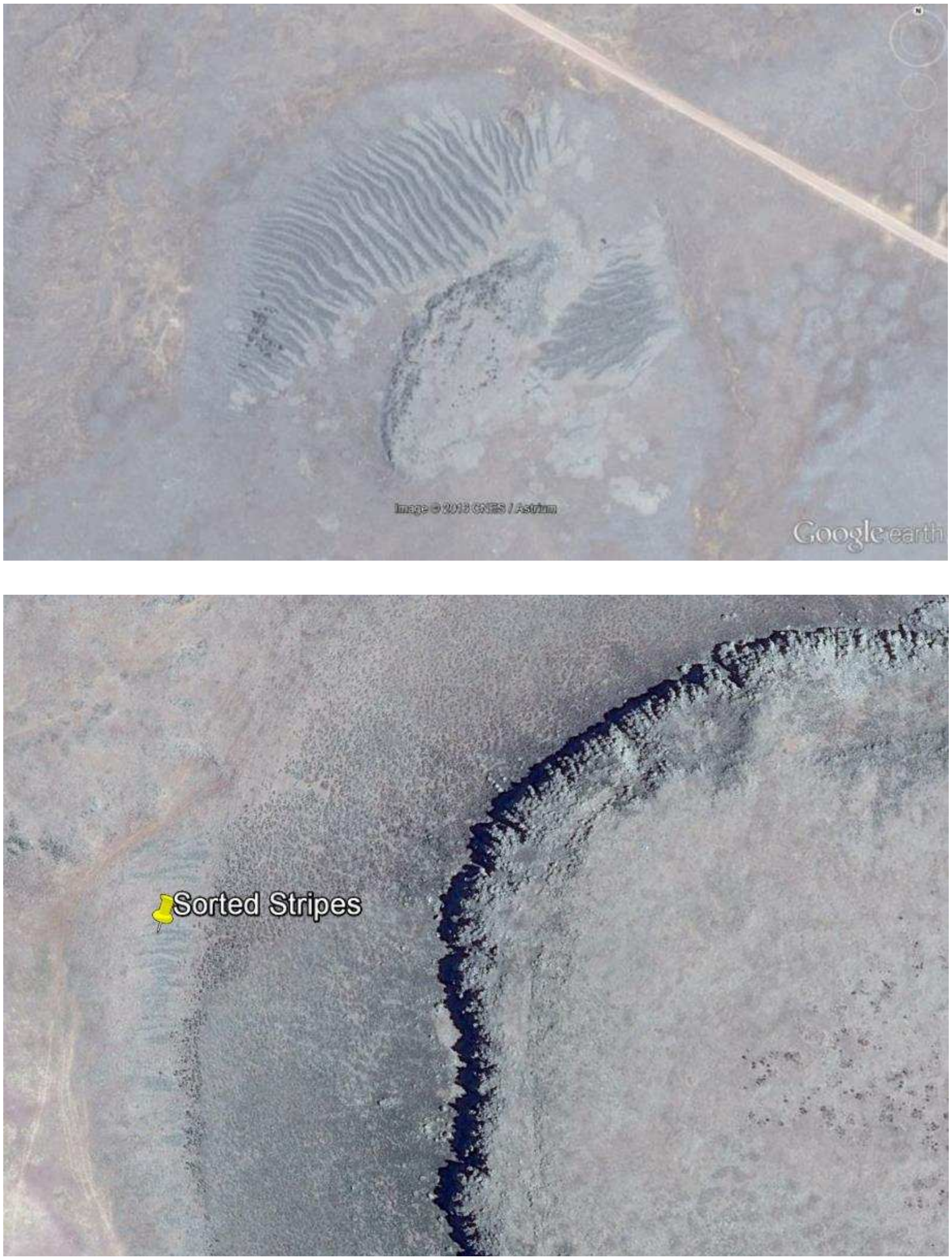


Figure A7: Google Earth images showing examples of periglacial landforms including sorted stripes and relic permafrost polygons on the Bale plateau. The top image is located at approximately 4,000m asl on the slopes of a relic volcanic plug, just outside the boundary of the ice cap during the last glacial maximum. The bottom image is located at the base of a volcanic plug at approximately 3800m in the Morobawa region.

APPENDIX 5 – FIELD SURVEY PHOTOGRAPHS AND POINTS

Figure A8: Ephemeral wetland at kettle fringe, dominated by *Carex* spp. tussock grasses.

Figure A9: Ephemeral wetland (throughflow), dissected by small headwater channels.

Figure A10: Heavily grazed ephemeral lentic wetland near with pipes and channels connecting to lakebed.

Figure A11. Heavily grazed riparian zone looking north. The perennial channel and riparian area emerges from seeps at the base of the cinder cones visible in the background and eventually flows off the edge of the southern escarpment.

Figure A12: Flow in the hyporheic zone just below the surface of the riparian area approx. 8 m from the wetted channel of Sida Stream.

Figure A13: Sida Stream just before southern escarpment.

Figure A14: Large canyon of weathered columnar basalt. A narrow, spring-fed stream flows at the bottom toward the southern escarpment.

Figure A15: Ephemeral wetland in perched valley near the edge of the upper lave flow toe.

Figure A16: First-order stream and riparian zone emerging from lava flow toe outcrop (left).

Figure A17: Spring-fed perennial riparian wetlands on southern slope of the plateau, with horses grazing the tussock grasses.

Figure A18: Water is conveyed from spring-fed riparian channel to large basin wetland at the southern escarpment. Smoke is the result of anthropogenic burning of Erica shrub on the escarpment.

Figure A19: Looking east across large perennial basin wetland near southern escarpment.

Table A2. Northings and Eastings (WGS 1984 UTM Zone 37N) of point locations of perennial wetlands observed during the field survey (February 28 – March 3, 2015). These were the presence points used to develop the distribution model of perennial wetlands.

ID	Northing	Easting
1	750822.6089	586555.46
2	750787.649	586540.4872
3	750510.506	586484.9064
4	750475.8108	586496.8976
5	750155.3937	586549.2446
6	750105.8394	586533.6321
7	750068.0031	586517.448
8	749998.2878	586477.1134
9	749810.0226	586347.1239
10	749787.2076	586321.964
11	749693.2296	586249.8406
12	749528.5288	586198.1648
13	749501.297	586176.3271
14	749326.7885	586144.3378
15	749590.4396	586197.8442
16	750260.2821	586531.1724
17	751158.2384	586680.6763
18	751195.3405	586721.2835
19	751206.7808	586753.9756
20	751264.1233	586868.0382
21	751340.2435	586903.4983
22	747781.9722	594927.7135
23	747720.4055	594935.669
24	747652.6754	594959.4396
25	747197.5789	594999.367
26	747062.1205	595047.9032
27	746931.2779	595143.2919
28	745520.1262	597500.4776
29	745456.4208	597670.6884
30	745204.3772	598174.3612
31	745261.8204	598148.394
32	745311.7323	598115.0355
33	750861.337	586576.1731
34	748633.1319	594090.8633