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The Bale Mountains of Ethiopia contain the largest contiguous area of alpine habitat in Africa. The region provides critical water resources and other essential environmental services to highland communities, endemic wildlife, and millions of downstream people in East Africa. Increasing land use change has created concern over degradation to headwater wetlands and potential impacts on hydrologic regimes. Baseline understanding of wetland dynamics is lacking, however, and little is known about their function in the regional hydrologic system. We used remote sensing, machine learning, and field surveys to map the distribution of Afroalpine wetlands in the Bale Mountains. We developed a wetland typology based on hydrogeomorphic characteristics and a conceptual model of surface-groundwater flow. Our results show that wetland extent more than doubles between wet and dry seasons and that only 4 percent of the Afroalpine zone is saturated year-round. We also found evidence of a hydrologic continuum based on volcanic and glacial legacies, with wetlands at elevations above approximately 3,800 m asl likely to be ephemeral and wetlands at lower elevations tending to be perennial. Further interpretation suggests that local geology is a principal control on wetland distribution and hydrologic attenuation in the Bale Mountains. This lays the foundation for further research into surface–groundwater connectivity, climate change impacts, and conservation planning. *Key Words: Afroalpine, Ethiopian highlands, HGM classification, mountain water tower, tropical alpine.*

埃塞俄比亚的贝尔山群包含非洲最大的连续高山栖地。该区域为东非的高原社群、该地特有的荒野生活，以及数百万居下游居民提供关键的水资源与其他重要的环境服务。逐渐改变的土地使用，已造成对河流源头湿地的侵蚀以及对水文体制的潜在冲击之隐忧。但我们却缺乏对湿地动态的基本理解，而其在区域水文体制中的角色亦鲜为人知。我们运用遥测、机器学习、以及田野调查，绘製贝尔山群非洲高地湿地的分佈。我们根据水文地貌特徵与地表与地下水迳流的概念模型，发展出湿地地形学。我们的研究结果显示，湿地范围在乾季与雨季之间增加两倍以上，且仅有百分之四的非洲高地地带终年呈现饱和。我们同时根据火山和冰河遗迹，发现水文持续性的证据，其中高于海拔约三千八百公尺的湿地，可能仅只是短暂存在，而位于低海拔的湿地则倾向终年存在。进一步的诠释显示，在地的地质，是贝尔山群的湿地分佈与水文减弱的的主要控制。此一发现为有关地表与地下水连结、气候变迁冲击，以及保育计画之未来研究打下基础。*关键词：非洲高山地带，埃塞俄比亚高地，HGM分类，山区水塔，热带高山地带。*

En las Montañas Bale de Etiopía se halla el área contigua más grande de hábitat alpino en África. Esta región genera los recursos hídricos críticos y otros servicios ambientales esenciales para las comunidades de montaña, la vida silvestre endémica y para millones de personas que viven aguas abajo en África Oriental. El incremento de cambios en el uso del suelo ha causado preocupación por la degradación que sufren las cabeceras húmedas y por los impactos potenciales sobre los regímenes hidrológicos. Sin embargo, se carece de conocimientos básicos sobre la dinámica de los humedales y poco se sabe de su función en el sistema hidrológico regional. Usamos percepción remota, aprendizaje con máquina y estudios de campo para mapear la distribución de los humedales afroalpinos en las Montañas Bale. Desarrollamos una tipología de humedales con base en las características hidrogeomórficas y en un modelo conceptual del flujo de aguas superficiales y freáticas. Nuestros resultados indican que la extensión de los humedales es más del doble entre las estaciones de lluvias y de sequía, y que tan solo un 4 por ciento de la zona afroalpina se satura durante todo el año. También hallamos evidencia de un continuo hidrológico basado en herencias volcánicas y glaciales, con humedales a elevaciones aproximadamente por encima de los 3.800 m sobre el nivel del mar, probablemente efímeros, y humedales a elevaciones inferiores que tienden a ser perennes. Una interpretación adicional sugiere que la geología local es el control principal de la distribución de los humedales y de la atenuación

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hidrológica en estas montañas. Esto sirve de base para una mayor investigación de la conectividad del agua de superficie y la subterránea, los impactos del cambio climático y los planes de conservación. *Palabras clave: afroalpino, tierras altas etíopes, clasificación HGM de la torre de agua montañosa, alpino tropical.*

Tropical alpine environments provide critical environmental services at local, regional, and global scales (Célleri and Feyen 2009; Buytaert, Cuesta-Camacho, and Tobón 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, Cuesta-Camacho, and Tobón 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, Cuesta-Camacho, and Tobón 2011; Mosquera et al. 2015). Because 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 semiarid environments (Viviroli et al. 2007; Buytaert, Cuesta-Camacho, and Tobón 2011).

Tropical alpine wetlands represent key components of these systems. Filtration through wetland vegetation and soils regulates the movement of water from the headwaters to lower elevations (Fonkén 2014; Mosquera et al. 2015), preventing erosion and setting the biogeochemical state for downstream flows (Buytaert, Cuesta-Camacho, and Tobón 2011). Mountain wetlands provide drinking water, provide building materials, and have cultural significance for many highland communities, simultaneously providing crucial water and grazing sources for livestock and habitat for wildlife during dry months (Bragg 2015).

Although these benefits are increasingly recognized, fundamental knowledge gaps on ecohydrological processes remain in tropical watersheds (Hamel et al. 2018). To date, most research on tropical alpine hydrology has focused on Andean wetlands (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, Alvarez, and Hemp 2016; Grundling and Grootjans 2016).

The Bale Mountains of south-central Ethiopia contain the largest contiguous area of tropical alpine habitat in Africa (commonly referred to as "Afroalpine"; Figure 1). The region is a globally important biodiversity hotspot and supports a host of endemic and endangered plants and wildlife (Evangelista et al. 2012; Kidane, Stahlmann, and Beierkuhnlein 2012). The physiography of the area results in orographic precipitation that falls as rain and snow across its Afroalpine plateau. This water collects in numerous alpine lakes and wetlands (Figure 2), which regulate water quality, nutrient cycling, groundwater recharge, and discharge timing throughout the dry season (Frankfurt Zoological Society 2007). The area serves as the headwaters of five major rivers that flow across the arid lowlands of eastern Ethiopia and into Somalia and northern Kenya (Frankfurt Zoological Society 2007). These rivers are the only perennial source of water for approximately 12 million people, who rely on it for irrigation, livestock, industry, and human consumption (Hillman 1988; Nelson 2011).

Preservation of this hydrologic system is a primary purpose of the Bale Mountains National Park (BMNP), which was established in 1969 (Nelson 2011). In 1983, an all-weather road was completed across the eastern Afroalpine zone of BMNP, stimulating travel and development (Hillman 1988). The concurrent development of large-scale mechanized agriculture in the surrounding region pushed thousands of lowland pastoralists into the mountains (Hillman 1988; Flintan et al. 2008; Fial 2011). Government villagization programs led to increasing settlement and cultivation and in 2003 it was estimated that 40,000 people lived within the park boundaries (Frankfurt Zoological Society 2007). Grazing that was once seasonal now occurs year-round (Fial 2011). Competition for land and natural resources has resulted in conflicts between local people and park management (Mamo and Pinard 2011), which considers human activities the single most important cross-cutting issue for the BMNP (Nelson 2011). Specifically, concern exists that overgrazing of the Afroalpine vegetation will increase erosion and affect nutrient loading, biogeochemical states, and connectivity of water and sediment (Frankfurt Zoological Society 2007; Fial 2011; Dullo et al.

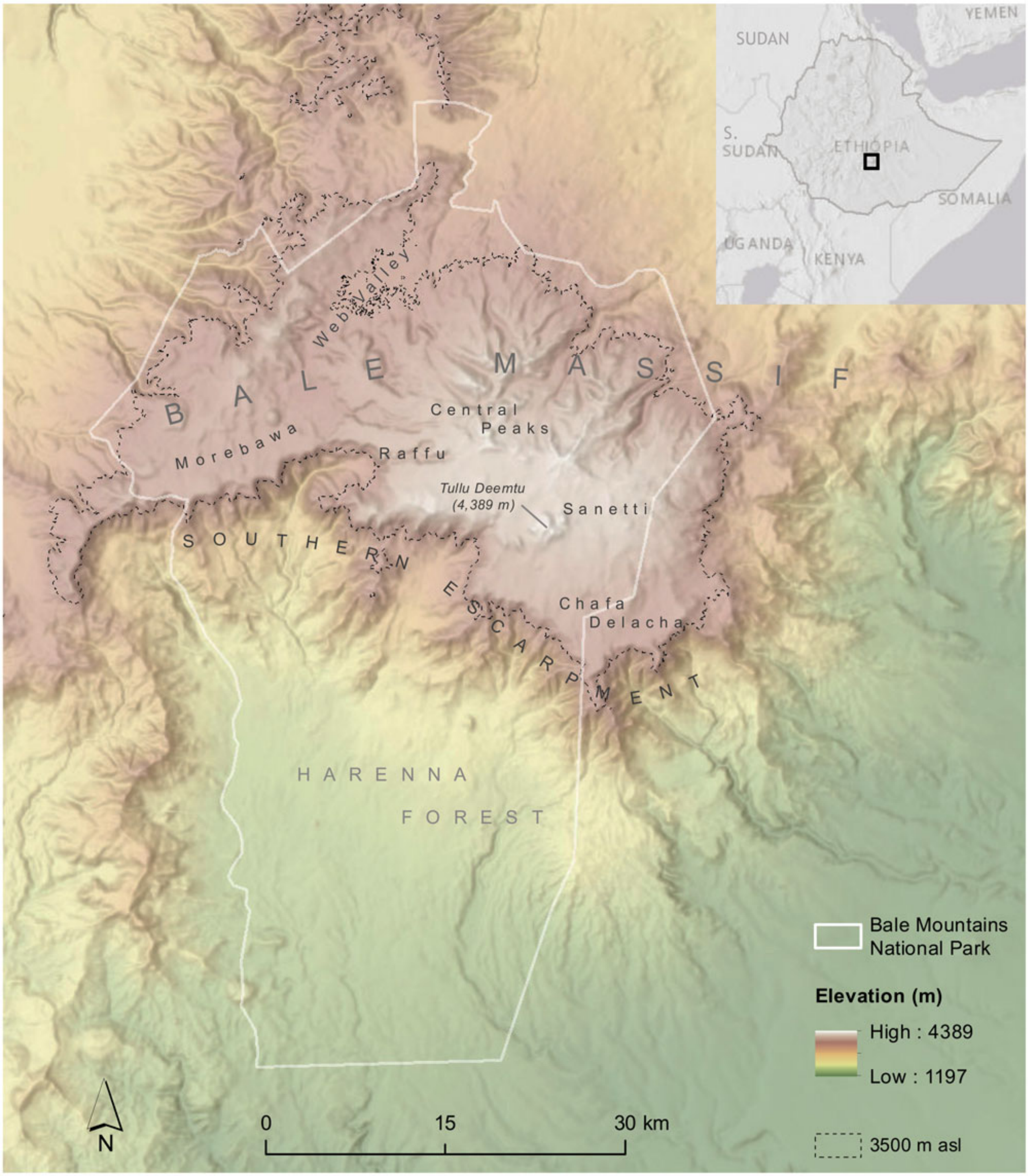

Figure 1. The Bale massif, Bale Mountains National Park, and surrounding region. (Color figure available online.)

2015). Although these concerns are warranted, connectivity between land change and hydrologic processes is not well understood in tropical mountain regions (Polk et al. 2017). Little work exists on the groundwater of the Bale Mountains (Kebede 2013), and we are not aware of any studies focused on wetland dynamics, despite this being a top research priority of BMNP for over a decade (Frankfurt Zoological Society 2007). Thus, basic research on Afroalpine wetlands and their relationships to the hydrologic system is needed for effective resource management and conservation.

Figure 2. Afroalpine habitat of the Bale Mountains, Ethiopia (short wet season conditions). Wetland complex is visible in the background; endemic *Lobelia rhynchopetalum* dominates the foreground. Image captured in the Sanetti region, 22 May 2014. (Color figure available online.)

In this article, we combine field surveys, remote sensing, and machine learning to map the distribution of perennial and ephemeral vegetated wetlands within the Afroalpine zone of the Bale Mountains. We interpret these results using field observations and ancillary data, and draw on the literature from similar alpine regions to develop a wetland typology. Finally, we propose a conceptual flow model of the hydrologic system and discuss its implications for future research and management.

Methods

Study Area

The Bale Mountains are the remnants of a massive shield volcano, composed of horizontally bedded basalt and trachytic lava flows from the late Neogene period (Berhe et al. 1987; Hillman 1988). This created a large massif that was separated from the western highlands of Ethiopia by the formation of the Rift Valley (Hillman 1988). The uppermost elevations of the massif form a low-relief plateau interspersed with numerous volcanic plugs and cinder cones. Many of the cinder cone peaks are the product of recent eruptions, dated at only 2.5 million years old (F. M. Williams 2016). The dominant peaks occur in the central part of the plateau, with the highest summit being Tullu Deemtu (4,389 m asl).

Like many tropical mountain systems, the Bale massif exhibits clear ecological zonation based on elevation (Uhlig 1988; Woldu, Feoli, and Nigatu 1989; Miehe and Miehe 1994). The highest of these, the Afroalpine zone, includes 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 occurs in diurnal freeze–thaw patterns during the colder months above 3,600 m asl (Grab 2002). The region has a bimodal climate, with a short wet season from March to May and a longer wet season from July to October (Hillman 1988; Buytaert, Cuesta-Camacho, and Tobón 2011). Rainfall is approximately 1,150 mm per year on the northern slopes and decreases southward toward the central part of the plateau (Hillman 1988). Moisture increases again at the southern escarpment, where regular fog and cloud misting provides water to the Harenna Forest (Hillman 1988; Woldu, Feoli, and Nigatu 1989). Miehe and Miehe (1994) observed that elevations above 4,000 m asl could form temporary snowpacks reaching depths of up to 20 cm. Although no permanent snowpacks exist today, frost is common above 4,000 m asl and the plateau receives precipitation in the form of hail or snow that can remain for days (Eggermont et al. 2011). Paleoclimatic and geomorphic studies show evidence of at least two glaciations, the most recent occurring 2,000 years ago (BMNP 2017). Glaciation took place in two forms: a 30-km^2 ice cap centered over Tullu Deemtu and a number of valley glaciers descending down the northern slopes of the plateau (Osmaston, Mitchell, and Osmaston 2005). In total, 180 km^2 is 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; Osmaston, Mitchell, and Osmaston 2005).

Evidence from pollen and peat records shows a shift in the climate at the end of the Pleistocene, which initiated the retreat of the glaciers (Mohammed and Bonnefille 1998). This legacy remains in a variety of glacial and periglacial landforms across the plateau (Grab 2002; Osmaston, Mitchell, and Osmaston 2005). To the south of Tullu Deemtu, patterned ground, including stone circles and sorted stone stripes, shows visible evidence of frost heave cycles. Disrupted drainage patterns form a series of channels that run north–south along the plateau. To the east, kettles created during glacier recession host numerous lakes and wetlands in depressions 1 to 2 m lower than the average surrounding elevation (Eggermont et al. 2011). Their small size, shallow depth, and dependence on orographic rainfall contribute to their high inter- and intraannual variability in moisture and extent (Eggermont et al. 2011). Riparian areas and marshes form in the Web Valley and other depressions that descend north and northwest from the central plateau, whereas deep sedge swamps occur near the edge of the southern escarpment (Tallents and Macdonald 2011). Numerous mineral springs (*horas* in the local Oromo language) occur across the Afroalpine zone and the surrounding region, particularly the Harenna Forest (Chiodi and Pinard 2011). Together, the lakes, wetlands, rivers, and springs comprise the principal 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), and wetland species such as *Haplocarpha rueppellii* and *Ranunculus* sp. Cushion plants and *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 1963; Flintan et al. 2008), and glacial meltwater might have provided a reliable source of water for prehistoric people and wildlife at the onset of the Holocene. The Afroalpine habitat is expanded through rotational burning of *Erica* by pastoralists seeking to improve pasture for their livestock (Johansson 2013). Most pastoralists manage livestock under *godantu*, a vertical transhumance system involving seasonal journeys to the plateau from the surrounding region to allow animals to graze the Afroalpine vegetation, drink at *horas* (Chiodi and Pinard 2011), and access salt from the soils (Flintan et al. 2008). The *horas* in particular are extremely valuable for the livelihoods, identities, and spiritual practices of Oromo people (Chiodi and Pinard 2011). Peak livestock numbers occur in the Afroalpine in the wetter months, from April to August, when animals are moved from lower pastures where crops are grown (Flintan et al. 2008).

Modeling Overview

To map the extent of Afroalpine wetlands, we adapted a correlative distribution modeling approach (Figure 3) developed for use in data-scarce mountain regions (Chignell et al. 2018). The approach finds relationships between environmental variables and locations where wetlands are known to be present or absent, and uses these to predict distribution across the landscape. It employs a presence–background technique, combining field observations of presences with pseudo-absences created by sampling the “background” of the modeling space (Barbet-Massin et al. 2012). This is useful for modeling rare classes with limited presence data that are dependable but not perfectly random (Pearce and Boyce 2006).

Model Inputs

We used a variety of types of data to develop the wetland distribution models (Figure 3A). These are summarized in Table 1 and described in detail in the following sections.

Field Data. We carried out a scoping trip to the study site in May 2014 (short wet season), followed by a field survey from 28 February through 2 March 2015 (dry season). The survey was conducted during the end of the dry season when any wetlands with flowing water are assumed to be perennial. Sampling

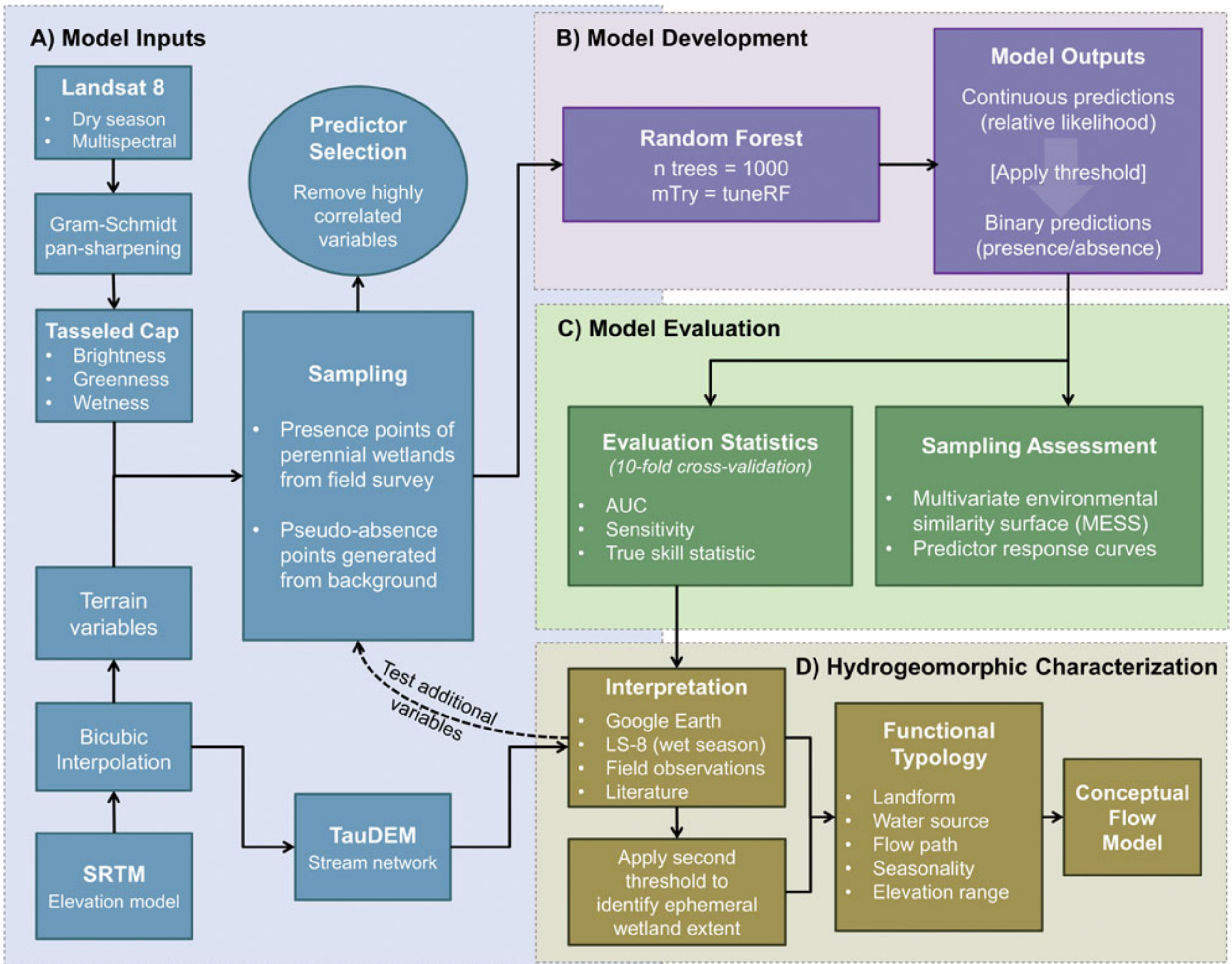

Figure 3. Flowchart of the study methodology. (Color figure available online.)

Table 1. Summary of data used in the study

Data type	Specifications	Date	Source
Presence points of wetland occurrence	Latitude/longitude, photographs, presence/absence of moisture	2015	Field survey
Landsat 8 imagery (wet and dry seasons)	9-band multispectral (Operational Land Imager)	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

was opportunistic but targeted, guided by prior examination of Landsat data and high-resolution imagery from Google Earth. At each site ($N = 146$), we recorded latitude and longitude, the presence or absence of moisture at the surface, and photographs in each of the cardinal directions. In addition to the Sanetti region, we walked longitudinal transects along two spring-fed streams that were flowing at the time of the survey. We followed both channels downstream until they reached the southern escarpment. For wider stream reaches with deeper channels, we recorded latitude and longitude along the vegetated stream bank using a Global Positioning System (GPS) unit. For narrower reaches with shallow channels, we stood in the thalweg to avoid spectral mixing with upland vegetation outside the wetted margin. We recorded all points at least 30 m apart to prevent pseudo-replication in subsequent model development. With the exception of the cinder cone summits, the survey covered the entire elevation gradient of the Afroalpine zone. A selection of photographs, descriptions, and location data from the field survey are available in the supplemental materials.

Satellite Imagery. We acquired an L1T terrain-corrected Landsat 8 image for path 187, row 42 from the U.S. Geological Survey Earth Explorer data portal. This image was captured on 3 March 2015, which represents late dry season conditions and is nearly coincident with the dates of the field survey. We 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, we did not perform further corrections so as to avoid unnecessarily injecting error into the spectral values (Young et al. 2017). We also acquired a Landsat 8 image for the same scene, captured on 11 November 2014. This was one of the only wet season images in the Landsat archive to show large parts of the plateau without cloud cover. We used this image to aid our evaluation and interpretation of the model results.

For 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, we pan-sharpened the 30-m multispectral bands with the 15-m panchromatic band using the Gram–Schmidt (GS) method (Laben and Brower 2000) in ENVI. The GS method has been shown to be highly effective at preserving the spectral and spatial fidelity of the original multispectral data (Kumar, Sinha, and Taylor 2014; Sarp 2014) and has enabled accurate mapping of small ($\geq$0.20 ha) wetlands using Landsat imagery (Frohn et al. 2009; Frohn et al. 2012). We assessed the quality of the GS pan-sharpening using qualitative and quantitative approaches. For the qualitative assessment, we used a variety of band combinations to highlight known features on the landscape (e.g., field-validated wetlands, roads, vegetation communities) and visually inspected how well their spectral and spatial characteristics were preserved between the original and pan-sharpened data. For the quantitative assessment, we resampled (bilinear) the 15-m pan-sharpened data to 30-m and calculated band-by-band Pearson's correlation coefficient and root mean square error between the sharpened data and the original 30-m data (Gangkofner, Pradhan, and Holcomb 2008; Ashraf, Brabyn, and Hicks 2012; Ai et al. 2016). Pearson's correlation coefficient scores ranged from 0.84 to 0.99 and root mean square error scores ranged from 0.015 to 0.037, indicating strong agreement between the pan-sharpened and original multispectral data.

Following the assessment, we applied a tasseled cap (TCAP) transformation to the pan-sharpened multispectral bands (Baig et al. 2014). The TCAP is a commonly used technique that uses band-specific coefficients to orthogonally transform raw spectral values into a new set of uncorrelated bands (Crist and Cicone 1984; Crist 1985). TCAP bands 1, 2, and 3 are commonly associated with brightness, greenness, and wetness on the landscape.

Digital Terrain Data. To capture terrain characteristics, we acquired a 1 arc-second (approximately 30-m at the equator) Shuttle Radar Topography Mission digital elevation model (DEM) (National Aeronautics and Space Administration, 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, we 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 sixteen pixels and has been shown to be able to interpolate DEMs to finer spatial resolutions with minimal error propagation (Rees 2000; Kidner 2003; Shi, Li, and Zhu 2005). We used ESRI's ArcMap v10.3 and the 15-m DEM to derive maps of slope, dissection, landform, and roughness (Evans et al. 2014). We created each metric at different scales using a circular window, incrementally increasing the radius by five cells from five to forty to account for the variation in sizes of geomorphic features on the plateau. To support model interpretation, we generated a stream network using the Terrain Analysis Using Digital Elevation Models ArcGIS tool (Tarboton 2016).

Model Development

We used the Software for Assisted Habitat Modeling (SAHM; Morisette et al. 2013) for all model development and evaluation (Figure 3B). Specifically, we used the random forest technique (Breiman 2001), which is an ensemble classifier that generates numerous regression trees that are aggregated to produce a more accurate classification. It is well suited for presence–background modeling with small sample sizes (J. N. Williams et al. 2009) and high-dimensional, multisource data sets (Chan et al. 2012; Belgiu and Drăguţ 2016). To parameterize the model, we set *n tress* = 1,000 and used the *tuneRF* function to determine the *mTry* value that minimizes out-of-bag prediction error (Stevens et al. 2015).

Developing models within homogenous landscapes helps to reduce landscape variability (Kassawmar et al. 2018), which is important for distinguishing complex wetland signatures from surrounding features. This is particularly necessary in the Bale Mountains, because the moist vegetation on the surrounding escarpment would likely confound the model and be misclassified as wetlands. To isolate the Afroalpine habitat from the rest of the massif, we used ArcMap to extract elevations >3,500 m asl from the DEM. A small portion of this area fell outside the western edge of the Landsat scene, and we therefore clipped the extracted area to match the edge of the image. We also excluded a few peaks to the north of the BMNP that lie within the elevation range but are disconnected from the plateau. These refinements resulted in a final study area boundary of 1,042 km^2, which we used to clip all predictor variables prior to model development.

For presence data, we used only the wetland locations identified as perennial during the field survey ($n = 34$). For background locations, we 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. We extracted the values of each predictor variable at the locations of each of the presence and background points and examined the correlation between each pair of predictor variables. To prevent issues related to multicollinearity (Millard and Richardson 2013; Jarnevich et al. 2015), we retained only one of each pair of correlated predictors with a Spearman, Pearson, or Kendall correlation coefficient $|r| \geq 0.70$ for use in the final models (Dormann et al. 2013). We made these selections based on the percentage deviance explained from a univariate generalized additive model for each variable and ecological interpretation of the response curves. This is an iterative procedure in which an initial model is run, its outputs are evaluated and interpreted, and variables are added or removed for subsequent model runs. This process helps to refine the model by enabling multiple variables to be tested before a final selection is made (Jarnevich et al. 2015; West et al. 2017).

The final set of predictors is listed in Table 2. TCAP brightness was highly correlated with TCAP wetness, and we chose to keep the former because it accounts for the most variability in the image (Baig et al. 2014) and was 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

Table 2. Summary of predictor variables used to develop the model, as well as their associated environmental characteristics, source data, and references

Variable	Environmental characteristics	Reference	Included in final model
Brightness	Albedo	Baig et al. (2014)	Yes
Greenness	Cellular structure of green vegetation and photosynthetic activity	Baig et al. (2014)	Yes
Wetness	Soil and plant moisture	Baig et al. (2014)	Removed due to high correlation with brightness
Slope	Slope	N/A	Yes
Dissection	Dissection of the landscape	Evans (1972)	Removed due to high correlation with landform
Landform	Curvature/convexity (i.e., terrain shape)	Bolstad and Lillesand (1992)	Yes
Roughness	Terrain complexity/variance	Blaszczynski (1997); Riley, DeGloria, and Elliot (1999)	Removed due to high correlation with landform

with depressions, especially at finer scales (<15 cell radius). For the final model, we used landform at a 40-cell radius because of its percentage deviance explained and demonstrated ability to highlight hydrogeomorphic (HGM) features of wetlands in other landscapes (Van Deventer et al. 2014).

The model produced a continuous raster surface with cell values that represent the relative likelihood of occurrence of a perennial wetland. We used this continuous 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 objective threshold optimization method is recommended for use with models developed without true absences (Liu et al. 2013). To create a map of ephemeral wetlands, we manually selected a second threshold by comparing the probability surface to high-resolution Google Earth imagery and locations that possessed wetland vegetation and geomorphic characteristics but lacked moisture during our field survey.

Model Evaluation

We conducted a tenfold cross-validation to assess model predictions (Figure 3C). Cross-validation is repeated data splitting, in which multiple models are developed and tested with results averaged over the repetitions (Hastie, Tibshirani, and Friedman 2009). This approach is useful with small training data sets, because it makes use of all of the data points for training and testing and is, therefore, more robust to spurious results that can occur from simple data splitting (Jarnevich et al. 2015). We used this to calculate a series of evaluation statistics including area under the receiver operating characteristic curve (AUC; Fielding and Bell 1997), sensitivity (proportion of positive pixels correctly predicted), and the true skill statistic (TSS; Allouche, Tsoar, and Kadmon 2006). We paired these quantitative evaluations with critical examination and interpretation of the response curves and distribution maps, checking for overfitting and the "eco-plausibility" of the outputs (i.e., whether the predicted patterns make ecological sense; Jarnevich et al. 2015; Jarnevich et al. 2017). Finally, we generated a multivariate environmental similarity surface to measure the degree and location of extrapolation and interpolation across the study area (Elith, Kearney, and Phillips 2010).

Hydrogeomorphic Characterization

For wetland studies to be useful for conservation or management, 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). The final step in our workflow (Figure 3D) thus involved an HGM wetland characterization and development of a conceptual flow model for the hydrology of the Afroalpine zone. The HGM classification system (Brinson 1993; Smith et al. 1995) describes wetlands by their water source, hydrodynamics, and geomorphic setting. These characteristics are used to identify reference wetlands that are representative of a particular function and can be monitored for signs of change. The approach has been adapted to develop wetland classifications at local, regional, and national scales (Nielsen, Guntenspergen, and Neckles 2005; Brooks et al. 2011; Van Deventer et al. 2014). It is also the basis of the Landscape Position, Landform, Water Flow Path, and Waterbody (LLWW) system (Tiner 2014), which operationalizes the HGM concept to create inventories of wetland function using geographic information systems (GIS) and remote sensing. For this study, we adapted HGM and LLWW terminology to describe the wetlands predicted by the final distribution model. We used the following criteria to develop a wetland typology: (1) landform setting, (2) water source, (3) flow path, and (4) seasonality. Finally, we used this typology to create a conceptual flow model for the overarching hydrologic system.

Results

The final models (Figure 4) achieved high scores for AUC (0.99), sensitivity (0.80), and TSS (0.80), indicating good model performance. The discrete maps show that wetland and riparian zones occupy 17 percent (175 km^2) of the Afroalpine study site (4 percent perennial and 13 percent ephemeral). Of these wetlands, 23 percent (41 km^2) are perennial and 77 percent (134 km^2) are ephemeral. This indicates a decrease of 53 percent (93 km^2) in wetland area from the wet season to the dry season (Table 3). The multivariate environmental similarity surface showed that 98.8 percent of the study area fell within the range of sampled values, indicating low levels of model extrapolation. Detailed model

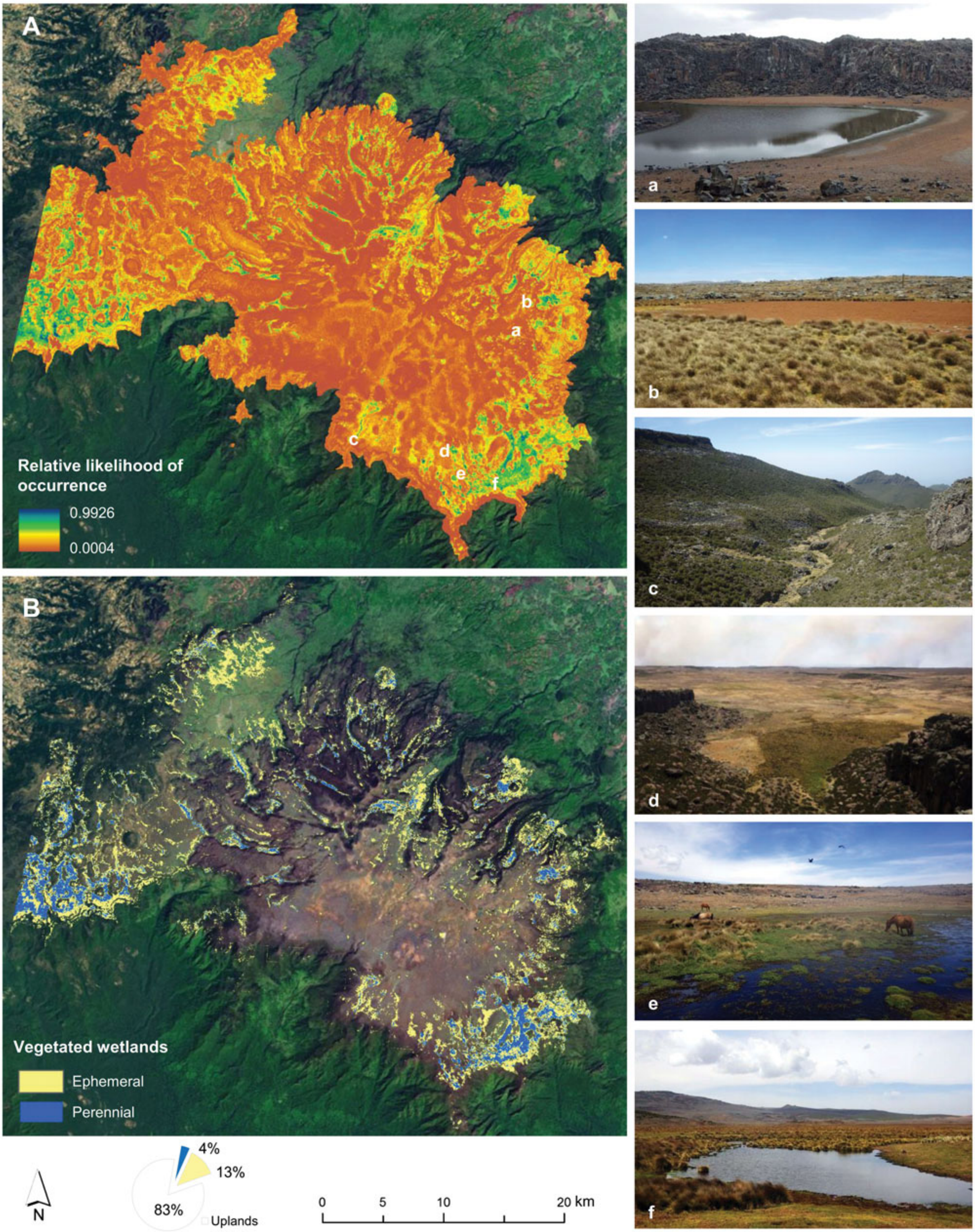

Figure 4. Predicted Afroalpine wetlands of the Bale massif. (A) Continuous model predictions showing relative likelihood of perennial wetland occurrence. (B) Discrete maps derived from continuous model (percentage of total area for each class listed in legend). Photographs of different types of wetlands in the region (not comprehensive): (a) Sanetti lake at low level; (b) dry kettle pond and vegetated fringe; (c) incised stream and riparian area; (d) seep emerging from base of outcrop and associated outflow channel; (e) perennial stream and floodplain; (f) extensive basin wetland fed by streams. All photographs captured between 28 February and 2 March 2015 (late dry season conditions). (Color figure available online.)

Table 3. Summary statistics of Afroalpine wetland and upland area in the Bale Mountains

Cover type	Area (km^2)	% of total wetland area	% of total Afroalpine area
Perennial wetland	40.93	23.4	3.9
Ephemeral wetland	133.81	76.6	12.8
Upland	867.44	0.0	83.2

Note: Total study area is 1,042.18 km^2.

results and spatial outputs are available in the supplemental materials.

Predictor influence was spread fairly evenly among the variables, signifying that the model captured biotic and abiotic controls on wetland distribution. TCAP greenness was the most influential variable, with a 33 percent decrease in model accuracy upon removal. Greenness values <0.03 show very low likelihood of occurrence, but values greater than 0.03 show increasing likelihood before leveling out at 0.08. This indicates that perennial wetlands are unlikely to occur in areas lacking photosynthetic vegetation. The response curve for landform shows a higher likelihood of occurrence in concave areas (value <0) as compared to convex areas (value >0), and the response curve for slope shows a low likelihood of occurrence on slopes steeper than 10°. Relative likelihood for TCAP brightness was highest between 0.42 and 0.48, indicating that perennial wetlands are most likely to occur in areas that are brighter than open water but darker than the bare or sparsely vegetated surfaces of the surrounding alpine environment.

The response curve for elevation is particularly interesting in that it shows a sharp decrease in the likelihood of perennial wetland occurrence between 3,800 and 3,900 m asl (Figure 5). The spatial outputs also reflect this pattern, because wetlands in the uppermost elevations 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. These are represented in the elevation response curve by the spike at approximately 3,650 m asl. The spatial outputs also show a gradient at the scale of individual wetlands, with core perennial patches surrounded by increasingly ephemeral margins. This

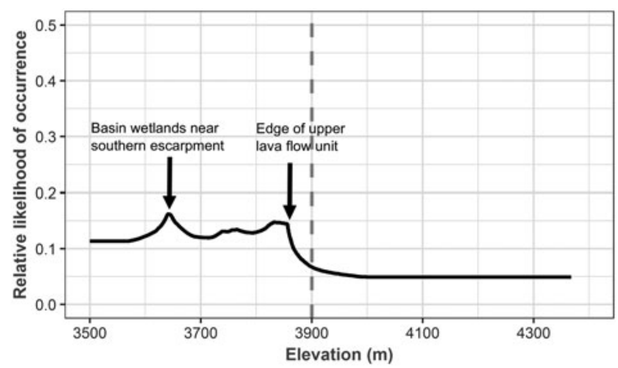

Figure 5. Response curve for elevation in the final random forest model. The *y*-axis represents the relative likelihood of perennial wetland occurrence, holding all other variables at their means (0–1 range has been rescaled to 0.0–0.5 to show detail). The dashed line indicates the transition from perennial to ephemeral wetlands at approximately 3,800 to 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 fractured outcrops. The spike at approximately 3,650 m asl corresponds to underlying lava flow units and their discharge to riparian zones and basin wetlands near the edge of the plateau.

Table 4. Afroalpine wetland typology for the Bale Mountains with primary hydrogeomorphic characteristics and approximate elevation ranges

Type	Landform	Water sources	Flow path	Seasonality	Elevation range (m asl)
Seep	Slope	Groundwater (cinder cone), precipitation	Outflow	Perennial	3,900–4,200
Lake/pond	Kettle, lake fringe	Precipitation	Vertical, outflow (fill and spill)	Ephemeral	4,000–4,150
Fen	Kettle, slope	Precipitation, upstream outlet channels, shallow groundwater flow	Throughflow, outflow, vertical	Ephemeral	3,900–4,150
Riparian	Channel fringe	Groundwater (spring), overland flow	Throughflow	Ephemeral, perennial (depending on water source)	3,500–3,900
Swamp/marsh	Basin	Groundwater, precipitation/fog	Throughflow, vertical	Perennial	3,600–3,750

corroborates the intrawetland variability described by Dullo et al. (2015), who conducted a detailed dry season study of a fen in the Sanetti region of the plateau.

Wetland Typology

We defined five types of Afroalpine wetlands on the Bale massif (Table 4). In addition to the four HGM criteria, we estimated an approximate elevation range for each type of wetland. Although some overlap occurs, we sought to capture the primary HGM characteristics that define each class. In the following sections, we present evidence for and an interpretation of each grouping, starting at the cinder cone peaks and moving down in elevation to the edge of the Afroalpine zone.

Cinder Cone Seepage Slopes (3,900–4,200 m). Our models indicate that the highest elevation wetlands of the Bale massif are seep wetlands that occur on the slopes of Tullu Deemtu and the central summits. Cinder cones tend to form during the postshield stage of shield volcano development, during which the lava chemistry changes and produces highly viscous flows (Gingerich and Oki 2000). Because of their higher viscosity, the aquifers that form in postshield rocks generally have lower permeability than underlying shield-stage lava flows (U.S. Geological Survey 2013). This increases residence time and can serve as an important groundwater resource in tropical volcanic regions (Gingerich and Oki 2000; U.S. Geological Survey 2013; Jefferson et al. 2014). In the Bale Mountains, cinder cones comprise nearly all areas above 4,000 m asl. As rain falls on the cones and snow and hail melts from diurnal changes in temperature, a portion of the water likely infiltrates into the underlying rock until it emerges from the flank of the cone or at the foot of scree slopes. Some of the scree slopes might be the remnants of ancient gelifluction, as most exist within the estimated boundary of the glacier cap. The seeps that emerge from the cinder cones represent the vast majority of perennially saturated wetlands in the upper elevations of the plateau. This perennial flow is likely the product of the low hydraulic conductivity of the cinder cone rock. Outflow channels from many of the seeps form small perennial streams that follow the local topographic gradient to the edge of the escarpment, whereas others contribute flow to larger ephemeral channels. In rare cases, outflow channels feed directly into a nearby kettle, allowing the lake to persist well into the dry season.

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, Mitchell, and Osmaston (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 the plugs. The freeze–thaw 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 regional climate was cooler and more humid (Mohammed and Bonnefille 1998). These landforms are visible near the two plugs to the south of Tullu Deemtu, as well as the large plug in the Morebawa region. Those near Tullu Deemtu are much more pronounced than in Morebawa, likely because of 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, because these areas are beyond the lower limit for periglacial processes on the plateau (3,800 m asl).

Kettle Lakes and Fens (3,900–4,150 m). 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 Lake Garba Guracha, many of the lakes have been filled with sediment and are shallow and temporal (Eggermont et al. 2011). Other depressions have completely filled, likely forming the playas to the north and northeast of the base of Tullu Deemtu. The position of the kettles in the upper elevations of the plateau and their highly variable water levels—many are completely dry by the end of the dry season—strongly suggest that they are entirely rain-fed. The majority of these lakes have no perennial surface outlet (Miehe and Miehe 1994; Osmaston, Mitchell, and Osmaston 2005), however, observations from Dullo et al. (2015) and Google Earth reveal that many possess an ephemeral outflow channel. These are the products of "fill-and-spill" dynamics in which the lake level rises until the water spills over the edge and is conveyed downslope in the ephemeral channels. This process is common in geographically isolated wetlands and represents episodic surface connectivity (Cohen et al. 2016). Many of the lakes support vegetated wetlands on their margins, which are inundated after rain events and subsequently dry up as the wetted edge recedes. Downslope and adjacent to the lakes are numerous peat-forming fens that receive precipitation inputs as well as shallow groundwater flows (Kebede 2013; Dullo et al. 2015). Some of these fens are connected by surface channels to upstream lakes, which convey water that spills over during wetter periods. Together, the lakes, fringe wetlands, and peat fens make up a highly dynamic wetland complex in the uppermost elevations of the plateau.

Perennial Riparian Areas and Basin Wetlands (3,500–3,800 m). Our results show that the majority of perennial wetlands occur below 3,800 to 3,900-m asl. Satellite imagery suggests that this elevation break corresponds to the edge of the uppermost lava flow on the plateau and its intersection with the underlying basal unit. Moreover, our field observations in these areas revealed numerous springs emerging from fractured basalt columns at the end of the dry season. Young volcanic landscapes are highly porous at the surface and subsurface, which results in high rates of precipitation infiltration and exceptionally high hydraulic conductivities (Tague and Grant 2004). This "layer-cake" stratigraphy can play an important role in subsurface flow, as the geometry of lava flows can be a strong control on groundwater movement (McGuire et al. 2005; Jefferson, Grant, and Rose 2006; U.S. Geological Survey 2013). On the Bale massif, it is likely that water from the upper elevations infiltrates into the uppermost lava flow until it meets the older underlying basal unit. The water moves laterally through the interflow zone, following the topographic gradient, until it emerges from fractures in basaltic dykes and outcrops formed from the weathered edge of the upper flow unit (Tewodros 2005; Kebede 2013; Figure 6). This process is similar to other mafic volcanic regions such as the U.S. Pacific Northwest (Jefferson, Grant, and Rose 2006; Tolan, Lindsey, and Porcello 2009), Hawaii (U.S. Geological Survey 2013), and the Simien Mountains of northwest Ethiopia (Kebede 2013). Some of this water supports small perennial channels and associated riparian areas, as well as the large basin wetlands of the Chafa Delacha and Morebawa regions near the southern escarpment.

Conceptual Flow Model

We propose the following conceptual flow model for the Afroalpine hydrology of the Bale Mountains (Figure 7): During the wet season, precipitation falls as rain and snow across the plateau. This forms temporary snow cover in higher elevation cinder cones, while providing direct inputs to the surrounding kettle lakes. As additional precipitation falls and diurnal temperature fluxes melt the snow, water infiltrates into the dense postshield rock of the

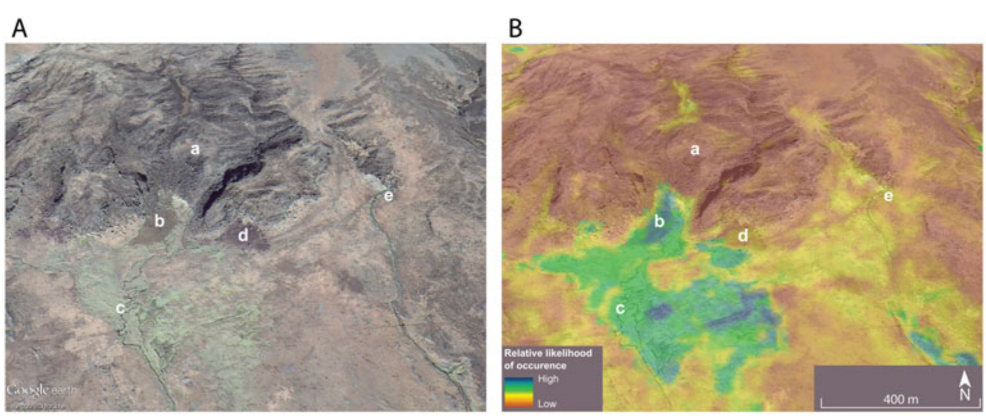

Figure 6. Oblique view of large outcrop in the Chafa Delacha region. (A) Google Earth image captured 20 December 2013. (B) Continuous model predictions of perennial wetlands (displayed using bicubic interpolation and transparent overlay). (a) Edge of outcrop at approximately 3,830 m asl; (b) perennial seep with outflow channel emerging from outcrop base; (c) small channel and surrounding wetland; (d) human settlement; (e) spring with rocky channel conveying water toward southern escarpment. (Color figure available online.)

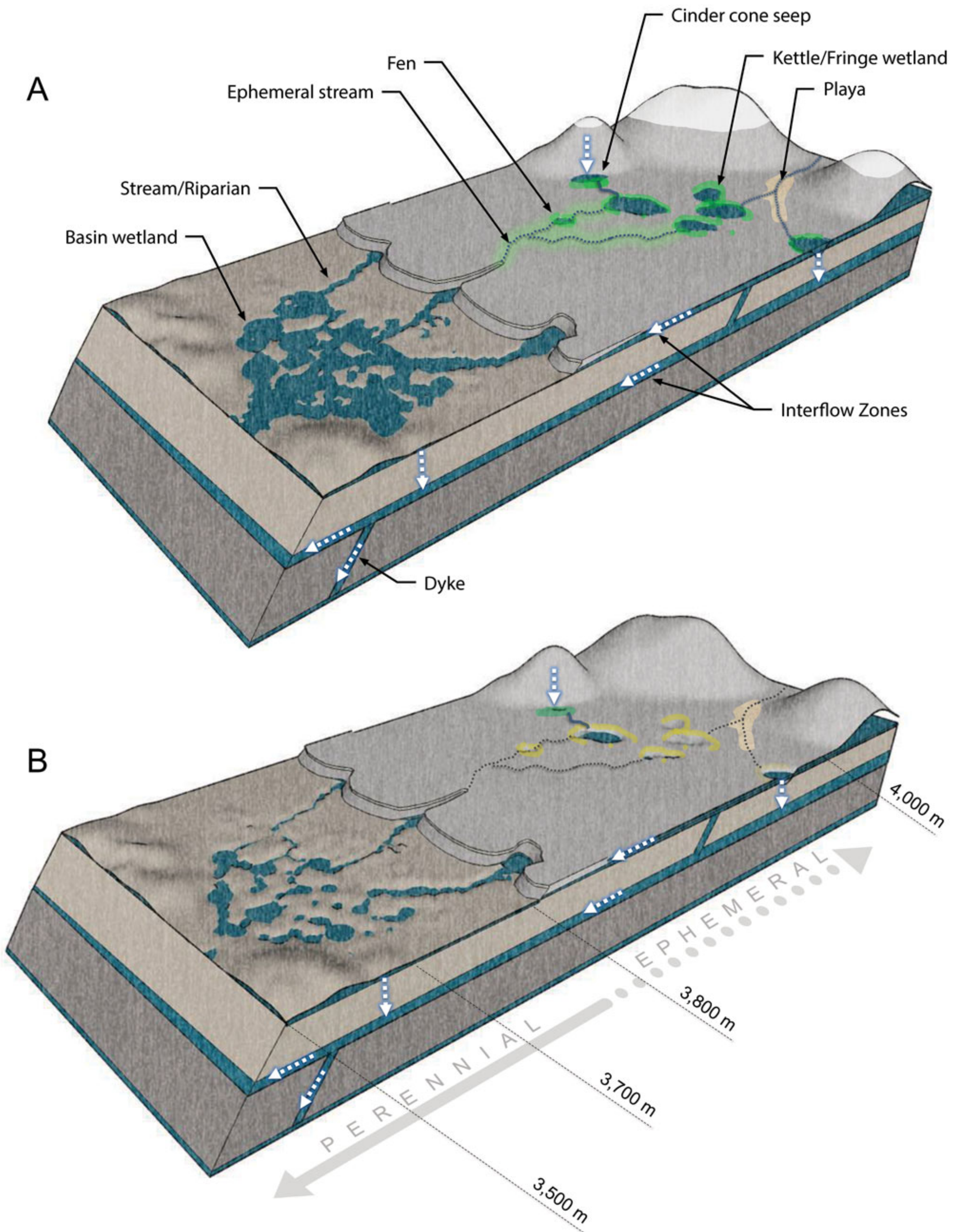

Figure 7. Conceptual flow model of the hydrology of the Bale massif (not to scale). (A) Wet season conditions with different types of wetlands, groundwater flows (white arrows), and intermittent snow and hail on cinder cone peaks. (B) Dry season conditions showing the perennial-ephemeral continuum and reference elevations. (Color figure available online.)

cinder cones. Meanwhile, the water in the kettles infiltrates through the lake beds and walls. Once the soil in the bed is saturated, 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 playas and fens through ephemeral channels. These are at first losing streams but eventually become gaining streams as the soil is saturated and the water table rises. As precipitation wanes, the ephemeral playas, lakes, and streams begin to dry. The longer residence time of the cinder cones, however, results in a perched groundwater system that discharges to the seeps that continue to flow throughout the dry season. As lake levels drop, kettles shift to purely vertical flow until they dry out. A few particularly deep or disconnected lakes—as well as those that receive surface inputs from cinder cone seeps—stay wet throughout the dry season. Water infiltrates through the porous uppermost lava 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 masl). The springs source small perennial channels and riparian zones that convey water to the large basin wetlands in Chafa Delacha and Morebawa, as well as the northern declivities and the Web Valley. Some water from the uppermost lava flow unit infiltrates into deeper layers through dykes and fractures, recharging the regional aquifer or emerging as lower elevation *horas* around the escarpment and in the Harenna Forest. This process results in a hydrologic continuum in the Afroalpine zone: Wetlands and streams in higher elevations tend to be ephemeral (with the exception of the cinder cone seeps), whereas those in lower elevations tend to be perennial, with the transition being the lower limits of the uppermost lava flow. This altitudinal zonation has been observed in similar regions, including northwest Ethiopia, and suggested for the Bale massif (Kebede 2013).

Discussion

The results of predictive correlative distribution models should be treated as hypotheses to be tested with further field data collection, experimentation, and modeling (Jarnevich et al. 2015). Our study provides a working hypothesis and foundation for building a better understanding of the hydrology of the Bale massif and surrounding region. Future research should use our results to guide field assessments and identify reference wetlands for the wetland types we have proposed. Integration with additional vegetation and soil data could help to refine our typology by defining HGM subclasses. Combining this information with our baseline maps and additional modeling would enable monitoring of HGM class distribution. Because wetland function is strongly coupled to the type of wetland, a change in the distribution of a certain type of wetland might indicate a loss of a specific function (Brooks et al. 2013).

Future work should also include monitoring of seep wetlands and *horas* along the elevation gradient of the Bale massif. Springs represent windows into the subsurface and can reveal 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, Grant, and Rose 2006; Grant et al. 2010). This has important implications for management, because interannual variability in discharge from springs can be used to interpret sensitivity to climate variation (Grant et al. 2010). Isotope tracing techniques can also help to understand the impacts of land use change on recharge, runoff, and nutrient transport but might require adaptations for application to tropical latitudes (Hamel et al. 2018).

Our results indicate that the Afroalpine wetlands of the Bale massif are highly dynamic across space and time. Regular measurements of water levels in each type of wetland and discharge of outflow channels would provide insights into fill-and-spill dynamics, water conveyance, and hydrologic attenuation. These data would support mapping of longitudinal stream connectivity (Wohl et al. 2017) and how this might or might not change with wetland degradation or shifts in hydrologic regime. The increasing availability of moderate- to high-resolution multispectral satellite data might provide enough temporal coverage to capture numerous cloud-free images each year. Linking this imagery with observations from low-cost, modular weather sensors would support research into ecohydrologic connectivity between the Afroalpine zone and the Harenna Forest.

The combined pressures of climate change, population growth, and land use modification underscore the urgent need for greater understanding of tropical mountains (Slaymaker and Embleton-Hamann 2018). Our study shows that much can be gained from comparing mountains with similar latitudes, climates, and geologic histories. In much the same way that shield volcanoes in Hawaii and Oregon can inform our understanding of the Bale massif, the Bale massif could help us to understand processes at work in other mountain systems such as the Andes or Kilimanjaro, which are currently undergoing rapid deglaciation and land use change. Such comparisons should be done critically, however, recognizing the uniqueness of each site and the heterogeneity in hydrologic responses to climate and land change (Jefferson et al. 2010; Ponette-González et al. 2014). This calls for further collaboration among land managers, local people, and scientists from different disciplines and geographic foci.

Conclusions

We conducted baseline research on Afroalpine wetland seasonal dynamics and hydrogeomorphic function in the Bale Mountains, Ethiopia. Our results show that Afroalpine wetlands of the Bale massif are highly dynamic across space and time; perennial wetlands occupy 4 percent of the Afroalpine area and more than double in extent between dry and wet seasons. The majority of perennially saturated areas are sustained by groundwater from upstream springs and seepage slopes. This relates to a hydrologic continuum based on volcanic and glacial legacies, with higher elevations being largely ephemeral and lower elevations largely perennial.

Meaningful geomorphic characterization and description underpin effective interpretation and explanation, providing a basis from which to forecast future conditions (Brierley et al. 2013). We demonstrated how correlative distribution modeling using field surveys and remote sensing data can be used to characterize ungauged, often inaccessible tropical alpine environments. Coupling these efforts with HGM assessments produces insights and understanding that goes beyond what is possible with traditional land cover mapping. Our wetland typology and conceptual flow model serve as starting points for studies on surface–groundwater connectivity and can be used to target conservation, field assessments, and monitoring of change. We also showed 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 during the wet season. Timing field data collection with coincident satellite image acquisition adds confidence and interpretability to resulting predictions.

An urgent need exists to move beyond conceptualizations of tropical mountains as remote canaries in the coal mine for climate change (Zimmerer et al. 2017). Our results underscore that the current hydrologic system of the Bale Mountains is the product of multiple legacies that overlap in space and time. The first is the geologic history, which largely determines when and where water flows throughout the dry season. The second are the landforms left by glacial and periglacial processes, which influence wetland HGM 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 (Flintan et al. 2008; Hailemariam, Soromessa, and Teketay 2016). This continues throughout Ethiopia today with large-scale hydropower projects and land concessions that feed distal urban markets, often at the expense of rural livelihoods (Chignell and Laituri 2016; Carr 2017). 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 additional data collection, as well as a concerted effort to develop research and management frameworks that are holistic, transdisciplinary, and inclusive of multiple perspectives.

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Supplemental Material

Supplemental data for this article can be accessed on the publisher's website.

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