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Establishing ecological baselines around a temperate Himalayan peatland

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Abstract Temperate wetlands provide ecosystem services for Himalayan communities and are important targets for biological conservation. However, over the past decade, management activities around these sites have lagged due, in part, to limited baselines on their historical ecology and hydrologic dynamics. This article advances Himalayan wetland studies by reviewing available data from Khecheopalri, a temperate peatland located in the Sikkim Eastern Himalayas. Formed after the Last Glacial Maximum, Khecheopalri contains distinctive ecological assemblages as well as a central waterbody considered sacred to Indigenous and local groups. Environmental organizations have collaborated with cultural institutions to conserve these natural resources. Nevertheless, significant anthropogenic changes have continued at Khecheopalri since the late 1980s. By reviewing these developments, this article establishes baselines for future management activities at this peatland. It also presents the first collated record of Himalayan peatland biodiversity, which includes 682 species representing 5 kingdoms, 196 families, and 453 genera reported at Khecheopalri. Results emphasize the need for continued, systematic surveys of biodiversity as well as rigorous hydrologic sampling throughout the Eastern Himalayas. Such data will support ongoing efforts to recognize this site as both a Ramsar Wetland of International Importance and a UNESCO World Heritage Site.

Keywords Wetland management · Biodiversity conservation · Himalayan peatlands · Khecheopalri · India

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Introduction

The Eastern Himalayas house complex networks of small, dispersed wetlands that are vital to the ecologies and economies of the region (Prins et al. 2017). These wetlands provide critical habitat and breeding ground for threatened species, including migratory birds, and support diverse provisioning services for local groups (Bhatta et al. 2018; Sharma et al. 2015). As environmental sinks for carbon dioxide and sources of methane, they too play an important role in state of Earth's climate (Steffen et al. 2018; Petrescu et al. 2015; Rühland et al. 2006). Despite these functions, regional governments have largely relied on environmental organizations to advance wetland management (e.g., Chatterjee et al. 2010; Gujja 2007). Increased federal oversight is needed to ensure that communities both adhere to state wetland policies and structure their management objectives in a measurable and meaningful way (Tambe et al. 2008; Keeney 1994).

Although most extensive at northern latitudes, peatlands occupy wide swaths of the Greater Himalayas and Tibetan Plateau (Cao et al. 2019; Treat et al. 2019; Ma et al. 2017; Morris et al. 2018). Peatlands are generally defined as wetlands with waterlogged substrates that include, at minimum, 30 cm of partially-decomposed organic matter, also known as peat (Mitsch and Gosselink 2015). In the Eastern Himalayas, these ecosystems generally occur in high-altitude zones (i.e., alpine) where atmospheric and topographic conditions favor peat formation (Ma et al. 2017). Notwithstanding, isolated bogs are also reported within temperate Himalayan valleys (Chaudhary et al. 2017; Sharma and Bhattarai 2005; Jain et al. 2000). These temperate peatlands are largely unstudied yet house distinctive ecological communities that are important for trans-boundary conservation (Gurung et al. 2019; Kandel et al. 2016, 2018). Establishing ecological baselines around these sites is key for managing resilient landscapes throughout the region (Kandel et al. 2019; Manish and Pandit 2019).

This article follows O'Neill (2019) in reviewing publicly available and accessible data on the hydrogeomorphology, ecology, and management of Khecheopalri, a temperate peatland located in the Sikkim Eastern Himalayas (Fig. 1; hereafter, Khecheopalri).[1] In recent years, the Government of Sikkim (India) has platformed this site as a Ramsar Wetland of International Importance, especially for Waterfowl Habitat, as well as a UNESCO World Heritage Site (Islam and Rahmani 2008; Government of India 2018). Nevertheless, this peatland's designation is pending on both accounts; baseline reports remain dated and/or unavailable to environmental managers. By summarizing available data, this review advances Himalayan wetland studies and evaluates the conservation significance of Himalayan peatlands.

Regional climate and setting

The Sikkim Eastern Himalayas are a subset of the Himalayan Biodiversity Hotspot and are contiguous with the northeast-Indian state of Sikkim. Regional climate is dictated by the Asian monsoon as well as continental factors, with seasons broadly classified as: (1) monsoon (June to September); (2) winter (October to March); and, (3) spring (April–May). Located within a sub-basin of the Raman River, Khecheopalri receives approximately 85% of its precipitation during the monsoon (Jain et al. 1999). This amounts to an average total rainfall of 2100 mm $year^{-1}$ with a maximum recorded rainfall of 3840 mm $year^{-1}$ (Jain et al. 1999, 2000). Precipitation enters the wetland via several seasonal inlets and exits via one seasonal outlet (Nayek et al. 2018; Jain et al. 2004b; Roy and Thapa 1995, 1999; Venu et al. 1990). Water is otherwise stored in a basin comprised of Kangchenjunga gneisses, including banded-streaky migmatite and augen-bearing biotite gneiss with sillimanite, kyanite, mica and schist (Bose 1989; Government of India 1984). In terms of soils, peat and sandy loam dominate local horizons, the latter exhibiting a profile of 13–14% clay, 36–40% silt, and 47–50% sand (Jain et al. 2000; ISRIC 2018). Soil bulk density ranges from 0.074 to 0.917 g m^{-3} with organic matter

[1] Search terms were modified to capture anglicized names for the Tibetan *mkha spyod dpal ri* (Wylie): *chhogo*, *kaychupalri*, khachoedpalri, *khe-cheod-palri*, *khecheopalri*, *khecheodpalri*, *khecheoperi*, *khecheodperi*, *khechepere*, *khecheperi*, *khechepuri*, *khecheoperi*, *khecheopuri*, *khecheypery*, *khechiperi*, *khechipery*, *khechoperi*, *khechupalri*, *khechuperi*, *khechupery, tso-shuk-tso, mkha-spyod-dpal-ri, kha-chot-palri. lethang chojo*. The Biodiversity Heritage Library and the Global Biodiversity Information Forum were included as additional sources in this review.

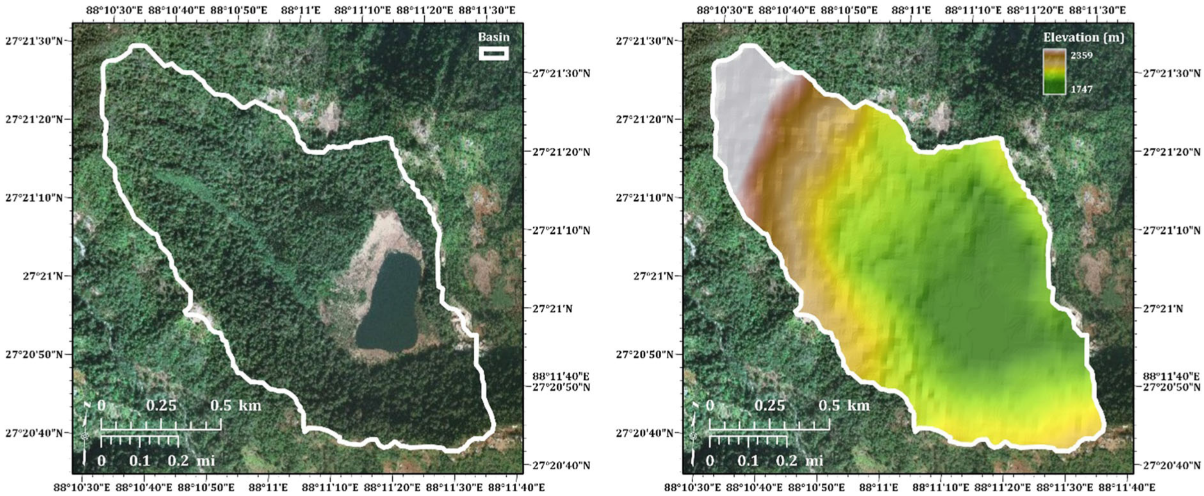

Fig. 1 The Khecheopalri basin with reference to elevation

varying significantly with distance from the basin's center (Fig. 2). Although hydrologic data are limited, preliminary surveys suggest that Khecheopalri is an acidic, weakly minerotrophic fen (Electronic Supplementary Material). A water budget based on available data highlights significant gaps in hydrologic research (Fig. 3; Jain et al. 1999, 2000; Sharma et al. 2007).

Environmental history and change

Khecheopalri formed as Himalayan glaciers retreated during the early Holocene and shed large ice blocks that developed into kettle lake depressions (Raina 1966). Evidence suggests that one such lake persisted within the Khecheopalri basin until c. 2000 BCE (Jain et al. 1999, 2000, 2004b). By that time, isolation from groundwater, poor buffering of inflow water, and changing climate facilitated *Sphagnum* growth and peat-mat expansion along the basin's edge (Meetei et al. 2007). Today, this peatland occupies approximately 10 ha of Khecheopalri's 140 ha basin with peat structured into three discrete strata: (1) mat peat, with 45–93% organic matter and 89–218 cm thick; (2) debris peat, with 13–83% organic matter content and 93 to 262 cm thick; and, (3) gyttja layer (lake bottom), with 30–70% organic matter (Jain et al. 2004b). Depth-wise carbon dating (^{14}C) suggests that peat in the upper strata approaches 580 years in age, while the middle and lower strata range between 120 to 780 years and 1410 to 2970 years, respectively (Jain et al. 2004b). Peat evolution has proved dynamic, with remote sensing surveys revealing peatland expansion between the 1960s and 1990s (Fig. 4; Jain et al. 2004b).

As early as 1000 BCE, mixed-broad leaved stands of Oak (*Quercus* spp.), Alder (*Alnus* spp.), and Pine (*Pinus* spp.) colonized Khecheopalri's basin rim. These communities advanced toward the peatland over the following two millennia, developing a rich understory unique to the Sikkim Eastern Himalayas (Biate and Agrawala 2018; Ganguli-Lachungpa et al. 2011). Charcoal deposits dated 1118 CE to 1334 CE evidence fire frequency during this time (Jain et al. 2004a, b). Otherwise, forest expansion was limited at the peatland by high soil acidity (pH 4.2–4.4) and soil saturation (water level 2 to 8 cm below soil; Jain et al. 2004b, 2005a, b). An 8-ha polymictic waterbody rests at the basin's center. Its water temperatures range from 4.5 to 19.6 °C with transparency gauged between 9.86 cm (June) and 35.8 cm (January; Roy and Thapa 1995, 1999; Jain et al. 1999, 2000). The waterbody's other characteristics are poorly understood. For instance, some bathymetric studies suggest depths of 1.2 m to 7.6 m, while others estimate average and maximum depths of 14.6 m and 27.7 m, respectively (Roy and Thapa 1999; Venu et al. 1990). Local taboos and state notifications that prevent boating, fishing, and casting of lines complicate possible field sampling (Evershed and Fish 2006; Jain et al. 2004a).

Little was reported on Khecheoplari between the fourteenth and twentieth centuries. The earliest

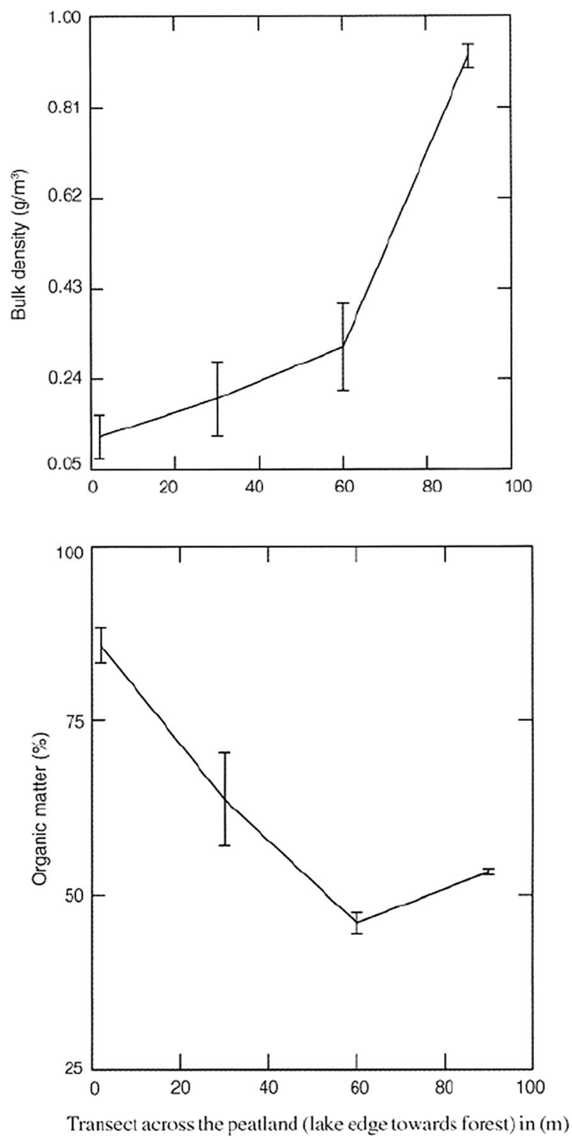

Fig. 2 Soil characteristics at Khecheopalri peatland (Jain et al. 2004b)

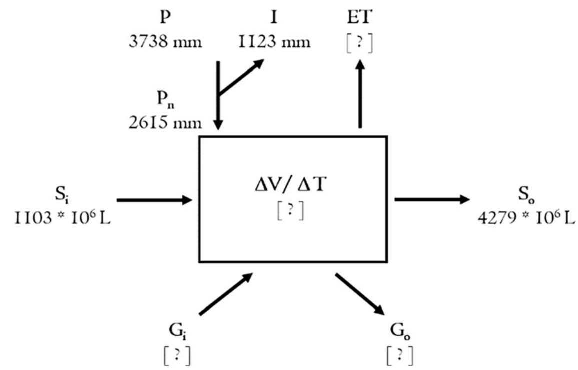

Fig. 3 A generalized water budget for Khecheopalri based on available data (Jain et al. 2000; Sharma et al. 2007); *P* precipitation, *ET* evapotranspiration, *I* interception, P_n net precipitation, S_i surface inflow, S_o surface outflow, G_i groundwater inflow, G_o groundwater outflow, $\Delta V/\Delta T$ change in storage per unit time

English anecdotes on the system, including nearby Chojo marsh, were reported by botanist Joseph Dalton Hooker in his *Himalayan Journals* (1854/1905). Guided by an Indigenous Lepcha interpreter, Hooker described Khecheopalri as a sacred, hardwood forest unexploited by locals because of their obligations to the peatland's presiding nymph, which is described as a *dakini* or *mung* spirit (Sprigg 1983). Indigenous and local records, including Lepcha *delúk* texts, also describe the forest in terms of its diversity—a nexus where human and non-human beings interacted on their journey to the afterlife (Plaisier 2012). Most extensive, however, are oral narratives recalling rapid environmental transformations within the Khecheopalri basin, such as flood events (Evershed and Fish 2006; Jain et al. 2005a). In the future, oral histories could inform ecological hypotheses on Khecheopalri's historical ecological dynamics (Bart 2006).

During the twentieth century, changes in land cover and land use significantly altered Khecheopalri's ecology and hydrology (Sharma et al. 2007; Sundriyal and Sharma 1996). Namely, threefold increases in human settlement, agricultural expansion, and tourism visitation were correlated with increased forest conversion and peatland sedimentation (Rahaman 2014; Maharana et al. 2000; Sharma et al. 2000). By and large, these changes commenced in the late 1980s when Sikkim experienced rapid infrastructural developments and population growth (Rai 2007; Rai and Sharma 1995, 1998a, b). Roads increasingly connected the Khecheopalri region with Nepali and Marwari migrants as well as economic structures based in Gangtok, the capital city of Sikkim. Thereafter, forest land was progressively cleared for agriculture and exploited for fuelwood, timber, and fodder. At the turn of the twenty-first century, households extracted *c.* 28% of wood from annual biomass increment at Khecheopalri (7.5 Mg household^{-1}) and *c.* 47% of subcanopy biomass (Chettri et al. 2005a, b; Jain et al. 2005a, b). Subcanopy biomass included a variety of medicinal and aromatic plants sold in South and Central Asian markets

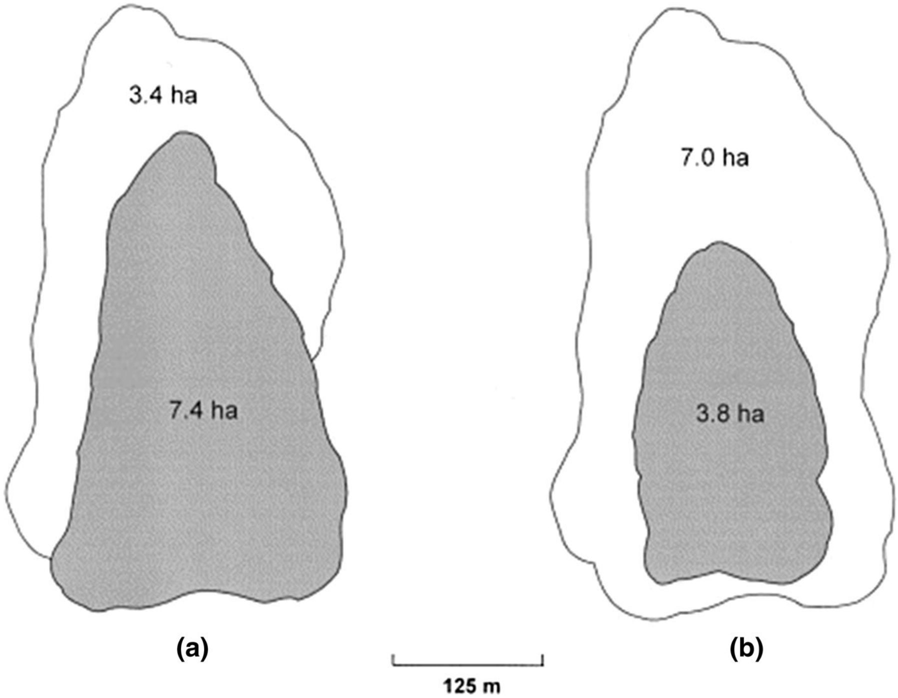

Fig. 4 Peatland transformation documented between 1963 (**a**) and 1997 (**b**) where unshaded space indicates peatland and shaded space indicates open water (Jain et al. 2004b)

(O'Neill et al. 2017; Uprety et al. 2016; Pradhan and Badola 2011, 2015; Sundriyal et al. 1994). Human activities remain the primary drivers of environmental change within the Khecheopalri basin.

Environmental management and policies

Khecheopalri is a sacred natural site and pilgrimage destination for diverse communities of the Sikkim Eastern Himalayas. Oral histories trace the peatland's sanctification to the eighth-century Buddhist mystic Padmasambhava, also known as Guru Rinpoche. Locals recall that Padmasambhava converted diverse non-human spirits inhabiting this Himalayan landscape to Buddhism (Mullard 2011; Balikci 2008). In doing so, he sanctified Sikkim as a sacred valley termed *Beyul Demojong¸* or the "Hidden Fruitful Valley". Belief in this sacred landscape narrative has broad implications on human–environment relationships in the Eastern Himalayas and influences the Government of Sikkim's approach to biological conservation (Ramakrishnan 2008).

Buddhist monasteries in Sikkim have encouraged wetland management both directly through monitoring and indirectly through cultural influence for over two centuries (Acharya and Dokham 1998). Since its founding in 1788, Tashi Choling Monastery has maintained primary oversight on Khecheopalri peatland itself (Vandenhelsken and Wongchuk 2006; Acharya 2005; Waddell 1973). By the twentieth century, the Government of Sikkim formally recognized the religious importance of the peatland and its monastic community via State Notifications 59/HOME/98 and 70/HOME/2001 (Government of Sikkim 1998). These notifications specified natural sites falling under India's Provisions of the Places of Worship (Special Provision) Act of 1991 as enforceable under Article 371F of the Indian Constitution. This act prohibits the conversion of any place of worship in India and mandates maintenance of the religious character of such places as they existed at Indian Independence. In effect, these provisions also buttressed the Sikkim Fisheries Act of 1980 and Sikkim Fisheries Rules of 1991 which prevented fishing in "religious" waterbodies. This legal structure underpins wetland management at Khecheopalri and mandates maintenance of ecological features as they existed on 15 August 1947.

In 1996, Khecheopalri was incorporated as a reserve forest into the southern-most buffer of the Khangchendzonga Biosphere Reserve (KBR; Zone IV). The KBR was a 935 km^2 addition to Khangchendzonga National Park that bridged biological conservation and sustainable development goals in Sikkim (Badola and Subba 2012). Sikkim's Forest, Environment & Wildlife Management Department (FEWMD) turned to environmental organizations, like the G. B. Pant Institute, The Mountain Institute, and the Kangchendzonga Conservation Committee, for capacity building at Khecheopalri. Implemented from 1996 to 2000, their Sikkim Biodiversity and Ecotourism Project incorporated cultural institutions, known as *dwichi* committees, to encourage both biological and cultural conservation. A governing body called the Holy Lake Welfare Committee (HLWC) was later formed, and achieved notable successes before disbanding *c*. 2004. For example, in June 2002, HLWC collaborated with the State Medicinal Plants Board to reduce harvesting pressures and develop a 3-ha Khecheopalri Herbal Garden (Tambe et al. 2003). Additionally, a wooden boardwalk was installed at this time (Fig. 5).

By the early 2000s, Khecheopalri was an established destination for both domestic and international visitors (Chiron 2013; Maharana et al. 2000). Around 8000 domestic and 2000 international tourists visited the lake in 2000, with around 25,000 total visits in 2010 (Tambe et al. 2008; Jain et al. 2004a, b). State officials recognized the need for additional infrastructure as well as decentralized management of the state's wetland resources. In 2006, they proposed a participatory framework in collaboration with the World Wildlife Fund, The Mountain Institute, and Kalpavriksha notified as 355/F, "Guidelines for Lake Conservation in Partnership with Gram Panchayats and Pokhri Sanrakshan Samiti's in Sikkim". Based on the HLWC experience, this notification transferred authority over wetland management to the Khecheopalri community in 2008. The community was empowered to collect conservation fees (Rs. 10 $person^{-1}$) with profits evenly divided among local stakeholders and FEWMD (Fig. 6). From 2010 to 2011, the Japan International Cooperation Agency (JICA) under the Sikkim Biodiversity and Forest Management Project further supported the state's ecotourism guidelines and policies (Government of Sikkim 2012; Watabe 2011). JICA-affiliated programs aimed at environmental conservation continue today.

State officials and community leaders have recently platformed Khecheopalri for inclusion on international environmental agreements, including the Ramsar Convention and the UNESCO World Heritage Program. Both bids center on the peatland as a representative, rare, and unique wetland type in the Eastern Himalayas that is important for threatened and endangered species. However, data underpinning these bids were largely qualitative with data quality and interpretation questioned by UN-affiliated programs (e.g., UNESCO 2016). In 2017, the Kangchendzonga National Park was fully recognized as a mixed-criteria UNESCO World Heritage Site (O'Neill 2017). Sites within the KBR, like Khecheopalri, are undesignated but qualify for inclusion based on their biological and cultural importance to Eastern Himalayan communities.

Ecosystem structure and biodiversity

Khecheopalri's status as a sacred wetland has historically framed conservation programs at the peatland, including checklist biodiversity surveys conducted since the mid-1990s (Uprety and Sharma 2012; Jain et al. 2005b, 2009). These surveys report 682 species representing 5 kingdoms, 196 families, and 453 genera within the Khecheopalri watershed. Surveyed species include 460 species of plants (126 families, 311 genera) and 165 species of birds (49 families, 119 genera), of which several are threatened according to the International Union for the Conservation of Nature (see Electronic Supplementary Material). Additionally, Khecheopalri is one of a few Himalayan wetlands surveyed for its bacterial, chromist, and fungal diversity (e.g., Das and Keshri 2013, 2016; Das 2013; Das and Verbeken 2011; Singh 2013; Sinha and Singh 2005). Nearly 30 chromists have been identified (13 families, 25 genera, 28 species) as well as 20 fungi (10 families, 14 genera) and two bacteria (2 families, 2 genera). Localized abiotic factors, such as aspect, pH and slope, influence the distribution of the peatland's species, which are broadly classified into two vegetative communities: (1) Temperate Sphagnum Bog; and, (2) Warm-temperate Moist Deciduous Forest. Scientists have noted the temporal variation in plant

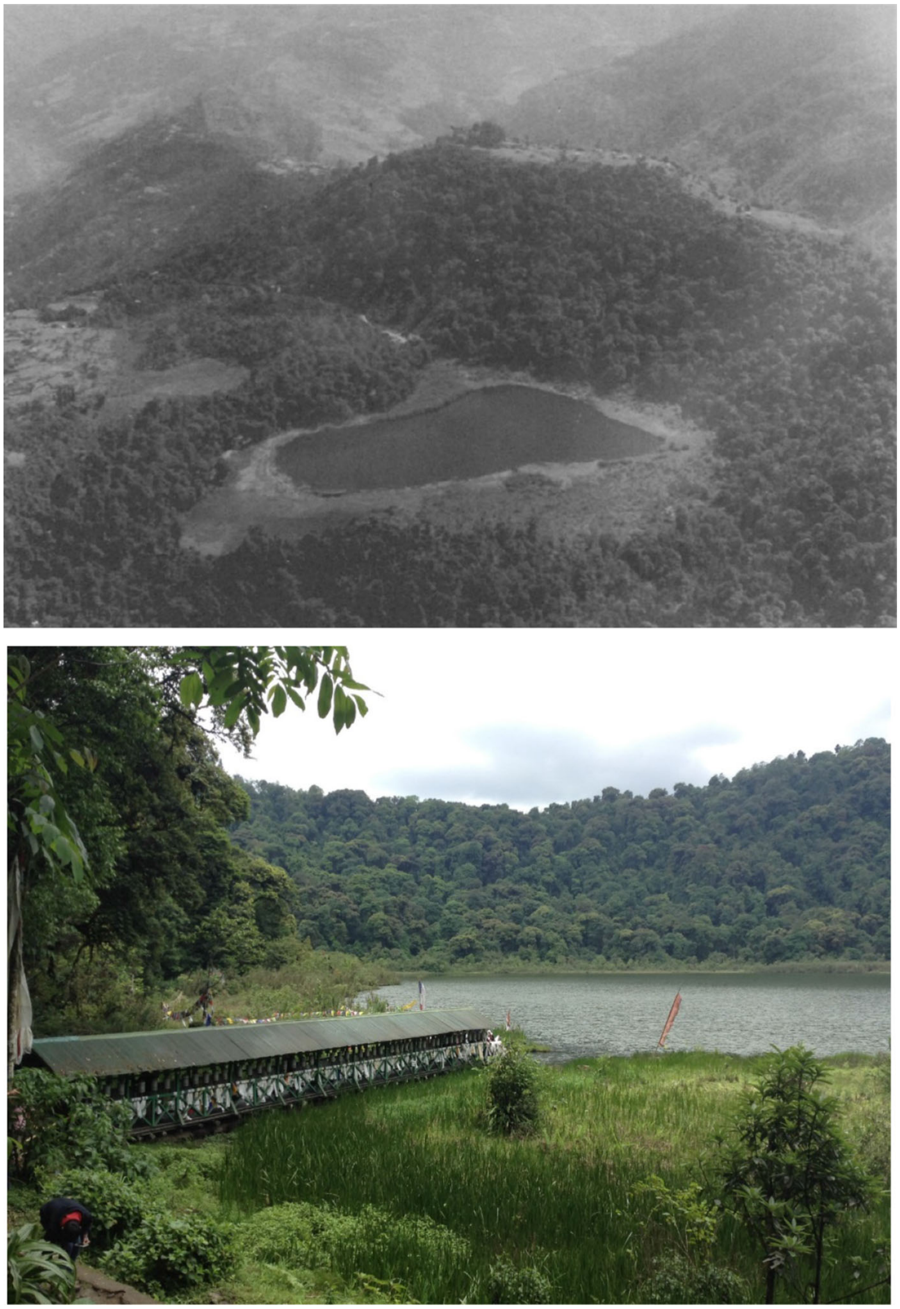

Fig. 5 Photograph of Khecheopalri from 1998 (above; Jain 2000) and 2016 (below) highlighting boardwalk installation

communities, with highest richness reported during monsoon.

Khecheopalri's temperate bog communities persist upon a floating *Spaghnum* mat (*Sphagnum nepalense*, *S. palustre*) populated by Ericaceous species, primarily from the genus *Vaccinium (V. dunalianum, V. nummularia*, *V. vacciniaceum*). Several Sedges (*Carex filicina*, *C. eleusinoides*, *C. insignis*) and Rushes (*Juncus effuses*, *J. inflexus*) also inhabit highly saturated zones (Biate and Agrawala 2018; Hajra and Verma 1996). Approximately 2 m from the lake, plant density approaches 575 plants m^{-2} (*c*. 85% mosses) with an associated basal coverage of 28.98 cm (Jain et al. 2005a). Within the lake, over 60 species of algae,

Fig. 6 Ecotourism tickets that support community-based environmental management

diatoms, and phytoplankton have been reported. Phytoplankton density is reported from 0.75×10^4 units l^{-1} to 5.57×10^4 units l^{-1} in the bog and 4.84×10^4 units l^{-1} to 19.45×10^4 units l^{-1} in the lake conditions; zooplankton density ranged from 0.70×10^4 units l^{-1} to 2.20×10^4 units l^{-1} in the lake (Jain et al. 2005b). Together, their seasonal productivity ranges from 16 mg C m^{-2} d^{-1} to 247 mg C m^{-2} d^{-1}, with corresponding respiratory loss measured between 12 and 160 mg C m^{-2} day^{-1} (Jain et al. 2005b). Although taxonomic surveys are relatively robust, several species of algae and phytoplankton have been only identified by genera, namely *Mougeotia*, *Scenedesmus*, *Ulothrix*, and *Zygnema*. Several copepods and planktonic rotifers are only identified by genera: *Alonella, Asplanchna, Brachionus, Chydorus, Cyclops*, *Cypridopsis*, *Daphnia*, *Didinium*, *Eudorina*, *Mesocyclops*, *Nauplius*, *Philodina*, and *Sida* spp. (Roy and Thapa 1995, 1999; Venu et al. 1990; Murray and Rousselet 1906).

In terms of animal communities, the bog provides important habitat and layover site for 11 reported species of waterfowl (GBIF 2019; Ganguli-Lachungpa 1988, 1998; Ganguli-Lachungpa et al. 2011). Reported ducks (Anatidae) include the critically endangered Baer's Pochard (*Aythya baeri*) as well as the Ruddy Shelduck (*Tadorna ferruginea*), Tufted Duck (*Aythya fuligula*), Goosander (*Mergus merganser*), Common Teal (*Anas crecca*) and Mallard (*Anas platyrhynchos*). Bird surveys also indicate that populations of Great Cormorant (*Phalacrocorax carbo*), White-breasted Waterhen (*Amaurornis phoenicurus*), Black-tailed Crake (*Porzana bicolor*), Black-necked and Little Grebes (*Podiceps nigricollis*; *Tachybaptus ruficollis*) also inhabit the watershed (Chettri et al. 2005a, b). Though several species are noted by genus, only two fishes are identified to species, specifically the Grass Carp (*Ctenopharyngodon idella*) and Giant Danio (*Danio aequipinnatus*). Occurrence records of *Garra*, *Schistura*, and *Schizothorax* spp. from the waterbody pend confirmation (Roy and Thapa 1995, 1999; see Bhatt et al. 2012; Karmakar 2006).

Woody taxa like Rhododendron (R*hododendron griffithianum*) and Viburnum (*Viburnum erubescens*) are found in mesic zones toward the peatland's margin (c. 60 m from the lake) (Justice 1992). By 30 m from the central waterbody, moss cover drops to 65% with herbs and shrubs increasing by 21% and 13%, respectively (Jain et al. 1999, 2000, 2004b). Knotweed (*Persicaria* spp.) and Sweetflag (e.g., *Acorus calamus*) become increasingly abundant within this transition zone. Trees account for upwards of 85% of plot-surveyed species by 90 m, with shrubs and herbs accounting for approximately 5% and 10%, respectively (Jain et al. 2004b, 2005a, b).

Characterized by a canopy of Oak (*Quercus finestrata*, *Q. lamellosa*, *Q. pachyphylla*) and Chestnut (*Castanoposis hystrix*, *C. tribuloides*), Khecheopalri's temperate forest is notable for its dense mid-story and rich herbaceous layer. Mid-story trees, including Bay (*Machilus edulis*), Cinnamon (*Cinnamomum *bejolghota*, *C. impressinervium*, *C. tamala*), Eurya (*Eurya cerasifolia*, *E. japonica*), Tan-oak (*Lithocarpus elegans, L. pachyphyllus*), Magnolia (*Magnolia campbelli*, *M. cathcartii*, *M. doltsopa*), and Sweetleaf (*Symplocos dryophila, S. glomerata, S. lucida, S. sumuntia*), constitute the majority of stand biomass and exhibit lower diameter classes and average heights of 16 $\pm$ 1 m than both Oak and Chestnut (Jain et al. 2005a, b). A rich, herbaceous layer settles the deciduous forest floor. This includes 47 species of Orchid (24 genera) and numerous bryophytes, pteridophytes, ferns and mosses (e.g., Baite and Agrawala 2018; Kholia 2014; Dey and Singh 2010; Lucksom 2007). In sum, total basal cover is reported at 58 m^{-2} ha^{-1} with a canopy cover 6805 m^{-2} ha^{-1} (Jain et al. 2005a, b).

Little exists in terms of Khecheopalri's amphibian, arthropod, and mammal diversity (e.g., Kundrata et al. 2018; Jendek 2016; Hazra et al. 2003; Sanyal 2003). Nevertheless, anecdotal reports suggest Himalayan Black Bears (*Ursus thibetanus*), Yellow-throated Martens (*Martes flavigula*), Himalayan Porcupine (*Hystrix brachyura*), and Hodgson's Giant Flying Squirrel (*Petaurista mangificus*) can be found within the watershed. These claims pend expert review. With regards to arthropod diversity, Lepidopteran surveys may prove an effective subject due to high reported diversity in Sikkim as well as their popularity among citizen scientists (Acharya and Vijayan 2015).

Management recommendations and trends

The Government of Sikkim has taken progressive strides toward decentralizing wetland management at Khecheopalri and establishing biodiversity baselines throughout the state (Subba et al. 2018; Dahal et al. 2017a, b, 2018; Pradhan and Lachungpa 2015; Pradhan et al. 2015a, b). Supported by research at Sikkim University and by environmental organizations, these efforts have resulted in comprehensive species lists that can inform management decisions around Himalayan wetlands. The case of Khecheopalri, however, highlights significant gaps in wetland research from the Eastern Himalayas (Biate and Agrawala 2018). Hydrologic and climatic surveys, wetland mapping and classification, and biocultural studies remain in their infancy (O'Neill 2019). Yet, immediate and proactive measures are needed to address forest conversion and peatland sedimentation reported at Khecheopalri and other high-altitude wetlands (Bhatta et al. 2018; Jain et al. 2004b). Maintaining the ecological functions of Khecheopalri peatland will require historical perspectives that also acknowledge that site-ecological conditions will change in unanticipated and unpredictable ways (Mawdsley et al. 2009).

Our current understanding of environmental change at Khecheopalri is based on limited field and remote sensing surveys conducted in the late 1990s. These studies relied on experimental methodologies that have proven prohibitive to replicate or model. In the future, thorough ecosystem assessments following standardized protocols are needed to inform management activities and related planning at this peatland. For example, repeated and systematic surveys of tree size and health, growth, mortality and removal by harvest could guide forest management and support emerging ecosystem service, or natural capital, markets (see Bechtold and Scott 2005). When coupled with remotely sensed imagery, these data can then be used to re-evaluate past analyses that leveraged IRS-1A, LISS-II, and IRS-1C, FCC satellite data and Survey of India topographical maps. Moreover, remotely sensed imagery when integrated with geographic information systems (GIS) can be used to develop management alternatives based on community-defined objectives and measures.

Direct management activities, such as riparian forest planting and introduced species removal, could benefit the ecological function of Khecheopalri and further support local livelihoods. Because the watershed occupies a relatively small area and receives direct conservation funding from ecotourism fees, restoration activities can proceed in a targeted and cost-effective way (Mawdsley et al. 2009). To reduce erosion and promote hardwood regeneration, trees facing extractive pressures, such as Oak, Chestnut, Eurya and Sweetleaf, could be planted around the basin. Closer to the peatland, Sweetflag and other native plants could abate overland flow (Jain et al. 2009). FEWMD and the State Medicinal Plants Board already provide horticultural services to local communities. In the future, their operations could be expanded to meet these current needs. Regarding introduced species, state interventions are needed to control Grass Carp. These fish pose immediate threats to Khecheopalri's freshwater ecosystems by outcompeting native species and disturbing the floating peat mat (Evershed and Fish 2006). Local Buddhists, however, protect these fish and associate them with their ancestors; they are protected by state laws due to religious importance. Environmental managers must, therefore, seek alternatives that are culturally sensitive. Here, it is worth noting that pilgrims also burn the leaves of Cedar (*Cryptomeria japonica*) and Juniper (*Juniperus recurve, J. indica)* as incense and offer fruit and flowers (Jain et al. 2004a) These actions have measurable effects on both the peatland and its water quality (Jain et al. 2009).

Ecotourism at Khecheopalri is projected to grow exponentially as travel restrictions to the Sikkim Eastern Himalayas ease and state infrastructure expands (Joshi and Dhyani 2009; Tambe et al. 2008). Yet agriculture remains important to the livelihoods and culture of Indigenous and local communities, and should be encouraged for the purposes of biocultural conservation. Various approaches to agroforestry and permaculture are already practiced in the Eastern Himalayas (Sharma et al. 2016). Encouraging more diverse, forested agricultural systems could promote landscapes resilient to anticipated climatic changes and promote regional food security. Large Cardamom plantation under Nepal Black Cedar may prove most valuable to local economies and promote biodiversity (Gaira et al. 2016; Sharma et al. 2002). Other medicinal plants may also be sustainably grown and marketed from agroforestry and permaculture systems. Overall, future conservation efforts at Khecheopalri will require sustained partnerships between the state government, environmental NGOs, and community leaders. Together, these groups can address notable gaps in current research on Himalayan peatlands and build cooperative, resilient institutions that benefit local economies and the environment.

Conclusion

Himalayan peatlands house distinctive ecological assemblages that are important to the livelihoods and cultures of Eastern Himalayan groups. At Khecheopalri, 682 species representing 5 kingdoms, 196 families, and 453 genera have been reported. Several state and national policies protect the Khecheopalri peatland as a biocultural resource. However, forest conversion and sedimentation have continued within its surrounding watershed since the 1980s. Additional data on Khecheopalri's historical ecology and hydrologic dynamics are needed to support management programs. Sustaining partnerships among the peatland's diverse stakeholders will ensure resilient conservation outcomes.

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Data availability Geospatial and review data are available either as an Online appendix and/or upon request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Consent for publication The authors of this manuscript consent for publication.

Ethics approval and consent to participate This study is exempt from IRB approval because it involves online and open-access data. As such, there was no need to request consent for participation in this study.

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