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Spatiotemporal analysis of hydropower projects with terrestrial environmentally sensitive areas of Nepal

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ABSTRACT

Hydropower project construction is increasing, which can affect the terrestrial environment. Hydropower projects located in environmentally sensitive areas have higher environmental impacts, so we analyzed the spatiotemporal interaction between hydropower project locations and terrestrial environmentally sensitive areas of Nepal to visualize the probable environmental impacts. Most existing projects lie on the Hills (Middle Mountains); however, future projects are moving northward toward the Himalayas. Among the 12 eco-regions of Nepal, hydropower projects are located in 10 eco-regions. Hydropower projects were found to interact with more than half of the biodiverse areas of the country (28 out of 45), and more than five thousand megawatts of hydropower projects are located completely inside these biodiverse areas. The study suggests that the interaction between hydropower projects and environmentally sensitive areas might increase in the future. Hydropower projects should avoid environmentally sensitive areas such as biodiverse areas and protected areas as much as possible to minimize the impacts. Rapid hydropower development is necessary for countries such as Nepal, so further studies on the effects of hydropower projects on environmentally sensitive areas as well as improvement of the quality of the environmental assessment of the projects are necessary for environmentally friendly development.

Introduction

Renewable energy is expected to have lower environmental impacts than fossil fuel consumption; however, there might be impacts on biodiversity and the environment during the construction and operation of renewable energy projects (Ho, 2014; Northrup and Wittemyer, 2013; Williams, 2019). Hydropower is one of the major sources of renewable energy, supplying 16.4% of the world's electricity from all sources in 2016 (www.worldenergy.org, accessed on 2 August 2019), and its construction is increasing in the Himalayan region, including Nepal (Alley et al., 2014; Brown et al., 2019; Chandy et al., 2012; Huber, 2019; Sharma and Awal, 2013) as well as other parts of the world (Couto and Olden, 2018; Grill et al., 2019; Zarfl et al., 2015).

Nepal has a high potential for hydropower projects (total of 83,000 MW, technically feasible 45,610 MW, and financially feasible 42,133 MW), and the requirement for electricity is increasing (up to 15,000 MW installed capacity will be required in 2030) (WECS, 2017). In Nepal, approximately 95% of electricity (Ghimire et al., 2021) and more than 99% of renewable electricity are produced from hydropower projects (www.doed.gov.np, accessed 6 September 2018). To overcome the shortage of electricity in the country (Sharma and Awal, 2013) and to meet the increasing demand for electricity, the government of Nepal planned to accelerate hydropower project development and adopted the National Energy Crisis Reduction and Electricity Development Decade-related Action Plan in 2016, which helped to increase the construction of hydropower projects.

Studies in various parts of the world show that hydropower projects can severely affect the environment and biodiversity (Anderson et al., 2018; Fekete et al., 2010; Finer and Jenkins, 2012; Jumani et al., 2017; Williams, 2019; Winemiller et al., 2016; Ziv et al., 2012); however, most of them have focused on the detrimental effects of hydropower projects on fish diversity, richness, migration, and their important habitats (Anderson et al., 2018; Grumbine and Pandit, 2013; Lees et al., 2016; Mcallister et al., 2001; Winemiller et al., 2016; Ziv et al., 2012). The few studies that are conducted on the effects of hydropower projects on the terrestrial environment suggest that hydropower projects might affect terrestrial biodiversity and faunal species (Grumbine and Pandit, 2013). However, these studies mainly focused on the direct impacts due to dams and inundation on forests (Pandit and Grumbine, 2012), montane birds (Jolli, 2017), and the migration of caribou (Mahoney and Schaefer, 2002). There are inadequate studies on the effects of hydropower project development on environmentally sensitive areas. The

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biodiverse area and protected areas are important areas for biodiversity and environmental conservation; however, the degradation and deterioration of these areas due to hydropower projects can severely undermine the environmental quality (Butchart et al., 2012; Eken et al., 2004; Gray et al., 2016; O'Dea et al., 2006; Pack et al., 2016). Therefore, we considered these environmentally important areas as sensitive areas for hydropower project development (i.e., areas should be avoided). The terms environmentally important areas (biodiverse areas) and environmentally sensitive areas are used interchangeably in this article.

Hydropower projects have a large number of structures, such as dams, tunnels, canals, powerhouses, internal project roads, access roads, camps, and transmission lines (hydropower project components including associated and auxiliary structures) (Gracey and Verones, 2016), and most of these structures cause habitat fragmentation, which affects terrestrial faunal species and biodiversity in environmentally sensitive areas (Alamgir et al., 2019; Benítez-López et al., 2010; Nellemann et al., 2001; Nellemann and Cameron, 1998; Torres et al., 2016; Vistnes and Nellemann, 2001). Similarly, studies show that hydropower projects are one of the main causes of degradation in environmentally sensitive areas (Huđek et al., 2020; Pack et al., 2016; Rosendal et al., 2019; Zeng et al., 2005).

The location of the hydropower project is an important parameter for assessing the environmental impacts (Benchimol and Peres, 2015; Mcallister et al., 2001). The projects located in environmentally sensitive areas such as protected areas and biodiverse areas have a higher environmental impact and severely degrade these areas (O'Dea et al., 2006; Rosendal et al., 2019; Schwarz and Vienna, 2015; Zeng et al., 2005). Therefore, studies on the distribution of hydropower projects in protected areas and biodiverse areas have been conducted in various parts of the world (Huđek et al., 2020; Pack et al., 2016; Punys et al., 2019; Schwarz and Vienna, 2015). Similarly, there is a study on the distribution of other infrastructure projects (rail and roads) in environmentally sensitive areas such as protected areas and Terai Arc Landscapes in Nepal (Sharma et al., 2018). However, no study has been carried out to assess the distribution of hydropower projects in environmentally sensitive areas in Nepal until now. Therefore, the main aim of this study is to visualize how hydropower projects are distributed in the environmentally sensitive areas of Nepal.

The spatial approach is important for estimating the impacts of hydropower projects, and the distribution of hydropower projects can be insightful for estimating the probable impacts (Bakken et al., 2014; McManamay et al., 2015). Therefore, we spatially analyzed the potential interactions between current and future hydropower projects with environmentally important/sensitive areas. Hydropower projects interacting with species-rich areas (biodiverse areas) and protected areas have higher environmental impacts (Mcallister et al., 2001; McManamay et al., 2015). Therefore, our objective for this study is to analyze the numbers and capacities of existing, underconstruction, and proposed hydropower projects within geographic regions and important terrestrial habitats (environment protection area, protected areas, important bird and biodiversity areas, and key biodiversity areas) of Nepal.

Methods

Study area

Nepal, situated in the Central Himalayan region, has an area of 147,181 sq. km and is located in latitudes 26° 22′ to 30° 27′ N and longitudes 80° 40′ to 88° 12′ E (Bhuju et al., 2007). There are 12 national parks (IUCN category II), one wildlife reserve (IUCN category IV), one hunting reserve (IUCN category VI), six conservation areas (IUCN category VI), and 13 buffer zones (IUCN category VI); and the country's 23.39% area is protected under these areas (DNPWC, 2017). Most of these protected areas are distributed in the northeast and southern areas, and a few protected areas are located on the Hills (Chaudhary, 2000; Hunter and Yonzon, 1993) (Fig. 2, Supplementary Fig. S1, and Supplementary Table S2). Additionally, the Chure Environment Protection Area (hereafter CEPA) extends from the west to the east of the entire country, covering 12.78% of the area of the country, which is designed for the protection of the fragile Siwalik region, especially from landslides, soil erosion, sand, boulder extraction, and deforestation (www.chureboard.gov.np, accessed on 6 September 2018) (Fig. 2, Supplementary Fig. S2). The Chure region is the transition region between Hills and the Terai and the geologically fragile region (Supplementary Fig. S2).

The country has a variety of biodiversity due to vast variations in altitude from 67 masl (meters above sea level) to 8848 masl on Mount Everest (Bhuju et al., 2007). Nepal has been divided into three geographic regions: northern areas with a low population density that contain the Himalayas up to a height of 8848 m called Mountains (also known as the Himalayas); mid-range areas with moderate population density having gorgeous mountains, high peaks, hills, valleys, and lakes called Hills (also known as Middle Mountains); and densely populated southern flat terrain called Terai (also known as Lowlands) (CBS, 2014). The eastern part of Nepal has one of the biodiversity hotspots, the Eastern Himalayan Biodiversity hotspot (Myers et al., 2000), making it important from a global conservation viewpoint.

Data sources

The data and maps for the study were collected from secondary sources from 16 August to 15 September 2018. The hydropower projects' location (latitudes and longitudes), status, and capacity were collected from the Department of Electricity Development (DoED) website (www.doed.gov.np, accessed on 6 September 2018). Nepal's protected area information was downloaded from the ICIMOD website (www.icimod.org, accessed on 27 August 2018) and verified using the WCMC/IUCN and Nepal geoportal databases. (www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas, accessed on 27 August 2018; www.nationalgeoportal.gov.np, accessed on 27 August 2018). The Chure Environment Protection Area (CEPA) data were downloaded from the President Chure-Terai Madesh Conservation Development Board, Nepal website (www.chureboard.gov.np, accessed on 27 August 2018). Nepal's geographic area data were downloaded from the ICIMOD website (www.icimod.org, accessed on 27 August 2018).

The important bird and biodiversity area (IBA) and key biodiversity area (KBA) of Nepal data were downloaded from Birdlife International on request (www.birdlife.org, accessed on 28 August 2018; www.keybiodiversityareas.org/site/requestgis, accessed on 6 September 2018). Nepal administrative boundary data were downloaded from Nepal geoportal (www.nationalgeoportal.gov.np, accessed on 27 August 2018).

Data extraction

We considered the license boundary of the project issued by the DoED (for government projects that do not require a license, the coordinate listed on the DoED website was considered) as the location of hydropower projects, as most of the project structures are located inside the license boundary. Although most previous studies on hydropower projects' impacts focus on the number of dams (Anderson et al., 2018, 2008; Grumbine and Pandit, 2013; Kibler and Tullos, 2013; Pandit and Grumbine, 2012; Ziv et al., 2012), there are debates about whether single large or several small hydropower projects have higher environmental impacts (Bakken et al., 2014, 2012; Couto and Olden, 2018; Dursun and Gokcol, 2011; Egré and Milewski, 2002; Kibler and Tullos, 2013; Mcallister et al., 2001; Rosenberg et al., 1995). Therefore, we considered the numbers and total capacity of hydropower projects for this study. For this study, projects with a capacity of one megawatt (MW) or more were considered because projects with a capacity less than one MW do not require environmental assessment (such as Environmental Impact Assessment (EIA) see (Ghimire et al., 2021)) based on installed capacity (GoN, 1997), are localized and managed at the local level and are expected to have minimal environmental impacts.

For the study, we considered different categories of hydropower projects, such as existing projects (projects that have undergone commercial operation), underconstruction projects (projects whose feasibility and environmental assessment have been completed, and acquired construction licenses from DoED, and include one government underconstruction project), and proposed projects (projects that have received survey licenses and are in the study phase, projects whose study is completed and have applied for construction licenses, and government projects in the study phase, as well as the study completed but, have not gone to the construction phase). We did not consider projects that applied for the survey license as they are in the preliminary stage, and permission for the study has not been issued by the government.

We studied the geographical and eco-regional distribution of the project to show which areas have the highest number and capacity of the projects. In Nepal, the IBA and KBA areas overlap. The IBA, KBA, and protected areas were merged and named PIKs (short form for protected areas, IBA, and KBA) or biodiverse areas (Table 2) because most of the protected areas are found to be IBA and KBA, and vice versa in Nepal. The 27 IBA and KBA and 33 protected areas (including buffer zones) were located in the country; combining them, a total of 45 PIKs or biodiverse areas were included in the analysis. The Chure Environment Protection Area (CEPA) data were merged into a single layer from the given KMZ file, and due to its unique nature (it is not included in IUCN categories, it is designated to protect the fragile environment and established under different Act than other protected areas), it was separately analyzed.

Analysis

Altogether, 608 hydropower projects with a total capacity of 35.98 GW were considered in the analysis. The current installed capacity of existing projects was found to be 1.01 GW (73 projects), 162 projects (5.00 GW capacity) were underconstruction, and 373 projects (29.97 GW capacity) were proposed.

We used ESRI Arc Map 10.3 GIS software for spatial analysis (ESRI, 2014). The maps were converted into Modified UTM 84 using the project tool, as most of Nepal's data are in this projected coordinate system. We conducted most spatial analyses between hydropower projects and environmentally important areas (PIKs and CEPA) using selection and field calculators in ArcMap 10.3. The findings are expressed as percentages and numbers.

An analysis of the geographic and eco-regional distribution of hydropower projects was conducted to determine the number and capacity of projects found in each region. For the hydropower projects' distribution with respect to CEPA and PIKs, the number and capacity of the projects whose project area interacted with the CEPA and PIKs areas as well as the number and capacity of hydropower projects that were completely within them, were spatially analyzed using ArcMap. As the areas of PIKs vary greatly (less than one sq. km. to more than 7000 sq. km), the hydropower project number and capacity were analyzed while considering the areas of the PIKs as the number and capacity of hydropower projects per 100 sq. km of the area (named the number density and capacity density, respectively) and compared them among various PIKs. During the analysis, if one project was located in two or more regions/areas, its capacity and number were considered in both regions/areas.

The data analysis was conducted in Microsoft Excel with the help of the add-in 'STATISTICIAN (version 2.00.01.81)'. First, we analyzed the data normality of the capacity of projects whose project area interacted with environmentally sensitive areas (PIKs and CEPA) using the Shapiro-Wilk test, as it was most appropriate to test the normality (Razali and Wah, 2011; Yap and Sim, 2011). The data were not found to be normally distributed. In addition, the number of projects whose project area interacted with PIKs and CEPA is a discrete variable (count). Therefore, we used the Kruskal-Wallis H test to assess the differences in the number and capacity of existing, underconstruction, and proposed projects in environmentally sensitive areas (PIKs and CEPA) because this test is appropriate for nonnormal and discrete data (Hecke, 2012; Van Emden, 2019). In addition, we used linear regression to analyze the trends of the interactions between hydropower project locations and PIKs and CEPA to assess future interactions.

Results

Geographical distribution of hydropower projects

The highest number of all hydropower projects was found in the Hills; however, the highest capacity of all hydropower projects was found in the Mountains. The highest number and capacity of existing projects were located on the Hills. Although the highest number of underconstruction and proposed projects were located on the Hills, the highest capacity of the underconstruction and proposed projects was located on the Mountains (Fig. 1). Details are given in Table 1.

Hydropower projects and environmentally important/sensitive areas

There were significant differences in the number ($\chi^2 = 15.4$, df = 2, $p = 0.0005$) and capacity ($\chi^2 = 22.83$, df = 2, $p < 0.0001$) of existing, underconstruction and proposed projects that were located in the environmentally sensitive areas (PIKs and CEPA) of Nepal. There was no significant difference between existing and underconstruction projects that were located in environmentally sensitive area interms of the number ($\chi^2 = 2.07$, df = 1, $p = 0.1503$) and capacity ($\chi^2 = 3.17$, df = 1, $p = 0.075$). However, the proposed project number ($\chi^2 = 6.39$, df = 1, $p = 0.0115$) and capacity ($\chi^2 = 10.21$, df = 1, $p = 0.0014$) in environmentally sensitive areas were significantly higher than those in underconstruction projects (Supplementary Table S1 and Fig. 2).

No hydropower projects were found to be located entirely within the CEPA. A total of 19 hydropower projects (total capacity 3481.87 MW) interacted in the CEPA, and their capacity ($R^2 = 0.75$) and numbers ($R^2 = 0.59$) increased from existing to proposed projects: four existing projects (total capacity 45.02 MW), two underconstruction projects (total capacity 62 MW), 13 proposed projects (total capacity 3374.85 MW) were in the CEPA (Supplementary Table S1 and Fig. 2).

Out of the 45 PIKs, 275 hydropower projects (45.23% of the number of projects) had a capacity of 17,994.24 MW and were found to be partially or fully located in 28 (62.22% of the number of PIKs) PIKs. The percentage of hydropower projects partially and fully overlapped with PIKs increased from existing and underconstruction projects (40%) to the proposed project (47%). The overall number ($R^2 = 0.925$) and capacity ($R^2 = 0.893$) of hydropower projects in the PIKs increased from existing projects to proposed projects: 29 existing projects (330.83 MW capacity) and 67 underconstruction (3167.03 MW capacity) to 179 proposed projects (3496.38 MW capacity). Among those 275 projects, a total of 150 hydropower projects with a capacity of 5103.98 MW were found to be located entirely within the PIKs, and their number ($R^2 = 0.93$) and capacity ($R^2 = 0.99$) were also found to be increased from existing to proposed projects: 16 existing projects (132.03 MW capacity) and 37 underconstruction (1685.37 MW capacity) to 97 proposed projects (3286.58 MW capacity) (Fig. 2).

Among the PIKs, the highest number of hydropower projects was found to be located in the Annapurna Conservation Area; however, the number density (number of projects per 100 sq. km of the PIK areas) of hydropower projects were highest in the Lantang Buffer Zone (Table 2 and Supplementary Table S1). The highest capacity and capacity density of hydropower projects (capacity of projects per 100 sq. km of the PIK areas) were in the Makalu Barun Buffer Zone (Table 2 and Supplementary

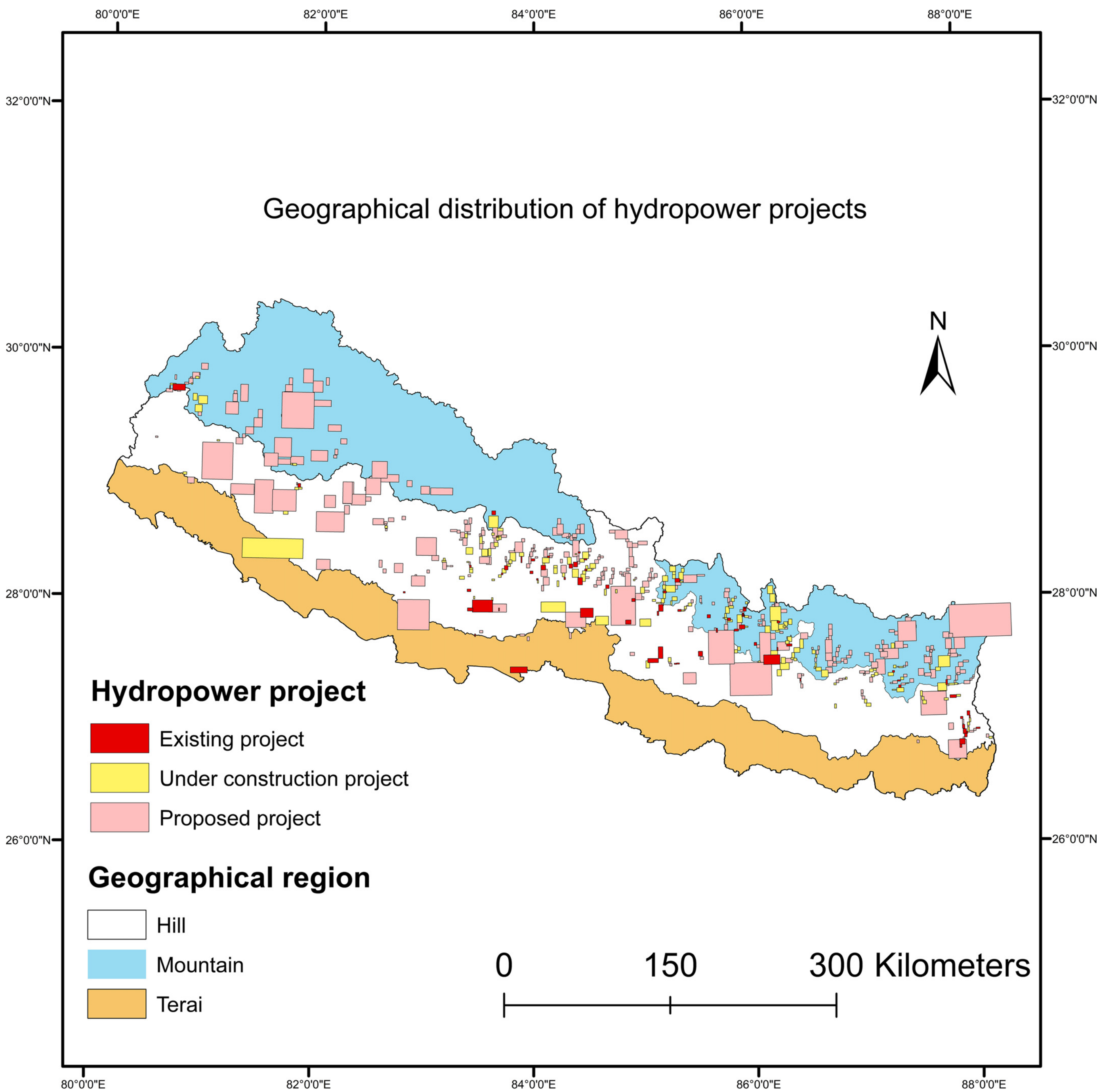

Fig. 1. Geographic regions of Nepal and hydropower project distributions
Data Sources: www.doed.gov.np, www.icimod.org, www.nationalgeoportal.gov.np.

Table 1
Geographical distribution of hydropower projects in Nepal.

Geographical Areas	Existing projects		Under-Construction projects		Proposed projects		Total Hydropower projects	
	Number	Total capacity (MW)	number	Total capacity (MW)	number	Total capacity (MW)	number	Total capacity (MW)
Terai	2	16.02	3	151.3	11	1408.16	16	1575.48
Hill	54	837.11	103	2013.7	201	17,679.08	358	20,529.89
Mountain	24	252.16	79	3523.91	196	19,493.48	299	23,269.55

Some projects are located in two or more regions, and their capacity and number are considered in all located regions in this case.
Data Sources: www.doed.gov.np, www.icimod.org.

Table 2
Number and capacity of hydropower projects per 100 sq.km of environmentally important/sensitive areas.

S.N.	Name of the environmentally important area	Type	Number of projects/100 sq.km.				Total capacity of the projects (MW)/100 sq.km.			
			Existing projects	Under-Construction projects	Proposed projects	Total Hydropower projects	Existing projects	Under-Construction projects	Proposed projects	Total Hydropower projects
1	Annapurna	CA_IKBA	0.12	0.22	0.63	0.97	1.53	15.41	89.85	106.79
2	Api – Nampa	CA	0.05	0.11	0.37	0.53	1.58	0.58	17.10	19.25
3	Banke	NP	–	0.18	–	0.18	–	8.45	–	8.45
4	Banke - Buffer Zone	NPBZ_IKBA	–	0.31	–	0.31	–	14.66	–	14.66
5	Barandabhar forests and wetlands	IKBA	–	–	–	–	–	–	–	–
6	Bardia	NP_IKBA	–	0.11	–	0.11	–	5.35	–	5.35
7	Bardia - Buffer Zone	NPBZ_IKBA	–	0.18	–	0.18	–	8.63	–	8.63
8	Chitwan	NP_IKBA	0.08	–	–	0.08	1.24	–	–	1.24
9	Chitwan - Buffer Zone	NPBZ_IKBA	0.14	–	0.14	0.27	2.06	–	6.85	8.90
10	Dang Deukhuri foothill forests and west Rapti wetlands	IKBA	–	–	0.06	0.06	–	–	22.77	22.77
11	Dharan forests	IKBA	–	–	0.12	0.12	–	–	0.22	0.22
12	Dhorpatan	HR_IKBA	–	–	0.08	0.08	–	–	69.43	69.43
13	Farmlands in Lumbini area	IKBA	–	–	–	–	–	–	–	–
14	Gauri-Shankar	CA	0.36	1.00	1.13	2.49	5.56	118.58	119.92	244.06
15	Ghodaghodi Lake	IKBA	–	–	–	–	–	–	–	–
16	Jagdishpur Reservoir	IKBA	–	–	–	–	–	–	–	–
17	Kanchanjunga	CA_IKBA	–	0.05	0.59	0.68	–	13.94	93.42	107.36
18	Khaptad	NP_IKBA	–	–	–	–	–	–	–	–
19	Khaptad - Buffer Zone	NPBZ_IKBA	–	0.37	0.37	0.74	–	0.57	102.20	102.77
20	Koshi Tappu	WR_IKBA	–	–	–	–	–	–	–	–
21	Koshi Tappu - Buffer Zone	WRBZ_IKBA	–	–	–	–	–	–	–	–
22	Krishnasar	CA	–	–	–	–	–	–	–	–
23	Langtang	NP_IKBA	0.06	0.30	0.72	1.08	1.33	30.14	45.36	76.82
24	Lantang - Buffer Zone	NPBZ_IKBA	–	2.14	2.35	4.49	–	79.74	108.04	187.78
25	Mai Valley forests	IKBA	0.99	0.49	0.86	2.34	15.59	4.55	16.25	36.38
26	Makalu-Barun	NP_IKBA	–	–	0.50	0.50	–	–	160.86	160.86
27	Makalu-Barun - Buffer Zone	NPBZ_IKBA	–	0.13	2.69	2.82	–	5.76	1615.27	1621.03
28	Manaslu	CA	–	–	0.49	0.49	–	–	105.82	105.82
29	Nawalparasi forests	IKBA	–	–	–	–	–	–	–	–
30	Parsa	NP_IKBA	–	–	–	–	–	–	–	–
31	Parsa - Buffer Zone	NPBZ_IKBA	–	–	–	–	–	–	–	–
32	Phulchoki Mountain Forests	IKBA	–	–	–	–	–	–	–	–
33	Rampur valley	IKBA	–	–	–	–	–	–	–	–
34	Rara	NP_IKBA	–	–	–	–	–	–	–	–
35	Rara - Buffer Zone	NPBZ_IKBA	–	–	1.01	1.01	–	–	82.65	82.65
36	Sagarmatha	NP_IKBA	–	–	0.09	0.09	–	–	6.62	6.62
37	Sagarmatha - Buffer Zone	NPBZ_IKBA	–	–	1.45	1.45	–	–	326.85	326.85
38	Shey-Phoksundo	NP_IKBA	–	–	0.03	0.03	–	–	8.53	8.53
39	Shey-Phoksundo - Buffer Zone	NPBZ_IKBA	–	–	0.15	0.15	–	–	24.16	24.16
40	Shivapuri-Nagarjun	NP_IKBA	–	–	0.89	0.89	–	–	1.89	1.89
41	Shivapuri-Nagarjun- Buffer Zone	NPBZ	–	–	0.86	0.86	–	–	1.82	1.82
42	Suklaphanta	NP_IKBA	–	–	–	–	–	–	–	–
43	Suklaphanta - Buffer Zone	NPBZ_IKBA	–	–	–	–	–	–	–	–
44	Tamur valley and watershed	IKBA	0.07	0.60	1.27	1.94	0.37	34.61	66.03	101.02
45	Urlabari forest groves	IKBA	–	–	–	–	–	–	–	–

IBA and KBA overlapped in Nepal, and IKBA in the table indicates both important bird and biodiversity areas as well as key biodiversity areas.
CA- Conservation areas, NP- National Park, WR- Wildlife Reserve, NPBZ- National Park's Buffer zone, WRBZ- Wildlife Reserve's Buffer zone.
Some projects are located in two or more areas, so their number and capacity are considered in all located areas in that case.
Data Sources: www.doed.gov.np, www.icimod.org, www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas, www.birdlife.org, www.keybiodiversityareas.org/site/requestgis, www.nationalgeoportal.gov.np.

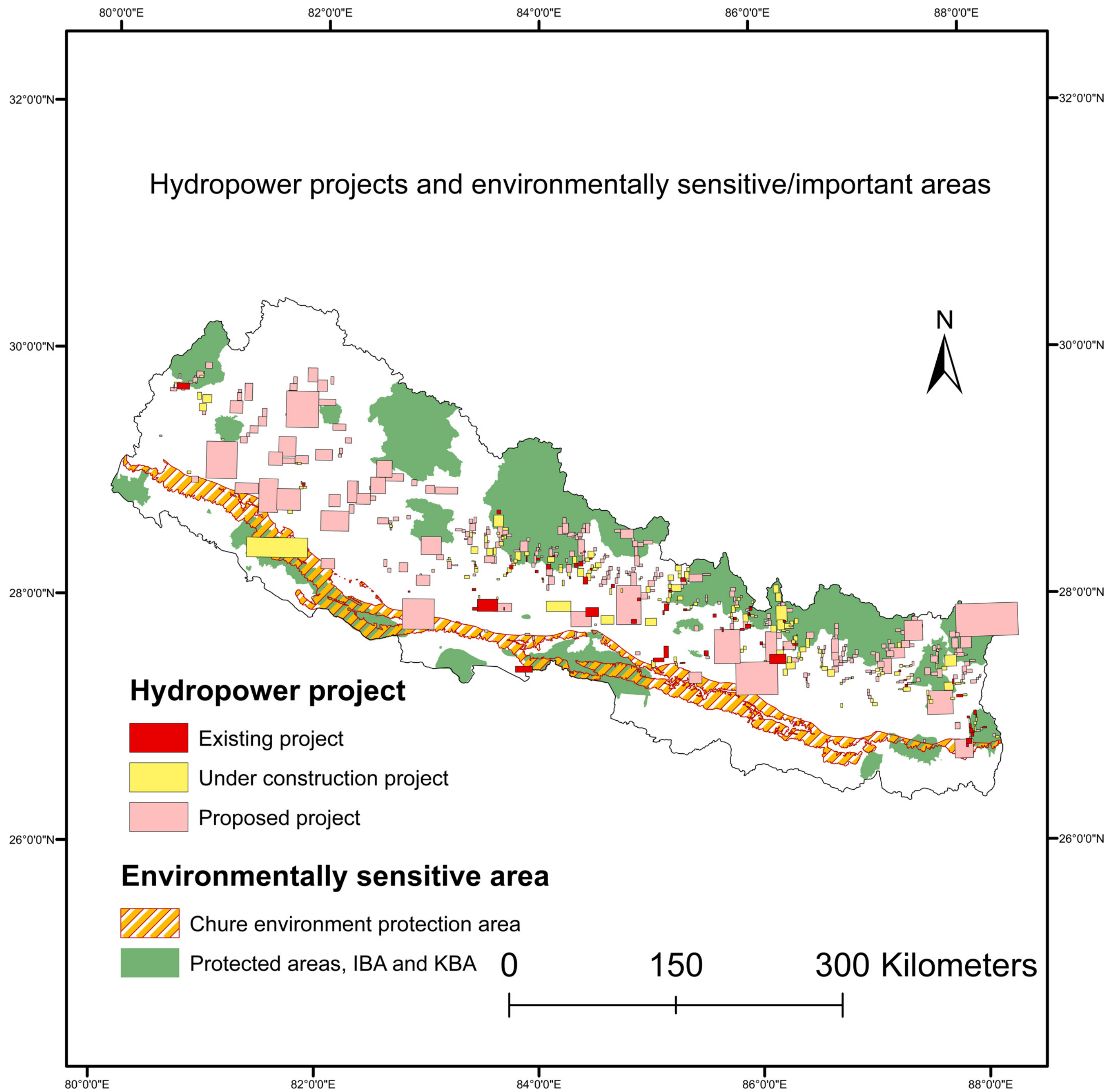

Fig. 2. Distribution of hydropower projects with respect to environmentally sensitive/important areas in Nepal
Data Sources: www.doed.gov.np, www.icimod.org, www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas, www.chureboard.gov.np, www.nationalgeoportal.gov.np, www.birdlife.org, www.keybiodiversityareas.org/site/requestgis.

Table S1). Among existing projects, the highest number of projects were in the Annapurna Conservation Area; however, Mai Valley Forests had the highest number density of the operated projects. The highest number, capacity, and capacity density of underconstruction projects were in the Gaurishankar Conservation Area; however, the highest number density of underconstruction projects was in the Lantang Buffer Zone. The highest number of proposed projects was found in the Annapurna Conservation Area. Nevertheless, the highest number density, capacity, and capacity density of the proposed projects were in the Makalu Barun Buffer Zone. Details are given in Table 2 and Supplementary Table S1.

Discussion

While hydropower projects are considered green development, they have several environmental problems (Williams, 2019; Winemiller et al., 2016; Zarfl et al., 2015; Ziv et al., 2012). Large hydropower projects have severe adverse regional environmental impacts due to secondary effects such as deforestation, regional development, and disturbance to wildlife (Alho, 2011; Kibler and Tullos, 2013; Mcallister et al., 2001). Similarly, the cumulative effect of several hydropower projects in an area also has several adverse environmental impacts (Anderson et al., 2018; Bakken et al., 2014, 2012; Couto and Olden, 2018). Likewise, noise can affect wild fauna even if the infrastructure does not directly affect it (Eigenbrod et al., 2009; Jolli, 2017): blasting during tunnel excavation and other project construction activities of a large project or several smaller projects might severely affect a large geographical extent. Therefore, a large number of hydropower projects, large capacity, or both in an area suggest the higher adverse impacts of hydropower projects on that area.

Hydropower projects and their associated structures might have substantial impacts on terrestrial biodiversity, especially in remote locations. Hydropower projects in remote locations need to construct a long transmission line, access roads, and an electricity line for construction power. In intact remote areas, these structures might have detrimental ecological impacts (Alamgir et al., 2019). Our study suggests that although most of the existing projects' capacity is found in the Hills, future projects' capacity is shifting northward toward remote Mountains (Himalayas). In addition, the number of projects in the Mountains is increasing from existing to the proposed project, suggesting the northward shifting of projects. As the northern region of Nepal is fragile, less populated, and biodiverse, with many protected areas (Bhuju et al., 2007; CBS, 2014; Chaudhary, 2000; Hunter and Yonzon, 1993) (Fig. 2, Supplementary Fig. 1), future projects might have a higher impact on the terrestrial environment.

The findings of this study are consistent with the impacts of the rapid development of hydropower projects in other countries of the Himalayan areas on forests (Pandit and Grumbine, 2012), montane birds (Jolli, 2017), fish (Brown et al., 2019), and the overall environment (Huber, 2019; Pandit et al., 2014), suggesting that hydropower projects severely affect the natural ecosystem of the Himalayas.

As PIKs are an important basis for biodiversity conservation and are helpful for mitigating global biodiversity loss (Butchart et al., 2012; Eken et al., 2004; Gray et al., 2016; O'Dea et al., 2006), the impact on these areas might significantly affect conservation efforts. In this study, a considerable number and capacity of hydropower projects are located in natural and fragile areas, such as CEPA and PIKs, similar to the study conducted in the adjoin Himalayan area, Andean Amazon areas, and Balkan region (Finer and Jenkins, 2012; Grumbine and Pandit, 2013; Schwarz and Vienna, 2015). These hydropower projects are expected to affect terrestrial biodiversity due to habitat fragmentation. Habitat fragmentation decreases species abundance and sometimes causes the disappearance of species (Benchimol and Peres, 2015; Jha et al., 2005; Pandit et al., 2007; Pandit and Grumbine, 2012; Saunders et al., 1991; Strassburg et al., 2010). In addition, hydropower projects can change the landscapes and geodiversity of PIKs, which severely impacts the environment and biodiversity in these areas (Brilha, 2002; Crofts and Gordon, 2014; de Paula Silva et al., 2015; Rodrigues and Silva, 2012). Although few existing projects with less capacity are in environmentally sensitive areas, the number and capacity of hydropower projects are found to increase significantly in the future and are expected to have severe impacts on the environment. In addition, the number and capacity of hydropower projects located completely inside the PIKs are also increasing, suggesting more threats in the future.

Although there are some additional conditions for the construction of hydropower projects in protected areas in Nepal, hydropower projects are allowed in protected areas as per the Working Policy on Construction and Operation of Physical Infrastructure inside the Protected Areas 2065 BS (MoFSC/GoN, 2009). According to the policy, hydropower projects located in national parks, wildlife reserves, and hunting reserve should release downstream environmental flow at least 50 percent of monthly flow. In addition, the feasibility study should try to avoid the national park, wildlife, and hunting reserve as much as possible. Similarly, the project located at the edges of national parks, wildlife reserves and hunting reserve, and the project located in conservation areas and buffer zones should release downstream environmental flow that is at least 10 percent of monthly flow. In addition, only national priority projects are allowed in the national parks, wildlife reserves, hunting reserve, and buffer zones. However, all hydropower projects and associated structures (such as transmission lines and access roads) are national priority projects in Nepal. No such restriction is about constructing hydropower projects in IBA, KBA and CEPA in Nepal.

More than half of the biodiverse areas (PIKs) of Nepal are affected by hydropower projects, and approximately 40% of the existing projects and underconstruction projects and approximately 48% of the proposed projects are located in PIKs, which is higher than that in the Amazon region (Alho, 2011) and comparable with the Balkan region (Schwarz and Vienna, 2015). The hydropower project number density in most PIKs is higher than nearby Indian Himalayas, which suggests only 0.16 hydropower projects per 100 sq. km (Pandit and Grumbine, 2012). Both the highest number density (in the Langtang Buffer Zone) and capacity density (in the Makalu Barun Buffer Zone) of hydropower projects are found in PIKs' located in the Eastern Himalayan biodiversity hotspot. Makalu Barun National Park, which is also considered the only Strict Nature Reserve of Nepal with negligible human interference (Carpenter and Zomer, 1996), does not have operated and underconstruction projects. However, it will be also affected by the proposed (future) projects. The hydropower projects proposed in the national park can downgrade its status (Huđek et al., 2020; Neupane et al., 2022; Pack et al., 2016), which suggests that the national park's strictness might be hampered in the future. These PIKs are mostly affected by proposed projects that suggest possible higher impacts in the future on the sensitive region if the developments are not managed properly. Most of the hydropower projects of Nepal are run of river projects, and run of the river projects are expected to have fewer environmental impacts than reservoir projects. However, study shows that run of river projects can also severely change land use and land cover in Nepal (Neupane et al., 2022). In addition, hydropower projects located in environmentally sensitive areas of Nepal do not implement the recommendations of approved environmental reports (Ghimire et al., 2021), which can aggravate the problem.

All of the proposed projects might not result in implementation; however, they have a higher probability of implementation because the project proponent has invested in license and feasibility studies, and the projects look feasible from a desk study. Studies show that infrastructure development in natural areas significantly affects faunal species and biodiversity (Palomino and Carrascal, 2007; Saunders et al., 1991). Hence, it is important to study the distribution of hydropower projects to determine the effect on terrestrial biodiversity if they undergo construction and to assess the future trends of the impacts of hydropower projects on terrestrial biodiversity. As hydropower development faces various environmental challenges, social conflicts, seismic hazards, and political challenges, risk analysis is suggested to minimize such challenges and attract investment (Butler and Rest, 2017; Hussain et al., 2019; Sharma and Awal, 2013). Hydropower projects located in environmentally sensitive areas can have higher environmental conflict, and this study suggests that such conflict will increase in the future in Nepal. Therefore, regulators should formulate policies to minimize such conflicts for sustainable hydropower development.

Despite some environmental concerns, renewable energy is the basis for sustainable development as well as the energy security of a country (Dincer, 2000; Oelz et al., 2007). Although hydropower projects have the greatest impact on the environment among renewable energy sources (Gibson et al., 2017), hydropower projects are the only energy resource that can generate electricity on a large and small scale in various parts of the country and replace fossil fuel consumption in Nepal (Sharma and Awal, 2013). In addition, hydropower projects are necessary for national development (Dincer, 2000), so their construction is necessary and urgent for countries such as Nepal. To minimize the environmental impact of hydropower projects, environmental studies are conducted before the implementation of the projects; however, these studies are not sufficient to analyze the impacts of these projects in Nepal or in other countries (Agrawal et al., 2010; Bhatt and Khanal, 2009; Erlewein, 2013; Pinho et al., 2007). As environmental assessments (such as Environmental Impact Assessments) are short-term analytical studies that depend on scientific evidence and information; a lack of information degrades the quality of the environmental assessment (Cashmore, 2004; McManamay et al., 2015). As managed hydropower project development helps to achieve sustainable development (Dursun and Gokcol, 2011; Muller, 2019; Sharma and Awal, 2013; Zarfl et al., 2015), and a significant number and capacity of hydropower projects are located in environmentally sensitive areas, it is necessary to conduct further studies to analyze the impact of the projects on terrestrial biodiversity to determine the ways for sustainable development of hydropower projects with minimal compromise on the environmental quality and biodiversity. In addition, a robust study design should be incorporated into the environmental assessment to minimize the adverse effects of hydropower development on environmentally sensitive areas (Rodrigues dos Santos et al., 2021).

Limitations and conclusion

The focus of this study is analyzing the distribution of existing, underconstruction, and proposed projects within Nepal's geographical regions and environmentally sensitive areas. A comparison between various types of hydropower projects: the run of river, peaking run of river, and reservoir projects were not included in this paper. The project-specific impacts, nature of impacts, quantification of the impacts, and cumulative impacts of hydropower projects are beyond the scope of the paper.

Studies in other parts of the world also suggest that a higher number of projects or larger capacity of projects in environmentally sensitive areas have higher adverse impacts in these areas (Alho, 2011; Anderson et al., 2018; Benchimol and Peres, 2015; Grumbine and Pandit, 2013; Mcallister et al., 2001; Rosenberg et al., 1995). The study found that hydropower projects interact with more than half of the biodiverse areas of Nepal, and hydropower projects having more than five thousand megawatt capacity are completely inside biodiverse areas. In addition, the number and capacity of hydropower projects in biodiverse areas will increase as more future projects are proposed. The interaction between hydropower project locations and terrestrial environmentally sensitive areas suggests that hydropower project development in Nepal might adversely impact important terrestrial habitats, and the impact might worsen in the future. It also gives the idea of highly affected regions and important terrestrial habitats by providing the relative distribution of hydropower projects and capacity.

The development of hydropower projects in such critical habitats might have severe impacts on terrestrial biodiversity, development should be carefully planned, and policy should be formed to avoid these areas as much as possible. In the case of the development of hydropower projects in PIKs, the appropriate terrestrial biodiversity management plan should be included in environmental studies of hydropower projects and strictly implemented to minimize threats. In addition, research on how ecological integrity and economic development can be balanced for the development of hydropower projects inside the PIKs as in (Rosendal et al., 2019) should be conducted in Nepal. Similarly, further studies should be conducted to quantify the impacts of hydropower projects on the environment and biodiversity of PIKs. The development of hydropower projects is inevitable and necessary in Nepal, so research on hydropower projects' impact on terrestrial biodiversity and its mitigation is crucial, along with improving the quality environmental assessment of hydropower projects to minimize such threats.

Declaration of Competing Interest

The views expressed in this article are not views of the Department of Electricity Development and National Natural Resources and Fiscal Commission. All ideas, views, and concepts presented in the article are of the authors themself. None of the data and information given here is confidential, all data are publicly available, and sources are duly acknowledged in the article. Although the map of Nepal has been updated recently, this study used a previous map because analysis and manuscript writing were already completed before the new map. The authors declare no competing interest.

Data Availability

All data are in public domain and can access easily, The data sources are provided in the paper itself.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100598.

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