Are EIA studies sufficient for projected hydropower development in the Indian Himalayan region?

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The Indian Himalayan Region (IHR) with its major river systems has vast potential for hydropower development. Recognizing this potential, the Government of India in its recent initiative for 50,000 MW power generation proposes to develop several hydropower projects in the IHR. Based on the understanding of the prevailing policy framework of the country for hydropower development, a case study of Alaknanda catchment located in Uttarakhand (part of the IHR) is presented. The catchment is endowed with vast hydropower potential; however, in the present study, some of the important social and environmental issues are raised that arise due to dense allocation of hydropower projects in the ecologically sensitive Himalayan region. It is recognized that in the Himalayan region which is important from the conservation point of view, project-specific Environmental Impact Assessment studies are probably insufficient to tackle the environmental issues that are likely to result on account of the proposed hydropower projects.

Keywords: Alaknanda catchment, Environmental Impact Assessment, hydropower development, Indian Himalayan region.

THE Indian Himalayan Region (IHR) spreads from Arunachal Pradesh in the east to Jammu and Kashmir in the west covering 530,795 sq. km of geographical area holds a special place in the mountain ecosystems of the world[1]. These young and fragile mountains of the Himalayas are of high conservation significance due to their floral, faunal, geo-hydrological, ecological, sociocultural and aesthetic values. The region is also known as the water tower of the Earth[2] and gives water to a larger part of the Indian subcontinent. The availability of a large volume of water combined with suitable slopes offers tremendous potential for the hydropower development in the region. Looking at the rich water potential of the IHR and increasing energy demands of the country, the Government of India recognized the fact that the hydropower potential of the country needs to be harnessed to the maximum for the economic development of the country. According to the assessment made by the Central Electricity Authority (CEA), the country's hydropower potential is 148,701 MW, however, only 22.37% hydropower potential has been developed and 9.09% is under construction[3]. IHR accounts for approximately 18% of India's total geographical area and contrarily own more than 75% (117,139 MW[3]) of total exploitable potential (Table 1). National Electricity Policy of India has been accordingly framed for fully meeting the power demands of the country by 2012 along with increasing per capita availability of electricity to over 1000 units by 2012 (ref. 4). In a landmark move towards implementation, the Prime Minister of India launched a 50,000 MW hydroelectric initiative programme, formulated by CEA for preparation of Preliminary Feasibility Reports of 162 new hydroelectric schemes (47,930 MW) and surprisingly out of these 162 schemes, 133 are in IHR[5].

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Environmental implications

Over the years, there has been a realization that development of hydropower projects has significant environmental and social impacts[6]. Ecological disturbances, loss of biodiversity, loss of productive lands, damage to forests, dilapidation of other natural resources, social and cultural change, change in socioeconomic status, etc. are the major implications of hydropower projects which a region and its people may have to face. Issues directly related to design and development of hydropower projects are location specific, thus the environmental and social

Table 1. Status of hydroelectric potential development

Region/state	Identified capacity (as per reassessment study) MW	Capacity developed MW	Capacity developed (%)	Capacity under construction MW	Capacity under construction %	Capacity yet to be developed MW	Capacity yet to be developed %
Uttarakhand	18,175	2980.1	16.40	1926.0	10.60	13,269.0	73.01
Jammu and Kashmir	14,146	1864.2	13.18	899.0	6.36	11,382.9	80.47
Himachal Pradesh	18,820	6085.5	32.34	4435.0	23.57	8,299.6	44.10
Meghalaya	2,394	185.2	7.74	84.0	3.51	2,124.8	88.76
Sikkim	4,286	594	13.86	2015	47.01	1,677	39.13
Arunanchal Pradesh	50,328	423.5	0.84	2600.0	5.17	47,304.5	93.99
Nagaland	1,574	99.0	6.29	0.0	0.00	1,475.0	93.71
Assam	680	375.0	55.15	0.0	0.00	305.0	44.85
Manipur	1,784	105.0	5.89	0.0	0.00	1,679.0	94.11
West Bengal	2,841	156.5	5.51	292.0	10.28	2,392.5	84.21
Tripura	15	15.0	100.00	0.00	0.00	0.0	0.0
Mizoram	2,196	0.0	0.00	0.0	0.00	2,196.0	100.00
Total	117,239	13,425.0	11.45	12,336.0	10.52	93,000.3	79.32

Source: Central Electricity Authority, as on 31 August 2009.
The above table does not include schemes below 3 MW up to March 2003 and thereafter up to 25 MW under construction.

consequences will certainly vary spatially. Establishment of a hydropower project involves substantially large infrastructure development in terms of storage structures, diversion tunnels, powerhouse, residential/office area, roads, transmission lines, etc. Undeniably such a massive action has the potential to greatly affect the expanse, predominantly if it is taking place in the fragile Indian Himalayan Region. Again it is worth noting that the entire Himalayan system is well knit and alterations to any one aspect may have cascading effects[7]. Therefore, developmental interventions in the mountains should have a different approach, given the fragility and vulnerability of the ecosystem on account of unique mountain specificities[1].

Existing EIA framework

Environmental Impact Assessment (EIA) legislation has emerged as a management tool for mitigating the environmental implications of developmental interventions and is now being practised in more than 100 countries worldwide[8]. EIA aims to achieve or support the ultimate goals of environmental protection and sustainable development and proposes mitigation of adverse impacts. In India, EIA was introduced in 1994 when the Ministry of Environment and Forests introduced EIA notification under the Environmental Protection Act (EPA) 1986 and made EIA mandatory for 29 highly polluting activities. Further amendments in EIA notification (2006) included a total of 32 activities under obligatory consideration. A summarized view of the entire process of environmental appraisal as per present EIA framework is presented in Figure 1. The other allied legislations dealing with the environmental clearance process are: Wildlife (Protection) Act 1972, Forest (Conservation) Act 1980, the Water (Prevention and Control of Pollution) Act 1974, Water (Cess) Act 1977, National Environment Appellate Authority Act 1977, Air (Prevention and Control of Pollution) Act 1981, Environment (Protection) Act 1986, the Public Liability Insurance Act 1991 and the National Environment Tribunal Act 1995 (web: http://envfor.nic.in/).

Despite the existence of good EIA guidelines and legislation, environmental degradation continues to be a major concern in developing countries[9]. From the references it has been observed that EIA alone has not been effective in controlling the impacts owing to limitations, weaknesses and loopholes used effectively by the processors. EIA, therefore, has not been able to provide 'environmental sustainability assurance'[10]. In the context of upcoming hydropower projects in the IHR, immediately after the launch of 50,000 MW hydroelectric initiatives, serious environmental concerns and disparities in EIA studies of few of the hydropower projects have highlighted the inadequacies of EIA studies[11,12].

In an effort to understand the root causes of the environmental concerns rather than only discussing them, study of Alaknanda river catchment up to Karnprayag in Uttarakhand has been done with a view to find appropriate answers for ensuring environment friendly hydropower development in the IHR.

Case study

Alaknanda, a major Himalayan glacial stream, originates at an elevation of 3641 m amsl from Alakpuri glacier (Bhagirath Kharak and Satopanth) and traverses 229 km before its confluence with Bhagirathi at Devprayag and flows as the Ganga in Uttarakhand. The maximum and

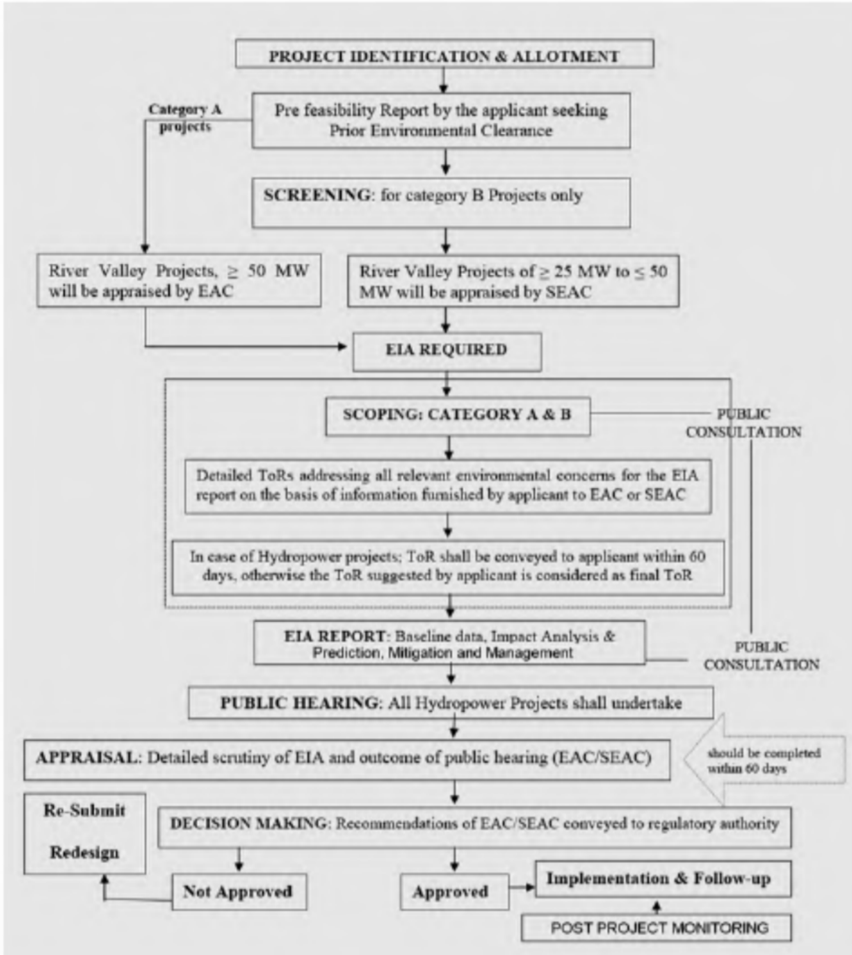

Figure 1. Summarized framework for EIA of hydropower projects.

minimum discharge of Alaknanda was measured as 3000 and 85 cumec respectively at Devprayag (before confluence with Bhagirathi) during 1990–91 (ref. 13). Alaknanda catchment, located between 30°0′N to 31°0′N and 78°45′E to 80°0′E, covers an area of about 10,882 sq. km, and represents the eastern part of the Garhwal Himalaya; the catchment area selected for the present study is up to Karnprayag (90 km upstream of Devprayag) has an area of 6168.82 sq. km (Figure 2).

As the elevation of the study area ranges from 1451 m to 8000 m amsl, the local climate very largely depends on altitude. The annual rainfall in the Alaknanda basin ranges from 1000 to 1600 mm, and nearly 75% of the rainfall occurs during the monsoon season[13] (June to September). The Alaknanda valley comprises a highly diversified ecological region since it covers a wide range of climatic conditions under altitudinal variation. Thus, the entire region is provided with a great variety of landscape, which has resulted in diverse flora and fauna[14–16]. Only few regions of Himalayas have the charm and splendour that matches the Alaknanda catchment. Within the catchment, the protected areas (PAs) like 'Nanda Devi Biosphere Reserve' (NDBR), 'Valley of Flowers' (VOF) and 'Kedarnath Wildlife Sanctuary' are located and are considered as the gems of Himalayas (Figure 2). NDBR having an area of 5860.69 sq. km, comprises a unique combination of ecosystems including mixed temperate forests, alpine meadows, glaciers, high mountain peaks and harbours about 400 tree species, 570 herbs and shrubs, 86 mammal species, 534 birds species and 54 reptiles and amphibians species[17]. NDBR has two core zones, viz. Nanda Devi National Park (624.62 sq. km) and VOF National Park (87.50 sq. km). The high percentage of endemic species richness in the NDBR itself suggests the conservation value of the valley[18]. Recognizing the importance of the area, initially it was upgraded to Biosphere Reserve in 1988 by UNESCO and subsequently included in the UNESCO's World Network of Biosphere in 2004. Kala *et al.*[19] recorded 521 species of vascular plants and 13 wild mammal species within the park and its vicinity. The VOF has been included in the list of eight World Heritage Sites by UNESCO with

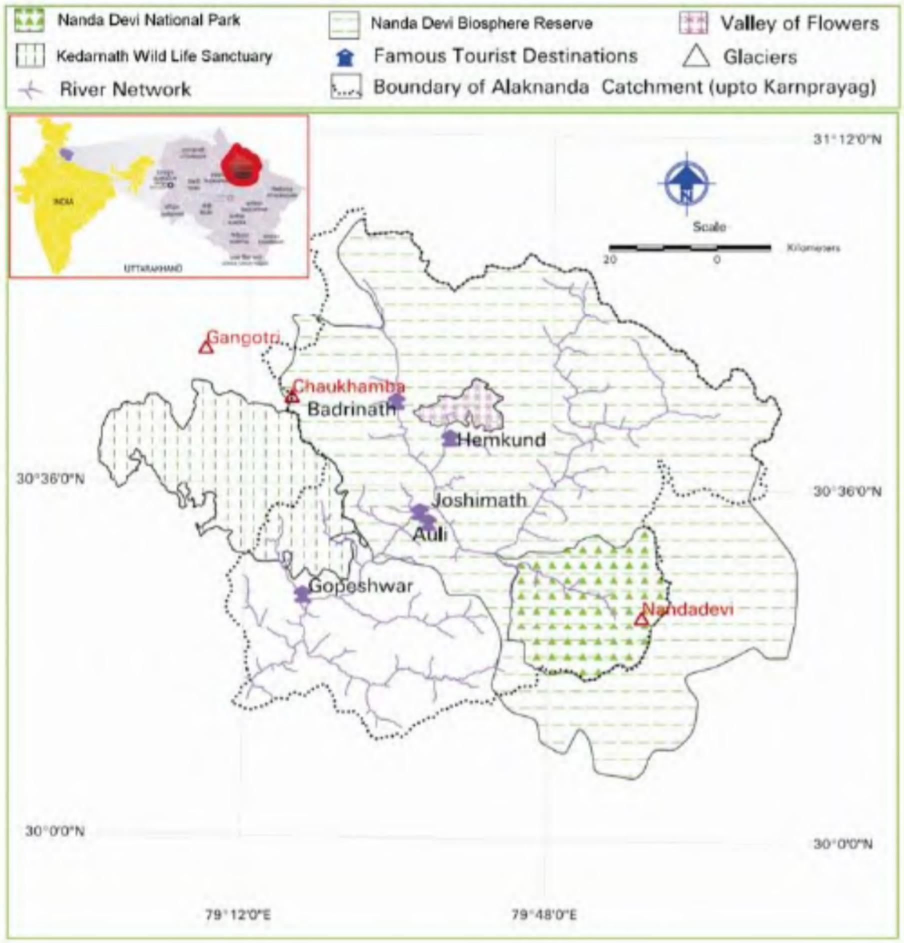

Figure 2. Location map of the study area (Alaknanda catchment up to Karnprayag) along with major drainage network, snow bound area, boundaries of protected areas, prominent tourist destinations and places.

effect from 14 July 2005 (ref. 20). Apart from rich floral and faunal diversity, the Alaknanda river itself is rich in aquatic diversity. The river sustains about 39 fish species from 15 genera and 5 families. Of these species, 14 are abundant whereas 7 are vulnerable, 15 are at lower risk level and another 2 fall under the endangered category[21]. Besides rich biodiversity, the valley is also famous for its mythological importance. There are several heritage sites within the study area like Badrinath Dham, Hemkund Sahib, etc. The holiest of the four main Hindu shrines, 'Badrinath' is situated along the left bank of river Alaknanda. With the splendid Neelkanth mountains as the backdrop, it is an important destination on the sacred itinerary of every devout Hindu, astonishing beauty attracts a large number of tourists every year. In addition, Auli adds to the list of important tourist destinations in the area, which is now popular for snow sports. Figure 2 presents the location of important tourist destinations in the study area and Table 2 presents the tourists inflow statistics over the last few years; the trend clearly suggests that the number of tourists visiting the valley is increasing every year.

On account of its biodiversity richness and cultural uniqueness, the region has been a source of inspiration for several environmental conservation movements. The well-known, 'nonviolent Chipko movement' of the 1970s (ref. 22) emerged in this part of the Indian Himalayas and its legacy inspires the current environmental struggles in the NDBR as well. The 'Tolchha' subcommunity of Bhotiyas, who reside in 10 villages of this region[23] have begun another struggle in order to protect their culture and ensure the economic welfare of their community. This community is famous in the entire IHR for its cultural specialties and traditional knowledge.

With this unique background of the study area, it is noteworthy that under the proposed hydropower expansion plan, there are 10 hydropower projects which are likely to come up in the study area. A list of these proposed projects along with their salient features are given in Table 3.

Out of the total study area, 37.99% area is snow bound, 34.21% is under the wasteland category and 19.12% of the total area is covered by seven different forest types; the land-use/land-cover map of the area is given in

Table 2. Number of national and international tourists visiting different destinations of Alaknanda catchment

	2004		2005		2006	
Tourist places	National	International	National	International	National	International
Joshimath	160,992	506	355,396	823	370,056	599
Auli	7,145	162	10,525	456	11,365	311
Badrinath	500,579		598,818		695,230	12
Hemkund	278,918		548,389	25	576,626	32
Valley of Flowers	4,514	437	4,664	547	5,489	455
Gopeshwar	18,831	53	22,834	80	26,480	96

Source: Compiled from database maintained by Tourism Department, Chamoli, Govt. of Uttarakhand.

Table 3. Salient features of the proposed hydropower projects in Alaknanda catchment

Project name (project code)	Developer	Installed capacity (MW)	Location of dam/barrage: Latitude	Location of dam/barrage: Longitude	Dam/barrage height (m)	Submergence area (ha)	PMF (cumec)	Length of tunnel (km)	Influence zone area (sq. km)
1	2	3	4	5	6	7	8	9	10
Malari–Jhelum (10)	THDC	55	30°40′ 54.7″	79°53′4.5″	24.5	10.45	5325	4.5	217.37
Jhelum–Tamak (9)	THDC	60	30°38′45″	79°49′57.5″	24.5	13.9	5845	5.7	241.23
Tamak–Lata (8)	UJVNL	280	30°36′00″	79°47′00″	12	NA	3560	12	332.76
Lata–Tapovan (7)	NTPC	171	25 km u/s of Joshimath	NA	NA	NA	NA	7.51	255.53
Tapovan–Vishnugad (4)	NTPC	520	30°33′51″	79°33′46″	22	10	NA	11.77	363.86
Vishnugad–Pipalkoti (3)	THDC	444	30°30′50″	79°29′30″	65	24.5	10,800	13.4	323.604
Vishnuprayag (6)	JPVL	400	30°40′10″	79°30′35″	NA	NA	NA	11.334	268.63
Alaknanda (Badrinath) (5)	GMR Energy Ltd	140	30°43′09″	79°29′49″	36	3.74	3530	2.84	231.726
Bowala–Nandprayag (2)	UJVNL	300	Near Birahi village	NA	5	NA	20,000	10.37	254.30
Nandprayag–Langasu (1)	UJVNL	141	30°19′30″	79°18′20″	15	NA	11,000	5	204.68

Information in columns 2–9 is based on extracted information from feasibility reports of the hydropower projects. NA stands for 'not available'. Influence zone area statistics is based on 1 : 50,000 scale base map of the study area.

Figure 3. In the study area of Alaknanda catchment, influence zone of each proposed projects is delineated taking 7 km aerial distance from the project sites (dam) according to the EIA guidelines[24] (Figure 4). It also depicts the overlapped segments of the influence zones coded as alphabets (a–p). Total influence area of these proposed hydropower projects is 2693.70 sq. km and the individual influence area of the respective hydropower projects is given in Table 3. Linking the environmental setting of the study area with the likely environmental impacts that may result as a consequence to the proposed hydropower projects, it can be visualized that certain major environmental concerns may arise.

Results and discussion

- Hydropower projects in the study area are located so densely that the influence boundary of one project overlaps the influence zone boundary of another one or more hydropower projects located nearby (Figure 4). The cumulative overlapped impact zone is calculated and it is found that 924.85 sq. km (34.33%) of the total influence zone area is being overlapped. From the various past surveys, it is documented that the cumulative environmental effects result from spatial and temporal crowding of environmental perturbations[25,26]. In view of the rich biodiversity, the synergistic and cumulative impacts resulting from these crowded projects would certainly be overlooked by the project-specific EIAs in the absence of tactical assessment of these cumulative impacts.
- Damming of a river has been called a cataclysmic event in the life of a riverine ecosystem[27]. The hydroelectric projects interrupt and alter the river's important ecological processes by changing the flow of water, sediment, nutrient, energy and biota[28]. According to the United Nations, 60% of the world's 227 largest rivers are already severely fragmented by dams, diversions and canals, leading to the degradation of ecosystems[29]. Due to dense allocation of hydropower projects in the study area, water released from the tail of the tunnel would enter the reservoir of another hydropower project. As indicated in Table 3 along with the salient features and 'dry river stretch' marked on Figure 4, the proposed hydropower

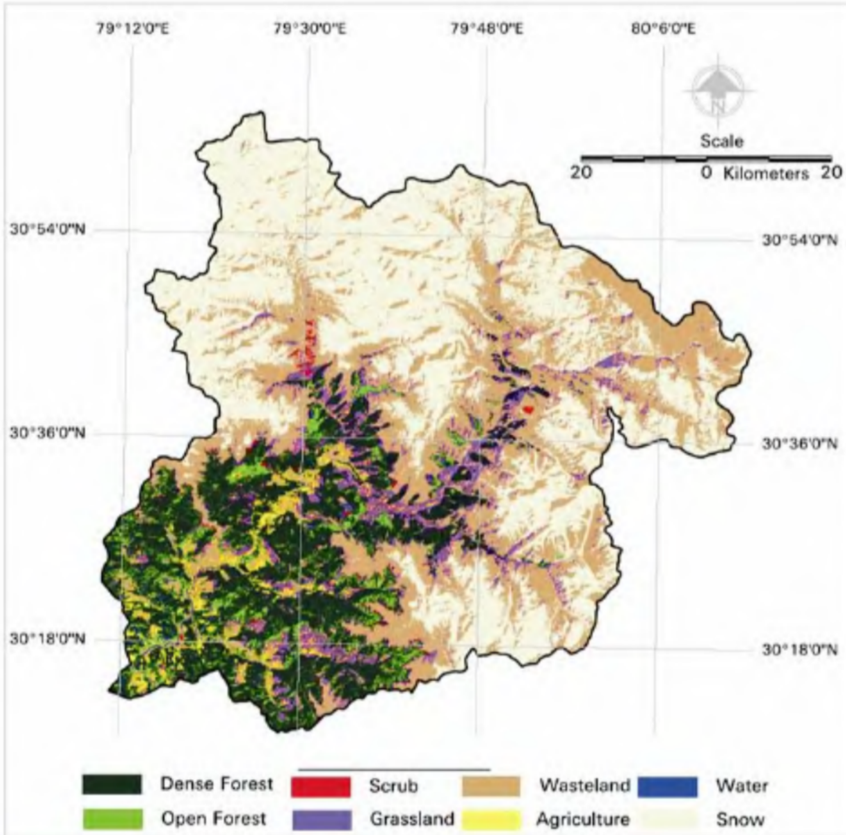

Figure 3. Land-use/land-cover map of the study area (Alaknanda catchment up to Karnprayag).

projects in the study area would cause practical drying up of the river stretch of almost 75 km especially during the lean season flow period. As a result, the velocity and volume of flow would change suddenly in stretches and this would have serious implications for the aquatic ecology of the cold water fisheries of the region. Although a minimum flow throughout the river course would always be maintained, the survival of aquatic ecosystem would certainly be severely threatened as a consequence of damming and diversion.

- An extremely important issue pertains to dam failure. It is well known that the Alaknanda catchment lies in the geo-dynamically sensitive Himalayan region (Seismic zone IV; IS 1893:2000), thus naturally prone to disasters. Earthquakes of magnitude of 8.5 on Richter scale have been recorded in the Himalayas. It needs to be noted that the kind of developmental interventions associated with hydropower projects, serious manmade disaster due to failure of dam/s may occur. The reasons of the dam failure could be technical flaw in the design or extreme rainfall event, etc. However, it is beyond argument that huge destruction of life, property and environment is expected. According to the EIA guidelines of MoEF, dam break analysis for disaster management planning is required for individual projects, wherein, there can be no consideration for other dam/s in upstream and downstream, ignoring the cascading effects of dams proposed in a series. However, in real world situation, if a single structure is failing, that will trigger chances for failure of another structure in the downstream and so on.
- With the development of hydropower projects, the natural flow of the river will be fragmented and would also disappear into the tunnels causing tremendous loss to the panoramic landscape of the region. Besides this, construction of hydropower projects will also lead to modernization of the area and in turn will cause degradation of the natural beauty of the valley that is characterized by scattered small hamlets spread over the mountain slopes with intermittent agricultural fields and herds of domestic animals being bred by ethnic communities attired in traditional dresses. In brief, the development of hydropower projects in the region would certainly affect the tourism potential of the area.
- Another important implication would be felt by the pastoral communities of the region. It is analysed that the construction of the projects will lead to an influx of outsiders – labourers and contractors in the region, and this would lead to the dilution of the culture of the pastoral

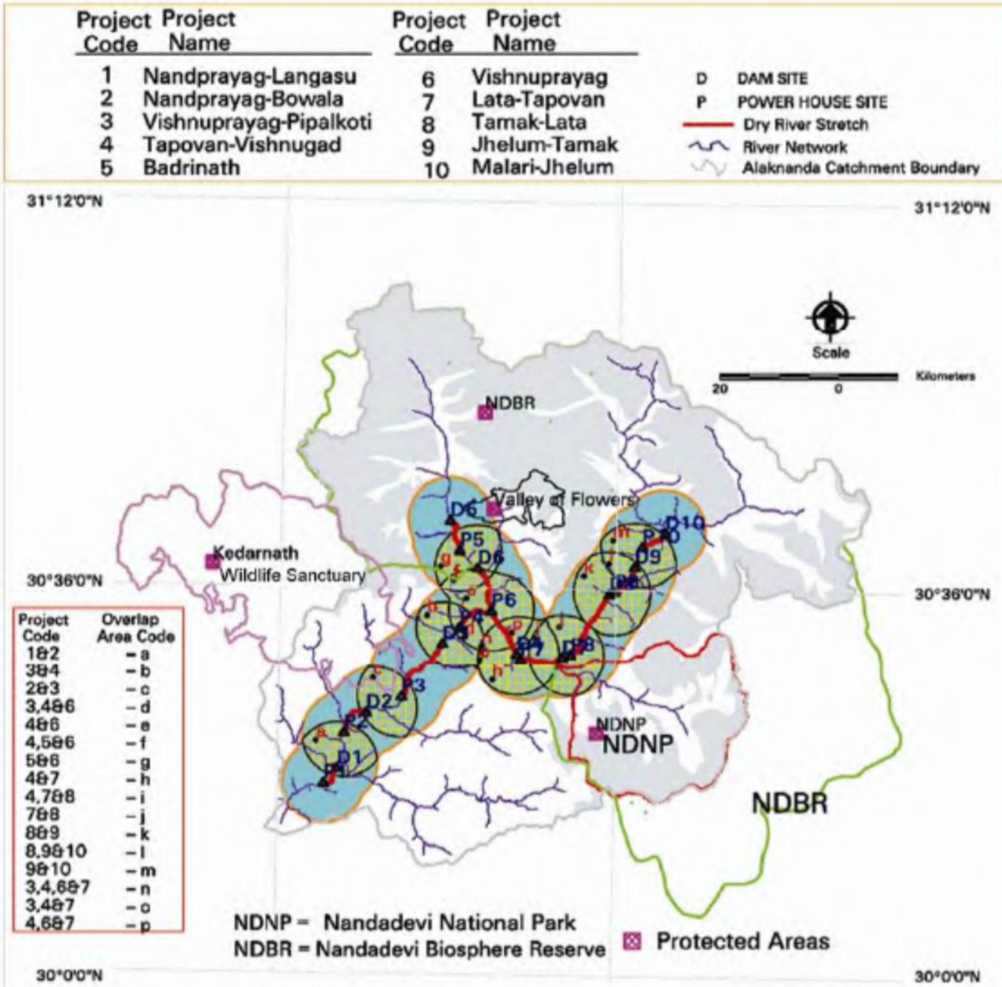

Figure 4. Influence zone of the proposed hydropower projects and river stretches likely to run dry in the study area (Alaknanda catchment up to Karnprayag).

communities. Further, development of hydropower projects will cause change in land use pattern and this may significantly affect the availability of already limited pasture land (on account of increasing number of livestock) to the pastoral communities. According to Nautiyal *et al.*[30], the land use change pattern (such as growing influence of production forestry, expansion of agriculture on traditional grazing lands and intensification of agriculture through introduction of winter wheat) is said to be the prime reason for restrictions on accessibility of grazing resources to the transhumant pastoralists of the region.

In a nutshell, it is summarized that the proposed intense allocation of hydropower projects in various parts of the Himalayan region is likely to have major implications in terms of biodiversity elements, natural and man-made hazards, tourism potential and sociocultural setting of the region.

Conclusions

The present study elaborates the scenario of opaque development of hydropower projects in inimitably priceless and fragile Indian Himalayan region, and consequential environmental implications as a result of shortcomings of project-specific EIAs in mitigation and management of environmental impacts holistically. Looking on to the discoursed specificity of the Himalayan region and feature stresses, it is felt that the present framework for EIA, specifically for Himalayan river valley projects is insufficient to handle the concerns in a region of unique importance. Although the basic structure of EIA notification have been amended at times to rectify the identified shortcomings and making it more effective, this currently practised decision tool is operating as a 'stand-alone' approach and is thus confined to a single project activity only. There is no escape from the fact that hydropower development is vindicated for national needs and the Himalayan region is a potential source; however, making such a huge development sustainable in IHR indeed solicits regional/basin-wise cumulative and strategic assessment of impacts for effectual decision making.

Environmental assessment at region-wise planning/policy level instead of project level approach can serve the purpose of environmental sustainability in the IHR. In the middle to late 1980s, a new decision tool came into debate internationally to cope with such issues, known as Strategic Environmental Assessment (SEA). SEA offers scope for making better decisions regarding policy level planning for a large scale development. Although the concept of SEA is limited in India, it has been successfully implemented in the last two decades in various sectors in many countries. Looking at international experiences and our earnest needs, it is important to explore the opportunities of SEA for sustainable development in IHR. Along with scientific research and experimentation, discussions among planners/policy makers and stakeholders, appropriate and strong SEA framework should also be developed that can be effectually applied to sectoral development in India.

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Evaluation of groundwater resource and estimation of its potential in Pathri Rao watershed, district Haridwar (Uttarakhand)

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The present study attempts to delineate aquifers in the piedmont zone of Himalayan foothill region in Pathri Rao watershed, district Haridwar, Uttarakhand, India by using integrated hydrogeologic and geophysical techniques. The geophysical techniques included vertical resistivity soundings, two-dimensional resistivity image profiling and electromagnetic surveys. Nuclear isotope studies have been carried out to estimate groundwater recharge and its relative age. An assessment of groundwater availability and stage of groundwater development has also been made from the available and generated field data. On the basis of the study, it was found that the rate of recharge into the aquifers is of the order of 19% and the stage of groundwater development in the watershed is 164% indicating critical over-exploitation of groundwater. Based on the findings, possibilities of artificial recharge of groundwater have been looked into in the study area for augmentation of groundwater resources by proposing a few check dams at the suitable sites in the upstream areas of the watershed.

Keywords: Aquifer delineation, groundwater assessment, isotope studies, watershed resistivity imaging.

Introduction

GROUNDWATER forms one of the important sources of water supplies in many areas, as it is believed to be safe and free from pathogenic bacteria and from suspended matter. The pace of groundwater withdrawal in many fertile regions is increasing phenomenally due to the fast pace of population growth accompanied by agricultural and industrial development. Large databases need to be developed for relating the aquifer geometry vis-á-vis availability of groundwater resources especially in the hilly regions of Himalayas. The present study attempts to delineate aquifers in the piedmont zone of Himalayan foothill region in Pathri Rao watershed, district Haridwar, Uttarakhand by using integrated hydrogeologic and geophysical techniques. Nuclear isotope studies have been carried out to estimate groundwater recharge and its age. An assessment of groundwater availability and stage of groundwater development has also been made from the available field data.

Previous work

Remote sensing and GIS techniques have been increasing in use to generate groundwater potential maps[1,2]. The satellite remote sensing data along with collateral information and limited field checks have been used to establish base line data for groundwater prospective zones[3–7]. A critical review of the assessment of the groundwater recharge was given by Lerner *et al.*[8] and Scanlon *et al.*[9] in which the recharge estimation was made by considering rainfall infiltration and seepage from irrigation fields. The Groundwater Estimation Committee[10] of the Government of India suggested comprehensive norms and methodology for estimation of groundwater potential in the soft and hard rock areas. This approach is currently in common use by the government agencies. Israil *et al.*[11,12] gave applications of resistivity surveys, GIS analysis and isotope studies for hydrogeologic zoning and for evaluation of groundwater resource of the Ratmau–Pathri Rao watersheds of district Haridwar. Subsequently, Israil *et al.*[13] described the use of geophysical methods for direct delineation of aquifer configuration in the Pathri Rao watershed.

Study area

The study area is located between lat. 29°55′–30°3′N and long. 77°59′–78°6′E and covers an area of about 52 sq. km in the Pathri Rao watershed (Figure 1). The area is comprised of two hydrogeomorphic units, viz. Siwaliks and the Upper Piedmont zone, also referred to as 'Bhabhar' in the Himalayan foothills region, Uttarakhand. A third unit, viz. Lower Piedmont (Terai) zone falls further south of the Upper Ganga Canal. A notable flood plain has also been demarcated in the central part towards the eastern fringe of the watershed (Figure 2).

Geologically, the study area is comprised of sediments derived from Tertiary deposits of the Siwaliks. The

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Siwaliks are exposed towards the northern extreme of the Pathri Rao watershed. The Bhabhar deposits are composed of unconsolidated coarse sand with boulders, fine to medium sand with pebbles, boulders and clay, derived from the Siwalik ranges. The formation exhibits high porosity and permeability, allowing easy infiltration of water with considerable recharge possibilities for the extensive aquifer system. The infiltrating waters move down along the steep gradient towards south and emerge as springs near the junction of Bhabhar with the Terai near the southern boundary of the area. South of this 'spring line', the Terai belt is present with effluent seepage at land surface resulting in marshy conditions.

Groundwater conditions

Mufid[13], Shimeles[14] and Kachhwal[15] carried out detailed study of this area using available lithologs of borewells and vertical electrical resistivity sounding data. They found that the depth of aquifers in the area is irregular and varies in a wide range. Admixtures of clay, sand and gravels of varying sizes are present in tube wells, though their properties vary from one place to another. The aquifers are composed of sand with pebbles and boulders generally fining upwards. Clay beds are also present with variable thickness but with limited aerial extent; however, at places, thick clays are present in some parts. Though all types of aquifers, i.e. unconfined, confined, semi-confined and perched aquifers are present, generally unconfirmed or confirmed two aquifers are commonly met with.

The fluctuation of groundwater table has been monitored in the study area in six existing well hydrographs. The locations of these wells are shown in Figure 1. However, these wells are located mostly in central and southern parts. It may be mentioned that the northeastern hilly terrain is an inaccessible and protected forest; therefore, no direct hydrogeological observations in this zone have been possible. The depth of water table was monitored during pre-monsoon (pre-rainy season) and post-monsoon (post-rainy season) period for 2004 and 2005 which are given in Table 1.

From overall water table data of the watershed, it is observed that the depth of water table is minimum (8.7 m bgl) near Qutubpur (W-4) located near the southwestern boundary of the Bhabhar zone and the deepest water table (32 : 79 m in June 2005) being recorded in the northern part of Bhabhar zone at Hetampur (W-10). The reason for occurrence of generally deep water table (9–32 m bgl) in the Bhabhar zone seems to be the high permeability of assorted and unconsolidated deposits in the vadose zone and due to the general absence of confining clay layers at shallow depths. Figure 3 shows a generalized groundwater potential map of the watershed based on selected seven geohydrological parameters[11].

Geoelectrical studies

With the purpose of aquifer delineation in the study area, an integrated approach comprising of vertical electrical soundings (VES), resistivity image profiling (EIP) and time domain electromagnetic (TEM) surveys was planned. Two-dimensional (2D) resistivity tomography carried out through EIPs helped in defining the horizontal and vertical geometry of the aquifer system[16]. A total of 11 VES, two TEM profiles and nine EIP profiles were recorded as shown in Figures 1 and 2. VES data were recorded using the Schlumberger configuration with maximum

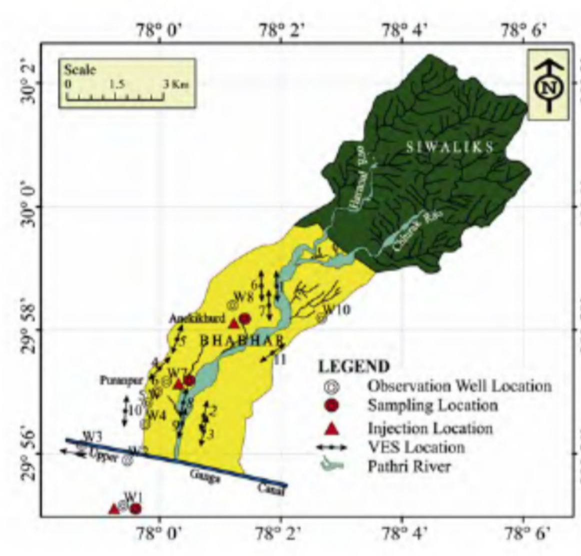

Figure 1. Location map of the project area.

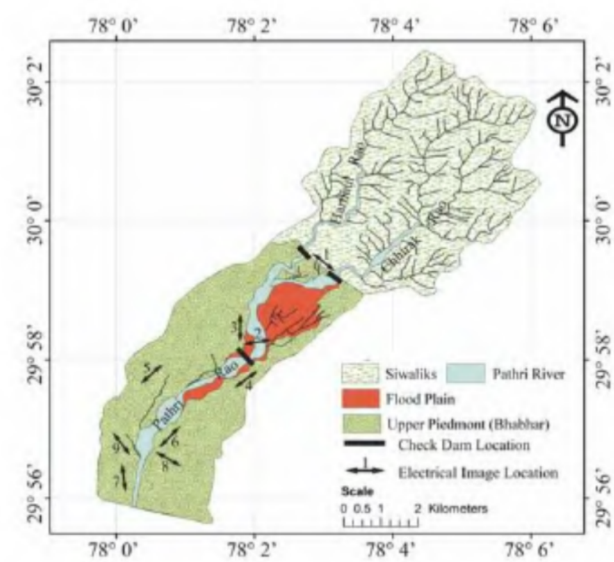

Figure 2. Hydrogeomorphological map of Pathri Rao watershed.