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Integrating energy justice and earth observation to examine the social dimensions of hydroelectric dams

Garima Gupta [a,*], Shubham Pawar [a], Chris Littleboy [a], Nils Bunnefeld [a], Jennifer Dickie [a], Isabel L. Jones [a]

[a] University of Stirling, Biological and Environmental Sciences, Faculty of Natural Sciences, FK9 4LA, Stirling, UK

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ABSTRACT

Hydropower is increasingly promoted as a cornerstone of global low-carbon energy transitions, yet the long-term social consequences of large dams remain inadequately understood. Existing assessments often focus on short-term displacement and overlook evolving socio-spatial harms that persist well beyond construction. This study addresses this gap by applying an interdisciplinary energy justice framework to the Tehri Dam in the Indian Himalaya nearly two decades after its commissioning. Drawing on semi-structured interviews and Earth Observation analysis, we examine how affected communities experience distributional, procedural, recognition, capabilities, and restorative injustices across space and time. The findings reveal that injustices extend far beyond physical relocation. Communities continue to face sustained livelihood loss, reduced access to health and education services, long-term isolation caused by disrupted connectivity, and heightened environmental risks such as land subsidence. These indirect and cumulative harms remain largely invisible in conventional impact assessments. By integrating spatial evidence with lived experiences, the study demonstrates how Earth Observation can uncover hidden and emerging inequalities associated with large-scale energy infrastructure. This research advances energy justice scholarship by foregrounding the spatial and temporal dimensions of hydropower impacts and by illustrating the value of mixed-methods approaches for sustainability research. The findings underscore the need for policy frameworks that recognize both material and non-material losses and support more equitable, community-centred energy transitions in vulnerable regions.

1. Introduction

Climate change, driven by human activities, threatens both humanity and biodiversity, potentially leading to a sixth mass extinction [1]. Fossil fuel combustion is the largest contributor to climate change, prompting global efforts like the Paris Agreement, Kyoto Protocol, and United Nation's Sustainable Development Goals (SDGs) 13 to drive urgent climate action. However, meeting escalating global energy demands, projected to rise by 50 % by 2050 [2], presents a formidable challenge to these efforts. Consequently, the Intergovernmental Panel on Climate Change (IPCC) emphasizes the critical need for a rapid global energy transition from fossil fuels to clean and low-carbon energy sources and recent international agreements have set this transition in motion at a global scale [3].

Hydropower has emerged as a primary focus in the global energy transition, contributing over 70 % of renewable electricity worldwide [4]. Frequently described as the backbone of low-carbon electricity generation, hydropower is valued for its flexibility and reliability compared to other renewable sources such as solar, wind, and tidal energy [5]. In addition to electricity production, dams provide benefits such as flood control, irrigation, and water supply, making them an important component of energy infrastructure globally [2,6], particularly in developing countries [7], where millions of people remain off-grid and lack access to electricity [8].

India is the world's third-largest energy consumer, and is experiencing a surge in energy demand, further intensified by its recent status as the most populous country [9]. Currently, 57 % of India's energy needs are met through coal, oil, and biomass [10], making it the third-largest carbon emitter globally. Recognizing the need for urgent climate action, India pledged its '*Panchamrit*' commitments at the 2021 COP26 Climate Summit, aiming for net-zero emissions by 2070 and targeting 50 % of energy generation from renewables by 2030 [11]. To

* Corresponding author.
E-mail address: garimagupta1606@gmail.com (G. Gupta).

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achieve these ambitious goals and meet rising energy demands, India is rapidly expanding hydropower projects throughout the country. The Himalayan basins—particularly the Ganga, Indus, and Brahmaputra—are key sites for dam construction due to their vast hydropower [12]. India has thus become the third largest dam building country in the world with over five thousand large dams constructed [13].

Despite being a low-carbon energy source, large dams are often linked to increased social and environmental inequalities across temporal and spatial scales due to the socio-ecological fragmentation they induce [14]. Dams have profound impacts on river ecosystems including biodiversity loss, habitat fragmentation, and disruption of species migration pathways [15,16]. In the Indian Himalayan Region—home to nearly 50 % of India's recorded biodiversity, much of it is endemic to the region [17]. Furthermore, 88 % of these dams are planned within ecologically sensitive subtropical and temperate forests, which are highly vulnerable to biodiversity loss driven by land-use changes [18]. Beyond ecological impacts, large dams often have significant social consequences. They frequently lead to the displacement and resettlement of local communities, often with minimal or no prior consultation [7]. Studies estimate that out of the 200 million people displaced worldwide by infrastructure projects in the last century, 40 % were displaced due to dam construction [19]. This displacement disrupts livelihoods [20], exacerbates food insecurity, and diminishes social capital, risk of joblessness resulting in psychological stress [21] thereby undermining progress towards achieving the United NationsSDGs relating to food security (SDG 2), livelihood (SDG 8), life on land (SDG 15), and life below water (SDG 14). Still, social impacts caused by hydropower dams are understudied or poorly understood and are currently ineffectively addressed by dam development companies [22].

In this study, we adopt an interdisciplinary approach, combining social science and Earth Observation (EO) to explore the social dimensions of the Tehri Dam development—one of India's largest hydroelectric projects (See Fig. 1). Using the Energy Justice Framework [23], we aim to capture the complexities of the long-term social impacts experienced by communities around the Tehri Dam within a consistent and structured framework. Our approach builds upon the foundational work of energy justice scholars such as Sovacool and Dworkin (2015) [24], Jenkins et al. (2016, 2021) [25,26], and McCauley et al. (2019) [27] who conceptualize energy justice through the interrelated dimensions of distributive, procedural, andrecognition justice. The five-tenets framework proposed by Castro-Diaz et al. (2024) [28] extends these earlier formulations by adding restorative and capabilities justice—two dimensions that are particularly relevant in post-displacement and infrastructure-affected contexts. This expanded framework enables a more holistic understanding of energy-related injustices by considering not only how impacts are distributed, but also how affected communities are recognized, involved in decision-making, and supported in rebuilding their lives following displacement or other dam-related impacts. We therefore adapt the definitions of the five energy justice pillars (Table 1) from Castro-Diaz et al. (2024) [28] to examine hydropower development in the Global South, where questions of long-term restoration, equity, and well-being remain central to achieving a just and sustainable energy transition.

Tehri Dam represents a useful case study to examine the social impacts of dam development as it is one of the tallest dams in the world standing at 260.5 m high and has been the site of social and has been the site of social and environmental conflicts for several decades. It resulted in submergence of several towns displacing around 100,000 people [33]. The Tehri region, known for its fertile land due to the sediment deposits from the Bhilangna and Bhagirathi River, historically relied on agriculture as the primary source of livelihood. However, the reservoir created by the dam submerged large tracts of agricultural land, leading to the loss of fertile agricultural lands of many people. Using the tenets of energy justice, we analyse how the positive and negative impacts are distributed across space and time. The Energy Justice Framework, recognized as a conceptual, analytical, and decision-making tool [24], provides valuable insights into what constitutes social justice or injustice in energy systems [23].

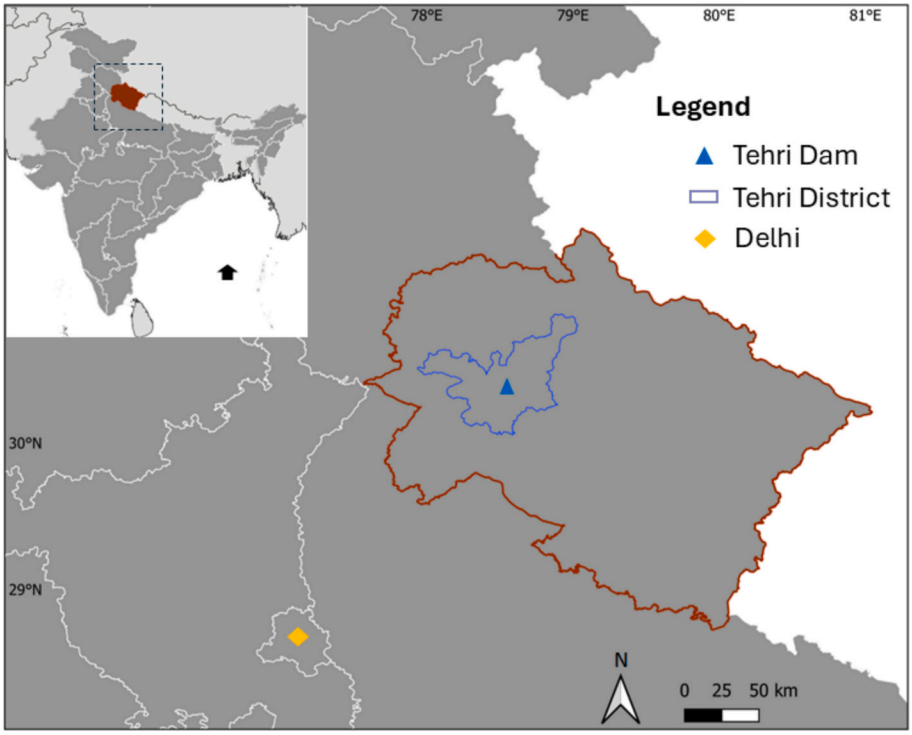

Fig. 1. Map showing the study site, the Tehri Dam (in blue colour triangle) in the Tehri district outline in blue within Uttarakhand, outline in brown - a state of India and its proximity to Delhi (in yellow colour rhombus). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Definition of five tenets of energy justice adapted from Castro-Diaz et al., (2024) [28].

Energy Justice	Definition
Distributional Justice	*Refers to the uneven allocation of cost and benefits an energy project generates, such as electricity, drinking and irrigation water (in the case of a multipurpose dam), and long-term employment opportunities* [24,28]
Procedural Justice	*Refers to the fairness of institutional decision-making process and the participation of different stakeholders in public hearings and other meetings* [24,28,29]
Recognition Justice	*Calls attention to local histories of oppression and exclusion; therefore, understanding how individuals and communities are recognized is inseparable from distributional and procedural justice* [28,30].
Restorative Justice	*Aims to repair any harm done to society or environment, including by energy projects. Restorative Justice focuses on the people who have been harmed; this tenet seeks recognition, reparation of their harm, and restoration of their dignity* [31]. *It aims to repair the damage concretely and symbolically, requiring 'those who have been harmed to provide an opportunity to define their needs, rather than having others or a system define needs for them'* [28,32].
Capabilities Justice	*It suggests looking beyond the resource to what people could do or become because of this resource. In this approach, energy systems should aim not only to provide energy but also to expand the capabilities of individuals, households, and communities to achieve their goals and reach their human potential* [28,29].

Perspectives on the developmental value of hydropower projects like the Tehri Dam can vary significantly, particularly between stakeholders. While some view such schemes as essential for progress, others, especially those directly affected, may emphasize negative experiences. These narratives, often shaped by displacement and compensation dynamics, can carry inherent biases. To strengthen and complement our interview-based findings, we integrate a quantitative approach using EO data. This allows us to examine land cover changes over time to assess shifts in agricultural livelihoods and evaluate changes in village connectedness prior to and after dam construction. By triangulating these data sources, we aim to provide a more robust and comprehensive perspective on the long-term social impacts of the Tehri Dam.

To our knowledge, this study marks the first application of the Energy Justice Framework to explore the positive and negative social impacts of a hydroelectric dam in India. Communities were categorized into three groups based on their proximity to the Tehri Dam, and interviews were conducted to: (i) understand the social impacts nearly 20 years after the dam's commissioning; (ii) provide an overview of energy injustices experienced by these communities; and (iii) assess the spatial and temporal distribution of these injustices.

2. Methods

This study adopts mixed-methods, interdisciplinary research approaches to examine the long-term socio-environmental impacts of the Tehri Dam through the lens of energy justice. Semi-structured interviews were conducted with individuals from three community categories—displaced, affected-but-not-displaced, and downstream—to capture diverse lived experiences of dam-induced change. These qualitative insights were analyzed using a modified matrix framework based on five tenets of energy justice (distributional, procedural, recognition, capabilities, and restorative justice), along with spatial and temporal dimensions. To complement and triangulate these findings, we used EO methods—including land cover change detection and travel time analysis—to assess environmental transformations such as agricultural land loss and altered connectivity over time.

2.1. Study site

The Tehri Dam is a multi-purpose hydroelectric dam with a total of 2400 MW of installed capacity. It is located at the confluence of the Bhagirathi and the Bhilangana Rivers, two major tributaries of the river Ganges in the Tehri Garhwal region of Uttarakhand, India. Commissioned in 2006, the Tehri Dam stands at 260 m high and spans a reservoir area of 42 km^2, making it one of the tallest dams in the world (see Table 2 for more details). A total of 135 villages were submerged in the Tehri Dam reservoir, permanently displacing approximately 100,000 people who were compensated and resettled to different locations [34].

To manage this large-scale displacement, the Tehri Hydro Development Corporation Limited (THDC) formulated a Rehabilitation and Resettlement (R&R) Policy in 1988 [35], outlining provisions for land-for-land compensation, housing plots in resettlement colonies, and livelihood restoration support, including employment opportunities in the project. However, despite its stated objectives, the policy's implementation has been widely critiqued as inconsistent and inadequate. Land scarcity in the hill region forced many families to accept cash compensation or to be resettled in regions far from Tehri, which often proved insufficient to support long-term resettlement. Promised employment opportunities were rarely fulfilled, and essential infrastructure at resettlement sites—such as schools, health centres, and transport facilities—remained underdeveloped.

Several studies and field reports [35–37] highlight that these gaps between policy design and practice resulted in enduring socio-economic disruptions and deepened community vulnerabilities. Injustice was most visible in the lack of participatory planning, prolonged displacement processes, and limited efforts towards restoring livelihoods or social cohesion. These shortcomings reflect critical procedural and restorative injustices, which continue to influence the lived realities of displaced and affected communities around Tehri.

The Tehri Dam Complex was planned in three phases: a) Tehri Hydro Power Plant (Tehri HPP)-1000 MW (4 × 250 MW). Commissioned in 2006; b) Koteshwar Hydro Electric Project (Koteshwar HEP)-400 MW (4 × 100 MW) Commissioned in 2011; c) Tehri Pumped Storage Plant (Tehri PSP)-1000 MW (4 × 250 MW) Under Construction.

2.2. Stakeholders

Before commencing fieldwork, a reconnaissance (recce) visit was conducted to ground-truth the region and better understand the local socio-political context. During this visit, we consulted with local environmental activists and individuals involved in grassroots movements advocating for community rights. Based on their recommendations, we identified potential villages that had either been directly affected by hydropower development or were actively engaged in grassroots action advocating for community rights.

To structure the study, we categorized communities into three groups—displaced, affected but not displaced, and downstream—and selected two villages from each category (Table 3). This design allowed for meaningful comparisons across groups while maintaining manageable fieldwork logistics. Villages were chosen because they represented typical experiences of each category (e.g., resettled displaced households; affected-but-not-displaced communities that lost connectivity or services; and downstream villages facing ecological and livelihood disruptions). Accessibility was another important factor in site selection. Villages experiencing very high levels of out-migration were excluded

Table 2
Tehri Dam at a glance.

Type of dam	Embankment, earth and rock fill
Height	260.5 m
Base	1128 m
Width at top	25.5 m
Length at the top	592 m
Total electricity produced	2400 MW
Other benefits	Irrigation and Drinking Water
Total capacity of reservoir	3.54 billion m^3
Total area of reservoir	42 sq. Km.

Table 3
Definitions of the three categories of communities and number of participants.

Category	Definition	Number of Interviewees
Displaced	Communities whose lands and homes were submerged and who were displaced to other areas and were considered directly affected by the dam. These communities were entitled to the compensation	3
Affected but not displaced	Communities indirectly impacted by the dam, such as through loss of connectivity due to bridge submergence, landslides, or loss of livelihoods, were not considered affected and were not entitled to compensation	5
Downstream	Communities located downstream of the dam. These communities were not entitled to any compensation	4

because their reduced populations would have limited opportunities for sustained community interaction and data collection. Our aim was not to capture the "worst affected" cases, but to document a diversity of lived experiences across categories in ways that could be triangulated with EO data.

Participant identification relied on a combination of community introductions and snowball sampling. In some villages, we met the *gram pradhan* (village head), who facilitated introductions and suggested individuals with relevant knowledge and experiences. As interviews progressed, community members expressed interest in participating and often recommended others, enabling an organic snowballing process.

Interviews were conducted in both individual and group settings. Group interviews typically featured one spokesperson responding on behalf of others, who listened, agreed, or added perspectives. Thus, while the formal number of interviews was 12 - of which seven were conducted individually and five in group settings - discussions often reflected the views of multiple participants. We aimed for gender and age inclusivity, ensuring that interviewees included university students, a group of women, young men, and elderly individuals. The exact number of individuals present in group interviews was not systematically recorded, as the focus was on capturing shared community perspectives rather than individual-level participation. Participants ranged in age from 20s to 80s years, allowing for intergenerational and gendered insights into experiences of displacement and energy injustice.

We acknowledge that the sample size is small relative to the scale of displacement (over 100,000 people). However, the purpose of this study was not statistical representativeness. Instead, it was designed to generate an in-depth qualitative understanding of lived experiences, which could be meaningfully triangulated with EO data to build a richer picture of the social impacts of dam development.

2.3. Ethics

The study was reviewed and approved by the General University Ethics Panel at the University of Stirling (GUEP 2023 10,434 9066). As the research involved human participants, ethical approval was required to ensure compliance with institutional and international research standards.

Key ethical considerations included ensuring complete anonymization of the data [38]. Interviews were conducted only with the informed consent of participants, who were fully briefed about the aims of the study prior to data collection. Participants were assured that their involvement was voluntary, that they could withdraw at any time if they felt uncomfortable, and that their anonymity and confidentiality would be strictly protected.

To maintain these safeguards, interviews were documented with participants' consent, but no audio or video recordings were made. Instead, notes were taken to minimize risks of identification. In addition, the locations of the interviewees were not recorded, ensuring that participants' identities and community affiliations remained untraceable.

Although the study addressed sensitive issues related to displacement and energy injustice, participants were not considered vulnerable populations under formal ethical classifications (e.g., children, individuals unable to provide informed consent). Nevertheless, we conducted interviews in a respectful and culturally sensitive manner, prioritizing participants' autonomy and comfort throughout the process.

2.4. Interview data analysis

All interviews were conducted in Hindi and subsequently transcribed and translated into English by the first author, Garima Gupta. As a native Hindi speaker with fluency in English, she ensured that the translations remained as close as possible to the original meaning, preserving the intent, tone, and nuance of participants' responses. In qualitative research, translation is not a neutral act—it involves interpretation, and meanings can shift in the process [39]. Care was therefore taken to ensure the integrity and contextual accuracy of the data during this phase. Our analysis was guided by the five-tenets framework of energy justice—procedural, recognition, distributional, restorative, and capabilities justice [28] —which served as the central conceptual lens for this study. To present findings in a way that captures the complexity of the case, we developed a visual matrix on the dam's social impacts, based on dimensions and components following the model proposed by Kirchherr and Charles (2016 and 2018) [40,41] (Fig. 2). The purpose of this matrix was not to introduce a second framework, but to serve as an organizing tool that embeds the five tenets of energy justice within spatial and temporal dimensions. Specifically, the matrix enables systematic comparison across different phases of dam development (planning, construction, and operation) and across different community groups (displaced, affected-but-not-displaced, and downstream). The "value" dimension further distinguishes whether impacts were perceived as positive or negative. In adapting this framework, we replaced the original categories (infrastructure, livelihood, and community) with the five energy justice pillars—procedural, recognition, distribution, restoration, and capabilities. The dimensions remained unchanged, encompassing space, time, and value, but were reinterpreted to reflect our case: the "space" dimension captures how energy in/justices are distributed among displaced, affected-but-not-displaced, and downstream populations; the "time" dimension focuses on key phases of dam development (planning, construction, and operation); and the "value" dimension assesses whether the impact is positive or negative. We analyzed interview transcripts using thematic coding, informed by both deductive categories (the five energy justice tenets) and inductive themes emerging from the data [42,43]. The use of NViVo12 [44] facilitated systematic coding and comparison across categories of communities and phases of dam development.

2.5. Data sources for land cover change analysis

Two land use/land cover datasets were used for the analysis: the landcover data from the Natural Resource Census - Land Use Land Cover Database (1:50 K: 2005–2006) [45,46], representing conditions before or during dam construction, and the Space-Based Information Support for Decentralized Planning (SIS-DP) project (1:10 K: 2018–2023) [47] for the post-construction scenario. Both datasets follow the National Natural Resources Management System (NNRMS) land cover classification standards. The analysis focused on Level 1 NNRMS classifications, which include agriculture, built-up areas, barren land, forests, grasslands, and water bodies.

The 2005–2006 Land Cover map was generated using satellite imagery from Resourcesat-1 LISS III, applying a supervised classification approach combined with visual interpretation. This dataset was further refined using ancillary information on wastelands and forests. For the 2018–2023 Land Cover map, fused imagery from Cartosat and LISS-IV

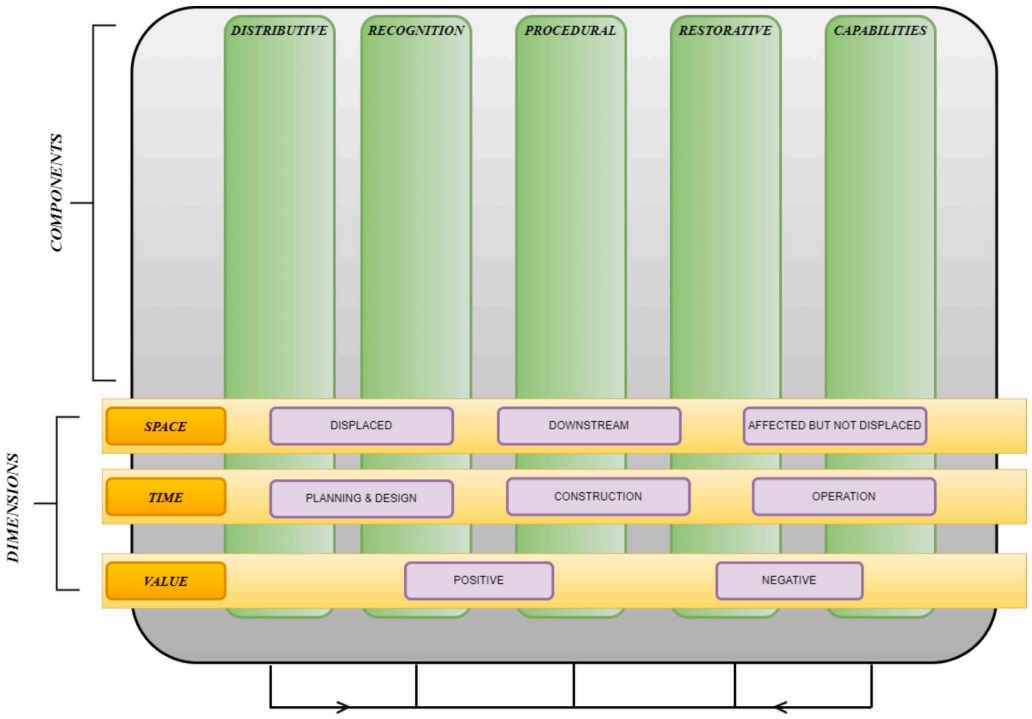

Fig. 2. The matrix framework adapted from Kirchherr and Charles [40]. Visual matrix used to organize interview data. The matrix embeds the five tenets of energy justice as components, situated across three dimensions: space (displaced, downstream, and affected-but-not-displaced communities), time (planning, construction, and operation phases), and value (positive or negative impacts). The matrix serves as a visual representation of the five-tenets framework, designed to make findings more transparent and accessible.

sensors was used. The image was segmented into smaller units, which were then classified into landcover categories by dissolving or splitting segments based on land cover types [48]. Given the differences in spatial resolution between the datasets (1:10,000 for 2018–23 and 1:50,000 for 2005–06), a direct comparison was not feasible. To allow for a meaningful comparison, the 2018–23 high-resolution landcover dataset was resampled to 1:50,000 scale using standard resampling techniques. This resampling ensured that both datasets were compatible for time-series analysis. To assess land use changes at the local level, a buffer zone of 2 km and 5 km from the existing reservoir was considered, as these areas were significantly impacted in terms of livelihoods and land loss following dam construction. Within this buffer, resampled land cover data from 2018 to 23 was compared to the 2005–06 dataset, with a particular focus on changes in agricultural land use.

2.6. Travel time analysis

The qualitative findings on the increased remoteness of villages following Tehri's construction were corroborated using a travel time analysis for the region. To do this we downloaded satellite imagery in Tehri from before and after the dam was built from the Landsat image archive five years before (2001) and five years after (2011) [49]. From the raw satellite imagery, we computed the Normalised Difference Vegetation Index (NDVI) values as the mean NDVI of all downloaded images for each time period. Areas covered with water have negative NDVI values [50]. "Friction" values – the inverse of potential speed travelled – were calculated for each pixel using Digital Elevation Model data and Tobler's hiking function [51]. These friction values were adjusted so that water bodies without a bridge have high friction. We then created layers for towns and bridges in QGIS to show where people can cross the reservoir. Finally, we calculated the walking time to Old Tehri (before the dam was constructed) and to New Tehri (after the dam was constructed) using the costDistfunction in the R package terra [52].

3. Results

The affected but not displaced communities raised the most energy injustices, with 43 references, followed by downstream communities with 33 references, and displaced communities with 29 references (Fig. 3). The highest frequency of injustices raised by the affected but not displaced communities occurred during the operation phase (32), followed by the planning phase (7) and the construction phase (4), with only three positive references overall. The affected but not displaced communities voiced issues of recognition and distribution frequently followed by procedure, capabilities, and restoration. In the case of displaced communities, respondents highlighted the most injustices during the planning phase (15), followed closely by the operation phase (14), with no mention of injustices during the construction phase. All references were negative with a maximum number of procedural injustices followed by distribution injustice. For downstream communities, most injustices were raised during the operation phase (29), followed by the planning phase (4), with just one positive reference. Downstream communities voiced maximum issues of distributional injustices closely followed by recognition injustices. There were other injustices mentioned by the communities, but distribution, recognition, and procedural injustices were most commonly mentioned in the interviews.

The following sections present the findings organized around the five tenets of energy justice—procedural, recognition, distributive, restorative, and capabilities—allowing a systematic exploration of how different forms of injustice manifested across communities and phases of dam development.

3.1. Distributional justice

Distributional justice concerns how the costs and benefits of dam development are shared across different social groups. In the case of the Tehri Dam, injustices were most evident in the unequal distribution of economic losses and environmental risks borne by local communities,

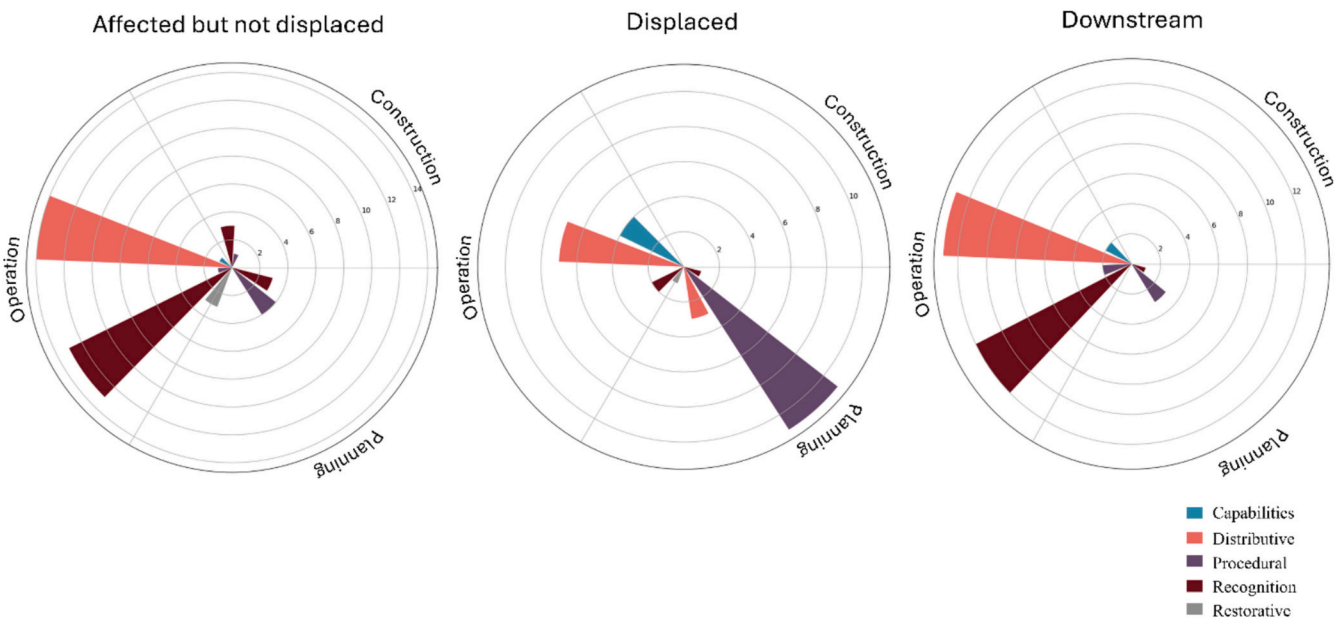

Fig. 3. Radar Plot showing number of references to energy injustices mentioned by different communities during different phases of dam development.

who received few of the promised benefits such as electricity, employment, or infrastructure.

3.1.1. Loss of livelihood

The loss of agricultural livelihoods represents a key manifestation of distributional injustice, as the burdens of dam construction were borne disproportionately by local communities who received none of its economic benefits. Most of the local inhabitants interviewed reported losing their primary source of livelihood—agriculture. This loss has placed severe economic pressure on these communities, as they are now forced to depend more heavily on the market to purchase essential goods. Without the means to generate income, their economic hardship has deepened, amplifying the adverse consequences of the dam's construction on their livelihoods and well-being.

The construction of the Tehri Dam has significantly impacted the livelihoods of almost all communities in the Tehri region, particularly the affected but not displaced and downstream communities.

Loss of agricultural activities in the village that has a negative impact on cultural traditions. Everything grew on our lands, but it has changed now. We are dependent on markets now for everything (more dependency on markets).

(Interviewee 8, Affected but not displaced)

We lost our fertile agricultural land, which was our main source of livelihood. We used to grow everything on our land but now we are completely dependent on the market for everything and for that we need more money, but there is no other source of income generation in the village.

(Interviewee 9, Affected but not displaced)

We had livestock and agriculture was our main livelihood source. We used to grow everything (wheat, rice, maize, potato, tomato etc) for our subsistence and sometimes we used to sell them too, but everything has changed.

(Interviewee 4, Downstream)

Our agricultural land in Tehri was very fertile. We used to grow a lot of things on our field such as Rice, paddy, Jhingora (Barnyard Millet, is a super food grown in the lush Himalayan valleys of Uttarakhand. These are tiny, white & light brown, round grains belonging to the millet family), Mandua (Finger millet), lentils. We never bought anything from the market.

(Interviewee 2, Downstream)

Agriculture was the main source of livelihood or the source of income for my family, but we have lost our only source of income. I have a contractual job and not even a permanent job.

(Interviewee 5, Displaced)

These narratives of agricultural decline are corroborated by our EO analysis. Land cover classification shows that agricultural land decreased by 9 % within the 2 km buffer zone and by 4 % within the 5 km buffer zone between 2005 and 2006 and 2018–2019. At the same time, the barren area around the reservoir increased from 4 % to 9 % in the 2 km zone and from 2 % to 6 % in the 5 km zone (Fig. 4). Given that these land cover changes are spatially concentrated within the 2–5 km buffer zones surrounding the reservoir, and coincide with the post-construction period, they can be attributed to the construction and operation of the Tehri Dam rather than to broader regional or infrastructural developments. These findings provide spatial evidence that much of the agricultural land near the reservoir was lost or degraded after dam construction, mirroring the experiences reported by affected communities. Previous studies have also highlighted similar localized agricultural losses in the immediate surroundings of the dam, even while regional agricultural practices appeared to benefit from the project at a broader scale [46].

The temporal alignment of these land cover changes with the dam's construction and reservoir filling phases, combined with consistent reports of agricultural loss from all three community groups, indicates that these changes are directly linked to the dam rather than to other regional environmental or infrastructural factors. The inundation of fertile land, submergence of forests, and subsequent soil instability due to fluctuating water levels collectively contributed to the observed decline in agricultural productivity and increase in barren land.

Importantly, interviews revealed that the decline in agriculture was not only the direct result of inundation but also of ecological changes triggered by the dam. Communities consistently described how the submergence of large forest areas displaced wildlife, pushing animals such as monkeys, wild boars, and leopards closer to human habitation. This, in turn, has caused severe crop raiding and destruction, leading many farmers to abandon their lands. These accounts help explain the increase in barren land detected in the EO data, suggesting that agricultural decline reflects both direct submergence and indirect ecological pressures. The ongoing threat posed by wildlife further discourages farming, compounding the economic and cultural impacts of agricultural loss.

All wild monkeys have migrated to the higher up villages and destroy

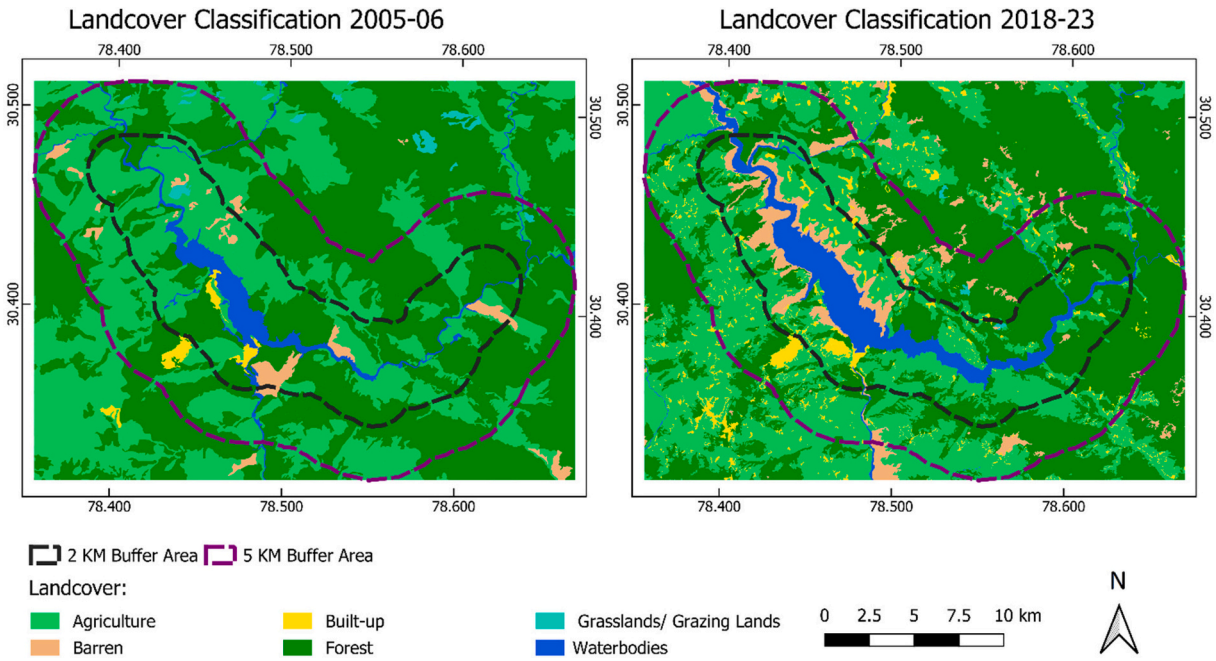

Fig. 4. Land Cover Classification Maps 2005–2006 and 2018–2019. The black line around water body represents the 2 KM buffer area and the purple line shows the 5 KM buffer area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the farming.

(Interviewee 3, Downstream)

The increase in wildlife such as wild pigs, monkeys and leopards in the area has made life more difficult for the local communities. Whatever land was left for us, we had to abandon that because the wild animals destroy everything we grow, so we have stopped growing anything on the fields and now our agricultural land has turned into forests.

(Interviewee 9, Affected but not displaced)

Agriculture is all lost now, it's all finished. With most people migrating to other places, not much is left on their agricultural fields for the wild animals, so all the animals such as monkeys, wild boars and pigs used to attack the farms of those people who are left in the village, as a result of which everyone in the village has left farming.

(Interviewee 2, Downstream)

3.1.2. *Access to benefit sharing*

The distribution of benefits from the Tehri Dam has been perceived to be unequal. The local communities were initially promised free electricity, access to drinking water, and irrigation water, but these commitments have been reported as not fulfilled. Instead of receiving subsidized rates, residents report that they are charged regular prices for electricity, and they still lack access to adequate irrigation and drinking water. Having lost their primary source of livelihood—agriculture—many community members reported that they also did not receive the promised employment opportunities from the dam project, further exacerbating their economic struggles.

There are no proper irrigation facilities, natural springs have dried up. We had a machine to even make jaggery, but because of lack of water availability, there was no more sugarcane cultivation in the area. We had to stop rice farming in 2013 because of the land subsidence, the irrigation canal used for rice cultivation collapsed and there is no alternate for irrigation.

(Interviewee 4, Downstream)

There are no advantages of dams for us, only disadvantages and repercussions. The payment received for the house was not enough to survive so I had to sell off the land and even today we live in a rented house whereas I had my own house, which was submerged.

(Interviewee 5, Displaced)

THDC has recovered the project cost and is now making profits, but the people of Tehri still haven't received even one unit of free electricity.

(Interviewee 6, Displaced)

There is no boat for us to cross the reservoir/river, we didn't get free electricity, no employment opportunities.

(Interviewee 9, Affected but not displaced)

Communities expressed frustration that individuals from large metropolitan cities, such as Delhi, are reaping the benefits of the dam project, including access to free electricity and employment opportunities at the dam site. They feel strongly that these advantages should have been directed towards them, given the immense sacrifices they made for the nation's development.

The people in Delhi are getting free electricity whereas we suffered so much and sacrificed everything for the development of our nation and yet we do not get benefits from the dam and have to pay the bills for electricity.

(Interviewee 8, Affected but not displaced)

Not all promises made by the government were fulfilled. Local people were not given the employment opportunities but people from outside were employed.

(Interviewee 1, Downstream)

No employment benefits for the local villagers or communities. People from other states are working at the dam site.

(Interviewee 1, Downstream)

3.2. *Procedural justice*

Procedural justice addresses the fairness and inclusivity of decision-making processes. For the Tehri Dam, communities consistently reported that their voices were excluded from planning and implementation stages, with consultation processes either absent or superficial. This lack of transparency and participation eroded local trust and reinforced perceptions of institutional neglect.

3.2.1. *Lack of participation in decision making*

The interview data reveal that none of the community members were included in the decision-making process. They also mentioned that no public hearing took place at all. The construction of the Tehri Dam was

started in 1970s and until then no environmental impact assessment existed, which led to a very slow process.

No public hearing happened, and no one was consulted regarding dam construction.

(Interviewee 8, Affected but not displaced)

No one heard our issues and complaints, they just wanted to remove us from our lands.

(Interviewee 1, Displaced)

We were not listened to properly. No proper policy or formal document was there for proper rehabilitation. Overall, the rehabilitation process was not smooth.

(Interviewee 6, Displaced)

3.2.2. Lack of policy

The construction of the Tehri Dam lacked a Rehabilitation and Resettlement (RnR) Policy at the national level at the time, leading to a perceived chaotic situation in the region. According to the communities, the resettlement process took significantly longer than anticipated, and even after its completion, it remained inconsistent, leaving many communities with resentment.

There was not a proper RnR Policy or any other policy addressing displacement issues and no policy addressing environmental issues. Since there was no RnR Policy in place, people could not go to court to fight for their rights. It was more like a Policy Paralysis situation for people of Tehri.

(Interviewee 6, Displaced)

The government only focused on the dam, but the RnR was not a priority for them.

(Interviewee 8, Affected but not displaced)

3.2.3. Insufficient access to information

Interviews suggest that communities in and around the old Tehri town were largely unaware of the true scale of the dam and the resulting reservoir. Lacking access to crucial information, many residents reported that they never had the opportunity to participate in any public hearings. According to them, no public hearings took place, and they only heard rumours about a large dam being built. However, they were unable to fully comprehend the scale of the reservoir or its potential impacts.

There was no public hearing, no public participation of local people in any policy making and all Government Orders were confidential and were not available in public domain.

(Interviewee 6, Displaced)

If we had even the slightest idea how big the reservoir would be, we wouldn't have allowed the dam to be made. These people have left us at God's mercy.

(Interviewee 12, Affected but not displaced)

We had no idea that there would be such a big dam ever. Whenever anyone said there will be a big reservoir or so much water, we never believed.

(Interviewee 2, Downstream)

3.3. Recognition justice

Recognition justice emphasizes acknowledging the lived realities, identities, and needs of all affected communities. In the Tehri case, non-recognition was particularly evident among those not formally classified as "displaced," yet who suffered infrastructural isolation, land subsidence, and forced migration. Their exclusion from official definitions of "affected populations" reflects a systemic failure to recognize evolving vulnerabilities.

Communities in the vicinity of the dam faced non-recognition injustices due to their location and distance from the dam site. While the affected but not displaced communities reported that they lost vital infrastructure, including connectivity, medical, and educational facilities yet, they were not considered for compensation or resettlement. Since they were indirectly affected by the dam, they were excluded from consultation processes and public hearings, which, according to the communities, never took place.

As reported by affected communities, the severance of connectivity to the mainstream and the consequent loss of access to essential services such as healthcare and education led to patterns of forced migration to nearby towns—movements that were perceived to be indirectly driven by the impacts of the dam. Furthermore, communities expressed living in constant fear of landslides and land subsidence, adding to their sense of insecurity.

These overlapping experiences of outward migration and land subsidence illustrate a profound form of recognition injustice. Although these communities continue to bear the risks and consequences of the dam, they are not formally acknowledged as "affected" populations by state authorities or the dam developer. This exclusion denies their lived realities and prevents them from accessing compensation or rehabilitation support. In effect, these are communities rendered invisible within official frameworks, despite facing escalating physical dangers and social marginalization. Their displacement is not the result of planned resettlement but of structural neglect and environmental risk, reflecting a broader failure to recognize evolving vulnerabilities beyond initial project boundaries.

3.3.1. Outward migration

Interviews with people from 'downstream communities' and 'affected but not displaced communities' revealed that people started migrating to nearby towns and cities after the dam was built because they lost connectivity to the original, Old Tehri town, which resulted in a lot of disruptions in their day-to-day life. Due to no connectivity to the mainstream and submergence of Old Tehri, they reported that they had no access to the medical centres during any medical emergency. Most of the children from nearby villages used to go to Old Tehri for education but after the construction of the Tehri Dam, they lost their schools. People also lost markets to sell their agricultural products and milk, their only livelihood source. Community members preferred village life but felt they had no choice to migrate elsewhere, to access better health and education facilities and connectivity.

Outward migration can be stopped if better education, health facilities and employment opportunities are available for the local village. We do not want to leave our land and move to big towns and cities because we do not belong there and we are village people, we love to breathe fresh air not the polluted air of the big cities.

(Interviewee 1, Downstream)

If better facilities are provided by the government, people from my village don't want to migrate elsewhere, which could avoid outward migration. Outward migration could have been avoided if there were proper benefits.

(Interviewee 10, Affected but not displaced)

3.3.2. Increased rates of land subsidence and landslides

According to the communities still residing in the area, the rate of landslides has reportedly increased significantly since the reservoir was created. They are experiencing cracks and fissures in their homes and lands, making the area uninhabitable and forcing them to live in constant fear for their safety. The natural springs and aquifers—their only source of irrigation and potable water—have dried up due to ongoing land subsidence. This has made it difficult for them to grow crops, leading many to abandon agriculture, their primary source of livelihood. Despite these impacts, these communities are not recognized as being affected by the dam and have not received any compensation for the loss of their homes or agricultural lands.

There are cracks in the house. Although it is still habitable, cracks have started appearing. It's been several years. They started appearing since the lake/reservoir was created. There are cracks on the windows and veranda as well.

(Interviewee 11, Affected but not displaced)

Only problems. Nothing grows in the fields, and we don't get proper water. The natural springs, our drinking water source has been destroyed. Even the animals are starving. The forests we used to bring fodder for our animals from, are all submerged.

(Interviewee 12, Affected but not displaced)

Yes, many dangers have increased. During the rainy season, we fear that someone, a child or an adult, might slip and fall into the lake. Landslides have also increased, posing a threat. There was a landslide just above our village some time ago, and another happened a short distance from here. We are constantly afraid now.

(Interviewee 12, Affected but not displaced)

3.3.3. *Loss of connectivity*

The prolonged isolation of these communities underscores a form of recognition injustice, where the lived experiences and mobility needs of those not officially labeled as "displaced" were overlooked in project planning. Despite not being relocated, these populations suffered years of infrastructural neglect and social exclusion, revealing how administrative classifications can obscure real vulnerabilities.

One of the significant impacts reported by communities that were affected but not displaced was the loss of connectivity to the main town for many years. They reported that villages such as Pratap Nagar, Raulakot, and Madan Negi were referred to as *'Kala Pani'* (Black Water) for years, as those villages were completely cut off from the rest of the region and left to live in hardship. This isolation forced many residents to abandon their lands and migrate elsewhere. According to the communities, before the dam was built, the people from these villages relied on Old Tehri town (now submerged) for essential services such as medical facilities, schools, markets, and administrative services like the municipality office and courts. However, after the dam's construction, the only bridge they had to cross the river was submerged, and with New Tehri town resettled on the opposite side of the valley, everything became inaccessible to them. After years of protests and court cases, Dobra-Chanti Suspension Bridge was finally built.

Before Dobra Chanti Suspension Bridge, which took 20 years to get built, people had to travel a distance of 90 KM, which was just 24–25 KM before the dam was built.

(Interviewee 10, Affected but not displaced)

Connectivity should have been provided before the construction of dam started. Our Village was disconnected from the mainstream for many years. Dobra Chanti should not have taken 20 years to get built. THDC should have been bounded to build bridges, schools, colleges and medical centres in villages disconnected from the mainstream.

(Interviewee 10, Affected but not displaced)

These lived experiences of isolation are corroborated by our travel time analysis (Fig. 5). The maps show that while access to Old Tehri town was relatively convenient prior to the dam, the submergence created significant barriers. Following the dam's construction, travel times to New Tehri increased sharply, especially for villages on the northern side of the reservoir, which became markedly more remote. Even after the completion of the Dobra-Chanti bridge—two decades later—many villages still face longer journeys than before the dam, underscoring the uneven distribution of accessibility.

Our village like many other villages, lost its connectivity to the mainstream and yet it was not considered affected by the dam, and we were not heard.

(Interviewee 8, Affected but not displaced)

This integration of spatial analysis with community accounts demonstrates how the dam's impacts extended beyond physical displacement to include long-term infrastructural neglect. The case of delayed bridge construction highlights procedural and recognition injustices, as communities repeatedly protested and appealed through the courts but remained unheard for years.

3.4. *Capabilities justice*

Capabilities justice focuses on ensuring individuals have the real freedoms and opportunities to live the lives they value [53]. In the context of the Tehri Dam, displacement and livelihood disruptions have eroded these capabilities — particularly the ability to sustain livelihoods, preserve cultural identity, and exercise agency over one's future — resulting in diminished well-being and autonomy.

The loss of these freedoms extends beyond material deprivation to include social, cultural, and spiritual dimensions of life. Interviewees from all three communities, particularly the displaced, described how the Tehri Dam fragmented their social networks and dissolved long-standing cultural traditions. These intangible losses — which are rarely acknowledged in policy or compensation frameworks — represent a profound erosion of people's capabilities to live meaningful, connected, and self-determined lives.

There should not be such big dams, they are dangerous. Big dams are not just bad for environment and landslides, but the culture and traditions of a place get submerged in the reservoir too. We have lost the recreational aesthetics and happiness of our villages.

(Interviewee 8, Affected but not displaced)

Riverine communities got disconnected from the river. The whole lifestyle was around the river, which has completely changed. The life was very simple and now we have lost our identity. Sense of social security is lost.

(Interviewee 6, Displaced)

A culture or heritage has been destroyed completely. The whole community of Old Tehri has been displaced and settled elsewhere, such

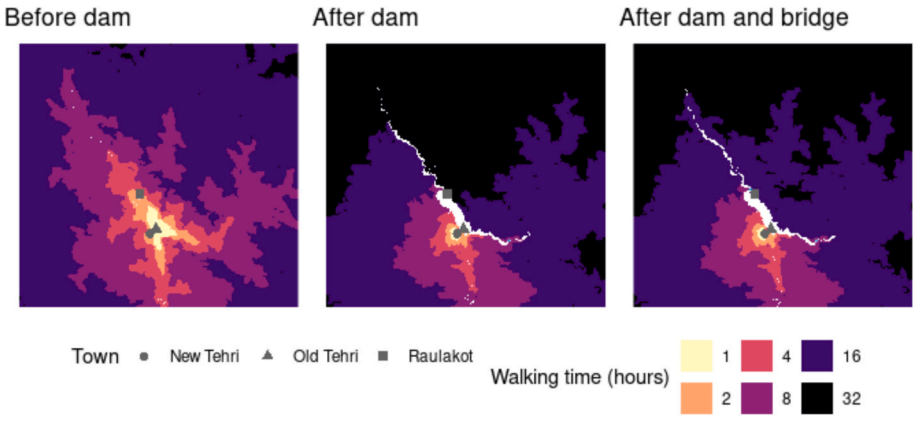

Fig. 5. Travel time comparison over time in and around Tehri region. The left panel shows travel time from all points to old Tehri town, the middle panel shows travel times between all points to New Tehri after the construction of the dam. The right panel shows travel times following the construction of the dam and the bridge.

as Dehradun and now they are trying to revive or protect the cultural heritage, is it possible? If you hear the folk songs, they talk about Rhododendron trees and the blooming of flowers in springtime, which had a very strong cultural significance. But can you grow a Rhododendron tree in Dehradun? No, because the climatic conditions are not conducive.

(Interviewee 7, Displaced)

Even our God and Goddess in Uttarakhand were not glamorized. For example, one of our Gods, 'Nagarja', any stone near any farm or land in the shape of a snake, people would go and worship that, we didn't need big temples for our gods. Another example is of 'Timru ki Lathi' which translates to environment, 'Narsingh' is our local/regional God meaning 'Nar' (human) and 'singh' (Lion), so that's our god, basically befriending animal and human. This shows that we worship Nature, and our Gods and Goddess were nothing but a form of nature and environment and all of this is lost.

(Interviewee 7, Displaced)

These testimonies reveal how the Tehri Dam disrupted not only livelihoods but also the deeper structures of meaning and belonging that underpin people's quality of life. The dam diminished individuals' capabilities — their substantive freedoms to maintain valued ways of living, cultural continuity, and social well-being.

While the erosion of capabilities reflects the loss of freedom and agency at the individual and community level, the absence of effective mechanisms to repair these harms highlights the broader failure of restorative justice. The following section examines how gaps in rehabilitation and institutional accountability have deepened these long-term injustices.

3.5. *Restoration justice*

Restorative justice concerns efforts to repair harm, restore dignity, and rebuild relationships between affected communities and institutions. Although the THDC implemented an extensive R&R package, many respondents viewed it as incomplete or insufficient, particularly in addressing long-term social and cultural losses that persist decades after displacement.

Interview data revealed that the affected but not displaced and downstream communities are facing issues related to restorative justice. As these two groups are among the worst affected by the dam and have not been considered for compensation, they believe that the government and THDC (the dam developers) should invest in the development of their regions by building medical facilities, schools, and creating employment opportunities. They also feel that if the government provided subsidies for agriculture, it could help prevent outward migration from their communities.

Pratapnagar and other nearby villages should be developed. Agriculture can stop outward migration if proper subsidies are given by the government.

(Interviewee 10, Affected but not displaced)

4. Discussion

The social and environmental impacts of large hydropower dams are often not fully considered, even though they can significantly offset the intended benefits. Consequently, policymakers worldwide increasingly shifted away from endorsing large hydropower projects in recent decades [40]. Large dams remain a contentious topic, facing significant resistance from activists, environmentalists, and local communities due to their high potential for adverse social impacts.

However, with the growing urgency to address climate change and meet net-zero' targets, recent global forums such as COP28 have reintroduced hydropower as a key component of renewable energy strategies, particularly due to its role in energy storage and grid stability [54,55]. As a result, policymakers are increasingly considering a renewed push for hydropower development, which makes it even more critical to assess these projects through a justice-oriented lens.

Despite THDC's extensive R&R package, our study shows how, even 20 years after the commissioning of the Tehri Dam, local inhabitants continue to face challenges, including secondary displacements caused by continuous landslides and land subsidence, loss of livelihoods, lack of basic infrastructure such as schools and hospitals, and social and cultural fragmentation. It is also important to recognize that THDC offered what is widely regarded as a strong R&R package. From land-for-land compensation to the provision of new housing and public amenities, their approach was designed to set a benchmark for ethical dam development in India. However, our findings suggest that even this best-practice model falls short in addressing the full range of injustices experienced by affected communities. Moreover, it often fails to account for non-material assets [28], such as a sense of place, social and cultural connections, traditional customs, and heritage—all of which are integral to human existence. For all three communities especially the displaced individuals, this neglect constitutes a form of capabilities injustice, as they grapple with the everyday loss of these intangible yet vital elements that shape their identity and well-being. This oversight is particularly pronounced in rural and tribal communities, where people have a deep connection to nature and their surroundings, which are essential for their livelihoods [56]. Among those most profoundly affected are older generations and women, who often feel uprooted and lost when removed from their ancestral lands. Indeed, the existing R&R policies have been shown to be male-biased, systematically leading to the marginalization and impoverishment of women in the dam-affected communities, primarily through the denial of land rights and compensation due to patriarchal land tenure systems, and the destruction of their traditional livelihood and social networks based on access to common property resources [36]. As Sundaram et al., [33] observed, "Older people prefer to stay in their homes as long as possible because it provides them with control over their lives; it enables them to keep their identity and well-being". One of the interviewees stated that 'the displacement caused by the Tehri Dam was particularly painful and harassing due to a lack of governance and policy'. At the time of its inception, there were no national-level policies or legislation in place at national level to ensure the proper rehabilitation and resettlement of displaced communities. It was not until 2007, one year after the commissioning of the Tehri Dam, that the National R&R Policy was enacted [57].

In the context of the Tehri Dam, capabilities justice is reflected in the communities' ability to sustain livelihoods, maintain cultural and social ties, and exercise agency over their lives. The erosion of these freedoms—through displacement, disrupted livelihoods, and the loss of ancestral lands—represents not only material deprivation but also a profound curtailment of people's basic capabilities to live with dignity and self-determination.

This paper builds on a growing body of energy justice literature by applying the tenets of distributional, recognition, procedural, capabilities, and restorative justice to explore how these communities experience and articulate injustice [28]. However, our study makes a novel contribution by emphasizing the spatial and temporal dimensions of these injustices, which are typically overlooked in both academic literature and policy frameworks [58]. Existing environmental and social impact assessments conducted by dam developers often evaluate risks and benefits at a single point in time—usually the pre-construction or early planning stage—and for a narrowly defined group (primarily displaced communities) [59,60]. They fail to capture the ongoing, evolving nature of impacts, especially for downstream and adjacent populations who may not be physically relocated but face continuous disruption to their lives and livelihoods. While it is challenging to directly compare the number of injustices reported by different communities due to variations in the number of respondents—three from displaced communities, four from downstream communities, and five from affected-but-not-displaced communities—the findings reveal that local inhabitants across all three groups continue to face distinct injustices caused by the

dam and its reservoir, particularly during its operational phase, which they describe as a source of ongoing hardship and disruption.

Large hydropower dams have been prioritized to generate electricity for meeting the growing demands of industries and urban populations in big cities. However, communities close to development are often left behind, bearing the brunt of socio-environmental damages and loss of livelihoods [61]. Our study reveals that distributional injustice is the most pervasive form of injustice experienced by all three communities during the planning, construction, and operational phases of the dam. These communities receive none of the benefits accrued from the dams—they lack access to free electricity, employment opportunities, or drinking water as originally promised by the dam development company. Additionally, the submergence of agricultural fields, absence of irrigation facilities, and increased wildlife attacks have led to significant losses in livelihoods and food security. This underscores how decision-makers are compromising several Sustainable Development Goals (SDGs), such as SDG 8 (decent work and economic growth), SDG 6 (clean water and sanitation) and SDG 2 (zero hunger), to achieve SDG7 (affordable and clean energy) and SDG 13 (climate action) and meet 'net-zero' targets.

Another significant yet often overlooked impact of the Tehri Dam is the ongoing problem of land subsidence and slope instability in surrounding areas. Local residents report recurrent landslides and ground sinking, particularly in resettlement zones, which they attribute to the fluctuating water levels of the reservoir. These fluctuations create a reservoir drawdown effect [62]—the repeated wetting and drying of slope materials—which increases pore-water pressure, weakens hill slopes, and accelerates ground deformation. Empirical studies have confirmed that the hydrostatic loading and unloading of the Tehri reservoir has led to increased landslide frequency and ground subsidence in nearby settlements such as Koteshwar, Pipaldali, and Bhagirathi valley slopes [63]. Remote sensing and field-based analyses further reveal that the altered stress regime and groundwater dynamics have intensified soil creep and micro-seismicity in the dam vicinity [64,65].

The social implications of these environmental changes are profound. The affected communities—excluded from formal definitions of displacement—receive no recognition or compensation despite living under continuous physical and economic risk. This situation exemplifies recognition injustice, wherein institutional frameworks fail to acknowledge the lived realities and vulnerabilities of people who fall outside official categories of "project-affected." In this context, land subsidence not only represents an environmental hazard but also a form of forced displacement, driven by neglect and the absence of inclusive governance mechanisms that could safeguard these populations.

Addressing these long-term consequences requires not only recognition but also reparative justice—a deliberate process of acknowledging harm, accepting institutional responsibility, and providing redress to those who continue to bear the environmental and social costs of hydropower development. Without such reparative measures, the injustices surrounding Tehri risk becoming perpetually embedded in the landscape, further eroding trust between local communities, policy-makers, and developers. Our study reveals how certain communities, while not directly displaced by the Tehri Dam, experienced significant and persistent disruptions due to reduced connectivity. These communities primarily located downstream or on the periphery of the reservoir, lost access to the main town and critical infrastructure such as medical facilities, schools, and markets. Despite facing severe constraints on their mobility and everyday lives, they were not formally recognized as "affected" by the dam. This exclusion reflects a form of recognition injustice—not through the failure to acknowledge cultural identity, but through the failure to acknowledge the lived realities and needs of communities who fall outside narrow administrative definitions of displacement.

Our EO analysis reinforces these findings by spatially mapping the extent of reduced accessibility caused by the dam's construction and the delayed development of replacement infrastructure, particularly the Dobra-Chanti bridge. Prior to its completion, these communities faced extreme isolation, which contributed to indirect and cumulative injustices such as outward-migration, loss of services, and further marginalization. EO helped visualise these spatial dimensions of injustice—insights that might not be captured through qualitative interviews alone.

The ability to track land-use change, submergence, and infrastructure development over time offers a powerful tool to support justice-oriented planning. When integrated with community narratives, EO can strengthen environmental and social assessments by providing empirical evidence of overlooked or emerging impacts. Incorporating EO technologies can significantly strengthen future assessments by enabling multi-temporal monitoring and better-informed decision-making. We argue that this integration of EO with justice frameworks offers a powerful method for improving the accountability and equity of large infrastructure projects.

The Tehri Dam serves as a compelling case study, underscoring the importance of conducting multitemporal and multispatial analyses to fully understand the complex energy justice issues that arise during the three distinct phases of dam construction. These injustices, which disproportionately affect marginalized groups, particularly rural communities, are distributed across various spaces. The dam exemplifies how large-scale infrastructure projects often impose significant injustices on vulnerable populations who rely on fertile land, river access, and associated resources for their livelihoods, including water supply, fisheries, trade, and transportation [66].

Additionally, the absence of procedural justice remains a glaring issue. The interviewees mentioned that the local voices were not meaningfully included in decision-making processes, either during the planning or operational phases of the project. In fact, some community members were not fully informed about the risks they faced until the construction had already begun. This failure to recognize the agency and knowledge of local populations continues to erode trust in institutions and developers. Despite THDC's pride in its R&R scheme, the perceived legitimacy of the process among affected communities remains low, largely due to the absence of long-term engagement and procedural transparency.

We acknowledge that our qualitative sample ($N = 12$) represents a very small proportion of the more than 100,000 people displaced or otherwise affected by the Tehri Dam. As such, the interview findings should be understood as illustrative rather than representative of the wider population. Our intention was not to provide statistically generalisable results, but to capture a diversity of lived experiences across three categories of communities—displaced, affected but not displaced, and downstream. The inclusion of group interviews, in which one spokesperson represented the views of several participants, further broadened the perspectives reflected in the data. By triangulating these insights with EO analyses of land cover change and travel-time accessibility, we were able to contextualize quantitative patterns within community narratives of energy injustice. This integrative approach allowed us to highlight not only the material but also the social and cultural dimensions of dam-induced transformations, while recognizing the scope and limitations of our dataset.

In sum, the Tehri Dam exemplifies how even well-intentioned and well-resourced development projects can perpetuate or exacerbate injustices when they fail to account for the spatial and temporal complexities of social and environmental impacts. Our study reveals that injustices occurred across all three phases of the dam—planning, construction, and operation—manifesting in different forms for displaced, downstream, and affected-but-not-displaced communities. Despite THDC's comprehensive R&R policy, and the company's pride in offering what is still considered one of the best compensation packages in India, communities continue to face ongoing hardships including livelihood loss, cultural fragmentation, and unfulfilled promises. This underscores the need for future hydropower development to be guided by a justice framework that is inclusive, multi-scalar, and long-term in scope,

addressing not only displacement but also post-operational and downstream impacts. Integrating participatory justice approaches with Earth Observation tools can help uncover hidden and evolving injustices, offering a robust foundation for more transparent, accountable, and equitable planning. As countries pursue renewable energy transitions to meet climate goals, it is essential to recognize and mitigate the trade-offs between competing SDGs, especially in the Global South. This is where large-scale renewable projects are often concentrated, yet governance capacity, social protection measures, and participatory mechanisms tend to be weaker. Consequently, communities already facing socio-economic vulnerabilities are more likely to bear the hidden costs of "green" development. A just transition must therefore balance environmental objectives with the protection of local livelihoods and rights. The burden of these transitions must not fall disproportionately on the most vulnerable. Ensuring genuinely just and sustainable energy systems requires development pathways that prioritize both ecological integrity and social equity—not only in rhetoric, but in practice.

This paper is both timely and significant in light of the renewed global emphasis on accelerating renewable energy development following the outcomes of COP28. As part of the "UAE Consensus," countries committed to tripling renewable energy capacity by 2030, which implicitly includes a role for hydropower [54,55]. However, while hydropower is often promoted as a clean and flexible energy source crucial to meeting climate goals and reversing biodiversity decline, this paper highlights the often-unseen social and spatial injustices associated with large dam development. It offers critical insights into how these projects can continue to harm vulnerable communities long after construction is complete. Although addressing climate change and achieving net-zero targets are essential, policymakers must acknowledge and address the social trade-offs involved in renewable energy expansion. Our findings underscore that a just energy transition cannot treat hydropower development as a purely technical solution. Instead, it must be rooted in inclusive, participatory, and spatially aware planning frameworks that respect community rights and livelihoods. This study contributes to growing calls for policy-makers to balance ecological imperatives with social equity, ensuring that the path to a greener future does not deepen existing inequalities [40,66].

CRediT authorship contribution statement

Garima Gupta: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shubham Pawar:** Software, Formal analysis. **Chris Littleboy:** Writing – review & editing, Software, Formal analysis. **Nils Bunnefeld:** Writing – review & editing, Supervision. **Jennifer Dickie:** Writing – review & editing, Software, Formal analysis. **Isabel L. Jones:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author used ChatGPT (OpenAI) to assist with improving the clarity, flow, and consistency of the text, as well as to support language editing and refinement. The tool was used to enhance readability and coherence and did not generate original data, analyses, or interpretations. After using this tool, the authors critically reviewed, edited, and revised all content as needed and take full responsibility for the accuracy, originality, and integrity of the published article.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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