

Review

Open-Access Satellite Data Are Not Truly Open: A Critical Review of the Last-Mile Problem in Least Developed Countries—Lessons from Nepal for the Remote Sensing Community

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Highlights

What are the main findings?

- Legal openness of satellite data is necessary but insufficient for operational EO use; three accessibility layers (legal, technical, and institutional) collectively determine real-world EO impact.
- Prevailing EO tool design systematically embeds resource, capacity, and bandwidth assumptions that exclude LDCs, a structural barrier distinct from legal access restrictions, evidenced by Nepal's governance context.

What are the implications of the main findings?

- Cross-sectoral synthesis calls for a shift beyond open data policy toward addressing technical and institutional barriers that prevent EO integration into governance decisions.
- The “Pixels to Policy” framework offers a replicable model for translating open satellite data into actionable governance outcomes in resource-constrained contexts.

Abstract

Open-access satellite data from major Earth observation (EO) missions, including Landsat, Sentinel, and MODIS, have transformed environmental monitoring globally, yet in most least developed countries (LDCs) this data abundance has not translated into operational decisions or policy impact. This review argues that the dominant narrative in the remote sensing community, that open data leads to democratized impact, is fundamentally incomplete. Using Nepal as an illustrative case study, we demonstrate that legal openness alone is insufficient without parallel advances in technical usability and institutional accessibility, the two layers of EO accessibility that the community has largely overlooked. Through a cross-sectoral synthesis spanning forests, agriculture, disaster management, and land cover monitoring, we identify a persistent “last-mile problem”: the systematic gap between data availability and operational governance integration. Systemic barriers including limited internet infrastructure, skills gaps compounded by brain drain, fragmented institutional mandates, and the absence of a national EO coordination mechanism collectively prevent technically sound EO outputs from informing routine planning and policy decisions. Nepal's small geographic extent, growing digital literacy, and ongoing governance reforms create strategic opportunities for transition, but realizing these requires a functioning geospatial ecosystem integrating data systems, technical infrastructure, human capital, and institutional frameworks. We propose the “Pixels to Policy” framework to operationalize



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this ecosystem and identify three priority research directions for the global remote sensing community: lightweight data formats for low-bandwidth settings, capacity-aware tool design, and implementation science for EO uptake. These directions reframe the community's responsibility from delivering open data to ensuring it can be used.

Keywords: open satellite data; earth observation; least developed countries; geospatial ecosystem; Nepal; last-mile problem

1. Introduction

Over the past few decades, remote sensing (RS) and Earth observation (EO) have become indispensable tools for environmental monitoring and supporting research and development across diverse geographic and thematic contexts [1–4]. By delivering spatially extensive and temporally consistent data, these technologies enable scientists, planners, and policymakers to systematically monitor landscapes, natural resources, and socio-environmental processes at scales that are challenging or even impossible to capture through conventional field surveys [5,6]. The increasing availability of freely accessible satellite datasets, coupled with advancements in computational platforms and analytical methodologies, has facilitated the transition of EO from predominantly academic research into operational and development-oriented applications [4,7,8]. These applications primarily encompass natural resource management [9,10], disaster risk reduction [11,12], climate monitoring [13,14], and sustainable development planning [15,16]. Consequently, EO plays a critical role in evidence-based decision-making, evaluation of environmental dynamics, and formulation of strategies that address global development challenges [5,17–19].

Despite these advances, significant disparities remain in the utilization of EO and RS technologies between developed and developing countries [1,7,20–22]. Nations with strong technical, financial, and institutional capacities are able to integrate multi-source datasets, develop automated processing pipelines, and generate near real-time decision-support products, whereas many developing countries continue to face structural and operational constraints, including limited computational infrastructure, insufficient technical training, restricted access to high-resolution datasets, and inadequate policy and institutional frameworks [1,7,8,21,23]. Much of the global EO infrastructure, including major satellite missions such as the Landsat and Copernicus, has been developed and operated by technologically advanced agencies, such as National Aeronautics and Space Administration (NASA) and European Space Agency (ESA). Although datasets from these missions are freely accessible through policies such as NASA's 2008 Landsat open data policy [24] and the Copernicus free and open data policy [25], their full potential remains underutilized in many developing countries. To address these gaps, several international initiatives have emerged. Notable examples include SERVIR (<https://www.servirglobal.net/>; accessed on 15 April 2026), a NASA-USAID partnership establishing regional hubs for environmental monitoring, disaster management, and climate adaptation across Asia, Africa, and Latin America [26,27]; the Group on Earth Observations (GEO; <https://earthobservations.org/>; accessed on 15 April 2026), which integrates satellite and in situ data into national and regional decision-making frameworks [17,28]; the Committee on Earth Observation Satellites (CEOS; <https://ceos.org/>; accessed on 15 April 2026) which coordinates global civil EO efforts and promotes data sharing [29]; and the World Bank's Global Initiative on Remote Sensing for Water Resources Management, which emphasizes operational applications of EO for water planning and monitoring [30]. While these initiatives highlight ongoing efforts to translate EO data into actionable policies, many developing countries continue to

face challenges in systematic adoption of these technologies [31,32]. Nepal, representative of many least developed countries (LDCs) [33], exemplifies such disparities.

Nepal's highly diverse topography, spanning subtropical lowlands to the high Himalayas, makes the country particularly vulnerable to a wide range of environmental hazards [34,35]. Flooding is common in the southern plains, landslides frequently occur in the hilly regions, and glacial lake outburst floods (GLOFs) threaten high mountain areas as rising temperatures accelerate glacier melting [36]. Additional hazards, including windstorms, heavy precipitation, forest fires, earthquakes, and other glacier-related events, further contribute to Nepal's complex disaster risk profile, which is increasingly intensified by climate change and anthropogenic pressures such as deforestation [37]. At the same time, natural resources such as forests, glaciers, snow cover, water systems, and agricultural landscapes, form the foundation of livelihoods for much of the population [38–40]. Forests cover approximately 45% of the country [41], while nearly 56% of land is designated for biodiversity conservation [42], reflecting their ecological, economic, and cultural significance, often captured in the national proverb “Hariyo Ban Nepal Ko Dhan” (“green forests are Nepal's wealth”). Together with agriculture, forests contribute substantially to Nepal's GDP and energy supply [43] and are highly prioritized by the government in development planning [40].

Given Nepal's situation, marked by frequent natural disasters and critical natural resources located in geographically remote and inaccessible areas, RS and EO technologies offer a cost-effective, efficient, and reliable option for monitoring [44–46]. In fact, EO was developed precisely to overcome such challenges, enabling systematic observation of large, inaccessible regions [17,47]. Recognizing this potential, RS and EO technologies have gained increasing prominence in Nepal's government policies and strategies over the past decade, [37,40,48]. Freely available datasets such as Landsat, Sentinel, and MODIS have demonstrated strong potential for applications including forest inventory and cover change monitoring [40,48], flood monitoring [49], glacier and snow mapping [50], and agricultural assessments [51]. Nevertheless, despite pilot demonstrations and growing policy recognition, these initiatives have not yet matured into comprehensive, operational systems, even as Nepal pursues ambitious targets such as graduating from LDC status in 2026 and achieving United Nations Sustainable Development Goals (SDGs) by 2030 [33].

The adoption of RS and EO technologies in Nepal is limited by several human, institutional, and technical constraints [52,53]. Many rural and regional government agencies lack personnel trained in data visualization and processing, interpretation, and advanced workflows, including machine learning and EO integration, limiting effective use of available datasets [52,54]. Several government offices, schools, and hospitals still have intermittent or no internet, while public access remains patchy and costly despite government efforts [55,56]. Even when data are accessible, gaps in policy support, insufficient research funding, and weak inter-agency coordination hinder systematic implementation [57,58]. LDCs such as Nepal also tend to invest less in research due to differing socio-economic priorities [57,59]. Connectivity challenges [60] and the high cost of internet and computing resources [56] further restrict access to open-access cloud-based platforms such as Google Earth Engine (GEE). In addition, freely available medium-resolution datasets often fail to meet local monitoring needs, leaving institutions and researchers with limited analytical options [21,53] and reducing incentives for continued research. Moreover, the absence of standardized, and integrated national RS programs means that even existing high-resolution datasets are rarely documented, shared, or operationalized [61,62]. Furthermore, EO research culture in Nepal also remains limited by insufficient faculty, poor infrastructure, and scarce job opportunities [53,63]. Consequently, the full potential of RS and EO in Nepal remains largely untapped, as the effective societal value of these observations

depends not only on data availability but also on alignment with local needs, user capacity, institutional support, and decision-making workflows [64].

Building on these challenges, this review examines how freely available remote sensing datasets have been used in Nepal and evaluates their potential to support sustainable natural resource management, disaster preparedness, and climate adaptation. Unlike previous reviews that have focused primarily on technical applications, this paper provides a critical, cross-sectoral analysis of the systemic barriers: institutional, human, and technical, that prevent open data from being translated into operational use. By synthesizing existing research across different disciplines such as forests, agriculture, hazards (natural and anthropogenic), water resources, and urbanization, the paper highlights both the opportunities and limitations of RS and EO, with a particular focus on open-access satellite data. It further identifies key technical, institutional, and capacity-related barriers that create the ‘last mile problem’ (the gap between open data availability and operational use) and discusses pathways for translating pixel information into actionable insights for policy and decision-making. The article concludes by proposing a conceptual framework, ‘Pixels to Policy’, that synthesizes the interplay of data, barriers, opportunities, and institutional pathways required to operationalize RS and EO in resource-constrained settings. While Nepal serves as the primary case study, the lessons and framework presented are relevant to the many developing and LDCs where open data remains an unfulfilled promise highlighting that the transition from pixels to policy depends not on data alone, but on the deliberate cultivation of human capacity, institutional coordination, and sustained political commitment. This contrast between the expectation and reality of EO applications is illustrated in Figure 1.

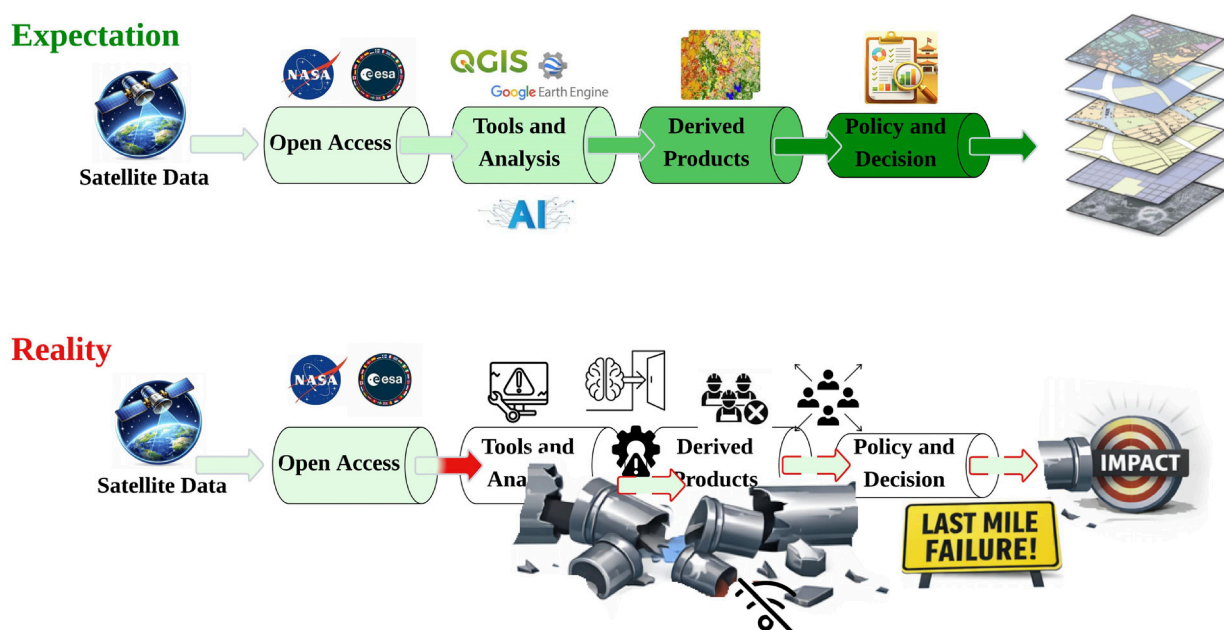


Figure 1. Conceptual illustration of the expectation versus reality gap in open satellite data utilization for developing and least developed countries (LDCs). The upper pathway represents the assumed linear progression from open-access satellite data through analytical tools and derived products to policy decisions and real-world outcomes, whereas the lower pathway depicts the observed reality in countries such as Nepal, where limited technical capacity, inadequate infrastructure, and weak institutional support prevent translation into policy and operational decisions, yielding minimal or unsubstantiated real-world impact. This flowchart demonstrates the last mile problem examined in this review.

This review makes three distinct contributions: (1) a cross-sectoral synthesis mapping EO outcomes against legal, technical, and institutional accessibility layers; (2) identification of recurring structural failure modes in the last-mile transition; and (3) the ‘Pixels to Policy’ framework as a replicable model for operationalizing EO in resource-constrained contexts, accompanied by priority research directions that reframe the remote sensing community’s responsibility from delivering open data to ensuring it can be used.

2. Methods: Approach and Scope of Review

This paper adopts a narrative, purposive review methodology appropriate for cross-sectoral syntheses where the goal is critical interpretation rather than exhaustive enumeration [65,66]. A systematic review was not pursued because the evidence base spans heterogeneous source types such as, peer-reviewed studies, national policy documents, government reports, and grey literature, that cannot be meaningfully standardized into a single inclusion protocol without discarding the institutional and governance evidence most central to the paper’s argument.

Source selection was guided by two complementary streams. The first was a global stream identifying literature on open-access EO, satellite mission capabilities, and barriers to adoption in developing and LDCs, sourced through Google Scholar, Web of Science, and Scopus in March 2026, using terms including “open satellite data,” “earth observation,” “least developed countries”, “Landsat open data policy”, “Sentinel”, and “Google Earth Engine”. The second was a Nepal-specific stream encompassing peer-reviewed studies, national policy documents, and reports from ICIMOD, SERVIR, and the World Bank, using “remote sensing Nepal” combined with sector-specific keywords across forestry, agriculture, disasters, and land cover. Urban and water-resource evidence was captured within the land cover and disaster-related keyword sets respectively, consistent with the thematic organization adopted in Section 5. The grey literature includes national policies such as the Geo-satellite Policy 2077 [67], National Development Plans [68,69], and the Disaster Risk Reduction and Management Act [70], alongside institutional reports from ICIMOD, SERVIR, and the World Bank. No publication date restriction was applied, though post-2008 literature was emphasized, coinciding with the Landsat and Sentinel open data policies. Sources were selected based on relevance to the central question of how open EO data translates into operational governance decisions, with preference given to studies discussing operational outcomes rather than technical performance alone.

The author’s professional experience across research, government, and non-governmental sectors in Nepal was drawn upon as complementary contextual insight, consistent with established practice in applied policy reviews [71]. However, two major limitations are acknowledged. First, as a researcher professionally embedded in Nepal’s EO ecosystem, the author’s familiarity with the subject may have influenced source selection and interpretation. Nevertheless, this risk was mitigated by actively seeking evidence from comparable LDC contexts beyond Nepal, and by explicitly distinguishing throughout the paper between three evidence tiers: (1) findings documented in peer-reviewed literature; (2) findings reported in government or institutional sources; and (3) observations based on the author’s professional experience, flagged with language such as ‘based on professional observation’. Second, peer-reviewed literature on EO applications in Nepal remains sparse in some sectors, and limited published evidence does not necessarily reflect limited on-the-ground activity.

3. Rethinking “Open Earth Observation”: Beyond Availability

The dominant narrative in contemporary EO policy and advocacy rests on an implicit but consequential assumption: that legal openness is equivalent to operational accessibility.

This assumption underpins major open-data milestones—NASA’s 2008 Landsat open data policy [24], the European Commission’s Copernicus free and open data policy [25], and the longstanding free availability of MODIS [72]—and the international initiatives built upon them. It is not wrong; however, it is incomplete in ways that matter most precisely where EO is most needed. Nepal’s experience, examined in detail in Sections 5 and 6, demonstrates that removing the legal barrier to data access is a necessary but far from sufficient condition for operational EO uptake. To understand why, it is necessary to disaggregate “accessibility” into the three interdependent layers that actually determine whether satellite data inform decisions.

The first layer, legal openness, refers to the removal of licensing restrictions and cost barriers on satellite data. This layer has largely been achieved for major missions. Its achievement is genuinely significant—the pre-2008 pay-per-scene Landsat model directly suppressed use in LDCs—and should not be minimized. But legal openness is the entry condition for EO use, not its guarantee.

The second layer, technical usability, refers to the ability to process, analyze, and interpret EO data using available computational infrastructure, software, and skills. Even when data are legally free, effective use requires sufficient internet bandwidth to download large files; hardware capable of handling multi-gigabyte datasets; software for processing and analysis; proficiency in scripting languages such as Python, R, or JavaScript for anything beyond basic visualization; and domain knowledge to interpret outputs meaningfully [56,73]. In low-income settings, each requirement represents a potential—and often actual—point of failure. The global EO community has made significant progress on legal openness while largely treating technical usability as a downstream problem to be solved by users rather than a design responsibility of data providers and tool developers.

The third layer, institutional accessibility, refers to the integration of EO-derived information into decision-making workflows, governance systems, and sectoral planning processes. This is simultaneously the least developed and the most consequential layer. Technical barriers, once overcome, still leave EO outputs unused if they are not produced on timelines that match decision cycles; formatted for non-technical decision-makers; embedded in legal or regulatory mandates; supported by sustained budgets for updating and dissemination; or trusted by the institutions expected to act on them [74,75]. Institutional accessibility cannot be achieved through data policy alone; it requires deliberate investment in governance architecture.

The relationship between these three layers is not additive but conditional: progress at layer two is contingent on layer one, and progress at layer three is contingent on both. Nepal has achieved full legal openness for all major EO missions, but technical usability is severely constrained by internet infrastructure, computing capacity, software access, and skills gaps, while institutional accessibility remains the least developed layer overall, though its development varies across sectors, as the forest monitoring sector illustrates in Section 5. The result is a country where open data exists in abundance and operational EO use remains minimal—not despite open data policies, but alongside them. This is the contradiction that the dominant narrative cannot explain, and that this review sets out to address.

4. The Global Promise of Open-Access Satellite Data

Satellite remote sensing has become a cornerstone of natural resource monitoring [1,9,76,77], disaster management [78,79], agricultural monitoring [80,81], urban planning [82,83], and climate change research [84,85] worldwide. The adoption of open-data policies by leading space agencies represents a turning point in the democratization of

EO, significantly expanding global access to satellite imagery for research, operational monitoring, and policy applications [24,25].

The Landsat program, jointly operated by NASA and USGS since 1972, remains the foundational long-term record of the Earth's surface. Landsat has been central to global analyses of deforestation, land cover change, agricultural dynamics, and urban expansion across multiple decades [5,86]. The 2008 open data policy dramatically increased its uptake in global environmental studies and operational monitoring systems [9,77,87]. Complementing Landsat's spatial and historical depth, NASA's MODIS sensors aboard Terra (1999) and Aqua (2002) deliver near-daily observations, enabling continuous tracking of vegetation dynamics, wildfire activity, snow cover, and climate-related processes [72,88].

The ESA's Copernicus program has further advanced open EO through the Sentinel missions [25]. Sentinel-2 supports applications in agriculture [89], forest monitoring [90,91], and ecosystem assessment [92], whereas Sentinel-1 synthetic aperture radar (SAR) enables reliable all-weather monitoring used alone [93,94] or in combination with optical data [95,96], enhancing monitoring across crop classification, disaster assessment, and land cover mapping—capabilities that are particularly valuable in cloud-prone and topographically complex terrains such as Nepal.

Freely available topographic datasets provide critical complementary information for environmental modeling and hazard assessment. The Shuttle Radar Topography Mission (SRTM), and the ASTER Global Digital Elevation Model (ASTER GDEM), have been extensively applied in hydrological studies [97], landslide and flood susceptibility mapping [98,99], and glacier modeling [100].

Several additional missions extend the global EO landscape. Japan's ALOS and ALOS-2 support forest biomass estimation, land cover mapping, and disaster monitoring [101]; NASA's Global Precipitation Measurement mission (GPM, 2014) delivers near-global precipitation data [102]; and the Visible Infrared Imaging Radiometer Suite (VIIRS) provides high-quality observations supporting wildfire detection [103], nighttime light monitoring [104], and vegetation assessment [105].

Collectively, these missions constitute an unprecedented open-access data infrastructure for environmental monitoring at regional and global scales. Yet the breadth and technical quality of this infrastructure have not translated into equitable utilization—a contradiction examined through Nepal's experience in the following sections, organized through the three accessibility layers introduced in Section 3.

5. Evidence of RS and EO Technology Applications in Nepal

This section is organized around four thematic areas—land cover, forests, disasters, and agriculture—rather than the six sectors named in the Introduction. Urban-related EO applications are addressed within LULC Monitoring (Section 5.1), where most urban change studies focus on Kathmandu. Water resource applications are addressed within Disaster Monitoring and Risk Assessment (Section 5.3), where flood mapping is the dominant use case. This structure follows the concentration of available evidence rather than narrowing the scope of the review.

The growing body of RS and EO research in Nepal spans multiple sectors and demonstrates clear technical capability across freely available satellite platforms. Yet a consistent pattern emerges from this literature: research applications are proliferating while operational integration into national monitoring systems and policy frameworks remains persistently limited. This section critically synthesizes evidence across these four areas to identify not only what has been accomplished, but where and why the translation from research output to operational use breaks down. Each subsection identifies the main barrier to operational EO use in that sector, mapped against the three accessibility layers

introduced in Section 3. Freely available datasets including Landsat, Sentinel-1, Sentinel-2, MODIS, and DEM products have been central to this body of work, providing spatially consistent and temporally robust information at low cost [45,106].

5.1. LULC Monitoring

Despite being the most prevalent application of open EO data in Nepal, LULC monitoring exemplifies the gap between research output and operational impact. Studies are numerous, methodologically improving, and geographically diverse, yet they remain largely disconnected from routine planning and policy cycles.

Multi-decadal analyses in rapidly urbanizing areas such as Kathmandu have documented substantial declines in forest cover, agricultural land, and water bodies since the 1990s, alongside rapid urban expansion [107–110]. At broader spatial scales, district and regional studies have mapped transitions across major land cover classes using freely available EO datasets [111,112]. Methodologically, the field has advanced considerably, with growing adoption of Sentinel-2 imagery, machine learning classifiers, and cloud-based platforms such as GEE enabling improved accuracy and scalable multi-temporal analysis [112–114]. The National Land Cover Monitoring System (NLCMS), developed in collaboration with ICIMOD, represents the most, institutionally significant effort to date, providing standardized, updated land cover products to support national planning and reporting [48]. However, its operational reach remains constrained by the same technical and institutional barriers discussed in Section 6, underscoring that product availability alone does not guarantee uptake. The forest research and training center (FRTC) creates these products; however, does not hold the authority to enforce land use policies. The binding constraint in LULC monitoring is institutional accessibility: the technical and legal layers are largely satisfied, but no single agency owns the mandate to operationalize outputs into routine planning cycles, and no sustained budget exists for updating and disseminating products beyond project timelines.

5.2. Forest Monitoring

Forest monitoring is arguably the most institutionally mature application of RS and EO in Nepal, yet even in this case the transition from research output to sustained operational systems remains incomplete—revealing how sector-specific commitment and technical capacity alone are insufficient without broader ecosystem support.

The institutional foundation is relatively advanced compared to other sectors. National forest inventories, REDD+ carbon accounting frameworks, and the NLCMS have all leveraged open EO data, particularly Landsat and Sentinel-2, to generate policy-relevant products [48,115,116]. Multi-temporal analyses spanning several decades have enabled consistent tracking of forest cover change, supporting national reporting and long-term assessments of deforestation, degradation, and forest recovery [41,117–119]. Beyond cover change, freely available satellite datasets have been applied to assess forest fragmentation [120], wildlife habitat dynamics [121,122], aboveground biomass and carbon stocks [123–125], and community forestry dynamics [126–128] across Nepal's diverse physiographic regions.

Despite this breadth, critical gaps persist. The integration of SAR data—particularly Sentinel-1—to improve monitoring in cloud-prone and topographically complex terrain remains underexplored relative to its demonstrated potential [91,94]. More fundamentally, research output in this sector, as in others, tend to remain within academic and project cycles rather than informing routine forest governance. The forest monitoring sector thus illustrates both the ceiling of what is achievable under current conditions and the distance that remains to full operational integration. The forest research and training center (FRTC) holds the primary institutional mandate, and the legal and technical layers are

relatively well developed compared to other sectors. The binding constraint here is therefore institutional, specifically the absence of sustained funding, standardized workflows, and cross-agency data sharing mechanisms that would embed EO outputs into routine forest governance rather than project cycles.

5.3. Disaster Monitoring and Risk Assessment

Disaster monitoring and risk assessment represents one of the most active and policy-relevant domains of RS and EO application in Nepal, yet it also illustrates one of the sharpest disconnects between research productivity and operational impact. Despite a growing body of technically sophisticated work, EO-derived hazard information rarely feeds into routine emergency preparedness or land use planning in a systematic way.

Nepal's exposure to a wide range of hazards—including floods, landslides, GLOFs, forest fires, and soil erosion—has driven substantial investment in satellite-based monitoring and susceptibility modeling. Multi-source datasets including Landsat, Sentinel-2, Sentinel-1 SAR, MODIS, and DEMs have been applied across these hazard types, with flood mapping [129–131], landslide susceptibility assessment [132,133], GLOF monitoring [134,135], forest fire risk mapping [136,137], and soil erosion estimation [138,139] all represented in the peer-reviewed literature. DEM-derived terrain metrics combined with spectral indices such as normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and normalized difference snow index (NDSI) have proven particularly valuable for characterizing watershed characteristics, glacier retreat, and snow cover dynamics critical for early warning systems and climate adaptation planning.

However, three limitations occur across this body of work. First, most studies focus on susceptibility modeling or post-event mapping rather than near real-time operational monitoring, limiting their utility for emergency response. Second, outputs are rarely formatted or disseminated in ways accessible to district-level disaster management offices, where decisions are made. Third, while the Disaster Risk Reduction and Management Act 2017 explicitly mandate integration of geospatial hazard information into policy and operations [70], implementation of this mandate remains largely aspirational. The disaster sector thus demonstrates that legislative recognition of EO's value, while necessary, is far from sufficient to bridge the last mile. The Ministry of Home Affairs (MoHA) holds the primary mandate through the Disaster Risk Reduction and Management Act 2017, and legal openness is fully achieved. Technical usability is partially achieved for research purposes but not at operational level. The binding constraint is therefore technical plus institutional because the outputs are not formatted or disseminated for local-level decision-makers, and the legislative mandate lacks the enforcement mechanisms, budget allocations, and workflow integration required to translate it into operational practice.

5.4. Agriculture and Food Security

Agriculture represents perhaps the most striking example of the gap between EO potential and operational uptake in Nepal. Despite the sector's centrality to national food security, rural livelihoods, and GDP [140], and despite explicit policy emphasis on agricultural modernization and digital transformation [141], RS and EO remain comparatively underutilized in routine agricultural monitoring and decision-making relative to their demonstrated technical capability.

The research base, while growing, reflects this underutilization. Satellite-derived vegetation indices, particularly NDVI, combined with topographic and meteorological variables, have been applied to map crop areas and cropping patterns, monitor seasonal growth and soil moisture, and estimate yields for major staple crops including rice, maize, and wheat [142–145]. Land suitability assessments for different crops have further demonstrated

the analytical potential of multi-source EO data in supporting agricultural planning [146]. The growing adoption of Sentinel-2 has enabled higher-frequency monitoring of crop phenology and stress at improved spatial and spectral resolution compared to the MODIS and Landsat datasets that historically dominated this domain [142]. Importantly, Sentinel-1 SAR data offer significant advantages in Nepal's monsoon-dominated environment where persistent cloud cover limits optical observations, and have been applied effectively for crop area estimation [51,147].

The most operationally significant initiative to date—the ICIMOD-led in-season rice area estimation system developed in partnership with the Ministry of Agriculture and Livestock Development (MoALD) [51]—illustrates both the potential and the limits of current approaches. Despite ministerial approval and demonstrated utility for agricultural statistics, nationwide operationalization remains incomplete and long-term sustainability uncertain, largely due to dependence on external technical expertise and the absence of institutionalized geospatial capacity within the ministry itself. This pattern—technically sound, externally driven, institutionally fragile—recurs across sectors and lies at the heart of the last-mile problem examined in Section 6. The MoALD holds the primary institutional mandate for agricultural monitoring, and the legal layer is fully achieved through open access to RS datasets. However, the technical layer is partially achieved and remains externally dependent, with operational workflows relying on ICIMOD expertise rather than internalized ministry capacity. The binding constraint is therefore institutional.

Across all four domains, the pattern is consistent: technically sound EO outputs are produced but not operationally sustained. The limiting factor is not data availability—Landsat, Sentinel-1/2, MODIS, and open DEMs have proven suitable for purposes across all sectors examined—but the institutional, human, and technical conditions required to translate these outputs into routine governance decisions. Section 6 examines these conditions systematically.

6. Barriers to Effective Use of RS and EO Technologies in Nepal

The barriers documented below are not independent constraints suitable for sequential solutions. They are mutually reinforcing: weak institutional frameworks reduce incentives for capacity investment; skills gaps limit the ability to advocate for infrastructure; poor infrastructure prevents trained individuals from applying their skills; and absent sustained funding undermines all three. This interdependence explains why piecemeal interventions—training workshops, pilot projects—have repeatedly failed to produce lasting operational change. The analysis draws on peer-reviewed literature, national policy documents, and the author's professional experience across research, government, and non-governmental sectors in Nepal, consistent with established practice in applied policy reviews [71].

6.1. Technical Barriers: Software and Computational Constraints

Technical infrastructure constraints are frequently acknowledged in the EO literature but rarely examined with sufficient precision to be actionable. The relevant question is not simply whether infrastructure is inadequate, but at which specific workflow stages it fails—and with what operational consequences.

Proprietary software costs are a real but second-order barrier. Tools such as ArcGIS and ENVI remain financially inaccessible to many Nepali institutions [148,149], but open-source alternatives—QGIS, Python, R—mean that software cost alone is not the binding constraint. The more fundamental problem is that effective use of any of these tools requires stable internet connectivity, adequate computing hardware, and sustained training: conditions that cannot be assumed across district-level offices or regional universities. Cloud platforms such as GEE partially address local hardware limitations but introduce a

different dependency—reliable high-bandwidth internet—which remains unavailable to a large proportion of potential users. According to the World Bank [56], only 51.6% of the Nepalese population had internet access in 2024 (38.4% in 2022), and 6229 of 11,570 secondary schools lacked connectivity. Fixed broadband performance remains limited, with Nepal ranked 108th globally in 2021, and 150th out of 193 countries in the 2024 Oxford Artificial Intelligence (AI) Readiness Index [150]. At the institutional level, connectivity in government offices outside major urban cities is often shared, bandwidth-constrained, or unreliable; approximately 12% of ward offices had no internet access as of 2024 [56]. Moreover, during the monsoon season, when hazards require timely monitoring, network performance may further deteriorate, making routine download of even a single Sentinel-2 tile—exceeding 600 MB—operationally impractical for most district offices.

Computational demands compound these constraints. Machine learning classification, time-series change detection, and SAR processing require processing and storage capacity that is routinely unavailable across Nepal’s institutional landscape, forcing practitioners toward reduced datasets or simplified workflows that limit both accuracy and operational relevance [151,152]. The cumulative effect, illustrated in Table 1, is that technically capable individuals frequently cannot complete end-to-end EO workflows within their institutional environment—not because knowledge is absent, but because the infrastructure to apply it is not. Critically, global EO workflows, data formats, and platform architectures have been designed for high-bandwidth, high-compute environments: the assumption of adequate infrastructure is embedded in the tools themselves. Efforts to deliver EO products in formats requiring minimal preprocessing by end users, such as Analysis Ready Data (ARD) [29,153] and Cloud-Optimized GeoTIFFs (COGs) [154], represent important steps toward reducing bandwidth and processing burdens in resource-constrained settings. However, their adoption in LDC-facing workflows remains inconsistent [21,31,155], reflecting a product design gap compounded by structural resource constraints in LDCs. Therefore, addressing this gap requires collaborative effort from the EO community alongside national governments and development partners.

Table 1. Technical barriers in a typical Nepal’s district-level EO workflow.

Workflow Stage	Open Data Assumption	Reality in Nepal Local Office	Technical Gap
Data download	High speed, unrestricted internet	Weak, intermittent, shared connectivity	Large EO datasets are slow or fail to download
Preprocessing	Python/JavaScript/R environment with admin access	Software unavailable; restricted permissions	Basic preprocessing cannot be performed
Analysis	Cloud based platforms (GEE, Sentinel Hub) with stable access	Limited skills, connectivity, and hardware constraints	Advanced analysis not feasible
Visualization	GIS software (ArcGIS Pro, QGIS) with trained users.	Limited/no training; reliance on non-spatial tools	Spatial outputs (e.g., maps) not produced
Decision integration	Automated dashboards/workflows	Paper-based processes; no integration	EO data never used in decision-making

Table 1 illustrates a conceptual example of how these technical constraints manifest at each stage of a typical EO workflow in a local, for instance a district-level government office in Nepal. The table contrasts the assumptions embedded in the global open-data workflows with the realities on the ground, identifying specific technical gaps that prevent translation from data to decision.

6.2. Human Capacity and Skills Gap

Skills gaps are widely cited as barriers to EO adoption in LDCs [21,73], but the critical issue is not simply the number of trained individuals—it is the structural conditions that prevent training from translating into sustained institutional capacity.

Nepali university curricula offer introductory geospatial content within geography, environmental science, and forestry programs, but specialized training in satellite data processing, cloud-based analysis, and machine learning remains limited [53,63], reflecting outdated curricula, insufficient qualified faculty, and poor computational infrastructure [156]. These conditions are self-reinforcing: without trained faculty, curricula cannot be modernized; without modern curricula, the next generation of faculty cannot be produced locally. The result is a shallow pipeline of operationally competent practitioners entering government agencies each year.

International programs led by ICIMOD and SERVIR have partially compensated through targeted training and technical assistance [45,52] but share a structural vulnerability: they build individual competence without necessarily building institutional capacity. When a trained individual leaves a government post—through migration, career change, or retirement—the capability they represent typically departs with them. Brain drain accelerates this dynamic: highly trained geospatial professionals migrate to institutions in developed countries offering superior infrastructure and career prospects, and sustained return remains limited [157,158]. Given that, diaspora engagement is not uniformly lost: experiences from India's scientific diaspora networks and China's Thousand Talents Program demonstrate that overseas professionals can contribute meaningfully to national capacity through mentorship, co-authorship, and remote technical collaboration when enabling conditions exist [159]. Such engagement can therefore serve as a pathway for EO uptake, as further discussed in Section 7. Beyond the brain drain challenge, the rapid evolution of machine learning, cloud computing, and large-scale data fusion further widens this gap over time [160,161], as training programs struggle to keep pace with technological change. Without structural reforms that create sustainable career pathways, retain trained professionals within the national system, and embed geospatial expertise as permanent government positions rather than project-funded roles, capacity-building efforts will continue to produce capable individuals without producing capable institutions.

6.3. Institutional and Governance Challenges

Among the three barrier categories, institutional fragmentation is the most critical and the least amenable to technical solutions. Nepal currently lacks a central EO coordinating body. The National Remote Sensing Center, established in 1980, was merged into the Forest Research and Survey Center in 1989 and reduced to a Remote Sensing Section [162]—dispersing rather than consolidating national EO capacity at a moment when the field was expanding rapidly. No equivalent institutional authority has since emerged.

The practical consequences are measurable. Geospatial mandates are distributed across forestry, agriculture, disaster management, urban planning, and environmental agencies, producing overlapping responsibilities, incompatible data standards, and minimal cross-agency data sharing [30,163]. Each agency develops monitoring approaches and classification systems in isolation—duplicating effort while preventing the multi-source data integration that any comprehensive national monitoring system would require (based on professional observation, consistent with findings in [54]). The methodological discontinuity between DFRS [164] forest cover products and the NLCMS [48], noted in Section 5.1, is a direct consequence of this fragmentation.

National policies across multiple instruments—the Geo-satellite Policy 2077 [67], Fifteenth and Sixteenth Development Plans [68,69], Disaster Risk Reduction and Management

Act [70], and National REDD+ Strategy [116]—mandate or strongly encourage spatially explicit monitoring. Yet legislative recognition has not produced operational implementation, because these mandates lack enforceable mechanisms, sustained budget allocations, and designated institutional ownership. Policies that require EO use without providing the infrastructure, personnel, or funding to support it are aspirational rather than operational. Dependence on short-term donor-funded projects further compounds this fragility: when project funding ends, the systems, workflows, and trained personnel associated with them typically do not persist within government structures, a pattern documented across development sectors in Nepal [57] and in EO capacity-building programs across comparable LDCs [31,155]. Addressing these institutional barriers falls primarily within the responsibility of national governments rather than the EO community, though data providers and tool developers can support transition by designing products and workflows that are compatible with existing governance structures and decision cycles.

6.4. Empirical Examples of Last-Mile Problem

Case 1: In-season rice area estimation (ICIMOD and MoALD). Integrating Sentinel-2 with Sentinel-1 SAR data to overcome monsoon cloud cover limitations, ICIMOD developed an operational rice area estimation system in partnership with the MoALD as the institutional owner [51]. The system received ministerial approval and contributed to national agricultural statistics, representing a meaningful threshold of institutional recognition. However, its nationwide implementation remains incomplete and long-term sustainability is uncertain. The system's technical workflows depend on external ICIMOD expertise that has not been internalized within the ministry, and no permanent geospatial position exists to maintain and update the system independently. Ministerial approval, in this case, was necessary but insufficient: without institutionalized capacity and a sustained budget, approval represents endorsement rather than operationalization. Thus, the failure mode in this case is institutional fragility—a technically sound, externally driven system without permanent institutional ownership. More specifically, in terms of the workflow stages outlined in Table 1, the data download, preprocessing, and analysis stages were completed successfully through ICIMOD's technical support, but the decision integration stage was not internalized within the ministry, illustrating that infrastructure constraints are not the only obstacle at this final stage.

Case 2: National forest cover maps (Department of Forest Research and Survey; DFRS). Using RapidEye imagery, the DFRS produced forest cover maps for all 753 local government units and publicly released them as a geographically comprehensive, and technically sound product in 2018 [164]. The institutional owner was DFRS under the Ministry of Forests and Environment, and both the legal and technical accessibility layers were largely satisfied. However, operational uptake remained severely constrained by inadequate digital infrastructure in Nepal, with 42 local governments lacking internet connectivity entirely as of March 2024 [56]. The subsequent replacement of these maps by the NLCMS [48], produced under different classification specifications, further compromised temporal comparability and reduced the analytical utility of both products. This case thus illustrates a failure mode distinct from Case 1: rather than institutional fragility, the binding constraint was inadequate infrastructure, as the product reached its intended users in name but not in practice, underscoring that data availability and operational uptake are not equivalent conditions. Here, the failure occurred earlier in the workflow than in Case 1: limited internet connectivity at the local government level constrained the data download and analysis stages identified in Table 1, preventing the maps from reaching the visualization and decision integration stages regardless of the product's technical quality.

Case 3: Satellite-based hazard forecasting tools (SERVIR-Hindu Kush Himalaya, SERVIR-HKH, and Department of Hydrology and Meteorology, DHM). NASA SERVIR developed the High-Impact Weather Assessment Toolkit (HIWAT), an ensemble forecasting system based on the Weather Research and Forecasting (WRF) model, to provide probabilistic forecasts of thunderstorm-related hazards, including damaging winds, hail, frequent lightning, and intense rainfall, for national meteorological services in the Hindu Kush Himalaya region including Nepal. The system incorporates satellite observations, including a sea surface temperature product derived from MODIS and VIIRS, and its precipitation forecasts are then used as input to a hydrological model to generate flash flood predictions for small, fast-responding basins [165]. In Nepal, DHM was the primary national partner. HIWAT demonstrations were conducted with DHM during the 2018 and 2019 pre-monsoon and monsoon seasons, including training sessions in Kathmandu to familiarize DHM forecasters with the system [165]. Subsequently, DHM has included forecasts from these tools in its regular flood outlook [166]. This case illustrates progress across all three accessibility layers. The underlying satellite-informed forecast tools are openly accessible, DHM has incorporated its outputs into a routine product, and the Disaster Risk Reduction and Management Act 2017 [70] provides an institutional mandate for DHM to apply such tools. The binding constraint, however, remains institutional. According to [166], DHM and other partners have demonstrated interest in incorporating HIWAT-based forecasts into their operational systems, but DHM's use of these forecasts remains complementary to its existing methods, with full integration into their core forecasting operations identified as a goal for continued collaboration rather than an achieved outcome. The SERVIR-HKH initiative, through which this tool was developed and maintained, formally concluded in January 2025, raising questions about the continuity of technical support needed to sustain and further integrate it. With reference to the workflow stages in Table 1, the analysis and visualization stages are functioning and feed into DHM's routine flood outlook, while the decision integration stage, in which these forecasts would form a primary rather than supplementary basis for warnings, remains incomplete.

Three recurring failure modes emerge across both cases and the broader sectoral evidence in Section 5: dependence on external actors for system development and maintenance; absence of long-term institutional ownership and funding; and failure to embed EO outputs within decision-making workflows that survive the end of project support. These failure modes are not independent and reflect the same underlying deficit: the absence of the functioning geospatial ecosystem that Section 7 identifies as the necessary condition for translating open data into operational governance.

7. Opportunities and Pathways for Enhanced Use of EO in Nepal

Despite the barriers outlined above, several mutually reinforcing opportunities position Nepal to significantly enhance its use of RS and EO technologies. These opportunities encompass technological, geographic, human, and governance dimensions, each offering distinct pathways to bridge the gap between data availability and operational application. The following sub-sections evaluate these opportunities, highlighting how they can be strategically leveraged to accelerate the adoption and impact of RS and EO in Nepal.

7.1. Opportunities

This section outlines four promising opportunities for advancing RS and EO in Nepal, namely technological, geographic, human capacity, and governance dimensions, each explained in detail below.

7.1.1. Technical and Data-Driven Advancements

Recent advancements in RS and EO technologies have significantly expanded opportunities for applications globally, with particular relevance for countries such as Nepal. The availability of freely accessible satellite datasets—including Landsat, Sentinel-2, MODIS, topographic data, and SAR—has created a comprehensive data ecosystem that provides complementary spatial, temporal, and spectral information for robust environmental analysis. With respect to Nepal's complex and cloud-prone terrain, the integration of optical, SAR, and DEM data are particularly valuable, improving the accuracy and reliability of applications such as land cover mapping, forest monitoring, agriculture, and hazard assessment [131,167]. Moreover, advances in cloud computing platforms, such as GEE, further enable large-scale and multi-temporal analyses without the need for high-performance local hardware, reducing technical barriers to working with dense EO datasets [8,73]. This benefit, however, accrues primarily to users with reliable internet connectivity, such as universities, and national research centers; for district-level offices facing the bandwidth constraints described in Section 6.1, cloud platforms substitute one infrastructure dependency (local hardware) for another (stable connectivity) rather than removing the barrier altogether. In addition, open-access GIS software such as QGIS are available to strengthen the spatial analysis and visualization of EO data and results. Specifically, for a resource-constrained country like Nepal, where financial and technical capacity to invest in proprietary data and infrastructure remains limited, the open access to these datasets and platforms is especially critical, enabling broader adoption of RS and EO technologies without substantial upfront costs [168,169].

Simultaneously, the rapid development in the field of machine learning and artificial intelligence has enhanced the capacity to process and analyze big data (large EO datasets in our case) through automated and scalable workflows, improving classification accuracy, change detection, and near real-time monitoring [160,161]. On the other hand, emerging tools such as unmanned aerial vehicles (UAVs) further complement satellite observations by providing high-resolution data for localized analysis [170]. Collectively, these advancements highlight the growing technical potential to leverage EO data for efficient, scalable, and timely environmental monitoring at a minimal initial cost.

7.1.2. Small Country Advantage

Nepal's relatively small geographic extent (~147,181 km²) provides a unique advantage for remote sensing applications, enabling frequent, high-resolution monitoring with relatively modest data and computational requirements. For instance, at 30 m spatial resolution, the entire country can be covered with just 13 Landsat tiles [118], while Sentinel-2 requires a manageable number of tiles despite higher spatial resolution, and MODIS requires even fewer tiles for broader-scale analyses. Evaluating the global practice, countries such as the United States rely on programs like the National Agriculture Imagery Program (NAIP) to acquire high-resolution imagery for the entire country, which entails significant data storage, processing, and operational costs [171]. In contrast, Nepal could establish similar systematic monitoring programs, covering forests, agriculture, and hazards, at a fraction of the cost and logistical complexity, facilitating the creation of routinely updated, nation-wide EO datasets and products [155]. Furthermore, Sentinel-2's 10 m imagery with a five-day revisit interval, together with Sentinel-1's all-weather radar capabilities, makes repeated nationwide observation technically feasible and operationally efficient, offering an opportunity for Nepal to implement comprehensive, near-real-time environmental monitoring systems comparable in concept to high-resource programs in developed countries [172,173]. However, small geographic extent does not automatically translate into operational simplicity. Nepal's rugged topography, persistent monsoon cloud cover, and

high spatial heterogeneity in land cover and hazard exposure impose significant analytical demands regardless of data volume. Administrative fragmentation across federal, provincial, and local governments, combined with uneven internet connectivity and technical capacity across these levels, means that national-scale EO coverage remains logistically and institutionally complex even when data acquisition is straightforward. The small country advantage is therefore most meaningful when paired with the institutional coordination and infrastructure investments discussed in the following pathways.

7.1.3. Human Capacity and Awareness

The effective use of RS and EO technologies in Nepal has currently been supported by a growing base of digital and geospatial awareness among students, researchers, and professionals. The expansion of smartphone uses, and mobile internet connectivity has facilitated the integration of digital technologies into daily activities, thereby enhancing basic computer literacy and exposure to data-driven applications [56,174,175]. While not yet at the level of developed countries, this digital familiarity has created a foundation for developing geospatial skills, and academic institutions are progressively integrating RS, EO and GIS into their curricula. Major universities, for instance Tribhuvan University and Kathmandu University, and newer institutions like Agriculture and Forestry University offer courses and seminars in RS, GIS, and spatial technologies within programs in forestry, agriculture, geography, environmental science, and engineering [63,176,177].

Notably, the number of geospatial research publications led by Nepal-based scholars has been steadily increasing, reflecting the expansion of local expertise in areas such as land cover change, forest monitoring, hazard susceptibility and impact assessment, and agriculture (refer to Section 5). In addition, Nepali scientists working abroad, both individually and through organizations such as Nepali Academics in America (NACA; <https://www.nepaliacademics.org/>; accessed on 15 April 2026), contribute significantly to this growing body of work by mentoring students, co-authoring research, and promoting science and technology including RS and EO methodologies in Nepal and internationally. These efforts strengthen local capacity and facilitate exposure to global practices.

National RS and EO societies, such as NRSPS, have been further enhancing awareness by organizing workshops, seminars, and outreach activities that bring together RS and EO enthusiasts and professionals across the country and overseas. Collectively, rising digital literacy, expanding academic offerings, mentorship from Nepali experts abroad, and active professional societies are driving an upward trend in human capacity, helping to create a skilled and motivated workforce capable of leveraging EO for research, operational applications, and national development priorities. Nepal's scientific diaspora, engaged through organizations such as NACA and NRSPS, represents an underutilized yet growing asset for domestic capacity building. Realizing this potential requires deliberate institutional enabling conditions, including remote collaboration infrastructure, formal recognition of diaspora contributions within national research frameworks, and sustained engagement mechanisms, that would transition diaspora networks from informal resources into structured complements to domestic training programs.

7.1.4. Emerging Governance Reform

Recent political developments in Nepal, characterized by youth-led movement (September 2025) advocating for accountability, transparency, and institutional reform, have contributed to a notable transformation in the governance landscape and the emergence of new leadership [178]. This movement has since translated into electoral representation and a shift in government leadership toward younger, reform-oriented figures, representing a broader societal shift toward modernization, digital governance, and data-driven

decision-making, with increasing influence of technologically oriented younger generations in shaping national priorities [179]. While the long-term policy implications of this transition for digital governance and EO adoption remain to be fully seen, such a reform-oriented environment presents a strategic opportunity to advance the adoption of RS and EO technologies by aligning them with evolving governance objectives. In particular, the growing emphasis on digital systems and transparency may facilitate the integration of EO into routine governmental processes, strengthen inter-agency coordination, and support the development of sustainable, operational monitoring frameworks. Importantly, youth-driven governance transitions [180] may also accelerate the cultural acceptance of digital tools within public institutions, reducing resistance to innovation and fostering the long-term sustainability of RS and EO-based systems, though realizing these opportunities will depend on sustained political commitment and institutional follow-through.

7.2. Pathways for Use

Realizing the full potential of RS and EO technologies in Nepal will depend on deliberate coordinated efforts across institutional, technical, and capacity-building fronts. The pathways elaborated below offer a roadmap for translating aforementioned opportunities into sustained practice.

7.2.1. Strengthening Institutional Policy and Geospatial Infrastructure

The effective operationalization of RS and EO technologies in Nepal requires urgent and targeted strengthening of institutional, policy, and technical frameworks. Currently, RS and EO-related mandates are dispersed across multiple sectoral agencies, resulting in fragmented monitoring, overlapping responsibilities, and minimal data sharing [181]. Without a centralized or formally coordinated governance mechanism, RS and EO applications remain largely project-driven and ad hoc, limiting their ability to inform evidence-based decision-making at national and local levels [155]. Therefore, establishing a dedicated National EO agency or an empowered inter-ministerial EO coordination body could unify mandates, standardize datasets, and ensure sustainable operation of national monitoring systems [182].

The necessity of strengthened institutional and technical frameworks is explicitly recognized in Nepal's strategic policies and development plans. The Geo-satellite Policy, 2077 (2020 AD) [67] explicitly envisions the development of indigenous satellite capabilities and integration of RS and EO into sustainable development planning. Similarly, five-year national development strategies, including the Fifteenth Plan (2019/20–2023/24) [68] and Sixteenth Plan (2024/25–2028/29) [69], emphasize the use of geospatial technologies for disaster risk reduction, climate adaptation, natural resource management, and digital governance. Sectoral policies such as the Disaster Risk Reduction and Management Act (2017) and Rules (2019) [70], National Forest Integrated Strategic Plan (2025–2043) [183], and National REDD+ Strategy (2025–2034) [116] further mandate spatially explicit monitoring and reporting systems, reinforcing the necessity of institutionalized RS and EO programs. Despite these directives, implementation has been constrained by weak inter-agency coordination, insufficient long-term funding, and limited technical capacity.

Complementing these governance and policy measures, the development of a coordinated RS and EO national database infrastructure represents a critical technical priority [182,184]. While ad hoc initiatives such as NLCMS illustrate the potential of satellite data for forest and land cover monitoring, a formalized national database infrastructure could harmonize standards, enhance data interoperability, and support cross-sectoral data sharing across federal, provincial, and local governments [117,181]. Additionally, institutionalizing satellite data acquiring, processing, and dissemination in standardized formats would en-

able routine analytical products to inform decision-making across sectors including disaster risk reduction, agriculture, forest conservation, and urban planning [45,69,185,186].

Finally, strengthening institutional, policy, and technical frameworks should be complemented by initiatives to cultivate human capacity, including formal linkages with universities and research centers, integration of RS and EO into national research funding streams, and embedding long-term operational budgets within sectoral agencies. Together, these measures can transform Nepal's RS and EO ecosystem from a fragmented, project-driven system into a functional, coordinated, and sustainable capability that directly supports development goals, disaster resilience strategies, and evidence-based natural resource management.

7.2.2. Regional and International Collaboration

Nepal can leverage regional and international partnerships to accelerate both research activities and the operational adoption of RS and EO technologies. International organizations and development partners, including agencies within the United Nations system, for example, United Nations Geospatial Network, Committee of Experts on Global Geospatial Information Management (UN-GGIM; <https://www.un.org/geospatialnetwork/>; accessed on 15 April 2026) [185] or those who work closely with UN goals such as GEO [187] and leading geospatial companies like Esri, offer targeted programs that support least developed and developing countries through access to technical expertise, high-resolution satellite data, analytical platforms, and capacity-building initiatives [188–190]. These collaborations play a critical role in complementing national efforts by lowering technological and financial barriers to RS and EO implementation.

At the regional level, ICIMOD represents a cornerstone of RS and EO collaboration in Nepal. Through initiatives such as SERVIR–Hindu Kush Himalaya (SERVIR-HKH), ICIMOD co-develops geospatial tools and services tailored to regional needs, supporting applications in forest monitoring, agricultural assessment, and disaster risk reduction [45,191]. These programs integrate training, in-country capacity development, and operational advisory support, effectively bridging gaps between research institutions, government agencies, and local stakeholders [52,163]. Strengthening and institutionalizing such partnerships can enhance knowledge transfer, promote the integration of RS and EO into decision-making processes, and support multi-sectoral applications aligned with national development priorities.

Beyond regional collaboration, Nepal can further expand partnerships with universities and research institutions in developed countries, where mutual benefits arise from shared data access, field-based research opportunities, and joint scientific outputs [159]. Moreover, access to research-licensed resources, including high-resolution commercial satellite imagery (e.g., PlanetScope) [192] and advanced analytical software such as ArcGIS Pro (Esri) and ENVI (L3Harris Geospatial) can significantly enhance both academic research and operational applications. Collectively, these regional and international collaborations provide scalable and practical pathways for strengthening Nepal's RS and EO ecosystem and advancing its capacity to support sustainable development, environmental monitoring, and disaster resilience.

7.2.3. Capacity Building in Academic and Government Institutions

Human capital is essential for translating the promise of RS and EO into operational outcomes [29,193]. While national policies emphasize research and technology development as priorities across sectors, universities and government agencies in Nepal often face challenges in maintaining consistent institutional capacity [57,194]. As universities and research institutions serve as the primary incubators of future scientists, they require

both well-designed programs and the infrastructure to effectively deliver them [57,195,196]. To that end, establishing and strengthening formal geospatial science programs at major universities would cultivate a new generation of practitioners equipped not only with advanced analytical skills but also with contextual understanding of local environmental and socio-economic conditions, enabling evidence-based decision-making and support for national development programs [52].

On the other hand, the systematic integration of RS and EO expertise into sectoral planning units within government agencies can facilitate the operational adoption of RS and EO technologies such as, satellite-derived products [197]. Moreover, collaborative initiatives with regional geospatial centers such as ICIMOD have demonstrated the advantages in terms of sustained skill development, particularly in areas like disaster management, forest monitoring and agricultural mapping [52,191]. Further, structured internship programs linking universities, research centers, and government bodies can foster mutual benefits: researchers provide technical expertise, agencies contribute rich datasets, and society gains spatially explicit products for planning and management [198]. Finally, the establishment of formal career pathways, sustained training programs, and strong institutional linkages can enable Nepal to develop and retain a skilled RS and EO workforce that complements broader policy and institutional frameworks. Such an approach would support the emergence of a nationally coordinated and sustainable RS and EO ecosystem in contrast to short-term, sporadic training initiatives that often fail to ensure continuity in workforce development and long-term capacity building.

7.2.4. Translating RS and EO Data into Actionable Insights

The ultimate value of RS and EO lies not only in data availability, but in its effective translation into actionable insights that inform decision-making processes [29,193]. Integrating RS and EO-derived products into key sectors, such as disaster preparedness, natural resource inventory and monitoring, and climate adaptation planning, can significantly enhance evidence-based decision-making across local, provincial, and national levels [52,199,200]. In the context of Nepal, where environmental resources and risks are spatially heterogeneous and often occur in remote regions, such integration is particularly critical for timely and informed interventions.

Pilot initiatives demonstrating the operational use of RS and EO, including disaster early warning systems, land cover monitoring, and crop yield assessments, have already established the practical feasibility and relevance of satellite-based information [51,201,202]. However, their long-term impact depends on transitioning from project-based implementations to institutionalized and sustained operational systems [193]. Beyond providing decision support, these applications contribute to building institutional confidence and stakeholder trust in RS and EO technologies. Furthermore, the development of standardized, multi-temporal datasets, coupled with user-friendly visualization platforms and decision-support tools, can enhance accessibility for non-technical users and facilitate the integration of RS and EO products into policy and management frameworks, as well as into broader societal applications and everyday decision-making [45,52,62]. Strengthening the interface between data producers and end-users will therefore be essential to ensure that RS and EO outputs are routinely embedded within planning, governance, and decision-making processes.

8. Discussion

The cross-sectoral evidence reviewed in Sections 5 and 6 points to a consistent finding: technically sound EO outputs are produced across all major sectors in Nepal, yet none have achieved sustained operational integration into national governance systems. This pattern

is not unique to Nepal. Evidence from comparable LDCs suggests that EO adoption follows a structurally similar trajectory: abundant open-access data, growing research output, but persistent failure to translate them into routine decision-making [21,31,155].

Comparative evidence from other LDCs illuminates both the generalizability and the specificity of Nepal's experience. A comprehensive assessment of Bangladesh's national spatial data infrastructure (NSDI) reveals that, despite advancements in EO technical capabilities, the system remains constrained by persistent institutional deficiencies: fragmented coordination among stakeholders, lack of skilled personnel, inadequate funding, and low user awareness [203] which are closely parallel to those identified in the Nepalese context. The same study further notes that even fundamental data sharing between government agencies is obstructed by concerns over data privacy, ownership rights, and the absence of an established legal framework. Consequently, Bangladesh remains reliant on external technical support for EO applications, including flood monitoring and agricultural assessment [163].

In African contexts, the AfriCultuReS (Enhancing food security in African agriCultural systems with the support of Remote Sensing) project, a primary EO-for-development initiative that includes eight countries with several LDCs namely Rwanda, Niger, Ethiopia, and Mozambique, documented that even well-designed EO capacity building programs failed to produce sustained operational uptake without permanent institutional embedding and government ownership of workflows [31]. Furthermore, a systematic review by [32] on EO applications in West Africa underscores that despite significant technical advances, the lack of institutional embedding, limited capacity, and insufficient reference data remain key barriers to sustained operational monitoring, a finding that aligns with the institutional constraints identified in the Nepal case. Across these contexts, the binding constraint is consistently institutional rather than technical or legal, validating the three-layer accessibility framework proposed in Section 3 beyond the Nepal case.

To overcome these limitations, Nepal's experience highlights the critical importance of a functioning geospatial ecosystem [74,75], an integrated network of skilled personnel, institutional support, and analytical workflows, that can transform raw RS and EO data into actionable knowledge. The integration of multiple freely available datasets and the adoption of cloud-based or open-access analytical platforms are essential, yet insufficient, without simultaneous investment in human capacity, digital infrastructure, and institutional support [184]. This finding further aligns with the broader implementation science literature, which consistently demonstrates that technically sound knowledge products fail to influence policy when they are not produced on timelines matching decision cycles, formatted for non-technical decision-makers, or embedded in governance workflows with clear institutional ownership [74,204,205]. The concept of boundary organizations; entities that bridge scientific knowledge production and policy application, offers a constructive lens for understanding this challenge [204]. In Nepal, however, no such institution currently exists. The absence of a dedicated bridging mechanism constitutes a structural gap that neither data providers nor government agencies alone can fill, perpetuating the disconnection between technical EO capabilities and operational policy uptake.

Nepal's experience thus offers a replicable diagnostic model for other LDCs navigating similar challenges. The convergence of natural hazards, resource dependency, and socio-economic constraints makes Nepal a distinctive yet informative case. In Nepal's context, the gap between open data availability and operational governance use is particularly visible. Moreover, Nepal's small geographic coverage and ongoing governance reform environment may make this gap more tractable than in larger or more institutionally fragmented settings. Whether that potential is realized, however, depends not on further

data availability but on the deliberate construction of the geospatial ecosystem described in Section 7, operationalized through the Pixels to Policy framework in Section 11.

9. Broader Implications Beyond Nepal

Although grounded in Nepal, the three-layer accessibility framework and the last-mile barriers identified in this review have direct relevance for the broader remote sensing community. The design choices of data providers, tool developers, and capacity-building programs embed assumptions about bandwidth, hardware, and institutional conditions that systematically exclude contexts where EO impact is most needed.

Furthermore, the three-layer framework also extends prior descriptions of barriers to EO adoption [21,31,64], which identify similar constraints such as infrastructure, skills, and institutional capacity but generally treat them as a list of separate, additive barriers. In contrast, the framework proposed in this study emphasizes that these layers are conditional on one another: progress in technical usability depends on legal openness, and institutional accessibility depends on both. This implies that, in Nepal and in comparable LDCs, interventions aimed at institutional accessibility, currently the least developed layer, are likely to offer the greatest gains, even where technical and legal conditions are already largely met.

The central implication of this review is that EO democratization, while necessary, is not sufficient to ensure societal impact. Open data policies alone do not guarantee operational uptake; without parallel investments in human capital, infrastructure, and governance, the societal value of EO remains largely unrealized [64]. This is not a critique of open data initiatives, but rather an argument for extending the RS community's responsibility from data delivery to ensuring that data can be and is used, a reorientation that requires engagement with governance, capacity, and infrastructure dimensions that have traditionally been treated as outside the community's concern.

10. From Fragmentation to Function: Prioritized Pathways for Action

Addressing the last-mile problem requires coordinated interventions that account for system interdependencies. The pathways below are intentionally sequential—progress in later stages depends on resolving foundational constraints first, and resource-constrained settings like Nepal cannot pursue all interventions simultaneously.

10.1. Institutional Foundation (Critical First Step)

The primary constraint is not data or tools but institutional fragmentation. All other interventions depend on this foundation being established first. Therefore, Nepal should:

- Establish a national EO coordination mechanism, most logically housed under the newly established Ministry of Science, Technology and Innovation (MoSTI), to unify mandates across FRTC, the Department of Survey, the DHM, and sectoral ministries. The Geo-satellite Policy 2077 [67] provides a relevant legislative basis for this coordination mandate.
- Define explicit operational relationships between the coordinating mechanism and existing institutions, for instance, FRTC for land cover and forest monitoring, the Department of Survey for establishing national mapping standards, the DHM for disaster and climate applications, and ICIMOD for regional technical support, to avoid duplication and ensure complementarity.
- Identify realistic budget mechanisms drawing on allocations under the Sixteenth Plan [69], supplemented by multilateral support through international partner agencies and organizations such as United Nations, USAID already active in Nepal.

10.2. Operational Enablement

Once coordination exists, focus shifts to making EO useful for non-technical decision-makers at subnational levels; Nepal should thereafter:

- Develop standardized, regularly updated EO products (e.g., monthly flood risk maps, quarterly forest change alerts, seasonal crop estimates) aligned with actual decision cycles, not research timelines.
- Integrate EO outputs into existing workflows—disaster preparedness meetings, agricultural extension services, local development planning, and national reporting frameworks such as REDD+ and SDG monitoring.
- Design delivery mechanisms for real user environments: dashboards, printed maps, mobile alerts, and summary reports rather than interactive GIS platforms requiring specialist skills.

10.3. Scaling, Innovation and Sustainability

With foundations and operations in place, expand reach and ensure long-term sustainability:

- Shift international partnerships (ICIMOD, SERVIR, GEO, and CEOS) from project-based technical assistance toward institutionalized knowledge transfer through training-of-trainers programs and structured secondments.
- Engage local technology companies, GIS service providers, and academic start-ups to drive innovation and create sustainable career pathways that reduce brain drain.
- Establish permanent geospatial positions within government agencies as a structural reform priority, recognizing that training programs alone are insufficient to sustain institutional capacity without embedded professional roles.

10.4. Priority Research Directions for the Remote Sensing Community

- Lightweight data formats: build on existing efforts such as ARD and COGs (Section 6.1) by integrating these formats into delivery pipelines designed for low-bandwidth settings, where a single Sentinel-2 tile exceeding 600 MB remains impractical despite such formats being technically available.
- Capacity aware tool design: build offline-first, menu-driven geospatial tools that operate on basic hardware without programming skills or reliable internet, extending beyond platforms such as GEE, discussed in Sections 6.1 and 7.1.1, which reduce local hardware demands but still require stable connectivity.
- Implementation science for EO uptake: shift evaluation focus from algorithmic accuracy toward understanding why products are or are not adopted, used consistently, and sustained after project support ends guided by frameworks such as boundary organizations [204]. In practice, this means evaluating whether EO outputs reach the right decision-makers at the right time, whether they are formatted for non-technical users, and whether clear institutional ownership exists to maintain them beyond project cycles, using the failure modes identified in Section 6.4, external dependency, absent institutional ownership, and incomplete decision integration, as criteria for evaluation [204,205].

11. Framework for Action

Leveraging the cross-sectoral evidence reviewed in Sections 5 and 6, the barriers identified in Section 6, and the pathways elaborated in Sections 7 and 10, we propose the Pixels to Policy framework to guide the systematic translation of open-access RS and EO data into governance practice in developing and LDCs. The framework illustrated in Figure 2 synthesizes the key elements identified throughout this review: open satellite

data, persistent barriers, enabling opportunities and pathways, and the resulting geospatial ecosystem that supports evidence-based decision-making.

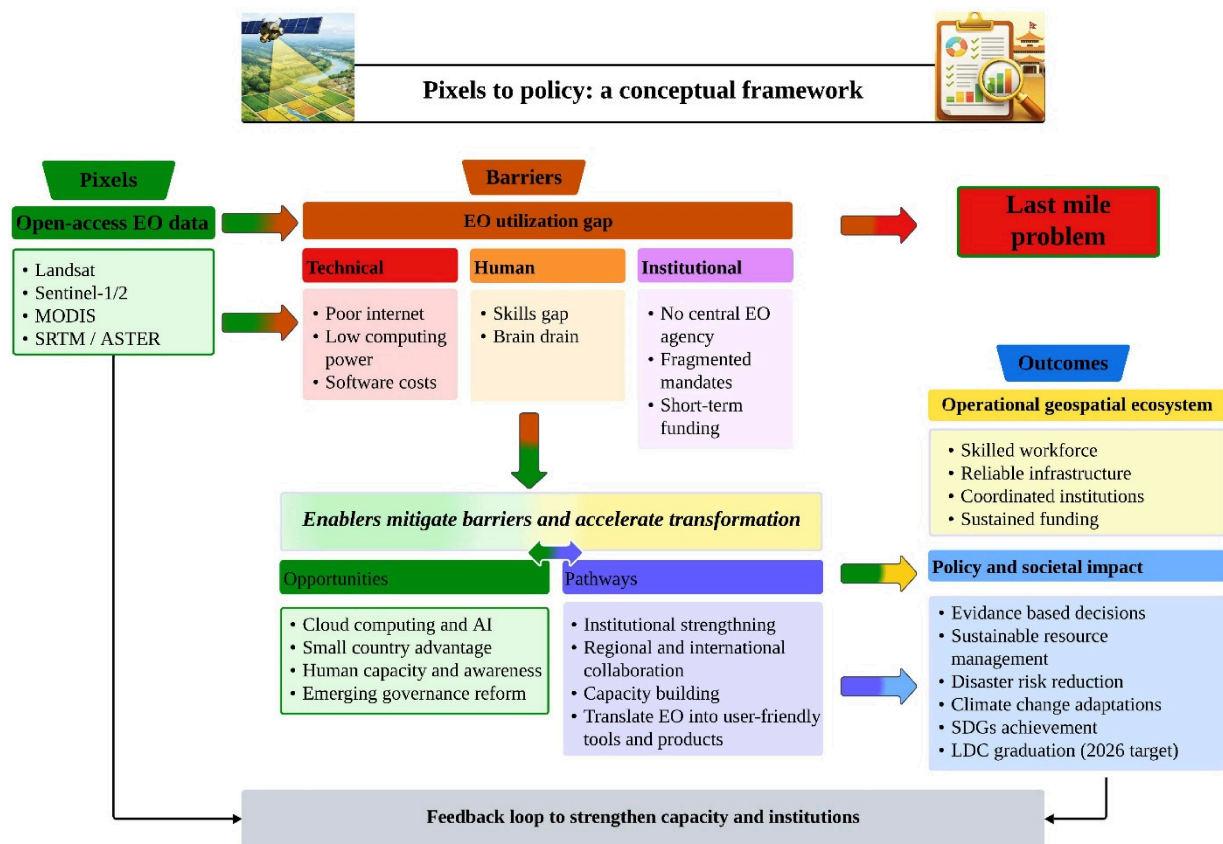


Figure 2. From pixels to policy: a conceptual framework for operationalizing RS and EO. The framework illustrates the progression from open-access satellite data, through persistent barriers and enabling opportunities and pathways, to the establishment of a sustainable geospatial ecosystem and, ultimately, evidence-based policy impact. RS: remote sensing; EO: earth observation; AI: artificial intelligence; SDGs: sustainable development goals; LDC: least developed country.

Open-access EO data (e.g., Landsat, Sentinel-1/2, MODIS, SRTM/ASTER) form the technical foundation of our framework. However, three categories of systemic barriers create the last-mile problem: technical (poor internet, low computing power, software costs), human (skills gap, brain drain), and institutional (no central EO agency, fragmented mandates, short-term funding).

Nevertheless, the abovementioned barriers can be mitigated through enabling opportunities and pathways. Opportunities include cloud computing/AI, Nepal's small country advantage (e.g., 13 Landsat tiles for full coverage), growing human capacity, and governance reforms that translate into four pathways: institutional strengthening, regional/international collaboration (e.g., ICIMOD, SERVIR), capacity building, and user-centered product development (e.g., flood alerts, crop advisories).

Finally, when implemented, these pathways produce four outcomes contributing to a functioning geospatial ecosystem: a skilled workforce, reliable infrastructure, coordinated institutions, and sustained funding. Subsequently, the functioning ecosystem results in policy and societal impact that includes evidence-based decisions, sustainable resource management, disaster risk reduction, climate adaptation, SDGs achievement, and support for Nepal's LDC graduation (2026 target).

Among the elements depicted in Figure 2, the open access data layer and the three categories of systemic barriers correspond to conditions already documented in Nepal in

Sections 5 and 6. The enabling opportunities vary in their current status: cloud computing platforms and Nepal's small geographic extent represent present conditions, whereas governance reform and the broader realization of growing human capacity remain at an early stage of development. The four pathways and the resulting geospatial ecosystem represent the proposed direction of change rather than conditions that currently exist. As Case 3 in Section 6.4 illustrates, individual elements of these pathways, such as institutional adoption of satellite-informed forecasting tools, may already be underway in a partial form without the broader ecosystem being established. The framework should therefore be understood as depicting a trajectory from documented present conditions toward a proposed future state, rather than as a description of an ecosystem that currently exists in its entirety.

A feedback loop connecting outcomes back to the geospatial ecosystem and its constituent elements namely data, barriers, and enablers, emphasizes that operationalizing EO in resource-constrained settings is not a linear process but an iterative one, requiring continuous reassessment of barriers and enabling conditions as contexts evolve.

This framework is designed to serve as a practical tool for policymakers, development partners, and implementing agencies. It highlights the critical last-mile bottleneck and identifies strategic leverage points, such as institutional strengthening, capacity building, and translation of data into user-friendly products, that can bridge this gap. While grounded in Nepal's context, the framework is structured to be adaptable to other developing and LDCs facing similar challenges in leveraging global RS and EO resources.

12. Conclusions

The global EO revolution has substantially expanded access to satellite data, yet this expansion has not been matched by a comparable development in operational decision-making capacity across LDCs. Nepal clearly illustrates this gap: despite abundant EO data, growing technical expertise, and supportive policy frameworks, the operational integration of EO into governance and planning processes remains limited.

This review concludes that the central challenge is not technological but systemic. Bridging the gap between EO data and policy impact requires a functioning geospatial ecosystem integrating data systems, technical infrastructure, human capacity, and institutional frameworks. In Nepal specifically, the binding constraint is institutional fragmentation, which no amount of additional data provision or training investment can resolve without a dedicated coordination mechanism to anchor and sustain these efforts.

Nepal's experience highlights a broader lesson: the value of EO lies not in pixels themselves, but in the systems that transform them into actionable knowledge. Without such systems, even advanced EO technologies risk limited operational uptake. Conversely, when these systems are in place, even resource-constrained contexts can achieve substantial impact. The pathway from pixels to policy is not automatic; it must be deliberately constructed through sustained investment in institutions, infrastructure, and human capacity.

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