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Mapping the digital divide: Using GIS and satellite data to prioritize broadband expansion projects

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Abstract

The persistent digital divide across rural and underserved communities in the United States continues to limit access to essential services, educational equity, economic opportunities, and healthcare connectivity. This study presents a comprehensive, data-driven framework for identifying, prioritizing, and executing broadband expansion projects using an integrated approach grounded in Geographic Information Systems (GIS) and satellite remote sensing technologies. By fusing geospatial data layers such as terrain ruggedness, population density, road infrastructure, and utility corridors, the study creates high-resolution broadband accessibility maps to classify unserved and underserved zones. The research also applies the Project Management Institute (PMI) framework to define strategic milestones, stakeholder roles, cost estimations, and timeline projections for phased deployment. Technological implementation draws from electrical and electronic engineering principles, including fiber-optic routing algorithms, 5G tower siting models, and satellite-borne internet systems for remote terrains. A critical emphasis is placed on sustainability, advocating for solar-powered relay stations and microgrid-supported base stations to ensure resilient, off-grid connectivity. Furthermore, the model assesses the socioeconomic multiplier effects of broadband access, especially in terms of workforce development in GIS analysis, network installation, and green energy infrastructure. The findings offer actionable insights for federal, state, and municipal agencies seeking to equitably expand broadband while meeting environmental and economic development goals.

Keywords: Geographic Information Systems (GIS); Satellite remote sensing; Broadband accessibility mapping; Project management (PMI/PMP); Sustainable telecommunications infrastructure; Rural digital inclusion

1. Introduction

1.1. Contextualizing the Digital Divide

The digital divide—the persistent gap in access to high-speed internet across geographies, income groups, and racial demographics—remains one of the most pressing infrastructure challenges in the United States. Despite technological advances and policy interventions, approximately 19 million Americans still lack access to reliable broadband services, with the majority residing in rural, tribal, and low-income urban areas [1]. These disparities significantly impact access to education, employment, healthcare, and civic engagement, reinforcing socioeconomic inequities and marginalizing already underserved communities [2].

While internet connectivity is often perceived as a commercial utility, its function in the 21st century more closely resembles that of a public good. Inadequate broadband infrastructure hinders digital learning, telehealth appointments, remote work, and small business development, compounding the challenges faced by structurally disadvantaged

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populations [3]. In rural school districts, for example, the lack of reliable internet has been directly linked to lower academic performance, reduced graduation rates, and limited exposure to STEM fields [4].

The digital divide is not solely a consequence of geographic remoteness or market failure—it is also a function of inconsistent data reporting and fragmented planning. The Federal Communications Commission (FCC) relies heavily on self-reported data from service providers, which frequently overstates coverage and overlooks local connectivity gaps [5]. In contrast, emerging analyses using satellite data and crowdsourced signal tests paint a more granular and often more alarming picture of broadband access across counties and ZIP codes [6].

Addressing this divide requires more than fiber-optic cables and spectrum allocation. It demands targeted, data-driven policy informed by accurate spatial analysis and needs assessments. Without precision in mapping and planning, funding efforts risk inefficiency and could further entrench digital exclusion. Bridging this gap requires a combination of technological infrastructure, community input, and cross-sectoral coordination built on robust and reliable data foundations.

1.2. The Role of Data-Driven Decision-Making in Broadband Planning

Effective broadband expansion depends on accurate, high-resolution data to identify underserved areas, prioritize investments, and measure progress. Historically, the lack of standardized, transparent broadband data has led to misallocated resources and underperforming infrastructure programs. The FCC's Form 477 data, which allows internet providers to declare a census block as "served" even if only one household has connectivity, has been widely criticized for masking service gaps [7]. As a result, funding efforts have often overlooked neighborhoods with the most urgent needs.

Recent advancements in remote sensing, geospatial analysis, and machine learning are transforming how broadband gaps are identified and addressed. Satellite imagery, signal strength mapping, and user-submitted speed test data from platforms such as M-Lab and Ookla have emerged as complementary tools to challenge and refine federal broadband coverage maps [8]. These tools not only improve accuracy but also reveal digital redlining and systemic underinvestment in marginalized communities [9].

Data-driven decision-making enables a more strategic allocation of public and private investments. Predictive analytics can help forecast demand in growing suburbs or remote corridors, while spatial clustering techniques identify digital deserts with compounded vulnerabilities—such as senior populations or medically underserved regions [10]. This ensures that funds from initiatives like the Broadband Equity, Access, and Deployment (BEAD) Program are directed where they yield the greatest public value.

Ultimately, the integration of diverse data sources enables state and local governments to move beyond generic infrastructure strategies and adopt precision planning models that are equitable, efficient, and transparent. This shift is central to closing the connectivity gap in a durable and just manner.

1.3. Objectives and Scope of the Article

This article explores how geospatial technologies, satellite data, and digital mapping tools are reshaping broadband equity strategies in the United States. It specifically investigates how more precise data inputs, combined with open-access analytics, can help overcome the systemic blind spots that have long plagued infrastructure planning and funding decisions [11]. By focusing on the intersection of technology, governance, and social justice, this work highlights pathways for inclusive digital transformation.

The primary objective is to demonstrate the value of data-driven broadband expansion strategies that prioritize community needs, spatial accuracy, and long-term sustainability. In doing so, the article synthesizes insights from recent federal programs, academic research, and local-level case studies that have utilized alternative data sources for broadband mapping and deployment [12]. These include efforts in states such as North Carolina, Georgia, and Michigan, where publicly accessible mapping portals have driven smarter and more equitable infrastructure decisions [13].

The scope encompasses both urban and rural digital divides, with attention to demographic disparities that intersect with geography—such as age, income, race, and disability status. It also evaluates how state and municipal actors are using data to leverage competitive funding opportunities and hold providers accountable for deployment milestones [14].

Through this lens, the article aims to inform policymakers, planners, and technology advocates about the practical and ethical dimensions of digital infrastructure development. By unpacking the capabilities and limitations of modern broadband mapping techniques, it contributes to ongoing conversations around digital equity and the future of inclusive internet access in America.

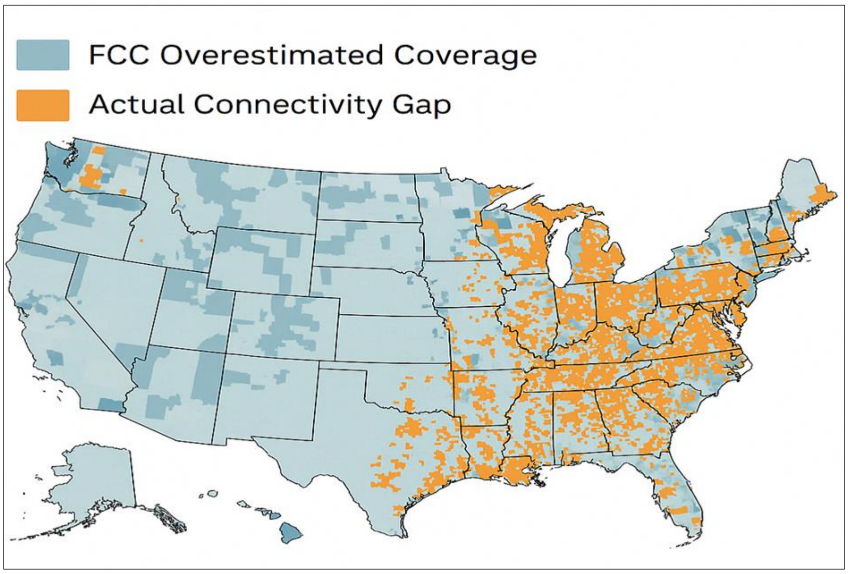

Figure 1 Visual illustration of U.S. broadband coverage disparities based on FCC vs. satellite data

2. The evolving landscape of broadband inequity

2.1. Historical Context: Policies and Patterns of Exclusion

Understanding the digital divide in the United States requires situating current broadband disparities within a broader historical context of infrastructural exclusion. Much like the 20th-century disparities in electrification, railroads, and public transportation, broadband deployment has been shaped by systemic policy choices that favored certain communities while neglecting others [6]. Historically marginalized populations—including Black, Latino, Native American, and rural communities—have routinely found themselves last in line for connectivity upgrades and digital infrastructure investments.

Federal initiatives, such as the Telecommunications Act of 1996, established a broad framework for universal service but lacked enforcement mechanisms and precise data to guarantee equitable outcomes [7]. Market-based approaches, which incentivized private companies to expand service, tended to favor affluent and urban areas with higher return on investment. As a result, low-income and remote communities were effectively deprioritized in rollout plans, leaving them with unreliable, expensive, or nonexistent internet access.

Compounding these challenges were practices akin to digital redlining, where internet service providers (ISPs) either avoided investment or offered substandard plans in neighborhoods with high poverty rates or significant minority populations [8]. This structural inequity persists in the form of underdeveloped infrastructure in inner cities and tribal lands, where even basic broadband remains inaccessible despite decades of federal funding efforts.

Public-private partnerships, often heralded as efficient mechanisms for expanding broadband, have also struggled with transparency and accountability. Projects designed to serve underserved areas have, in many cases, failed to meet deployment targets or were mired in inconsistent reporting [9]. The digital divide is not merely a technological lag but the cumulative outcome of policy neglect, discriminatory planning, and insufficient regulatory oversight.

By viewing broadband gaps through a historical lens, it becomes clear that closing the divide will require not just infrastructure expansion but a reckoning with the policy and governance failures that produced today's inequities. Recognizing this legacy is the first step toward designing inclusive solutions that resist the repeat of historical exclusion patterns.

2.2. Demographics and Geography of the Unconnected

The geography of the digital divide in the U.S. is shaped by stark demographic and regional disparities, revealing a pattern of exclusion that disproportionately affects rural, low-income, and nonwhite populations. According to recent data, 25% of households with annual incomes below $30,000 lack broadband at home, compared to only 6% of those earning above $75,000 [10]. These gaps underscore the extent to which income correlates with both connectivity and digital opportunity.

Rural residents, particularly in the Midwest, Appalachia, and parts of the South, continue to report the lowest broadband access rates due to terrain challenges, low population density, and limited competition among providers [11]. These communities are often served by legacy copper networks incapable of delivering high-speed internet, or worse, remain completely unserved despite being marked as "covered" in federal mapping systems [12].

In urban settings, broadband gaps are often hidden in plain sight. Low-income neighborhoods in cities like Detroit, Baltimore, and Dallas experience access challenges not because of physical infrastructure absence, but due to affordability, lack of service quality, or discriminatory pricing [13]. Many residents in these areas rely on mobile-only internet plans or shared Wi-Fi connections, which limit functionality and further marginalize their participation in digital society.

Racial disparities are also prominent. Black and Latino households are less likely to have high-speed home internet, even after controlling for income and education [14]. These discrepancies reflect deeper structural barriers, including historical housing segregation, employment gaps, and unequal educational access. Among Native American populations, the problem is even more acute, with over one-third of tribal lands lacking access to broadband entirely [15].

Educational attainment is another strong predictor of digital access. Households with a college degree are significantly more likely to adopt broadband, suggesting a dual relationship between connectivity and long-term socioeconomic mobility [16]. The digital divide, therefore, does not exist in isolation but intersects with multiple axes of inequality.

Understanding the full demographic scope of the unconnected is essential for equitable broadband planning. Data disaggregated by income, race, education, and geography must inform funding formulas, program eligibility, and performance metrics if policies are to be truly inclusive and effective.

2.3. Why Infrastructure Isn't Enough: Socioeconomic and Cultural Dimensions

While expanding broadband infrastructure is a vital component of digital equity, it alone does not guarantee meaningful access. The assumption that building fiber-optic cables or upgrading towers will automatically close the digital divide ignores the nuanced barriers that prevent many from adopting, using, or benefiting from broadband technology [17]. These barriers include affordability, digital literacy, trust in institutions, and culturally relevant content.

Affordability remains one of the most persistent challenges. Even when broadband is technically available, monthly subscription costs and device expenses often put connectivity out of reach for many families [18]. For some, choosing between internet access and basic needs like food or healthcare becomes a monthly dilemma. Subsidy programs, while helpful, are often underutilized due to complex enrollment processes or lack of awareness.

Digital literacy further compounds the challenge. Many older adults, non-English speakers, and low-income individuals lack the skills needed to navigate online services effectively [19]. This not only limits their access to job applications and telehealth but also increases their susceptibility to scams, misinformation, and data breaches. Without targeted digital education programs, access alone may deepen existing inequalities rather than alleviate them.

Cultural and psychological factors also influence broadband adoption. Distrust in government and private companies—fueled by histories of surveillance, discrimination, or exploitation—can deter participation in connectivity programs [20]. For immigrant or Indigenous communities, language barriers, lack of culturally appropriate support, and unfamiliarity with digital systems act as silent deterrents to broadband use.

Moreover, digital access must be contextualized within a broader ecosystem of support. Households lacking time, stable housing, or technical assistance may struggle to maintain consistent connectivity, even if service is available [21]. Public libraries, schools, and community centers play a critical role as digital anchors, offering not only access but guidance, training, and social reinforcement that encourage sustained use.

Equity-focused broadband planning must move beyond "build-out" metrics to embrace these socioeconomic and cultural realities. It calls for intersectional policy design that includes income-based subsidies, multilingual support systems, targeted digital literacy programs, and trust-building through community-led initiatives. Infrastructure provides the wires, but inclusion requires human investment, cultural understanding, and systemic accountability.

Table 1 Comparative analysis of broadband adoption rates by income, education, and race across states

State	< $30k Income (%)	No College Degree (%)	Black or Latino Households (%)
Mississippi	52	60	47
California	28	34	33
New York	30	37	35
Texas	34	41	39
North Dakota	18	22	12
Alabama	46	50	43
Arizona	39	45	40

3. Mapping tools and technologies: gis and satellite data

3.1. Overview of GIS in Public Infrastructure Planning

Geographic Information Systems (GIS) have become indispensable in public infrastructure planning, offering spatial tools that aid in the visualization, analysis, and decision-making processes essential for equitable development. Within the context of broadband expansion, GIS platforms provide a dynamic means of identifying underserved regions, optimizing network design, and evaluating project feasibility based on terrain, population density, and existing infrastructure [11].

GIS tools allow planners to integrate multiple data layers—such as school locations, healthcare facilities, road networks, and socioeconomic indicators—onto a single interactive map. This composite view supports a holistic assessment of community needs and infrastructure gaps, ensuring that digital expansion aligns with health, education, and economic priorities [12]. In particular, broadband planning benefits from GIS's ability to pinpoint connectivity deserts at granular scales, enabling precise targeting of high-impact interventions.

In rural contexts, GIS helps overcome the opacity of traditional broadband mapping, which often fails to reflect local topographic challenges. By incorporating elevation models and land cover classifications, GIS enables engineers to anticipate deployment constraints and select routes that optimize cost-efficiency and coverage [13]. In urban environments, it assists in identifying apartment buildings or housing blocks excluded from fiber rollouts due to economic or legal complexities.

Municipalities and state governments increasingly use open-source GIS tools such as QGIS or ESRI's ArcGIS to plan broadband corridors in coordination with housing, transportation, and emergency preparedness strategies [14]. The integration of GIS into public-sector planning has not only improved project accountability and transparency but also encouraged stakeholder participation through accessible mapping dashboards.

GIS also supports scenario modeling, where planners simulate future connectivity under varying funding levels, demographic shifts, or technological advancements. These simulations help forecast demand and prioritize investments over multi-year timelines. As digital infrastructure becomes foundational to economic resilience, GIS ensures that broadband strategies are informed, inclusive, and spatially optimized, positioning it as a cornerstone of modern infrastructure planning.

3.2. Advancements in Satellite Imagery for Geospatial Analysis

The utility of satellite imagery in geospatial analysis has advanced dramatically over the past decade, enabling increasingly granular assessments of terrain, human activity, and infrastructural development. High-resolution satellite data, captured by platforms such as Sentinel-2, Landsat-8, and commercial providers like Planet and Maxar, now play a critical role in broadband planning and digital equity analysis [15].

Unlike traditional datasets, which rely on administrative reporting or surveys, satellite imagery provides consistent and real-time observational coverage of even the most remote areas. This allows for independent verification of infrastructure claims made by service providers and supports the detection of unserved regions that are misclassified under self-reported maps such as those maintained by the FCC [16]. The spatial and temporal resolution of modern satellites allows for monthly or even daily tracking of changes in land use and built environments.

Machine learning and computer vision algorithms applied to satellite imagery can detect built structures, estimate population densities, and infer road accessibility—key proxies for broadband demand and feasibility [17]. When combined with parcel data and tax records, these insights provide a comprehensive picture of digital need that complements ground-based data sources.

Thermal imagery and spectral analysis also enable planners to identify industrial zones, commercial hubs, and housing clusters that may warrant prioritized broadband access. For example, near-infrared bands can help detect roofing materials or construction types, which influence wireless signal propagation and infrastructure placement decisions [18].

Furthermore, cloud-based platforms such as Google Earth Engine have democratized access to satellite analysis, allowing local governments, nonprofits, and researchers to process petabytes of imagery with minimal infrastructure investment. These platforms support reproducible workflows that increase the scalability of broadband planning initiatives and reduce the time needed to generate actionable insights [19].

As satellite sensors improve in spatial, spectral, and radiometric resolution, their integration into digital equity strategies is becoming not just supplemental but essential. They provide an unbiased lens through which planners can monitor digital development, evaluate program efficacy, and recalibrate expansion priorities in near real-time. Their unique vantage point is transforming how broadband gaps are seen, measured, and addressed at scale.

3.3. Integration of Satellite and Ground Data for Broadband Mapping

The integration of satellite-derived data with ground-level information creates a more robust and multidimensional approach to broadband mapping. While satellite imagery provides macro-level visibility into settlement patterns, land use, and terrain, ground data—including field surveys, speed test results, and infrastructure inventories—offers the specificity needed to validate and enhance remote observations [20].

Together, these datasets enable planners to cross-reference observed built environments with actual service availability. For example, a satellite may identify a densely populated housing development, but only through ground data can one confirm the presence or absence of broadband service, signal strength, and user experience [21]. This complementary process mitigates the risks associated with overreliance on a single data stream and improves the precision of funding eligibility determinations.

One widely adopted integration method is the use of mobile broadband speed tests, such as those conducted by Ookla and M-Lab, georeferenced and overlaid on satellite imagery. These crowd-sourced tests provide real-world performance metrics—including latency, jitter, and download speeds—against the spatial backdrop of rural or urban settlements [22]. This combination helps identify not only unserved areas but also underperforming regions where infrastructure exists but fails to meet baseline standards.

Moreover, integrating satellite and ground data facilitates predictive modeling. By correlating historical service patterns with imagery-derived development trends, analysts can project future demand zones and estimate where infrastructure expansion will yield the highest returns [23]. This is particularly valuable in fast-growing suburbs, disaster-prone zones, or migration corridors where static planning is insufficient.

The use of AI also enhances integration. Supervised machine learning algorithms can be trained on ground-truthed broadband data to classify satellite pixels into categories of connectivity potential, generating national-scale broadband opportunity maps [24]. These AI models can account for features such as road width, building density, or distance to fiber backhaul lines.

Ultimately, the hybrid model—fusing sky-level observation with street-level truth—creates a comprehensive, real-time, and scalable framework for broadband deployment. It aligns infrastructure expansion with actual user needs, ensures more effective allocation of federal and state resources, and strengthens accountability among ISPs and local governments alike.

3.4. Case Example: Night-Time Light Intensity as a Proxy for Connectivity

Night-time light intensity, as observed from space by satellites like NASA's VIIRS and DMSP-OLS, has emerged as a powerful proxy for mapping human settlement and economic activity—both critical indicators of broadband demand. These datasets capture artificial illumination patterns, which correlate closely with urbanization, electricity access, and population density [25].

Regions with high night-time luminosity typically demonstrate greater connectivity, while dark zones often correspond with rural, remote, or underserved areas. By layering night-time light data over FCC broadband maps, planners can identify discrepancies where populations appear active at night but lack documented internet service [26]. This divergence is particularly useful for targeting communities that are functionally connected to power grids and roadways but are systematically excluded from connectivity investments.

Light intensity trends can also serve as dynamic indicators. Changes in brightness over time suggest economic development, new construction, or population influx—signaling increased demand for broadband infrastructure. Conversely, declines in light can point to depopulation or post-disaster recovery needs where reestablishing digital access becomes urgent.

This cost-effective, globally available dataset enhances broadband planning, especially when paired with ground-level metrics. It strengthens equity analyses by revealing hidden geographies of exclusion that traditional data sources often fail to capture.

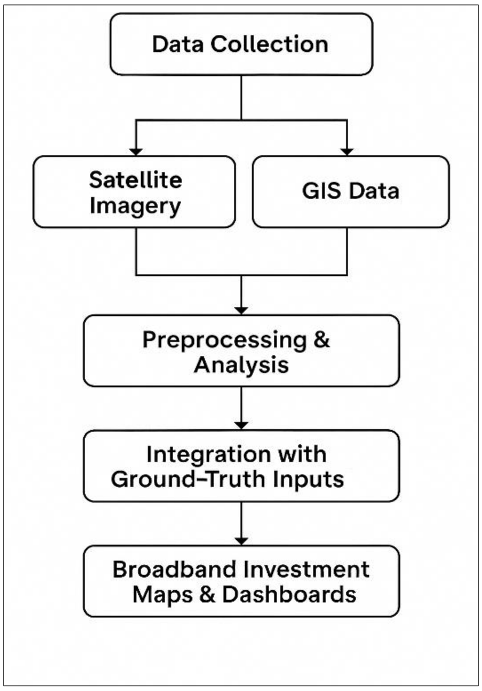

Figure 2 Workflow diagram of GIS and satellite data integration for broadband planning

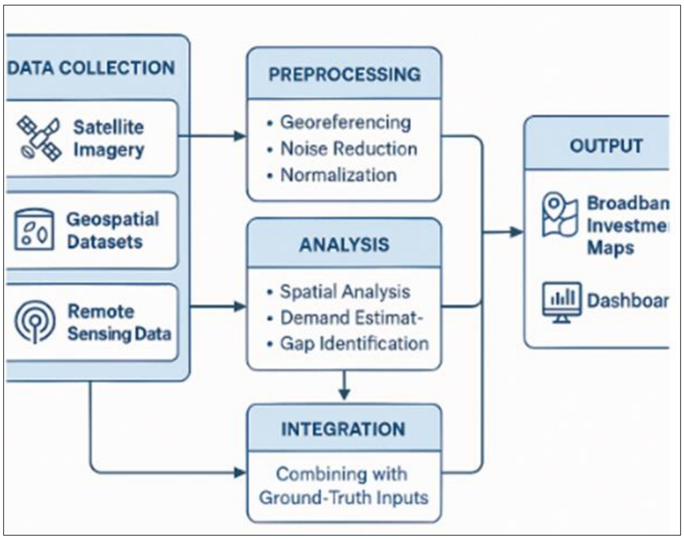

Figure 3 GIS and Satellite Data Integration

4. Methodology: identifying and prioritizing underserved areas

4.1. Data Sources: FCC Maps, Speed Test Aggregates, and Remote Sensing

Accurate broadband planning hinges on the reliability and integration of diverse data sources. Historically, the Federal Communications Commission (FCC) has served as the primary provider of broadband availability maps in the United States. However, its data collection practices have drawn criticism for overestimating coverage—particularly in rural areas—due to its reliance on Form 477 filings that mark entire census blocks as "served" even if only a single location has service [15].

To address these limitations, researchers and state agencies have increasingly turned to alternative and complementary data sets. Among the most widely adopted are speed test aggregates, which crowdsource real-time internet performance metrics from users across the country. Platforms such as Ookla, M-Lab, and Measurement Lab collect data on download and upload speeds, latency, jitter, and packet loss, geotagged to precise user locations [16]. These metrics not only validate FCC coverage claims but also reveal "underperformance zones" where internet service technically exists but fails to meet usability standards.

Remote sensing adds an observational layer that enhances traditional data with spatial context. High-resolution satellite imagery enables analysts to infer broadband demand based on settlement density, road networks, and built infrastructure [17]. In particular, indicators such as night-time light intensity, building footprints, and land cover classifications help refine assumptions about connectivity potential and population clustering.

Each of these data sources serves a specific purpose. FCC maps provide a regulatory baseline, speed tests reflect real-world user experience, and remote sensing captures the physical landscape and development patterns. When integrated through a Geographic Information System (GIS) platform, they allow planners to triangulate underserved zones with greater accuracy than any one source could offer independently [18].

Recent federal initiatives, including the Broadband Data Act and the NTIA's National Broadband Map, reflect this trend toward data fusion. These efforts incorporate provider-reported data, crowdsourced feedback, and satellite analysis into a unified framework, increasing both granularity and reliability [19]. By leveraging these diverse inputs, decision-makers can target investments with greater precision, maximizing the impact of limited broadband deployment funds.

4.2. Geostatistical Modeling to Identify Service Gaps

Once broadband data is collected, geostatistical modeling becomes essential to identify service gaps with analytical rigor. These models translate raw spatial data into interpretable outputs that highlight coverage disparities, project demand, and support infrastructure planning at varying scales. Common modeling techniques include kriging, spatial interpolation, and kernel density estimation, each tailored to account for geographic variability and spatial autocorrelation [20].

Kriging, a geostatistical method that estimates values in unobserved locations based on surrounding observations, is particularly useful for interpolating speed test results in areas lacking direct measurements [21]. For example, in rural counties where few households submit speed tests, kriging can estimate probable service quality by analyzing distance-weighted inputs from nearby locations. This yields continuous coverage maps that help visualize performance beyond isolated data points.

Spatial regression models further enable planners to evaluate how geographic features—such as elevation, road proximity, or housing density—influence broadband availability. These models often incorporate demographic variables, including income and education levels, to predict the likelihood of digital exclusion within specific census tracts or ZIP codes [22].

Machine learning algorithms like random forests and gradient boosting are increasingly employed to model service gaps by learning complex, nonlinear relationships between spatial and non-spatial features. These approaches are particularly effective when integrating satellite imagery and speed test data, enabling automated classification of underserved regions with high predictive accuracy [23].

In addition, hot spot analysis helps identify clusters of poor connectivity by comparing local values against global averages. This method is valuable for targeting neighborhoods within cities where digital redlining or systemic underinvestment has left pockets of low service surrounded by better-connected areas [24].

The output of geostatistical models often feeds into decision-support dashboards used by local governments, broadband offices, and grant-making agencies. These visual tools transform technical models into user-friendly formats that guide funding allocations and infrastructure priorities.

Ultimately, geostatistical modeling offers a scalable and data-rich approach to broadband planning. By combining mathematical precision with spatial insight, these models bridge the gap between raw data and actionable intervention, enabling more equitable and efficient distribution of digital resources.

4.3. Decision Criteria: Population Density, Infrastructure Cost, and Impact Scores

Determining where to expand broadband infrastructure involves a strategic balancing of need, cost, and impact. To guide this process, planners rely on decision criteria that quantify potential return on investment, social equity outcomes, and implementation feasibility. Three of the most important metrics include population density, infrastructure cost, and impact scores, each of which plays a critical role in site selection and prioritization [25].

Population density is a foundational criterion because it affects both demand and delivery economics. High-density areas offer economies of scale, allowing providers to serve more users with fewer resources. However, many rural regions with low densities are those most in need of connectivity, requiring policy frameworks that balance efficiency with inclusion [26]. GIS-based density mapping enables planners to identify clusters of homes or community anchors (like schools and clinics) where broadband expansion would serve concentrated populations.

Infrastructure cost assessments estimate the financial outlay required to deploy broadband technologies—such as fiber optic lines, fixed wireless, or satellite terminals—based on distance, terrain, and existing infrastructure. These cost models often incorporate elevation data, road networks, and utility corridors to predict construction complexity and material needs [27]. Lower-cost areas may be prioritized for quick wins, while high-cost regions may require alternative technologies or phased deployment strategies.

Impact scores synthesize multiple variables—such as poverty rates, educational attainment, health service availability, and unemployment rates—into a single index that reflects the social and economic benefits of broadband access. This ensures that investments target areas where digital inclusion can yield transformative community outcomes [28]. Impact scoring also supports equity by directing funds toward historically marginalized or economically distressed regions.

To operationalize these criteria, many agencies use multi-criteria decision analysis (MCDA) frameworks. MCDA allows decision-makers to assign weights to different factors based on policy goals, enabling transparent and adaptable prioritization [29]. For example, a state broadband office may assign higher value to areas with low-income populations than to pure cost-efficiency, reflecting social justice priorities.

Integrated into geospatial platforms, these decision criteria help create clear, replicable, and defensible strategies for broadband expansion. They ensure that funding decisions are not only data-driven but also socially responsive, maximizing the return on public investment while closing long-standing digital gaps.

Table 2 Scoring matrix used to prioritize expansion areas

Criterion	Weight (%)	Scoring Range	Description
Population Density	30	1–5	Higher scores for concentrated populations
Infrastructure Cost	25	1–5	Lower scores reflect higher deployment costs
Impact Score	30	1–5	Based on poverty, education, and healthcare indicators
Proximity to Anchors	10	1–5	Includes schools, hospitals, libraries
Current Service Level	5	1–5	Higher scores for currently unserved or underserved areas

5. Case studies of data-driven broadband expansion

5.1. Appalachia: Targeting Remote Settlements Using LIDAR and Terrain Models

The Appalachian region of the United States, characterized by rugged mountains, winding valleys, and dispersed rural settlements, presents unique challenges to broadband deployment. Traditional mapping methods often underestimate service gaps due to the area's complex topography and sparse infrastructure documentation. To address these limitations, planners have turned to Light Detection and Ranging (LIDAR) and terrain modeling as key tools for identifying and reaching unconnected communities [19].

LIDAR systems, deployed via aircraft or drones, emit laser pulses that bounce off surfaces to generate precise elevation models. These models allow analysts to construct detailed three-dimensional maps of terrain, vegetation, and built structures. In Appalachia, LIDAR reveals nuances such as deep hollows and dense canopies that obscure line-of-sight connections, especially for fixed wireless technologies [20]. This data is critical for determining where fiber installation is feasible and where alternative technologies, such as satellite or hybrid mesh networks, may be required.

By overlaying Digital Elevation Models (DEMs) onto settlement data, GIS platforms can predict the path of least resistance for broadband infrastructure while accounting for slope, water bodies, and geological obstacles. This level of detail improves cost estimation, project planning, and route selection, reducing the risk of expensive surprises during construction phases [21].

In addition to elevation mapping, terrain-based models also enable visibility analysis—an essential step for wireless tower placement. Planners can simulate signal propagation to determine which homes or clusters fall within coverage zones, helping to reduce coverage gaps caused by obstructive terrain [22]. This simulation supports precise targeting of towers or fiber routes, conserving resources and maximizing coverage efficiency.

Appalachian states such as Kentucky and West Virginia have piloted broadband expansion programs that incorporate LIDAR and terrain analysis with considerable success. These efforts are often combined with crowd-sourced speed test data and local road mapping to validate predicted service gaps and optimize deployment sequences [23]. Funding agencies increasingly require such granular planning to qualify for rural broadband grants.

Ultimately, using advanced terrain analytics ensures that broadband planning in Appalachia adapts to the physical realities of the landscape. Rather than relying on generalized assumptions, decision-makers are now empowered with tools that reveal hidden needs, reduce planning errors, and facilitate sustainable infrastructure investment in one of the nation's most underserved and topographically challenging regions.

5.2. Indigenous Territories: Blending Local Knowledge with Satellite Mapping

Broadband access on Indigenous lands in the United States remains among the most inequitable in the country, with over one-third of households on tribal lands lacking high-speed internet [24]. Standardized planning approaches have repeatedly failed to capture the complexities of these regions, where jurisdictional boundaries, infrastructure gaps, and cultural priorities require more nuanced solutions. A growing number of initiatives now combine satellite mapping technologies with local knowledge systems to guide broadband deployment in a way that respects tribal sovereignty and addresses real-world conditions [25].

High-resolution satellite imagery—particularly data from Sentinel and PlanetScope satellites—provides baseline information on housing density, road networks, and natural barriers across tribal territories. These images are used to identify infrastructure gaps and inform connectivity feasibility studies. However, satellite imagery alone may overlook informal settlements, seasonal structures, or culturally significant zones not visible from above [26].

This is where Indigenous knowledge systems play a pivotal role. Community-led mapping efforts involve tribal elders, local planners, and residents who ground-truth satellite data with firsthand observations. These collaborative efforts validate imagery-based assessments and ensure that connectivity plans do not conflict with sacred lands, wildlife migration paths, or traditional land-use patterns [27]. For example, tribes in Arizona and New Mexico have used participatory GIS workshops to mark broadband priority zones based on community needs, not just top-down algorithms.

Satellite-derived tools like Normalized Difference Vegetation Index (NDVI) also help identify areas where environmental constraints—such as soil erosion or flood risk—may affect infrastructure durability. When paired with tribal climate adaptation plans, these tools ensure that broadband projects are resilient to local ecological dynamics [28]. Moreover, terrain-sensitive analyses, similar to those used in Appalachia, are especially important for high-elevation or forested tribal regions.

Institutional partnerships further enhance this blended approach. Organizations like the Indigenous Connectivity Institute and Internet Society work with tribes to train local technicians, develop culturally aligned policy frameworks, and facilitate access to federal programs like the Tribal Broadband Connectivity Program [29]. These initiatives help ensure that infrastructure investment aligns with both technical feasibility and community-defined goals.

Blending satellite technologies with Indigenous expertise fosters both digital equity and self-determination. It transforms broadband planning from an extractive process into a participatory one—where the people most impacted by connectivity gaps are central to the data, analysis, and decision-making process. This shift is critical for closing the digital divide in a way that affirms cultural integrity and empowers tribal nations.

5.3. Urban Digital Deserts: Identifying Low-Income Unconnected Zones in Cities

While the digital divide is often portrayed as a rural issue, many of the most persistent connectivity gaps exist within America’s cities. Urban digital deserts are characterized by low-income neighborhoods that, despite being physically proximate to broadband infrastructure, lack reliable, affordable, or high-speed service. These underserved pockets often result from a combination of digital redlining, unaffordable service plans, and the systemic exclusion of low-income renters from infrastructure investment strategies [30].

Identifying these urban gaps requires fine-grained data that goes beyond provider coverage maps. GIS heatmaps integrating speed test results, income data, and housing tenure reveal stark patterns: neighborhoods with high poverty rates, majority Black or Latino populations, and high renter occupancy consistently exhibit lower connectivity rates—even when surrounded by connected zones [31]. These findings reflect decades of underinvestment in infrastructure and a market-driven model that deprioritizes areas with perceived low return on investment.

In cities like Detroit, Philadelphia, and Cleveland, speed test maps overlaid with FCC service data demonstrate how census blocks marked as “served” often contain entire streets with download speeds under 10 Mbps. These discrepancies are especially pronounced in multifamily housing units, where outdated wiring, lack of landlord participation, or service plan restrictions leave residents functionally unconnected [32].

Heatmapping techniques make use of kernel density estimation to visualize intensity patterns of digital exclusion. When layered with American Community Survey (ACS) data, these maps reveal not just where gaps exist, but whom they affect—providing policymakers with a powerful tool for equity-oriented planning. For example, combining broadband adoption rates with school-age population densities helps prioritize areas where children are most at risk of falling behind due to limited digital access [33].

Beyond residential gaps, digital deserts also manifest in the lack of broadband infrastructure in small businesses, community centers, and shelters. In response, some cities have implemented digital equity dashboards that integrate geospatial data with infrastructure audits to track progress in closing urban broadband gaps. These platforms enable coordination across departments, from education to housing, ensuring that digital access is considered in every urban development plan [34].

Solutions for urban digital deserts must consider both physical infrastructure and affordability. Municipal broadband initiatives, public Wi-Fi hotspots, and subsidy programs are increasingly paired with geospatial planning tools to ensure they reach high-need communities. However, these efforts must also contend with entrenched commercial barriers, including exclusive provider contracts and building access limitations.

By visualizing digital inequality at the block level, cities can better align interventions with community needs. GIS, when combined with disaggregated socio-demographic data, not only makes invisible gaps visible—it redefines urban broadband strategy as a matter of civil rights, economic opportunity, and inclusive growth.

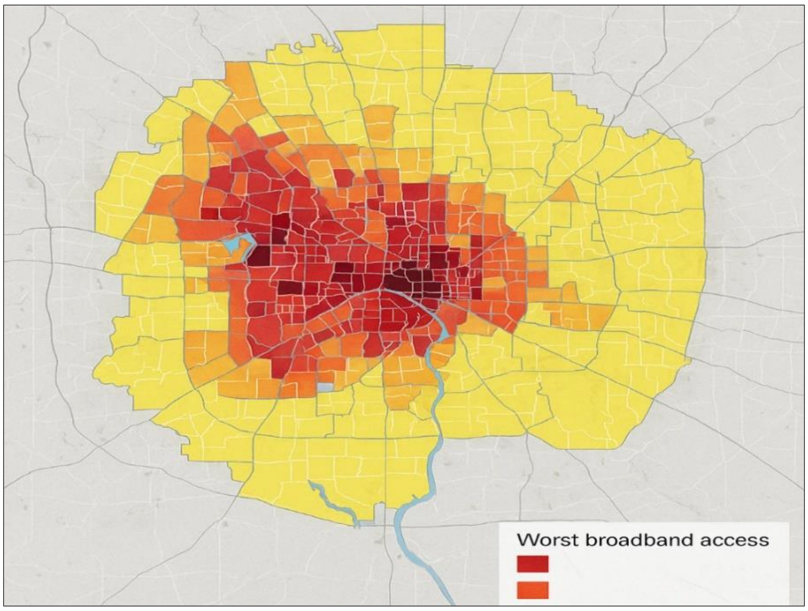

Figure 4 GIS heatmap of broadband gaps in a major U.S. metropolitan area

6. Policy implications and strategic planning

6.1. The Disconnect Between Federal Maps and Real-World Experience

Despite recent advances in broadband policy and funding, a persistent gap remains between federal coverage maps and the lived digital realities of millions of Americans. The Federal Communications Commission (FCC), through its Form 477 reporting system, has long been the primary source for determining broadband availability and funding eligibility. However, this system allows providers to declare entire census blocks "served" if even one location within the block has service, thereby overstating actual access [23].

This mapping limitation has resulted in substantial misallocations of resources, where communities officially marked as connected are denied critical infrastructure funding despite residents facing slow or nonexistent service. The discrepancy is especially pronounced in rural areas, multifamily housing units, and tribal lands, where granular detail is essential for accurate assessment [24]. Local officials and community organizations frequently report widespread service complaints in "served" zones, undermining confidence in the FCC's mapping approach.

Moreover, the federal maps often fail to reflect nuanced connectivity challenges such as service reliability, latency, and affordability. These qualitative indicators, while harder to capture, significantly impact the practical usability of internet service in marginalized communities [25]. Residents may technically be connected but experience speeds far below minimum thresholds, rendering the service functionally unusable for education, telehealth, or remote work.

To bridge this disconnect, many states and municipalities have turned to crowd-sourced speed test data, satellite analysis, and geospatial platforms that capture on-the-ground conditions in near real-time. Tools such as the National

Broadband Map and NTIA's Indicators of Broadband Need dataset now complement FCC maps, offering more detailed insight into actual service availability and performance [26].

The divergence between federal data and local experiences has fueled a growing call for reform. The Broadband DATA Act of 2020, for instance, mandates the use of address-level mapping and public feedback mechanisms to improve accuracy. Still, the success of such reforms depends on integrating diverse data sources—especially geospatial intelligence—that reflects the complexity of digital exclusion. Without such alignment, funding and policy decisions will continue to fall short of addressing the true scope of the broadband divide.

6.2. Regulatory Opportunities for Integrating Geospatial Intelligence

The growing importance of geospatial data in broadband planning presents a unique opportunity for regulatory reform. Federal and state agencies now have the technical capacity and public mandate to incorporate spatial intelligence into policy design, funding criteria, and accountability frameworks. Geospatial data not only enhances transparency and precision but also supports long-term planning in ways that traditional methods cannot [27].

At the federal level, the FCC and the National Telecommunications and Information Administration (NTIA) can standardize the use of satellite imagery, speed test aggregates, and GIS-based demographic overlays as part of official broadband maps. Doing so would enable a more holistic evaluation of connectivity conditions, especially in regions historically misrepresented by provider-reported data [28]. Regulatory guidelines could require ISPs to submit network coverage polygons validated against third-party datasets, introducing an independent check on coverage claims.

The integration of address-level data collection, enabled by geocoding and parcel analysis, allows regulators to verify service availability at the individual dwelling or building level. This granular data is essential for addressing digital redlining in urban areas and for targeting remote locations in rural communities that are otherwise excluded due to census block generalizations [29].

States are also positioned to lead in adopting geospatial intelligence. Broadband offices in California, North Carolina, and Georgia have developed publicly accessible GIS dashboards that integrate housing data, population density, and infrastructure layers to guide local deployment efforts. Regulatory bodies can support these initiatives by aligning grant reporting requirements with spatial performance indicators, such as coverage per square mile or population served per fiber mile [30].

Another regulatory frontier involves cross-agency data sharing. Health departments, education agencies, and transportation authority's maintain geospatial datasets that can be leveraged to inform broadband prioritization. For example, aligning school district boundaries or public health shortage areas with broadband maps ensures that underserved populations are systematically identified [31].

By embedding geospatial analytics into regulatory practice, governments can foster a culture of evidence-based decision-making. This reduces the risk of political or provider-driven distortions and ensures that infrastructure funding is allocated according to need, not assumption. Integrating geospatial intelligence is not merely a technical enhancement—it is a governance imperative for equitable broadband access in the digital age.

6.3. Funding Models and Resource Allocation Based on Spatial Equity

Traditional funding models for broadband expansion often prioritize population counts or cost-efficiency, inadvertently reinforcing service disparities by sidelining high-need but low-density or low-income areas. To correct this imbalance, emerging approaches now emphasize spatial equity—allocating resources based on the geographic distribution of digital need rather than sheer population or provider reach [32].

Spatial equity frameworks assess where digital gaps overlap with other indicators of disadvantage, such as poverty rates, educational attainment, public health deficits, or disability prevalence. These metrics are mapped through GIS platforms and layered with infrastructure and connectivity data to generate composite scores for prioritizing investment [33]. This approach ensures that infrastructure dollars reach communities where broadband access has the greatest potential to alleviate structural inequities.

Programs like the Broadband Equity, Access, and Deployment (BEAD) Program exemplify this shift. BEAD requires states to develop five-year action plans grounded in local data, community input, and geospatial analysis. It explicitly encourages targeting "unserved and underserved" areas, defined not only by speed thresholds but also by affordability, adoption, and reliability metrics [34].

Funding models that incorporate spatial equity use multi-criteria decision frameworks to balance infrastructure cost against social benefit. For instance, a mountainous rural community may be expensive to reach but could receive priority if it ranks high on digital disadvantage indices. These models are increasingly automated through decision-support systems that process large volumes of spatial and socioeconomic data to produce ranked investment maps [35].

State-level programs have also introduced point-based scoring systems that reward applicants for reaching high-need areas as identified through geospatial intelligence. For example, Wisconsin's Public Service Commission assigns additional points for projects that serve tribal lands, public housing, or school districts with low broadband adoption rates. These scoring systems create clear incentives for equity-focused deployment [36].

Resource allocation based on spatial equity helps bridge the gap between funding mechanisms and social outcomes. It ensures that broadband policy becomes a tool for reducing inequality, not reinforcing it. As connectivity becomes synonymous with opportunity, funding models that respond to geographic and demographic realities are critical to building a digitally inclusive future [37].

Table 3 Review of federal and state programs with geospatial components in eligibility criteria

Program Name	Administering Body	Geospatial Requirement	Focus Area
BEAD (Broadband Equity, Access, and Deployment)	NTIA	GIS-based state planning and underserved mapping	Nationwide broadband expansion
Tribal Broadband Connectivity Program	NTIA	Must identify eligible tribal land using GIS overlays	Indigenous connectivity
California Advanced Services Fund	California Public Utilities Comm.	Requires mapping of low-adoption zones and anchor sites	State-level urban/rural infrastructure
North Carolina GREAT Grant Program	NC Department of Information Tech.	Prioritizes underserved areas using spatial scoring	Rural broadband deployment
Wisconsin PSC Broadband Expansion Grant	Public Service Commission of WI	Point-based priority for tribal/public housing projects	Equity-focused rural expansion

7. Future directions and technological innovations

7.1. AI and Predictive Modeling in Connectivity Forecasting

Artificial Intelligence (AI) is reshaping how governments, providers, and analysts forecast broadband demand and plan infrastructure deployment. Traditional models, relying on census data or static growth projections, often fail to anticipate rapid urbanization, migration patterns, or shifting household technology needs. In contrast, AI-driven models can incorporate real-time and high-volume datasets to generate adaptive forecasts that reflect ground realities more accurately [38].

Machine learning algorithms, particularly random forests and neural networks, are now trained on diverse variables—ranging from building permit data and school enrollment trends to traffic flows and mobile device activity. These models can identify emerging broadband demand zones by detecting correlations between digital device proliferation and usage patterns across geographies [39]. The result is a more precise understanding of where internet infrastructure will be needed, both now and in the near future.

In rural and suburban settings, AI systems are particularly useful for modeling future service uptake. By analyzing factors such as land parcel development, proximity to employment centers, and topographical constraints, AI can forecast broadband adoption rates and simulate infrastructure rollout scenarios [30]. These insights help providers avoid over- or underbuilding, improving both efficiency and equity in resource allocation.

Importantly, predictive modeling can also enhance funding decisions. AI-generated connectivity forecasts enable federal and state programs to prioritize investment in regions that may not yet be underserved but are projected to face digital exclusion within a few years due to growth trends or infrastructure degradation [31]. When integrated with GIS platforms, AI strengthens broadband policy by turning complex data into actionable forecasts—advancing proactive, rather than reactive, decision-making.

7.2. The Promise of Low Earth Orbit (LEO) Satellites in Bridging Remote Gaps

Low Earth Orbit (LEO) satellite constellations are emerging as a powerful complement to terrestrial broadband infrastructure, particularly in hard-to-reach or prohibitively expensive areas. Unlike traditional geostationary satellites that orbit at approximately 36,000 kilometers, LEO satellites operate between 500 and 2,000 kilometers, allowing for lower latency and higher bandwidth potential [32]. These attributes make them a viable solution for rural and Indigenous communities, mountainous terrain, and post-disaster scenarios.

Companies such as Starlink, OneWeb, and Amazon’s Project Kuiper are at the forefront of LEO deployments, offering subscription-based broadband services that bypass terrestrial limitations. Their global coverage capacity means that areas long excluded from fiber and cable investments can now receive internet access with only a satellite dish and power supply [33]. This leap in accessibility could revolutionize digital inclusion for the most isolated populations.

Recent pilot programs have demonstrated promising outcomes. In parts of Alaska and northern Canada, LEO satellite service has delivered consistent speeds exceeding 100 Mbps, significantly outperforming previous technologies in those regions [34]. These early successes highlight LEO’s role as not merely a stopgap, but as a core element of long-term broadband strategy.

However, challenges remain. LEO infrastructure depends on clear sky visibility and reliable power sources, both of which can be limited in low-income or disaster-prone regions. Additionally, subscription costs—currently higher than subsidized terrestrial alternatives—must be addressed to ensure equitable adoption [35].

Still, LEO satellites represent a transformative opportunity. Their rapid scalability, combined with AI-optimized routing and ground station placement, positions them as essential to closing the final connectivity gaps. As technology matures and costs decline, LEO solutions will likely become integral to national broadband plans focused on inclusive

7.3. Emerging Open-Access Mapping Platforms for Civic Participation

As digital equity becomes a mainstream policy goal, open-access mapping platforms have emerged as vital tools for community participation in broadband planning. These platforms allow residents, nonprofits, and local governments to visualize coverage, submit feedback, and challenge inaccurate provider claims—all in real-time [36]. The democratization of broadband data ensures that decision-making is informed by those directly affected by connectivity gaps.

Tools like the National Broadband Map, M-Lab’s Measurement Dashboard, and Internet Equity Initiative's maps integrate crowd-sourced speed test results, infrastructure data, and demographic overlays. Users can explore internet quality by zip code or census tract, identify underserved areas, and compare multiple providers’ service levels [37]. In turn, this visibility pressures providers to improve service and offers policymakers evidence to target investments more equitably.

Importantly, many platforms include built-in functions for public comment and challenge submissions, allowing users to contest “served” status in grant applications or funding decisions. This level of transparency improves regulatory oversight and builds public trust [38].

As broadband access becomes a prerequisite for civic engagement, education, and economic mobility, open-data mapping platforms ensure that communities are not just recipients of policy—but active co-authors. They empower local voices in shaping an inclusive digital future.

8. Conclusion

8.1. Summary of Key Insights

This article has explored how geospatial intelligence, artificial intelligence, and participatory data tools are reshaping broadband planning in the United States. The persistent digital divide—particularly pronounced in rural, Indigenous, and low-income urban communities—demands a shift from traditional mapping and policy models toward more inclusive, precise, and data-informed approaches. Historical underinvestment, flawed FCC reporting systems, and siloed planning efforts have left millions without reliable internet access, perpetuating systemic inequities.

Geographic Information Systems (GIS), satellite imagery, and remote sensing now offer detailed visibility into underserved areas. When combined with speed test data, terrain models, and predictive analytics, these tools empower planners to target high-need areas with surgical precision. From Appalachia's remote hollows to urban digital deserts and tribal nations, case studies show that integrating local knowledge with modern data science creates a powerful foundation for equitable infrastructure deployment.

Moreover, the adoption of low Earth orbit (LEO) satellite networks and the rise of open-access mapping platforms offer scalable solutions and civic engagement pathways that can accelerate national broadband equity. Moving forward, sustained impact will require that policymakers, communities, and industry adopt shared frameworks grounded in spatial justice, ensuring that digital access is treated as a universal right, not a market privilege.

8.2. Reaffirming the Importance of Geospatial Equity

At the heart of effective broadband expansion lies the principle of geospatial equity—the recognition that where people live should not determine whether they are connected. Geospatial tools uncover not only who lacks access, but where and why. By revealing patterns of exclusion and opportunity, they allow planners to direct resources where they are most needed, rather than where they are easiest to deploy.

Equity in digital infrastructure must account for the diverse geographic and cultural contexts of American communities. Urban cores, rural backroads, tribal lands, and immigrant neighborhoods all face distinct challenges. A one-size-fits-all strategy cannot succeed. Instead, policies must be tailored through spatially grounded analysis that respects both the data and the lived experiences behind it.

Reaffirming geospatial equity means embedding it into every layer of broadband planning—from eligibility criteria to funding formulas—so that digital access becomes not just widespread, but fair and future-ready.

8.3. Call to Action: From Maps to Meaningful Access

The tools to close the digital divide now exist. What remains is the collective will to use them strategically, inclusively, and urgently. Policymakers must act on the insights provided by geospatial data, predictive modeling, and community mapping to transform static maps into actionable blueprints for universal connectivity.

Funding decisions must be transparent, equitable, and grounded in spatial evidence. Federal and state agencies should prioritize projects that serve historically marginalized communities, empower local planning capacity, and integrate real-time monitoring to ensure lasting outcomes. Industry partners must also embrace data sharing and accountability, recognizing that public trust is essential to long-term viability.

Most importantly, communities must remain at the center of this transformation. Civic mapping platforms, broadband planning workshops, and local advisory boards should not be exceptions—they must become the norm. From maps must come meaningful access—where every household, regardless of geography, can connect, participate, and thrive in a digital society.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Sawada M, Cossette D, Wellar B, Kurt T. Analysis of the urban/rural broadband divide in Canada: Using GIS in planning terrestrial wireless deployment. Government Information Quarterly. 2006 Jan 1;23(3-4):454-79.

[2] Grubesic TH, Murray AT. Constructing the divide: Spatial disparities in broadband access. Papers in regional science. 2002 Apr;81:197-221.

[3] Akhtar MS, Mathur G, Kravchenko O, Rakhra M. Connecting the unconnected: bridging the digital divide with affordable satellite through enabled smartphones. InE3S Web of Conferences 2023 (Vol. 453, p. 01054). EDP Sciences.

[4] Hambly H, Rajabiun R. Rural broadband: Gaps, maps and challenges. Telematics and Informatics. 2021 Jul 1;60:101565.

[5] Ahmad M, Humnekar TD, Maqsood M, Chemingui H. OpenStreetMap Empowering Digital Infrastructure for Emerging Markets. InConverging Economic Policy, Corporate Strategy, and Technology for Emerging Economies 2025 (pp. 155-174). IGI Global Scientific Publishing.

[6] Olaniyan J. Balancing cost and security: Affordable IT solutions for small businesses facing social engineering risks. International Journal of Research Publication and Reviews. 2024 Dec;5(12):1551–63. Available from: https://doi.org/10.55248/gengpi.5.1224.3559

[7] Ugwueze VU, Chukwunweike JN. Continuous integration and deployment strategies for streamlined DevOps in software engineering and application delivery. Int J Comput Appl Technol Res. 2024;14(1):1–24. doi:10.7753/IJCATR1401.1001.

[8] Oyana TJ. Exploring geographic disparities in broadband access and use in rural southern Illinois: Who's being left behind?. Government Information Quarterly. 2011 Apr 1;28(2):252-61.

[9] Heimann C, Minnie S, Abrams MC. UMGCINI-Empowering Rural Communities through Geospatial Data and Digital Connectivity. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. 2025 Mar 12;48:59-64.

[10] Chukwunweike JN, Chikwado CE, Ibrahim A, Adewale AA Integrating deep learning, MATLAB, and advanced CAD for predictive root cause analysis in PLC systems: A multi-tool approach to enhancing industrial automation and reliability. World Journal of Advance Research and Review GSC Online Press; 2024. p. 1778–90. Available from: https://dx.doi.org/10.30574/wjarr.2024.23.2.2631

[11] Martin N, Dogar F. Divided at the Edge-Measuring Performance and the Digital Divide of Cloud Edge Data Centers. Proceedings of the ACM on Networking. 2023 Nov 28;1(CoNEXT3):1-23.

[12] Adedeji Omolola M. Histone deacetylase 2 (HDAC2) inhibitors: advancements in cognitive enhancement and potential therapeutics for neurodegenerative diseases (2025). Int J Eng Technol Res Manag ;9(4):143. Available from: https://doi.org/10.5281/zenodo.15186576

[13] Leidig M, Teeuw RM. Quantifying and mapping global data poverty. PloS one. 2015 Nov 11;10(11):e0142076.

[14] Khan S, Butt UF. GIS as a planning tool for the USF Co rural telecom and E-service project in Pakistan. Procedia-Social and Behavioral Sciences. 2011 Jan 1;19:11-20.

[15] Adebowale OJ. Battery module balancing in commercial EVs: strategies for performance and longevity. Int J Eng Technol Res Manag. 2025 Apr;9(4):162. Available from: https://doi.org/10.5281/zenodo.151866212

[16] Lambrechts W, Sinha S, Lambrechts W, Sinha S. Bridging the Digital Divide: Innovative Last Mile Internet Connectivity Solutions. Last Mile Internet Access for Emerging Economies. 2019:1-40.

[17] Worden D, Hambly H. Willingness to pay and pricing for broadband across the rural/urban divide in Canada. Telecommunications Policy. 2022 Mar 1;46(2):102247.

[18] Ashuri B, Guhathakurta S, Koo BW, Shahandashti M, Mistur E, Oh HJ, Stanovski L, Bani-Hani A, Darghiasi P. Sustainable and Equitable Innovative Funding Strategies for Enhancing Broadband Initiative in Underserved and Disadvantaged Communities. Center for Transportation, Equity, Decisions and Dollars (CTEDD)(UTC); 2023 Nov 20.

[19] Ruimy D. Broadband connectivity in rural Canada: overcoming the digital divide. Canada: House of Commons; 2018 Apr.

[20] Okeke CMG. Evaluating company performance: the role of EBITDA as a key financial metric. Int J Comput Appl Technol Res. 2020;9(12):336–349

[21] Chukwunweike Joseph, Salaudeen Habeeb Dolapo. Advanced Computational Methods for Optimizing Mechanical Systems in Modern Engineering Management Practices. International Journal of Research Publication and Reviews. 2025 Mar;6(3):8533-8548. Available from: https://ijrpr.com/uploads/V6ISSUE3/IJRPR40901.pdf

[22] Abdallah L. Sustainability Impacts of Satellite Internet: Digital Inclusion vs Environmental Sustainability.

[23] Olaniyan J. Leveraging IT tools to safeguard customer data from social engineering threats. International Journal of Research Publication and Reviews. 2024 Dec;5(12):1564–75. Available from: https://doi.org/10.55248/gengpi.5.1224.3560

[24] Lincaru C, Pirciog S, Grigorescu A, Tudose G. Low-Low (LL) high human capital clusters in public administration employment-predictor for digital infrastructure public investment priority-Romania case study. Entrepreneurship and Sustainability Issues. 2018 Dec 1;6(2):729.

[25] Martin N, Dogar F. Measuring latency reduction and the digital divide of cloud edge datacenters. arXiv preprint arXiv:2304.05481. 2023 Apr 11.

[26] Barton CE, Amory-Mazaudier C, Barry B, Chukwuma V, Cottrell RL, Kalim U, Mebrahtu A, Petitdidier M, Rabiu B, Reeves C. eGY-Africa: Addressing the digital divide for science in Africa. Russian Journal of Earth Sciences. 2009;11(1):1-5.

[27] Olaniyan J. The role of employee training in combating social engineering attacks on small businesses. International Research Journal of Modernization in Engineering Technology and Science. [Internet]. 2025 ; Available from: https://www.doi.org/10.56726/IRJMETS65055

[28] Young JC, Lynch R, Boakye-Achampong S, Jowaisas C, Sam J, Norlander B. Volunteer geographic information in the Global South: barriers to local implementation of mapping projects across Africa. GeoJournal. 2021 Oct;86(5):2227-43.

[29] Yuguchi K. The digital divide problem: An economic interpretation of the Japanese experience. Telecommunications Policy. 2008 Jun 1;32(5):340-8.

[30] Ahmad M, Ali A, Hussain H. Spatial Data Infrastructure for Effective Information Management: A Case Study of Pakistan. InEssential Information Systems Service Management 2025 (pp. 251-278). IGI Global.

[31] Pelumi Oladokun; Adekoya Yetunde; Temidayo Osinaike; Ikenna Obika. "Leveraging AI Algorithms to Combat Financial Fraud in the United States Healthcare Sector." Volume. 9 Issue.9, September - 2024 International Journal of Innovative Science and Research Technology (IJISRT), www.ijisrt.com. ISSN - 2456-2165, PP:- 1788-1792, https://doi.org/10.38124/ijisrt/IJISRT24SEP1089

[32] Cullinan J, Flannery D, Harold J, Lyons S, Palcic D. The disconnected: COVID-19 and disparities in access to quality broadband for higher education students. International Journal of Educational Technology in Higher Education. 2021 Dec;18:1-21.

[33] Forati AM, Ghose R. Examining Community Vulnerabilities through multi-scale geospatial analysis of social media activity during Hurricane Irma. International Journal of Disaster Risk Reduction. 2022 Jan 1;68:102701.

[34] Olasehinde A. Biodegradable growth media alternatives for sustainable hydroponic farming. Curr J Appl Sci Technol. 2025 Feb;44(3):147-152. doi: 10.9734/cjast/2025/v44i34506.

[35] Dawson K. Bridging the Digital Divide: Using Ecological Modeling to Enhance Adult Student Recruitment and Retention in Higher Education.

[36] Olayinka OH. Data driven customer segmentation and personalization strategies in modern business intelligence frameworks. World Journal of Advanced Research and Reviews. 2021;12(3):711-726. doi: https://doi.org/10.30574/wjarr.2021.12.3.0658

[37] Oakland A. Minnesota's digital divide: How Minnesota can replicate the Rural Electrification Act to deliver rural broadband. Minn. L. Rev.. 2020;105:429.

[38] Elijah Olagunju. Cost-Benefit Analysis of Pharmacogenomics Integration in Personalized Medicine and Healthcare Delivery Systems. International Journal of Computer Applications Technology and Research. 2023;12(12):85–100. Available from: https://doi.org/10.7753/IJCATR1212.1013

[39] Mbah Geraldine O, Sanni Ismail Oluwasola. Navigating the 50-state privacy maze: Startup strategies to avoid legal pitfalls. Int J Sci Res Arch. 2025;15(01):746-764. Available from: https://doi.org/10.30574/ijsra.2025.15.1.1065