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Evaluation of ICT Deployment in Mountainous Regions: Assessing Telephone Service Efficiency in The Aurès Mountains, Algeria

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Information and communication technology clearly affects regional development in several aspects, most notably facilitating access to services. This has led to its widespread adoption, which faces significant geographical and social obstacles that limit its efficiency. This study aims to assess the state of information and communication technology in the Aurès Mountains of Algeria, with a particular focus on the structure of telephone services in order to illustrate the challenges that hinder regional development. The current situation of telephone communication infrastructure in the area was analysed using geographic information systems, in addition to the construction of a weighted spatial regression model to demonstrate the relationship between the efficiency of telephone services and network coverage variables. The findings revealed that the existing infrastructure is constrained by the challenges of terrain and by social factors related to unequal population density and distribution. Based on these aspects, solutions were proposed to improve the effectiveness of telephone services, with an emphasis on addressing the identified gaps to enhance regional development through strategic actions by decision-makers, thereby improving access to services and contributing to bridging the digital divide in the future.

Keywords: Aurès Mountains; Algeria; coverage towers; Geographically Weighted Regression; telephone services; Viewshed analysis; Weighted Overlay

I. INTRODUCTION

Information and communication technology is one of the key components of regional development and has become an integral part of modern life (Roberts *et al.*, 2017). This is due to its contribution to improve the quality of life and enabling residents to easily access various essential services (Hidalgo & Rodríguez-Sickert, 2008). It also plays a significant role in reducing the gap between urban and rural areas (Hauptman *et al.*, 2023), especially in the latter, considering their limited geographical, social, and economic potentials, which pose a barrier for developing infrastructure and digital service levels. This has led to an implicit bias from decision-makers and economic partners towards urban areas at the expense of geographically and socially isolated rural areas (Inkpen & Wilson, 2013). In this context, rural areas have focused on developing the field of wired and wireless communications as it is the most widespread area in information technology, with mobile phone ownership recorded at around 80% worldwide and about 66% in Africa. Internet usage has also registered around 65% globally and

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38% in Africa (ITU, 2024). These figures highlight the spatial disparity in the rates of benefiting from information technology services and the differing factors affecting their efficiency from one region to another.

This is evident from previous studies, including the study by (Hauptman *et al*., 2023) that discussed digitisation in rural areas in Slovenia, focusing on the development steps and the digital divide. It concluded that the telecommunications infrastructure has a significant impact on controlling the digital divide. Meanwhile, the study by (Espinoza & Reed, 2018) found that the topographical features of mountainous areas contribute to increase costs of distributing telecommunications networks and improving their service, and it represent a range of alternative solutions. According to (Sawada *et al*., 2006), geographic information systems play a major role in the proper planning for the deployment and distribution of wireless communication services in Canada and in reducing the gap between urban and rural areas. In 2016 (Liu, 2016). evaluated the sustainability of IT programs in developing countries, focusing on Sichuan, China, and found that isolated rural areas remain dependent on economic operators and commercial interests. A study conducted by (Imran *et al*., 2024) addressed the geographical challenges faced by these isolated rural areas, leading to increase costs of service provision and improvements, paving the way for the inclusion of sixth-generation services in the near future. A study by (Mwantimwa, 2020) found that geographic isolation, high costs, and inadequate infrastructure posed barriers for accessing information services in Tanzania. Similarly, a study conducted by (Hussein *et al*., 2011), titled "Spatial Analysis in Mobile Communication Services in Egypt Using Geographic Information Systems", highlighted the relationship between service efficiency and population density in urban areas, suburbs, industrial and tourist regions. (Omogunloye *et al*., 2013) found that the main barrier to the optimal distribution of towers and coverage lies in the varying heights of the city, which resulted in well-covered areas and others that lack coverage. Meanwhile, the study by (Habibi *et al*., 2017) focused on measuring and analysing the quality of mobile phone services in Afghanistan from the user's perspective, concluding that service quality and prices positively affect user satisfaction. In the study by (Al-Ani Al-Issawi *et al*., 2018) titled "The Efficiency of Spatial Distribution of Communication Network Services in Al-Rutbah District Using Geographic Information Systems," the researchers focus on analysing the spatial distribution of coverage towers. The study found that there are vast areas deprived of services due to the numerical limitation of coverage towers.

In Algeria, the telecommunications sector is among the fields included in the state's plans for development. The mobile phone market in Algeria consists of three operators: Algeria Telecom Mobilis, Ooredoo, and Djezzy with an estimated total of 49.26 million subscribers in 2024, which represents 104.35% of the total population, according to the report from the Ministry of Post and Telecommunications (MPT, 2024) Despite these numbers and indicators being theoretically acceptable, there are still significant regional discrepancies, especially concerning the geographical characteristics of each area and the resulting variations in service levels in general and coverage in particular, which implicitly affect call quality and internet speed, especially in areas with difficult terrains.

The Aurès region in Batna province has diverse topographical and social characteristics since it's a mountainous area (Soto *et al*., 2024). It's been inhabited since ancient times (Côte & Zeraib, 2019), making it an important case for study. Given the widespread communication services since 2000-2023, the number of subscribers across various networks has seen rapid growth due to several variables that directly affected the recorded numbers locally, reaching about 167,136 subscribers, which is 97.07% of the total population of the region. This highlights the significant importance of telephone services in the daily lives of the Aurès residents. Therefore, the central question of this study is: What are the levels of efficiency in the spatial distribution of telephone coverage in the Aurès region, and how does it affect the efficiency of telephone services?

This study aims to assess information and communication technology in mountainous areas, focusing on telephone services, which are considered the most important and widespread indicators. It involves analysing the current mountainous infrastructure using Geographic Information Systems (GIS) and the spatial challenges that hinder the ideal provision of services, along with potential opportunities for improvement. This is aimed at ensuring comprehensive social and economic development that meets the aspirations of local residents.

II. METHODS AND MATERIALS

A. Introducing the Study Area

The Aurès region is located in the eastern part of the Saharan Atlas mountain range, bordered by the high plains of Constantine to the north and the Ziban region to the south. Geographically, it lies between the latitudes of 35° 0' 0'' and 35° 30' 0'' North, and the longitudes of 5° 50' 0'' and 6° 40' 0'' East (Figure 1).

Figure 1. Location of study area

Administratively, it belongs to the province of Batna and includes six administrative districts: Arris, T'kout, Ichemoul, Teniet El Abed, Bouzina, and Menâa, along with seven municipalities: Oued Taga, Inoughissen, Foum Toub, Ghessira, Tighanimine, Tigharghar, and Chir., covering an area of 2051.51 km². To the north, it is bordered by Tazoult and Timgad (municipalities that belong to Batna Province), while to the east it shares a border with Khenchela Province, and the western and southern borders are with Biskra Province (Hamzaoui *et al.*, 2025).

The region can be divided into several topographical units, primarily represented by the mountains that extend in all directions, the most significant being Mount Ashmoul at 2100 metres, and Mount Al-Mahmal at 2321 m. These mountains appear almost parallel and form their slopes and bases, which serve as a habitat for some urban centres and act as natural barriers between them. The second unit consists of basins, with elevations ranging from 1100 metres to 1300 m, oriented from North-East to South-West. This includes the White Valley basin, which represents the axis of the Eurasian landmass (Côte & Zeraib, 2019). Its area is estimated at around 1292 km², while the Abdi Valley basin has an area of about 832 km², becoming narrower as we follow the valley's course. The third unit consists of plains, which are wide alluvial plains in the Northern part that narrow as we head South, the most important of which are Bouzina Plain, the Energy Valley, and Foum Etoub. Due to its location nestled among the mountain ranges, these plains have considerable elevations reaching up to 1100 m. From this, we can say there is a variation in the topographical units in the study area, dominated by mountainous terrain, making it a highly rugged region.

The area is characterised by a semi-arid climate with a cold wet winter and a hot dry summer, noted for its irregularity and extreme variability in precipitation (Soto *et al.*, 2024).

B. Methodological Approach and Analysis Tools

A descriptive analytical approach was adopted in the study. Spatial data from national databases and aerial imagery were collected to analyse the distribution and ratios of coverage towers. Annual reports from telecom companies and the Ministry of Postal Services and Communications were used to obtain subscriber numbers, annual growth rates for each operator, and coverage ratios. Information on call quality and internet service was gathered through interviews and field investigations. The efficiency of telephone services in the study area was evaluated by integrating Geographic Information Systems (GIS) techniques with the Geographically Weighted Regression

(GWR) model, focusing on the spatial distribution of coverage towers.

1.Kernel Density Estimation – KDE

This method is widely used in analysing infrastructure networks and is considered one of the most important techniques for assessing the density distribution of point phenomena and identifying irregular spatial patterns (Eaglin *et al*., 2017). Accordingly, the distribution of mobile coverage towers in the study area was evaluated to determine active zones with dense tower concentration and areas with insufficient coverage.

Initially, the kernel function was specified, and the Gaussian Kernel was selected due to its efficiency in handling data, which strongly supports the interpretation of spatial results (Zheng *et al*., 2019). The bandwidth selection was then determined using an adaptive bandwidth (Adaptive KDE) to analyse the impact of each tower on surrounding areas, considering the uneven distribution of towers and the significant influence of topographical factors and population distribution (Davies & Lawson, 2019). Finally, a coverage variance map was produced to identify areas requiring improvement in mobile infrastructure.

2. Viewshed analysis

The aim is to identify areas with good coverage and blind spots where coverage is lacking since communication signals (both wired and wireless) spread according to the law of direct propagation. This requires an unobstructed line of sight to effectively reach the intended target with good strength (Aben *et al*., 2018). Signal coverage for thirty-six communication towers was analysed using the viewshed tool in ArcGIS 10.8, following these steps:

First, the coordinate reference system was set to the WGS84 projection system. The projected coordinate system applied was 'UTM Zone 31° North.' A projected reference coordinate system was required because viewshed analysis in geographic information systems involves distance calculations, which are most accurately performed within a projected system (Musa *et al*., 2024). Second, the locations of coverage towers were identified as points for analysis along with their technical specifications. Tower height was set at 30 m, and the transmission radius was defined to range between 5 and 10 km depending on each tower's technical capacity. In addition, the horizontal viewing angle was adjusted between 0° and 360°, while the average height of a person holding a phone was set at 1.75 m. Third, the digital elevation model (DEM) with a spatial resolution of 30 m was incorporated, obtained from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/).

3. Weighted overlay

The Weighted Overlay technique based on Geographic Information Systems was then applied (Kuru & Terzi, 2018). After the covered areas and blind spots were identified, the main criteria and sub-criteria affecting signal propagation and phone coverage efficiency were integrated. These included the results from the Viewshed technique, population density distribution, slope, elevation, and the proximity of towers to the road network, which was determined by applying the Euclidean distance feature. The specified weights of the criteria and the ratings of the sub-criteria, obtained with the assistance of experts and specialists from relevant stakeholders, were used as shown in (Table 1). In the final stage, a classification of the main criteria was prepared and adapted for the overlay process, enabling the identification of priority intervention areas and the creation of a comprehensive map of regions requiring improved coverage.

Table 1. Criteria and sub-criteria ratings used in weighted overlay analysis

Criteria	Subcriteria	Average Score	Average Weight
Viewshed Results	Fully visible	5	35%
	Visible	4	
	Moderate visibility	3	
	Not visible	2	
	Totally invisible	1	
Population density	Very High	4	25%
	High	3	
	Moderate	1	
	low	2	
	Very low	5	
Slope	<5%	4	15%
	5%-10%	3	
	%10-%25	5	
	%25-%40	2	
	>40%	1	
Elevation	Very High	2	15%
	High	4	
	Moderate	5	
	low	3	
	Very low	1	
Proximity of towers to roads (m)	>1000	5	10%
	1001-3000	4	
	3001-5000	3	
	5001-7000	2	
	<7000	1	

4. *The geographically weighted regression (GWR)*

In this study, Geographically Weighted Regression (GWR) was employed to analyse the efficiency of mobile phone coverage in a mountainous area, taking into account the geographic and social variables that influence its quality. GWR was selected because it enables the analysis of relationships between the dependent variable and independent variables while incorporating spatial variations, making it more suitable than ordinary least squares regression models (Wheeler, 2021). The annual increase in the number of subscribers was designated as the dependent variable, as it represents the most significant indicator of service availability and local variation, in addition to being the indicator for which data were available in the study area.

Regarding the independent variables, population density was included as an indicator of demand for mobile services, reflecting its influence on both the increase in the number of users and the local distribution of towers. Areas lacking coverage, derived from the statistical results of the Weighted Overlay technique, were also incorporated as a critical variable, since the annual increase in the number of subscribers in mountainous regions is primarily associated with coverage availability, making this relationship fundamental in the modelling process. In addition, the variable of call and internet quality, obtained from field surveys, was integrated, given its significant influence on subscription decisions and, to a lesser extent, on the choice of service provider.

After the inputs were set up in ArcGIS 10.8, the adaptive kernel type was selected because the data in the study areas were spatially heterogeneous (da Silva & Fotheringham, 2016). To determine the optimal bandwidth and ensure a balance between model accuracy and complexity, the corrected Akaike Information Criterion (AICc) was applied. The performance of the GWR model was evaluated using the following assessment indicators: Local R^2, to measure the proportion of variance in the dependent variable explained by the independent variables locally; Residuals, which were analysed using Moran's I test, alongside a visual inspection to assess homogeneity of variance and examine the error distribution in order to ensure the absence of spatial autocorrelation that could indicate omitted variables or model inadequacy (da Silva & Fotheringham, 2016); and Local regression coefficients, which were employed to analyse the local impact of each independent variable on the dependent variable.

III. RESULTS AND DISCUSSION

A. Analysis of Subscribers' Number Development from 2000 to 2023

Due to the widespread availability of communication services in the study area during the period from 2000 to 2023, the number of subscribers in various telecom companies experienced rapid growth influenced by several variables that directly affected the recorded figures. In about 2006, the number of subscribers was around 14,450, which is the reference year for the period from 2000 to 2006. Out of this, the share of Djezzy was 9,769 subscribers, accounting for 67.14% of the total subscribers, making it the top company in the study area, thanks to its leadership in mobile phones and relatively better coverage compared to other competitors. Meanwhile, Algeria Telecom (Mobilis) registered 2,822 subscribers, representing 19.52% of the total subscribers, placing it in second position due to its relative newness in the field, while Ooredoo came in third with 1,859 subscribers, also at 19.52% of the total, as the company was quite new at that time and faced limitations in coverage and offerings.

The period from 2006 to 2014 saw a significant increase in mobile phone usage due to numerous offers and strong competition among operators and businesses. The cost of using a phone became affordable for everyone, especially in terms of pricing. By around 2014, the number of subscribers reached about 90,450, with Algerie Telecom (Mobilis) registering 53,758 subscribers, accounting for 59.34% of the total subscribers, placing it in first place ahead of Ooredoo and Djezzy, which recorded 18,615 and 18,077 subscribers, with 20.58% and 19.98% of the total subscribers respectively. This was due to significant investment in infrastructure by Algerie Telecom (Mobilis) and attractive offers, especially for employees across various sectors, which led most people to use two mobile lines at the same time. Ooredoo advanced to second place at the expense of Djezzy, which experienced an unexplained slowdown in its investment activities, as shown in (Figure 2).

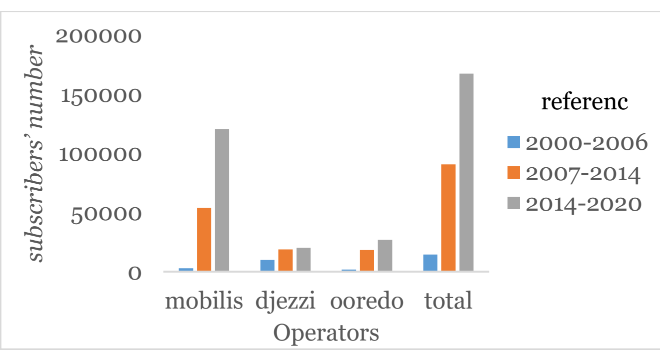

Figure 2. subscribers' number development in the study area from 2000 to 2023

From 2014 to 2023, there was a rapid growth in the number of subscribers across various telecom companies, reaching around 167,136 subscribers by 2023. Of these, Mobilis had 120,337 subscribers, making up 71.99% of the total, followed by Ooredoo with 26,718 subscribers, which is 15.98% of the total. In third place was Djezzy with 20,081 subscribers, accounting for 12.01% of the total during this period. The ranking of the companies remained unchanged due to a fairly consistent activity regarding investments in infrastructure, coverage levels, and very similar offerings.

B. Spatial Distribution Analysis of Coverage Towers

1. Kernel Density Estimation – KDE

The kernel density tool was used to identify the concentration of mobile towers in the study area by relying on the locations of the towers and the broadcasting radius of each tower. After creating map number 02, it was observed that active areas are concentrated around the main urban centres, including areas like Arris, Ishmoul, T'kout, Oued Taga, and Bouzina, in addition to Tniet El Abed. These municipalities have a high population density, with the active area percentage in these municipalities ranging from 10.35% to 20.48% of the total area (Figure 3). On the other hand, the municipality of Tigharghar was an exception, showing a significant concentration of coverage towers, given that most of its area consists of mountains. As for the municipalities of Ghessira, Foum Toub, Tighanimine, Inoughissen, and Chir, they fall within areas of average to low activity levels, due to the concentration of towers in main urban centres and a sort of neglect towards isolated rural areas. The percentage of area for these ranges is between 31% and 62% of the total area, and these municipalities experience a lack of total alignment between active areas, population density, and the distribution of people.

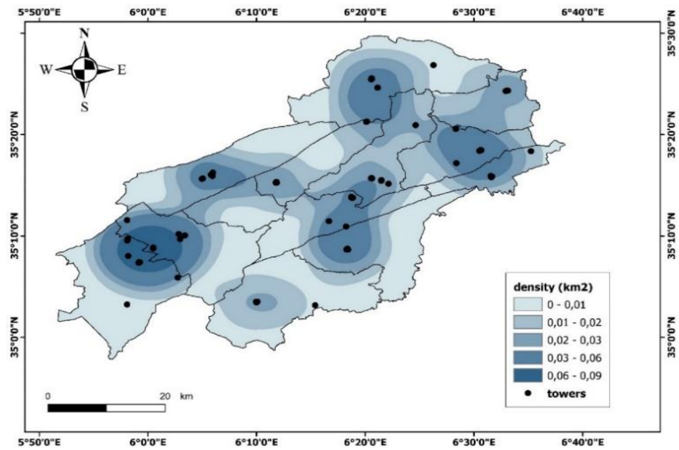

Figure 3. Kernel Density of coverage towers in study area

2. Analysis of visibility fields for the towers in the study area

The viewshed analysis in GIS was used to determine the fields of view for each coverage tower and to approximate its true coverage area and the way terrain limits it. This was done by identifying the locations of the coverage towers as analysis points and including their technical dimensions. The model used a tower height of 30 m and transmission radius of 5–10 km (varying by tower capability), assuming an observer height of 1.75 m. Additionally, A 30 m-resolution digital elevation model was added to capture the terrain.

The results shown in map number 03 indicate that 1434.7 km² are non-visible areas, which accounts for 69.31% of the total study area, while the visible areas cover 635.3 km², representing 30.69% (Figure 4). This is attributed to the rugged topography of the area, where significant obstacles such as mountain ranges exist, in addition to the tower locations primarily concentrating in urban settlements and near road networks that are also affected by the terrain's ruggedness.

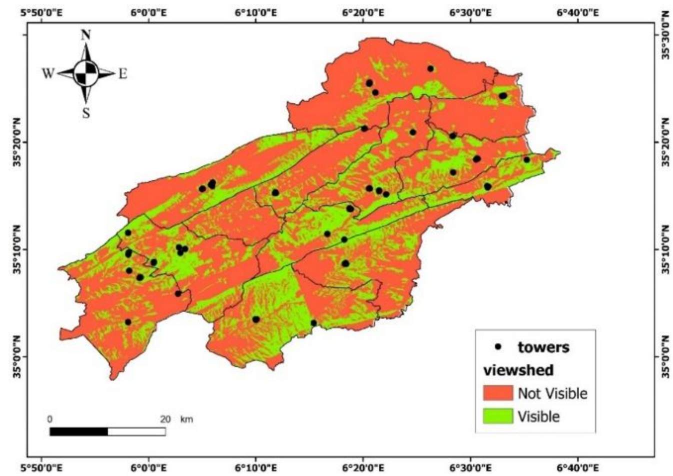

Figure 4. visibility fields for the towers in the study area

3. Weighted overlay analysis

Using a weighted overlay, the key factors that shape tower coverage were combined to pinpoint where new towers could be added to raise coverage levels. Based on the Viewshed results, a weight of 35% was assigned through field interviews with technicians at telecom companies, while population density was assigned a weight of 25%, elevation was then incorporated as a factor with a weight of 15%, and slope was also included with a weight of 15%, proximity to roads was added as a tower-related factor with a 10% weight. The five maps were then reclassified into five levels, yielding Map 04. Areas classified as very high to high coverage efficiency are shown in dark green and green (see Map 04), covers an area of 822.98 km², accounting for 39.75% of the total area, and is distributed uniformly with the road network and the basins formed in the midst of mountain ranges. Meanwhile, the medium level represented in yellow is the dominant one in terms of area, estimated at 1178.71 km², or 56.94% of the total area. The very weak levels represented in orange and red appear at the peaks of the mountain ranges and the study area's boundaries, covering an area of 68.30 km², which is 3.29% of the total area, and these are coverage-deficient areas that require intervention to improve coverage efficiency (Figure 5).

The comparison between the results of kernel density maps, viewsheds, and weighted overlays reveals that the current distribution of communication towers has not met expectations and does not take into account the actual needs of the area's residents. It was observed that the invisible area, representing 69.31%, is located within regions where towers cover 33.5% of the total area. Conversely, this area corresponds medium to very high priority zones in the weighted overlay map, accounting for approximately 60.23% of the total area.

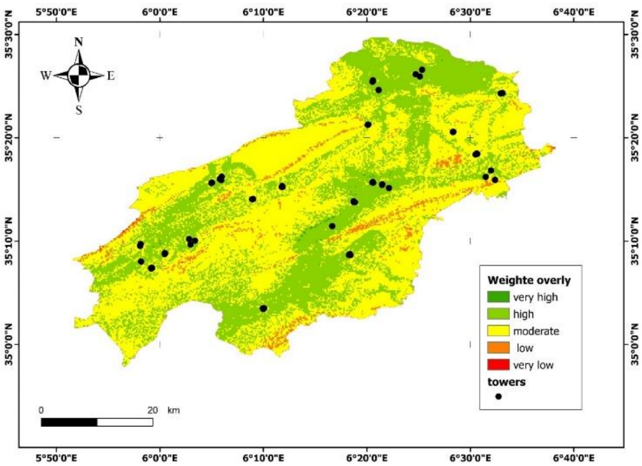

Figure 5. Weighted overlay analysis in the study area

C. Geographically Weighted Regression (GWR) Analysis

The model was executed as outlined above, and the results are summarised in Table 2. where the ideal distance (Bandwidth) used to determine the number of geographic points affecting each point is estimated at 6.35019. The value of Residual Squares is estimated at 8.042223, which is a low value indicating good accuracy of the model in representing the data. Meanwhile, the value of AICc is estimated at 49.255706, which is the low value that prompted us to select this specific model. Additionally, the R^2 value, estimated at 0.8238, indicates that 82.385% of the variance is explained by this model, while the Adjusted R^2 value, estimated at 0.764856, indicates the quality of the model and confirms its suitability after adjusting the number of independent variables.

Table 2. Geographically Weighted Regression results

VARNAME	VARIABLE	DEFINITION
Bandwidth	6.35019	
Residual Squares	8.042223	
Effective Number	4.010987	
Sigma	0.945871	
AICc	49.255706	
R^2	0.823858	
R^2 Adjusted	0.764856	
Dependent Field		Annual subscriber growth
Explanatory Field		Population Density
Explanatory Field		Percentage of uncovered areas
Explanatory Field		Quality of Calls and Internet

1. *Residual Analysis*

The hypothesis of a linear relationship between the annual increase in the number of subscribers as a dependent variable and population density, the percentage of areas lacking coverage, and the quality of calls and internet as independent variables was tested using residual analysis. This was based on Moran's I index to analyse the spatial pattern of the residuals produced by the model, and the results showed Moran's I = -0.262670, confirming the presence of a diverse spatial pattern of residuals. Additionally, locations with high values tend to be distributed away from those with low values. Z-SCORE found is equal to -1.213355, which falls within the non-significant statistical range, indicating no statistically significant spatial line in the model's residuals. Regarding P-VALUE = 0.224994, which is greater than 0.05, it suggests that the residuals are randomly distributed. These results indicate that the model is sufficient to explain the spatial variance of the dependent variable and that there are no unaccounted patterns affecting the model's performance. To verify homoscedasticity in this model, visual analysis of the residuals shown in Figure 6 (Residuals vs. Fitted Values Plot) was used, which confirms that the residuals are randomly distributed around the zero line without a clear pattern, thus meeting the condition of equal variance and reinforcing the model's validity.

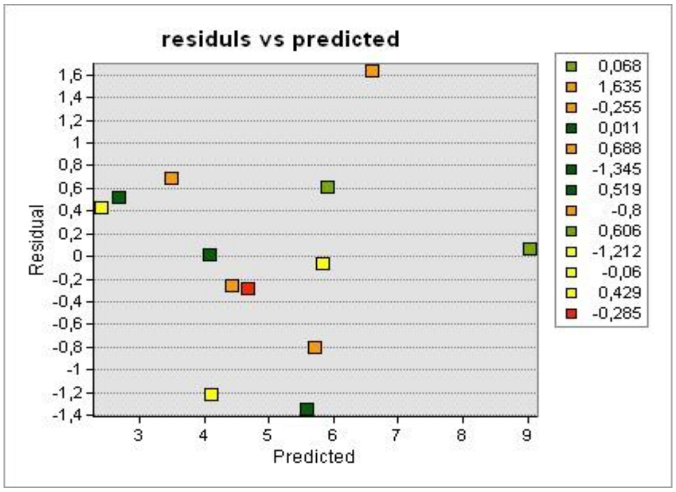

Figure 6. Residuals vs. Fitted Values Plot

2. *Local R² spatial distribution analysis*

The model's adequacy can be assessed at the level of the municipalities in the study area based on the results shown in map number 5. The Local R^2 values range from 0.823512 to 0.823608, indicating that the model struggles to explain the spatial variation in these municipalities. This difficulty arises due to the fact that these municipalities are located in a very rugged area, particularly in Tigharghar, Menaa, Chir, and Teniet Al Abed. These municipalities also have a low population density ranging from 28 to 54 residents per km². It was concluded that the nature of the terrain and the low population density have generated variable data, making it hard for the model to explain, which suggests the possibility of other variables contributing to the service efficiency level, like population concentration in major settlements and dispersed areas. These municipalities are considered rural agricultural municipalities with an urbanization rate between 32.7% and 39.4% of the total population.

On the other hand, the municipalities of Arris, T'kout, and Teniet Al Abed have Local R^2 values ranging from 0.823609 to 0.823682, reflecting a fair correlation between population density and coverage level of the network as well as call and internet quality as independent variables, with an annual increase in the number of subscribers as the dependent variable. This is due to a relatively consistent spatial spread of the service with various variables, as these municipalities are characterised by high population concentration, with Ares municipality, for example, having 92.13% of its total population located in the main settlement. This corresponds to a concentration of coverage towers that has contributed to improved coverage efficiency and, consequently, service efficiency.

Regarding the municipalities represented in red on the map, the Local R^2 values are higher than 0.823683, reflecting significant harmony between the independent variables and the dependent variable. These include the municipalities of Oued Taga and Fum Toub due to their relatively flat site characteristics, located on the northeastern slopes of the Aurès Mountains, as well as the municipalities of Ichmoul and Inoughissen, given the size of their populations and their distribution, which is largely consistent with the distribution of coverage towers (Figure 7).

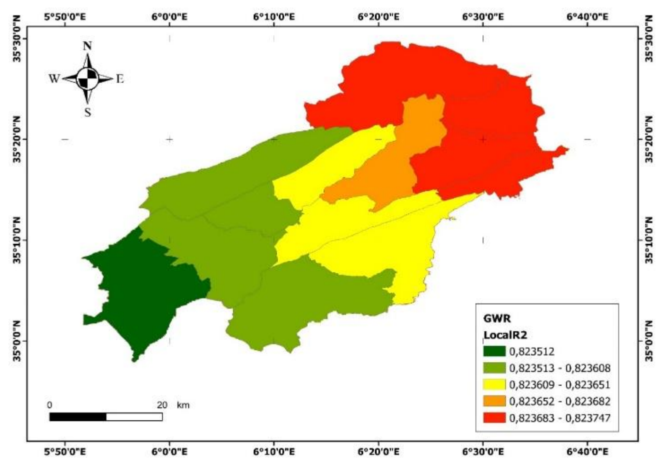

Figure 7. Local R² spatial distribution

3. *Local Coefficients spatial distribution Analysis*

Call and internet quality values for this variable range between 0.527270 and 0.525481, indicating a variation in effect across subscribers' municipalities with an average of 0.529575. A significant impact in the municipality of Tigharghar was observed, attributed to the area's steep topography and the uneven distribution of its population, which contributes to call drop rates and internet flow issues.

The distribution of areas lacking phone coverage shows spatial transaction values for this variable ranging between -2.339802 and -2.333152, which is a negative indicator; any increase in underserved and isolated regions contributes to a decrease in the annual growth rate of subscribers by -2.337150 on average. For this coefficient, we see a similar gradient in the levels of impact as in the previous coefficient due to the same reasons, leading to the conclusion that the effect of coverage rates on increasing the number of subscribers is inversely related.

Population density shows values for this coefficient ranging between 4.053155 and 4.056451, meaning that each unit increase in population density contributes to an annual increase in the number of subscribers by 4.05227 on average. The gradient of impact aligns closely with the spatial transactions of the previous variables.

Based on the spatial transactions derived from this model, the levels of phone service efficiency in the study area are concentrated in the northeastern region and contrast when moving to the southwestern region. This reinforces the results obtained in the spatial analysis of phone coverage and tower distribution (Figure 8).

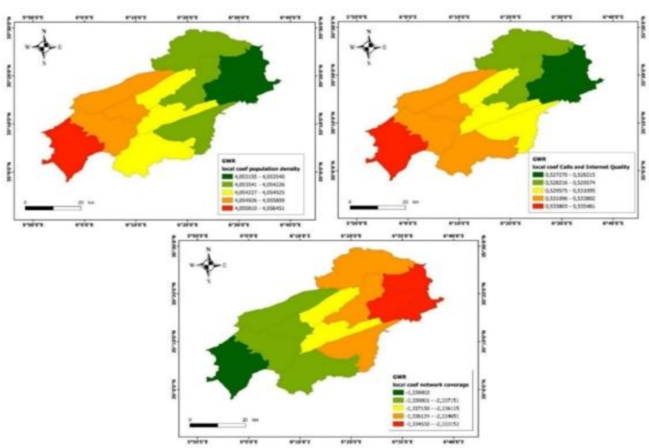

Figure 8. Local Coefficients spatial distribution

IV. CONCLUSION

This study assessed information and communication technology (ICT) by comprehensively analysing telephone-service efficiency within a mountainous setting. Kernel density estimation was used to map the spatial intensity of coverage towers, viewshed analysis was applied to delineate effective coverage under terrain constraints, and a weighted overlay integrated key determinants—population density, topographic slope, elevation, and the spatial relationship between towers and the road network. These procedures were designed to clarify how coverage is distributed and how geographic conditions shape service quality. Furthermore, a geographically weighted regression (GWR) was fitted, specifying the annual increase in subscriber numbers as the outcome and the extent of uncovered areas, population density, and call and internet quality as explanatory variables.

The results showed clear spatial variations in the distribution of phone coverage, primarily affected by the rugged terrain and slopes characteristic of the study area, as well as population density and the uneven distribution of residents relative to the area. Additionally, the planning of coverage towers does not meet the actual requirements for achieving the desired coverage. This underscores that topographical obstacles and socio-economic variables play a crucial role in determining the efficiency of phone service in particular and information and communication technology in general.

Based on these results, the need for sustainable solutions is emphasised to improve the efficiency of the phone network in mountainous areas. Furthermore, this study opens new avenues for research on how to apply smart technologies like machine learning to analyse and enhance the future performance of communication infrastructure in mountainous regions through:

An evaluative study of telecom tower sites based on spatial analysis aims to improve coverage in isolated areas to overcome challenges and topographical obstacles.

Relying on modern technologies to enhance coverage efficiency in low-density and rugged areas, small cells and signal boosters must be mentioned.

Encouraging investments in satellite communication technologies in areas that cannot be covered by existing networks.

Strengthening collaboration between telecom companies and local bodies by implementing network improvement projects according to local development priorities.

Regularly involving the local community in ongoing evaluations by opening communication channels that allow subscribers to report coverage issues, thus building an accurate database to assist in effective future planning.

Offering material and moral incentives to specialised companies and researchers in the field to develop and innovate solutions for communication problems in mountainous areas.

Developing and analysing more advanced models such as Adaptive GWR (Geographically Weighted Regression), which allows for a more precise understanding of local variations in telecom network efficiency across different regions.

Incorporating seasonal variables in spatial analysis and considering the impact of climatic factors like snow and heavy rainfall on overall service performance, while providing technical solutions to address these challenges.

Utilising artificial intelligence and machine learning to analyse mobile coverage levels and predict areas that might face issues in the future, relying on smart monitoring systems that track tower performance and detect faults to help shorten downtime.

Employing renewable energy solutions, such as solar power, to operate towers in areas without electricity, contributing to sustainable operation.

Working to combine spatial analysis models with economic models to study the financial returns of investments in improving communication infrastructure in mountainous regions.

Investigating the impact of 5G network deployment on coverage efficiency in mountainous areas, and whether it can provide solutions to current challenges.

Using advanced geographic information systems (GIS) for more accurate analysis of existing issues, which helps in making effective decisions regarding the distribution of telecom towers.

This study can be seen as a starting point that can be built upon in future research to develop communication networks in the study area specifically and in geographically isolated areas in general, aiming to enhance digital inclusion and provide ideal communication services for residents, regardless of the challenges they face.

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