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Georeferencing of exposure from EMF base stations in urban areas

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ABSTRACT

Background: In modern society, the use of sources that emits electromagnetic radiation (EMR) such as television, radio, mobile telephony, etc. constantly increases, resulting in a parallel increase in the stress of the general population, about the effects that may be caused to health. For this reason, EMR measurements and their evaluations should be communicated to the population to reduce misinformation and undue stress. The purpose of this work is to is to Georeferencing of Exposure to 4G and 5G Radiofrequency Electromagnetic Fields from mobile phones in Thessaly Region (Central Greece).

Methods: 220 measurements were performed in the region of Thessaly, in order to compare the electromagnetic exposure before and after 5G installation. A portable field strength analyzer (SRM 3006, Narda Safety Test Solutions, Pfullingen, Germany) and a three-axis isotropic antenna were used, and 4G and 5G electromagnetic radiation measurements were performed in 3 cities of Central Greece, in the region of Thessaly. We used GIS, especially Kriging algorithm to create electromagnetic environment maps.

Results: Before the installation of 5G, measurements conducted in the Thessaly region, in all cities (Larisa, Karditsa, Volos) showed an mean exposure ratio of 0.0003, with a median value of 0.0001. After the installation of 5G, measurements showed an mean and median exposure ratio of 0.0008.

Conclusions: The recorded exposure values within the Thessaly region consistently remained below the internationally recommended benchmark levels established by the ICNIRP. Consequently, there is no significant risk of electromagnetic radiation from mobile phones and base stations in sensitive lands (schools, kindergarten etc) located in the cities of Thessaly.

1. Introduction

The manner in which electromagnetic radiation interacts with matter is contingent upon its frequency, and various terms are employed to describe radiation based on its distinct physical characteristics. The electromagnetic spectrum spans the frequency range from low-frequency radio waves (radio, TV, communications) to high-frequency gamma waves (PET scan, diagnosis and therapy). (International Agency for Research on Cancer, 2013).

Technological advancements have led to an exponential expansion in the field of telecommunications. In recent decades, telecommunications have undergone a dramatic change in the nature of the system, speed, technology, and frequency. For example, mobile wireless networks started with the first analog generation of mobile telephony (1G), which was developed in the early 1980 s with limited features (analog voice) and continues to be developed in the newer generations 5G and 6G, which support almost instant communication and big data transfer without compromising on network efficiency. (Muheidat et al., 2022).

Given these technological developments, the presence of radio frequencies (RF) from wireless networks and other technologies has become ubiquitous. RF transmitters have become commonplace in homes, offices, and schools. (Alexias et al., 2020; Kiouvrekis et al., 2020) In terms of mobile communication, in 2020 the number of mobile users worldwide amounts to 6.95 billion and is estimated to reach 7.49 billion by

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2025, a number that represents approximately 91 % of the world's population. (Statista, 2023) Due to high demand, a huge number of communication networks interconnect societies around the world, and mobile wireless technology networks are growing significantly, especially after the development of 5G.

Numerous studies (Groves et al., 2002; Lagorio et al., 2021; Lönn et al., 2005; Schüz, 2011; Schüz et al., 2006; Takebayashi et al., 2008) have investigated whether there is a correlation between exposure to radiation from mobile phones and the occurrence of certain types of cancer or other diseases. Most of these studies have not found evidence of a correlation. Some studies have suggested a potential link between the use of mobile phones and brain cancer, but broader scientific assessments have not reached a unanimous conclusion. The general population is not sufficiently familiar with the concepts of electromagnetic radiation and combined with a lack of information, public fears about the effects of radiation on humans remain justified.

International organizations such as International Commission on Non-Ionizing Protection (ICNIRP) have established standards (ICNIRP, 2020) with the aim of protecting both the general population and professionals from electromagnetic radiation and the effects it can cause on health. These recommendations are adopted by the European Union and then it is up to each country whether to accept them exactly as they are or to modify them. In Greece, the safety limits for the general population are 30 % lower compared to the corresponding EU limits. For sensitive areas such as schools, hospitals, and nursing homes located within 300 m of an antenna station, the limits are reduced by 40 % compared to the EU standards.

The aim of this paper is to:

1. present the measurements and evaluations of electromagnetic radiation exposure to the population from 4G and 5G.
2. depict the results graphically applying Geographic Information Systems (GIS) methods, to evaluate the EM burden from all present EM sources by areas and not only by specific points.

GIS play a pivotal role in the production of electromagnetic exposure maps, offering a powerful tool for visualizing and analyzing the distribution of electromagnetic fields in our environment. GIS technology enables researchers (Al–Sahly et al., 2018.; Barrile et al., 2009; Gonzalez-Rubio et al., 2016; Nuckols et al., 2004; Pesaresi and Pavia, 2021; Ramirez-Vazquez et al., 2020) and professionals to collect, manage, and analyze spatial data related to electromagnetic emissions from various sources, such as base stations. By integrating datasets from multiple sources, GIS helps create accurate and informative exposure maps that assist in assessing potential health risks and making informed decisions regarding electromagnetic radiation levels in specific areas. This capability of GIS contributes significantly to our understanding and management of electromagnetic exposure, ensuring the safety of general population and especially children. (Nguyen et al., 2023; Ramirez-Vazquez et al., 2020; Rinaldi, 2009).

2. Materials and Methods

2.1. Calculation of electromagnetic field levels – Measurement system

A portable field strength analyzer (SRM 3006, Narda Safety Test Solutions, Pfullingen, Germany) and a three-axis isotropic antenna covering frequencies from 27 MHz to 6 GHz were used for environmental electromagnetic radiation measurements. The values displayed by the SRM-3006 during the measurement express the total electric field strength measured in V/m but also the contribution of all the individual RF sources.

The frequency selective measurements were performed according to the standard proposed by ICNIRP 2020. Three different heights corresponding to the exposed human body (110 cm, 150 cm and 170 cm) above the ground were measured for a period of 6 min each. At each location the average spatial intensity E_i of the electric field was recorded. The exposure ratios λ_{if} for each height i and each frequency range f were calculated from the equation (1), where $E_{i,f}$, is the electric field strength at height i for frequency band f, and $E_{L,f}$ the electric field reference level at frequency band f.

$$\lambda_{i,f} = \left(\frac{E_{i,f}}{E_{L,f}}\right)^2 \quad (1)$$

The average electric field for three heights intensity was also obtained from the spatial average electric field values at each height as follows:

$$E_{avg} = \sqrt{\frac{\sum_{i=3}^{3} E_i^2}{3}} \quad (2)$$

The total Electric Field Strength was calculated to consider emissions from all sources in the range of 27 MHz-3 GHz:

$$\mathrm{E}_{Total} = \sqrt{E_1^2 + \cdots + E_N^2} \quad (3)$$

The exposure ratio λ_f in the frequency band f is obtained as the mean value of the measurements over the three heights (equation 3).

$$\lambda_f = \frac{1}{3}\sum_{i=1}^{3} \lambda_{i,f} \quad (4)$$

Thereafter, the total exposure ratio Λ for the given measurement spot was derived as the sum of the exposure ratios λ_f in each frequency band f.

$$\Lambda_f = \sum_f \lambda_f \quad (5)$$

Λ is used to estimate the exposure of the population to electromagnetic fields, compared to the safety limits as defined in the current legislation.

2.2. 5G measurements procedure

Utilizing both theoretical insights and the innovative beamforming technique of 5G antennas, we performed measurements on 5G signal, at Karditsa and Bolos, cities in the Thessaly region. We perform 5G measurements with the same equipment (SRM 3006) as in 4G with a dynamic range of 0.14 mV/m to 160 V/m Table 1. In accordance with their established protocol, the laboratory recorded the 6-minute average and maximum electric field (E) values in distinct scenarios:

A. "Active": Activating a user equipment (mobile phone) it commenced downloading 4 K resolution YouTube content or/and performed a speed test.
B. "Non-active": The measurements were taken while the mobile phone continued to remain active without downloading any data from the Internet.

The aim was to evaluate the variation of electric field strength by simulating a scenario where a non-active user is close to an active user. Fig. 1..

The exposure stemming from 5G networks is anticipated to remain comfortably below the safety thresholds set by the ICNIRP 2020 guidelines, and this exposure level is comparable to that of older legacy

Table 1
RF Exposure Index for 4G electromagnetic radiation.

	Median	Mean
before	0,0001	0,0003

[1] Tables may have a footer.

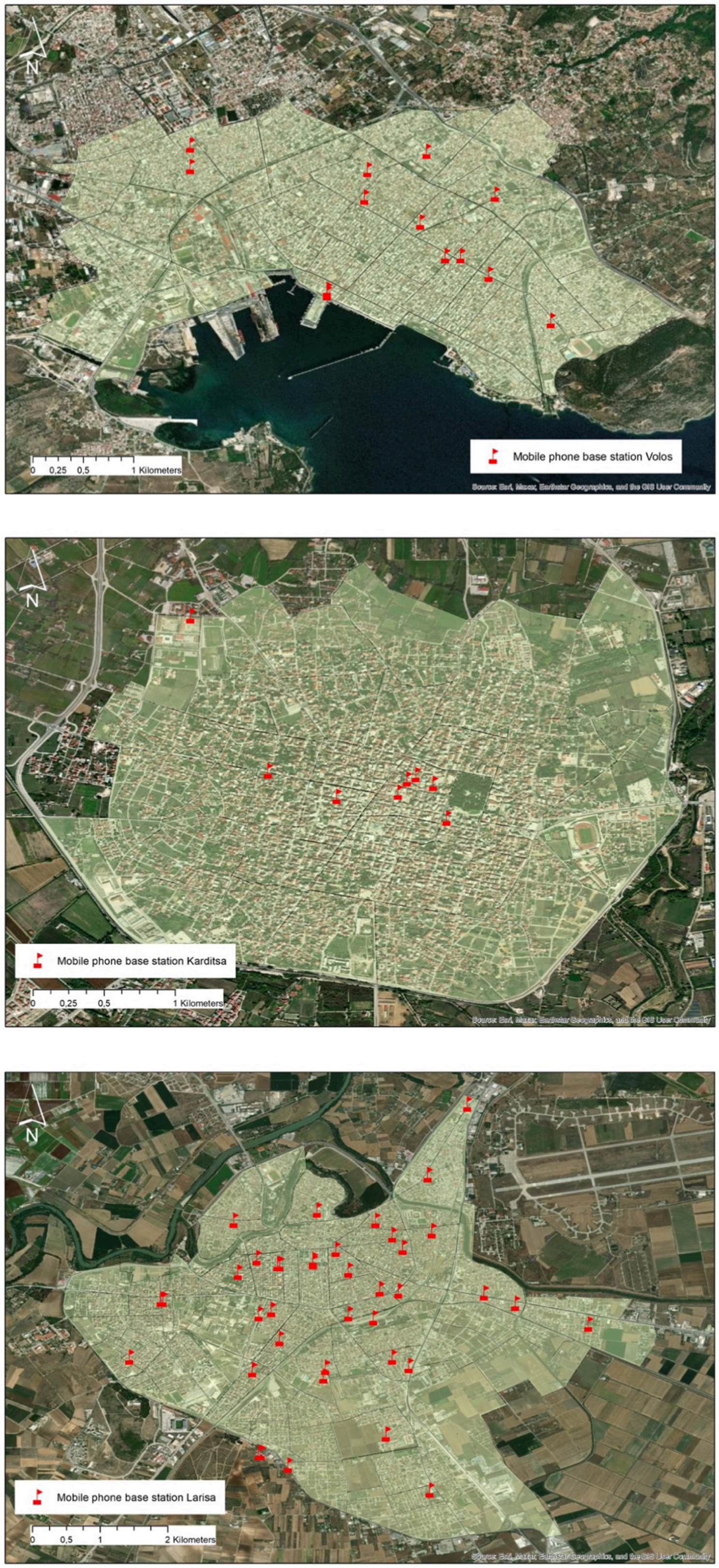

Fig. 1. Base stations of the three Thessaly cities.

technologies. This is facilitated by the beamforming phenomenon, which allows the electromagnetic field emitted by an antenna to be precisely directed towards the user, leading to a substantial reduction in exposure levels beyond the targeted beam.

Numerous international organizations and reputable laboratories have verified these estimations through comprehensive 5G exposure assessments conducted in real-world environments. The University of Thessaly has contributed to this body of research by conducting measurements encompassing frequencies up to 6 GHz, which includes the present 5G spectrum. These measurements affirm (Tyrakis, 2023) that the existing exposure levels remain consistent with those of legacy technologies and, crucially, remain well below the safety thresholds outlined by the ICNIRP 2020 guidelines.

2.3. Geospatial services – Geographic Information system

Various methods can be used to obtain reliable data about the intensity of the distribution of electromagnetic fields affecting the environment. One of these methods is mathematical modeling or the use of data visualization techniques applying informational technologies. Geographic Information Systems (GIS) are powerful spatial information platforms that can be used to develop digital maps of various topologies, graphically visualize spatial geodata, and obtain additional necessary data about the objects under study. (Faiz et al., 2023) They can integrate data from measurement tools and maps to support monitoring activities, help to identify and mitigate hazardous situations and convince to ensure a suitable quality of life by monitoring electromagnetic fields (EMF) from sources such as power lines and base stations. (Ghosh et al., 2011) When utilizing GIS, the outcome is usually an electromagnetic environment map, that can be seen as an abstract description of the electromagnetic spectrum environment with geographic information. The electromagnetic environment map is mainly constructed with various spatial interpolation algorithms, which can be classified into spatial statistics, spatial geometry, and function. Spatial statistics algorithms include Kriging. (Shan et al., 2018) Kriging is a stochastic spatial interpolation method that estimates the value of a phenomenon at unsampled locations. It does this by using a linear combination of observations of the phenomenon in the vicinity of the desired location. The weights of the linear combination are chosen to minimize the variance of the estimate. (Jawad et al., 2014) It provides the best linear unbiased estimates and information about the distribution of the estimation error, and it has strong statistical advantages over other interpolation techniques. (Wang et al., 2009).

The equation used for Kriging Spatial interpolation is:

$$z(x) = m + \sum_i w_i * z_i \tag{6}$$

where:

- $z(x)$ is the estimated value at point x
- m is the mean of the observations
- w_i are the kriging weights
- z_i are the observed values at the neighboring points.

The estimated value at point x is equal to the mean of the observations plus the weighted sum of the observed values at the neighboring points.

The kriging weights are calculated using the equation:

$$w_i = \left(\frac{1}{\sigma^2}\right) * \sum_j (z_i - m) * R(x - x_j) \tag{7}$$

where:

- σ^2 is the variance of the observations
- $R(x - x_j)$ is the semivariogram at the lag between point x and point x_j

The semivariogram is a measure of the spatial correlation between observations. It is calculated as the average of the squared differences between pairs of observations at a given lag.

APPLICATION STUDY: Region of Thessaly.

In the present study, the effect of mobile electromagnetic radiation on the human population in three different cities (Larissa, Karditsa, Volos) was calculated using the proposed framework. The measurements were conducted in schools of several educational levels across the three cities of Thessaly to demonstrate a safe and conductive learning environment for students physical and emotional health. The measurements were performed by SRM-3006 to evaluate radiofrequency exposure (27–3000 MHz and 27 MHz to 6 GHz) in areas of sensitive land use. A two hundred and twenty (220) measurements were carried out at the three cities of Thessaly and several urban/rural locations.

The following maps depict:

a) **in bold color**, the cities' surface and municipal boundaries, and
b) **with red flags**, the locations of base stations that affect the measurement points.

It was considered that, according to the inverse square law, antennas located at least 1000 m away from the measurement point do not pose a significant exposure risk to the measurements.

In order to create the electromagnetic environment maps, using the ArcGIS 10.8.1 software, each city was divided into polygon areas with defined boundaries, with regard to city block density and main roads. A polygon shapefile for each city was created.

Because the measurements of electromagnetic radiation in the areas were not continuous, Ordinary Kriging Interpolation in ArcGIS 10.8.1, was utilized to create continuous raster files for the three cities for 4G and 5G (when available) radiation. For the creation of the final maps, we calculated the average RF value for each polygon for every city for 4G and 5G radiation, using Zonal Statistics in ArcGIS 10.8.1. The values were then joined with the attribute table (database) of the polygon shapefile, for each city. The final maps are visualizations of the spatial distribution of the electromagnetic radiation, which can be used to evaluate the radiation levels at the cities (Fig. 2).

3. Results

3.1. Measurements before installation of 5G

Before the installation of 5G, measurements conducted in the Thessaly region, in all cities (Larisa, Karditsa, Volos) showed an mean exposure ratio of 0.0003, with a median value of 0.0001.

3.2. Measurements after installation of 5G

After the installation of 5G, measurements were conducted in the Thessaly region, specifically in the cities of Karditsa and Volos. The measurements were performed in two ways. Initially, with the mobile data actively in use (YouTube 4 K video), and then at the same location with the mobile data turned off. The mean and median values of the exposure ratios were calculated in Excel, and as observed in Table 2, they are the same.

In Figs. 3 and 4, the field strength and median values are represented before and after 5G activation for each point.

Mood's Median test was conducted using SPSS for two groups of data:

- before and non-active
- before and active

The significant level for both tests are $\alpha = 0.05$.

At the group before and non-active the p-value was 0.24 and the hypothesis was the following:

If $p > \alpha$ then no significant difference between the two samples. In other case ($p < \alpha$) then the two samples are different.

In this case $p > \alpha$ and there is no difference between before and non-active groups.

(Fig. 5).

At the group before and active the p-value was less than 0.001 and the hypothesis was the following:

If $p > \alpha$ then no significant difference between the two samples. In

Fig. 2. Map development process.

Table 2
RF Exposure Index for 5G electromagnetic radiation.

	Median	Mean
active	0,0008	0,0008
Non_active	0,0008	0,0008

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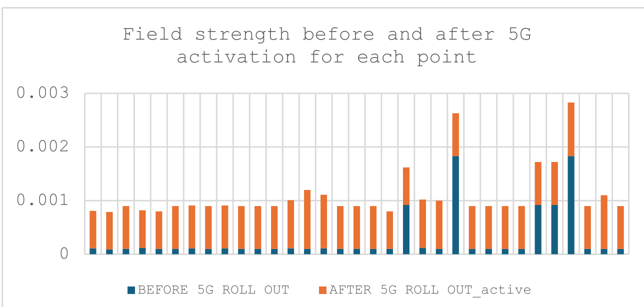


Fig. 3. Field strength before and after 5G activation for each point.

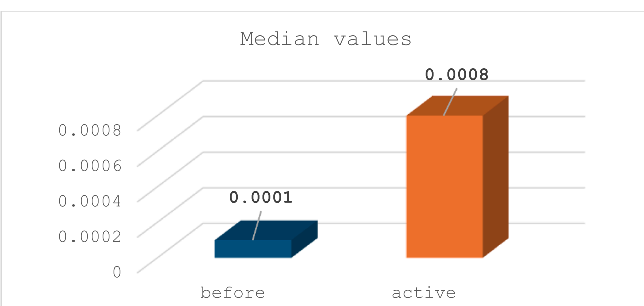


Fig. 4. Median values before and after 5G installation.

other case (p < α) then the two samples are different.

In this case p < α and there is difference between before and active groups.

(Fig. 6)Fig. 7.Fig. 8..

This difference is because of 5G. For the 5G case, the difference in the two medians is 8 times higher than the non-active group. But, focusing on the real concern, (health and safety limits compliance) the two values are equal, too low and in the background levels.

3.3. *Georeference demonstration*

Continuous monitoring and assessment are conducted to confirm compliance with these safety standards, providing reassurance to the community that schools in Thessaly are safe environments regarding to electromagnetic radiation. Mobile phones emit Non-Ionizing radiation, which is generally considered safe at the levels used in everyday communication. Parents, students, and school staff can be confident that their well-being is a top priority, and the use of mobile devices and communication infrastructure poses no substantial health risks in these

Median Test

Frequencies

		groups 1,00	groups 2,00
befeore_nonactive	> Median	5	10
	<= Median	28	23

Test Statistics[a]

		befeore_nonactive
N		66
Median		,0008
Chi-Square		2,157
df		1
Asymp. Sig.		,142
Yates' Continuity Correction	Chi-Square	1,380
	df	1
	Asymp. Sig.	,240

a. Grouping Variable: groups

Fig. 5. Mood's Median test for before and non-active groups.

Median Test

Frequencies

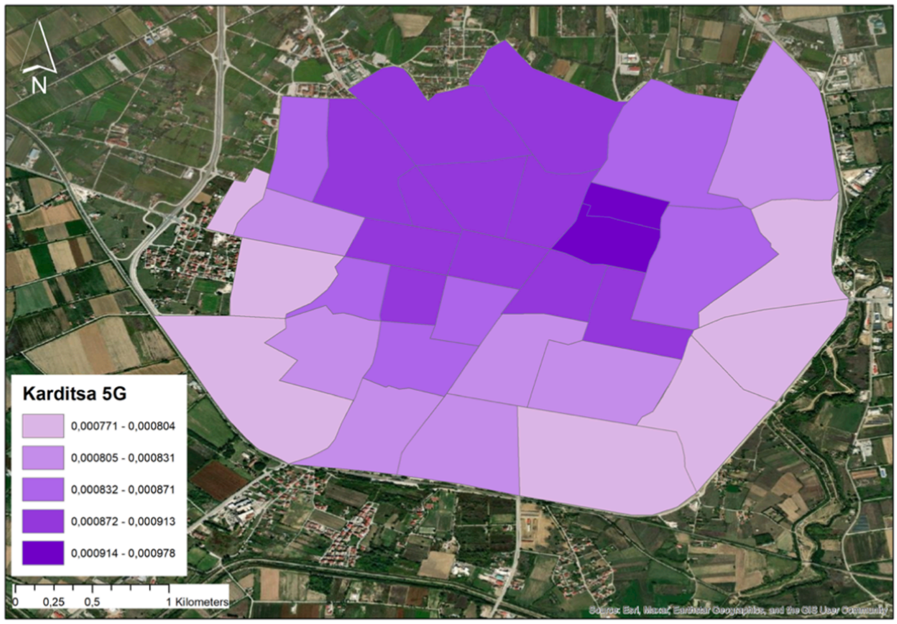
		GROUPS 1,00	GROUPS 2,00
BEFORE_ACTIVE	> Median	5	27
	<= Median	28	6

Test Statistics[a]

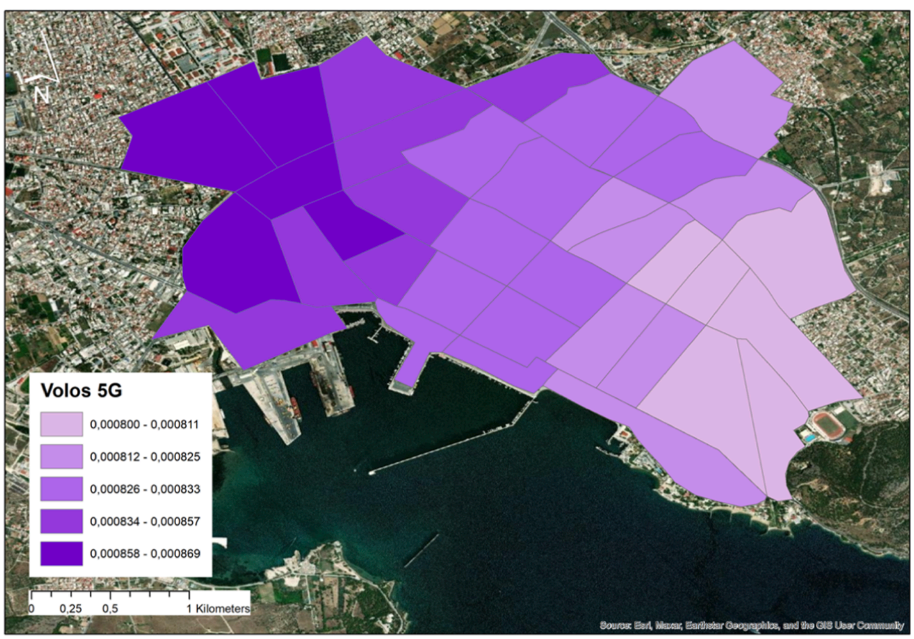
		BEFORE_ACTIVE
N		66
Median		,0007
Chi-Square		29,360
df		1
Asymp. Sig.		<,001
Yates' Continuity Correction	Chi-Square	26,752
	df	1
	Asymp. Sig.	<,001

a. Grouping Variable: GROUPS

Fig. 6. Mood's Median test for before and active groups.



(a)



(b)

Fig. 7. Electromagnetic radiation exposure after 5G installation: (**a**) City of Karditsa; (**b**) City of Volos.

urban areas of Thessaly.

Likewise, base stations are designed and operated to minimize any potential exposure risks to nearby residents, including students attending schools. This stems from the fact that having a greater number of towers allows for a reduction in the power output of each individual tower, resulting in an overall decrease in the electromagnetic radiation in the environment.

The presence of more mobile phone towers indeed corresponds to lower levels of radiation exposure, a principle that is supported by our measurements in Thessaly. This phenomenon is a result of the distributed network of towers, which allows for the transmission of signals at reduced power levels from each individual tower. As a result, the cumulative electromagnetic radiation in the area is minimized, ensuring that the levels of exposure to the population are well within established safety limits. Our measurements in Thessaly confirm that this approach effectively maintains both the quality of mobile phone services and the safety of the local community by keeping radiation levels at a minimum.

4. Discussion

In this section, we provide an overview of several RF exposure surveys. These surveys serve the purpose of evaluating the RF exposure

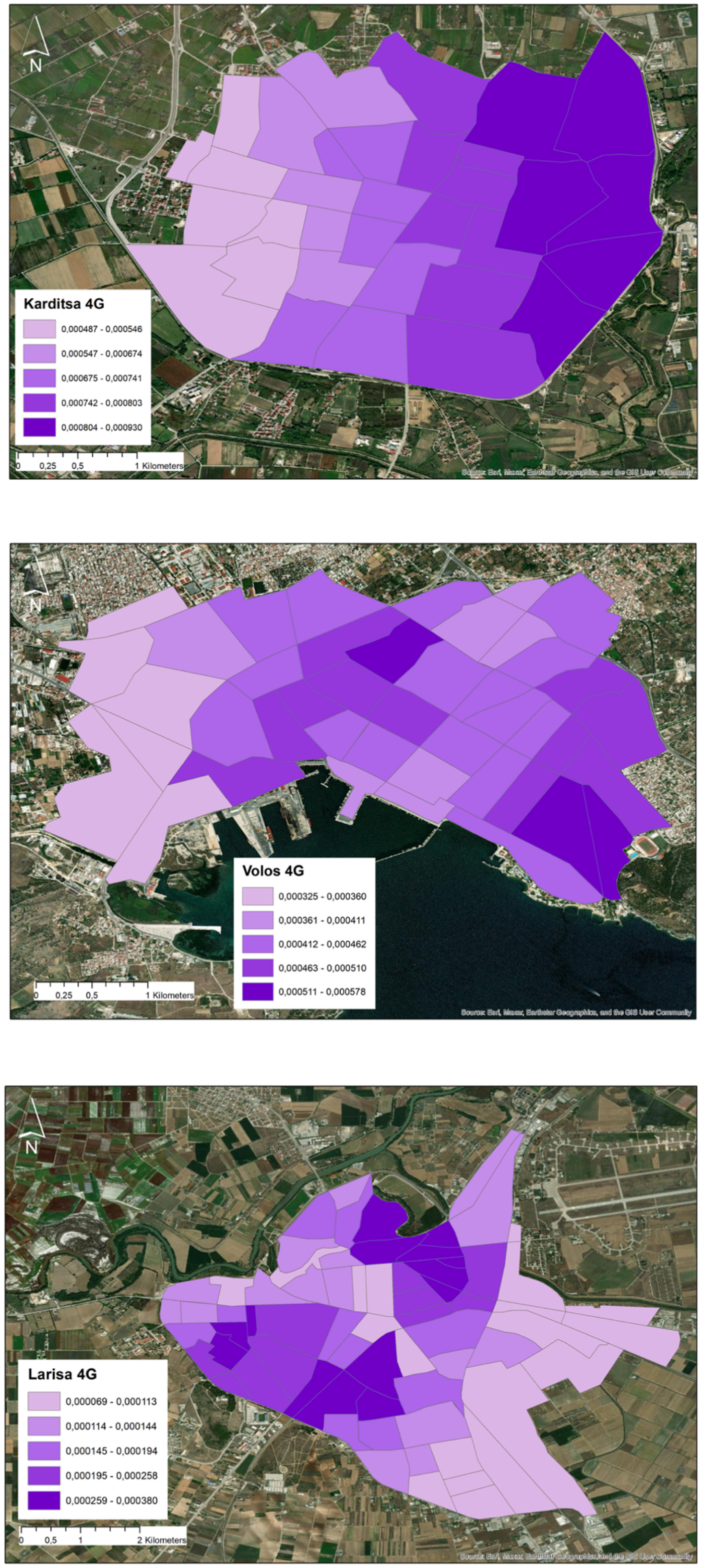


Fig. 8. Distribution of 4G exposure in Karditsa, Larissa and Volos.

levels associated with 5G networks and antennas, comparing them with 4G. Additionally, the surveys aim to assess the newly established safety distances and determine compliance with the safety limits set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

The UK's communications regulator, OFCOM (Office of Communications), conducted a technical report titled "Electromagnetic Field (EMF) measurements near 5G mobile phone base stations," last updated on 17 April 2020. (Office of Communications (OFCOM)., 2020), This report presents RF measurement results from 10 major UK cities, encompassing 22 locations. The measurements were carried out using the SRM-3006 analyzer with an electric field probe, operating within the frequency range of 420 MHz to 6 GHz, covering all mobile service generations (2G, 3G, 4G, and 5G). Key findings from this study, following the methodology standard IEC 62232:2017, indicate that EMF levels emanating from mobile phone base stations were consistently well below the limits specified in the ICNIRP Guidelines. (IEC 6, 2017). The highest recorded EMF level was approximately only 1.5 % of the relevant guideline. Notably, 5G technology contributed minimally to the measured EMF levels at each location. Instead, the predominant contributors were previous generations of mobile technology, such as 2G, 3G, and 4G. In fact, the highest level observed within the 5G band represented just 0.039 % of the relevant guideline. Subsequent reports from OFCOM have reaffirmed that RF exposure levels, both for 5G and the overall exposure, continue to remain at these low levels. These findings underscore the regulatory body's commitment to ensuring the safety of EMF exposure in the context of emerging 5G networks.

The French regulatory body, ANFR (Agence Nationale des Frequences), has undertaken a comprehensive project to assess 5G exposure levels in France. This initiative involves comparing exposure values before and after the 5G rollout, evaluating potential increases in exposure due to the new technology, and ensuring compliance with the ICNIRP's safety limits. (ANFR, 2021).

154 sites operate in 700 MHz band. 135 sites in 2100 MHz, and 1360 sites in the C-band (3500 MHz, or 3490 to 3800 MHz). Of the total of 1649 sites, 85 % are located at urban areas, and 15 % in rural environment.

The most recent report, issued in 2021, provides valuable insights:

f (MHz)	Before 5G rollout	After 5G rollout
700	Median exposure **0.16 V/m** (*700 MHz*) **0.46 V/m** (*broadband*), Maximum exposure **2.09 V/m** (*700 MHz*) **3.40 V/m** (*broadband*)	Median exposure **0.19 V/m** (*700 MHz*) **0.51 V/m** (*broadband*), Maximum exposure **3.14 V/m** (*700 MHz*) **4.50 V/m** (*broadband*)
2100	Median exposure **0.0 V/m** (*2100 MHz*) **1.0 V/m** (*broadband*), Maximum exposure **0.28 V/m** (*2100 MHz*) **6.19 V/m** (*broadband*)	Median exposure **0.09 V/m** (*700 MHz*) **1.01 V/m** (*broadband*), Maximum exposure **1.25 V/m** (*700 MHz*) **5.41 V/m** (*broadband*)
3500	Median exposure **0.07 V/m** (*3500 MHz*) **1.16 V/m** (*broadband*), Maximum exposure **2.1 V/m** (*3500 MHz*) **4.98 V/m** (*broadband*)	Median exposure **0.33 V/m** (*700 MHz*) **1.18 V/m** (*broadband*), Maximum exposure **2.58 V/m** (*700 MHz*) **4.33 V/m** (*broadband*)

5. Conclusions

There is no significant risk of electromagnetic radiation from mobile phones and base stations in sensitive lands (schools, kindergarten etc) located in the cities of Thessaly at the current time. The recorded exposure values within the Thessaly region consistently remained below the internationally recommended benchmark levels established by the ICNIRP. Strict safety regulations and guidelines are in place to ensure that these technologies operate well below the established safety limits for electromagnetic radiation.

Frequecies	IntensityEop,i (V/m)	Equivalent plane wave power density Seq (W/m2)
100 kHz – 10 MHz	$72{,}8/\sqrt{f}$	–
10 – 400 MHz	23,4	1,4
400 – 2000 MHz	$1{,}15\ \sqrt{f}$	f / 286
2 – 300 GHz	51	7

In Greece, the limits are stricter than the ICNIRP's limits. The above table represents reference levels *of electromagnetic fields in the* frequency range of 100 kHz – 300 GHz, as derived after the application of the reduction factor 0.7 (defined in paragraph 9 of article 30 of Law 4070, Government Gazette 82/A/10–04-2012), on the exposure limits (referred to in articles 2–4 of Ministerial Decision No. 53571/3839/6.9.2000).

The growing unease surrounding electromagnetic fields, especially at 5G and their potential health effects has become a significant issue for society. Therefore, it is crucial to emphasize the importance of electromagnetic radiation measurements. These measurements serve as a vital tool for addressing these concerns and providing valuable data that can help inform policies and regulations.

6. Author Contributions

All authors contributed equally to this work.

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CRediT authorship contribution statement

Vasiliki Softa: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis. **Christos Christakis:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation. **Nissren Tamam:** Writing – review & editing, Supervision, Investigation, Funding acquisition. **Abdelmoneim Sulieman:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition. **Charilaos Tyrakis:** Writing – review & editing, Writing – original draft, Project administration, Methodology. **Kiki Theodorou:** Writing – review & editing, Supervision. **Constantin Kappas:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2024.103391.

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