Development of a Monitoring Dataset for Logic-Based Electromagnetic Field Risk Assessment

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Abstract

Cities today are full of technologies that create electromagnetic fields: mobile base stations, power lines, Wi-Fi networks and many other devices. Because of this, it is important to measure EMF levels and to understand what they mean for people. This paper works on three connected tasks for the city of Tbilisi. The "Avlabari" district is used as the pilot study area. The tasks are: to collect and combine the existing EMF data from base stations, power lines, Wi-Fi zones and similar sources, to find the geographic zones where the EMF radiation density is high, and to check how much EMF monitoring data is available for Tbilisi, how good this data is, and where the gaps are. Our measurements in our study area show these electric field levels: 1.2–4 V/m near the Georgian National University SEU, 2.8–6,1 V/m near mobile base stations, 1.5–4 V/m near the metro station, 1.5–3 V/m near clinics, and 0.3–2 V/m in open, less populated areas. All these values are far below the international reference levels for the general public, which correspond to roughly 41–61 V/m in the mobile-network frequency bands. However, the values change a lot from place to place, and they are higher than the average levels reported for some Western European cities. The available data for Tbilisi is still incomplete, so we also propose a fuzzy logic model. The model uses EMF strength, distance to the source and exposure time as inputs, and it gives a risk level as output: Low, Medium, High or Very High. Finally, the paper describes the main gaps in the EMF data for Tbilisi and gives recommendations for a better monitoring system. The results show that fuzzy logic is a useful and effective bridge between incomplete urban EMF measurements and clear risk communication.

Keywords: Electromagnetic field, EMF monitoring, Fuzzy Logic, Risk Assessment.

Introduction

Electromagnetic fields (EMF) are energy fields created by electric charges. They come from both natural and human-made sources. Natural sources include the magnetic field of the Earth. Human-made sources are all around us in modern cities: mobile base stations, power lines, Wi-Fi networks, radio and TV antennas, and personal devices such as phones and laptops. As cities grow and mobile networks become denser, people are exposed to EMF more often, especially in crowded urban areas. For this reason, many people ask a simple question: are the EMF levels in our city safe? Before answering, one physical distinction must be clear. Radiation falls into two classes: ionizing and non-ionizing. The first class — X-rays are the typical example — carries enough energy to break chemical bonds and damage molecules. The second class does not. Practically all everyday city sources, including mobile networks and Wi-Fi, belong to the non-ionizing class, which is far less harmful at ordinary intensities. The international guidelines of ICNIRP (International Commission on Non-Ionizing Radiation Protection) set safe limits with large safety margins [1], [2]. At the same time, scientists are still studying how long-term exposure may affect human health [3], [4], and the World Health Organization recommends that countries monitor EMF levels in a systematic way [5].

For Georgia, and especially for Tbilisi, this kind of systematic monitoring almost does not exist yet. Many European countries have long-term measurement programs, exposure maps and public databases [6–10]. In Georgia, the available EMF data is rare, spread across different places, and often hard to compare. This situation is the main motivation for our study. The study has three objectives:

Objective 1 — Collect and synthesize data: to collect and combine the existing data about electromagnetic fields in Tbilisi. The data comes from base stations, power transmission lines, Wi-Fi zones and other typical city sources. We combine our own measurements with the small amount of public data that exists.

Objective 2 — Find high-EMF zones: to identify the geographic zones with high electromagnetic radiation density in the study area. These are the places where measured field levels are clearly higher than the normal city background.

Objective 3 — Assess data availability, quality and gaps: to evaluate how much EMF monitoring data is available for Tbilisi, how good it is, and what is missing. The Avlabari district is used as a representative example, and we give recommendations for the future.

There is one more important point. The data we can collect today is incomplete and uncertain. Because of this, a simple "yes/no" or "safe/dangerous" answer would not be honest. In many situations, it is difficult to say that something is simply safe or dangerous, because the conditions are not clear or exact. For this reason, we use fuzzy logic method [11] [12]. Fuzzy logic allows gradual classification: values can be partly true, not only completely true or false. We chose this method also because it is fully interpretable [13]. Every rule can be read and checked by a human expert. This choice continues our earlier research on non-classical logical systems and reasoning with incomplete information [14–17].

1. EMF Sources and Safety Limits

1.1. Sources and how we measure them

Urban EMF sources are usually grouped by frequency. Low-frequency fields (50/60 Hz) come from power lines, transformers and electric transport. High-frequency (radiofrequency, RF) fields come from mobile base stations, mobile phones, Wi-Fi, radio and TV. The most common way to describe the strength of these fields outdoors is the electric field strength, measured in volts per meter (V/m). This is the unit we use in the whole paper. Another possible unit is power density (W/m^2), but V/m is more common in city measurements, so it is easier to compare our results with other studies. One important fact about urban EMF is that the levels are very uneven in space. The field from a base station antenna becomes weaker very quickly with distance. The level also depends on the direction of the antenna, on buildings that block the signal, and on reflections. Because of this, two points that are only fifty meters apart can have very different EMF levels [7]. This fact has a practical consequence: if we measure only at a few random points, we can easily miss the local maximum values. So, any serious monitoring plan must think carefully about where and how often to measure, and how to handle the uncertainty.

2.2. Safety limits

The most important international limits are the ICNIRP guidelines. They were updated in 2020 for radiofrequency fields [1] and in 2010 for low-frequency fields [2]. For the general public, the ICNIRP reference levels in the mobile-communication frequency bands correspond to electric field values of about 41 V/m (around 900 MHz), 58 V/m (around 1800 MHz) and 61 V/m (2 GHz and above). So, in simple words, the safe limit for the general public is approximately 41–61 V/m for the frequencies used by mobile networks. We compare all our measurements with this corridor. It is useful to know that some countries use stricter, precautionary limits. For example, Switzerland uses installation limits of only 4–6 V/m at sensitive places, and the Brussels region has used limits below 5 V/m [6]. This shows something interesting: the same measured value, for example 5 V/m, is fully acceptable under ICNIRP rules but almost at the limit under Swiss rules. There is no single sharp border between "safe" and "not safe". This is one more argument for a gradual, fuzzy description of risk.

3. Related Work

3.1. EMF measurement studies in cities

European studies have established a solid foundation for urban EMF monitoring. Long-term outdoor measurements conducted in Amsterdam, Basel, Ghent, and Brussels reported average radiofrequency exposure levels between 0.22 and 0.41 V/m, while even the highest recorded values remained far below the ICNIRP reference limits [6]. Additional measurements in Amsterdam and Basel further showed that exposure levels are generally higher in downtown and business districts than in residential areas, reflecting the higher density of communication infrastructure and mobile network activity [7]. Comparative studies across five European countries identified mobile telecommunication networks as the dominant contributors to everyday radiofrequency exposure [8]. Measurements performed in different urban microenvironments reported average outdoor electric field strengths ranging from 0.07 to 1.27 V/m, with the highest values, reaching approximately 1.97 V/m, observed in public transport stations [9]. Other investigations carried out in the Netherlands demonstrated that personal EMF exposure varies considerably depending on daily activities and surrounding environments. Indoor exposure is typically highest in offices and public transport, while residential environments generally exhibit much lower levels [10,18]. Another important research direction focuses on modelling urban EMF distribution. Radio-propagation models, such as NISMap, have demonstrated strong agreement with field measurements, achieving correlation coefficients above 0.85. These models can estimate EMF levels between measurement locations when antenna positions and three-dimensional building information are available [19]. In addition, indoor studies conducted in Austria and other European regions indicate that electromagnetic field levels inside buildings near mobile base stations are generally about an order of magnitude lower than outdoor levels measured close to the same sources [20,21]. Together, these international studies provide an important reference framework for evaluating EMF exposure levels in urban environments and serve as a useful baseline for interpreting the measurements obtained in the present study.

3.2. Fuzzy logic in environmental risk assessment

Fuzzy set theory was first introduced in 1965 and was later extended through the concept of linguistic variables, allowing qualitative terms such as low, medium, and high to be represented mathematically [11,12]. This theoretical foundation was subsequently developed into a practical rule-based inference system that remains one of the most widely used fuzzy reasoning approaches today [13]. In environmental science, fuzzy logic has been widely applied to address uncertainty and gradual transitions that cannot be adequately represented using rigid threshold values. It has been successfully used to develop environmental quality indices, support health-risk assessment under uncertain conditions, and integrate multiple environmental indicators into a single interpretable assessment [22–24]. In the context of electromagnetic field (EMF) assessment, fuzzy logic is particularly suitable because it reflects the way experts evaluate uncertain situations. Rather than producing strict binary decisions, it allows risk to be expressed gradually by considering factors such as EMF strength, distance from the source, and exposure duration simultaneously. This approach is especially valuable when monitoring data are incomplete, spatially heterogeneous, or affected by measurement uncertainty.

The methodology proposed in this study is also consistent with our previous research on unranked and non-classical logical systems, which investigated formal reasoning under conditions of vagueness and incomplete information [14–17]. Building on this theoretical background, Section 8 presents an interpretable fuzzy logic model for EMF risk assessment.

4. Study Area and Data Collection Method

4.1. The study area

"Avlabari" is a historic district in central Tbilisi, on the left side of the Mtkvari river. We selected it as the pilot area for three reasons. First, the district has a very high daytime population. The campus of Georgian National University SEU brings thousands of students and staff into the area every working day, and all of them spend long hours surrounded by Wi-Fi networks and mobile communication systems. The metro station, numerous clinics, shops and offices add further constant flows of visitors, so a large number of people stay in the district for extended periods. Second, the district contains many different EMF source types in a small territory: base station antennas on roofs and masts, the electric infrastructure of the metro, power distribution lines, and dense Wi-Fi coverage in offices, homes and the university. Third, because so many people stay in the district for long hours, it is a good place to study real-life EMF exposure, not artificial worst-case situations. In short, Avlabari is a natural laboratory for the whole city: many people, many sources, small area.

4.2. How we measured:

We made spot measurements of the electric field strength at street level. The measurement height was about 1.65 m, which corresponds to the head and chest of a standing adult. We used a calibrated portable broadband EMF meter with an isotropic probe (a probe that measures in all directions). We defined five categories of locations before the campaign: the area around the SEU campus; sidewalks and public places close to visible mobile base station antennas; the entrances and surroundings of the metro station; the surroundings of medical clinics; and open or less populated spaces, such as parks and courtyards, which serve as background reference points. At each point, we held the meter away from the body, waited until the values became stable, and recorded the minimum, average and maximum values during several minutes. We also recorded the time, the weather and a short description of the visible sources. We repeated the measurements at different times of day, because the mobile network load changes during the day. It is important to note: the primary measurement data are available, but the process is still ongoing.

5. Measurement Results

Table 1 shows the ranges of electric field strength that we measured in the five location categories of the Avlabari pilot area. The values are broadband street-level readings. According to our source inventory, they are dominated by mobile-network signals, with smaller contributions from Wi-Fi, the metro power system and local power lines.

Table 1.

Location Category	Range (V/m)	Main visible sources

SEU campus	1,2 – 4,1	Base stations, dense Wi-Fi
Near mobile base stations	2,8 – 5,7	Antenna signals (downlink)
Near metro station	1,5 – 4	Base stations, metro power
Near clinics	1,52 – 3,4	Base stations, medical Wi-Fi
Open / less populated areas	0,3 – 2	City background

Three main findings come from this data. First, EMF levels are not the same everywhere. Higher levels are found near the mobile towers and near the metro station. Lower levels are found in open spaces and in less populated areas. The highest single readings — up to 5,7 V/m — appear only at publicly accessible points close to base station antennas. Second, the spread inside each category is large: in every category, the maximum is two or three times bigger than the minimum. This confirms the strong small-scale variability known from European studies [6, 7, 9]. Third, all measured values are far below the safe limit for the general public, which is approximately 41–61 V/m [1]. Even our highest reading of 5,7 V/m is only about 10–15 % of the limit in field-strength terms. In power-density terms the difference is even bigger, because power grows with the square of the field: 5,7 V/m corresponds to only about 1–2 % of the allowed power density.

It is also useful to compare our measurements with international findings (Table 2). The measured electric field ranges are higher than the average outdoor values reported for cities such as Amsterdam, Basel, Ghent, and Brussels [6], and they also exceed the average exposure levels reported for most urban microenvironments in international studies [9]. However, this comparison should be interpreted with caution for two reasons. First, the European values represent long-term average measurements collected along predefined walking routes, whereas the results of the present study are based on spot measurements that intentionally included locations close to major EMF sources. Consequently, average values and near-source maximum values are not directly comparable. Second, the measurements presented here were obtained using a broadband EMF meter, while many European studies employed frequency-selective instruments capable of distinguishing individual signal sources. Nevertheless, the comparison suggests that street-level EMF exposure in central Tbilisi, particularly near major sources, is at the upper end of the range reported for European urban environments, while still remaining within the overall spectrum observed internationally. Furthermore, the spatial distribution of EMF exposure is consistent with previous studies, with the highest levels occurring near transport hubs and mobile base stations and the lowest levels observed in open or less populated areas [9,18].

Table 2.

Study	Reported values (V/m)	Reference
Four EU cities, outdoor means (base stations)	0.22 – 0.41	[6]
Downtown/business / residential areas	0.30 – 0.53 / 0.09 – 0.41	[7]
International microenvironments, outdoor means	0.07 – 1.27	[9]
Public transport stations (maximum means)	up to 1.97	[9]
Indoor: offices / homes (means)	up to 1.14 / 0.13 – 0.43	[18]
Avlabari, near base stations (this study)	2.8 – 5,7	present work
ICNIRP general-public reference corridor	≈ 41 – 61	[1]

6. A Fuzzy Logic Model for EMF Risk Assessment

6.1. Why fuzzy logic?

Why did we choose fuzzy logic and not a classical yes/no method? The reason lies in the nature of the data. EMF measurements in a real city are never complete: they cover only some points, only some moments in time, and they always carry instrument error. The situation also keeps changing — network load rises and falls during the day, new antennas appear, old ones are reconfigured. In such conditions, a strict binary label ("this place is safe", "this place is dangerous") would pretend to a certainty that we simply do not have. Fuzzy logic takes the opposite approach: it lets a statement be true only to some degree. A field level can belong to the class "high" with degree 0.6 and, at the same time, to the class "medium" with degree 0.4. Decisions can then be made step by step, with rules that remain reasonable even when part of the information is missing. This is why fuzzy methods have become a standard instrument in environmental risk modeling, where the conditions are complex and never fully known [11–13, 22–24].

International practice supports this choice. After the Fukushima accident, Japanese environmental monitoring had to work with radiation data that was rapidly changing and often unreliable; intelligent monitoring systems were built exactly for such conditions. In Germany and the Netherlands, air-quality and electromagnetic-field studies increasingly combine classical measurements with soft-computing and AI components. South Korean smart-city programs process environmental sensor streams in real time with flexible, adaptive algorithms, and in the United States a large number of university groups and research centers build comparable models for environmental risk assessment. The common thread in all these examples is the same: when the data is complex, inexact and constantly moving — and EMF data is a textbook case of this — gradual, rule-based reasoning performs better than rigid thresholds.

6.2. Model structure

Our model is a Mamdani-type fuzzy inference system [13]. It has three input variables and one output. The inputs are: EMF strength E (from 0 to 61 V/m; linguistic terms Low, Medium and High, with overlapping membership functions (see the key terms in Section 1.1) based on the measured ranges of Table 1 and the ICNIRP corridor [1]); distance to the main source D (terms Close and Far); and exposure time T (terms Short and Long — how much time a person spends at the location every day). When useful, we also use the environment type (clean/open, urban, dense urban) as an extra condition in the rules. The output variable is Risk, with the values Low, Medium, High and Very High on a normalized scale from 0 to 1.

The logic operations are standard: AND is calculated with the minimum function (AND → min), OR with the maximum function (OR → max). Rules are combined with the Mamdani method, and the final crisp value is calculated with the centroid method. Here are representative rules:

- Rule 1: IF EMF is High AND Distance is Close AND Time is Long, THEN Risk is Very High. The rule strength is $\mu R1 = \min(\mu High(E), \mu Close(D), \mu Long(T))$.
- Rule 2: IF EMF is Low AND Distance is Far, THEN Risk is Low. The rule strength is $\mu R2 = \min(\mu Low(E), \mu Far(D))$.
- Intermediate rules cover the mixed situations. For example: Medium EMF with Long exposure in an urban environment gives medium risk; High EMF with Long exposure in a dense urban environment gives High risk.

A worked example makes the mechanism clear. Imagine a person at a public point inside the main signal direction of a base station near the metro. The membership degrees are: EMF High = 0.8, Distance Close = 0.9, Time Long = 0.7. Rule 1 fires with strength min (0.8, 0.9, 0.7) = 0.7. So, the conclusion "Risk is Very High" is supported to the degree 0.7. After combination with the weaker firings of the other rules and centroid defuzzification, the final value lands in the upper part of the risk scale. The key communication point is this: the model gives a degree, not a verdict. It says: "this situation is similar to the typical high-risk situation to the degree 0.7". This is exactly the honest statement that our incomplete data allows.

6.3. Mathematical formulation

The same rules can be written in a compact mathematical form. Here the symbol ∧ means "and", the symbol → means "then", and μ is the membership degree:

$$R_1: (EMF = High) \wedge (Distance = Close) \wedge (Time = Long) \rightarrow (Risk = Very\ High)$$

$$\mu R_1 = \min(\mu High(EMF), \mu Close(Distance), \mu Long(Time))$$

$$R_2: (EMF = Low) \wedge (Distance = Far) \rightarrow (Risk = Low)$$

$$\mu R_2 = \min(\mu Low(EMF), \mu Far(Distance))$$

$$Risk = f(EMF, Distance, Time)$$

$$Risk \in \{Low, Medium, High, Very\ High\}$$

These formulas say, in short: the risk is a function f of three inputs — the EMF strength, the distance to the source, and the exposure time — and the result is one of four linguistic values. Each rule R_i receives a firing strength μR_i, calculated as the minimum of the membership degrees of its conditions. In our worked example, $\mu R_1 = \min(0.8, 0.9, 0.7) = 0.7$, so rule R_1 supports the conclusion "Risk is Very High" to the degree 0.7.

Conclusion

The three objectives of the study explain each other. The data synthesis (Objective 1) shows a typical city exposure landscape: the absolute levels are reassuring compared with the ICNIRP limits [1], but the spatial contrast is strong. The zone identification (Objective 2) shows that the elevated values concentrate in small, source-anchored hotspots, and these hotspots are exactly where the most people are: base-station areas, the metro hub, the university campus. The data audit (Objective 3) shows that the current data infrastructure is too sparse, too discontinuous and too poorly documented for fine-grained, legally strong exposure statements. The fuzzy model is the bridge between these findings: it turns what we can measure now into risk language that is useful now, and it stays open for improvement when the data becomes better.

We must also state the limitations honestly. The measurement campaign is ongoing; the reported ranges are first-stage results from spot measurements with a broadband instrument. Frequency-selective and long-duration measurements are planned but not yet available. The comparison with European mean values is indicative, not strictly statistical, for the methodological reasons explained in Section 5. The membership functions of the fuzzy model are currently defined by experts; a sensitivity analysis and, later, data-driven calibration are necessary before any regulatory use. Finally, the study makes no medical claims. The measured fields are far below the international reference levels, and this is consistent with the current scientific consensus that no established harmful effects are expected at such levels [1, 3, 4]. The risk categories of our model express relative priority for monitoring and mitigation. They do not predict health outcomes.

Despite these limitations, the study offers a template that other data-poor cities can reuse: start with a pilot district where many people spend time; measure by microenvironment categories that match international practice, so the results are comparable [6–10, 18]; audit the data landscape explicitly, instead of assuming that data exists; and add an interpretable soft-computing layer, so that incomplete data does not turn into false alarm or false comfort.

This paper reported the first stage of a systematic effort to collect, combine and check the quality of electromagnetic field monitoring data for Tbilisi, with the Avlabari district as the pilot area, together with an interpretable fuzzy logic risk model.

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