A Study of Magnetic Fields from Power-Frequency Current on Water Lines

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Submitted to Bioelectromagnetics, September 21, 1995

Revised October 18, 1996

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Abstract

The magnetic fields from power-frequency current flowing on water lines were investigated in a new approach that involved an area-wide survey in a small town. Magnetic fields were measured outside the residence under power cables and over water lines, and each residence was characterized as to whether it received water from a private well or the municipal water system. The magnetic field data revealed two statistical modes when they were related to water supply type. The data also showed that in the case of the high mode, the magnetic field remained constant along the line formed by power drop wires, at the back of the house, and the water hookup service, in front of the house, all the way to the street. The patterns are explained by the coincidence of measurement points and the presence of net current flowing on power mains, power drop conductors, residential plumbing, water service hookups, and water mains. These patterns, together with other characteristics of this magnetic field source, such as the gradual spatial fall-off of this field and the presence of a constant component in the time sequence, portray a magnetic field more uniform and constant in the residential environment than has been thought to exist. Such characteristics make up for the weakness of the source and make net current a significant source of exposure in the lives of individuals around the house, when human exposure to magnetic fields is assumed to be a cumulative effect over time. This, together with the bimodal statistical distribution of the residential magnetic field (related to water supply type), presents opportunities for retrospective epidemiological analysis. Water line type and its ability to conduct power-frequency current can be used as the historical marker for a bimodal exposure inference, as Wertheimer et al. have shown.

Key Words: residential magnetic fields, power net currents, ground currents, water lines

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Introduction

Power currents that flow on water lines have been identified in numerous surveys (Zaffanella, 1993) as a very common source of magnetic field in the residence. Statistically this source is a fairly weak one, typically 0.5 mG, a level that in EMF epidemiological studies has often been portrayed as having no association with health effects. It has been of concern mainly because of elevated measurements in certain locations around the residence, affecting, for example, a toddler who might be playing on a kitchen floor that has a water pipe directly beneath it, or affecting a child sleeping in a bed whose headboard is against a wall that has water pipes in it.

That power currents flow on water lines has been known for a long time. Indeed, water supply engineers have voiced concern that such currents may contribute to pipe corrosion and leaching. Much study has been devoted to the cause and distribution of these currents, which are often referred to as "ground current." The efforts have focused on individual study cases, computer modeling (Zaffanella et al., 1991b; Mader and Zaffanella; Mader et al.), physical models (Zaffanella et al., 1991a), and statistical characterization (Zaffanella, 1993). But ground current is a neighborhood phenomenon as well as a residential one, and thus interesting to study from a community perspective. A systematic area-wide study to address ground currents that would involve municipal water lines, electrical services, type of neighborhood layout, community power consumption, and other parameters of a community character would likely add to the knowledge about ground currents. It could also be significant in determining the relevance of the weak magnetic field associated with ground currents. Wertheimer et al. (1995) have shown, for example, an association between this weak magnetic field and cancer incidence.

The South Republic survey (Lanera et al.) was a systematic survey of spot magnetic field measurements outside residences in a small town. It raised the scope of research from individual homes and that of "mini models," involving a dozen homes at most, to the level of a town with a few hundred homes, in the pursuit of a better understanding and characterization of ground currents. Notwithstanding the survey limitations, new and interesting patterns came to light. One of these was a statistical characterization of the magnetic field based on the type of water supply to the residence that turned out to match the one reported by Wertheimer et al. (1995). The other was a pattern of comparable measurements at different locations around the residence.

This paper reviews the South Republic survey, investigates the nature of some of the findings, and outlines characteristics of the magnetic field caused by net current that, although not new in themselves, collectively give an interesting new picture. The magnetic field caused by power currents that flow on water lines appears to be, more than any other source, a constant and uniform experience in the lives of individuals around their homes.

South Republic Survey

The survey was conducted in South Republic, Michigan, a town of about 250 residences. The power distribution system (Figure 1a) is a standard four-wire, three-phase, multigrounded, 7.2-kV to ground service, with 82 service transformers. The overhead distribution lines run along property limits, often with secondary mains, telephone, and other cables suspended underneath, coming to within 60 to 150 ft of a residence. No significant differentiation can be attributed to residences in terms of wiring code because of uniformity in power line construction and separation from residences. The core of the town is served by a municipal water line (Figure 1b). However, residences immediately to the north and south are not connected, but get their water from individual wells. Residences were divided into two groups based on this difference.

Spot measurements of the 60-Hz magnetic field were conducted in the spring of 1993 at the base of the transformer pole (one meter above ground and one meter from the pole), mid-span under the drop wires (one meter above ground and directly under the overhead line), and in front of the kilowatt-hour meter (one meter above ground and one meter from the outside wall of the house) for 82 residences, one residence for each service transformer. In addition, measurements were taken above the municipal water system (one meter above ground), near fire hydrants. The magnetic field was measured in terms of its root mean square resultant (Horton and Goldberg) using the EMDEX II, a three-axis magnetic field meter.

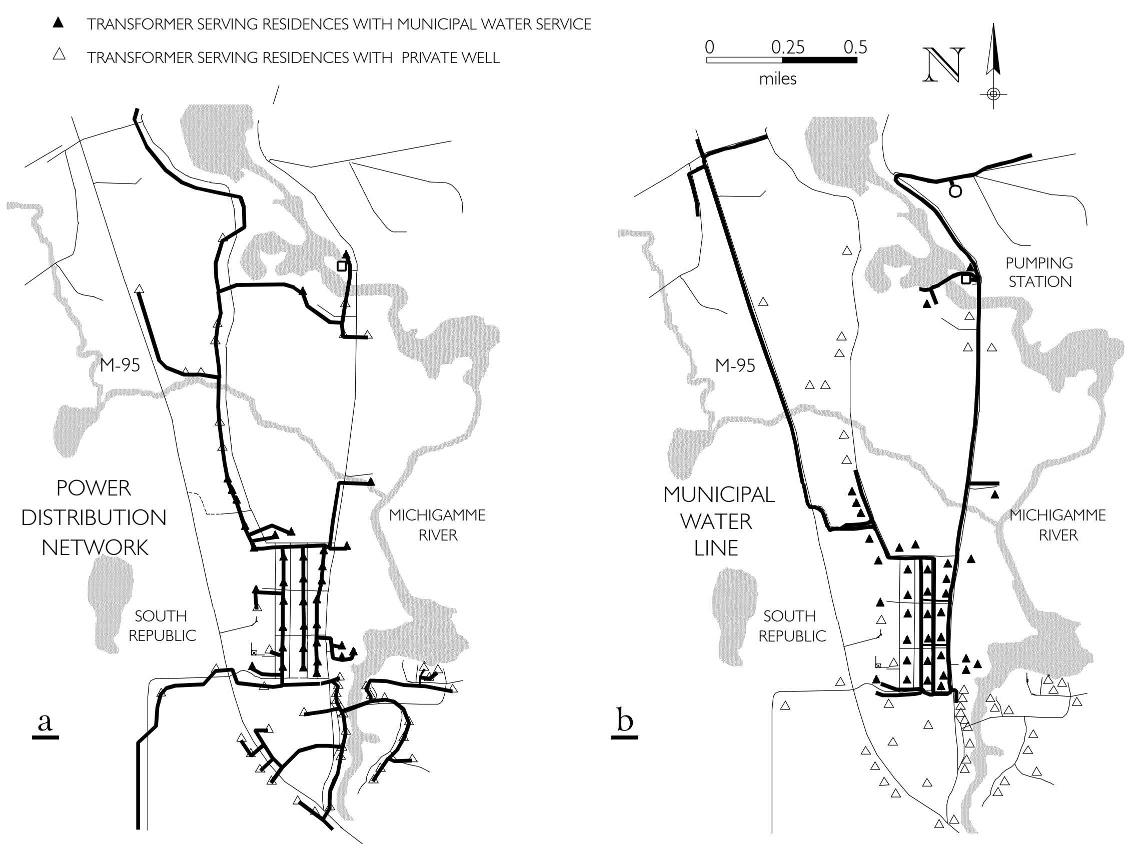

Figure 1. Power distribution line and water line in South Republic, Michigan.

Table 1 summarizes a statistical analysis of the magnetic field measurements grouped by location type. The magnetic fields at the three locations outside each residence on the municipal water system congregate around 1 mG (log-transformed distributions), while the magnetic fields for corresponding locations outside residences not on the municipal water system congregate around 0.3 mG. As shown by the 95% confidence intervals, the difference between these two means is statistically significant. The magnetic field mean at residences on the municipal water system is at least three times larger than the magnetic field mean at residences not on the municipal water line. The magnetic field mean and the corresponding ratio in front of the kilowatt-hour meter were much higher (1.84 mG) than the other sample means (around 1 mG) for residences on a water line, because the measurement was taken much closer to the source current, as will be shown later.

Table 1. Magnetic field survey statistics, South Republic.

	Individual Wells Sample Size = 46		Municipal System Sample Size = 36		Ratio of Means§
	Mean	95% CI†	Mean	95% CI†	
Transformer Pole	0.35 mG	0.21-0.60 mG	1.10 mG	0.65-1.76 mG	3.0
Service Drop	0.22 mG	0.15-0.35 mG	0.79 mG	0.49-1.27 mG	3.5
Kilowatt-Hour Meter	0.34 mG	0.24-0.48 mG	1.84 mG	1.04-3.24 mG	5.4
Fire Hydrant	—	—	0.80 mG	0.60-1.08 mG	—

† Confidence Interval

§ Municipal System / Individual Wells, $p<0.001$

Table 2. Power line measurement statistics, South Republic.

	Individual Wells Sample Size = 51		Municipal System Sample Size = 30	
	Mean	95% CI	Mean	95% CI
Neutral Voltage at Transformer Pole	1.16 V	0.96-1.40 V	0.37 V	0.28-0.49 V
Primary to Secondary Neutral Current	26 mA	18-38 mA	54 mA	32-93 mA

Various electrical parameters besides the magnetic fields mentioned above were measured at service transformer poles, to pursue associations between these magnetic fields and power lines. These parameters were the rms voltage between the neutral wire at the service transformer pole and a remote earth reference point, measured with a Fluke 87 meter, and the primary-to-secondary neutral current at a service transformer, measured with the Fluke 87 meter and an auxiliary current probe. A statistical analysis of these other parameters (Table 2) shows a similar difference according to water supply type.

Compared to homes with wells, residences connected to the municipal water system have voltages on the neutral wire at a transformer pole that are three times lower, and a neutral current flowing between the primary and secondary neutrals twice as large. The residential grounding impedance, estimated from the above parameters, is about six times smaller when the residence is connected to the municipal water line. The mean values for each of these characteristics is statistically different between water supply types, just as in the case of the magnetic field measurements. This supports the notion that the magnetic field and other electrical parameters outside the residence relate to the way residential and power line groundings are affected in the presence of municipal water lines.

The power consumption of South Republic residences was analyzed as a possible cause of the observed differences because it is known that service transformers in urban areas (with a municipal water system) typically serve many more residences than similar transformers in rural areas (with private wells). Company records were used to establish a year-long monthly power consumption average for the residences used in the survey. Because of the many rates involved, a meaningful comparison was limited to a subset of the original surveyed homes (Table 3), and to two main rates (nearly one-third of the residences had a second meter for hot water heating). The transformers not on the municipal water line in South Republic serve an average of two residences, while the transformers on the water line serve an average of four. Therefore, the service transformers on municipal water lines handle twice as much power as service transformers not on water lines. This is corroborated by the primary-to-secondary neutral current (Table 2), which was, on average, twice as large for service transformers on municipal water lines. This does not explain the difference in magnetic field reported in Table 1 between service transformers on and off water lines. As will be shown later, the primary-to-secondary neutral current is too small to cause the magnetic fields measured at the base of service transformer poles. Furthermore, there is not a 2:1 statistical difference in residential power consumption between residences on the municipal water line and those with wells to accompany the observed variation in magnetic field, as in the case of the service transformer.

Table 3. Power consumption statistics, South Republic.

	Individual Wells			Municipal System		
	Sample Size	Mean	Standard Deviation	Sample Size	Mean	Standard Deviation
		kWh/month			kWh/month	
Residential Power Standard Rate	29	576	316	20	592	315
Residential Power Hot Water Rate	11	548	282	16	529	262

A correlation analysis also showed that there was no association between the measured magnetic fields and the average residential power consumption ($r^2 < 0.3$). This is consistent with the findings in the "thousand-home survey" (Zaffanella, 1993). This excludes residential power consumption and service transformer power handling as causes for the observed magnetic field difference based on water supply type. On the other hand, the magnetic fields at the base of a transformer pole correlate well with the magnetic fields under the drop wires ($r^2 = 0.84$), suggesting a possible common source of magnetic field.

Secondary Net Current

Figure 2 diagrams the flow of secondary net current for residences with power and municipal water service. The primary neutral conductor, the secondary neutral conductor at each residence, the residential plumbing, and the municipal water system form an extensive network of electrically conductive pathways, often referred to as the grounding network.

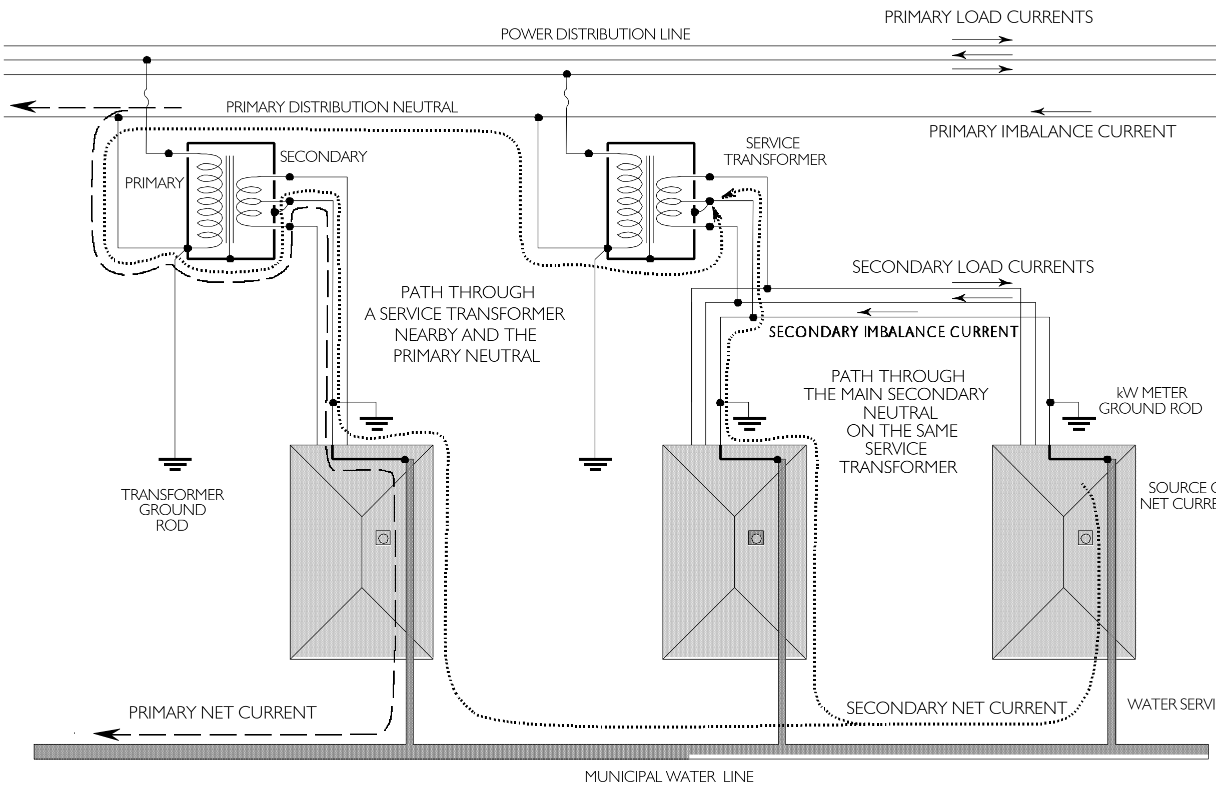

Figure 2. Typical power services and net currents on water lines.

The primary and secondary sides of a service transformer form two separate circuits, magnetically coupled at the transformer. The term “imbalance current” applies to both the primary and secondary circuits and refers to that portion of the supply system load current flowing on the ungrounded wires (those with voltage) that is not electrically balanced. This imbalance current appears on the neutral conductor,[1] which also happens to be the grounded conductor for safety purposes. Load and imbalance currents flow-

[1] While the secondary wiring is typical for all residences in the United States and some other countries, the primary wiring may not use a neutral conductor. The delta distribution system, for example, does not. While popular in Europe, the delta system is slowly disappearing as a distribution system in the United States.

ing on a supply cable form a vectorial zero-sum. More simplistically, whatever current flows toward the load (supply), an equal amount has to return to the power source (return). Overall, looking at it from a distance,[2] no current appears to be flowing on this supply cable, because the supply current is balanced by the return current. No magnetic field seems to be emanating from the supply cable, and it is said to have a net current of zero. However, if a portion of the imbalance current is diverted from the neutral wire and returns to its source through the plumbing, the power cable supply assembly will show as missing a portion of the imbalance current, resulting in net current on the power supply cable, the same as found on the plumbing.

The primary and secondary circuits are identical in terms of each having a grounded conductor (neutral). Net current can occur on both the primary and secondary sides of a service transformer; thus, these currents are referred to as primary and secondary net currents. Complications arise because these two neutral systems are interconnected at the service transformer.

The magnetic fields observed for residences on the municipal water system in South Republic are caused by a current on the power drop wires and on the plumbing. The possible sources (see Figure 2) are the primary net current, which returns to the substation via the residence and the plumbing of the municipal water system, and the secondary net current, which returns to the service transformer. The secondary net current, after traveling on the plumbing of neighboring residences, will return to the service transformer either through the secondary main neutral, for residences on the same transformer, or through the primary neutral, for residences not on the same transformer. The primary net current can be dismissed as a source of the high-mode magnetic field in the South Republic survey, because it is too weak to cause the magnetic field measured under the drop wires. A current of 0.054 amps (Table 2), flowing 10 feet (3 meters) high on a transformer pole, would cause a magnetic field of 0.05 mG at the base of the pole, 1 meter above ground. This is much less than the measured average of 1.1 mG.

Similar situations can be expected on services that depart from the Edison service (120/240 V, three wires), as long as they use water lines for grounding and for electrical safety, and produce net currents (Rauch and Johnson). The three-phase wye secondary service used in the United States and abroad (Swanson and Renew) is likely to produce similar situations.

Magnetic Field Space Variations

The South Republic survey shows that the magnetic field is nearly the same under drop wires at the back of the house, and over the water line in front of the house. This is more than a fortuitous coincidence, and we have shown that the magnetic field is due in both cases to secondary net currents. However, it is surprising that the field measurements are nearly equal, considering the difference in the two locations and the fact that the field changes with distance from the source. Figure 3 illustrates, in simplified terms, the path for the secondary net current as it flows on the drop wires, through the residence on the plumbing, and onto the municipal water main. Also shown in the figure are two of the measurement points used in the South Republic survey, under the drop wires and over the water hookup.

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[2] This distance is a function of the physical separation among the conductors in the supply cable. For further information, see Zaffanella, 1993, and Horton and Goldberg.

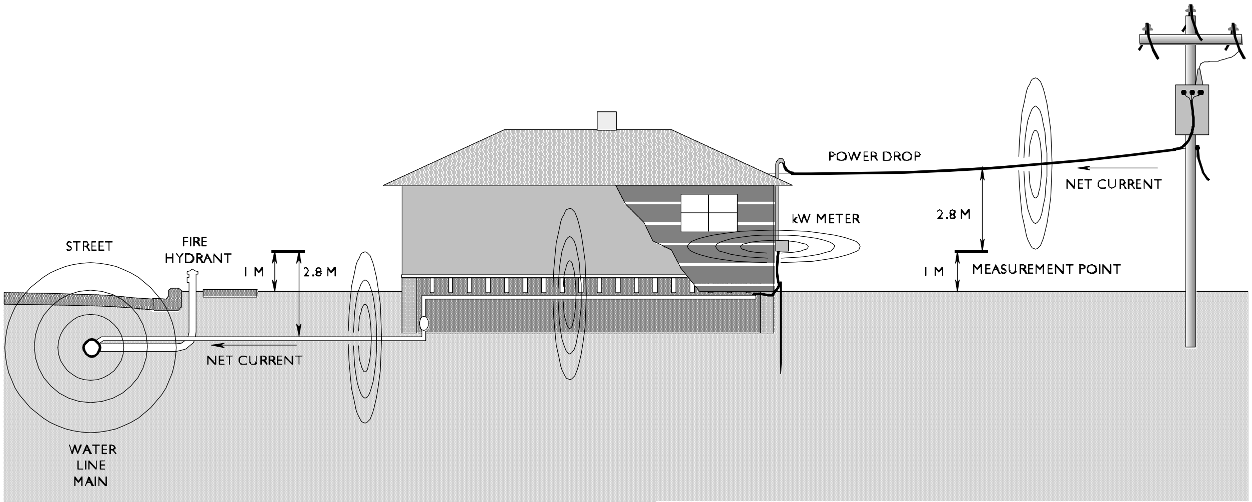

Figure 3. Secondary net current pathway just outside residence.

When measured at 1 meter above ground, the distance from the secondary net current is nearly the same whether the medium is the overhead wire or the underground water line. This is because the location 1 meter above ground is midway between the average height of overhead drop wires and the average depth of underground water lines. This distance is about 2.75 meters (9 feet) in South Republic. At any point under drop wires or above water lines, this field remains relatively constant and explains the observations in the survey.

This type of uniformity is referred to as longitudinal uniformity because the field from a line source remains unchanged as long as the observer remains at the same distance from the source and moves parallel to the line. This is the case, for example, with power transmission lines where, excluding for variations caused by wire sags, the magnetic field is unchanged along paths parallel to the power transmission line. Longitudinal uniformity was not expected, prior to undertaking the survey, especially because of the physical difference in the net current media, water lines and power drop wires.

$$B = \frac{2\ I}{\sqrt{d^2 + x^2}} \qquad \text{Equation 1}$$

B (mG)
d (m) = vertical separation of source current from 1-m point above the surface (Figure 3).
x (m) = lateral separation from the net current pathway.

On the other hand, as one moves laterally with respect to either line, the field decays slowly, as indicated in Equation 1. Although not measured directly in the original survey, the secondary net current on the South Republic water main can be estimated based on these geometrical considerations and the magnetic field data. Using Equation 1 with x = 0, d = 2.75 m, and using the magnetic field mean of 0.8 mG measured both in front (fire hydrant) and in the rear (drop wires) of the residence, net current is estimated to be 1.1 amps on average in South Republic. A similar result is obtained when using the measurement at the kilowatt-hour meter, with B = 1.84 mG, x = 0, and d = 1.22 m. The distance accounts for the depth of the kilowatt-hour meter (22 cm) and the 1-meter distance from the face of the kilowatt-hour meter where the measurement was made. This is based on simplifying assumptions that the secondary net current is dominant and that other sources can be ignored.

As the path for secondary net current zigzags in and out of residences, an important effect of longitudinal uniformity is the permeation of the environment with this magnetic field. This effect makes secondary net current, which is typically smaller than other current sources in the residence, a very pervasive presence. Figure 4 shows a rendition of what this presence may be like. The areas of influence are shown as rectangles in correspondence with secondary net current carriers. Although the field decays uniformly with distance (Equation 1), it is shown in Figure 4 as being well delimited with distance. This serves to illustrate two points. First, rectangles of various width and tapering serve to remind us of variations in both current magnitude and distance that affect the magnetic field. Such variations can be expected, such as in the burial depth of water hookups, which may increase uniformly from the house to the main. Second, if a small variation is tolerated in the magnetic field level as one moves about, which is acceptable in an exposure assessment problem, then the magnetic field can be considered uniform not just under or over the line of the secondary net current, but over a tract extending to both sides of this line. Using Equation 1, with d set at 2.75 m, a variation of 20% would result in a tract 4.1 m wide (13.5 ft), while a variation of 50% would yield a tract 9.7 m wide (32 ft). The collection of all these tracts (Figure 4) represents an area where the magnetic field due to secondary net current remains within a defined range. This is defined as quasi-uniformity; that is, the fact that at 1 m above ground in areas near the path of secondary net currents, the magnetic field tends to vary little.

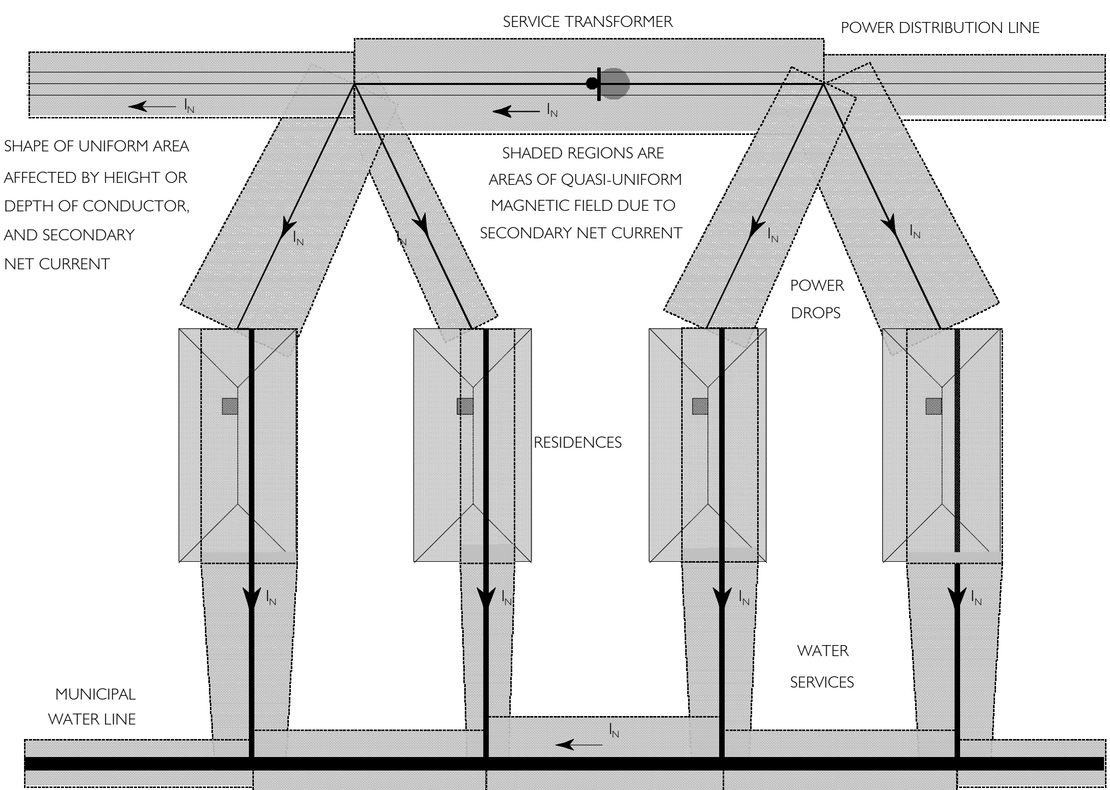

Figure 4. Areas of quasi-uniform magnetic field outside the residence.

Follow up efforts to verify such a picture using the mapping capabilities of the EMDEX II meter have produced mixed results. Surveys of this type are particularly demanding because of complications such as the time variability of secondary net current, which turns this into a contemporaneous space-time survey, and the weak nature of this field compared to confounding sources (e.g., power distribution lines).

These patterns are likely to hold up for many other situations and communities, because of commonalities existing in water and power services. For example, water services tend to be almost exclusively of the underground type, and power drops, if overhead, tend to be close to the minimum clearance mandated by construction codes. Where water and power services are on the same side of the residence, other patterns will exist, mostly on one side of the house, with results that may double or cancel this magnetic field, depending on the flow of secondary net currents. Multidwelling buildings present additional challenges in this respect. The limits of this quasi-uniformity need to be further examined due to the variety of construction possibilities.

Magnetic Field Time Variations

Time variations are just as important as spatial variations in determining human exposure to the magnetic field caused by secondary net currents. Following up on the original South Republic survey, a day-long recording of the magnetic fields was made recently at one of the residences involved in the original survey (Figure 5). This magnetic field time sample is very similar to patterns of secondary net current and related magnetic field reported by both Zaffanella (1989) and Mader et al.

Magnetic fields caused by secondary net current have been described as the most variable temporally (Zaffanella, 1989 and 1993; Mader et al.), excluding appliances. The temporal variation in Figure 5 is substantial, and characterized by "spikes." When compared to the magnetic field produced by some other sources, such as power lines, the magnetic field produced by secondary net currents is indeed much more variable in time. However, for exposure assessment, in light of the complex activity patterns by individuals inside or just outside the residence, these time variations are less significant than the presence of a steady magnetic field (Figure 5).

The magnetic field time series indeed can be separated into three mathematical components (shown graphically in Figure 5) that are linearly added to form the total pattern: a long-term component (daily average); a slow-changing component that completes a cycle every day; and instantaneous changes (spikes).

The daily average component in Figure 5 is 0.86 mG. It is most likely the result of integration of a myriad of randomly switching loads, not just inside one residence but throughout the community. Studies have shown (Zaffanella, 1989; Mader and Zaffanella) that at an elementary level each residence can be visualized as a source of net current, and that a characteristic pattern can be defined that describes the distribution of this net current in neighboring residences. The effect of all the residences at any one point on the grounding network is then taken to be the linear addition (including appropriate accounting for phase differences) of the effect of each residence in the community. This pooling of effect produces two new, unique characteristics: first, it yields a quantity that is likely to be much less variable than the individual components on which it is based; second, this quantity is less dependent on variations in individual sources, reflecting instead the contribution of all sources simultaneously. It is a process very similar to power flow, which can be very uniform and continuous when observed further up the distribution system, even though it may be quite discontinuous and irregular at the end points.

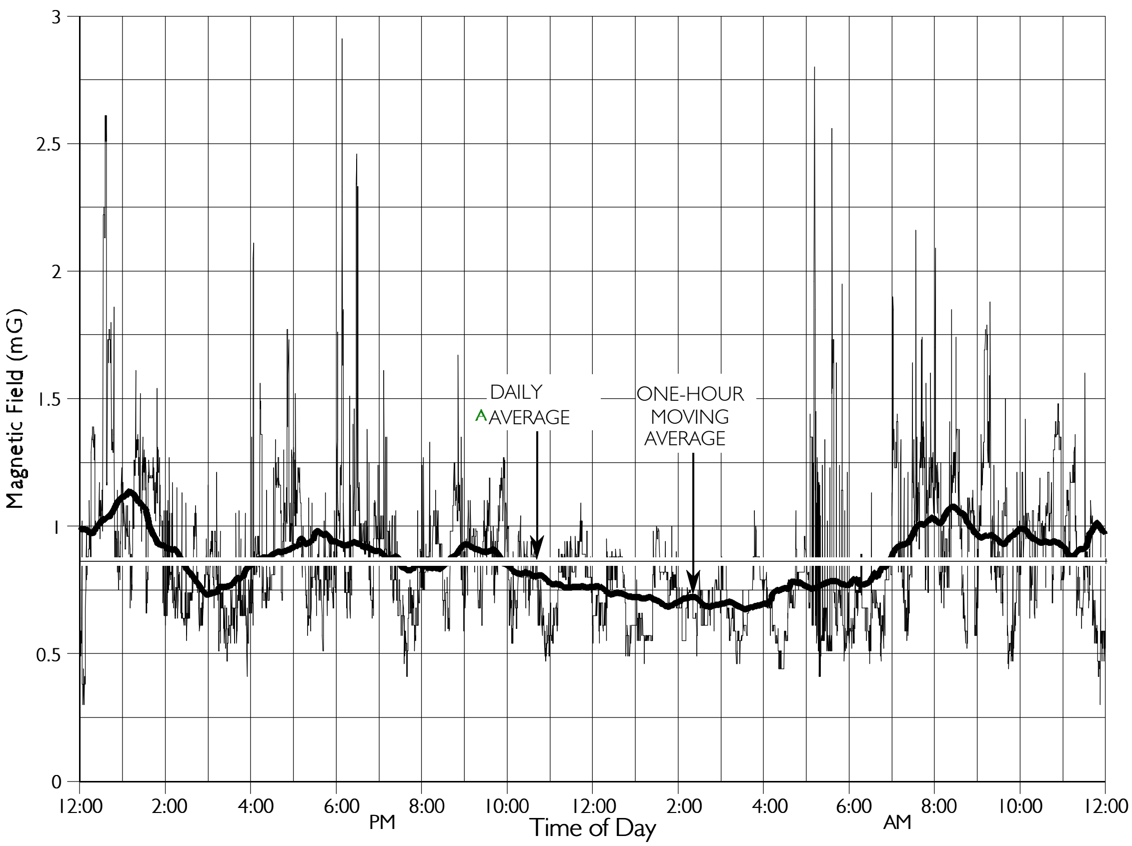

Figure 5. 24-hour magnetic field recording taken every 15 seconds under the power drop wires.

The slow-changing component in Figure 5 (one-hour moving average) varies as much as 0.5 mG from the daily average. It seems to follow the known consumer power consumption pattern, which peaks in the morning and evening, and bottoms out in the afternoon and late at night. Patterns of weekly and seasonal changes have also been documented (Swanson and Renew). This suggests that the overall level of the magnetic field and the secondary net current itself are related to the instantaneous power consumption in the community. This relationship is non-linear, because net current depends principally on the presence of a municipal plumbing system and its conductivity. Furthermore, the imbalance current, from which net current results, is not itself linearly related to the power load on the line. For example, the power drawn by an air-conditioning unit operating at 240 volts, although a substantial load, results in zero imbalance current.

What appears to contradict these observations is the earlier finding that there is no apparent correlation between spot magnetic field and monthly average residential power consumption. This contradiction may not be real; the two power quantities mentioned here are indeed different measures. The average residential power consumption is a statistical measure of tendency, while the instantaneous community power consumption is a specific, time-variable quantity. Furthermore, as stated above, the tie between spot magnetic field and instantaneous community power consumption is a non-linear one.

Water Line Conduciveness

Water line "conduciveness" is used in this paper to refer to the properties and circumstances in a water supply system that allow for and promote the formation and circulation of net currents among many residences. A community water distribution system that is electrically conductive, and water service hookups that are also electrically continuous and tied to the residential power grounding system, constitute cases of water line conduciveness. Private wells, plastic water lines, or metallic water hookups with electrical insulators constitute cases of non-conducive water lines, which impede the formation and flow of net currents.

Table 1 indicates that the resulting magnetic field in South Republic tends to congregate around 1 mG for conducive water lines, versus 0.3 mG for non-conducive water lines. The thousand-home survey (Zaffanella, 1993), which sampled residences throughout the United States, yielded similar results. In the Zaffanella survey, the respective magnetic field sample medians are about 1 mG and 0.3 mG for the sample highest 5% of magnetic fields due to secondary net currents (ground currents), depending on water line conduciveness (whether or not the residence is connected to a city main, and similarly whether the residence uses metallic or plastic water lines). It should be noted that these findings pertain to cases of high fields (top 5%), but include temporal variations. The study by Wertheimer et al. (1995) also fits with these results; the threshold of 0.5 mG falls in between the two modes of 0.3 mG and 1 mG.

There seems to be, therefore, convincing evidence that the residential magnetic field associated with water lines falls into one of two statistical modes, 1 or 0.3 mG, depending on the water line's conduciveness to net current. The low mode of 0.3 mG can be rationalized as being due to a combination of factors such as background magnetic field, study misclassifications of water line conduciveness, and instrumentation and protocol inaccuracies. The high mode of 1 mG, on the other hand, is intriguing because it seems not to be just a random statistical outcome, but an indication of the naturally occurring range of this magnetic field. We have seen, from the above, what the physical justifications for this outcome might be. The magnetic field related to water lines and net currents is then described statistically as having one of two modes depending on the water line's conduciveness to net current.

The value of this pattern is that it provides a means of estimating the historical magnetic field exposure using water line conduciveness as a metric, which has been shown by Wertheimer et al. to be a promising epidemiological approach. The quality of this generalization depends on the uniformity of water line construction practices. The very presence of a municipal water line can be used as a first approximation in using this bimodal result. However, the strength of association is diminished by misclassifications that can result from including sections of water line that are nonconductive, residential water hookups of plastic, or those that are intentionally isolated electrically. Specific assessments for each residence in the study would clear up the misclassifications and verify the results. Another factor to take into account in this regard is the shift from metallic to plastic plumbing material; this slow but steady, long-term change can provide both complications and opportunities for further study.

Conclusions

Our survey in a small town produced interesting results, in part due to its novel approach of addressing a whole community. The correspondence between the findings reported here and those reported by other researchers suggests that the findings are not unique to South Republic but may be representative for other larger communities as well. This study has shown that net currents arise in the community utility services when electrically conductive water distribution facilities are present. Secondary net currents are predominant, and flow on electrical utility distribution systems as well as water lines in order to complete their looping. These widespread and overlapping loops of current around the residence that spread over the neighborhood, coupled with the slow falling-off of the associated magnetic field with distance, cause a pattern of weak but very distributed magnetic field, a pattern that has been termed "quasi-uniformity." This study has also shown that there are constant components in the time sequence of this magnetic field that contribute to make this a constant experience for individuals in the residential environment. These factors are significant because they can contribute substantive doses of magnetic field exposure over time, nothwithstanding the weak nature of the field itself. This is a consideration not appreciated as well as the other acknowledged problems of this source, namely transients and net current "hot spots."

This study has also shown a statistical bimodal distribution of the magnetic field from secondary net currents, when related to type of water supply. The latter has been relabeled as residential water line conduciveness to describe in broad terms the capability of a residential water service to conduct net currents. The statistical bimodal pattern matches that reported by other researchers when water service conduciveness is used as the independent variable. This statistical characterization has been shown to have a basis in the quasi-uniformity and constant component of this magnetic field. Further, it has been shown that this characterization can be useful for retrospective studies to infer historical magnetic field exposure to this source, as done by Wertheimer et al. The marker for this exposure is water line conduciveness, which changes little over time and which quite readily can be tracked historically for individual residences.

The drawback to this theory is that secondary net current is but one of the sources that historically have contributed to personal magnetic field exposure around the house. The degree to which this pattern will hold up by region or across countries remains an interesting question. Many other issues also need to be considered: congested urban centers with multidwelling buildings merit special attention; seasonal variations of ground current and their dependence on community power consumption need further study; primary net current needs to be characterized and isolated from secondary net current; and, finally, more studies are needed at the municipal level to better understand the full role of net current in exposure.

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