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Designing Uncertainty Visualization for Noise Map

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Abstract:

Uncertainty in Geographic Information Systems (GIS) and cartography extends beyond traditional data quality metrics, such as accuracy and error. It encompasses vagueness, fuzziness, spatial variability within enumeration units, confusion in attribute categorization, and temporal dynamics, as distinguished by MacEachren (1992). Furthermore, Couclelis (2003) philosophically positions uncertainty as an intrinsic feature of complex geographic knowledge production, not simply an empirical flaw. They also argue that it contains logical limits as well as data issues. Building on these foundations, MacEachren et al. (2005a) models spatial data uncertainties, thereby influencing modern frameworks for uncertainty propagation.

Recent advancements, as reviewed in Goodchild (2020), span three decades of progress. It is from basic error analysis to handling big data synthesis, spatial autocorrelation via Tobler's First Law, and replicability across heterogeneous datasets. Turning to visualization, research by Kinkeldey et al. (2014a) classifies techniques into coincident/adjacent displays, intrinsic/extrinsic encodings, and static/dynamic methods, all aimed at better supporting decision-making. Additionally, MacEachren et al. (2005b) outline seven key challenges in uncertainty visualization and advocate transparency, crispness, and resolution as variables for effective map-based communication.

Building on this growing body of work, we have conducted a systematic literature review on uncertainty visualizations for the past 10 years. We have found that certain types of uncertainty are strongly associated with their common visual variables Afifah et al., (2026). We suggest that "uncertainty" refers to the lack of complete certainty in representing a measurement, model, or prediction. In the context of spatial data, it encompasses all properties that cause a model or map to inaccurately reflect reality. These arise from data inaccuracy, incompleteness, inconsistency, natural variability, or incomplete knowledge.

Our study centers on case studies involving urban noise models and maps. Among the various types of uncertainty in GIS and cartography, several are especially relevant to urban noise modeling: prediction uncertainty, temporal uncertainty, value uncertainty, and epistemic uncertainty. Prediction uncertainty stems from algorithmic assumptions in noise-propagation models, while value uncertainty arises from measurement errors in acoustic sensor data. Temporal uncertainty captures the variation in noise levels over time. Epistemic uncertainty results from incomplete knowledge of urban sound-source dynamics (Feizizadeh et al., 2014; Chun, 2019).

In our systematic literature review, we have listed the visual variables commonly used in cartographic and non-cartographic studies. The most commonly used visual variables are color hue, color value, and opacity/transparency. Some of the included studies also reported user studies evaluating the visualization. For example, Kübler et al. (2019) demonstrated uncertainty visualization on hazard maps using color gradients, Gaussian blur, and texture at zone boundaries. This was done in a house-buying decision task with eye-tracking. Their study with 37 participants showed that those intrinsic methods successfully guide multi-criteria choices on risk and location. Based on our knowledge, we are sure that every type of uncertainty should be studied closely using different case studies. Therefore, we look forward to seeing how the existing visual variables can be applied to the proposed visualization of urban noise models or maps in our case study. We aim to propose one that can also be used universally for other case studies, with some innovations.

In the context of noise maps, our research shows that people recognize the uncertainty resulting from the visualized noise levels ('Afifah et al., 2025). Building on this, we aim to provide decision-makers with enhanced visualizations of uncertainty. Drawing from existing examples, we sketched our proposed visualization, shown in Figure 1. Specifically, we represent uncertainty using four visual variables: opacity, interactivity/animation, sketchiness/blur, and grains or "noise annotations." For reference, Kinkeldey et al. (2014b) introduced noise annotation lines as a texture-based technique for visualizing thematic uncertainty on maps. Our multi-layer visualization lets users toggle individual uncertainty layers with distinct visual variables, enabling flexible exploration. When these variables overlap, they accumulate intuitively: an area affected by multiple uncertainties stands out. For example, when predictive, temporal,

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attribute, and data errors occur together, an area displays cues such as low opacity, dynamic motion, sketchy lines, and high graininess. These visual signals indicate a higher degree of uncertainty compared to the surrounding regions.

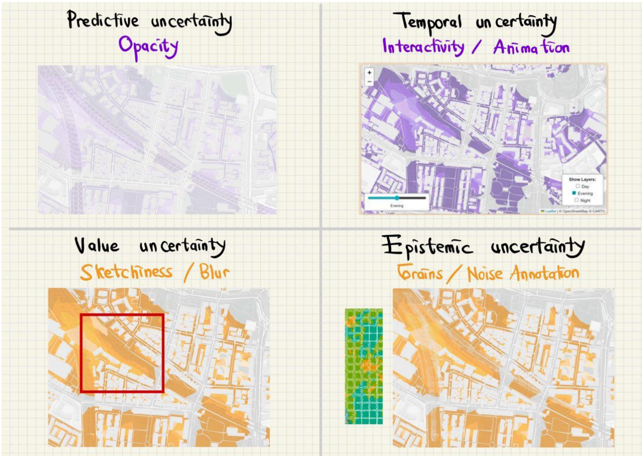

Figure 1. Sketch of the proposed visualization with visual variables for each uncertainty type layers, on the noise model generated using the NoiseModelling model builder and OpenStreetMap data. The 'noise annotations' reference is from Kinkeldey et al. (2014b)

We are enthusiastic about advancing this visualization towards a more robust prototype or proof of concept in the near future. Our ultimate goal is to implement the visualization in a web environment. Achieving this will require following a comprehensive development pipeline. Currently, we are working on initial sketches; we will then create a system mockup and deliver a proof of concept before progressing further. The next step involves consulting domain experts about the proof of concept. We plan to interview at least 10 experts using a semi-structured format to gather objective feedback. Based on their insights, we will revise the prototype and return the updated version to the experts. We will confirm their suggestions and solicit any further input before presenting it to an expanded audience.

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