Uncertainty visualization using maps for nuclear and radiological emergencies

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Abstract – Visual uncertainty representation and communication during nuclear and radiological emergencies face empirical and theoretical challenges. The work carried out focuses on visualisation of uncertainties as a decision support and communication tool. We represent uncertainty visually through maps and visual robustness indicators. An interdisciplinary approach was applied where both quantitative and qualitative methods were used to validate and test the tools developed in 6 different occasions/countries. The principles for building effective uncertainty representation and communication tools are presented. It is important to note that the visual approach offers a great opportunity to represent uncertainty to experts in the field of emergency planning especially in the nuclear/radiological one.

Keywords: nuclear / radiological / emergency / maps / robustness indicators / human computer interaction / uncertainty / visualisation / communication / knowledge modelling

1 Introduction

The way we visualize information related to radiological releases in emergency situations and associated uncertainties is of extreme importance for decision-making, both for experts involved in emergency management, as well as for the potentially affected population. Our current work builds on the results of PREPARE project especially on the work carried out for 1) information representation and 2) communication with the public (Marignac et al., 2016; Raskob et al., 2016). We extend the work further in two innovative directions: 1) we represent uncertainty visually and 2) integrate the tools in the decision-making cycle. As a common practice, experts produce a series of maps (e.g., ongoing or predicted releases, doses to the population, radioactive contamination, affected areas). They use different software tools and standards (e.g., specialized systems such as RODOS, GIS and Google maps) and apply different visualizations (e.g., colors, contours and measurement units). Decision-makers at different levels, from federal level to the mayor of a local community, and first responders need to interpret these maps and advise the population on protective behavior (e.g., consumption advice of vegetables from gardens of an affected area). Mass media often refer to these maps and publish them on-line (e.g., interactive maps). Maps also appear in social media (e.g., blogs and tweets). Affected population need to understand maps to know when to take certain actions in case of an emergency, and what to avoid (e.g., which roads to take during an evacuation, at what time).

A visual representation of the data conveys the uncertainty associated with the information used to derive decisions. However, conveying uncertainty only might increase the challenges a decision maker has to face in order to reach a well-informed robust decision. Pang defined uncertainty by presenting three types that can impact the comprehension and the decisions based on the data: 1) data uncertainty; 2) derived uncertainty and 3) visual uncertainty (Pang et al., 1997). Further, Pang introduced a concise taxonomy for visualization methods of uncertainty using glyphs including contour lines and pseudo coloring techniques (Pang et al., 1997). In another scholar work, Hunter defined uncertainty as the “degree to which the lack of knowledge about the amount of error is responsible for hesitancy in accepting results and observations with caution” (Hunter and Goodchild, 1993). Thomson developed a taxonomy of uncertainty relevant to visualization (Thomson et al., 2005), by defining core aspects of uncertainty as: accuracy/error, precision, completeness, consistency, lineage (provenance), subjectivity and interrelatedness.

Work in uncertainty can be categorized as uncertainty modelling and uncertainty propagation. This article focuses on visualisation of uncertainties on maps. It identifies main misinterpretations of radiation dispersion maps used for nuclear or radiological emergencies. We present maps and
robustness indicators as uncertainty communication and representation tool. We further share our recommendations on how to limit the introduction of new uncertainties for visual uncertainty representations.

The following section describes methods used for this research, followed by a section on relevant visual uncertainty representation approaches reported in literature. The article covers a dedicated section related to maps as a source of uncertainty. Further, our approach for visualisation of uncertainties and with robustness indicators are presented. The final section formulates recommendations on visualisation of uncertainties and general recommendations related to maps to be used during the decision-engineering cycle in case of radiological releases.

2 Method

A multidisciplinary research approach has been applied and collaboration among different expertise and scientific domains has been established: nuclear emergency experts, radiation protection officers, risk communication experts, modellers, researchers of social sciences, risk communication and information processing. The following methods have been applied:

- non-systematic, thematic literature and document review to identify the relevant theoretical state-of-the art work in visualisation of uncertainties and to identify the main challenges in understanding the role of maps in recent nuclear or radiological emergencies (maps related to measurements of limited traces of radioactivity in the air from radiological releases $^{106,103}$Ru, $^{131}$I) (Perko and Martell, 2019);
- modelling and cartographic solutions as examples to reflect with scientists and experts from various disciplines connected to radiation protection;
- non-participatory observation method applied in 11 national exercises in six countries throughout Europe, as well as one international exercise, with a total of 29 observation points, to assess understanding and interpretation levels of radiological maps used at the observed exercises;
- workshops and guided discussions in order to test the proposed maps and robustness indicators and collect comments (see Tab. 1).

Maps used for decision support in nuclear emergencies in general contain geographic information augmented with additional data such as dose rates and sheltering areas created by simulation software. The simulations are mainly based on several parameters such as weather prognosis, topology, source term and land use. Weather and source term are the main drivers of uncertainty in the assessment of a nuclear emergency (Leadbetter et al., 2018).

Source term uncertainty can be defined by a set of potential instances, e.g., worst, expected, and best estimate. Similarly, the weather uncertainty is defined by a set of different prognoses each with certain likelihood. By combining both of them, an ensemble of scenarios is created and evaluated, resulting in a set of maps for each possible map type like sheltering area.

At workshops and discussions five different cartographic solutions were presented as examples of a visual aid in case of a nuclear emergency. The examples of maps depicted a hypothetical but realistic case of a nuclear accident, with expected fallout of radioactivity (Fig. 1).

Table 1 summarises the feedback collection methods used to test the maps and the tools developed. For a comprehensive discussion on the stakeholders’ engagement process and methods used, we refer the reader to Perko et al. (2019a, 2019b).

3 Visual uncertainty representation approaches in literature

Bertin presented eight visual elements that are relevant to represent a concept visually: position, size, shape, orientation, value (lightness), colour hue, orientation, texture (Bertin, 1983). Bertin defines the variable as selective if it is able to immediately catch the attention of the viewer over the entire plan without considering individual marks sequentially.
Healey defined visual representation based on attentive and pre-attentive processing, where the pre-attentive basic visual properties are detected immediately by low level visual system and do not require high cognitive overload (Healey et al., 1996). Tufte identified an effective approach to visualize a concept as a way to give the viewer the greatest number of ideas in the shortest time (Tufte, 2001). Tufte identifies six principles in order to promote effective pre-attentive processing in the analyst/viewer’s visual system. The five main principles could be summarized as follows: 1) avoid data distortion, 2) support data comparison whenever possible, 3) reveal multiple levels of detail in the data, 4) integrate statistical markers, and 5) integrate text description into the visual representation.

Ware extended the concepts presented by Tufte through identifying three principles relevant to our work, similar to Bertin’s work. He referred to pre-attentive processing as one of the important aspects in developing effective visualization where marks can be used. Further, he stressed the need of inclusion of viewers with colour blindness and also mentioned that the usage of words is effective to present conditions (Ware, 2012).

Some of the early experimental work to visualize uncertainty for map-based measurements was carried out by Goodchild. The main findings of the work identified colour lightness (“value”) as an ineffective method for encoding uncertainty on bivariate choropleth maps (Schweizer and Goodchild, 1992). In other words dark and light colours for encoding uncertainty on maps were not useful in conveying the meaning of uncertainty without prior training. Thus, decision makers do not perceive lightness and darkness as independent without briefing. As a result, decision makers in emergency planning should be briefed about the meaning of darker or lighter hues in order to result in better understanding of uncertainty and be able to trust the meaning of the uncertainty representation.

Evans developed an experiment to identify the effectiveness of the different options to represent uncertainty through dynamic display of spatial data reliability. Four options were compared: 1) static separate maps, 2) static integrated maps, 3) animated maps, 4) interactive maps (Evans, 1997). The work concluded that the static integrated display was the most effective to represent uncertainty for decision makers since it was less confusing. As a result, it is advised to integrate the data maps and uncertainty maps for decision makers to
represent uncertainty according to Evans experiment. While
data and uncertainty integration could provide an effective way
to represent and handle uncertainty, resorting to interactive
maps offers an opportunity to provide more information on
demand in order to justify or motivate a decision.

Letiner and Buttenfield developed a guide for encoding
uncertainty using a variety of attributes including saturation.
The work concluded that visualization of information
uncertainty/certainty significantly increases the number of
correct responses for making decisions (Letiner and Butten-
field, 2000). Credible and certain data was encoded with lighter
value or finer texture. Further, no difference in time for difficult
or complex tasks was observed as a result of including
uncertainty information.

Edwards and Nelson developed four ways to encode data
quality and uncertainty in static graduated circle maps. The
methods compared included textual and uncertainty indicators
(color, value and texture). A graduated circle map to limit the
number of levels of certainty or uncertainty was used which
resulted in a significantly better display for the uncertainty
according to the findings. The graduated circle map was
compared as separate display and integrated where the display
(uncertainty and data) yielded the best results (Edwards and
Nelson, 2001). The reason behind that is the separate display
offers more work for the user both perceptually and cognitively
to construct the knowledge representation and process it. As a
result, the integrated visualisation is less cognitively involving
and demanding. Thus, to present information to radiological
decision makers and emergency decision makers it is
important to have a view where both data and uncertainty
meta data are combined in one display.

While inter-comparisons with different ensembles can be
an important part of building sound situational awareness for
an emergency it might not lower the uncertainties perceived.
As a result, careful selection of the model ensembles is
necessary to present a balanced view on the range of
uncertainties involved. Using reference areas has been an
important recommendation by the IAEA through Response
and Assistance Network (RANET, 2020). It is yet a
challenging task to represent uncertainty without introducing
further types or levels of uncertainty.

4 Maps as a source of uncertainty
recognized during exercises and
radiological events

Perko and Martell concluded that radiological maps are of
great use in visualizing the affected environment since they
reduce uncertainties and miscommunication (Perko and Martell,
2019); thus, offer an effective representation tool in
emergency management. Unfortunately, radiological maps
analysed in the context of this research were sometimes a
source of uncertainty, misinterpretation and caused communi-
cation issues. The preliminary findings were inconsistent with
our past experience which required further investigation.

4.1 Findings based on user feedback

There were many uncertainties on how to interpret
radiological dispersion maps observed during emergency
exercises. The following sentences taken from the observation
notes reflect these uncertainties: “The picture (plume) used for
the exercise has been misunderstood by some members.
Although we use this type of maps, this is not OK. There is a
need to use better maps that guarantees that these maps are
correctly understood”; “Our decision makers don’t under-
stand such scientific maps. Decision makers need other
maps.”; “The most important information is missing on this
map: intervention doses (it is not clear from the picture
whether is this an ongoing release or prognoses), is it
controlled release and what is duration of the release.”; “The
expert group sends by email to decision makers the maps and
doses: they received back a lot of questions by decision
makers—more clarity in the maps is asked.”; “Misdunder-
standing regarding the release and the map: How to
understand the (below) 6 km?”; “Communication cell: Maps
are discussed, however it is not easy for public information
officers to understand what they depict.”; “Measurement cell:
Coloured maps produced by JRODOS and HYSPRIT—
Format of the results have not been pre-defined (explanatory
legends were missing)”; “PR asked for a copy of the maps and
the measurements. A decision has been made to publish maps
showing the plume. PR asked who is going to prepare
explanatory notes about the maps and what extent of
uncertainty we have regarding the data.” (Perko et al., 2019b).

4.2 Summary of gaps identified

The following issues in visualisation on maps have been identified:
- maps lacking contextual information (e.g., on-going
release or predicted release; missing legend);
- non-unified and diverse measurement units were used to
describe the same attribute (e.g., mSv/h and mR/h);
- diversity of colors has been used unrelated to the meaning
of the colour (e.g., blue for the extremely low release,
below legal norms);
- zones for protective actions indicated using country
borders;
- scientific uncertainties not presented (e.g., related to the
release time, meteorological conditions), low doses
presented in many different ways (e.g., white colour, blue
colour and units), no indication of health impact.

While gaps and issues in maps can limit their usefulness,
they can be used as an effective means to build situational
awareness and effectively represent uncertainty when proper
design and usage guidelines are followed. In section 5, we
propose recommendations addressing the different issues that
showed up during the early versions of tools while testing.

5 Proposed uncertainty visualisation
guidelines for maps

In order to support decision makers to process complex
details while reducing heavily cognitive consuming details, we
list below the design guidelines for the development of visual
uncertainty representation tools (maps and robustness indica-
tors) based on our literature review and experiments:
Promote selective perception of the eye and emphasize the important regions and points;
- Support retrievability to provide explanation/reasoning behind the recommendation;
- Identify actionable recommendations in different uncertainty levels; whenever possible opt for robust adaptive strategies;
- Address colour blindness or low illumination conditions;
- Fuse different uncertainty magnitudes in one uncertainty index (e.g., source and measurements);
- Limit the number of uncertainty levels; keep them from 2 to 5 levels maximum; less levels are easier to reason with and make decisions based on them;
- Limit the introduction of new uncertainty in the visualization process;
- Plan for training or briefing the decision makers through focus groups and group exercises or concise tutorials before usage of the uncertainty indicators;
- Express conditions and preconditions textually in the design and avoid representing them visually.

6 Proposed robustness indicators for the uncertainty level of data presented at a map

The purpose of the robustness indicators is to tell end-users if a result is appropriate for decision making indicating the range of uncertainty/quality linked with it. For testing the approach in the panels, a prototype was realised in JRODOS. Assuming that the source term and the weather data have different classification rules, there is a need to find a classification of results that is based on the two input parameters. A colour code with five colours is proposed to indicate the level of uncertainty (Table 2) and the letters (see Fig. 2) in order to make the robustness indicator functional for end-users with deficiencies of colour vision or dyschromatopsia.

7 Recommendations related to visualisation of uncertainties through maps

The recommendations related to visualisation of uncertainties through maps are following:

| Endpoint                                      | Early phase (pre-release and release) | Early phase based on ensemble modelling* | Early phase based on data assimilation (food and source term)** | Transition phase | Long-term recovery phase |
|-----------------------------------------------|--------------------------------------|------------------------------------------|---------------------------------------------------------------|------------------|--------------------------|
| Dose maps                                     | red                                   | yellow                                   | red-yellow                                                   | yellow           | green                    |
| Dose rate maps                                | red                                   | yellow                                   | red-yellow                                                   | yellow           | green                    |
| Countermeasure areas                          | red-yellow                            | yellow                                   | red-yellow                                                   | yellow           | green                    |
| Plume arrival time                            | red-yellow                            | yellow                                   | n.a.                                                         | n.a.             | n.a.                     |
| Concentration in feed and foodstuffs          | red                                   | yellow                                   | yellow-green                                                | yellow           | green                    |
| Concentration in rivers from run-off          | red                                   | n.a.                                     | n.a.                                                         | yellow           | n.a.                     |
| Concentration in rivers from direct release   | red-yellow                            | n.a.                                     | n.a.                                                         | yellow           | yellow                   |
| Concentration in lakes and reservoirs         | red                                   | n.a.                                     | n.a.                                                         | yellow           | yellow                   |
| Concentration in marine food products         | red                                   | n.a.                                     | n.a.                                                         | yellow           | yellow                   |
| Inhabited area countermeasures                | red                                   | yellow                                   | yellow                                                       | yellow           | green                    |
| Food countermeasures                          | red                                   | yellow                                   | yellow                                                       | yellow           | green                    |

*: indicates that performance should be increased if ensembles are very close; **: as long as release is on-going assimilation of source term is uncertain.

Table 2. Indicator system based on five colours.
In order to aid the decision-making on the various countermeasures, a range of additional information should be available on maps besides the radiological situation (e.g., cities, population size, roads, drinking water reservoirs, evacuation routes etc.). However, since it is also important to keep the maps simple, interactive interfaces should be used where different layers with additional information could be turned on and off when needed;

- The design of the maps should be carefully thought through to make sure that it represents information in the most comprehensive way. The choice of colour coding should take into account existing codes that are already in use, the way different colours are perceived by people (e.g., red = danger); it should have enough contrast with the base map and be visible for people with disabilities;

- Maps should include informative legends with supplementary information on uncertainty among other things;

- It is extremely hard for people who are not used to maps and have not received any training to start using them in an emergency situation. Therefore, appropriate training and exercises for the use of maps are needed for the various stakeholders that will need to be involved in the decision-making;

- Where possible, uncertainty should be indicated on the maps and there are several solutions to how these could be presented, for example by varying brightness of colours, level of transparency and colour saturation, using glyphs and error bars. However, this representation will have to be situation-specific, since findings showed that even the expert participants were unable to articulate what their preferred uncertainty visualization methods were because they were convinced that this strongly depends on the task;

- Providing actionable recommendations is an important step towards increasing the value from the uncertainty representation whenever possible and applicable. When actionable recommendations are coupled with division of the map into zones and regions that offers better support for the decision maker and increases the trust in the uncertainty representation and communication;

- Support for examining patterns and distributions in the map is useful in addition to magnitudes to identify robust decisions;

- Emphasizing points and regions that might have a specific level of uncertainty helps focus attention of the decision makers to regions that the experts need to pay extra attention to the policies devised.

## 8 Conclusions

The work presented aims to identify effective approaches to visually represent uncertainty in the context of emergency planning with an emphasis on nuclear emergencies. Two tools were designed, developed and tested. The first was a map based visual representation while the second was a robustness indicator for the available information. A multidisciplinary approach was developed to identify and understand interpretation mechanisms of uncertainties presented on maps and robustness indicators by the different stakeholders. We identified the optimal approaches for application design and usage of uncertainty representation and communication. Further, we shared our best practices for relying on tools. Additional research work needs to be carried out in the future to further investigate potential causes for misinterpretation; the areas of work should target format, design, data and uncertainty. The future work should focus on interdisciplinary approaches from the fields of human computer interaction and social sciences. Future work should integrate theory based and empirical supported development of tools for visualization of uncertainties in particular, uncertainties during a radiological release.

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![Fig. 2](image-url)
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