UncertWeb

The *Uncert*ainty Enabled Model *Web*

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Deliverable 3.3

Tools for communicating and visualising uncertainties

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Task 3.3 Tools for communicating and visualising uncertainties

To maximise the uptake of the technology developed in UncertWeb we will implement open source tools to enable the visualisation and communication of the uncertain output of the service chains. Communication and visualisation of uncertainty requires intuitively appealing representations. In fact, humans can deal with uncertainty very well, as demonstrated in every-day life where we must cope with obvious uncertainties such as tomorrow's weather or the value of stock market shares. Among the many alternatives, approaches that will be implemented and tested are dynamic visualisation of possible realities in animation mode, confidence limits, and whiteness blurring. As with expert elicitation, this will be done using established, appropriate methods and quality standards. The tool developed will be a thick client which integrates seamlessly into the UncertWeb infrastructure.

Active partners: UOM, WU, AST, NILU, CNR

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Executive Summary

Efficient use of uncertainty information by various categories of users of the ModelWeb requires the development and implementation of uncertainty visualisation techniques. This deliverable presents i) the jStat client library for plotting uncertainty characterised by UncertML probability distributions and ii) a web-based (thin) client for uncertainty visualisation of spatial, temporal and spatio-temporal data in model inputs, outputs and intermediate results. The architecture, client implementation and visualisation service of these open source tools are presented in detail.

The uncertainty visualisation techniques implemented in the tools are not new but were derived from the scientific literature. A literature review showed that many different techniques have been developed over the years, with the adjacency method (i.e. an image of predictions next to an image of the associated uncertainty) is most popular with non-experts while interactive methods that provide detailed information at user-selected locations and time points are more appropriate for experts. Both methods were therefore implemented.

A requirement analysis carried out by the use cases of UncertWeb resulted in a list of data types for which uncertainty visualisation is required. Both continuous-numerical and categorical data types occur, and data that vary in space, time and space-time. Positional uncertainty was considered less important and was therefore excluded.

The open source tools described in this deliverable are prototypes that will be further developed and tested in the use cases in the final year of the project.

Contents

1 Introduction

The model web provides a facility to chain models and let users derive an intended product by selecting the right sequence of models and feeding each of the models with the required input data. Uncertainties about model inputs and the models themselves propagate through the chain, and this can be analysed using methods developed and implemented within the UncertWeb project. In this way the uncertainty about the final product can be calculated and reported to the end-user. One additional problem, however, is that end-users are typically not experts in statistics and may find it difficult to interpret the standard output of an uncertainty propagation analysis. It is therefore necessary to also work out and implement tools for visualisation and communication of uncertainties. This deliverable reviews existing uncertainty visualisation methods and makes a selection of methods that are implemented as web-based UncertWeb tools. It also describes the architecture of the tools and illustrates their functioning with examples.

Visualisation of uncertainty about environmental data is complex for several reasons. First, there are many types of data. Some data are measured on a categorical scale (e.g. land use, crop type), others on a continuous-numerical scale (e.g. temperature, soil pH, concentration of air pollutants). Second, data can vary in time, space, space-time or be treated as constant in space and time. Third, uncertainty can relate to the position of spatio-temporal objects as well as to their attribute values. Fourth, uncertainty is a difficult concept that can be described in various ways but always includes a fair amount of abstraction. In UncertWeb, a statistical or probabilistic approach is taken whereby uncertain environmental variables are characterized using probability distributions. These probability distributions can be very complex and may involve the specification of temporal and spatial correlations, cross-correlations and non-stationarities. As a result of the many complexities it is a real challenge to visualise uncertainty in an understandable way to non-statisticians. Visualisation of uncertainties in geospatial data may be complex but it is also important because it helps to understand the data and their reliability. In UncertWeb, visualisation of model results, input data or intermediate results and their uncertainties plays an important role in the application scenarios.

The visualisation tools presented in this deliverable were realised as thin instead of thick clients to ease the integration of the visualisation tools into the workflows. Furthermore, the requirement phase of the application scenarios had outlined specific goals that the visualisation tool should satisfy. The tools presented in this deliverable have been chosen and implemented with these requirements in mind and many of these will be applied in the final year of UncertWeb when the application scenarios are executed.

1.1 Structure of Deliverable

The deliverable is structured as follows. The remainder of this chapter gives definitions and acronyms. In Chapter 2 a summary of the requirements for visualising uncertainties from the application work packages in UncertWeb is given. Chapter 3 gives an overview of existing uncertainty visualisation methods collected in a literature review and usability assessment of relevant methods. The development, implementation, and evaluation of the UncertWeb visualisation tools are described in Chapter 4. Finally Chapter 5 gives conclusions on the presented work. In the Appendix, the complete responses to the requirement questionnaire are given.

1.2 Definitions

In order to ensure the use of a standard set of terms the following definitions are adhered to throughout the document.

Model web / Model chain: chain of model components connected through web service interfaces.

Model component: representation of a process or series of processes implemented as computer code, often called a simulator.

Model input: value, or series of values (if a spatial field or time series), that is provided to the model component to evaluate the model (likely to include parameters in the model component, initial and boundary conditions for the model component).

Model output: value, or series of values (if a spatial field or time series) produced by the model.

Uncertainty: lack of knowledge about the state of the environment.

Error: departure of a model of reality from reality itself.

Accuracy: degree to which an estimate of reality is close to reality.

Visualisation: means of communication with end users using graphics.

1.3 Acronyms

CDF	Cumulative Distribution Function
CI	Confidence interval
GML	Geography Markup Language
IQR	Inter quartile range
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
NetCDF	Network Common Data Format
O&M	Observations & Measurements
OGC	Open Geospatial Consortium
PDF	Probability Distribution/Density Function
POE	Probability of exceedance
SOS	Sensor Observation Service
UncertML	Uncertainty Markup Language
UPS	Uncertainty Proxy Service
UTS	Uncertainty Transformation Service
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Mapping Service

2 Visualisation requirements

This chapter summarizes the results of a questionnaire that was used to define the requirements of the uncertainty visualisation tool. The questionnaire was completed by all four use case partners (i.e. Work Packages 4 to 7) and helped to define which uncertainty visualisation components the tool must include to ensure that the use cases can visualise the uncertainties resulting from their model chains in a meaningful way. The questionnaire itself is provided in the Appendix.

2.1 General requirements

In UncertWeb the visualisation of uncertainties is necessary for model inputs, intermediate results, and for outputs of the model chains of the four application work packages WP4-7. Following the paradigm of UncertWeb, the visualisation tool development has to focus on the visualisation of quantified, probabilistic uncertainty. In Deliverable D8.1 the requirements for visualisation within the project were collected from the general requirements Deliverables D4.1-7.1.

For the development of the uncertainty visualisation tools these general requirements were rephrased into detailed requirements:

- Support uncertainty visualisation for points in space and time, i.e. uncertainty visualisation for non-spatial, non-temporal attributes.
- Support uncertainty visualisation of continuous and categorical data.
- Support uncertainty visualisation of spatial, temporal and spatio-temporal raster and vector data.
- Support different formats of raster (netCDF-U) and vector data (O&M, JSON) for uncertainty visualisation.
- Support different (UncertML) representations of uncertainties, i.e. realisations, statistics and distributions.
- Support interactive, web-based uncertainty visualisation.
- Support different uncertainty visualisation methods for different user types.

2.2 Specific requirements by work package

To collect more detailed information about the input data and model results per application work package that need to be visualised with associated uncertainties, an additional questionnaire was sent to work packages 4 to 7. Therefore, the consolidated requirements on **uncertainty type, data type, spatial data, data format, temporal data** and **data distribution** taken from the general requirement documents were presented to the participants and feedback was requested whether these requirements meet the specific requirements from each work package. Furthermore feedback was requested on missing requirements, visualisation preferences, whether positional uncertainty needs to be considered as well, which input data and intermediate results should be visualised and which users are expected. Example data were requested for each dataset that needs to be visualised.

Detailed responses to the requirement questionnaires are given in the Appendix ("Uncertainty visualisation requirement questionnaires"). In Table 1 the updated list of data, format, and uncertainty representation requirements to be supported by the visualisation tool is given with data examples from each work package. Although the table mentions positional uncertainty,

from the requirements in the project it turned out that positional uncertainty was of minor importance. Therefore, support of positional uncertainty is not considered as a requirement for the tool development in UncertWeb.

The requirements of visualisation methods also include the target audiences that the visualisation tasks aim for. The audiences range from domain experts, statisticians, authorities/decision maker/policy makers to the general public.

Table 1. Summary of specific visualisation requirements per work package.

Uncertainty type	Spatial data	Temporal data	Data type	Data format	Data distribution	WP4	WP5	WP6	WP7
Position	Spatial	Non-temporal	Continuous	Vector	Univariate	e-Habitat: SelectedArea			
Attribute	Spatial	Non-temporal	Continuous	Raster	Univariate	Mahalanobis distance			
			Continuous	Vector	Univariate				physical data - travel time
			Categorical	Raster	Univariate	land cover			
			Categorical	Vector	Univariate		land capability classification, initial cropping pattern		
		Temporal	Continuous	Raster	Univariate			emissions, TAPM meteorology, background concentrations, output concentrations	
			Continuous	Vector	Univariate				activity diary data
			Continuous	Vector	Multivariate				time dependent activity schedule
			Categorical	Vector	Univariate		LandSFACTS simulated cropping pattern		socio-economic data
	Non-spatial	Non-temporal	Continuous	-	Univariate	e-Habitat:HRI, summary statistics	summary statistics	summary statistics	summary statistics
			Continuous	-	Multivariate		crop transition matrices		
			Categorical	-	Univariate	summary statistics	summary statistics		
		Temporal	Continuous	-	Univariate	time series of summary statistics	time series of summary statistics	time series of summary statistics	time series of summary statistics
			Categorical	-	Univariate		regional yield per crop type		

3 Review of uncertainty visualisation methods

To fulfil the requirements summarised in Chapter 2, a review of existing methods for visualisation of spatio-temporal uncertain data was conducted. This review does not claim to be comprehensive, given the large number of methods reported in the literature. The aim was to get an overview of well-established and tested methods to cover the range of different data and user requirements in UncertWeb. The focus of the review was on visualisation of spatial data, i.e. maps, which can be extended to spatio-temporal visualisation by adding the temporal dimension. From the existing methods, a categorisation was developed to allow selection of suitable methods for each specific requirement listed in Section 2.2. Finally also usability studies on visualisation methods were analysed to evaluate the efficiency of uncertainty communication for different user groups. The methods selected for implementation are described in detail in Chapter 4.

3.1 Review of existing methods

For the visualisation of uncertainties in attributes, a large number of methods were developed and reported in the literature. For spatio-temporal data the visualisation of uncertainty adds an additional parameter to the map visualisation. Here it is important to avoid an overload of information that dilutes the explanatory power of the representation.

3.1.1 Non-spatial, non-temporal and temporal visualisation methods

For non-spatial and non-temporal data a number of simple statistical plots can be used to visualise uncertainty represented by probability distributions. If the full probability distribution function is known, this can be visualised in PDF or CDF plots. From the PDF or CDF other statistics can be derived, such as exceedance probability, cumulative probability or interval probability. As these statistics summarise the full PDF in single numbers, they can for example be used in time series plots, showing the variation of these statistics over time.

For samples or realisations or if only error limits are given, error bars, interquartile range, confidence intervals and box plots can be used to show the distribution of values. These can also be used in time series plots. For time series, it can also be an option to visualise a set of realisations in one plot, showing the width of the possible values for each point in time as shown in Figure 1.

Uncertainties about categorical data can be visualised using histograms, stacked bars or pie charts for the number of observations for each of the categories (see Figure 2 for an example). Stacked bars with a limited number of categories could be used for time series visualisation.
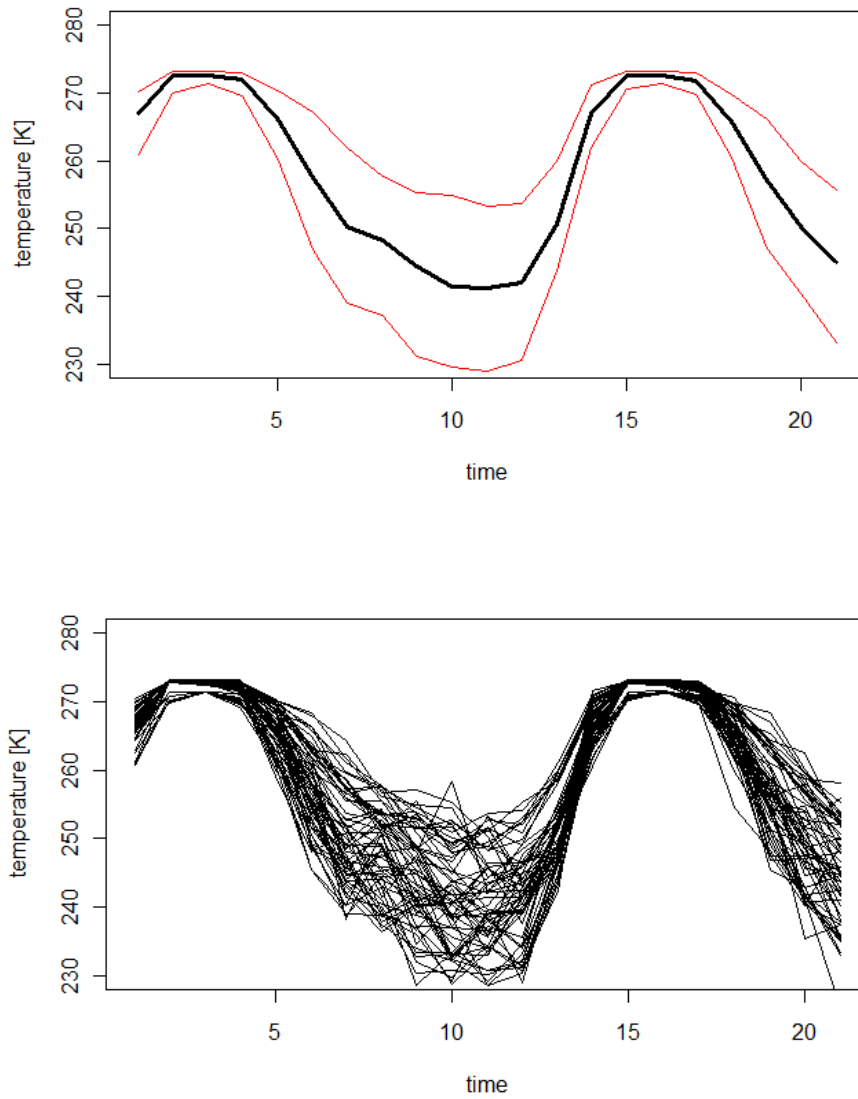
Figure 1. Examples of time series visualisation using confidence intervals (top, bold line represents the estimated value, coloured lines above and below represnt the limits of a symmetric 95% confidence interval) and realisations (bottom, 50 realisations overlaid on top of each other).
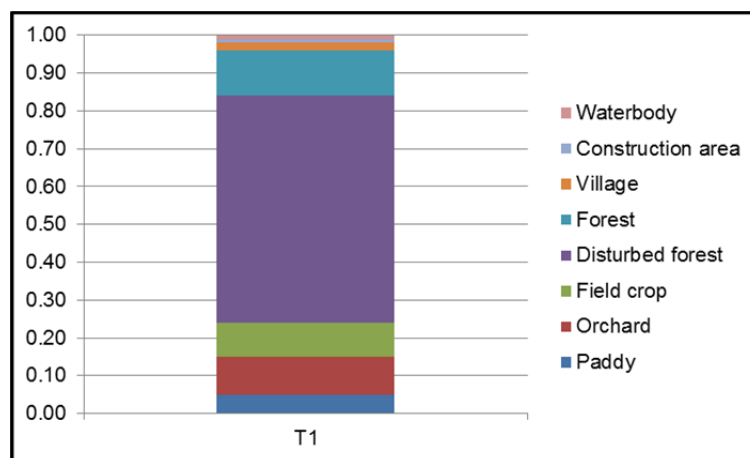

Figure 2. Example ofvisualisation of categorical data using stacked bars. Each land use type has a probability of being the true landuse and hence the probabilities add up to one.

3.1.2 **Spatial and spatio-temporal visualisation methods**

For uncertainty visualisation of spatial data it is important to distinguish between presentation techniques and presentation modes. General presentation techniques are (i) adjacent maps, (ii) sequential presentation and (iii) bi-variate maps [MacEachren 1992]. These techniques can be presented in three modes: static, dynamic and interactive. As an extension of static maps, time can be added as an additional dimension allowing the visualisation of spatio-temporal data in a dynamic or interactive way.

A common example of **adjacent maps** is the display of maps of the mean and standard deviation (as uncertainty measure) next to each other. Adjacent maps can be represented in a static, dynamic and interactive way. The dynamic representation could be an animation of time series of adjacent maps. The interactive mode is often realised by showing both maps on top of each other and giving the user the control to switch ("toggle") between both maps. **Sequential** presentation is usually shown in dynamic mode, e.g. as animation of realisations, quantiles or scenarios [Ehlschlaeger 1997].
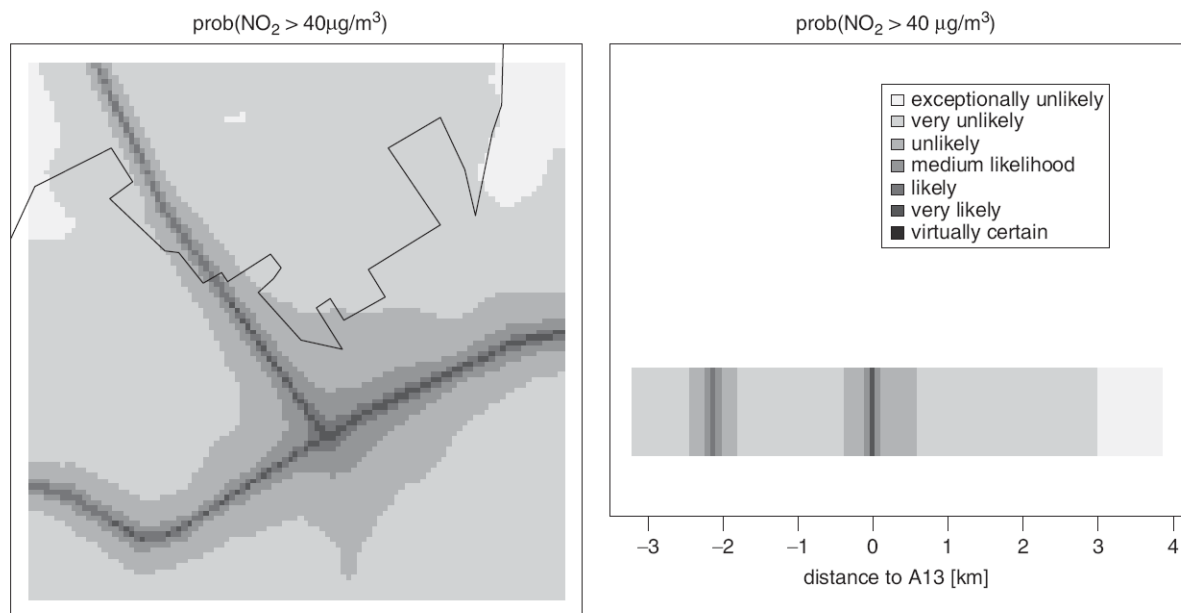

Figure 3. Probability of exceeding 40 g/m³ NO2 by IPCC terminology (Van de Kassteele and Velders 2006).

For **bi-variate** maps many applications exist. General (qualitative) uncertainty can be represented using the **focus metaphor** developed by [MacEachren 1992]. Uncertain regions are shown blurred by fog overlay, coarser resolution, contour fuzziness or reduced sharpness of patterns. A static technique called **whitening** uses colour hue to represent the value and saturation to represent uncertainty [Hengl 2003]. The amount of white colour, proportional to the error is mixed with the hue which represents the prediction. A similar result is obtained by the technique of pixel mixing in which uncertainty is represented by adding amounts of white pixels proportional to the normalised prediction error [Hengl 2006].

Several authors present overlays to represent uncertainties. Examples are texture overlay by **contouring**, using coloured lines [MacEachren 1998]and **hierarchical spatial data models** representing higher uncertainty with a coarser grid tessellation [Kardos 2003]. The concept of contouring or isolines can be extended to **animated isolines** [Fauerbach 1996]. Another possibility to combine visualisation of value and uncertainties are compound point symbols called **glyphs** [Cliburn 2002]. One application example is wind vector uncertainty using arrow glyphs in a map representation. Thereby wind speed and direction are depicted by

arrow length and direction while the width of the arrow head represents the angular uncertainty. The uncertainty in speed is shown by additional arrow heads marking minimum and maximum values [Pang 2001].

Drawing contour lines or **exceedance probabilities** for a threshold are useful to include uncertainties into, e.g. air quality maps as shown by [van de Kassteele 2006] in Figure 3. Bivariate maps are also commonly used for interactive presentation of uncertainty. Fisher [1993] for instance, used **blinking pixels** to draw the user's attention to uncertain regions. Pebesma et al. [Pebesma 2007] present a **statistical dimension in GIS** with the Aguila software which stores the cumulative distribution function (CDF) of each pixel in a map and allows the user to navigate either through the percentiles to show the value maps or through the values showing the associated percentiles, in other words the probability of exceeding the value (Figure 4).
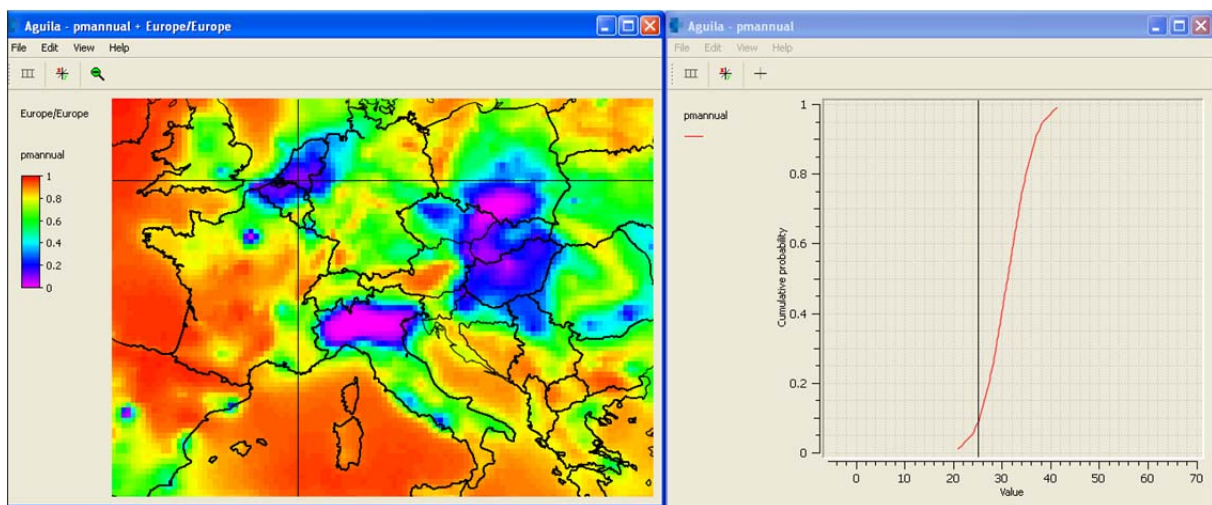

Figure 4. PM$_{10}$ concentration for Europe with uncertainites as displayed using the Aguila software. The left window shows the spatial distribution of the mean concentration, the right window depicts the CDF at the raster cell location selected in the left map window. The vertical bar in the right hand window represents an environmental threshold.

For visualising spatial categorical attribute uncertainty, the simplest method is using **adjacent maps** [MacEachren, 1992], which presents a map of the categorical data next to a map that quantifies its uncertainty. For example, Kempen et al. [2009] used a **map of the Shannon entropy** for the latter. The Shannon entropy measures the dispersion over categories and takes on a value between 0 and 1, where 0 means no uncertainty (100% probability for a single category, all other categories have zero probability) and 1 means maximum uncertainty (all categories have equal probability). Another method, named the "**double continuous approach**" [Hengl et al., 2004], visualises uncertain categorical maps to analyse ambiguity of each category and confusion among all categories. Instead of visualising each of multiple membership maps by grey or pseudo-colour scales, multiple memberships are visualised in combination where the categories' values are coded in hue and the confusion in whiteness. **Hierarchical spatial data models** [Kardos, 2003], is another way to visualise categorical data uncertainty. Finally, the **probability mapping method** [Logsdon et al., 1996] can be used to map the transitional probability between different categories in modelling dynamic change.

3.2 Usability and communication of uncertainties

To select useful methods it is not only important to check whether these fulfil the data requirements but also how users perceive and appreciate the way uncertainties are communicated. Thereby, it is likely that experience level and background of the user influences the preferred method. It may be that domain experts have a different understanding of the phenomenon and its uncertainty than a statistics expert or a non-expert user like a decision maker.

A number of usability studies have been carried out since the early 1990s, examining different methods and usability aspects. Evans [Evans 1997] assessed the Static Colour Bivariate Maps Flickering Animation method and Toggling. The Toggling method was least preferred by all users. MacEachren et al. [1998] assessed the Adjacent Maps Texture Overlay method and a Colour Model. The results showed that users preferred the Texture Overlay method for exploratory purposes and the Colour Model for presentation purposes. Cliburn et al. [2002] evaluated the usability of the Colour Model, Transparency method, and Glyphs method. Users with scientific backgrounds preferred the use of Glyphs, non-scientists preferred the Colour Model, while the Transparency method was preferred by decision makers. Aerts et al. [2003] compared the Adjacent Maps method and the Animated Toggling method. Users unanimously preferred Adjacent Maps slightly over the Toggling method. More recently, Gerharz et al. [2009] assessed Adjacent Maps, Whitening and the Statistical Dimension in GIS provided in the Aguila tool. The Adjacent Maps method was preferred by all users while the interactive method implemented in Aguila was found to be more suitable as an expert tool.

Senaratne et al. [2012] conducted a comprehensive web-based usability study using Contouring, Adjacent Maps, Symbols, Aguila and a first prototype of the UncertWeb visualisation client as described in Section 4.3 below. The prototype visualises continuous point data with time series values. Aguila, contouring and adjacent maps were used to visualise continuous raster data, while symbols visualisation was applied on categorical raster data. Participants were classified by their scientific background and their feedback was analysed separately. Results were analysed on performance (number of correct answers) and preference (selected as most preferable by the user). The prototype UncertWeb client showed the worst performance results especially for the non-expert group. Performance results were best for Adjacent Maps, Symbols and Contouring in all groups. When users were asked for their preference they chose most often Aguila, the Web Client and Contouring. Symbols were preferred least. For most users, especially non-experts, there was a discrepancy between performance and preference. While interactive methods were preferred, they performed badly when users answered questions about the data. It should be noted that the interactive methods were presented as videos allowing no true interaction by the user. Thus, poor performance results for Aguila and the UncertWeb client could be caused by the lack of interaction which made it less easy for users to understand and explore uncertainty. The results also showed that the first prototype of the UncertWeb client was rather difficult to use and understand. Solutions to resolve these difficulties were incorporated in the further development described below. As a conclusion the Adjacent Maps method was recommended for non-experts while Contouring, Aguila and the Web client were considered to be more useful for domain experts.

The findings above are in line with those of [Gerharz2009] indicating that interactivity with the data is appreciated by users. We hypothesise that interactive methods have more potential to be useful but the user needs to be guided carefully to interpret the visualisation correctly. However, all studies agreed, if assessed, that the presentation of uncertainty information is rather more helpful than confusing to the users.

4 Open Source Tools

The visualisation tools are developed as a web-based thin client to ease integration into the UncertWeb architecture. Based on the reviewed methods and usability results in the previous chapter, a number of methods were selected for implementation as described in Section 4.1. The developed tools comprise the client library jStat (Section 4.2) for plotting functionalities of UncertML distributions and the web-based client (Section 4.3) providing visualisation for spatial and temporal data using the jStat library. An evaluation of the tools is given in Section 4.4.

All developments are Open Source products and can be found on the jStat website[1] and the 52°North website[2]. Videos of the developed tools showing visualisations of spatio-temporal categorical and continuous vector data and spatio-temporal continuous raster data are available for demonstration purposes[3].

4.1 Visualisation methods in UncertWeb

From the identified methods for each parameter combination of attribute uncertainty, a number of reasonable methods are selected in the UncertWeb project. These methods cover continuous/categorical, spatial/non-spatial and temporal/non-temporal data focusing on univariate distributions. This is in accordance with the requirements identified in UncertWeb as shown in Table 2.

Table 2. Overview of implemented visualisation methods per uncertainty category.

Uncertainty type	Spatial data	Temporal data	Data type	Data format	Data distribution	Implemented method
Position	Spatial	Non-temporal	Continuous	Vector	Univariate	-
Attribute	Spatial	Non-temporal	Continuous	Raster	Univariate	Mean, Standard deviation, Variance, POE, CI, Interval Probability, Interval Exceedance Probability
				Vector	Univariate	
			Categorical	Raster	Univariate	Mode, Probability
				Vector	Univariate	
		Temporal	Continuous	Raster	Univariate	Animation (slider), Mean, Standard deviation, Variance, POE, CI, Interval Probability, Interval Exceedance Probability
				Vector	Univariate	
					Multivariate	
			Categorical	Vector	Univariate	Mode, Probability
	Non-spatial	Non-temporal	Continuous	-	Univariate	PDF, Box-and-Whisker plots, Error bars
				-	Multivariate	-
			Categorical	-	Univariate	Bar chart, Pie chart
		Temporal	Continuous	-	Univariate	Error bars, Realisations, POE, CI
			Categorical	-	Univariate	Probability for the mode

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[1]http://www.jstat.org/

[2]https://svn.52north.org/svn/geostatistics/main/uncertweb/

[3]http://giv-uw.uni-muenster.de/vid/

Following the results from the usability studies, we distinguish two categories of users in UncertWeb: experts and novices. Experts are considered domain experts or statisticians with knowledge in mapping and interpreting uncertainties in spatial and temporal data. Novice users are considered having only limited knowledge about the domain and little mapping and statistical background. The latter group might be more interested in a quick, simple overview of the results while the former group is expected to be interested in a more detailed exploration of the data. These assumptions do not imply that both user groups are restricted to the methods developed for their group. Novice users with deeper interest in the results might want to use the expert visualisation while experts might want to have only an overview of the uncertainties by looking at the simpler method.

In UncertWeb two approaches are applied to support users with different levels of experience. The method selected for novice users is the adjacent map method where value and uncertainty of a variable are shown separately to avoid confusion and overload of information in a single graphic. For expert users a multidimensional visualisation approach is chosen. This allows visualisation of spatio-temporal data with uncertainties in multiple windows, i.e. map, time series and statistical plots. The user can control which quantities are shown in the map and plots. Available non-spatial and non-temporal/temporal plot types, parameters and both methods are explained in the following sections.

4.1.1 Basic plots

The basic plotting functions available in the client are for non-spatial and non-temporal data. These could be summary statistics of regions or time periods or values at single points in space and time. For plotting continuous data, the jStat[4] library (described in Section 4.2) is used as shown for the combined PDF and CDF plot in Figure 5.For categorical data, the JavaScript library flot[5] to plot bar charts and pie charts is used, as shown in Figure 6.
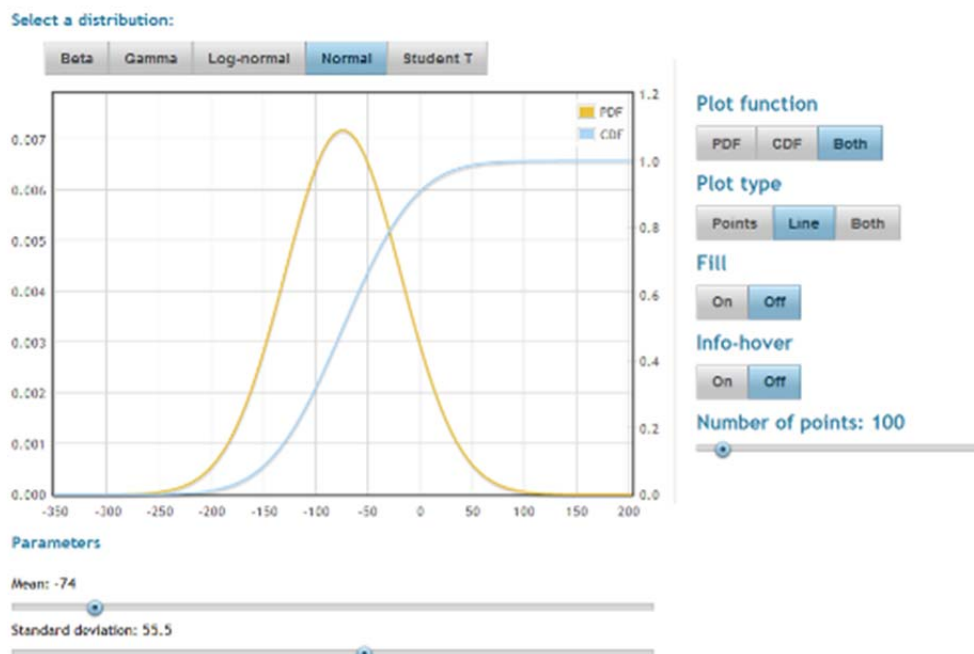

Figure 5. PDF and CDF visualisation using jStat.
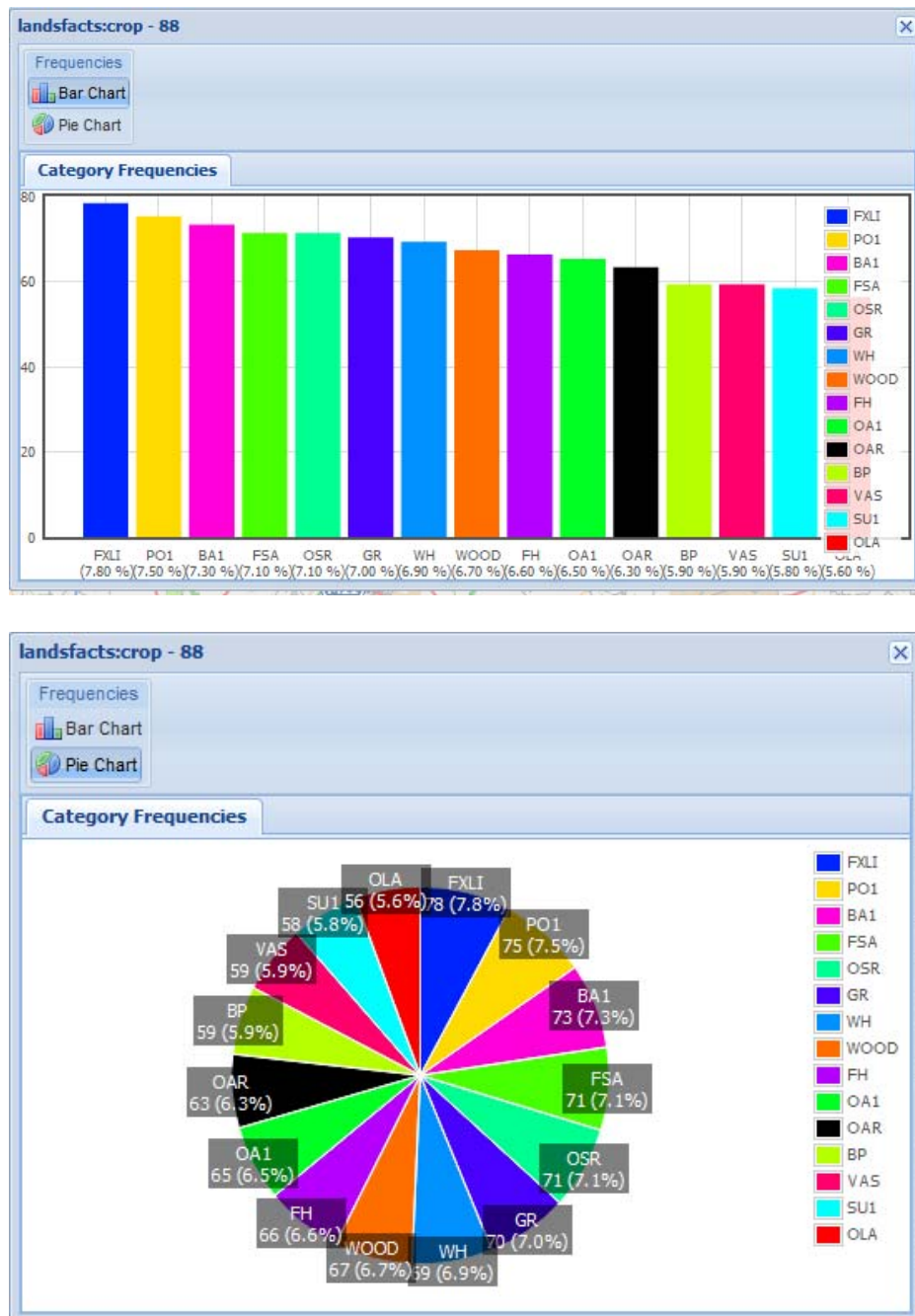
[4] http://www.jstat.org

[5]http://code.google.com/p/flot/

Figure 6. Visualisation of categorical data distribution as a bar chart with frequencies (top) and as a pie chart with probabilities (bottom).

4.1.2 **Time series plots**

Time series plots visualise the temporal behaviour of a non-spatial variable, i.e. values at one location or spatial constants. For the uncertainty, plots such as error bars can be used for each point in time showing the width of the distribution over the time. Examples of different visualisations for the same continuous variable are given in Figure 7.
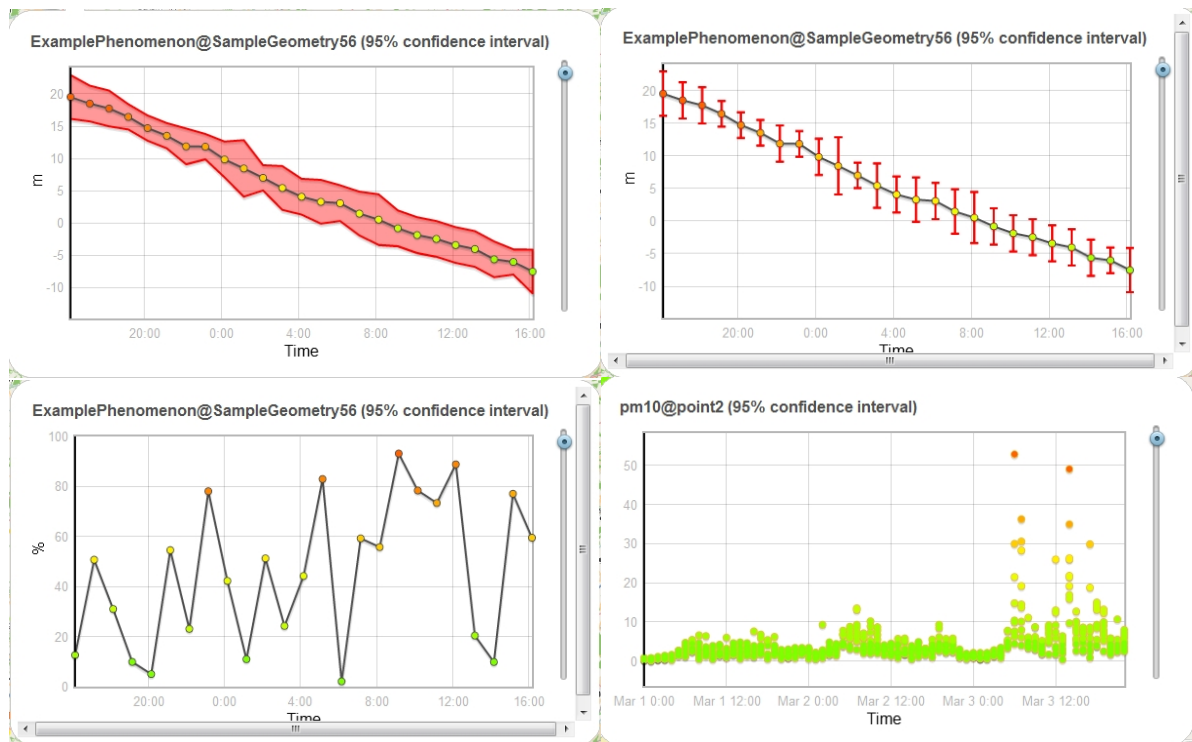
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Figure 7. For possibilities to visualise uncertainties in time series in the UncertWeb client: confidence intervals (top left), error bars (top right), probability of exceedance(bottom left) and realisations (bottom right).

4.1.3 **Adjacent map visualisation**

As explained before, adjacent maps simply show the value and uncertainty next to each other in two synchronised map windows. Thus, the map controls are connected for both maps, i.e. when zooming in one, the other one is zoomed in as well. The user should be able to choose the data shown in the map windows. For instance, besides visualising the expected value (mean) of the distribution with the uncertainty (standard deviation) also other visualisations can be compared, such as exceedance probability and mean as shown in Figure 8. For categorical data one map can show the mode of the categories while the other one shows the associated probability as shown in Figure 9.

This method is in particular useful for non-experts as it is possible to visualise the value and uncertainty next to each other.
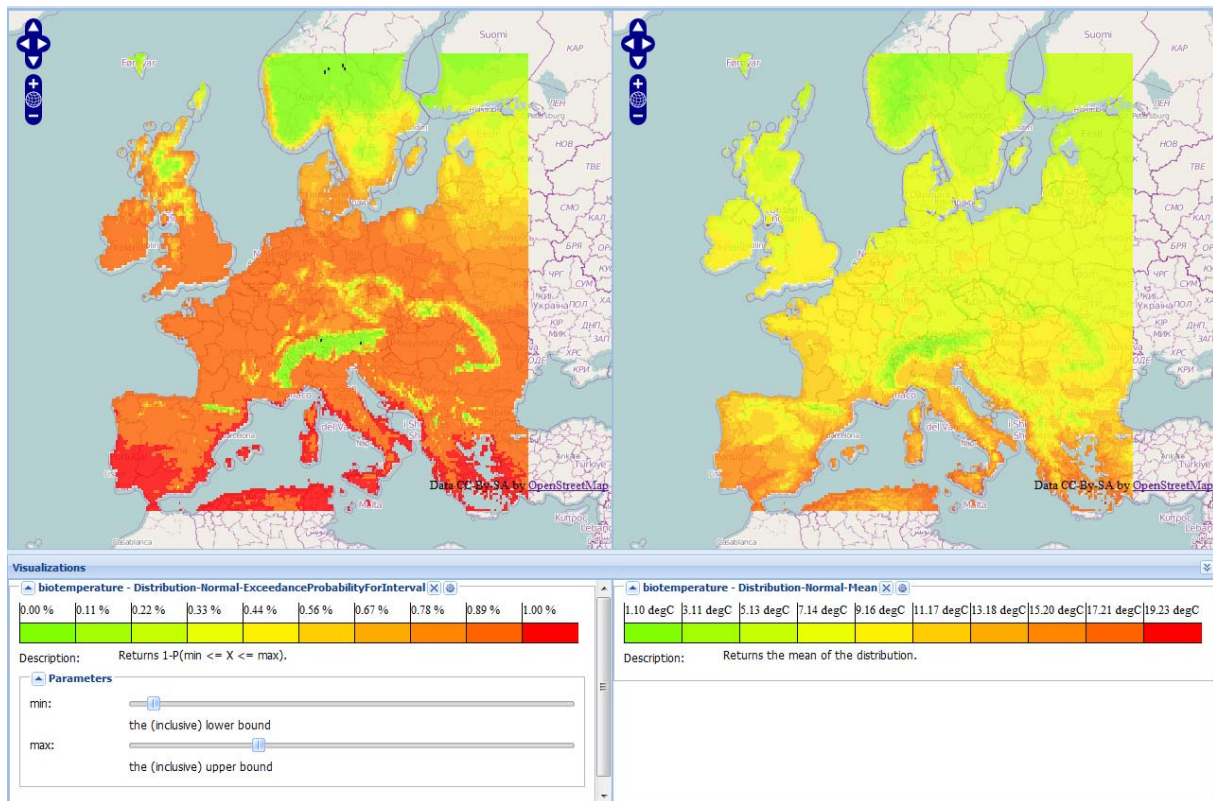
Figure 8. Adjacent map visualisation of exceedance probability (left) and mean (right) in the UncertWeb client.
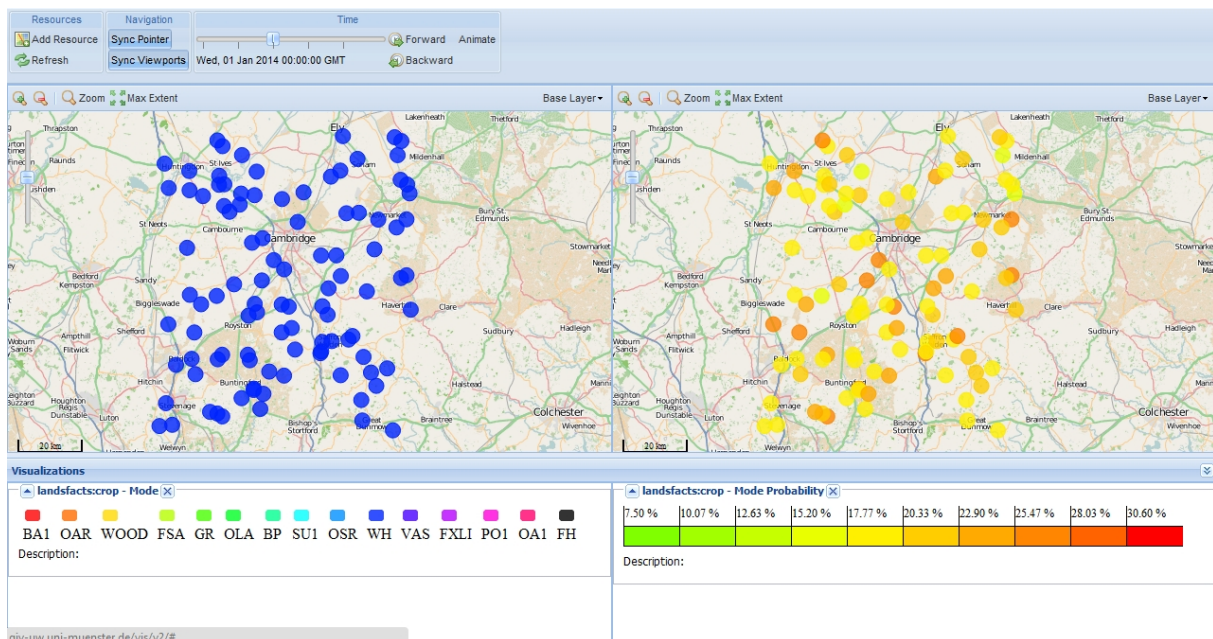

Figure 9. Adjacent map visualisation of the mode of land use categories (left) and the associated probabilities of the category mode (right) in the UncertWeb client.

4.1.4 **Multidimensional visualisation**

Multidimensional visualisation is used to visualise spatio-temporal uncertain data. Several methods for visualisation of non-spatial/non-temporal, temporal and spatial data were implemented to be used in combination for the visualisation of uncertainties in spatio-temporal data. This paradigm of multidimensional (space, time and uncertainty) visualisation is analogue to the stochastic dimension in a GIS realised in the Aguila software. Thus, a map

window can show the spatial distribution while a time series window displays the temporal variability at a selected location and a PDF or histogram plot allows the exploration of the uncertainty distribution at one particular point in space and time, as shown in Figure 10. The adjacent maps concept can also be combined with statistical and time series plots in the multidimensional approach, as shown for continuous data in Figure 11 and for categorical data in Figure 12.

This concept allows the user to control the amount of information shown by the client and is therefore considered an expert tool. Using sliders, the user can choose interactively the point of interest for the PDF plot, the location for which the time series is shown, the point in time for the displayed map and the probability or threshold for the value shown. For the map, the user can chose the quantity of the variable to be shown from a list of methods as shown in Table 2.
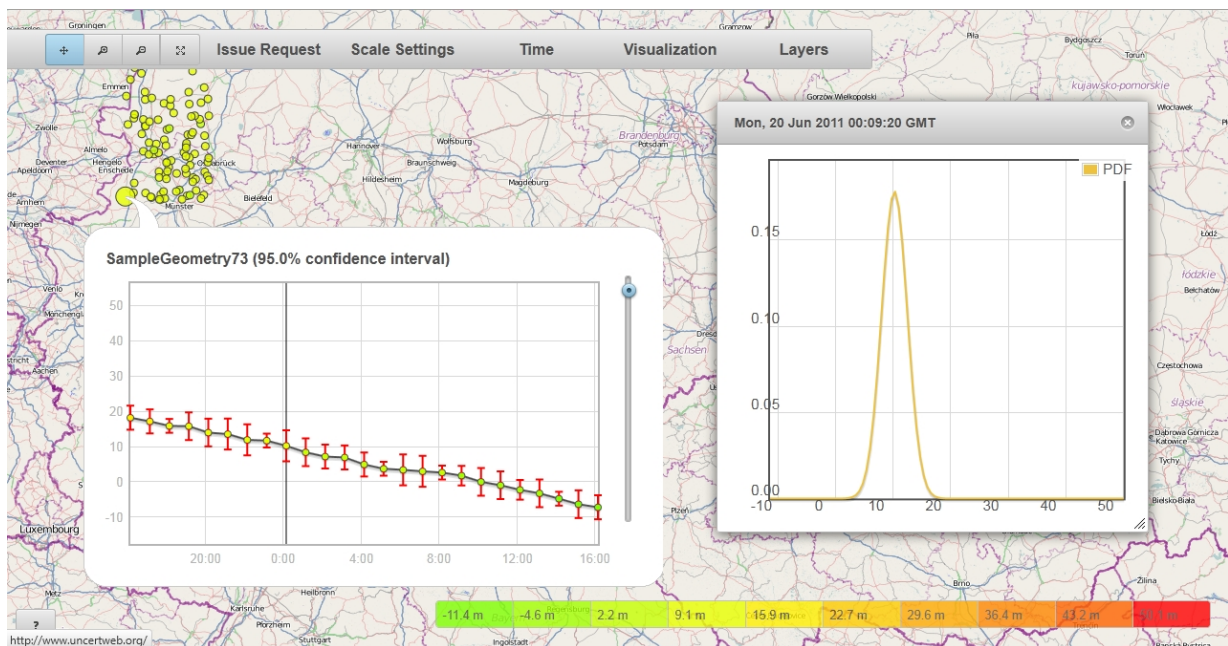

Figure 10. Uncertainty visualisation client showing a point measurement time series of continuous data with error bars of 95 % confidence intervals and the probability distribution function for the respective measurement point. Note that the graphics refer to a specific spatial location (big yellow circle) and can be displayed for any of the available locations on the map (yellow circles)
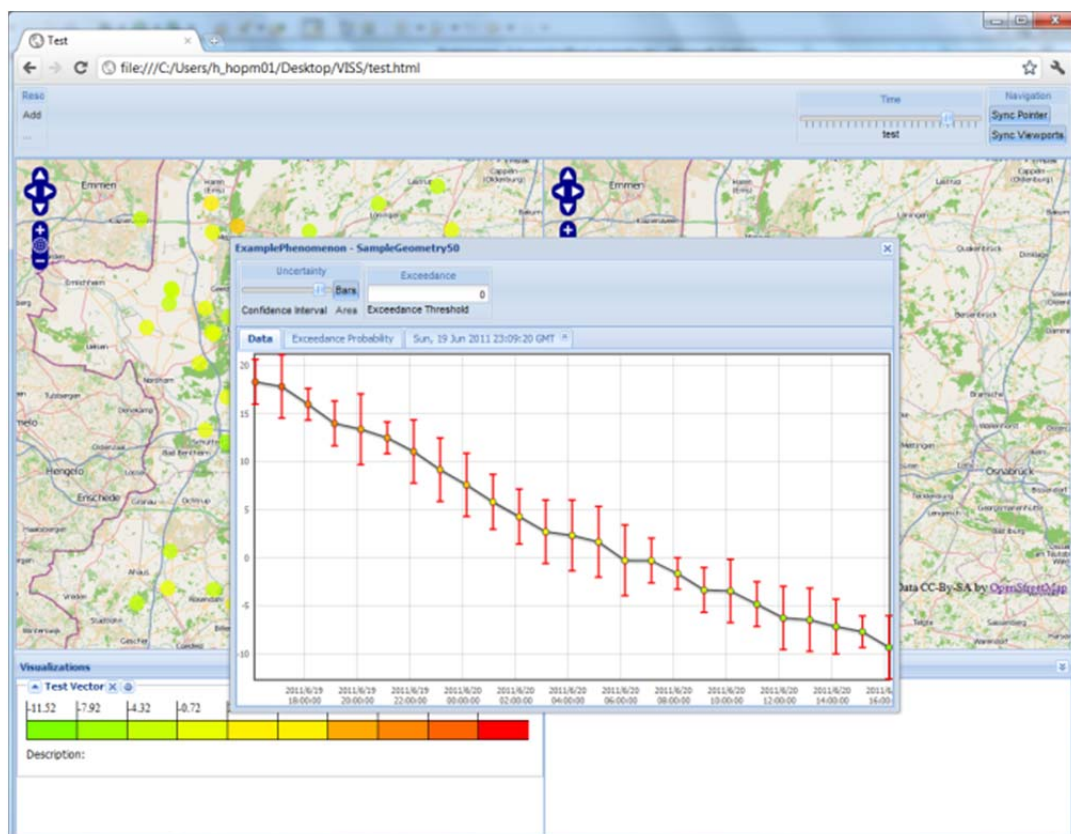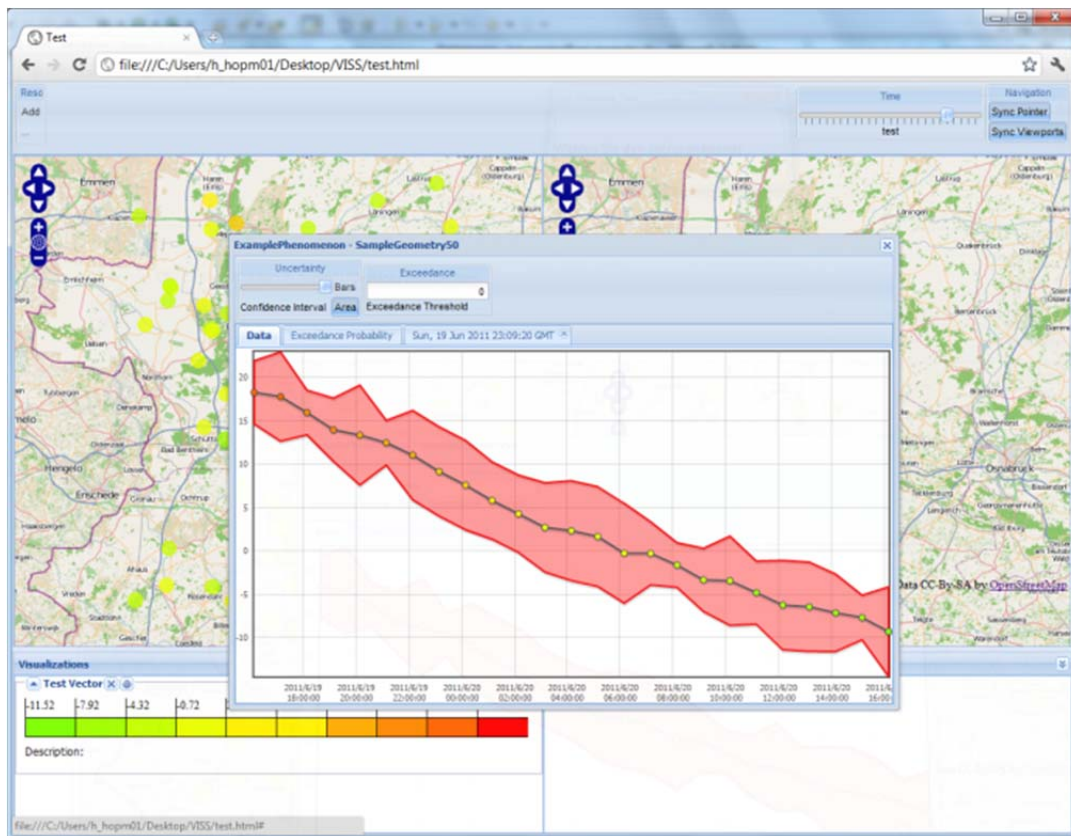
Figure 11. Adjacent maps visualisation with time series showing confidence intervals (top) and error bars (bottom). Note that the graphics refer to a specific location on the map and can be interactively plotted for other locations with time series information too.
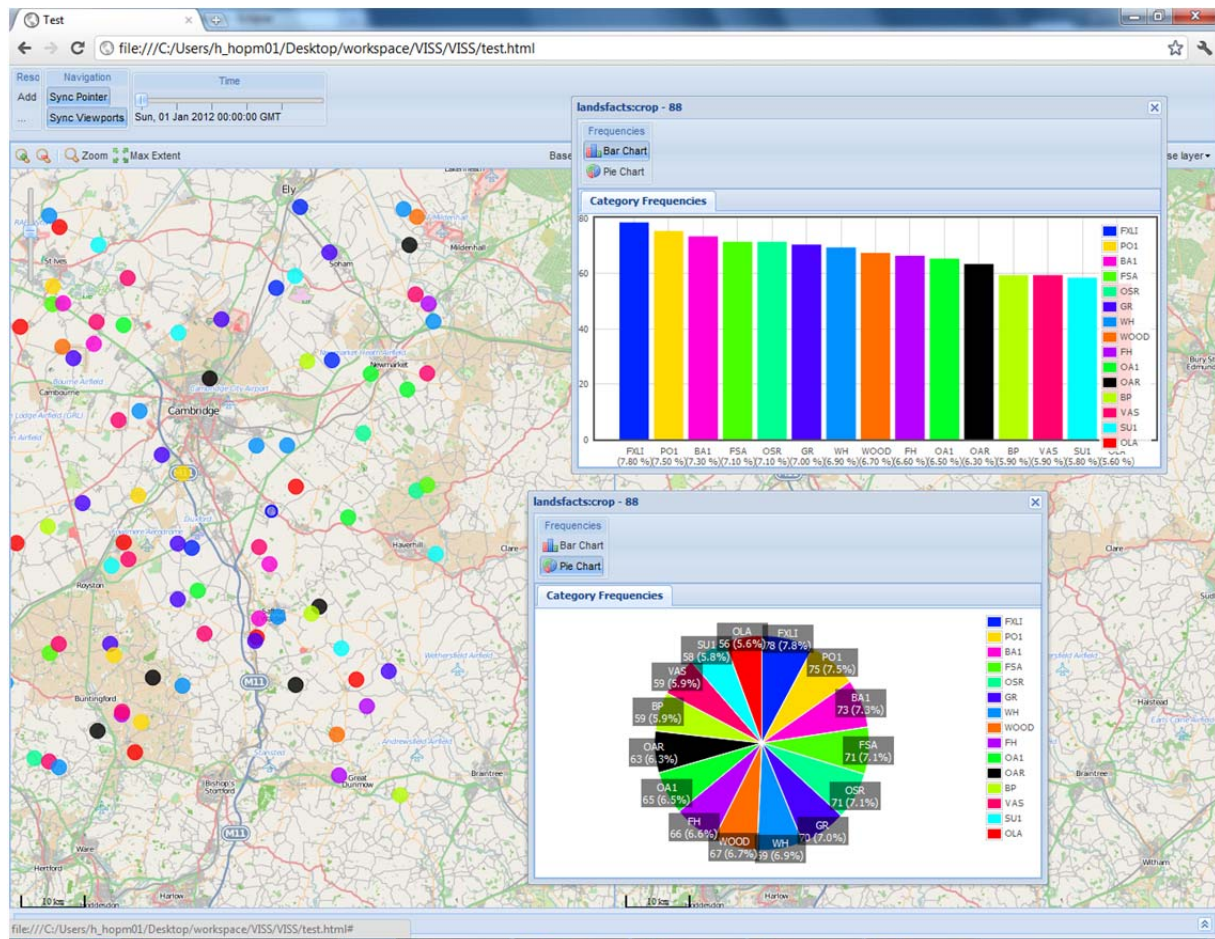
Figure 12. Visualisation of uncertain categorical vector data with bar chart and pie chart plots for one location and point in time.

4.2 JavaScript library for statistical plots

jStat is a statistical software library written in JavaScript. Initially developed as part of the elicitation tool (Deliverable D3.1), jStat provides a lightweight visualisation component for web-based tools.

The first release of jStat focussed solely on modelling and visualising continuous probability distributions. The core component allowed users to evaluate the probability density function (PDF) and cumulative distribution function (CDF) of the normal, log-normal, beta, gamma and non-central Student's T distribution. A visualisation component could then plot these functions using flot[6], a jQuery plug-in (Figure 13).

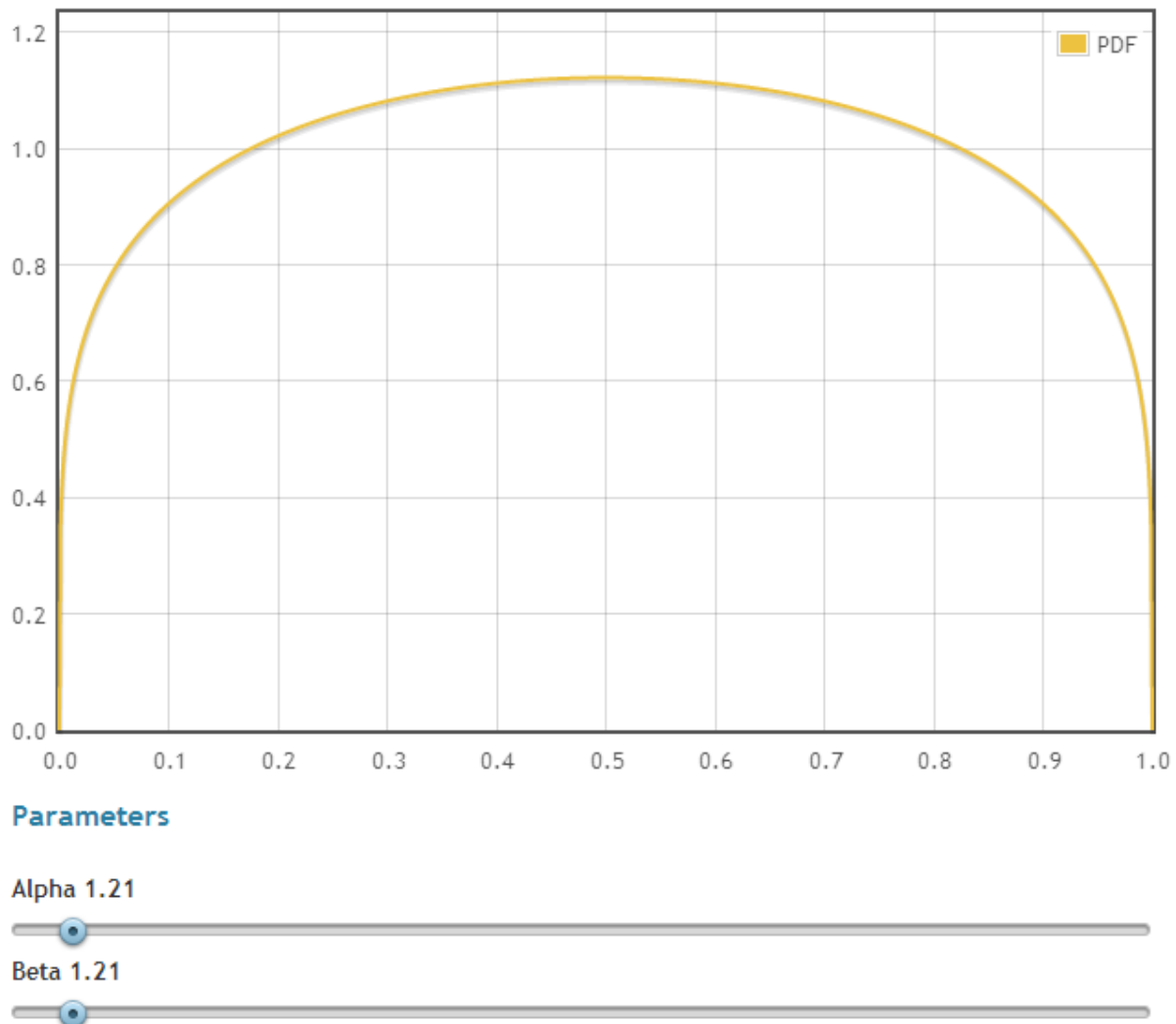---

[6]http://code.google.com/p/flot/

Figure 13. jStat visualisation of a beta distribution.

The benefit of a JavaScript library over a server-side language is that it allows real-time interaction. For example, users can visualise the effect of changing the parameters on a particular distribution, without any delay. This instantaneous interaction greatly enhances the end user's experience and understanding of how a subtle change to the parameters alters the shape of the distribution. The interactivity of JavaScript can also be harnessed to produce animations, for example the changing of a distribution over time.

The current syntax of jStat is modelled on the statistical language 'R'. However, an alternative object-oriented syntax is also available. Maintaining an R-like syntax allows existing statisticians to easily migrate their code to jStat. The following code snippet demonstrates how one would plot the distribution in Figure 13:

```
// generate a sequence of 100 values between 0 and 1.
var x = jstat.seq(0,1,100);

// calculate the PDF of a beta distribution
// with parameters alpha: 1.21, beta: 1.21
var y = jstat.dbeta(x, 1.21, 1.21);

// plot the distribution
jstat.plot(x, y);
```

jStat was initially developed for use within the expert elicitation tool. Specifically, it is used to render the elicited continuous distributions of the experts, and the pooled results. The benefits of a responsive language (JavaScript) are clear as an expert is provided instant feedback during the elicitation procedure. Figure 14shows a pooled distribution, rendered using jStat, depicting the result of an elicitation exercise.

Aston University / Height of main building

Pooled probability distribution

Figure 14. Pooled distribution results from an elicitation.

jStat is hosted on a public source code repository at GitHub. This repository currently has 232 interested developers and 21 active source code branches. jStat is currently undergoing a major change and currently includes over 15 distribution types, each with PDF, CDF, inverse CDF, mean, median, mode, variance and sampling functions. In addition, a number of other statistical operations have been added to the core component including numerous special functions and a linear algebra module. As part of the refactoring, the visualisation component was split from the core and moved to a dedicated repository, jStat-UI[7].

As part of the code refactoring, jStat-UI is now capable of plotting the PDF and CDF of all the previously listed distribution types. However, the future plans of jStat include a broad range of additional visualisation tools to enhance usability.

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[7]https://github.com/jstat/jstat-ui

4.3 Web-based Visualisation client

This section addresses the implementation of the web-based visualisation client. First, the architecture is described (Section 4.3.1), followed by the description of the core components, the client implementation (Section 4.3.2) and the visualisation service (Section 4.3.3).

4.3.1 Architecture

Following the inventory of requirements done within the project, visualisations are required for input data, intermediate and final results of the model chains. In order to support the visualisation of uncertainties in the Web, a thin Web client is developed in UncertWeb that supports different data formats, visualisation methods and user groups in all application work packages. Depending on the data format that needs to be supported and the data sources providing these data, different architectural solutions are necessary. For the UncertWeb tools, two different solutions for vector and raster data are implemented. An overview of the architecture is shown in Figure 15. In the simplest set-up data come from a Sensor Observation Service (SOS) or a Web Coverage Service (WCS), depending on whether it is vector or raster data, respectively. For raster data an additional Visualisation Server (VISS) is necessary to create visualisations of raster layers to be visualised by the thin Web client. The Thin Client and the VISS are described in more detail in the following subsections.

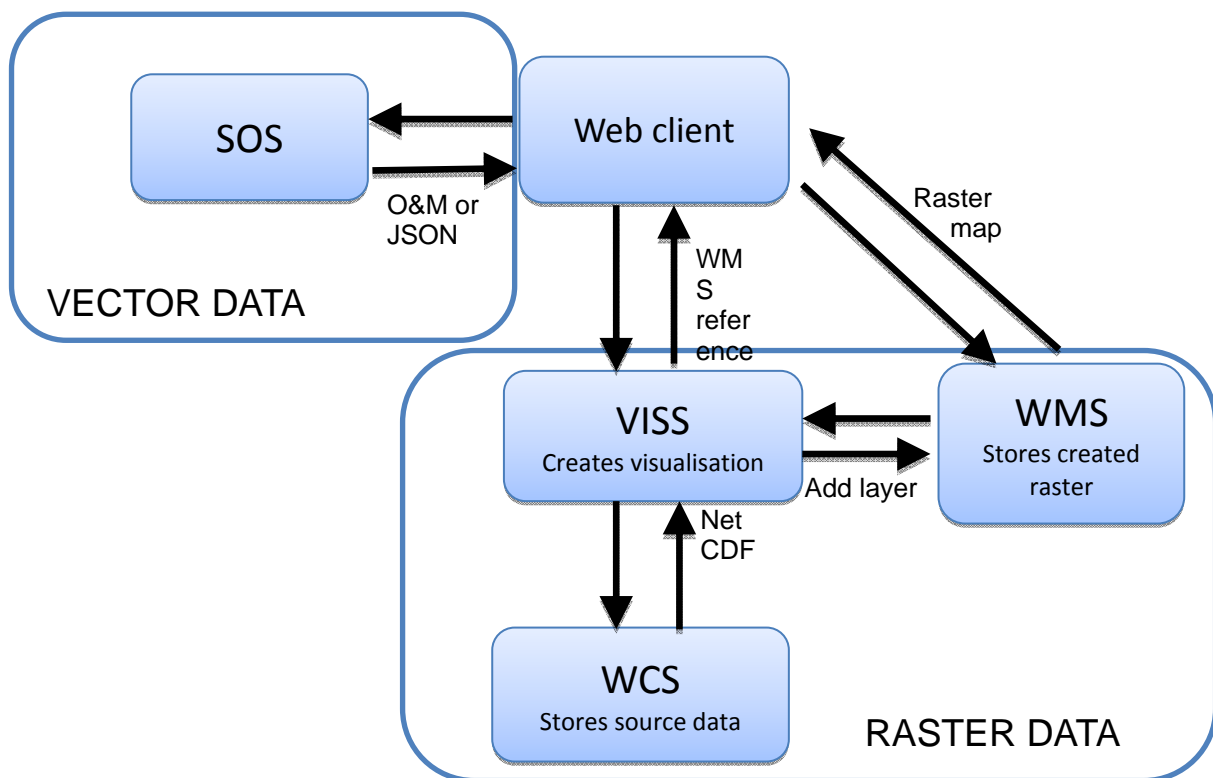**Figure 15. Architecture of the web-based visualisation in UncertWeb.**

4.3.2 Client implementation

The visualisation client developed in UncertWeb is based on the OpenLayers library[8]. OpenLayers offers a JavaScript library for visualisation of spatial and spatio-temporal data as dynamic maps in a web browser. The library provides standard map windows and navigation

---

[8] http://openlayers.org

tools, i.e. pan, zoom in/out, to allow interactive control for the user. The JavaScript API allows extension of the provided functionalities with specific UncertWeb components.

Supported data sources include, among others, KML, GML, GeoJSON and OGC WMS and WFS. For the visualisation of vector data with uncertainty as required in UncertWeb, the standard OpenLayers client was extended to support the data formats needed. Therefore, support for OGC O&M 2.0 as well as for JSON, following the UncertWeb encoding conventions (as described in Deliverable D8.2) is implemented. The client is able to parse both formats directly. Thus, for vector data, only the service instance providing the data in one of the UncertWeb encodings is necessary for the visualisation. Thereby, spatial as well as spatio-temporal data are supported by the client.

For the visualisation of categorical and continuous vector data, the JSON encoded data can be parsed directly by the client showing the geometry as an overlay on the map. The expected value (mean) of the distribution or the mode of the categories is shown for each feature in the map. The colour legend is adapted depending on the range of values for continuous data or on the categories of the data. If the data are spatio-temporal, the time series of values can be visualised by selecting a feature in the map. A slider allows moving through the points in time, changing also the values shown in the whole map to the respective time. By selecting one measurement in the time series, a second window can be opened showing the PDF or a bar or pie chart as shown in Section 4.1.4.

For the visualisation of uncertain raster data the respective encodings used in UncertWeb, i.e. NetCDF-U and GeoTiff (referenced from UncertML or O&M) cannot be parsed directly from the client. Both are binary formats which are not supported by JavaScript inherently. As the processing and storage capabilities in web browsers are limited, an additional server component is necessary to access the raw data and create different visualisations in a format suitable for the OpenLayers client. The service implementation is described in the next section. The created visualisations are stored in a WMS which can be accessed directly by the client. Thus, interactive changes in the user inputs when visualising raster data usually include data requests to the visualisation server, unlike for vector data where changes in the inputs are handled directly by the JavaScript client. Interaction with temporal data is done in a similar way as with vector data by using a slider to allow moving through time steps.

4.3.3 **Visualisation service**

The visualisation service (VISS) is required to access binary data formats such as NetCDF and GeoTiff and create visualisations in a form accessible to the OpenLayers client. The VISS component is implemented as a REpresentational State Transfer (REST)-ful web service [Fielding 2000] and based on three resource concepts: *Resource, Visualiser* and *Visualisation*. A *Resource* encapsulates the data source, e.g. NetCDF from a WCS, including the temporal extent and phenomenon description. A *Visualiser* is the implementation of a certain visualisation method, for example exceedance probability. This allows easy implementation of new methods for the VISS. Next the *Visualiser* creates a *Visualisation*, which can be one or several raster layers, from a *Resource*. The representation of resources is encoded by Uniform Resource Identifiers (URI). The REST paradigm makes the VISS stateless, i.e. independent from the client status, and reduces and therefore speeds up the communication between client and server by using only existing HTTP methods and URIs. For the VISS implementation JSON was chosen as communication medium as this means additional reduction in communication compared to XML.

Figure 16 shows the interaction scheme between client and VISS in a sequence diagram. In the first step the client registers a *Resource*, here aWCS layer, with the VISS. The *Resource* is requested and analysed by the VISS to provide important Metadata such as the temporal extent to the client. The available *Visualisers* for this *Resource* can now be requested from the VISS by the client. A list of available visualisation methods is shown to the user. The user selects an appropriate method and thresholds, if applicable, and the client then sends the selections to the VISS. The VISS creates the requested visualisation and adds it as a layer to a WMS. To the client a JSON file is returned that contains minimum and maximum values (required for visualisation), the WMS-URL and the WMS layer name for the OpenLayers client to create the layer. With the provided metadata the client can define the colour ramp and legend for the visualisation as a Styled Layer Descriptor (SLD) [Lalonde 2002] which is sent back to the VISS. After requesting the map, the resource can be deleted by the client if it is no longer needed. To allow a smooth interaction of the user with the client, a number of realisations, e.g. for each percentile, can be pre-processed and stored (cached) as layers on the WMS. Thus, the VISS checks for each request first if the *Visualisation* is available. To store the created Visualisations the Geoserver implementation of the OGC Web Mapping Service is used.

Figure 16. Workflow of the visualisation server and the web client for raster visualisation.

4.4 System evaluation

4.4.1 jStat Evaluation

Despite the large number of developers interested in jStat, it is still in its infancy. The limitations are clear: no mechanism of loading data – it must be generated programmatically using JavaScript, performance, and a limited number of functions and distributions. The first issue is a fundamental issue with JavaScript and is likely to remain a limitation for some time.

For this reason jStat's use will be limited to simple statistical analysis such as that used in the elicitation and visualisation tool. The lack of functions and distributions is already being addressed in version 2 (as mentioned in Section4.2) with over ten new distributions and countless additional functions already implemented. The final limitation is the performance of JavaScript. This is an issue with the language rather than jStat itself. However, the poor performance (relative to a compiled language such as C++) of JavaScript means that any computationally-expensive statistics would be better suited to R or another statistical language.

The roadmap for jStat-UI development for the last year of the project includes the following features:
- Integration of PDF/CDF chart interaction directly into the plot function.
- Categorical variable visualisations including: pie charts, bar charts and stacked bar charts.
- Box and whisker plots.
- Histograms.
- Interactive time series plots, e.g. zooming and panning. These will also include error bars.
- QQ (quantile- quantile) plots.

4.4.2 **Web client evaluation**

The visualisation system was developed as a thin client following the paradigm of the Aguila software which could have been used as a thick client. Although this required a considerable amount of re-implementation work, a web client has several advantages compared to a thick client. First of all it allows an easier integration into the web-based UncertWeb architecture since it follows the web-based paradigm as described in Deliverable D2.2. While a thick client would require the download and installation of software on the machine of the user, a web client can be used directly within the browser.

Differences in raster and vector data handling in the web client occur due to the different premises of the data encodings. While JSON provides a light-weight encoding for vector data which can be directly used in JavaScript applications, NetCDF-U is a more complex structure encoding raster data. Due to the additional processing necessary to produce visualisations of raster data, the interactivity is reduced compared to the JSON vector data case. However, thanks to the use of REST and the available structures in the OpenLayers client the interaction is still quite fast. This could be speeded up further if the WMS and VISS would be merged but with the price of reduced flexibility. Running both services on the same physical server would already reduce communication since the data could be exchanged as file references.

5 Conclusions

This deliverable describes the development of Open Source tools to support interactive visualisation and communication of uncertain spatio-temporal data in the Uncertainty-Enabled Model Web. Although initially a thick client was planned, the realisation as a thin client fits better in the web-based architecture of UncertWeb. Accordingly, the client can be seamlessly integrated into web service workflows to visualise data inputs, intermediate and final model outputs of the four use cases as assessed in the requirements.

To fulfil the various requirements on non-spatial, non-temporal, spatial, temporal and spatio-temporal data, different methods were reviewed and implemented in the tools. Furthermore, based on previously conducted usability studies, a differentiation between experts (in statistics or mapping) and non-expert users has been indicated to be useful. Therefore, the client included the concept of adjacent maps for non-experts and the multidimensional maps mode for expert users, as realised in the Aguila software. Although different studies indicated the differentiation as useful, further usability studies are necessary to test whether the tool fulfils the expectations and requirements of the different target user groups. The project use cases will be used for this.

The developed tools are implemented as prototypes. The integration into the application work packages has not been evaluated as not all implementations of the web service chains or the final architecture are complete yet. The development of the jStat library is still on-going and will in future allow a larger range of visualisation methods for continuous as well as categorical data. Similarly the web client will be further developed and tested on usability and interoperability using different kinds of web services providing the data to be visualised.

Although the tools have been developed within UncertWeb following the specific requirements of the application work packages, obviously these will also be useful outside the project as well and are available to interested parties. As all implementations have been developed as Open Source products, the development is intended to be continued beyond the project period.

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Appendix

Uncertainty visualisation requirement questionnaires

For the visualisation tool in Task 3.3 we summarised the visualisation requirements from the documents D4.1 – D7.1. A consolidated list of data/uncertainty types which need to be supported by UncertWeb is shown here:

Uncertainty type	Data type	Spatial data	Data format	Temporal data	Data distribution	Example
Location	Continuous	Spatial	Vector	Non-temporal	Univariate	e-Habitat:SelectedArea (WP4)
Attribute	Continuous	Spatial	Raster	Non-temporal	Univariate	TAPM: ECMWF ENSEMBLE (WP6)
Attribute	Continuous	Spatial	Vector	Non-temporal	Univariate	Albatross Activity diary data (WP7)
Attribute	Categorical	Spatial	Raster	Non-temporal	Univariate	e-Habitat:landcover (WP4)
Attribute	Categorical	Spatial	Vector	Non-temporal	Univariate	LandSFACTS:SimRot (WP5)
Attribute	Continuous	Spatial	Raster/ Vector	Temporal	Univariate	Albatross- Time dependent activity schedule (WP7)
Attribute	Continuous	Non-spatial	-	Non-temporal	Univariate	e-Habitat:HRI (WP4), CAM:CTM (WP5)
Attribute	Continuous	Non-spatial	-	Non-temporal	Multivariate	
Attribute	Categorical	Non-spatial	-	Non-temporal	Univariate	
Attribute	Categorical	Non-spatial	-	Non-temporal	Multivariate	
Attribute	Continuous	Non-spatial	-	Temporal	Univariate	e.g. summary statistics for time series

Answers from work package 4

1) **Is the (input/output) data used in your work package sufficiently supported according to this list?**

Yes, it seems so

2) **What is missing from the list? If something is missing, how should it be visualised?**

It is unclear to me where a set of spatial points at irregular locations would fit in, such as a SpatialPointsDataFrame in R. Not sure if we will need it, but it is common for many applications.

3) **Do you need visualisation of positional uncertainty (relevant for input in WP4), and if yes, for which spatial objects?**

The positional uncertainty in WP4 would typically be for the boundaries of the protected parks. It is unfortunately quite unlikely that we will be able to use such a tool within the context of UncertWeb, as it will be almost impossible to assess the uncertainty. We can provide a data set if you still want to develop tools for visualizing these uncertainties, but this should have the lowest priority, and should only be done if you are really interested in doing this.

4) **Besides visualisation of model outputs, is visualisation of input variables or intermediate results needed? If required, which intermediate results?**

No intermediate results, visualization of input variables could be relevant, this would mainly be the rasters. The challenge would in this case be how to plot a set of rasters next to each other with (colour) scales that aids the user in seeing the relationship between inputs and output.

5) **What kind of end users is expected in each Use Case (e.g. domain experts, statisticians, politicians, regular citizens)?**

Mainly domain experts and statisticians

6) **Please provide us with example datasets for uncertain model inputs and outputs which we can use for testing and developing the visualisation software.**

Example has already been provided for a set of raster images. An example with polygon data can be provided if this is something you really want to develop.

Answers from work package 5

Within the model chain for WP5, we would like to be able to visualize the following inputs/outputs:

1. The Land Capability Classification – we would like to be able to map the classification of the field parcels over the region of interest.

2. We would like to map the initial cropping pattern over the region – this is the baseline that the field use simulator will begin the future simulations from.

3. We would like to be able to visualize the information in the crop transition matrices, and also the uncertainty about this information. The form that this visualization could/will take is currently unclear.

4. From the field use simulator, LandSFACTS, we would like to be able to visualize the simulated cropping pattern over the years of the simulation – to map the land usage over the region, and how this is changing through time over the simulation period.

5. We would like to visualize the estimated yields (the regional estimates of future crop production), how these estimates change over the simulated years (through time), and the uncertainty in this final output.

1) **Is the (input/output) data used in your work package sufficiently supported according to this list?**

Most of the (input/output) data within the WP5 model chain is represented by the list.

2) **What is missing from the list? If something is missing, how should it be visualised?**

Object 4 in the list above is a categorical variable that we would like to map spatially and also temporally as well. Hence we would require a line in the table for "Attribute, Categorical, Spatial, Vector, Temporal, Univariate"? Or, this could be viewed as a "categorical and multivariate" object?
We are unclear as how we can visualise the information in the crop transition matrices, and the uncertainty in these. These are non-spatial, multivariate objects.

3) **Do you need visualisation of positional uncertainty (relevant for input in WP4), and if yes, for which spatial objects?**

No. The visualisation of positional uncertainty is not a requirement for WP5.

4) **Besides visualisation of model outputs, is visualisation of input variables or intermediate results needed? If required, which intermediate results?**

Objects 1, 2, 3 and 4 listed above are all intermediate results/outputs within the model chain, and we would like to visualize these if possible.

5) **What kind of end users is expected in each Use Case (e.g. domain experts, statisticians, politicians, regular citizens)?**

We expect the end users of the WP5 model chain to be the domain experts (land use experts), and possibly policy makers.

6) **Please provide us with example datasets for uncertain model inputs and outputs which we can use for testing and developing the visualisation software.**

We intend to supply some sample model inputs/outputs to Aston for the coding marathon, and these will be made available to the visualization team at the coding marathon.

Answers from work package 6

1) **Is the (input/output) data used in your work package sufficiently supported according to this list?**

I am not certain. I think I need:
1. Temporal non-spatial visualisation of the ensembles and/or uncertainties (plots with all ensembles and/or confidence intervals for non-spatial or spatially aggregated data)
2. Raster visualisation of means/medians and confidence intervals
3. Presentation of information in terms of probability of exceedance, as raster and as

non-spatial time series
4. Visualisation of spatially distributed wind vector uncertainty (good luck with that one!)

2) What is missing from the list? If something is missing, how should it be visualised?

Not certain

3) Do you need visualisation of positional uncertainty (relevant for input in WP4), and if yes, for which spatial objects?

No

4) Besides visualisation of model outputs, is visualisation of input variables or intermediate results needed? If required, which intermediate results?

Wind vector data in raster

5) What kind of end users is expected in each Use Case (e.g. domain experts, statisticians, politicians, regular citizens)?

Researcher/domain expert
Authorities/decision makers
Public

6) Please provide us with example datasets for uncertain model inputs and outputs which we can use for testing and developing the visualisation software.

Currently no example data set for output data. Can provide you with input data from ECMWF ensembles in the form of GRIB data. Can download an example of such data (one day with 50 ensemble members) from ftp://ftp.nilu.no/pub/NILU/Bruce/Uncertweb

Answers from work package 7

table.doc:

Uncertainty type	Data type	Spatial data	Data format	Temporal data	Data distribution	Example
Attributes, time, location	categorical	spatial	vector	temporal	Univariate	Activity diary data
Attributes	categorical	spatial	vector	temporal	Univariate	socio-economic data
Time	continuous	spatial	vector	not temporal	Univariate	Physical data-travel time
attributes, time and location	categorical and continuous	spatial	vector	temporal	Multivariate	time dependent schedule output

1) Is the (input/output) data used in your work package sufficiently supported according to this list?

I prepared a table named table.doc

2) What is missing from the list? If something is missing, how should it be visualised?

I prepared a table named table.doc

3) Do you need visualisation of positional uncertainty (relevant for input in WP4), and if yes, for which spatial objects?

The visualization of positional uncertainty would be good for schedule output.

4) Besides visualisation of model outputs, is visualisation of input variables or intermediate results needed? If required, which intermediate results?

Visualization of model input is not necessary.

5) What kind of end users is expected in each Use Case (e.g. domain experts, statisticians, politicians, regular citizens)?

Domain experts

6) Please provide us with example datasets for uncertain model inputs and outputs which we can use for testing and developing the visualisation software.

Activity diary of data is a diary that explains for each member of a specific household the start and end time and duration of all activities, location of them and with whom he will do and transportation mode he will use for activities in a day, we gather such data with giving questionnaire to people.

The table below displays the socio-economic data. These data is use for Albatross model so in a large are we need to get this information from synthesize population technique.

socio-economic data

Label	Definition
Urb	Urban density
Day	Day of the week
Comp	H composition
Child	Children category
Age	Age category
SEC	Socio-economic class
Ncars	# of cars in household
Driver	I has driving license
Gend	Gender of I
Wstat	Work status of I
Pwstat	Work status of P

The travel time is the travel time in network with different modes that is derived from basis network.

Time dependent schedule would be a schedule for each person in a household in a day that Albatross predicts and demonstrate at different time of day person do what, where, with whom, for how long and with which transport mode they travel to the location of activity