MASTERARBEIT

Effects of Uncertainty Visualization on Decision Making and User Confidence: An Empirical Study

Ausgeführt am Department für

Geodäsie und Geoinformation

der Technischen Universität Wien

unter der Anleitung von

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durch

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10.09.2019

Unterschrift (Student)

MASTER'S THESIS

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Conducted at the Department of

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Under the supervision of

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STATEMENT OF AUTHORSHIP

Herewith, I declare that I am the sole author of the submitted master's thesis entitled: "**Effects of Uncertainty Visualization on Decision Making and User Confidence: An Empirical Study**".

I have fully referenced the ideas and work of others, whether published or unpublished. I further declare that I have not submitted this thesis to any other institution.

Vienna, 10.09.2019 Bwisa Muyoka Metrine

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ABSTRACT

Uncertainty visualization methods have not yet been standardized as mapping techniques in cartography despite more than 20 years of research. To improve the current state of uncertainty visualization research, certain areas require more input, e.g. the user domain. Users´ differences and past experiences need to be analysed to understand how they relate with interpretation and understanding of uncertainty in specific fields.

This thesis investigates the effects of uncertainty visualization on user decision making and confidence in the decisions made. Extensive literature review was done to identify uncertainty visualization techniques recommended for use in hazard maps. Two methods were selected, intrinsic color value and extrinsic texture overlay. These techniques were incorporated into fictional flood risk maps that were used in an empirical study undertaken by a Kenyan user group.

The user group was divided into sub-groups based on profession (geography experts and novices), experience with uncertainty visualization and encounter with floods. Users were asked to decide to stay or leave a location, first when shown flood risk maps and then when given additional uncertainty information. The decisions and subsequent confidence levels reported by the sub-groups were analysed and compared.

Based on the results, the Kenyan user group was able to understand and interpret uncertainty visualized by color value and texture overlay. Novices interpreted color value better than texture overlay. Experts performed better than novices in interpretation of texture overlay uncertainty representations, although the difference was not statistically significant. The difference in interpretation of uncertainty between users with experience in uncertainty visualization, and those that were inexperienced was also statistically insignificant. Inclusion of uncertainty caused changes in decision making and users´ confidence in their decisions. There were instances of increased confidence when uncertainty was introduced.

Uncertainty visualization presents users with important information for consideration in decision making. This enables users to make informed decisions and has potential to increase the confidence of users in their decisions.

Keywords: Uncertainty visualization, color value, texture overlay, decision making with uncertainty, user confidence

Table of Contents

1. INTRODUCTION

This chapter contains an introduction into the uncertainty visualization topic. The history and gaps of uncertainty visualization research are highlighted leading to the justification of the relevance of this thesis. The study objectives and research questions are discussed and the outline for the remaining chapters is laid out.

1.1 Background

The term uncertainty has varied meanings. According to MacEachren et al., it is a concept that covers a broader range of doubt or inconsistency [1]. Uncertainty is a fact of information, which means, all information contains uncertainty in one way or the other [2].

Based on previous research, it has been proven that information uncertainty affects the process and outcome of information analysis and decision making [2]. Studies have also suggested that communicating information uncertainty has the potential to increase trust in the information [3]. Over time, the need for uncertainty visualization on maps is becoming increasingly important. However, further research in this field is inevitable due to existing gaps and the fact that visualization of uncertainty has not yet been standardized in cartography.

Most of previous research has dealt with developing methods or software applications for the display of uncertainty, or on developing suggestions about what may work. For example, in an empirical study on visual semiotics and uncertainty visualization, MacEachren et al. tested the relative effectiveness of a selected set of uncertainty representation methods. They found out that in representing uncertainty, iconic sign-vehicles are more accurately judged whereas abstract sign-vehicles are quicker to judge [2].

Another such study was done by Sven Christ, a South African student, who carried out a master thesis in 2017 on spatial visualization of uncertainty. He developed a tool for uncertainty visualization and tested it on geospatial industry personnel. His research concluded that uncertainty visualization improves the comprehension of statistics, and so of uncertainty [3].

However, previous studies have also identified gaps in uncertainty visualization research. For instance, MacEachren et al. state that, "much less research has been done to empirically evaluate whether the proposed techniques work, or whether the theoretical perspectives lead to supportable hypotheses" [1] (*p.151*).

Smith et al., in their 2017 study on domains of uncertainty visualization research, revealed that there is a big gap on studies focused on the map user. They developed a visual summary of all domains present in uncertainty visualization research as shown in figure 1. They then reviewed 40 recent papers on uncertainty visualization and summarized the domains that have been widely researched on as shown in figure 2.

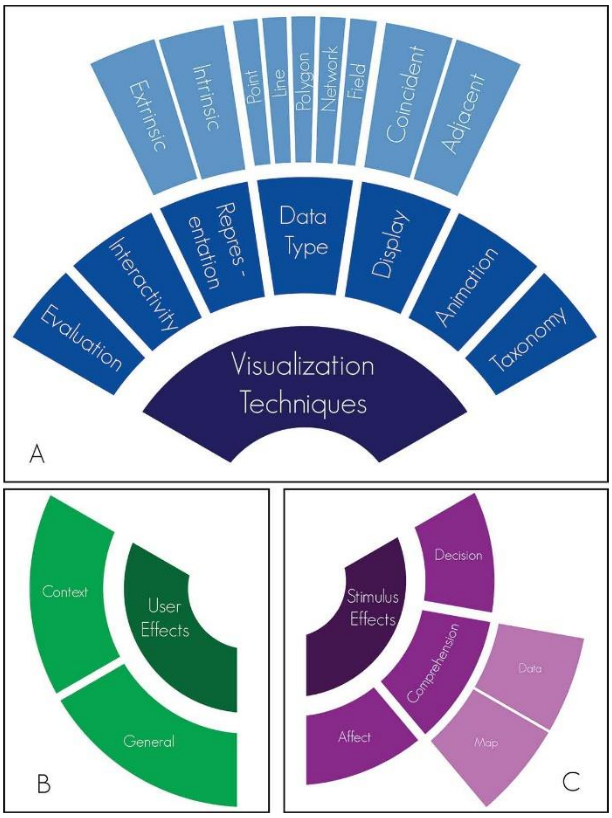


Figure 1: Domains of uncertainty visualization research divided into three main categories: (A) blue: Visualization Techniques, (B) green: User Effects, and (C) purple: Stimulus Effects. Copyright © 2019 Informa UK Limited [4]

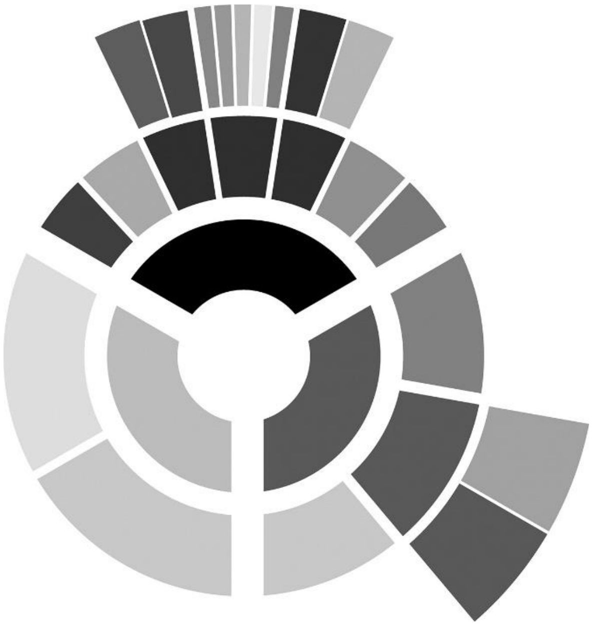


Figure 2: A reflection of how often a domain has been researched based on a summary of 40 research papers reviewed by Smith et al. Dark colors symbolize domains that have been widely researched. Copyright © 2019 Informa UK Limited [4]

Based on their findings, they recommended that more focus should be put on individual differences and users' prior knowledge to understand how this affects user interaction with uncertainty visualizations (domains B and C in figure 1) [4].

Research directed towards uncertainty visualization in specific fields is also limited. MacEachren et al. acknowledge that understanding components of uncertainty and their relationships to specific fields, users, and information need is a major challenge [1]. For these reasons, this thesis investigates the inclusion and effects of uncertainty information in the flood hazard and risk mapping domain.

Flooding is a major natural disaster that affects both developed and developing countries. Some of the major past flood events occurred in Pakistan 2010, Australia 2010/11, China, Thailand and Laos 2011, Nigeria and United Kingdom 2012 [5]. Several measures have been put in place worldwide to prevent or manage flood events; one such measure is the production of flood risk maps.

Flood risk maps show the possible consequences of floods in an area, such as number of people or economic activities affected [6]. They can be utilised for different purposes. For instance, insurance companies can use them to control insurance rates for properties in different flood risk zones and the general public can use these maps to arrive at decisions on where to buy property or whether to relocate from their current residence etc.

Research shows that loses caused by floods can be mitigated by providing reliable information to the public through flood inundation maps [7]. Hazards such as floods, earthquakes, landslides etc. are subject to uncertainty due to their complex nature of occurrence [8]. However, inclusion of uncertainty information in these maps has not yet been standardized despite previous extensive research. Kunz et al. researched on visualization of uncertainty on hazard maps, where they investigated how uncertainty is treated and communicated by Swiss natural hazards experts [8]. They noted that,

"Decision-makers in the field of natural hazard management need to understand the concept, components, sources, and implications of existing uncertainties in order to reach informed and transparent decisions. Until now, however, only few hazard maps include uncertainty visualizations which would be much needed for an enhanced communication among experts and decision-makers in order to make informed decisions possible" [8] (p.*1*).

However, the Swiss hazard experts interviewed were reluctant to communicate uncertainties contained in hazard maps, although they acknowledged that these uncertainties exist and their communication to experts is important [8].

For this reason, and due to the complexity of hazard maps and the delicate information they present, further research to investigate the Swiss hazard experts´ reluctance is necessary. There is need to find out whether risk maps with uncertainty information can be interpreted appropriately by both experts and novices. Additionally, it is necessary to determine whether including uncertainty on flood risk maps will enable the user to make a better and informed decision or it could result into difficulties in map interpretation and consequent decision making.

Fabrikant et al. went further with their research and studied the influence of uncertainty visualization on decision making with hazard prediction maps [9]. Their motive was to investigate whether presentation of uncertainty information on hazard maps influenced user decisions, in their case, house locations for purchase. Participants of their study chose different houses, depending on whether uncertainty was shown on the map or not. They concluded that user decisions, while using hazard maps, are influenced by presentation of uncertainty information.

This thesis investigates the effects of visualizing uncertainty on hazard maps in terms of user decision making and their confidence in the decisions they make. The focus of this thesis is the user domain in uncertainty visualization as recommended by Smith et al. [4]. By looking at the confidence level in decisions taken by respondents, this study is a step forward from Fabrikant et al. paper [8]. As recommended by MachEacren et al. [1], this uncertainty visualization research is carried out in a specific field, i.e. flood risk mapping.

Different from previous research, the user group here is based in Kenya an East African country. Most of the research referenced herein have been carried out in developed countries, especially in Europe, America and Australia. The aim of this thesis, therefore, is to improve the knowledge on user map interpretation, decision making and confidence in decisions, when presented with uncertainty visualization on flood risk maps.

1.2 Research Objectives and Questions

The overall objective of this research is to investigate user (geography experts and novices) map interpretation, decision making and confidence in decisions, when presented with two sets of flood risk maps; one where uncertainty is not provided and the other where it is provided. Additionally, the results shall give insights on the understanding and interpretation of uncertainty visualization by users from Kenya, a user group that has not been studied before.

Visualization techniques that shall be tested in this study will be chosen from literature review based on the most and best recommendations. To achieve my overall objective, the following sub-objectives shall be tackled:

1. Find out from literature review, the uncertainty visualization techniques applicable to flood risk mapping and select most and best recommended techniques from the reviewed literature.

2. Prepare fictional flood risk maps incorporating uncertainty information using the selected techniques.

3. Carry out an online map-based study with participants from Kenya, to investigate user understanding and interpretation of flood risk maps (with and without uncertainty information).

4. Investigate decision making patterns of the respondents based on flood risk maps (with and without uncertainty information).

5. Find out from the study results, the effects of uncertainty visualization on user confidence in the decisions they make.

The following research questions shall aid in addressing the above objectives:

- Which uncertainty visualization methods are recommended by previous research and are applicable to flood risk maps?

- Are the novices and experts user groups from Kenya able to understand and interpret uncertainty correctly?

- Based on the fictional flood risk maps and scenarios presented in the study, do the study users change their decisions when presented with uncertainty information?

- How does user confidence in the decisions they take vary when presented with uncertainty?

1.3 Thesis Outline

The remaining sections of this thesis are outlined here.

Chapter two contains literature review, which fulfils objective one of the study. A total of 18 papers are reviewed and uncertainty visualization recommendations from them are summarized graphically. These recommendations are used in fictional maps used in the survey as discussed in the methodology in chapter three. The empirical study carried out on users from Kenya, the questionnaire used in the survey, as well as the characteristics of the user groups are discussed in chapter three. Results from the survey are compiled, statistically analysed and discussed in chapter four. Conclusions based on the research objectives are highlighted in chapter five, and setbacks of this study together with the recommendations for future research are documented.

2. LITERATURE REVIEW

This section presents previous studies that compared uncertainty visualization techniques, with emphasis on findings useful for hazard mapping. Results and recommendations from these studies are summarized and used in the selection of uncertainty visualization methods to be tested in this thesis.

2.1 Overview of uncertainty visualization methods

Research on uncertainty visualization in the geospatial field dates to the late 20th century. MacEachren, Buttenfield and Goodchild are among researchers who kick-started major foundations in this field in the early 1990s [10-12]. A lot of research, both theoretical and empirical, followed thereafter. Kinkeldey et al. [13] proposed a systematic categorization of uncertainty visualization techniques into 3 major categories namely:

- Coincident/Adjacent
- Static/Dynamic
- Intrinsic/Extrinsic

Coincident approach refers to methods that represent data together with its inherent uncertainty on the same visualization. Adjacent techniques on the other hand represent data on one map and uncertainty on a different map usually side by side.

Static approach refers to methods that represent uncertainty using classical static maps, e.g. paper maps. On the contrary, dynamic approach uses interactivity to represent uncertainty, for instance, use of animation or interactivity controls to toggle between the map information and its uncertainty.

Intrinsic techniques manipulate the existing symbology on a map to represent uncertainties inherent in the data. For example, a map that uses color to represent data may use other color properties such as transparency of the colors used to represent uncertainty. Extrinsic techniques, on the other hand, add new objects to the existing symbology on a map to represent uncertainty, e.g. use of hachures on top of a base color map.

Kunz et al. [8] carried out a research on methods of visualizing uncertainty specifically on hazard maps. Their research suggested methods that are applicable to hazard maps such as those visualizing floods, landslides etc. They reviewed several methods giving advantages and disadvantages of each based on an expert user study.

Their research concluded that either of the six approaches coincident/adjacent, static/dynamic and intrinsic/extrinsic are usable for hazard maps depending on the task, the map users and other factors.

18 papers written between 1992 to 2017 were reviewed here. Academic databases and search engines used to retrieve the papers were ScienceDirect, Google Scholar, Mendeley and Google search. The selection of these papers was based on those that compared uncertainty visualization techniques theoretically or empirically and spread across the 25 years (1992-2017). The selection of techniques for use in the fictional flood risk maps was based on the most and best recommended methods by the 18 selected literature as summarised in Table 1.

Table 1: A summary of uncertainty visualization techniques from literature review

PAPER	PROPOSED/TESTED TECHNIQUES	RECOMMENDED TECHNIQUES	UNACCEPTABLE/DISCOURAGED TECHNIQUES
[2]	• Fuzziness • Location • Value • Saturation • Hue • Orientation • Shape • Arrangement • Size	• Fuzziness • Location • Value	For visualizing discrete entity uncertainty reported at the ordinal level: • Saturation • Hue • Orientation • Shape
[8]	• Bivariate intrinsic - color hue, color saturation, color value, transparency, texture, clarity (blurriness, fuzziness) • Bivariate extrinsic – glyphs, isolines, resolution/noise, modification of grid overlay, three-dimensionality, shading, dazzling, embellishments, slicing, animation	• Clarity (blurriness, fuzziness) • Color hue for 2D, 3D and qualitative information • Color saturation for quantitative information • Color value for quantitative information • Transparency for 2D • Glyphs for 2D and 3D • Modification of grid overlay for 2D and 3D • Animation for smoothly changing large data	Unsuitable for data sets with small areas or great variations: • Clarity (blurriness, fuzziness) • Embellishments Not suitable for data with great variation: • Isolines • Glyphs Tiring and annoying • Animation
[10]	• Size and value variables for uncertainty in numerical information • Color (hue), shape, and orientation for uncertainty in nominal information • Texture for either nominal or numerical data • Color saturation/purity • Focus, a general term for contour crispness, fill clarity, fog, resolution	• Color saturation • Focus	
[12]	• Value • Color • Texture/noise • Static • Dynamic /interactive	• Texture • Dynamic /interactive	

PAPER	PROPOSED/TESTED TECHNIQUES	RECOMMENDED TECHNIQUES	UNACCEPTABLE/DISCOURAGED TECHNIQUES
[14]	● Adjacent maps ● Coincident map with color fill for data and a texture overlay for reliability ● Coincident map using color characteristics to represent both data and reliability	● Texture overlay	● Color characteristics for both data and reliability makes it difficult for users to consider data and reliability independently
[15]	● Whitening ● Hue saturation where lighter values were used for higher uncertainty ● Maps combined ● Maps compared	● Less certain information should be visualized by light values ● Quicker decision for maps combined	
[17]	● Adjacent maps of value and the uncertainty ● Bi-variate map using whitening method of Hue-Saturation-Intensity colour model to combine value and uncertainty ● Interactive Aguila method that stores value and uncertainty as cumulative probability functions for each pixel in space and time	● Adjacent maps much easier to comprehend	● Interactivity makes the learning process more complicated and needs more time ● Bi-variate maps are overloaded by information.
[18]	● Static map comparisons; uncertainty depicted by colour lightness ● Toggling 2 maps; uncertainty depicted by colour lightness	● Static map comparisons; uncertainty depicted by colour lightness	● Some participant noted they were annoyed by the toggling technique
[19]	● Traditional error bars ● Scaled size of glyphs ● Color mapping on glyphs ● Color mapping of uncertainty on the data surface	● Color mapping of uncertainty on the data surface ● Scaled size of glyphs	● Traditional error bars
[20]	● Color saturation ● Texture ● Value	● Lighter value for more certain and darker value for less certain information.	
[21]	● Boundary ● Color hue ● Color value ● Transparency ● Texture ● Text	● Color hue was the most preferred representation ● Text representation led to the most successful outcomes	

PAPER	PROPOSED/TESTED TECHNIQUES	RECOMMENDED TECHNIQUES	UNACCEPTABLE/DISCOURAGED TECHNIQUES
[22]	● Greyscale ● Blur ● Dashing ● Sketchiness	● Greyscale best in accuracy ● Blur second best	
[23]	● Transparency (or opacity) ● Colour saturation	● Higher effectiveness with transparency	
[24]	● Transparency ● Color mapping ● Ball and arrow glyph techniques ● Multi-point glyph	● Transparency ranked best for ease of identification ● Multi-point glyph and ball and arrow glyph appear most advantageous	
[25]	● Reliability diagrams ● Legend statements ● Value-size combination ● Bivariate focus	● Bivariate focus	● Legend statements and reliability diagrams require extra eye movements and mental overlay process
[26]	● Animated display of data and its level of reliability ● Composite static display of data and reliability ● Map displaying only reliability information ● An interactive toggling between the data and reliability	● Composite static display of data and reliability ● Animated display of data and its level of reliability	Methods found inefficient or ineffective: ● Map displaying only reliability information ● An interactive toggling between the data and reliability
[27]	● Static grey scale display ● Serial animation ● Histograms	● Static grey scale display	Unsuccessful method: ● Serial animation.
[28]	● Contouring ● Adjacent Maps ● Web Client ● Symbols ● Aguila	● Static visualisation methods i.e. Contouring, adjacent maps and symbols	

Some of the papers cited several approaches in one study while others compared two specific approaches. There are instances where some papers recommended more than one technique based on the outcome of their study. The results are graphically summarised as illustrated in figures 3-5.

2.2 Coincident versus Adjacent Approach

Several researchers have compared these two approaches, including MacEachren et al. [14], Kubíček and Čeněk Šašinka [15], Viard et al. [16], Gerharz and Pebesma [17], etc. A common conclusion from their research was that adjacent techniques are easier to comprehend for simple tasks such as value retrieval. However, this thesis selected the coincident approach based on reasons given from the above studies and emphasised by Kinkeldey et al. [13] and Viard [16] as follows:

- It saves time needed in the exploration of the data and uncertainty
- It is suitable for complex tasks, in this case decision making using risk maps with uncertainty information
- It is suitable where retrieval of data and uncertainty at the same time is necessary
- It minimizes cognitive burdens for the users when dealing with visualizations dedicated to real-world applications

2.3 Static versus Dynamic Techniques

Six papers from the 18 reviewed directly compared these two techniques, i.e. papers [12] [17, 18] and [26-28]. Five recommended static technique whereas only two [12] and [26], recommended a dynamic/animated technique. The dynamic techniques were discouraged using words such as complicated, annoying, inefficient, ineffective and unsuccessful. Figure 3 shows the most recommended approach between static and dynamic techniques.

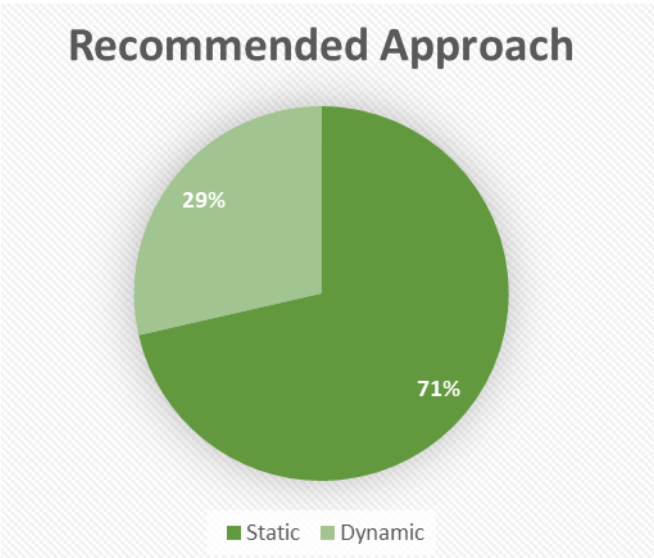


Figure 3: Comparison of static versus dynamic techniques

2.4 Extrinsic Techniques

Extrinsic techniques were tested in five of the reviewed papers [8] [12] [14] [19] and [24]. The techniques are texture overlay, glyphs, isolines, noise, animation, 3-dimentionality, grid overlay, shading, traditional error bars, embellishments and slicing. In most cases, they were compared to intrinsic techniques. One paper [28] compared dynamic to static extrinsic contouring and symbols. The conclusion made was that, generally, the static extrinsic performed better than dynamic.

Out of the five papers, glyphs were recommended three times, texture two times and grid overlay was recommended once. However, texture overlay was favoured in place of glyph overlay which was termed unsuitable for data with great variation [8] as is the case of the fictional maps used. Figure 4 shows the percentage recommendation of the reviewed extrinsic techniques.

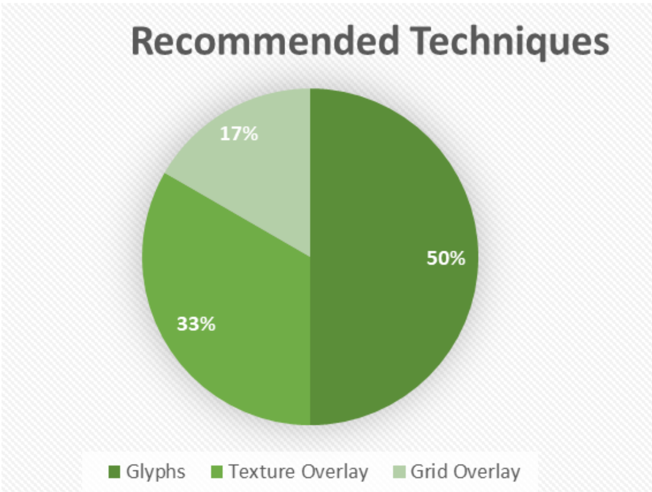


Figure 4: Comparison of extrinsic techniques

2.5 Intrinsic Techniques

Most of the papers reviewed compared various intrinsic approaches, in some cases to extrinsic but mostly to other intrinsic methods. 13 out of the 18 papers i.e. [1] [8] [10-12] [14-15] and [17-23] studied size, value, shape, orientation, texture, saturation, focus, hue, transparency, location, arrangement, dashing, sketchiness and whitening. Hue was disregarded here because it is already used for the representation of flood risk which is the base information in this study. Location was also disregarded as it is not applicable to this study.

The recommended techniques were focus (five times), color value (five times), transparency (three times) and saturation (two times) as shown in figure 5. This thesis favoured color value despite its tie with focus, because according to Kunz et al., fuzziness and focus are unsuitable for data sets with small areas or great variations [8] as is the case for the fictional maps used here.

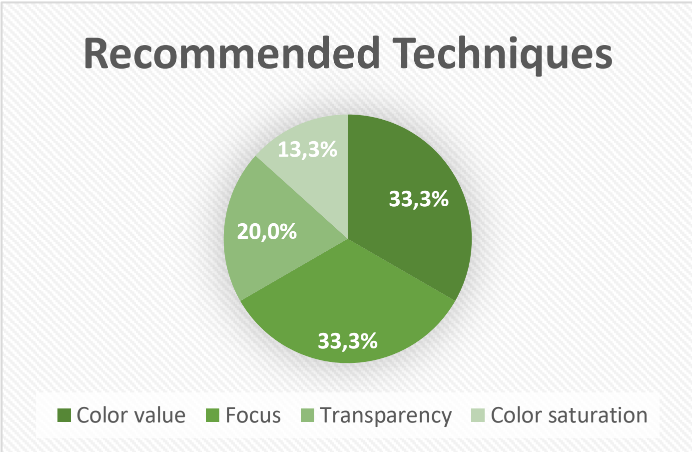


Figure 5: Comparison of intrinsic techniques

2.6 Methods tested

Based on the 18 reviewed papers and backed up with Kunz et al. paper [8] that focused on uncertainty visualization in hazard maps, this research shall test the following techniques:

- Coincident approach
- Static technique
- Intrinsic colour value
- Extrinsic texture overlay

These techniques were integrated into fictional flood risk maps which are discussed in detail in chapter 3.

3. METHODOLOGY

This chapter discusses the processes involved in creating the fictional maps and the questionnaire used for the user study. The choice and justification of the approaches used in the study as well as the composition of the survey and user group are also discussed here in detail.

3.1 Methodological approach

A mixed method approach was applied in this study because both qualitative and quantitative analyses were necessary to address the research questions appropriately. A quantitative approach was used to measure:

- the ability of the Kenyan user groups (geography experts and novices) to comprehend uncertainty information
- instances of changes in decision making when presented with uncertainty information
- the trend in decision making with and without the provision of uncertainty information, among users who experienced floods before and those who did not
- variation in the confidence of users while making decisions, with and without the provision of uncertainty information

On the other hand, a qualitative approach was used to interpret the experience and opinion of users on visualization of uncertainty information, based on their comments and feedback.

3.2 Methods of data collection and analysis

Data was collected using an online questionnaire that was created with google forms and distributed through email addresses. This method was necessary to reach the targeted user groups based in Kenya. The questionnaire contained a variety of questions including multiple choices, open ended and ranking. In most cases, there were maps to be interpreted or used for decision making.

The maps were created in Adobe illustrator © 2019 Adobe. The flood risk zones were represented by color hue. High risk zones were encoded in brown (RGB 217, 95, 14), medium risk zones in a lighter orange (RGB 254, 196, 79) and low risk zones in yellow (RGB 255, 247, 188). This color scheme was inspired by color brewer 2.0 [29]. Uncertainty was depicted by manipulation of color value and texture overlay within/on top of the flood risk zones. For easier comprehension and to obtain accurate responses, the term uncertainty was reversed and depicted on the maps as certainty. This decision helped to reduce user cognitive load and improve understanding for those unfamiliar with the uncertainty visualization topic.

Data collected was analysed in Microsoft excel using the Real statistics Resource Pack created by Dr. Zaiontz [31].

3.3 Preliminary study

A preliminary study was done with 9 respondents, including 5 females and 4 males. Feedback from the study helped in refining the questionnaire and editing maps prior to the main survey. An example of changes made to the maps is shown in figures 6 and 7. Figure 6 (used in the preliminary study) included a river, and certainty was also visualized on zones not under investigation. Additionally, all the zones on the map were visualized by color hue.

Based on results from the preliminary study, new versions of the maps were produced. Figure 7 is a sample of the improved maps, where the river was removed and only zones under investigation were highlighted. Background zones were sequentially greyed out. The changes were made to remove unnecessary content hence make it easier for the respondent to read the relevant parts of the map. Additionally, the river was removed to prevent users from basing their decisions on it rather than on the flood zones and certainty as seen during the preliminary study.

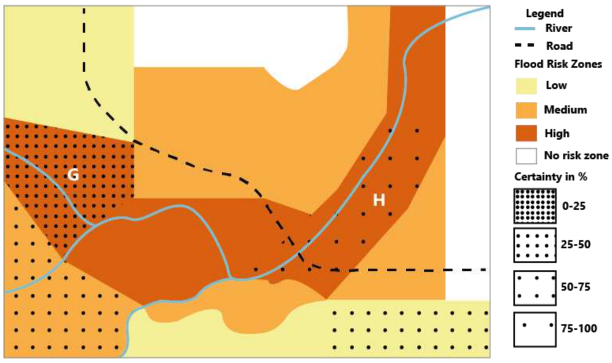


Figure 6: A Map used in the preliminary study

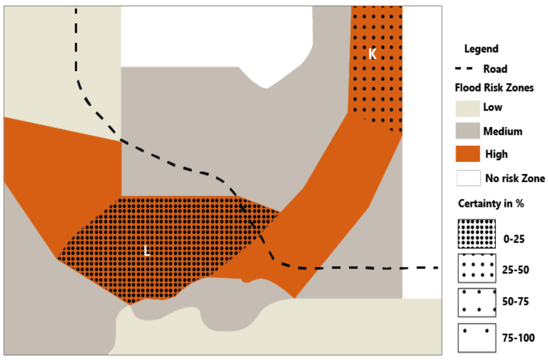


Figure 7: An improved version of the map in figure 6 as used in the main study

3.4 Main study

The main study was an improved version of the preliminary study. 53 respondents including 28 females and 24 males answered the questionnaire. One respondent preferred not to report on gender.

The questionnaire was divided into three sections, namely:

a) User background information - aimed at gathering data on users' age, gender, profession, previous experience with certainty/uncertainty visualization and encounter with floods. Users that encountered floods or had prior experience with certainty/uncertainty visualization were asked to elaborate their experience.

b) Flood risk and certainty visualization - aimed at testing user interpretation and understanding of flood risk maps, and similar maps with additional certainty information in words, texture overlay or color value as shown in figures 8-12. Prior to the questions, a brief explanation on the meaning of flood risk and certainty was given. Contact information was also provided in case clarification was needed. Each map was accompanied by a caption containing a reminder of the meaning of certainty.

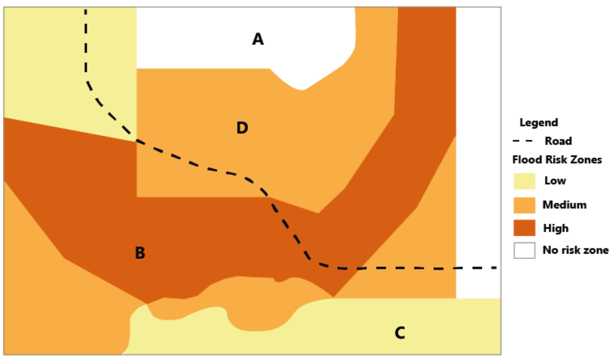


Figure 8: Flood risk zones. (Users were asked to rank the zones from safest to riskiest)

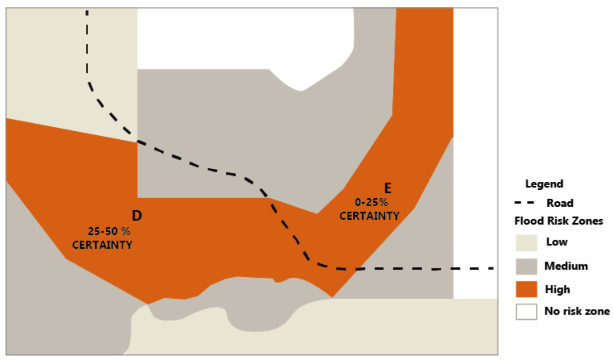


Figure 9: Certainty encoded in word. (Users were asked to select the safest Zone between D and E)

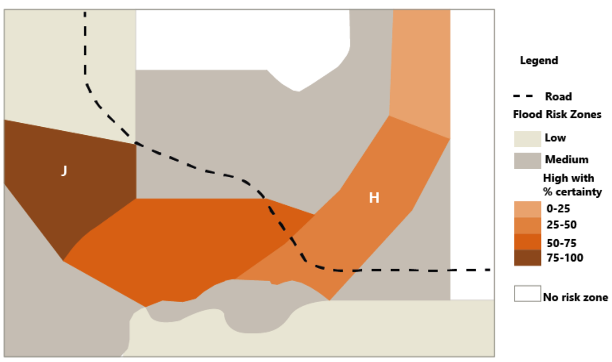


Figure 10: Certainty encoded in color value. (Users were asked to select the safest zone between J and H)

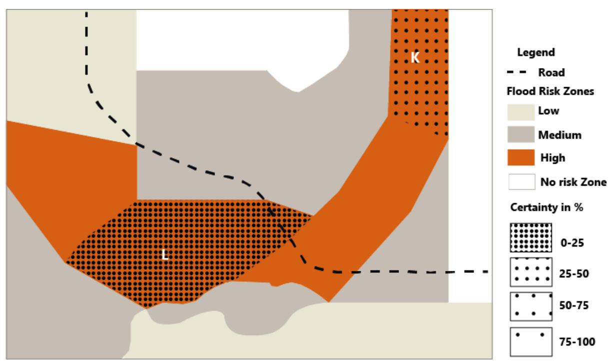


Figure 11: Certainty encoded in texture overlay. (Users were asked to select the safest zone between K and L)

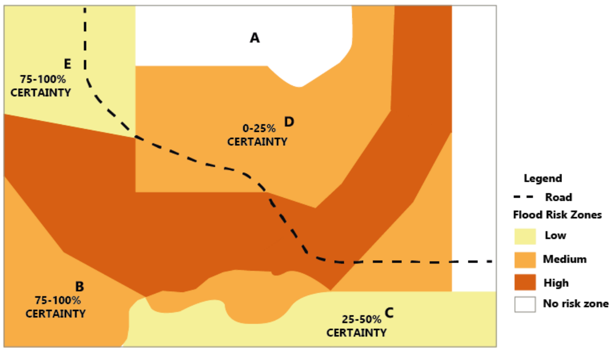


Figure 12: Certainty encoded in word. (Users were asked to rank the zones A-E from the safest to the riskiest)

c) Decision making - presented flood risk maps and certainty information, for users to make decisions based on their interpretation. Users were first shown the low, medium and high flood risk zones without inclusion of certainty and asked to choose to leave or stay at the marked locations. This was repeated using flood risk maps with additional certainty information encoded by texture overlay and color value, for all the three flood risk zones. Samples of the maps are shown in figures 13-15.

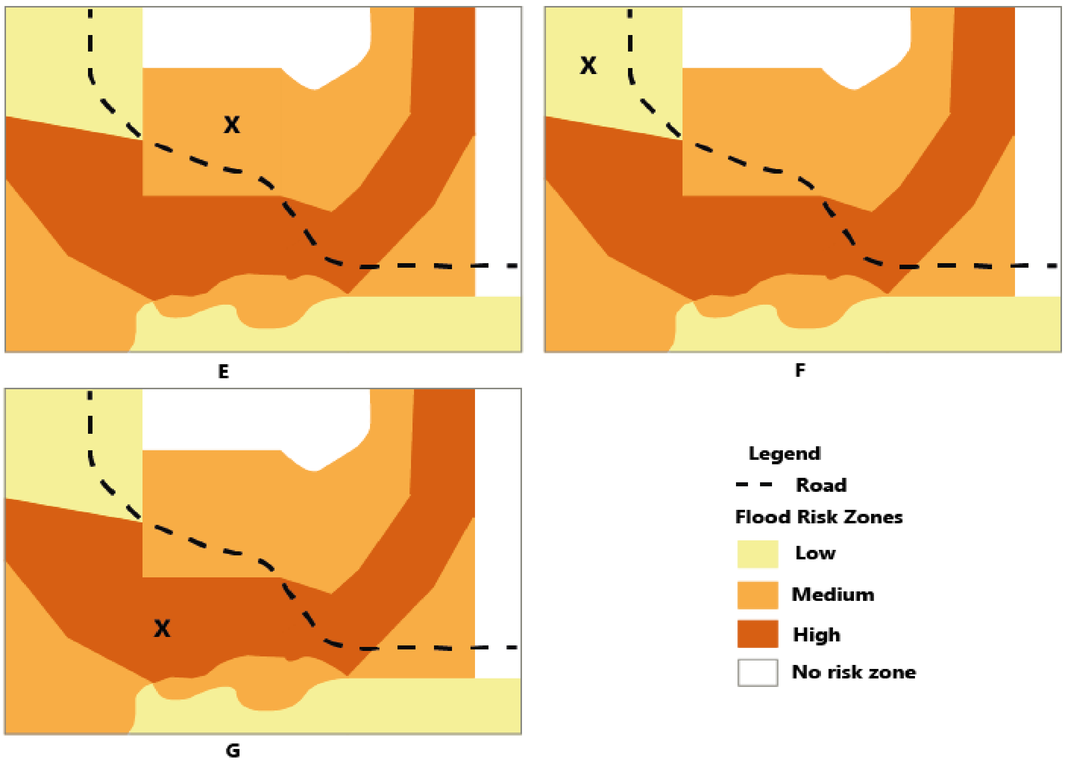


Figure 13: Low, medium and high flood risk zones. (Users were asked to choose to stay or leave the locations marked X on each map)

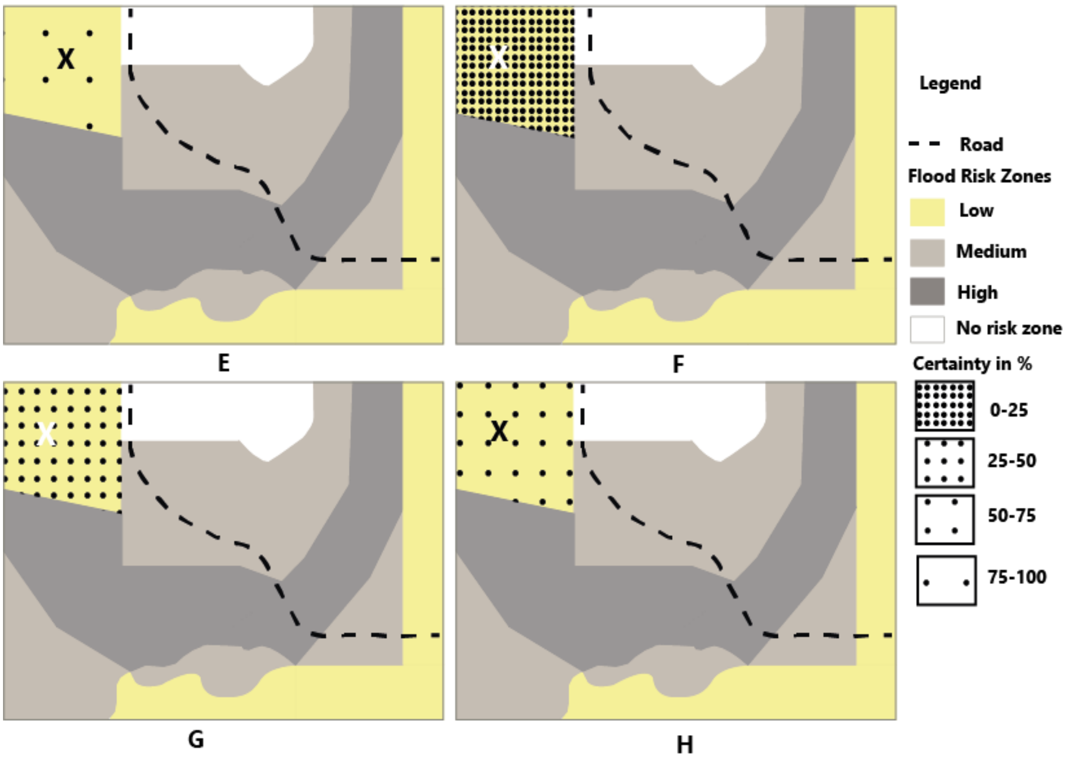


Figure 14: Low risk zones with certainty encoded by texture overlay. (Users were asked to choose to stay or leave the locations marked X on each map)

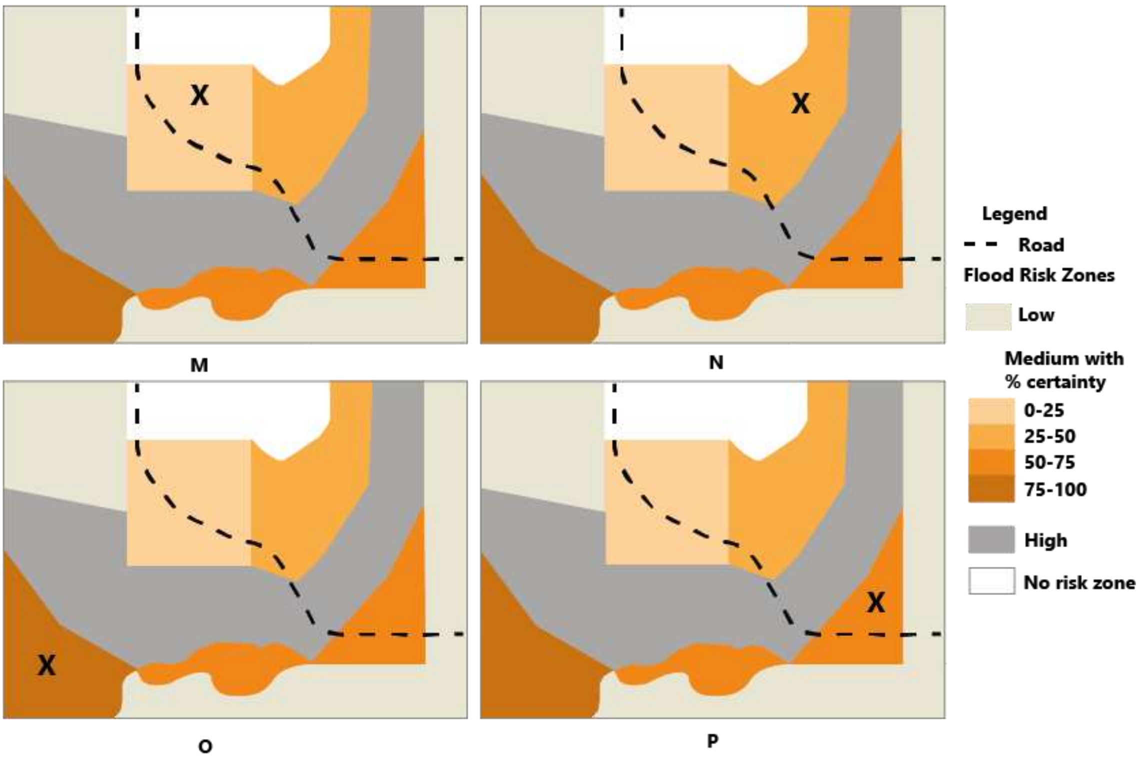


Figure 15: Medium risk zones with certainty encoded by color value. (Users were asked to choose to stay or leave the locations marked X on each map)

Sections 2 and 3 included a measure of user confidence in the decisions they made. Respondents were asked to state how sure they were with the decision to stay or leave a location given the flood risk and certainty information. The confidence ranged from very sure, sure, unsure to very unsure. This four-level scale, two on each side, forced the user to choose a side without being neutral.

3.5 User group

The respondents were all Kenyans aged between 21 and 46 years. The mean age was 28.08 (28 years) and the standard deviation of the ages was 4.02. Majority (mode) of the respondents were 28 years. Based on professional backgrounds, the users were divided into two user groups, i.e. geography experts and novices. Targeted experts were from the geospatial sciences, mapping, geography and statistical career fields, whereas novices were any other professionals from non-geographic backgrounds. All respondents were decision makers at an individual level.

The survey was carried out successfully within 40 days, and there was no set time limit per individual for responding to the questionnaire. Results from the survey are discussed in detail in chapter 4.

4. RESULTS AND ANALYSIS

This chapter presents the survey responses, summarised in words and graphics and statistically analysed using Pearson's Chi-square test for independence, Fischer Exact test and Mann Whitney U test.

The Pearson's Chi-square test ascertains whether an observed distribution occurred by chance or was dependant on another factor. It tests the null hypothesis that variables are independent of one another, as such, the results obtained are not influenced by one of the variables [30]. If samples from the variables in consideration are small, i.e. less than 5, a Fischer Exact Test (based on the Pearson's Chi-square test) is used for a more accurate judgement of variable independence [31]. These two tests calculate a p-value based on the observed and expected values, which is used to judge the dependence or independence of the variables under investigation. A p-value greater than 0.05 confirms the null hypothesis whereas a value less than 0.05 means the null hypothesis is rejected.

These results are divided according to the three sections of the questionnaire, to enable a step by step analysis.

4.1 Users' background information

A total of 53 responses were received from 24 males, 28 females and one individual who preferred not to report on gender. These responses were divided into two major groups for analysis based on the professional field and experience of the respondent in reading and using maps. The groups are novices (28 respondents) and experts (25 respondents), broken down as follows:

- Experts
    - Geospatial science
    - Urban planning
    - Mapping and map visualization
    - Hazard and risk management
    - Statistics
    - Geography
    - Disaster management
    - Water resources engineering
    - Electrical and Electronic engineering

- Novices
    - Accounting, Finance and Economics
    - Psychology
    - Medicine
    - Sustainable development
    - Communication and marketing
    - Education
    - Information and Communication Technology
    - Customer management
    - Sports
    - Construction
    - Law

Out of the 53 respondents, 15 claimed to have previous experience with certainty visualization. This number was revised down to 13 based on the respondents´ elaboration of their experience. The 13 had varied experience ranging from basic viewing of certainty graphs, to professionally working with maps and imagery containing certainty information. 28 of the total 53 encountered floods but none had been permanently displaced before.

4.2 Results of users' flood risk and uncertainty interpretation

An overview of responses from section two of the questionnaire, based on the two groups (experts and novices) is illustrated in figures 16 -19.

4.2.1 Experts vs. novices' ranking of flood risk zones

Figure 16 shows the percentage comparison of experts versus novices who correctly/incorrectly ranked the flood risk zones from safest to riskiest. Based on the pie-charts, novices performed better than experts at ranking the flood risk zones correctly at 86% versus 80%.

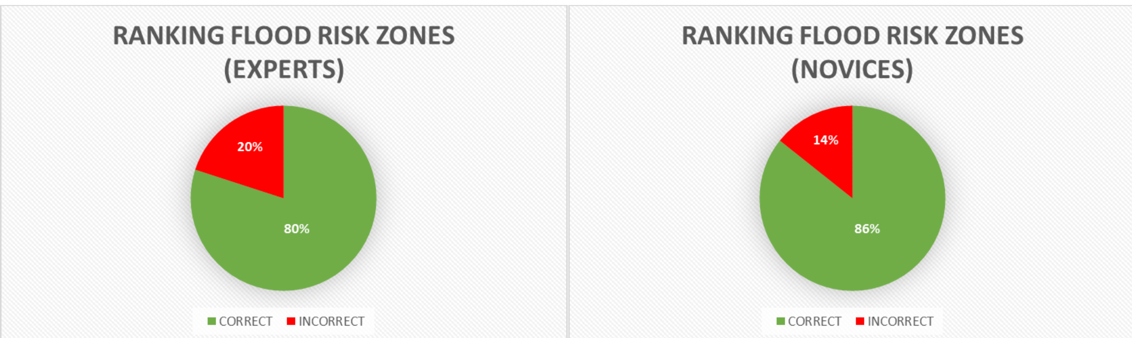


Figure 16: A comparison of experts vs. novices' ranking of the flood risk zones from safest to riskiest

A fischer exact test was performed to ascertain whether the difference in ranking the flood risk zones by experts and novices was statistically significant. A hypothesis was formulated and tested as shown in table 2.

Null hypothesis: The event of being an expert/novice is independent from ranking the flood risk zones correctly/incorrectly.

Based on the obtained p-value of 0.7194, which is greater than 0.05, the respondents could correctly rank the flood risk zones from safest to riskiest regardless of whether they were experts or novices. Therefore, there was no significant statistical difference in ranking flood risk zones between experts and novices.

Table 2: Fischer test results for ranking flood risk zones

OBSERVED VALUES	Correct	Incorrect	Total
Experts	20	5	25
Novices	24	4	28
Total	44	9	53
EXPECTED VALUES			
Experts	20,754	4,245	
Novices	23,245	4,754	
CHI SQUARE P-VALUE	**0,5804**		
FISCHER EXACT P-VALUE	**0,7194**		

4.2.2 Experts versus novices' interpretation of certainty visualised by words

Figure 17 shows the percentage comparison of experts versus novices in interpretation of uncertainty visualized by words. Novices performed better than experts at 100% correct interpretation, whereas, 96% of the experts correctly interpreted uncertainty visualized by words.

Figure 17: A comparison of experts versus novices' interpretation of certainty visualized by words

A fischer exact test was done to check whether there was a statistically significant difference between the responses from experts and novices.

Null hypothesis: The event of being an expert/novice is independent from interpreting certainty represented by words correctly/incorrectly.

A p-value of 0.4716 which is greater than 0.05 was obtained as shown in table 3. This means there was no statistical difference between responses from the two groups. The respondents could correctly interpret certainty visualized by words regardless of whether they were experts or novices.

Table 3: Fischer test results for interpretation of certainty represented by words

OBSERVED VALUES	**Correct**	**Incorrect**	Total
Experts	24	1	25
Novices	28	0	28
Total	52	1	53
EXPECTED VALUES			
Experts	24,52830189	0,471698113	
Novices	27,47169811	0,528301887	
CHI SQUARE P-VALUE	**0,285327477**		
FISCHER EXACT P-VALUE	**0,471698113**		

4.2.3 Experts versus novices' interpretation of certainty visualised by texture overlay

The percentage comparison of experts versus novices' interpretation of uncertainty visualized by words is illustrated in figure 18. 92% of the experts interpreted uncertainty by texture overlay correctly, whereas, 86% of the novices interpreted it correctly.

Figure 18: A comparison of experts vs. novices' interpretation of certainty visualized by texture overlay

To test for a statistically significance difference between the two results, a fischer exact test was used.

Null hypothesis: The event of being an expert/novice is independent from interpreting certainty represented by texture correctly/incorrectly.

Based on the null hypothesis and a fischer exact test p-value of 0.6717, there was no statistically significant difference between the two results. This implies that the respondents could correctly interpret certainty visualized by texture regardless of whether they were experts or novices. The test results are shown in table 4.

Table 4: Fischer test results for interpretation of certainty represented by texture

OBSERVED VALUES	**Correct**	**Incorrect**	Total
Experts	23	2	25
Novices	24	4	28
Total	47	6	53
EXPECTED VALUES			
Experts	22,16981132	2,830188679	
Novices	24,83018868	3,169811321	
CHI SQUARE P-VALUE	**0,519797366**		
FISCHER EXACT P-VALUE	**0,671793246**		

4.2.4 Experts versus novices' interpretation of certainty visualised by color value

Figure 19 illustrates the percentage comparison of experts versus novices in interpretation of uncertainty visualized by color value. Novices performed better than experts at 96% correct interpretation, whereas, 92% of the experts correctly interpreted uncertainty visualized by color value.

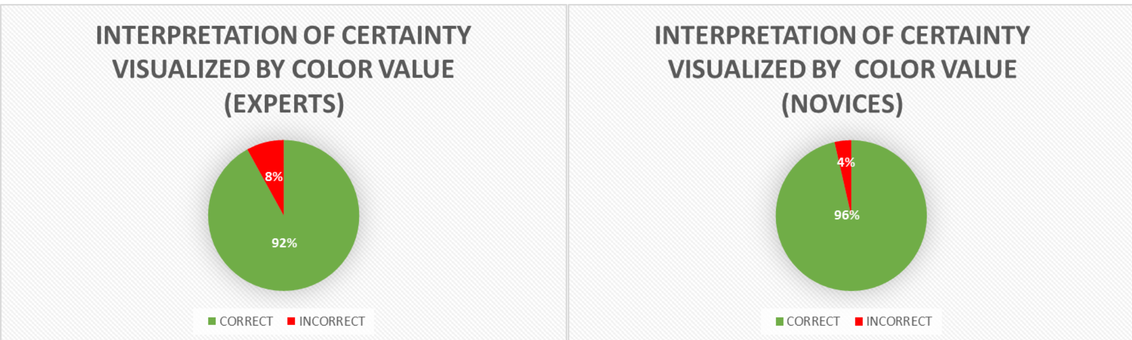


Figure 19: A comparison of experts vs. novices' interpretation of certainty visualized by color value

A fischer exact test was done to check for a statistically significant difference between responses from the two groups.

Null hypothesis: The event of being an expert/novice is independent from interpreting certainty represented by color value correctly/incorrectly.

A Fischer test p-value of 0.5966 which is more than 0.05 was obtained as shown in table 5. This means that the respondents could correctly interpret certainty visualized by color value regardless of whether they were experts or novices.

Table 5: Fischer test results for interpretation of certainty represented by color value

OBSERVED VALUES	Correct	Incorrect	Total
Experts	23	2	25
Novices	27	1	28
Total	50	3	53
EXPECTED VALUES			
Experts	23,58490566	1,41509434	
Novices	26,41509434	1,58490566	
CHI SQUARE P-VALUE	**0,486131963**		
FISCHER EXACT P-VALUE	**0,596602066**		

4.2.5 Texture overlay versus color value interpretation

A comparison of the users' (both experts and novices) interpretation of certainty represented by texture overlay and color value was also done. This was to test whether there were differences in interpretation of the two techniques. Based on the percentages illustrated in figure 20, respondents interpreted color value better than texture at 94% versus 89%.

Figure 20: A comparison of users' interpretation of certainty visualized by texture vs. color value

To test whether there were statistical differences in the interpretation of certainty represented by texture and color value, a fischer exact test was done whose results are shown in table 6.

Null hypothesis: The interpretation of certainty correctly/incorrectly is independent of whether certainty is represented by texture overlay or color value.

A Fischer test p-value of 0.16377 was obtained, which means that there was no statistically significant difference in interpretation of certainty represented by texture overlay and color value.

Table 6: Fischer test results for interpretation of certainty represented by texture versus color value

OBSERVED VALUES	Correct	Incorrect	Total
Texture	47	6	53
Color Value	50	3	53
Total	97	9	106
EXPECTED VALUES			
Texture	48.5	4.5	
Color Value	48.5	4.5	
CHI SQUARE P-VALUE	0.295855		
FISCHER EXACT P VALUE	0.16377		

4.2.6 General reading and interpretation of flood risk and certainty

Results from section two of the questionnaire were the basis for narrowing down the responses for further analysis in section three. Only the respondents who got correctly the ranking of flood risk zones and interpretation of uncertainty represented by texture overlay and color value were eligible for further analysis of their decision making patterns. 39 out of the total 53 respondents answered all applicable questions in section two correctly. This is illustrated in figure 21.

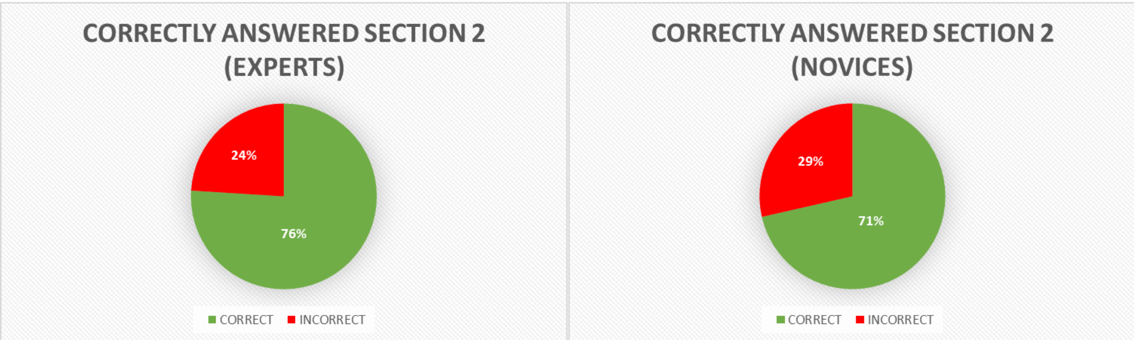


Figure 21: A comparison of experts versus novices who correctly answered all question in section two of the questionnaire

Based on a combination of all the responses from section two of the questionnaire, a Pearson's Chi-square test was done to test whether the general understanding and interpretation of flood risk and certainty is similar for both experts and novices. The number of samples from each of the variables was enough to carry out a Chi-square test. A null hypothesis was formulated and tested using the total number of correct and incorrect responses from the experts and novices.

Null hypothesis: Reading, interpreting and understanding of flood risk maps and certainty information (represented by words, texture and color value) is independent of whether a person is a geography expert/novice.

A Pearson's Chi-square test p-value of 0.7062, which is greater than 0.05 was obtained as shown in table 7. The null hypothesis was accepted. This implies that the general interpretation and understanding of flood risk maps and certainty information represented by words, texture and color value does not depends on whether one is a geography expert or novice.

Table 7: Chi-square test results for general understanding and interpretation of flood risk maps and certainty information represented by words, texture and color value

OBSERVED VALUES	Correct	Incorrect	Total
Experts	19	6	25
Novices	20	8	28
Total	39	14	53
EXPECTED VALUES			
Experts	18,396	6,603	
Novices	38,051	7,396	
CHI SQUARE P-VALUE	0.7063		

4.2.7 Users' experience versus inexperience in certainty visualization

Respondents who had an experience with certainty visualization in section one of the questionnaire were further analysed to find out whether their interpretation of the mapped certainty in section two was correct. 12 (92%) of the 13 users with experience interpreted the certainty visualization maps correctly, whereas, 85% of respondents with no experience in certainty interpreted it correctly. This is shown in figure 22.

Figure 22: A comparison of the interpretation of certainty between respondents with and without experience in certainty visualization

To test whether the results were statistically different between the two groups, a fischer exact test was performed.

Null hypothesis: Interpretation of certainty represented by color value and texture is independent of a person´s previous experience with certainty visualization.

A p-value of 0.6670 which is greater than 0.05 was obtained as shown in table 8. This means that a respondent was able to correctly interpret certainty represented by both color value and texture regardless of their previous experience with certainty visualization. There was therefore no statistical difference between results obtained from the two groups.

Table 8: Fischer test results for interpretation of certainty represented by both color value and texture by respondents with experience in uncertainty visualization

OBSERVED VALUES	**Correct**	**Incorrect**	Total
Experience	12	1	13
No Experience	34	6	40
Total	46	7	53
EXPECTED VALUES			
Experience	11,28301887	1,716981132	
No Experience	34,71698113	5,283018868	
CHI SQUARE P-VALUE	**0,498995947**		
FISCHER EXACT P-VALUE	**0,667032578**		

4.3 Decision making and confidence measures

In this section, responses from 39 respondents (both experts and novices) who correctly answered all questions in section two were analysed. The 39 respondents were eligible for further analysis of the decisions they made in section three of the questionnaire. The decision to combine responses from experts and novices was made because there was no statistical difference in interpreting flood risk and certainty between the experts and novices as shown in chapter 4.2.6.

Here, the respondents were expected to choose to stay or leave a location indicated on the map based on their interpretation of the flood risk and certainty information where provided. There were no right or wrong answers.

4.3.1 Decision making patterns with and without provision of certainty information

4.3.1.1 Decision making without provision of certainty information

The first set of decisions to stay or leave were made on low, medium and high flood risk zones with absence of certainty information.

Figure 23 illustrates the number of respondents who chose to stay or leave each of the flood risk zones (low, medium and high). Undecided respondents, i.e. those who chose both options were filtered out. In the low risk zone, there were 38 valid responses and all the respondents chose to stay. In the medium risk zone, only 12 out of 39 valid respondents chose to stay. In the high flood risk zone, one respondent chose to stay and 38 chose to leave.

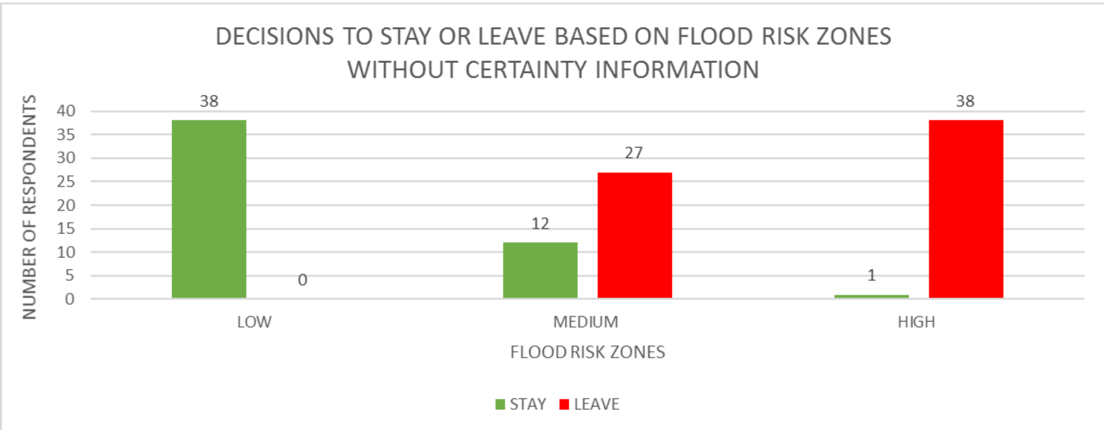


Figure 23: Decisions by the respondents to stay or leave a location based on the flood risk only

4.3.1.2 Decision making with provision of certainty information

The respondents were then asked to choose to stay or leave each of the three zones (low, medium and high) when presented with additional certainty information in percentage between 0 and 100%.

Analysis was done on responses based on certainty represented by color value only. This is because the respondents performed better in interpretation of color value than texture overlay as shown in figure 20 chapter 4.2.5. Moreover, there was no statistical difference in the interpretation of the two techniques as proven by table 6 of chapter 4.2.5.

Low risk zone

In the low risk zone, the number of respondents who chose to stay or leave when presented with certainty information were almost equal between 50-100% certainty. This was different for 0-50% certainty, where most of the respondents chose to stay regardless of the certainty information provided. This is shown in figure 24.

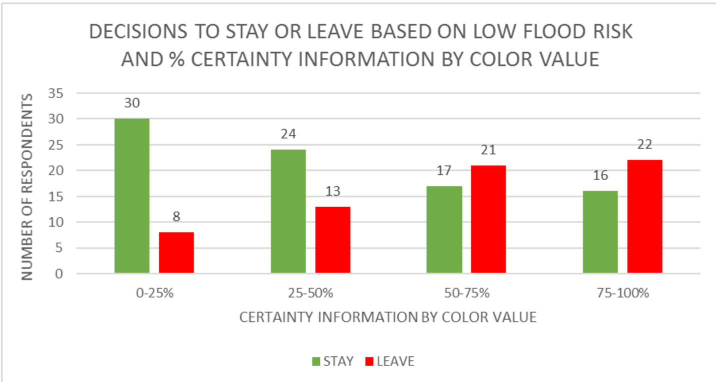


Figure 24: Decisions to Stay or leave the low risk zone when given certainty in color value

When certainty is provided at different percentages in the low risk zone, a noticeable change in decision making pattern is observed when compared to the decision pattern without provision of certainty information as in figure 23.

Stacked bar graphs were made to compare the number of respondents who maintained against those who changed decisions when certainty was provided at the different percentages. Figure 25 shows the change in decision making pattern when certainty is provided in the low risk zone. Based on the stacked bar graph, 42% of the decisions to stay or leave changed when certainty was provided in the low risk zone.

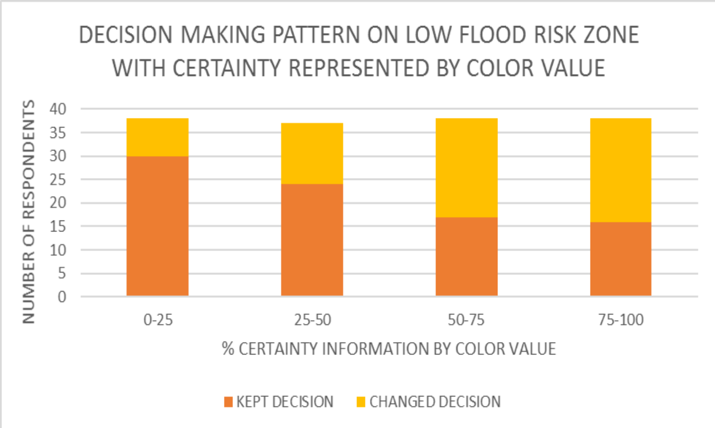


Figure 25: A comparison of the number of respondents who maintained versus those who changed decisions based on color value certainty and low flood risk

Medium risk zone

Certainty information represented by color value was also added in the medium risk zone. Respondents were asked to make decisions to stay or leave the zone based on the different certainty percentages. Their decisions are illustrated in figure 26. Most of the respondents decided to stay when given 0-25% certainty, i.e. 30 out of 39. The number of respondents who chose to stay versus those who decided to leave when given 25-50% certainty was almost equal. Most of the respondents decided to leave when provided with 50-100% certainty.

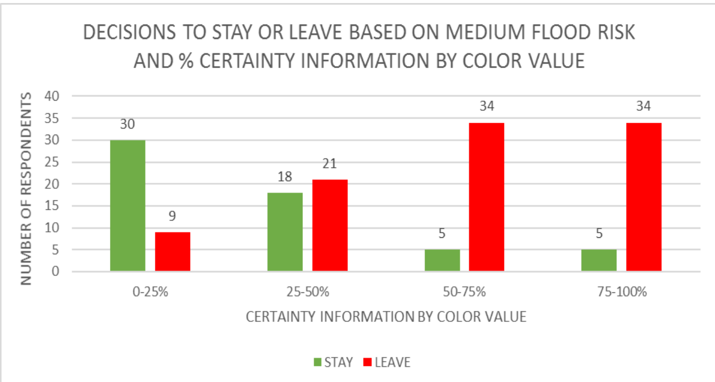


Figure 26: Decisions to Stay or leave the medium risk zone when given certainty in color value

A change in decision making pattern in the medium risk zone is also observed when compared to the decision pattern without provision of certainty information as in figure 23. To analyze the change in decisions when certainty is provided, a stacked bar graph was made as shown in figure 27. 65% of the decisions to stay or leave the medium risk zone changed when certainty was provided at the different percentages.

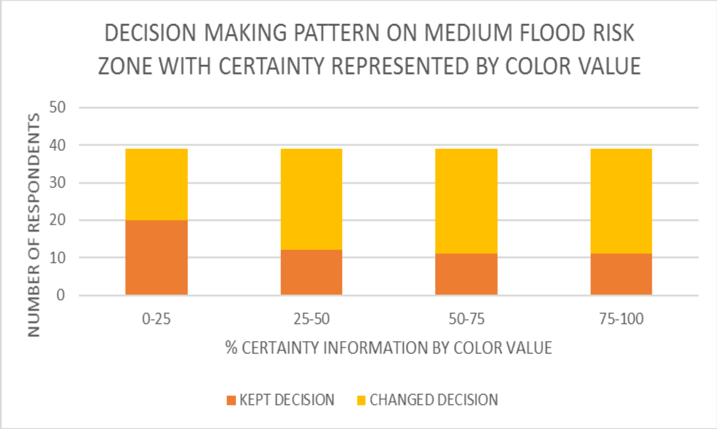


Figure 27: A comparison of the number of respondents who maintained versus those who changed decisions based on color value certainty and medium flood risk zone

High risk zone

When 0-50% certainty is provided in the high flood risk zone, the decision to stay or leave the location was almost split among the respondents. On the contrary, most of them decided to leave the zone when presented with 50-100% certainty. Only one respondent decided to stay regardless of 75-100 % certainty for high floods. This is shown in figure 28.

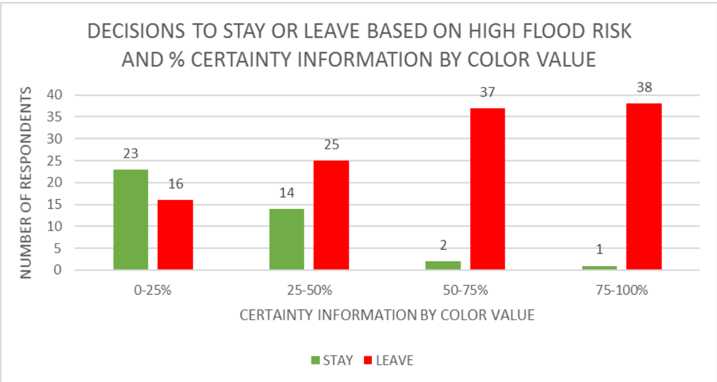


Figure 28: Decisions to Stay or leave the high flood risk zone when given certainty in color value

A stacked bar graph was also made to compare the decision-making pattern in the high flood risk zone when certainty was provided. Based on figure 29, 25% of the decisions to stay or leave the high flood risk zone were changed.

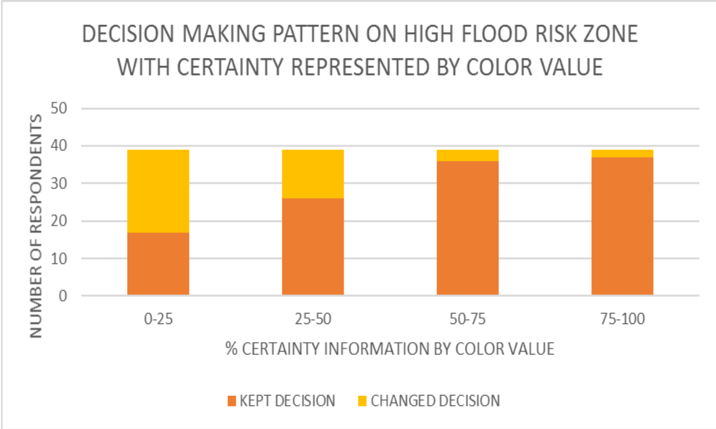


Figure 29: A comparison of the number of respondents who maintained versus those who changed decisions based on color value certainty and high flood risk

Results from the low, medium and high flood risk zones are evidence that the presentation of certainty information caused changes in the decision to stay or leave a zone.

4.3.2 Confidence levels with provision of certainty information

In the previous section, it was proven that provision of certainty information caused changes in decision making. In this section, the confidence levels of the respondents as a result of their change/ lack of change in their decisions when given certainty information is analysed.

Respondents were asked to indicate their confidence in the decisions to stay or leave each of the flood risk zones when provided with certainty information presented by color value. The confidence ranged from very sure, sure, unsure to very unsure. These confidence levels were compiled and compared between respondents who changed versus those who maintained their decision when certainty information was given.

A Mann Whitney U test was then used to test whether there were significant statistical differences in the confidence levels between the two groups (those who kept versus those who changed decisions due to provision of certainty). This test calculates significant differences in ordinal data based on two independent samples, in this case, Likert scale data represented by confidence levels very sure, sure, unsure and very unsure.

A p-value of less than 0.05 rejects the *null hypothesis*, which states: There is no significant statistical differences between the median of confidence levels recorded by respondents who kept their initial decisions and those who changed their decision when presented with certainty information. A value more than 0.05 confirms the null hypothesis, which means, there is no significant difference between the confidence levels reported by the two groups.

Low flood risk zone

Grouped bar graphs were made to show the number of respondents who changed or maintained their decisions against their confidence levels for the low risk zone with color value certainty. This was done for the different levels of certainty, i.e. 0-25, 25-50, 50-75 and 75-100%.

Figure 30 illustrates the confidence levels of respondents when presented with 0-25% certainty. Those who maintained their initial decisions were mostly very sure or sure of their decision i.e. 16 versus 9 respondents. Whereas, the respondents who changed their initial decisions were either sure or unsure (4 respondents for each) and 2 respondents were very sure of their decisions.

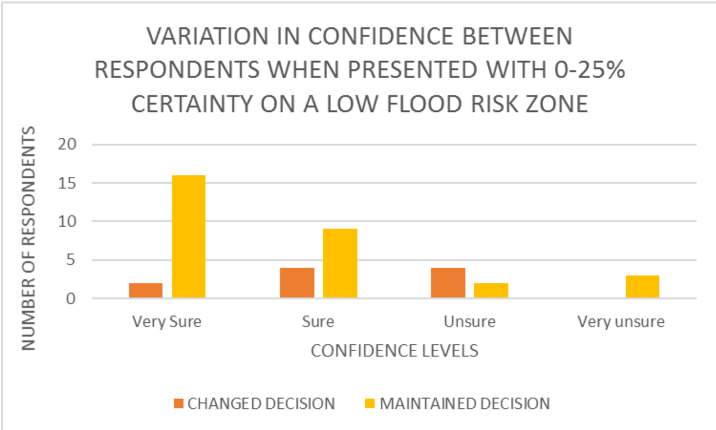


Figure 30: Confidence levels between respondents who changed versus those who maintained decisions when shown 0-25% certainty on a low flood risk zone

A Mann Whitney U test p-value of 0.1074 was obtained for the difference in confidence levels reported when 0-25% certainty was provided. This implies that there was no statistical difference between the confidence of respondents who maintained versus those who changed their decisions.

Figure 31 shows the confidence levels of respondents when presented with 25-50% certainty. Most of the respondents who maintained their initial decisions, i.e. 12, were sure of the decision, seven respondents were very sure, three were unsure and one was very unsure. Six respondents who changed their decisions were sure, four were unsure and three were very sure.

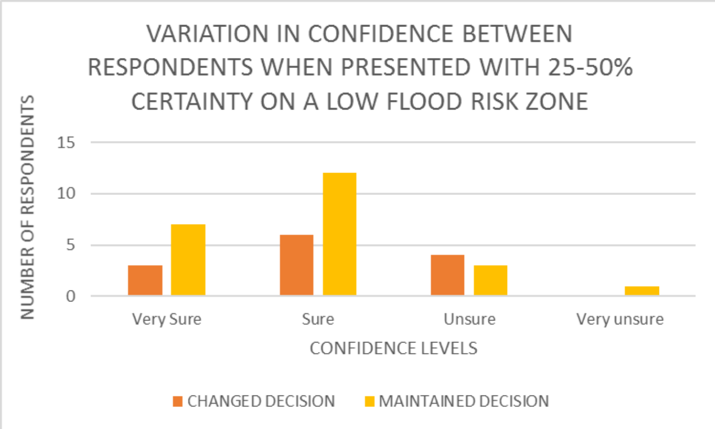


Figure 31: Confidence levels between respondents who changed versus those who maintained decisions when shown 25-50% certainty on a low flood risk zone

A Mann Whitney U test p-value of 0.4965 was obtained for the difference in confidence levels reported when 25-50% certainty was provided. This means that there was no statistical difference between the confidence of respondents who maintained versus those who changed their decisions.

The confidence levels of the respondents when presented with 50-75% certainty is shown in figure 32. Most of the respondents who changed their initial decisions were either very sure or sure of their decision (9 respondents for each level), and three were unsure. Respondents who maintained their initial decisions were mostly sure, i.e. 11, three were unsure and two were very sure.

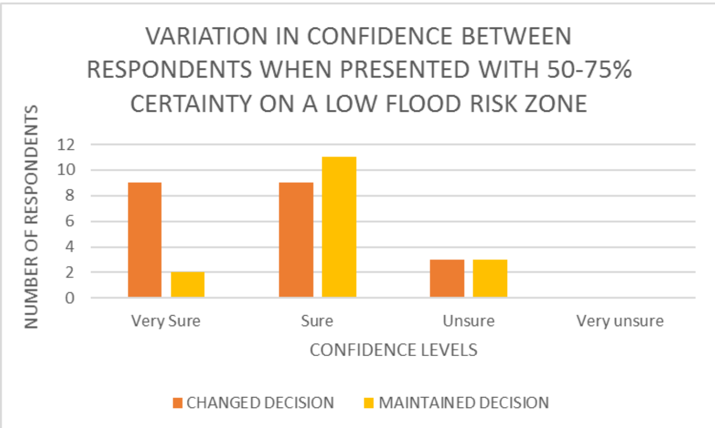


Figure 32: Confidence levels between respondents who changed versus those who maintained decisions when shown 50-75% certainty on a low flood risk zone

A Mann Whitney U test p-value of 0.1443 was obtained for the difference in confidence levels reported when 50-75% certainty was provided. This means that there was no statistical difference between the confidence of respondents who maintained versus those who changed their decisions.

Figure 33 shows the confidence levels of respondents when presented with 75-100% certainty in the low flood risk zone. Most of the respondents who maintained their initial decisions were sure, i.e. seven, followed by five respondents who were unsure of their decision. Only three respondents were very sure. 11 respondents who changed their decisions were very sure, 9 were sure and only 2 were unsure of their decisions.

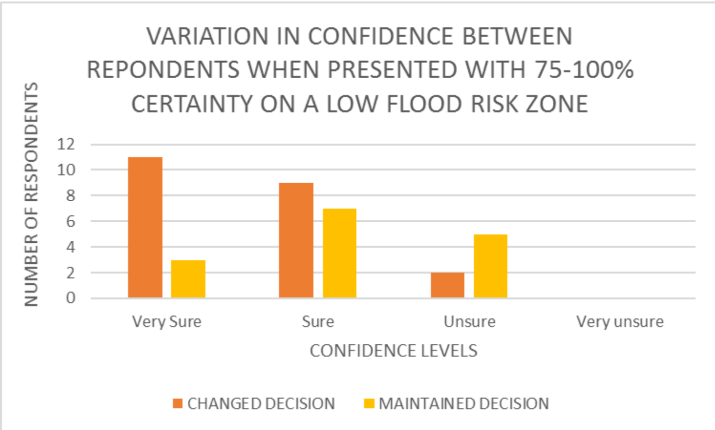


Figure 33: Confidence levels between respondents who changed versus those who maintained decisions when shown 75-100% certainty on a low flood risk zone

A Mann Whitney U test p-value of 0.0455 was obtained for the difference in confidence levels reported when 75-100% certainty was provided. This is less than the 0.05 threshold, which means that the difference between the confidence of respondents who maintained versus those who changed their decisions in this case is statistically significant. Respondents who changed their decisions with provision of 75-100% certainty had higher confidence than those who maintained the decisions.

Medium flood risk zone

A comparison of the confidence levels of respondents who changed versus those that maintained their decisions was also done for the medium risk zone with color value certainty. This was done for the different levels of certainty, i.e. 0-25, 25-50, 50-75 and 75-100%.

Figure 34 shows the confidence levels of respondents when presented with 0-25% certainty in the medium flood risk zone. Most of the respondents who maintained their initial decisions were sure, i.e. 10, followed by seven respondents who were very sure and two were unsure of their decision. The respondents who changed their decisions were also mostly sure, i.e. 10 followed closely by 9 respondents that were very sure and only one person was unsure of their decision.

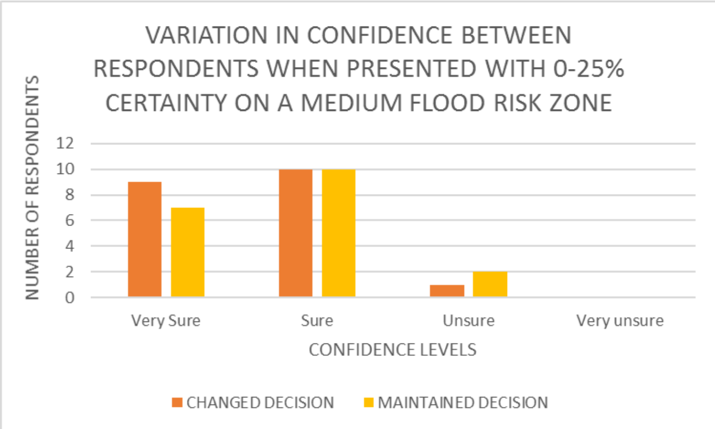


Figure 34: Confidence levels between respondents who changed versus those who maintained decisions when shown 0-25% certainty on a medium flood risk zone

A Mann Whitney U test p-value of 0.5754 was obtained for the difference in confidence levels reported when 0-25% certainty was provided. This is more than the 0.05 threshold, which means that the difference between the confidence of respondents who maintained versus those who changed their decisions in this case is not statistically significant.

Figure 35 shows the confidence levels of respondents when presented with 25-50% certainty in the medium flood risk zone. Respondents who maintained their initial decisions were mostly very sure or sure of their decision, i.e. 12 in both cases. Only three of the respondents in this group were unsure of their decisions. Respondents who changed their decision were mostly sure, i.e. nine, followed by two who were unsure and one who was very sure.

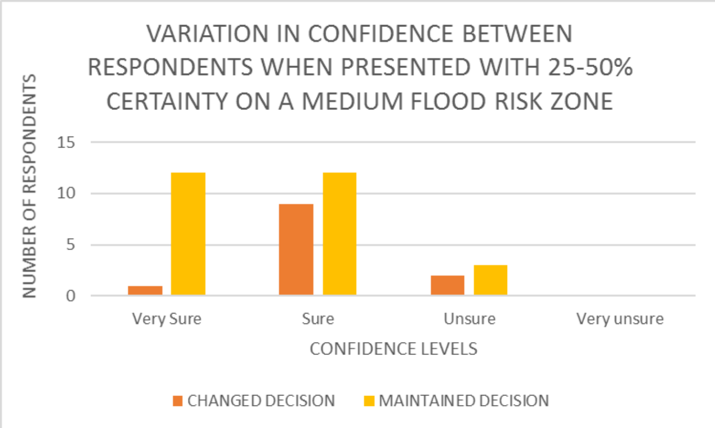


Figure 35: Confidence levels between respondents who changed versus those who maintained decisions when shown 25-50% certainty on a medium flood risk zone

A Mann Whitney U test p-value of 0.0536 was obtained for the difference in confidence levels reported when 25-50% certainty was provided. This is more than the 0.05 threshold, hence the difference between the confidence of respondents who maintained versus those who changed their decisions in this case is not statistically significant.

The confidence levels of respondents when presented with 50-75% certainty in the medium flood risk zone is illustrated in figure 36. 16 respondents who maintained their initial decisions were sure, followed by seven who were very sure and four that were unsure of their decision. Seven respondents who changed their decision were sure, followed by three who were very sure. Both groups had one respondent who was very unsure of the decision made.

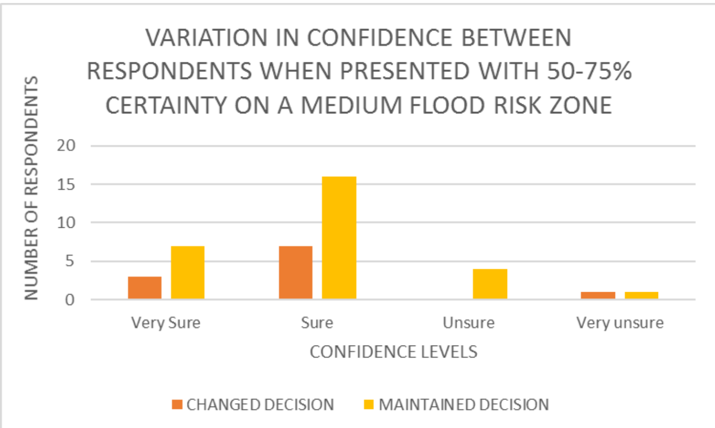


Figure 36: Confidence levels between respondents who changed versus those who maintained decisions when shown 50-75% certainty on a medium flood risk zone

A Mann Whitney U test p-value of 0.8181 was obtained for the difference in confidence levels reported when 50-75% certainty was provided. This is more than the 0.05 threshold, meaning, the difference between the confidence of respondents who maintained versus those who changed their decisions in this case is not statistically significant.

Figure 37 shows the confidence levels of respondents when presented with 75-100% certainty in the medium flood risk zone. 14 respondents who maintained their initial decisions were sure, eight were very sure, seven were very unsure and five were unsure. Respondents who changed their decision were mostly sure, i.e. seven, followed by three who were very sure and one who was unsure.

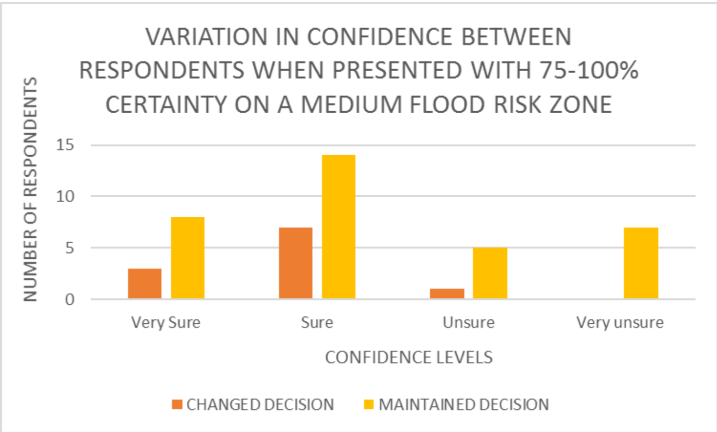


Figure 37: Confidence levels between respondents who changed versus those who maintained decisions when shown 75-100% certainty on a medium flood risk zone

A Mann Whitney U test p-value of 0.2340 was obtained for the difference in confidence levels reported when 75-100% certainty was provided. This is more than the 0.05 threshold, hence the difference between the confidence of respondents who maintained versus those who changed their decisions is not statistically significant.

High flood risk zone

Lastly, a comparison of the confidence of respondents who changed versus those that maintained their decisions was done for the high flood risk zone. The different levels of certainty, i.e. 0-25, 25-50, 50-75 and 75-100% were analysed.

Figure 38 illustrates the confidence levels of respondents when presented with 0-25% certainty in the high flood risk zone. 11 respondents from each of the groups were sure of their decision. Similarly, two respondents from each of the groups were unsure of their decision. Four respondents who maintained their decision were very sure, whereas, nine who changed their decisions were very sure.

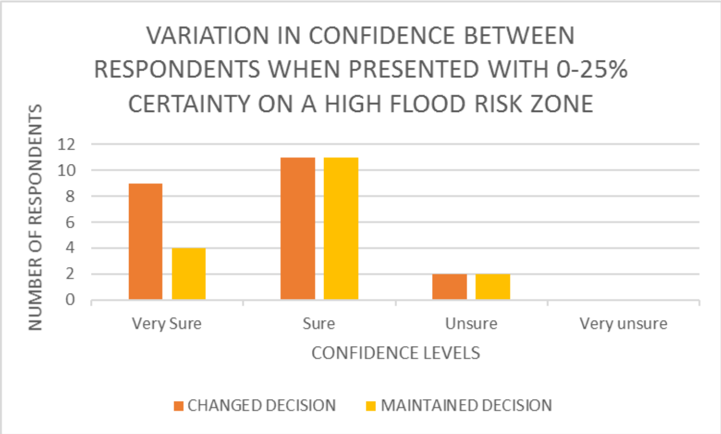


Figure 38: Confidence levels between respondents who changed versus those who maintained decisions when shown 0-25% certainty on a high flood risk zone

A Mann Whitney U test p-value of 0.3628 was obtained for the difference in confidence levels reported when 0-25% certainty was provided in the high flood risk zone. This is more than the 0.05 threshold. Therefore, the difference between the confidence of respondents who maintained versus those who changed their decisions is not statistically significant.

Figure 39 shows the confidence levels of respondents when presented with 25-50% certainty. 16 respondents who maintained their decision were sure, seven were very sure and three were unsure. Six respondents who changed their decision were sure, three were very sure and three were also unsure.

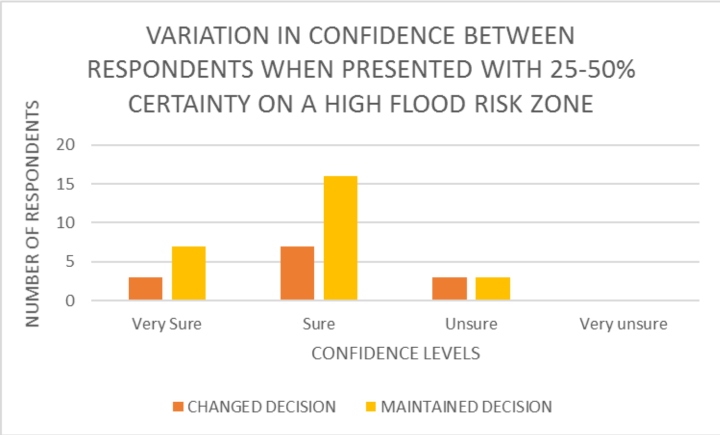


Figure 39: Confidence levels between respondents who changed versus those who maintained decisions when shown 25-50% certainty on a high flood risk zone

A Mann Whitney U test p-value of 0.5619 was obtained for the difference in confidence levels reported when 25-50% certainty was provided. This is greater than the 0.05 threshold which means that the difference between the confidence of respondents who maintained versus those who changed their decisions is not statistically significant.

Figure 40 illustrates the confidence levels of respondents when presented with 50-75% certainty. 21 respondents who maintained their decisions were sure, twelve were very sure and four were unsure. Only two respondents changed their decision in this case, and they were sure of the changed decision.

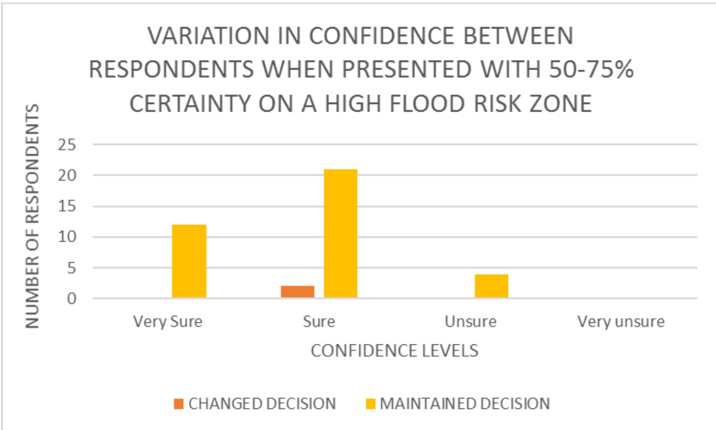


Figure 40: Confidence levels between respondents who changed versus those who maintained decisions when shown 50-75% certainty on a high flood risk zone

A Mann Whitney U test was not applicable for the scenario in figure 40. One of the groups, i.e. the respondents who changed their decisions, had less than 5 respondents in total, therefore, the two groups were incomparable.

The confidence levels of respondents when presented with 75-100% certainty is illustrated in figure 41. 22 respondents who maintained their decisions were sure, 12 were very sure and four were unsure. Only one respondent changed the initial decision in this case, with a sure confidence level.

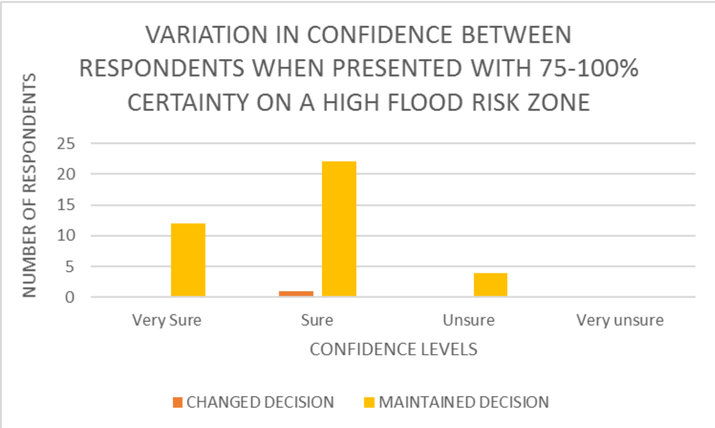


Figure 41: Confidence levels between respondents who changed versus those who maintained decisions when shown 75-100% certainty on a high flood risk zone

A Mann Whitney U test was also not applicable here. The group with respondents who changed their decisions had less than 5 respondents in total, therefore, the two groups were incomparable.

4.3.3 Decision making by respondents with and without floods encounter

20 out of the 39 respondents whose results were analysed in section three, had previously encountered floods. Their responses were analysed and compared with the remaining 19 respondents who had no encounter with flood.

Fischer exact tests were done to test for significant differences between the two groups. This was done for responses in all the flood risk zones and percentage certainty. The *null hypothesis* tested was: The decision to stay or leave a flood risk zone (with certainty represented by color value) is independent of a person´s encounter/lack of encounter with floods. A p-value of less than 0.05 would reject the null hypothesis, meaning, the statistical differences between the two groups are significant. On the contrary, a p-value of greater than 0.05 confirms the null hypothesis, which means that a respondent's encounter or lack of encounter with floods did not influence their decision to leave or stay at the location.

Low risk zone

Figures 42 and 43 illustrate the differences in decisions to stay or leave the low risk zone, between the respondents with and without floods encounter. The two graphs appear to be generally similar. Respondents with previous floods encounter recorded higher numbers for the choice to stay when given 0-50% certainty. Most of the respondents without previous floods encounter, i.e. 13, chose to stay when shown 0-25% certainty. On the contrary, when given 50-75% and 75-100% certainty, 11 respondents chose to leave for each of the two levels.

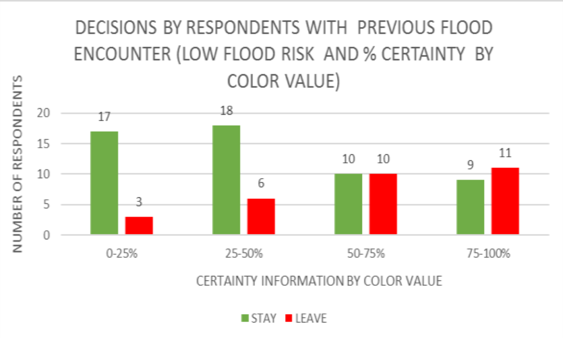


Figure 42: Decisions by respondents to stay or leave the low risk zone with certainty shown by color value (respondents had previous encounter with floods)

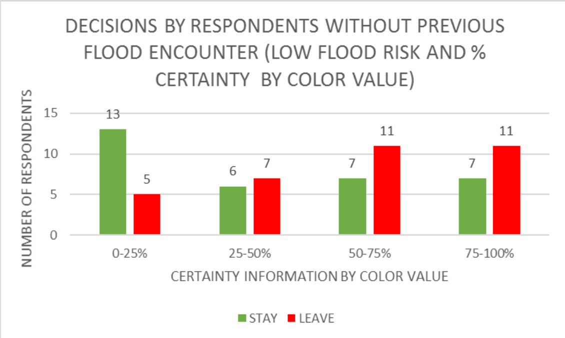


Figure 43: Decisions to stay or leave the low risk zone with certainty information represented by color value. (Respondents without previous encounter with floods)

Responses from the two groups as shown in figures 42 and 43 were analysed for statistically significant differences using the fischer exact test. P-values of 0.4381, 0.1477, 0.5318 and 0.7521 were obtained for the certainty levels 0-25%, 25-50%, 50-75% and 75-100% respectively. All the p-values in the low risk zone were greater than the 0.05 threshold. Therefore, there were no statistically significant differences across all the certainty levels, between choices made by respondents with and without previous floods encounter.

Medium risk zone

Figures 44 and 45 illustrate the differences in decisions to stay or leave the medium risk zone, between the respondents with and without floods encounter. The two graphs appear to be generally similar between 50-100% certainty. 36 respondents with floods encounter chose to leave and 32 respondents without floods encounter also chose to leave, given 50-100% certainty. A small but noticeable difference is seen between 25-50% certainty. Respondents with floods encounter had equal numbers of those who chose to stay or leave the location i.e. 10, whereas, more respondents without floods encounter chose to leave i.e. 11 against 8.

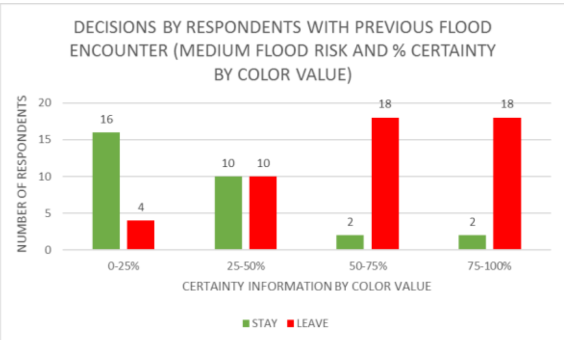


Figure 44: Decisions by respondents to stay or leave the medium risk zone with certainty shown by color value (respondents had previous encounter with floods)

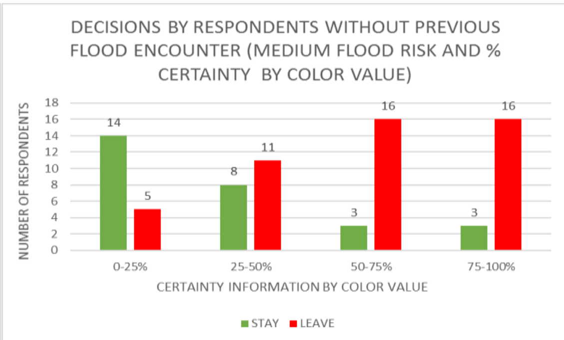
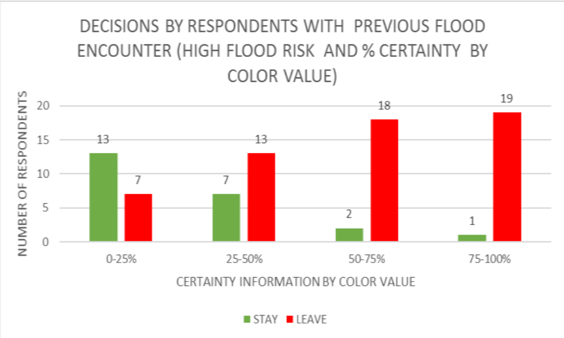


Figure 45: Decisions by respondents to stay or leave the medium risk zone with certainty shown by color value (respondents without previous encounter with floods)

Responses from the two groups as shown in figures 44 and 45 were also analysed for statistically significant differences using the fischer exact test. P-values of 0.7164, 0.7511, 0.6614 and 0.6614 were obtained for the certainty levels 0-25%, 25-50%, 50-75% and 75-100% respectively. All the p-values in the medium risk zone were greater than 0.05. There were no statistically significant differences across all the certainty levels, between choices made by respondents with and without previous floods encounter.

High flood risk zone

Figures 46 and 47 illustrate the differences in decisions to stay or leave the high flood risk zone, between the respondents with and without previous floods encounter. The two graphs appear to have a general trend with slight differences in the number of respondents across the confidence levels. Both groups recorded higher numbers of respondents who chose to leave when given 50-100% certainty, i.e. 37 from respondents with floods encounter and 38 from those without floods encounter. When given 0-25% certainty, 13 respondents with floods encounter and 10 respondents without floods encounter chose to stay.



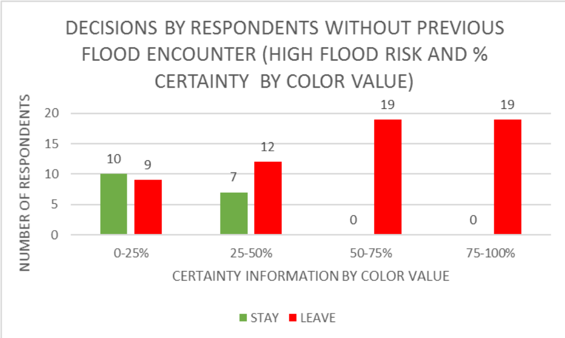


Figure 46: Decisions to stay or leave the high flood risk zone with certainty information represented by color value. (Respondents had previous encounter with floods)

Figure 47: Decisions to stay or leave the high flood risk zone with certainty information represented by color value. (Respondents without previous encounter with floods)

Fischer exact test p-values of 0.5231, 1, 0.4871 and 1 were obtained for the certainty levels 0-25%, 25-50%, 50-75% and 75-100% respectively. All the p-values in the high flood risk zone were greater than 0.05. Therefore, there were no statistically significant differences across all the certainty levels between choices made by respondents with and without previous floods encounter.

4.3.4 Respondents' recommendation on certainty visualization

Respondents were asked for opinions on whether and why they would recommend visualization of certainty information on flood risk maps. 51 out of the 53 respondents recommended visualization of certainty. They gave reasons such as:

- "It helps one have more information on the flood risk of an area"
- "It helps for disaster reduction because people will worry less and prepare well in advance after learning how serious the risk is"
- "Increase confidence in the prediction risk"
- "To help people in calculating the risks associated with either leaving or staying in their zones based on the certainty risk levels predicted"
- "It allows for a wider range of grading for the flooding risk"
- "So that an individual is sure to what extent the information presented is accurate"
- "It gives more confidence on the results after interpretation"

On the contrary, two respondents were against certainty visualization. One of the two stated that:

- "It can be confusing at times"

Based on these responses, 96% of the respondents would appreciate visualization of certainty information for informed and better decision making while 4% would not recommend it.

5. CONCLUSIONS

5.1 Overview

This thesis has addressed suggested gaps in uncertainty visualization as pointed out by Smith et al. [4]. In their paper, they identified domains within uncertainty visualization that require research attention, for instance the user domain. They highlighted the need to study the effects of user individual differences and prior knowledge on interpretation of uncertainty visualization [4]. Based on their recommendation, this study has successfully tested the differences in interpretation of uncertainty between geography experts and novices from Kenya. Additionally, user prior knowledge and experience with uncertainty visualization has also been studied and analysed here.

As seen from the study results, both experts and novices could comprehend and make sound decisions based on uncertainty represented by texture overlay and color value. Although the percentage of experts who answered the questions correctly was higher, there was no statistical difference between experts and novices in terms of reading and interpreting flood risk maps, with or without uncertainty information.

Based on the study results, users' inexperience in uncertainty visualization does not have a negative effect on the interpretation of uncertainty. Both the users with and without experience in uncertainty visualization were able to appropriately interpret flood risk maps with uncertainty information represented by texture and color value. There was no statistical difference in uncertainty interpretation by the two groups.

Kunz et al. pointed out the reluctance of Swiss hazard experts to communicate uncertainties on hazard maps due to the complexity of these maps [8]. To challenge the experts´ reluctance, this study tested whether the Kenyan novice user group would be able to correctly comprehend and make decisions, based on uncertainties represented by color value and texture overlay on flood risk maps. The user group was able to comprehend both techniques correctly, but they performed best with color value. However, there was no statistical difference between the comprehension of the two techniques.

All the users were also asked for their opinion on whether they would recommend visualization of uncertainty after their experience with this survey. 96% of the users (both experts and novices) recommended inclusion of uncertainty as it would help them make better and informed decisions.

Fabrikant et al. investigated whether users' decisions based on hazard maps are influenced by uncertainties [9]. They found out that users made different decisions when presented with uncertainty [9]. This thesis confirms their findings based on the Kenyan user group and uncertainty represented by texture overlay and color value. In the low risk zone, 42% of decisions made were changed; in the medium risk zone, 65% of the decisions were changed; and 25% of the decisions in the high flood risk zone were also changed when uncertainty was provided.

This research went further to investigate users' confidence in the decisions they made and whether there was a change in confidence levels as a result of changed decisions due to uncertainties. Predominantly, the confidence levels recorded by the two groups (respondents who maintained their initial decisions versus those who changed their decisions due to uncertainties) were not statistically different. However, in one scenario (low flood risk with 75-100% certainty), users who changed their decision due to the additional uncertainty information, recorded statistically significant higher confidence levels than those who maintained their initial decision. Therefore, it can be concluded that inclusion of uncertainty information has potential to increase confidence in decisions taken depending on the underlying information presented on the map.

Based on the research objectives and questions, the following conclusions were made from this research in relation to the Kenyan user groups (geography experts and novices):

I. Experts and novices were able to correctly interpret and rank flood risk zones represented by color hue from the safest to riskiest.
II. Experts and novices correctly interpreted uncertainty information represented by words.
III. Novices seemed slightly better at reading and interpreting uncertainty represented by color value than by texture overlay. However, there was no significant statistical difference in the reading and interpretation of uncertainty by texture overlay and color value by novices.
IV. Experts were able to read and interpret uncertainty represented by both color value and texture overlay efficiently.
V. Generally, there was no statistical difference between experts and novices in reading and interpreting flood risk maps, with or without uncertainty represented by color value or texture overlay.

VI. Both texture overlay and color value techniques of representing uncertainty were well interpreted by the respondents. There was no statistical difference in interpretation of the two techniques.

VII. There was no statistical difference in the reading and interpretation of uncertainty (by texture overlay and color value) between users with and without previous experience in uncertainty visualization. Both groups were able to correctly read and interpret uncertainty regardless of their experience.

VIII. Inclusion of uncertainty information on flood risk maps lead to a change in decision making by users when compared to the decisions made without uncertainty information.

IX. When asked to stay or leave a flood risk zone with uncertainty information, there was no statistical difference in the decision making patterns between users with a previous flood encounter and those without. Both groups exhibited a similar pattern.

X. The confidence level of respondents who changed their decisions when presented with uncertainty was different from those who maintained their initial decisions. There was an instance of increased confidence in decisions made by users who changed their decisions.

XI. Both experts and novices recommended the inclusion of uncertainty information on flood risk maps for better and informed decisions.

5.2 Survey setbacks

The fictional maps used in the survey represented flood risk maps using color hue. Specific colors were selected for the different zones, i.e. brown (RGB 217, 95, 14) for high risk zones, orange (RGB 254, 196, 79) for medium risk zones and yellow (RGB 255, 247, 188) for low risk zones. Given that the survey was rendered online, the colors may have appeared differently depending on the characteristics of the users' computer screens, operating systems and web browsers. The colors perceived by users may have influenced their decisions differently as compared to the intended colors.

Most of the respondents reported that the questionnaire needed ample time and good concentration to fill up. On the one hand, this was advantageous as those who responded took time to understand the maps before submitting their responses. On the other hand, the targeted user group of at least 75 respondents was not met as several people did not complete the questionnaire within the given time frame.

In this study, users were expected to make decisions to stay or leave a location based solely on flood risk and uncertainty. However, such a decision would normally involve other factors such as availability of alternative homes, funds for relocation, insurance of property etc. All these factors were kept constant in this survey.

The categorization of users into geography experts and novices was based on their professional background. This can be debatable depending on the experience of the user in their profession and their personal experience with maps and uncertainty visualization.

5.3 Recommendations for future studies

Future research can extend this study by introducing additional base map information to the fictional maps. Additionally, more information such as the economic situation of the respondent etc. can be put into consideration in the design of the questionnaire. This can further influence the decision taken by the respondent when such information is considered.

In this study, some respondents did not submit proper explanation for their responses as was required. Such situations were filtered out to improve the outcome. To avoid similar experiences, future studies could consider using performance-based incentives, a concept widely used in experimental economics to control user response and avoid unthought-of responses [8].

Similar future studies should involve a bigger user group. This would improve the results obtained here, as more responses would be able to statistically prove additional hypotheses and differences between groups.

The techniques tested here are static and coincidence methods of representing uncertainty (color value and texture overlay). The decision to investigate these methods was influenced by recommendations from the literature reviewed here. Future work should explore alternative uncertainty visualization techniques from the dynamic and adjacent methods as well as other static and coincidence approaches.

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List of Figures

List of Tables

Appendix

Research Questionnaire

Title: A survey on visualization of flood risk and its certainty

Section 1: User information

1. How old are you?

2. What is your gender?

    a) Male
    b) Female
    c) Prefer not to say

3. What is your professional background?

    a) Geospatial Sciences
    b) Geography
    c) Urban planning
    d) Mapping and Map visualization
    e) Hazard and risk management
    f) Statistics
    g) Other, specify.

4. Do you have any experience with certainty/uncertainty visualization on maps?

    a) Yes
    b) No

    If yes, please specify your experience.

5. Have you had any kind of encounter with floods?

    a) Yes
    b) No

    If yes, please give details of your encounter.

<u>Section 2: Flood risk and certainty</u>

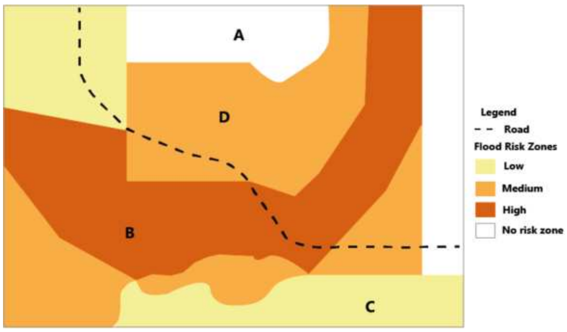
Background literature:

Flood risk is a prediction of how much flooding and damage is most likely to occur in an area/zone. The zones are categorized into high, medium or low risk zones, based on the likelihood for damage to occur due to floods.

Certainty is the confidence in prediction of the flood risk. It varies from 0 to 100%, where 0 = very low confidence and 100 = high confidence that the predicted flood risk shall occur. For example, a high flood risk zone with 75-100% certainty means there is a 75-100% confidence that the area shall experience high level floods and damages.

N/B If you do not understand the meaning of certainty please consult the author prior to filling in the questionnaire.

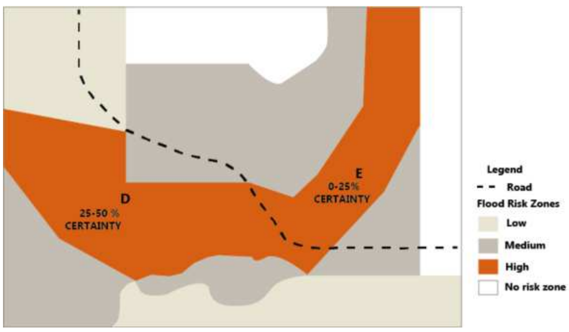
1. (a) Please rank the zones A, B, C and D, in order from the safest to the riskiest to live in?



(b) How sure are you with the ranking?

a) Very sure
b) Sure
c) Unsure
d) Very unsure

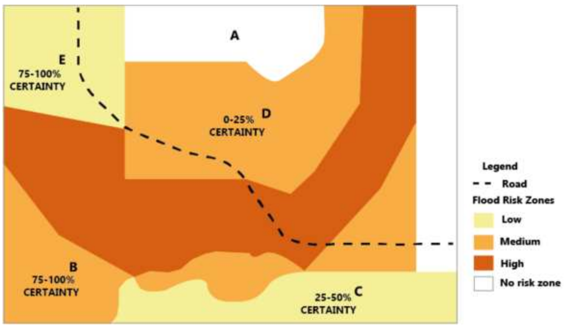
2. (a) Based only on flood risk and certainty, which of the zones D and E is most likely to flood?



N/B Certainty – confidence in the flood risk prediction

(b) Please give reasons for your choice

3. (a) Please rank the zones A, B, C, D and E in order from the safest to the riskiest based on flood risk and certainty.

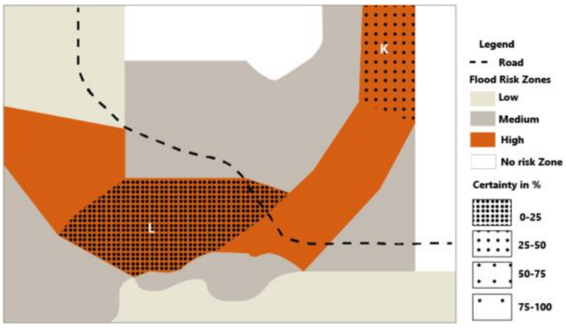


N/B Certainty – confidence in the flood risk prediction

(b) How sure are you with the ranking?

a) Very sure
b) Sure
c) Unsure
d) Very unsure

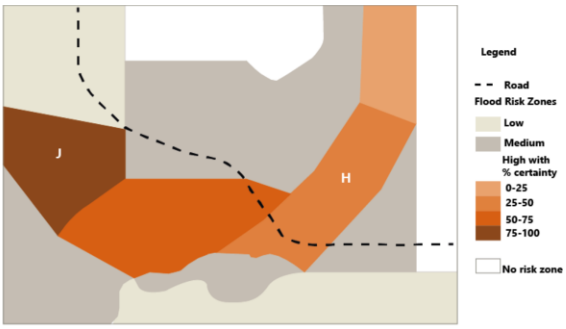
4. (a) Based on flood risk and certainty, which of the zones K and L is most likely to flood?



N/B Certainty – confidence in the flood risk prediction

(b) Please give reasons for your choice

5. (a) Which of the zones J and H is most likely to flood based on flood risk and certainty?



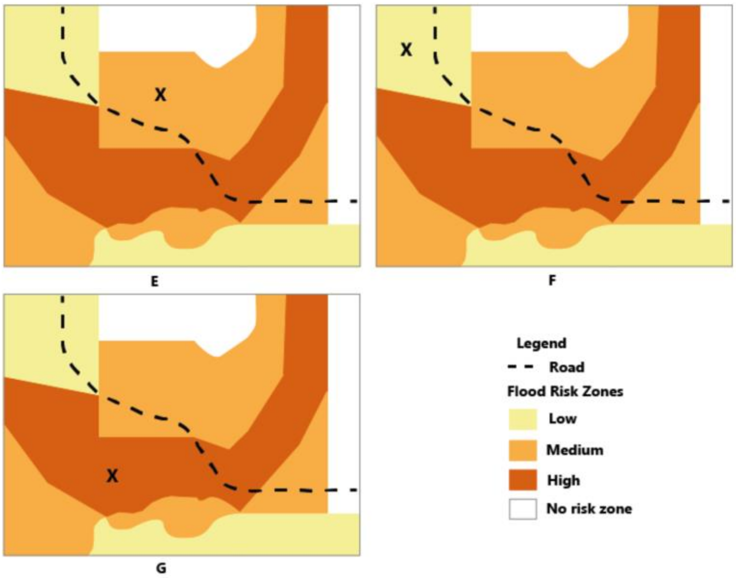
N/B Certainty – confidence in the flood risk prediction

(b) Please give reasons for your choice

<u>Section 3: Decision making</u>

In this section you will be shown a series of maps depicting flood risk and/or certainty. Imagine you live at the location marked X. You are expected to make a decision to leave or stay at X based on flood risk and the certainty information presented.

1. (a) Based on flood risk only would you stay or leave at X on each of the following maps?



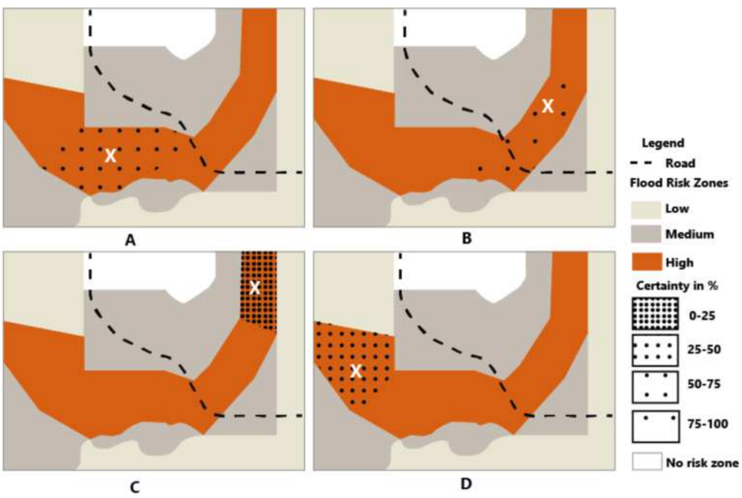
(b) Please explain your decision for each of the maps.

(c) How sure are you with your decisions for each map?

a) Very sure
b) Sure
c) Unsure
d) Very unsure

<u>Texture overlay</u>

2. (a) Based on both flood risk and certainty, would you stay or leave at X on each of the following maps?



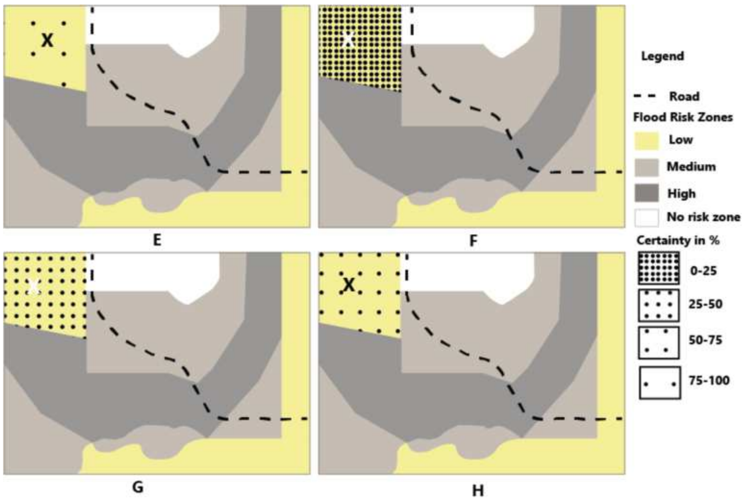
N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.

ii. How sure are you with your decisions for each map?

   a) Very sure
   b) Sure
   c) Unsure
   d) Very unsure

(b) Would you stay or leave at X?



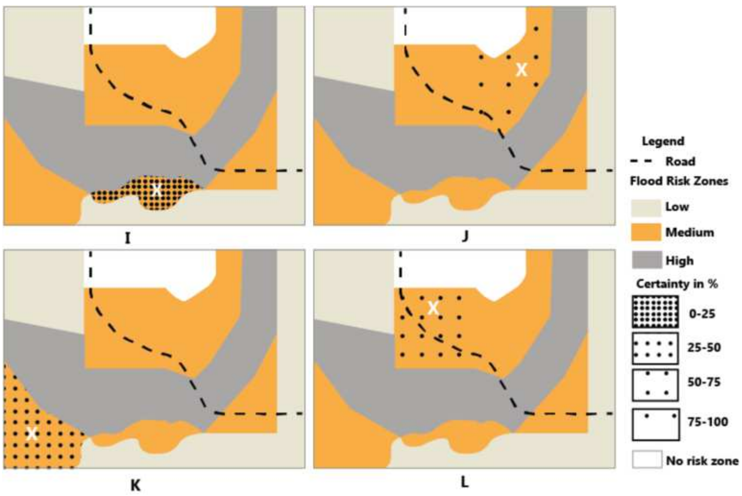
N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.

ii. How sure are you with your decision for each of the maps?

   a) Very sure
   b) Sure
   c) Unsure
   d) Very unsure

(c) Would you stay or leave at X?

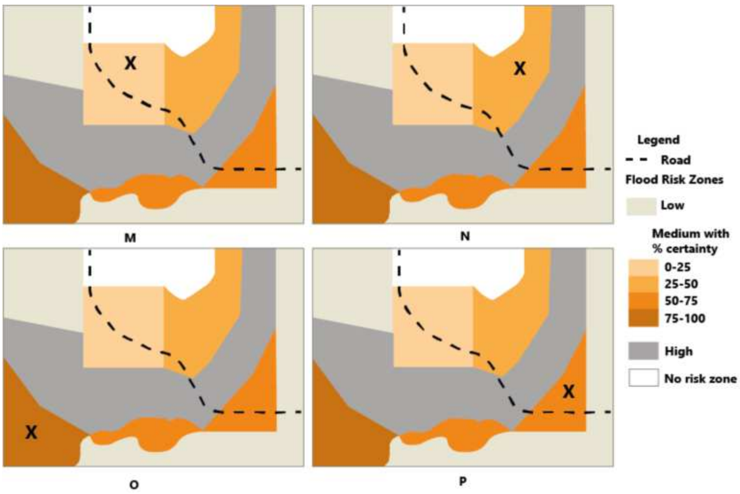


N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.
ii. How sure are you with your decision for each of the maps?
   a) Very sure
   b) Sure
   c) Unsure
   d) Very unsure

<u>Color value</u>

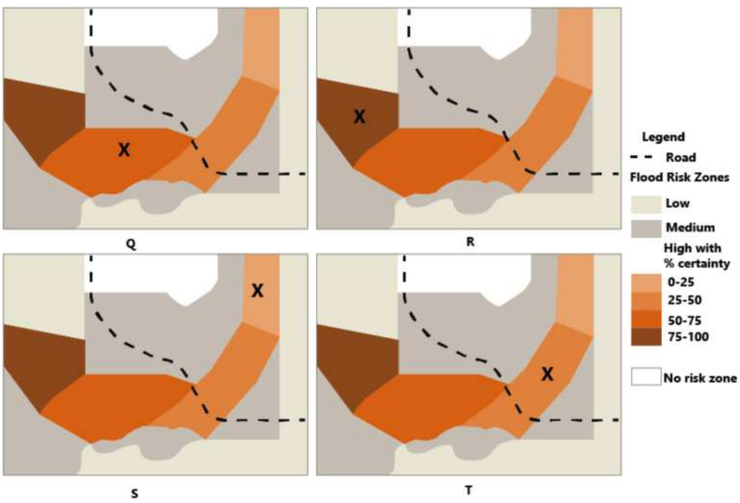
3. (a) Based on both flood risk and its certainty, would you stay or leave at X on each of the following maps?



N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.
ii. How sure are you with your decision for each of the maps?
   a) Very sure
   b) Sure
   c) Unsure
   d) Very unsure

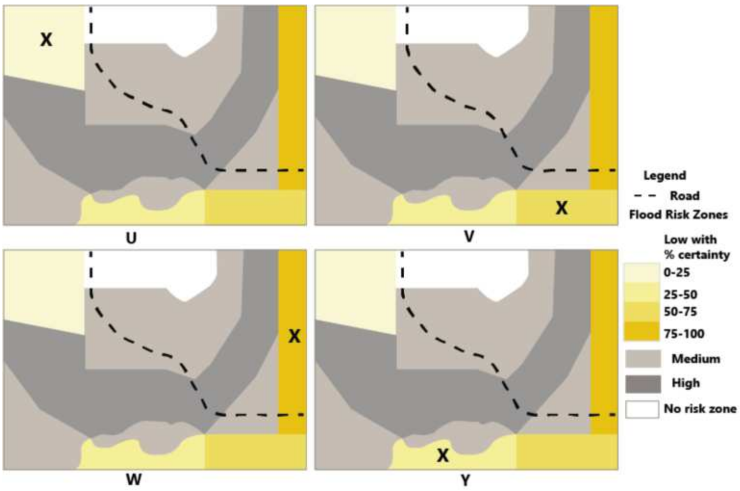
(b) Would you stay or leave at X?



N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.
ii. How sure are you with your decision for each of the maps?
    a) Very sure
    b) Sure
    c) Unsure
    d) Very unsure

(c) Would you stay or leave at X?



N/B Certainty – confidence in the flood risk prediction

i. Please explain your decision for each of the maps.
ii. How sure are you with your decision for each of the maps?
    a) Very sure
    b) Sure
    c) Unsure
    d) Very unsure

4. Do you think certainty information should be added on flood risk maps? Why?