Immersive visualization for ecosystem services analysis and trade-offs

by

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Abstract

Changing land use to improve one ecosystem service can affect other ecosystem services, so a potential land use change should be analysed before implementation. Land use analysts using existing ecosystem services modelling software, and users of the results of ecosystem services analysis identified problems with modelling tools applied to ecosystem services analysis. A User Centred Design process was adopted in this study, to design and implement an immersive Virtual Reality (VR) visualization system, Immersive ESS Visualizer.

Immersive ESS Visualizer was designed, and implemented for users of differing levels of geospatial expertise, to assist with visualization and analysis of ecosystem services data. Features include multiple handheld maps, a scenario map, layers, filters, zoom, and navigation by gliding. Handheld maps allowed users to create layouts with multiple maps for comparison.

A user study was performed to compare the effectiveness of Immersive ESS Visualizer to existing media, a 2D screen and paper maps. The user study investigated the effectiveness of Immersive ESS Visualizer for communication to a stakeholder. The most highly ranked features of Immersive ESS Visualizer included the file list, tab menus, handheld map, and zoom buttons. The study found that Zoom assisted participants with their comparison of data in VR, Immersive ESS Visualizer was good for inspecting hillshade, placing maps side-by-side was useful for comparing data, and participants adopted 3D positioning techniques to arrange maps to assist their analysis. Participant expertise was classified based on VR expertise, data expertise, map expertise, location expertise, and spatial

technology expertise.Participants with more VR expertise found Immersive ESS Visualizer more effective. Participants had positive responses to their experiences communicating with the researcher while using VR, the zoom feature. The laser pointer and the facilitator's 2D screen assisted participants to communicate while in the VR HMD. Immersive ESS Visualizer could potentially be extended to other datasets, the features available could be extended into a multi-user system.

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Chapter 1

Introduction

Contents

Ecosystem services are the benefits to humans provided by ecosystems through their internal natural processes [59]. Humans can derive benefits from ecosystem services directly or indirectly. For example, agricultural farmland provides ecosystem services directly by producing goods [134]. Farming increases agricultural production but can negatively impact other ecosystem services by reducing biodiversity and producing runoff containing nitrogen and phosphorus [134]. Indirect ecosystem services could support another direct ecosystem service [94], for example, improving species habitat is an indirect ecosystem service. Land use is how humans manage, alter and conserve the ecosystem services and goods provided by the land [105]. Changing land use to improve one ecosystem service can negatively affect other ecosystem services, so a potential land use change should be analysed before its implementation [122]. Analysing land use change helps to prevent undesirable reductions in other ecosystem services and ensures that proposed changes are effective for the ecosystem service being improved. *This thesis investigates the effectiveness of an immersive visualization system for analysing geospatial data relating to land use, to inform of the potential effects of land use change on ecosystem services.*

Modelling ecosystem services with software can assist with analysing and predicting the effect of implementing a land use change to improve particular ecosystem services and identify where existing land use should be conserved. The ecosystem services can be modelled at a site, catchment, or national scale. An analysis of an individual farm is an example of site scale analysis. Scale should be chosen based on the intended purpose of the analysis and more detailed analysis of smaller areas requires more detailed data.

A data visualization system shows visual representations of data which assist with an understanding of the dataset [123]. Visualization is useful for problems where humans are required as part of the solution of the system. An alternative to visualization would be to use an algorithm to make decisions about land use. However, visualization has the advantage of allowing humans to see the result of running models and decide if the result is suitable rather than entrusting decision-making to a computer with an AI method for data analysis [123]. An advantage of visualization over AI decision-making is explainable analysis results which are verifiable by people. When data is visualized a person can discover information about the dataset that they are not necessarily looking for at the start of their analysis, for example, problems with the collection of the data or the presence of trends and relationships among the data which were not known before the analysis. The exploratory nature of visualization could assist with an analysis of ecosystem services.

Ecosystem services model results such as nitrogen and phosphorus require elevation as an input [89]. Interviews with expert users of the LUCI model for ecosystem services analysis identified that the resolution, and artefacts in the Digital Elevation Model(DEM) affect model output (§ 4.2.4). The 3D elevation makes the analysis problem a good candidate for VR visualization, because VR headsets are stereoscopic, and allow for interaction with 3D content through physical movement.

Immersive Analytics can be defined as the analysis of data through alternative interfaces which enhance the immersive nature of the experience [152]. For example, a Virtual Reality (VR) Head Mounted Display (HMD) or a large configuration of monitors can improve immersion [152], however, the interface may not be visual, and could be audio or target a different sense. Interfaces for VR systems can allow touch and gestures to be used to interact with the virtual world [63]. The VR interface could allow interface designs which incorporate 3D layouts for interface components so that users can place them with physical movement. Immersive analytics systems can create a "sense of presence" and build engagement while exploring data [63], however, the medium used to display visualizations can impact the effectiveness of the visualization presented [117]. Engagement is required for ecosystem services analysis, as multiple different groups of stakeholders and decision-makers in land use planning can have varying expertise compared to land use analysts. Immersive Virtual Reality/Augmented Reality (VR/AR) could improve user engagement and understanding of geospatial data in a virtual world compared to a visualization system without immersion.

Virtual Geographical Environments (VGE's) can make geospatial data easier to understand through interaction [109]. Virtual geographical environments can communicate multi-dimensional data through data visualization, interaction, collaborative technologies, allowing experts such as scientists working in meteorology to model and simulate geographical processes from within the system. VGE's can facilitate these experts to then communicate to decision-making stakeholders [109]. An evaluation of which visualizations are most suitable for geospatial analysis tasks could improve future immersive analytics systems by informing the design of systems developed specifically for geospatial analysis workflows.

Immersion can make visualization systems more effective to analyse data, however, when analysing ecosystem services, more research is needed to determine which visualizations are most effective in an immersive environment and when a non-immersive screen would be more suitable [152]. The aim of this project was to evaluate how immersion affects users' analysis of ecosystem services and land use. A user-centred design methodology was applied in this thesis to design, implement, and evaluate an immersive VR visualization system for analysing the effect of land use changes on ecosystem services. The evaluation compared the VR system to existing media, 2D screens and Paper maps.

1.1 Motivation

This project was motivated by the need for better tools specifically designed for assisting the analysis and exploration of land use decisions, and their effect on ecosystem services. These tools needed to be designed for stakeholders in the land use planning process, that allowed tradeoffs to be analysed and compared, and allowed errors in the input data to be detected by different stakeholder groups. Expert users in a specialized domain have different requirements from the tools they use compared to non-experts as the tasks they perform are different [125]. The user centred design process recommends consultation with actual users throughout the development of a system [128]. Since different tasks impact the effectiveness of visualizations, experts from different domains performing different tasks with a dataset have their own visualization requirements.

Existing tools for analysing geospatial data in an immersive environment, such as OpenGEOSys, have been developed with the input of domain experts in geospatial analysis [140]. However, one limitation of Open-

GEOSys was that the domain experts consulted were all geospatial analysts, but land use decision making may also require experts in other domains who were not interviewed. Land use decision-making can involve landowners, regional councils, and catchment groups [34]. These groups may not have the necessary skills to use tools designed for geospatial analysts. OpenGEOSys contains models for thermo-hydro-mechanical-chemical (THMC) processes. There are ecosystem services, such as habitat connectivity, which are not described by THMC processes which are outside the scope of OpenGEOSys, and ecosystem services tradeoff analysis is also not within the scope of OpenGEOSys. The Land Use Management Support System (LUMASS) tool supports the visualization of maps in an immersive environment [84], however, LUMASS does not support the required data visualization functionality for an immersive analytics system with multiple visualization types for performing analysis. Previous VR systems such as DEM's were analysed in 2D by domain experts using ArcGIS **??**. Based on inspection of the data and problems described by users, research questions were identified to in VR for analysing ecosystem services.

In order to visualize ecosystem services affected by land use, an immersive analytics system could apply ecosystem services models and tradeoff mapping to generate visualizations. The choice of model depends on the type of land use decisions so that the scale of the modelling is suitable for the scale of the decision making. The Land Utilization Capability Indicator (LUCI) is an ecosystem services model which includes flood risk mitigation, agricultural production, carbon sequestration, diffuse pollution, and erosion [89]. Tradeoff maps determine whether an area would benefit from land management changes, would benefit from preservation or has no good ecosystem services, and therefore would not benefit from a change [34, 89]. LUCI was developed by researchers at Victoria University of Wellington. The researchers developing the LUCI model later formed a private consultancy, Nature Braid. The development of the LUCI model and the accompanying toolbox for ESRI's ArcGIS desktop is an ongoing maintained project [9]. Applications of LUCI include a study of the tradeoffs between agricultural productivity and water quality in the Lake Rotorua catchment [163], and an analysis of how ecosystem services have been lost in the Ruamahanga Basin [160]. Both farm scale management applications and catchment scale management are possible with LUCI [29]. LUCI is used by stakeholders with an interest in land use from different backgrounds. Geospatial analysts, farmers, and community groups were identified as potential user groups who could benefit from immersive visualization of LUCI data.

An immersive visualization tool could help land use analysts to better understand the sites categorized by a system like LUCI by creating a sense of presence in the data, and augmenting the ecosystem services model with other geospatial datasets and media. By representing the same data in different ways, stakeholders would be able to investigate the effect of land management decisions and produce visualizations to communicate ideas to other stakeholders improving the decision making process.

This research project involved designing and evaluating an immersive visualization tool for experts analysing ecosystem services to augment their existing workflow analysing data. The visualization tool was evaluated to determine the effectiveness of visualizations performing analysis tasks. LUCI was chosen due to the availability of expert land use analysts who use the model and were available to participate in requirements gathering and usability testing. The immersive ecosystem services visualization techniques developed for this research could also be more generally applied to LUMASS or other similar ecosystem services models with visualization capabilities. Head-mounted VR was chosen as an immersive environment over AR, MR, Large High Resolution Displays (LHRD's) or CAVE due to the fully immersive nature of the experience. VR allows the user to be present in a virtual environment [119] whereas AR and MR HMD's show virtual content overlaid onto the real world.

Other VR systems such as Multifaceted Environmental data Visualization Application (MEVA) have been applied to the analysis of geospatial data [83]. The MEVA system for geospatial visualization was usability tested in a CAVE environment and 88% of the participants suggested that they would use it for data analysis, 94% suggested they would use it for presentation and 81% would use it for exploration [83]. The positive experiences of participants using the MEVA system suggest that VR could also benefit an analysis of ecosystem services. HMD's were chosen over a CAVE environment due to the practical considerations of incorporating VR into a regular workflow. CAVE environments require large room scale spaces for the analysis and VR HMD's are usable at a desk.

1.2 Problem Statement

The following three problems were identified with the use of current immersive visualization systems for land use planning:

1. Planning land use changes requires the input of experts in several domains, including land owners, geospatial analysts, community groups, and regional councils. One problem with the currently available immersive geospatial visualization tools was that they were not specifically designed for analysing ecosystem services before and after land use changes. This analysis requires complex communication to different stakeholder groups which would benefit from more user-centred tools than those currently available which are not necessarily designed for the requirements of the required stakeholder groups. Immersive visualization systems need to be developed for real scientific workflows in order for the visualization system to be useful in real world scenarios [169].

2. Data publicly available sometimes needs to be supplemented with additional information collected at the site to correct inaccuracies in

the landcover or annotate structures which could affect the analysis. The collection of detailed information at a site scale can require consultation with landowners or other stakeholder groups which creates communication issues. Visualization could assist with a detailed analysis of an area by providing a method to view the results of the analysis, and allow publicly available information about a site to be validated by a relevant stakeholder without experience in geospatial analysis and associated software.

3. Existing immersive analytics software for visualizing geospatial data are limited. Immersive geospatial data analysis systems included OpenGEOSys, MEVA, HurricaneVis and Visualizer [35, 37, 83, 140]. The literature review for this study did not find an immersive visualization tool which allowed all of the required ecosystem services to be analysed such as habitat diversity, flood risk, nitrogen, phosphorus and carbon stocks. Tradeoff comparison among ecosystem services was also not visualized by any reviewed immersive systems. This research contributes to research in immersive analytics by visualising Ecosystem Services (ESS) model data for the required services as well as tradeoffs among subsets of these services.

1.3 Research Questions

In this research project, the usability and effectiveness of an immersive environment for geospatial data analysis was investigated by addressing the following research questions:

RQ1 How can immersive visualizations affect the comparison of the impact of land-use change for multiple ecosystem services?
When domain specific experts analyse tradeoffs between ecosystem services, there are complex requirements (§ 3, 4.1, 4.2.4, 5.4) in analysing the effect of land use changes. Comparing land use scenarios in

VR could allow expert analysts to visualize how model results are affected by elevation, and compare different layers for consistency with an aerial imagery layer. One potential future application of an immersive visualization system could involve supporting decisions on the selection of future scenarios for analysis. How could immersive VR visualizations assist with the comparison of different scenarios for the effect of land use change on ecosystem services?

RQ2 How effective is immersive visualization for facilitating communication to stakeholders analysing the impact of land use change on ecosystem services?
Different stakeholder groups have different requirements for the analysis of ecosystem services. Analysing future land usage scenarios requires communication between different stakeholder groups. Visualization allows data from land-use scenarios to be viewed in a way that could facilitate a greater understanding of data by different stakeholder groups. For example, deciding on suitable locations for riparian planting could require communication between researchers, community groups and regional councils. How can an immersive visualization system help to communicate the impact of land use on ecosystem service changes to a stakeholder, and facilitate comparison amongst different land use scenarios? How could visualizations improve communication to a stakeholder, in the process of choosing land areas for intervention and choosing how much to intervene by?

1.4 Research Objectives

The research objectives describe the steps that were performed to satisfy the research questions in § 1.3.

OB1 To develop the requirements for an immersive visualization system for comparing the impact of land-use changes for multiple

ecosystem services.
The extended literature review in (§ 2.7), interviews and focus groups with different groups of stakeholders addressed the need for requirements gathering. The interviews and focus groups provided the information to identify the necessary functionality for users of ecosystem services models with differing levels of expertise, and users receiving the results of ecosystem services analysis using the system. An extended literature review identified gaps in the research already conducted (§ 2.7).

Interviews were conducted with domain-specific experts in geospatial data analysis and the requirements for the design of the visualization system were identified for members of this user group. Focus group sessions further developed the identified requirements. The requirements specified the functionality implemented, and the workflows described how the functionality was incorporated into the analysis process and identified other software used during an analysis of ecosystem services. Workflows for using LUCI were compared among user groups and literature on ecosystem services modelling to find tasks which would benefit from visualization and generalize to other ecosystem services modelling tools. The requirements gathered through interviews and focus groups contributed towards answering RQ1 and RQ2 by informing the development of the features of the visualization system.

Objective OB1 contributed towards answering RQ1 by providing information about which immersive visualizations should be developed and evaluated. RQ1 benefited from an interviewing process because the visualizations were designed to be applicable to realistic tasks, and domain specific experts brought an understanding of the field which better informed the development of the visualizations.

OB2 Develop an immersive geospatial visualization system based on the requirements gathered in OB1

In order to answer the research questions, an immersive visualization system, Immersive ESS Visualizer, was designed and implemented for analysing the effect of land use change on ecosystem services (RQ1) and to assist with communicating analysis results (RQ2) through visualization. The extended literature review (§ 2.7) identified no current visualization systems which satisfied all of the requirements identified in OB1 for analysing land use.

A visualization system suitable for performing immersive visualization of ecosystem services data was designed and implemented. Features of the system included visualizations, menus, data filtering, movement and data processing. The map visualizations had a base map layer with additional spatial data layers overlaid on top. The visualizations were chosen based on a user-centred design process where information from interviews with user groups (OB1) informed the development of the system. The development of the immersive system involved consultancy for each intended user group and visualizations were created based on the tasks that the groups needed to complete.

OB3 To evaluate the effectiveness of visualizations for analysing ecosystem services.

The research questions, RQ1 and RQ2 were answered by performing user studies with domain specific experts.

The LUCI model was used as a case study. The research question RQ1 was answered by performing a user study where analysts were required to perform an analysis of ecosystem services at a study location and then provide both qualitative and quantitative feedback on their experiences. During the evaluation participants were required to perform tasks using the VR system, paper map tasks, and a 2D screen so that the VR could be compared to existing methods of analysis. Researcher observation collected information from the use of the VR system in addition to user feedback.

1.5 Contributions

This research contributes towards the visualization of ecosystem services model data by providing information on what immersive visualizations are suitable for assisting the analysis of ecosystem services, analysing the change in ecosystem services with land use and comparing ecosystem services trade-off maps. The contributions consisted of visualizations designed to assist with ecosystem services analysis, case studies to demonstrate the application of visualizations to ecosystem services analysis for land use management, and user testing for the effectiveness of visualizations for analysing the data.

The contributions consisted of:

1 **Requirements for an Immersive visualization tool for ecosystem services analysis are developed through interviews and focus groups.** The requirements developed for an immersive visualization system are a novel contribution as they contribute to the understanding of what expert users of ecosystem services models, and end users receiving the results of an analysis would find beneficial to assist them with analysing and visualizing data for ecosystem services with immersive analytics tools.

2) **An immersive VR visualization system for analysis of ecosystem services.**
The visualization system was developed with a user-centred design process to benefit experts analysing ecosystem services and end users. Interviews were conducted to gather requirements.

3) **Evaluation techniques for the usability evaluation of geospatial immersive visualization software were extended through developing a categorization for relevant expertise.**
The user evaluation of the system involved participants with domain expertise in reading maps, knowledge of ecosystem services, and/or the location for the user study. Participants were categorized according to their VR expertise, data expertise, spatial technology expertise, map expertise and location expertise according to the responses provided in a pre-study questionnaire. Linear mixed effects models were run on the TLX score data, and SUS score data, to test for correlations among expertise measures within media conditions (VR, paper maps, 2D Screen). The method of categorization for the participant expertise is a research contribution, as it could be adapted to other geospatial visualization systems to evaluate how participant expertise is related to the results of user studies.

1.6 Thesis Organization

The remainder of the thesis is structured as follows.

- **Chapter 2** contains a background and literature review covering Immersive Data Visualization, ecosystem services visualization and modelling, user centred design and a review of research methods.

- **Chapter 3** describes the research methods for this PhD project.

- **Chapter 4** describes the elicitation of system requirements based on interviews and focus groups.

- **Chapter 5** presents the design and implementation of the Immersive Visualization system.

- **Chapter 6** describes the design of the final user study.

- **Chapter 7** presents the results of the evaluation of the visualization system.
- **Chapter 8** presents the conclusions and future work.

Chapter 2

Background

Contents

Ecosystem services models were reviewed (§ 2.1) because designing visualizations was task based, and different models were used to perform different analysis tasks. Since the visualization system for this research project was about visualizing geospatial data, Virtual Geographic Environments (VGE's) were reviewed (in § 2.1.1, 2.3), as well as immersive systems for visualizing geospatial data. The visual techniques generating ecosystem services models were reviewed (§ 2.4) to ensure that the choice of immersive visualizations were suitable for ecosystem services models being visualized. This research evaluated the immersive visualization system developed, so an extended review of evaluation techniques was performed (§ 2.7, 2.8, 2.9) to assist with choosing appropriate evaluation techniques.

2.1 Ecosystem services tools

Ecosystem services are the benefits to humans provided by ecosystems through their internal natural processes [59] (see § 1). A detailed review of ecosystem services models is beyond the scope of this thesis, however in order to better understand the process of analysing ecosystem services data and to inform the design of visualization techniques, a brief review of ecosystem services models is provided. Spatially explicit ecosystem services models were reviewed, and visual outputs showing the results of these models were discussed so as to ensure that immersive visualizations designed for ecosystem services visualization were appropriate. The design of visualizations in this thesis followed a user-centered design process [125], so reviewing literature assisted with understanding the requirements for model visualizations when creating mockup designs for interviews with users. Nielsen et al. recommended showing examples of designs during focus groups to assist users with understanding designs, so knowledge of model outputs assists with making prototype examples more realistic [125].

In this research project, Nature Braid provided data for visualization. This data consisted of model output from the LUCI ecosystem services model, so the visualizations developed for this project needed to be suitable for the LUCI model. Spatially explicit ecosystem services models were reviewed for comparison, with particular attention to the way that outputs were presented.

Ecosystem services modelling tools were compared by Ochoa et al. [130] and Sharps et al. [149]. Ochoa et al. followed a systematic method to extract literature and compared the number of publications, the services supported, and the training materials. Both Ochoa et al. [130] and Sharps et al. [149] reviewed the models ARIES and InVEST. However, Ochoa et al. did not review LUCI. Ochoa et al. found that the most widely used models by publication were the InVEST, SWAT, and ARIES models for ecosystem services. Sharps et al. compared three systems, LUCI, InVEST and ARIES, for modelling ecosystem services for a UK river. SWAT, LUCI, InVEST and ARIES were all spatial modelling tools [149, 130] with different model assumptions, strengths and weaknesses. Sharps et al. suggested that LUCI was good for investigating detailed changes in rural land use, ARIES works well with small amounts of data available, and InVEST had good support for economic valuation. Sharps et al. modelled water yield, nutrient retention and carbon storage for the area catchment using each of the three different tools. Due to differences in data requirements of tools, the same input data could not be applied to all three. Both InVEST and ARIES used a 50mx50m UK Center for Ecology and Hydrology (CEH) Integrated Hydrological Digital Terrain Model (IHDTM) and UK Land Cover Map (LCM). An Example of the Mapping Ecosystem Services to Human well-being (MESH) platform for InVEST is shown in Figure 2.1. The LUCI tool ran models at high resolutions, input data included a 5mx5m Digital Elevation Model (DEM)[1], a vector LCM, and soil type data. When comparing the annual water yield, InVEST provided output at the resolution of sub-catchments, LUCI and the ARIES 'flow and use' model provided the most accurate annual flow predictions compared to the data measured from two stations. LUCI additionally identified areas which mitigated flooding and areas where floods were concentrated. This research project applied visualization to LUCI output data as a case study because the pool of participants contacted through supervisors for user-

[1]A DEM is a raster of the elevation with elevation values stored in each pixel of the raster, elevation is processed to remove vegetation, buildings and other objects on the surface [53].

centred design interviews were users of the LUCI model for ecosystem services analysis (§ 3.1).

Figure redacted for copyright reasons

Johnson et al MESH example 500m res Volta basin.png

Figure 2.1: The Volta basin, Africa, with the colour scale indicating which order to conserve land, based on a ranking of ecosystem service provision. Source: Johnson et al. [92]

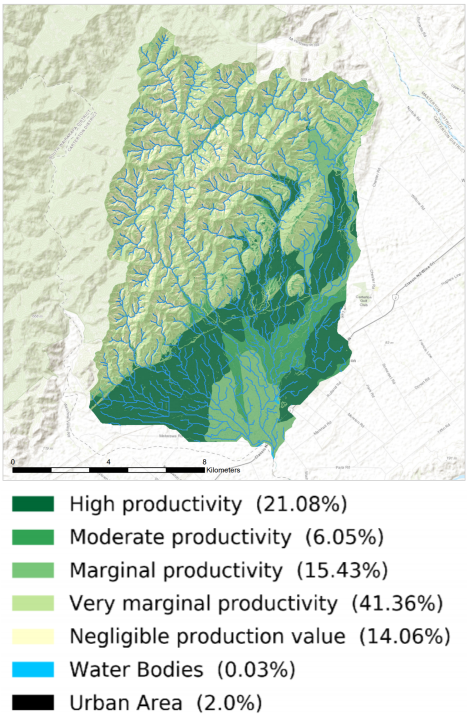
The LUCI ecosystem services model includes flood risk mitigation, agricultural production, carbon sequestration, diffuse pollution, and erosion [89].LUCI models are implemented as a toolbox for ArcGIS [89]. LUCI takes input data from a digital elevation model, stream networks, annual rainfall, annual evaporation, spring additions and abstractions, land cover, and soil data. There are quality assurance metrics which can be applied to DEM's [133] when deciding on whether a DEM is suitable. The quality can be categorized as topologic quality and elevation quality [133]. LUCI can run on models at high resolutions e.g 5m, or 1m resolution. Aberrations in the DEM can cause differences in the output results for the LUCI model, so showing the DEM data which is input to the model would assist users to evaluate the quality of the output results, since DEM's at different resolutions had an effect on the LUCI results. There are methods for processing DEM's which can affect the quality of the data, so substituting layers which have been preprocessed by different service providers could affect a user's ability to find anomalies. Finding anomalies in layers was a use case of the Adviser system [67]. DEM quality also affects metrics such as the topographic wetness index, and corrections can be applied to DEM's in order to adjust for the resolution of the data [175]. LUCI can evaluate several ecosystem services to determine where improvements could be made and which services would benefit from preservation. LUCI models different ecosystem services and produces maps that optimise services based on input data [89].

Visualizing data stereoscopically in VR could assist users with finding aberrations in the DEM, and checking the results of ecosystem services analysis. Models such as InVEST and ARIES can use 50mx50m elevation, so the visualization techniques for elevation input used by LUCI will also generalize to these models when inspecting the same area sizes. Since the model output is affected by DEM quality an interface which allows users to compare data as well as finding anomalies could be beneficial for LUCI users as they can check the quality of results.

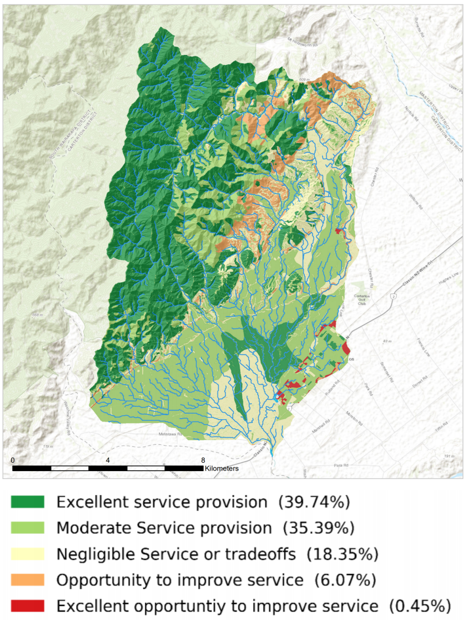
2.1.1 Visualization

LUCI can generate rasterized maps for both individual ecosystem services [89], and tradeoffs between ecosystem services. For example, the agricultural productivity model creates three maps; current agricultural production across the selected area of the map, optimal agricultural production and, the difference between current and optimal. Five categories describe the production value of the study area and sections of the map are shaded in colour according to their optimality (Figure 2.2a). LUCI can also analyse tradeoffs between different ecosystem services through tradeoff maps. Tradeoffs can be analysed according to criteria to determine whether an area would benefit from changes, would benefit from preservation or has no good ecosystem services, and therefore would not benefit from a change (Figure 2.2b). The ecosystem services tradeoff maps are rasterized images which categorize each cell (the land represented by one pixel. The colour on the overlay shows the category, however, it is difficult to determine which ecosystem services are reduced or improved as this information is provided as tables for each cell. Augmenting the visualization capabilities of LUCI through immersive visualization could create a sense of presence which could benefit the LUCI analysis. Applying immersive and interactive visualization techniques to the information generated as outputs from LUCI could help address the difficulty of working with the tradeoff maps by providing an alternative visual representation.

Three examples of LUCI's analysis are described to evaluate the application of LUCI's visualizations during its use in published literature. LUCI had been applied to an analysis of ecosystem services tradeoffs in the Lake Rotorua catchment [163], an analysis of the differences between ecosystem services in wetlands at a catchment scale [160], and the calculation of habitat diversity metrics [115]. The analysis of tradeoffs in the Lake Rotorua catchment suggested strategies for reducing the export of nitrogen and phosphorus to waterways [115]. Reducing the pollution from total nitrogen and phosphorus through mitigations applied to land



(a) Predicted optimal agricultural utilisation for the Mangatarere catchment area generated by LUCI. Source: Nature Braid [9]



(b) Agricultural productivity vs carbon tradeoff map generated by the LUCI ecosystem services tradeoff tool using an equal arithmetic method. Source: Nature Braid [9]

in the catchment area would also involve reducing agricultural productivity. LUCI also identified areas where agricultural production could be improved. Strategically placing mitigations and more effectively using areas which contribute less to total nitrogen and phosphorus export to waterways would minimize the regional impact on agricultural productivity while improving the quality of waterways. The analysis of the Lake Rotorua catchment found that visualizations enhanced the analysis of the catchment area and that both farmers and other stakeholders could benefit from the mitigations for nitrogen and phosphorus runoff suggested by LUCI [163]. The outputs from LUCI on the load and accumulated load for both nitrogen and phosphorus were further processed by Excel which was difficult and time consuming, so additional functionality could be built into a visualization system for ecosystem services to assist with a similar analysis. Since the LUCI toolbox runs inside ArcGIS, experience with GIS was required to perform the analysis. The spatially explicit outputs of the LUCI tool were analysed to inform strategies for reducing Nitrogen and phosphorus export into waterways [163]. Maps of nitrogen and phosphorus total load show trails of high load where nitrogen and phosphorus move across farmland into waterways. Management strategies included reducing the addition of nitrogen and phosphorus through fertiliser use on farmland and changing the land use to manage the movement of nitrogen and phosphorus across farmland into waterways. There were similar nutrient pathways for both nitrogen and phosphorus. Strategies for intercepting the flow of nitrogen included wetland restoration, vegetation planting, and denitrification beds. Phosphorus movement across farmland could also be managed through planting or converting steep land away from farmland.

Tomscha et al. [160] investigated the loss of ecosystem services in the Ruamahanga Basin, Wairarapa, New Zealand from draining wetland. The study compared historically drained wetlands with current wetlands by mapping nitrogen, phosphorous and sediment retention as well as agricultural productivity and flood mitigation from LUCI model. LUCI generated maps for each ecosystem service and provided estimates of the change in the ecosystem service for different future cases. The maps were presented with insets showing a zoomed in view of particular areas, however, LUCI does not support the generation of maps with insets for showing zoomed areas, which suggests that a visualization system which shows multiple zoom levels would be useful. A Sankey diagram (Figure 2.3) illustrates the number of services gained or lost when land cover was changed from wetland to another land cover. A change to a particular type of land cover can produce either a net gain or a net loss, however, changes to pastureland usually result in a net loss [160]. Visualizations, such as the Sankey diagram, are currently not provided by LUCI, so an immersive system which provides visualizations for understanding data about changes in ecosystem services could assist with the decision making process for land use changes and allow different scenarios to be explored. Integrating Sankey diagrams into an immersive system could also assist stakeholders to understand the model. A heat map illustrated the change in optimality for services when historical fens and swamps were converted to pastureland. The study found that in the case of land that was converted from wetland to agriculture, nitrogen and phosphorous held by the land was reduced. Conversion to agricultural land reduced the land's ability to prevent flooding. Although land converted to agriculture provided more agricultural production, much of the land converted to agriculture was underutilized. Tomscha et al. suggested that extending the research to cover other habitat and ecosystem services modelling would require more stakeholder engagement [160]. In this research applying immersive visualization could assist with stakeholder engagement. The study compared land use change to the number of ecosystem services gained or lost. Land uses which resulted in a gain of two ecosystem services included Broadleaved indigenous hardwoods, exotic forest, gorse and/or broom, indigenous forests or, manuka and/or kanuka (Figure 2.3). Conversion to pasture land can have both positive and negative effects, but the change to pasture land was more frequently associated with a negative change in ecosystem services.

Tomscha et al. performed an analysis where model outputs from LUCI were compared for different wetland land use scenarios, however Trodahl et al. perform an analysis of ecosystem services for a single scenario in order to identify areas of interest for reducing nutrient export. The difference in these two analysis methods indicate that analysis of LUCI output data would benefit both from the ability to analyse multivariate data for a single scenario, as well as methods for visualizing tradeoffs for different scenarios. Since both of these analysis methods involved analysing multiple maps output from LUCI, an interface to assist the visualization of multiple maps could be beneficial to analysis.

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Figure 9 Wetland conversion to different land covers.PNG

Figure 2.3: A Sankey diagram categorizing the number of ecosystem services gained or lost for types of land cover which have been converted from wetland. source: Tomscha et al.[160]

An immersive visualization tool could help hydrologists to better understand the land use categorized by an ecosystem services model by changing how the data is viewed through immersive media, creating a sense of presence in the data, and augmenting the ecosystem services model with visualizations of other geospatial datasets required to interpret the data. A visualization tool could incorporate generated data tables into the visualization to reduce the need for spreadsheet software, such as Excel, when performing frequently required analysis tasks. Visualizations designed for an immersive medium could improve the analyst's ability to interpret the data, and the visualization system could also make the results of an analysis easier to understand for stakeholders with less experience with geospatial analysis which would be of benefit to the decision making process. Different weightings for the importance of ecosystem services in a tradeoff comparison can present different outcomes based on the configuration of LUCI. Exploratory data analysis is an interactive activity and although the LUCI model will not run in real-time during a session, an interactive, immersive visualization tool could allow stakeholders to investigate the effect of land management decisions.

Interactive geospatial simulations have been evaluated for communicating scientific data to a non-scientific stakeholder group [165]. An interactive simulation system, RE:PEAT, displayed a 3D geospatial map of a Dutch peatland and simulated the effect of environmental management decisions [165]. The RE:PEAT system encouraged co-operation between non-scientific stakeholders with different roles and presented scientific information in a way that was prominent to stakeholders and easy to interpret without a scientific background [165]. When users participated in the study where intervention was performed to encourage co-operation, they were found less likely to make decisions to benefit only their own perspective. In this research project domain specific experts were interviewed to gather requirements from both the perspective of geospatial analysts and other experts with less scientific background as part of RQ2.

The literature review found no examples of immersive stereoscopic visualization that applied the analysis of ecosystem services tradeoffs. An immersive prototype needs to satisfy the requirements of both geospatial analysts while offering representations of the data which are understandable to users without the same analytical skills. This research fits a gap in the reviewed literature by taking a user centred approach to consulting with users who were involved in ecosystem services analysis, where users had different levels of expertise. The research project incorporated stereoscopic immersive visualization for geospatial analysis, and the tool was evaluated to determine whether the visualizations were effective for analysing ecosystem services.

Immersion, virtual reality, mixed reality and augmented reality systems was reviewed, § 2.2 reviewed different Extended Reality media. In § 2.3 visualization techniques were reviewed with a focus on their applicability to geospatial data.

2.2 Mixed Reality

This section defines terminology for immersive systems, virtual reality, mixed reality and augmented reality. An interface is immersive when it produces a greater sense of being in the world than a standard computer monitor. Virtual reality is a system which immerses the user into an artificial environment by providing input to a sense, responding to feedback provided by the user through an interface [119]. Virtual reality enhances the sense of presence and replaces the input to a sense with the virtual world, for example, a Head Mounted Display (HMD) shows visual sensory input to the user through a headset which covers a portion of the user's field of view. HMDs can either be transparent displays or opaque displays.

Mixed Reality as defined in this thesis included displays for both visual and non-visual senses. There are some differences and ambiguities in the definitions of Immersion, Virtual Reality, Augmented Reality and Mixed Reality across published research. A study interviewing mixed reality experts and reviewing published research was conducted by Speicher et al. [154]. The research found examples of 6 definitions of mixed reality. Mixed reality covers technologies from augmented reality to virtual reality where there is a mixture of both real and virtual content. This definition is consistent with the Reality-Virtuality continuum defined by Milgram and Kishino [120] (Figure 2.4). In the review conducted by Speicher et al., the scope of Mixed Reality definitions for other senses was discussed [154].

Çöltekin et al. [180] suggest the importance of investigating the application of XR environments as a laboratory for data analysis.

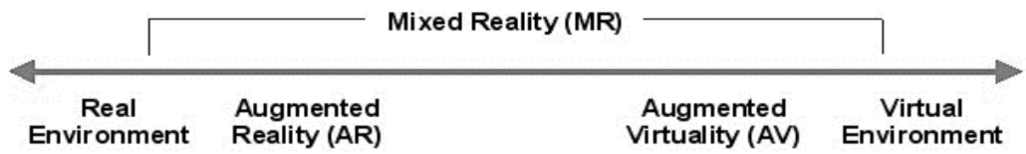


Figure 2.4: The reality-virtuality continuum defined by Milgram and Kishino. Source: Çöltekin et al. [180]

Augmented reality augments the sensory stimulus of the real world with additional content. Additional information is provided from a device adding to the user's perception of the real world [119]. For example, tablets and smartphones can overlay digital content onto a video feed to provide information to the user based on their GPS tracked location. AR HMDs can augment the user's vision of the real world with information displayed on an overlay.

A CAVE environment is stereoscopic virtual reality hardware which projects images onto the walls of a room and optionally the floor and ceiling [55]. The CAVE tracks the position of the user and corrects the perspective of the images projected based on the users viewing position. CAVE environments can require the user to wear shutter glasses [55] or polarized lenses [113] to filter two separate images, one image for each eye.

Immersive analytics systems use hardware interfaces to enhance the immersive nature of the experience when analysing data [152]. In this section, immersive analytics systems are reviewed to discuss the techniques for communicating data and evaluating the usability of these systems for data visualization. Examples of immersive systems include Large High Resolution Displays (LHRD), CAVE Automated Visualization Environment systems (CAVE) and HMDs. CAVE systems and HMDs are immersive hardware for stereoscopic visualization. LHRDs are immersive hardware for 2D visualization.

2.2.1 Visualization toolkits for immersive systems

Pre-existing software toolkits are available for generating visualizations for VR [50, 151, 51]. Both IATK and DXR allow users to specify visualizations using a grammar of graphics [50, 151]. They are both plugins for Unity game engine. Preset visualization types are specified which can be configured through the Unity editor UI. Unlike IATK, DxR uses a grammar based on JSON and a DXR prefab object loads the JSON grammar which can be edited by an advanced user. IATK is scriptable and provides an API for developing visualizations which cannot be produced from the presets. Additional visualizations can be added to DXR by extending the C# classes [151], however, unlike in DXR, IATK's API is similar to D3 [50]. DXR allows threshold filtering and tick box interaction, however, the grammar does not have options for linking visualizations together and brush interaction. IATK allows visualizations to be linked inside the Unity GUI interface [50]. ImAxes is an example of a visualization tool which was implemented with IATK and allows users to create visualizations by manipulating axes. ImAxes recognizes a grammar based on how the axes are positioned and generate visualizations, such as scatter plot matrices, histograms and parallel coordinate plots [51]. A user study was performed evaluating ImAxes for macroeconomics data [33]. The user study was performed in four stages, pilot study, formative study, and two summative studies. Each study phase involved 6 participants. The formative study was performed 'in the wild' and participants used the system for 3 weeks. The summative studies consisted of a tutorial, exploration phase, presentation and interview. An objective of the user studies was to identify additional functionality that would improve the system for analysing macroeconomics data. New functionality was added to the system throughout the study process and the participants use of the system was analysed.

IATK, DXR and ImAxes are all general-purpose toolkits for generating visualizations in an immersive world, however, they are not designed specifically for geospatial data so predictive models were out of the scope of the tools. The analysis of usability performed on ImAxis did not compare the usability to a non-immersive system or to other methods for creating and positioning visualizations inside an immersive world.

2.3 Immersive Geospatial Visualization

In this section, geospatial datasets, Geospatial visualization systems, Visualization techniques for 3D data, and visualization techniques are reviewed and compared. Geospatial visualization system are compared based on the types of data visualized, the hardware they are designed for and the visualization techniques applied.

2.3.1 Geospatial visualization systems

The data visualized by immersive systems are described and compared. Both the type of data and their semantic meaning affect the understanding of the information conveyed by the dataset [123]. Visualization of a dataset requires an understanding of what the data represents so that visualizations can be designed to communicate the data in the most meaningful context. The task that the user is required to perform with the visualization system is dependent on the meaning of the dataset since different models are applied by visualization systems such OpenGEOSys, the models and techniques applied to the system may not generalize to different data and applications.

Geospatial data can be visualized with immersive systems, such as OpenGEOSys [140]. Simulation data generated by a model can be visualized to allow an analyst to determine whether a model produces sensible results for a geographic region. In the event of unexpected behaviour in the simulation, errors in the input data can be discovered and fixed by the analyst. OpenGEOSys is a system for visualizing hydrological data and models [140], however, OpenGEOSys was designed for expert users to perform analysis. The visualization system was used in presentations to discuss data with scientists from other disciplines on a 6mx3m display wall. However, little work has investigated how visualization fits into the workflow of different stakeholders and which visualizations were suitable for users with different backgrounds to communicate the data.

The hardware can affect the usability of visualizations for performing analysis tasks [117], so a description of hardware is necessary for contextualizing the results of usability testing for visualization systems. Three immersive visualization systems are OpenGEOSys, MEVA and HurricaneVis. OpenGEOSys was designed for presentation on a 6 x 3m stereoscopic video wall and optical tracking. The MEVA system was implemented with the Unity Game Engine and targets CAVE environments, HMDs, 3D projectors, and desktop systems. HurricaneVis used VTK to implement the volume rendering as part of the visualization system and VRJuggler was used for running the system in a CAVE.

The OpenGEOSys software tool was developed for visualizing ecological data sets [140]. Both spatial and temporal data can be input and both vector and raster data visualized. Streams were represented as vector data. A system for visualizing the impact of climate change on a forest in Wisconsin was created to make an ecological model, LANDIS-II, more understandable [88]. The application visualized projected output from LANDIS-II for estimates of biomass and height for different tree species according to different projections for the effect of climate change on the environment.

A visualization system, MEVA, was developed for simulating meteorological models [83]. MEVA and OpenGEOSys were applied to visualizing the Weather Research and Forecasting model (WRF) [82, 83]. Both MEVA and OpenGEOSys utilized ParaView for data visualization. OpenGEOSys visualized and simulated meteorological data including wind, elevation, clouds, temperature and other variables. 2D data, 3D scalar and 3D vector data were visualized using the system [82]. MEVA was applied to visualizing both 3D scalar data and 3D flow data [83] and both meteorologists and visualization experts were consulted during the development of the software. HurricaneVis was developed for visualizing Hurricanes with volume rendering techniques in a CAVE environment [35]. The datasets chosen for the evaluation scenarios were from hurricanes Isabelle and Lili. The MM5 weather model generated the dataset for Hurricane Lili.

Visualizer is a system for visualizing magma flow, subduction and seismic tomography in a CAVE environment. The system was developed and tested to compare the usability of the application against a desktop version and TecPlot [37]. Visualizer can load 3D gridded data as input.

These examples [37, 83, 35, 140] show that volumetric data, vector data, 2D data and flow data were visualized in immersive environments.

2.3.2 Visualization techniques for 3D geospatial data

Techniques are discussed with the data type and the application that the visualization was used for, and relevant limitations to using the techniques. Immersive systems have been used to visualize both 3D and 2D data. Slices, isosurfaces and direct volume rendering are methods for visualizing 3D scalar data. Isosurfaces are polygon meshes which are generated to describe the shape of a 3D dataset using an algorithm, such as marching-cubes. Volumetric rendering represents 3D data as voxels and ray-casting algorithms can render volumetric data. Slices are 2D cross sections of 3D datasets. OpenGEOSys, MEVA, and Visualizer used slices to visualize 3D scalar data from numerical models [140, 83, 37]. Slices can be combined with rendering techniques such as isosurface contours and volumes to show a cut away. The Visualizer system used slices to render cross sections for subducting plates [37].

Both MEVA and OpenGEOSys applied visualization techniques to manage data occlusion in 3D. MEVA and OpenGEOSys applied transparency. OpenGEOSys also applied clipping panes and thresholding. OpenGEOSys, MEVA, HurricaneVis and Visualizer, applied isosurfaces to the visualization of 3D scalar data [140, 83, 35, 37]. OpenGEOSys and MEVA applied isosurfaces for rendering meteorological data from the WRF model. MEVA applied opacity to isosurfaces so that different time frames could be compared. OpenGEOSys, MEVA and Visualizer used slices with the isosurfaces so that volumetric details could be visualized, and slices were anecdotally useful in detecting artefacts in isosurfaces which were applied to a model of subducting plates inside Visualizer. One limitation of isosurface contours was that the contour has a mesh resolution, and fine details of the dataset may not be visible at the resolution of the isosurface contour. Unlike MEVA and OpenGEOSys, the HurricaneVis system applied direct volume rendering to visualize the dataset, direct volume rendering showed the dataset as points rather than generating a surface using polygons. Direct volume rendering was compared to isosurface rendering in a usability study. Berberich et al. claimed that the visual quality of the direct volume rendering was preferable to that of isosurface rendering [35]. OpenGEOSys visualized vector data by using glyphs to represent points and tubes to show the geometry of the dataset. Streams could be represented as vector data.

An alternative to mesh rendering for terrain is an adapted sphere tracing algorithm. Terrain could be modelled by combining together primitives [70], an advantage of sphere tracing was that surfaces can be rendered when the gradient is discontinuous [79]. The renderer used a Lipschitz constant for each primitive to set a bound on the distance that a ray can travel at each step of the algorithm without intersecting with the surface. The algorithm was applied to generate procedural terrain, rather than terrain from heightmaps, and the Lipschitz constant calculation was computed from the terrain height function for each primitive. The terrain was represented as a tree with primitives at the leaves, these were hierarchically combined with a weight blending function.

OpenGEOSys used Digital Elevation Models represented as raster data to generate surface meshes. This contrasts with Visualizer which visualized 3D data sets of subducting plates generated by simulations. VRGS can visualize lidar and structure from motion data for digital outcrops as point clouds, tiled models (terrain) or textured mesh [20]. An immersive virtual reality application was developed visualizing the Arctic Clyde Inlet in Baffin Island, Canada [112]. The application included textured terrain draped over meshes created from DEM's as well as bathymetric data. The meshes were created using Unreal engine's terrain tool which applied a Level Of Detail (LOD) algorithm to render more detailed meshes at closer viewing distances. Unreal engine produced detailed terrain, however, there were limitations to the size of the heightmaps that could be applied. The visualization application for the Clyde Inlet tiled terrains using world composition to create a grid of heightmaps and applied a time consuming manual process for setting up the landscape over the area of interest. The Unreal engine terrain could not be generated procedurally while the program executed. 3D globes were used in previous VR systems [4, 176]. A 3D globe can be egocentric, where a user was inside the globe, or exocentric where a user is positioned outside the globe [176]. A disadvantage of using either globes to visualize small areas is that the curvature of the earth's surface would also be small, so there could be little benefit for this research project because the area sizes being visualized are too small. Though flat or curved maps could provide an overview of the area of study. A system for drawing maps from photographs taken on Mars utilized a 3D immersive cylinder inside an HMD for displaying stitched stereoscopic snapshots so that users of the system could edit maps while inside the HMD [61]. 3D immersive cylinders could be used to display 360-degree photographic footage without covering the user's field of view completely.

A data visualization with space time cubes on virtual table tops, time tables [178] was developed which allowed the user to jump inside a space time cube on a table, filter temporal data and compare alternative views of the same data at different temporal resolutions. Users could interact with the system at different physical scales, so it was suitable for both room scale VR installations and operating in a confined space. This method was applied to visualizing data about buildings, and an invisibox was provided to users which allows individual buildings to be removed from the users view by making the contents of a positioned box invisible. Layers can be raised above the table in a space time cube to show building data at different times. Cylindrically warping the landscape could allow users to see over the horizon [47].

In order to choose the correct techniques for analysing land use data, the users were consulted in interviews and focus groups to find out how they perform their analysis. The details of the user analysis were used to choose suitable visualization techniques for the datasets available. LUCI output includes 2D maps of data, as well as elevation. Elevation data are raster so both mesh rendering and sphere tracing methods could be used for visualization.

2.4 Visualization Techniques

This section discusses techniques for visualizing data in immersive systems, the systems reviewed are not necessarily visualizing geospatial data, and visualization toolkits for creating data visualizations in VR are reviewed. An immersive system for visualizing geospatial data could benefit from more general data visualization techniques which would be carefully chosen so that they could be applied to the dataset and the application. For example, Sankey diagrams, heatmaps and scatterplots have previously been applied as 2D visualization techniques in printed reports about ecosystem services.

Treemaps could visualize hierarchical data through the size of rectangles nested within the area of rectangular categories. Rectangular categories were recursively nested within other rectangular categories and the area maps onto an attribute visualized [123]. The software city visualization was based on a treemap. Software cities visualize software hierarchically Packages inside the software were represented as squares containing other packages, interfaces or classes. The interfaces and classes were represented as rectangular prisms with the height mapping onto an attribute [171].

2.4.1 Rendering vector data onto terrain

Vector data could draped onto mesh surfaces [95, 148] and additionally, the mesh surface could be represented as multresolution tiles [95]. Vector data could draped in screen space [95, 148] or rendered to textures before being overlayed. Vector data could stored in a scene graph [95], stored in a BVH tree, or stored with a quad tree technique. More generic algorithms allowed SVG images to be rendered onto mesh surfaces, other algorithms specifically render lines or specific polygon shapes.

Techniques for rendering vector data onto a map could adapt algorithms for mapping shadows. For example the stencil shadow volume algorithm was adapted for rendering vector data [148, 164]. The stencil shadow volume based algorithm presented by Schneider et. al. [148] works in screen space and was based on the point-in-polyhedra problem. Using the stencil buffer made the point-in-polyhedra test efficient [148]. The algorithm selected either a z-pass shadow volume algorithm or a z-fail algorithm depending on whether the camera was situated inside the shadow.

Shadow volumes represented a shadow as a polygon enclosing a space in shadow [54]. The Z-pass method for shadow volumes was a method for drawing shadows, however Z-pass did not produce correct results when the shadow volume intersected with the near clipping pane of the camera [86]. The Z-fail method for shadow volumes counted the faces which fail the Z-test rather than the faces which pass the Z-test. The Z-fail method produced correct results when the camera is in shadow, however clipping from the far clipping pane could cause incorrect results, although this could corrected with a hardware extention to clamp geometry at the far clipping pane [124]. A disadvantage of Z-fail shadows was that occluded geometry needs to be drawn to the stencil buffer causing overdraw a performance impact for complex scenes where more geometry was occluded than shown on the screen.

ZP+ was based on the Z-pass method for shadow volumes, and adapted Z-pass to handle the case when the camera's near clipping pane intersected with the shadow. An additional rendering pass was rendered from the perspective of the light source to create initial stencil buffer values for correcting the Z-pass algorithm [86]. The ZP+ algorithm did not need to draw occluded geometry to the stencil buffer,

Shadow mapping was an alternative to shadow volumes where the scene was rendered from the perspective of the light source to create a map of where objects occlude the light source [173]. A linear map was applied to the points visible from the light source to transform them into coordinates for the viewer, so that shadowed regions could be computed. An advantage of the shadow volumes technique was that the shadow volume calculation was unaffected by the screen resolution, however with shadow maps a resolution was chosen for rendering the shadows from the screen position. Although shadow maps were capable of soft shadows, vector data representing streams only requires hard edged shadows.

Percentage Closer Soft Shadows applies a percentage closer filter to shadow maps to improve the quality [65], however, the PCSS algorithm does not correctly handle self-shadowing [101], or shadows from fine filaments such as hair [111].

Screen space shadows [52] processed a shadow map, then raymarched a line from each point on an object's surface where a shadow could be cast, to the light source. The area was rejected if the ray was occluded. However, the information in the depth buffer did not conclusively detect whether the area was in shadow as the depth buffer stores the distance closest to the camera for each point on the screen. Geometry behind the front face of an object which could cast a shadow was not being considered in the shadow calculation. Screen space shadows could apply multiple passes to detect the thickness of objects.

Distance fields can be used to render curves and lines onto a surface with texture mapping [74]. Distance fields store the distance to a curve inside a texture, and an alpha threshold can control the thickness of the curve by selecting a distance value where the texture is transparent above this value. Programmable fragment shader's can softening the edge or add outlines.

Shadow mapping algorithms, distance fields, and Z-pass shadow volumes were possible methods for projecting stream data since they can represent hard edges. Distance fields were simple to implement because they do not need an additional rendering pass to cast the shadow. Shadow maps require a rendering pass to calculate the shadow map, z-pass rendering also requires two rendering passes. Shadow maps [173] and distance fields can show edge aliasing, however, distance fields could antialias the edge of the curve with a softening effect based on screen space partial derivatives [74]. Both shadow maps and z-pass rendering projected the shadow from mesh, distance fields take a pre-rendered texture as input, which could be read in with image reading functions, however images may need to be high resolution for suitable quality at high zoom levels. Distance fields were chosen for implementation in Immersive ESS Visualizer for convenience, as texture rendering functions can position the streams.

2.4.2 Maps

Interaction with maps in immersive environments could assist users with the analysis of ecosystem services data. Literature for visualizing maps and globes is reviewed to identify possible methods applicable to the system developed as part of this research project.

3D globes were used in previous VR systems [4, 166]. A 3D globe can be egocentric, where a user is positioned inside the globe, or exocentric where a user is positioned outside the globe [176]. A user study compared exocentric globes, egocentric globes, flat maps and curved maps in VR for distance estimation, distance comparison and area comparison tasks [176]. The speed, accuracy, and motion sickness of participants was measured during the tests. Some notable findings were that the exocentric globe performed better in most tests than the egocentric globe and the curved map induced motion sickness more than the flat map, however, participants were able to judge distance more accurately with the curved map. The study compared globes and maps of the entire earth, however, there was no comparison of maps over smaller areas. Since this research will work with map which describe smaller areas, flat maps could be more suitable than globes.

A visualization of a city model and a globe was presented for investigating geographic datasets [166]. The dataset for the city model visualized solar energy production and the dataset for the globe visualized CO_2. Unreal Engine was chosen as a game engine, and the immersive VR environment also contained a scanned model of a room. Data required manual preprocessing to produce the city model. Point cloud data was processed to produce a DTM, then a mesh. The mesh was processed in a 3D modelling program to produce a mesh suitable for the game engine by reducing the number of polygons [166]. The VR system was performance tested on two different systems, and the performance was compared.

A study evaluated the ability of participants to draw maps from photographs taken on Mars [61]. There were two groups of participants; one using a stitched 2D cylindrical panorama on a desktop computer to view the images and the other using a 3D immersive cylinder inside a HMD. The HMD had infrared tracking so that the users could walk around inside the cylinder using physical movement. Participants in the study were positive about their experience in the HMD.

A study compared the usability of three different techniques for displaying several map layers inside multiple coordinated views [155]. A visualization technique, the MapStack, was introduced where maps are tilted and stacked on top of each other. The MapStack was compared to a grid of maps, and 'blitting' where maps are cycled temporally. A 'within-subjects' test was performed with 26 participants. All participants used all of the visualizations. The study questions were created based on a case study of light pollution where the participants were required to find the 'most problematic' areas of a city map, areas which either receive too much light or not enough. A tutorial was given to each participant to demonstrate the use of each visualization technique, and the participants were required to complete 9-scenarios after the tutorial with three scenarios for each system. The study measured the completion time, eye tracking information and questionnaire responses. The study found that there were correlations among the peak saccade amplitudes, the peak saccade velocities and the preferred visualization technique. Participants with faster peak saccade velocities preferred the grid, while participants with low saccade amplitudes, low peak saccade velocity and the longest fixation times preferred the blitting layout. The stack layout was preferred by participants who changed the gaze point the least.

2.4.3 Map labelling

Map labelling is required to identify points of interest on a map. Labels can be 2D or 3D.

Screen-space force directed layout techniques were applied to drawing 3D markers [143] (Figure 2.5c). The markers exerted electrostatic forces on each other, and also the border of the screen to position labeled markers which connected a line to the map. This technique would be problematic to apply in VR, because in VR there are two screens, so the markers would not align on both eye views because positioning at the same screen coordinates would correspond to different positions in the VR world. In order to apply a force directed layout, the physics and the label rendering would need to be adjusted to draw onto a surface other than directly onto the screen space.

A visualization of data as scattered orbs above a map was provided by the VIBE system. The system visualized environmental, land-use, urban, economic and ecological data collected about Berlin [27]. The height of each orbs visualized a percentage and the colour encoded the type of data. Twitter data was visualized with coloured glyphs representing tweets, the location of the tweets represented the location where the tweets were sent. Colour, size, type and motion of the glyph identified characteristics that gave the user information about the tweet. Selecting a tweet allowed a user to get details on demand and perform actions like showing an arrow to the same users next tweet [121].

Mapping polygons could be textured with an image to annotate a map with tactical symbology [97] (Figure 2.5a). Tactical symbols contained text, an icon, a number, a frame, a fill, and a graphic modifier. Unlike screen-space rendering, the symbols were positioned on the map, so their layout was not positioned on the plane of the screen. Positioning symbols in world space ensured that the symbols were positioned at the same place in both eyes. However, a disadvantage was that the symbols could occlude each other if they were positioned close together. Also, the graphics were rendered flat on the mapping polygon so they could cover up areas of the map.

Concentric layout for labels in augmented reality was applied to labelling 3D objects [179]. The labels were placed onto concentric rings and then sorted so that the labels for each ring were sorted alphabetically. The ring was enlarged at the start of the label list and tapered towards the end. Rings were colour-coded to denote reading order, clockwise or anticlockwise. The layout looked like it worked well when the object was fully visible and contained within the ring, however, in VR, maps could be partially visible. Additionally, the layout was for augmented reality, and the ring was drawn as an overlay to a physical real-world object. The positioning of labels onto different rings prevented the label lines from overlapping. However, on maps, the lines could be really long. For large maps, it may not be possible to find space to place the labels outside of the area where the map is drawn.

Landmarks can assist with wayfinding and navigation. A study in VR required participants to navigate a route in VR with 10 landmarks placed along the route. Participants performed two tasks, the first task required recalling the route, landmark positions and districts in the VR simulation. The second task required participants to recognise scenes and state whether a given landmark was present at the scene. The study found a correlation between the correct positioning of the landmarks and route accuracy [43].

Screen-space force directed layout techniques, and concentric rings were considered for marker layout, however concentric rings were not used due to the size of the maps that needed to be annotated. In Immersive ESS Visualizer, rendering for markers was in the space of the game world, rather than in screen space to ensure that the markers were rendered correctly in both eyes. Moran et al. [121] displayed details on demand by showing a bubble next to 3D objects in the environment, however in Immersive ESS Visualizer, details were shown on a panel attached to the controller, so that users could position and move the panel with the controller.

2.4.4 User experience design for immersive systems

In this section, interaction techniques for user interfaces are discussed with attention given to the task performed, and critiqued on evaluations measuring task performance. Interaction techniques include menus, widgets,

Figure redacted for copyright reasons

Automated-dynamic-symbology.PNG

(a) A tactical symbol consisting of mapping polygon, icon, fill, number, frame, text modifier, graphic modifier. Source: Youngseok et al. [97]

Figure redacted for copyright reasons

partially-sorted-concentric-layout.PNG

(b) A partially sorted concentric layout with labels attached to a model aircraft. The colour denotes the reading direction of the labels [179].

Figure redacted for copyright reasons

Physical-model-for-screen-space.PNG

(c) Force directed labels arranged in screen space [143].

Figure 2.5: Techniques for applying labels to 3D visualizations.

navigation techniques, and the devices used to control the interface, such as game controllers or gestures.

Menus

Menus can control applications by selecting options or objects. Menus in virtual environments were categorized for application control based on what the menus were intended to be used for [58].

Menus and 3D widgets for user interfaces were categorized based on intended use [57]. The categories were "Direct 3D Object Interaction", "3D Scene Manipulation", "Exploration and Visualization" and "System / Application control". The subcategories of most relevance to this research were "Navigation" which is a subcategory of "3D scene manipulation", and "Menu Selection" which is a subcategory of "System/ Application control". Based on interviews (§4.1) and focus groups (§ 4.4, 5.4), the menus for the system developed in this research were designed for data exploration, navigation, and menu selection to control the application.

Menus were categorized based on the depth of the hierarchy of options, and whether the menu was temporary or permanent [58]. The data for ecosystem services tradeoff comparison was hierarchical, and menus were visible

Menus in immersive systems could be 3D or 2D. Pie menus [69, 45] and linear menus [45] were 2D menus which could be displayed on surfaces to allow a user to select entries on the menu. The entries on pie menus and linear menus were selected by positioning a pointer over the entry. The entries on pie menus were the same distance from the centre, so when pie menus were displayed with the pointer in the middle, each entry could take the same amount of time to select. Pie menus (radial menus) and linear menus were compared in VR for selecting items and colours, the study found that pie menus were faster to use [144].

Spin menus [72] and Ring menus [71] had a 3D design and allow the user to select options from a ring. Items from the ring menu were selected by wrist rotation which also rotates the menu, there was a position on the ring which indicated the selected item. The mode of selection for the ring menu differed from the pie menu because items did not require the same

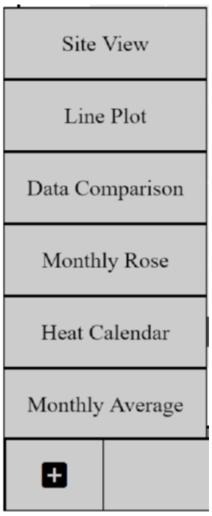


Figure redacted for copyright reasons

a-comparative-study-radial-menu.PNG

Figure 2.6: **a)** Atmovis linear menu showing visualization options to add to an interface [135]. **b)** A radial menu showing selectable colours [145].

amount of movement to be selected. The Spin menu allowed the user to rotate a ring of selectable objects [72]. Three different layouts were tested for the hierarchical selection of menu items. The crossed layout presented each of the orthogonal sub-menus as another ring. The concentric layout placed rings for each depth in the hierarchy outside the original ring. The stacked layout placed sub-menus above the original ring. Both the concentric and stacked layouts performed better than the crossed layout for the accuracy of the selection. The authors claimed that the concentric ring should contain at most 9 to 11 elements. Since an ecosystem services tradeoff analysis generates files for combinations of services this approach would only work for small numbers of services being traded off (less than 4). The spin menu would only work with a small number of tradeoffs. However, describing the data hierarchically could reduce the number of categories on each ring and allow the visualization to be adapted for use.

Figure redacted for copyright reasons

the-spin-menu-a-menu-system-for-virtual-environments-fig1.PNG

Figure 2.7: A spin menu showing a stacked layout with a hierachy of selectable objects [72].

TULIP menus were displayed attached to the fingers of a users hand, and users interacted with the menu by pinching haptic gloves [38]. TULIP menus, floating menus (linear menus) and a tablet interface were compared for the amount of time taken to complete a task adjusting the colour, texture and shape of a virtual object.

Collapsible Cylindrical Trees and Spin menus showed menu options hierachically [72, 58]. Hierarchical selection could benefit the exploration of data from ecosystem service tradeoffs when data for more than one variable is visualized. Collapsible Cylindrical Trees visualized selectable attributes on the surface of a cylinder, the cylinder was rotated and options were selected [56]. Selecting each option telescoped another smaller cylinder with subcategories which could also be rotated to show additional nested subcategories by telescoping the cylinder. The collapsible cylindrical trees showed a path through a tree of options. However, a disadvantage was that menu options could be located on the opposite side of the cylinder and invisible to the user. Formal usability tests for selecting options with collapsible cylindrical trees were not presented. Collapsible cylindrical trees were a possibility for this research project, however, the number of menu entries could cause occlusion.

Linear menus were chosen for the file menu and attribute list in Im-

Figure redacted for copyright reasons

collapsible-cylindrical-trees.PNG

Figure 2.8: Collapsible cylindrical trees showing website navigation [56].

mersive ESS visualizer, file names and attributes could become long, also the number of files could be too large for rings.

2.4.5 Tangible interfaces

Tangible interfaces use physical media to represent interfaces or data which can affect an immersive system. They could be used to visualize and interact with geospatial data.

Physical models were used as a tangible interface for creating a landscape in an immersive system [157]. A user could sculpt a model using physical media and the models were laser scanned into an immersive environment where they could be viewed inside a HMD. The system allowed the viewport for the camera to be specified on the physical model. Fly-throughs could also be scripted by interacting with the physical model with a laser pointer. The method of interaction was investigated in a case study where participants were asked to design a park. The case study contained three stages where the participants were asked to create water features, design patches of forest, and create trails. The case study method and the actions of the participants were reported, however, details about the usability of the application were not described. The authors claimed that the application could be used as a tool for educational courses. One possible issue with the tangible model was that the physical model did not have the same consistency and hydrologic behaviour as the soil landscape. For example, the soil absorbs water however the model used for the water did not model the consistency of the soil. Sediment controls could be required when performing earthworks, however, sediment runoff was not discussed.

A physical 3D printed model of a DEM was used as a tangible interface for a petroleum well-planning tool [127]. The tool had two separate interfaces, one interface for an 'overseer' and the other interface for an 'explorer'. The overseer was in a role where they were instructing the explorer remotely. The overseer had a tangible interface with a 3D model, and the explorer had a tablet interface. The overseer's physical interface allowed markers to be positioned for the explorer to investigate, and paths could be specified by drawing on the 3D printed model with a laser pointer. The explorer tablet interface allowed the explorer to access visualizations positioned geographically over the camera footage. The overseer could view information composited onto the 3D printed terrain by looking at the terrain through the camera of a tablet, or by using AR glasses. The explorer was tracked using a step detector, GPS, accelerometer, and magnetic sensor and this information tracked the explorer's position on the AR overlay. The AR application was trialled with a group of industry practitioners. A focus group session collected feedback about the system. The study found that the 3D printed model helped the participants to understand the shape of the surface and which locations on the map would be the most suitable for building oil wells. The application also received positive feedback about the collaborative nature of the experience and participants claimed that it would speed up the planning process. One limitation identified by the research paper was the quality of the 3D printing. The terrain was difficult to produce with accuracy.

2.5 Visualization Evaluation

2.5.1 Techniques

To understand whether an immersive system was suitable for geospatial data visualization or land use, it was necessary to evaluate how users experience the immersive system. In this section, methods for evaluating visualization systems were compared to inform the evaluation of the immersive system developed as part of this research project. Visualization systems could be evaluated for effectiveness by performing a user study, cognitive walk-through, or heuristic evaluation.

A study of scenarios for evaluating visualizations found that scenarios about "Understanding Environments and Work Practices" are mostly qualitative with data collected by observation, interviews, written responses, and audio/video recordings [106]. Studies could be performed in a workplace environment or in a laboratory. Study scenarios evaluating "Visual Data Analysis and Reasoning" (VDAR) could collect both qualitative and quantitative data. A scenario in the VDAR category evaluated the entire tool in the context of data analysis rather than evaluating individual visualizations or interactions within the software. Some typical recorded data were the "number of insights gained" from using the visualization tool, opinions and user experiences. Case studies, Interviews, "Laboratory Observations", and "Laboratory Experiments" were data collection methods.

In a cognitive walk-through, the programmer stepped through the process of using the software to ensure each task could be completed while analysing usability issues that could occur. In a heuristic evaluation, the programmer used criteria to evaluate the system [161]. One limitation of heuristic evaluation was that there is a lack of widely accepted heuristics for VR [91].

Both a cognitive walk-through and a heuristic evaluation could be performed by expert evaluators without additional participants [125]. A user study in contrast means the software was tested by participants and both quantitative and qualitative feedback could be collected about the participant's experience with the software. A user study on visualization systems could measure metrics such as the accuracy of using visualizations, speed of performing tasks, and mental workload. Studies could compare different visualizations for particular visualization tasks, or compare different media for tasks with the same visualization.

The SUS test and NASA TLX both contain measures suitable for usability testing. A factor analysis determined that the SUS scale measured a single dimension of usability [32] The NASA TLX task scales measured Mental demand, physical demand, temporal demand, performance effort and Frustration level [81].

In this study SUS test and NASA TLX were chosen as measures for usability testing because unlike cognative walkthroughs, and heuristic evaluations, SUS and TLX involve users in the process of evaluation. Heuristic evaluations and Cognative walkthroughs may not capture information about how users with different expertise would interact with Immersive ESS Visualizer because both heuristic evaluations and cognitive walkthroughs would need to be performed by researchers rather than end users.

2.5.2 Evaluations

In this section usability evaluations and evaluations comparing different visualizations for task effectiveness are reviewed to discuss testing methods.

Colour strategies and leader line highlighting were compared for geovisualizations [75]. Two geospatial visualization techniques with multiple coordinated views were tested; a map with a scatter plot and a map with a parallel coordinate plot. The geospatial visualization techniques used either "colour highlighting" or "leader line highlighting" to link the map with either a scatter plot or a parallel coordinate plot. Four variable combinations were statistically tested measuring task efficiency; accuracy, eye movement statistics and qualitative responses. A within-subjects test was performed with 32 participants sampled from UNSW Canberra students and staff. During the experiment, participants were required to name a highlighted area of the map and then read the value from the coordinated view associated with the highlighted area. The study found a significant difference in the amount of time required to read the axis of the parallel coordinate plot when linking with leader lines. Leader lines were faster, however with more errors which could have been caused by the implementation. The paper suggested that an alternative implementation which draws the lines curved from either the top or the bottom may reduce the reading errors. No significant differences were observed in the completion time between reading with leader lines and colour highlighting for the scatter plot. One limitation of the study is that there was no interactivity in the views. The visualizations were static. Brushing strategies for parallel coordinate plots and scatter plots were not investigated. The study was performed on a 19″ monitor rather than in an immersive environment, so more research would be required to investigate whether the same effects could be measured in a VR HMD.

A visualization system for analysing WRF data was able to evaluate the accuracy of the WRF model [82]. The accuracy of monitoring data was checked by showing both measurements from meteorological sites and the simulated data. The visualization system was evaluated at the TESSIN VisLab which contained a room-scale stereoscopic VR environment with 13 projectors and a resolution of 6400x1800px.

The MEVA system employed pre-existing visualization technologies, such as ParaView, to make the experience of using the system more user friendly [83]. The MEVA system was implemented with the Unity game engine and targets CAVE environments, HMDs, 3D projectors, and desktop systems. The target audience included both domain-specific experts and the general public. MEVA was evaluated in a case study visualizing

WRF weather forecasting data and a usability study was performed in the TESSIN VisLab with 16 participants. A gamepad controller was supplied as hardware for interacting with the application. The participants were introduced to the application prior to the test, then the study consisted of two tasks and a post-study questionnaire.

The HurricaneVis system was evaluated for speed and accuracy of participant responses for tasks specified [35]. VTK was used to implement the volume rendering as part of the visualization system and VRJuggler was used for running the system in a CAVE. The datasets chosen for the evaluation scenarios were from hurricanes Isabelle and Lili. The MM5 weather model generated the dataset for Hurricane Lili.

A usability test was performed to evaluate how the Visualizer system in a CAVE compared with the desktop version and TecPlot [37]. Tasks were performed by 19 participants using each of the three systems. Participants were required to identify features in a subducting tectonic plate using the visualization systems, the participants were questioned after the study. The study found feature location, identification and navigation were easier in the CAVE version of Visualizer compared to the desktop version and TecPlot.

The usability of a HMD was compared to a desktop display for visualizing a space-time cube [66]. The study collected qualitative information through a study questionnaire and quantitative measures of the participant's experience, completion time, accuracy and a NASA TLX questionnaire measured mental workload. The study was performed with 20 participants and required the participants to complete a set of seven usability tasks on two devices. The dataset was chosen randomly at the start of each trial as a separate condition, with two possible datasets. The study found that participants using the immersive system had less "mental workload" measured on the NASA TLX and produced more favourable subjective SUS test responses.

Interaction with a VR map through body gestures and a controller was compared for usability and efficiency [146]. The equipment provided to the participants included an Oculus rift HMD for displaying the virtual world, Leap motion sensor for detecting the gestures, and Oculus touch controllers. The study was performed with 12 participants who were required to read the name of a city on the map, then place a virtual marker over the city. The participants were given a tutorial on how to use the interface before the start of the trial. Speed and accuracy were measured for each trial. Questionnaire sheets were given to the participants to collect qualitative data on their experiences as well as Likert scales ranking the effort, precision, arm tiredness, leg tiredness and general tiredness. The experiment found that the controller was generally better than the gesture interaction, also participants using the controller were faster and made fewer errors.

Merino et al. compared the effectiveness of the "3D software city" visualization technique for analysing program source code using a standard monitor, HMD and a physical model [117]. A between-subjects test was performed on three groups of 9 participants, one group for each medium. Participants were required to perform 9 tasks. The tasks required participants to "find outliers", "identify patterns" or "locate and quantify". The study found that participants using immersive VR through a HMD had better memory recall about the model while, participants using a standard monitor were more accurate at identifying outliers and participants using the physical model were the fastest to find outliers.

The difficulties of producing AR and VR applications were investigated by interviewing participants who identified as designers, hobbyists or experts from domains unrelated to VR/AR software development. The participants were interviewed about their experiences using AR/VR software development tools [28]. The study investigated difficulties with understanding the AR/VR tools, during the "design and prototyping" stage and "implementation and testing" stage. Analysis of the interviews identified that domain-specific experts, hobbyists and designers all had different requirements from development tools when compared to professional software developers, due to differences in their experiences. The participants identified that testing and debugging VR/AR applications was challenging due to the physical difficulties of removing an HMD in order to access the console. When user tests were performed in AR/VR, the participants who could use one device could not necessarily generalize their experiences to use different devices.

When investigating usability studies testing methods included, post study questionnaires [66, 146, 83], likert scales [146], qualitative interviewing [37], SUS and TLX tests [66], speed [117, 146, 35], accuracy [117, 146, 35] and memory recall [117].

In this research the tasks were designed to realistically describe analysis participants may want to perform. So the difficulty of tasks was not graded. Speed and accuracy measurements such as Merino et al. [117] were not suitable for this study because participants may choose different approaches. Post study questionnaires, Likert scales, SUS and TLX tests and an interview were chosen as evaluation methods.

2.5.3 Evaluating visualization interaction techniques

In this section, usability evaluations specifically evaluating interaction techniques for immersive systems are discussed. A usability study compared a HMD to a desktop for navigating in a virtual maze [153]. The users were required to collide with 21 different objects which were placed in the maze. The maze was constructed so that the corridors were almost the same and there was no map provided indicating object location. The study was designed so that “travel” was tested rather than “wayfinding”. The participants were split into two groups, each group containing 21 participants. A test was conducted on two conditions. The first condition tested the desktop version first then the HMD. The second condition tested the HMD first then the desktop. The study found that in general, the desktop system was better because the median number of objects caught was larger.

Route planning and object visibility were compared in VR and on a desktop screen [167]. The VR system used 3D geodata in an urban setting. There were two versions of the desktop system, one with 2D geodata and the other with 3D geodata. The objective of the usability study was to find out whether participants performed better at route planning in immersive VR or using the desktop system. The number of users was not reported so the statistical significance cannot be established. However, the study reported that participants were fastest at using the desktop system with 2D geospatial data. The desktop 3D system produced the most accurate results for the identification of viewing locations overall. The VR-3D application produced the most accurate results for participants identifying the first point at which an object can be viewed. The study did not report the platform used for VR or the platform used for desktop 3D, so hardware differences could not be separated from the software differences to identify the reason for these results.

A mixed 2D and 3D immersive application, for visualizing geospatial data, was evaluated to determine the usefulness of multiple coordinated views for exploratory visualization [156]. The application combined both 2D visualizations on a Large High-Resolution Display (LHRD) and 3D immersive visualizations in an HMD. Visualization tasks were performed by participants in three separate environments for comparison: 2D display only, both 2D and 3D with visualizations which communicated through coordinated views, or both 2D and 3D with visualizations which were separate and did not communicate data. No option was given for 3D only. The participants were asked which environment they preferred and most participants chose both 2D and 3D with multiple connected views.

The behaviour of participants was investigated using a 3D immersive extension of multi-view map layouts [147]. Patterns were identified in the way that participants arranged the maps in the immersive environment, how overview maps related to detail views and how participants interacted with the maps. The study found that participants positioned their maps in a "spherical cap" layout as they performed tasks, and that the position of the views were often adjusted. One limitation of the study was that all of the maps used were small enough for the user to see the entire map from their viewpoint. The study also did not apply a digital elevation model to produce 3D effects to the hierarchical views. Integrating this technique with a large map of the terrain with a digital elevation model could produce additional usability concerns around the user's viewpoint which have not been investigated.

A study compared VR, paper floor plans and renderings, and a 3D virtual environment for experiencing future office spaces [170]. The study measured presence, user experience and engagement. A Slater-Usoh-Steed test was administered to measure presence. A UEQ-S test was administered to measure user experience. Facial expression analysis measured emotions. A pre-questionnaire and post-questionnaire were administered. The study measured correlations between user experience, sense of presence and engagement. Behaviour was observed to measure the engagement of participants with each of the three conditions, and in VR the amount of time spent at each position was measured. The Kruskal-Wallis test was applied to SUS test results to show significance, following a positive result the Mann-Whitney-Wilcoxon test was applied to detect differences between each pair.

2.5.4 Thematic analysis

Thematic Analysis (TA) is a collection of qualitative research methods that applies a systematic process to extract meaning from qualitative data [40]. The interview themes are information extracted from analysis of patterns in the interviews which state findings about participants in the study and which are contextualised by the research question [40]. An advantage of thematic analysis was that the process is an analysis method which can be applied to data, and does not constrain data acquisition methods, or place requirements on the coding process which could not be satisfied by a single researcher. Thematic analysis is compatible with data collection from multiple sources, so questionnaire responses were incorporated with interviews in this process. Reflexive thematic analysis encouraged researchers to think and write about their position in the research and how they could be a source of bias throughout the research process. However, Bowman et al. [39] claim that reflexive practices and positionality statements were under-reported in their review of thematic analysis for healthcare HCI research. Thematic analysis involved the following steps [39, 40, 42, 142]:

- Interview transcription.
- read transcriptions and post-study questionnaires to identify information of relevance.
- complete the coding process
- find themes.
- map themes and relationships and review the themes.
- name and define themes
- write-up.

Bowman et al. performed a scoping review reporting on results across 100 TA's in 78 papers to investigate contexts for the use of TA, approaches to TA, and reporting practices [39]. Results from the review found that thematic analysis was predominantly used to inform system design.

Thematic analysis was applied to analyse the use of virtual reality in nurse education [142] and develop design requirements for family communication technologies [42]. A virtual reality system designed to Enhance Men's Awareness of Testicular diseases (E-MAT) was administered to nursing students and their feedback about using VR for nurse education was recorded through interviews or a focus group [142]. Both Saab et.al. [142] and Brown et.al. [42] followed the 6-step process. Thematic analysis can be applied to interviews [42, 142] and focus groups [142]. Bowman et al. [39] found that team coding methods used by thematic analysis in healthcare HCI research published at CHI could involve one coder or multiple coders using methods such as consensus coding or collaborative coding. However, team coding methods were often under-reported [39]. Saab et al. [142] followed a coding process where the data was analysed by the first author and then cross-checked by two other authors. Brown et al. [42] did not identify which authors performed which parts of the coding process or how codes were incorporated from each author but used the pronoun "we" throughout their reporting of the coding. For this research project,qualitative information was coded by one researcher. Results from analysing the feedback of participants using E-MAT found that VR was engaging, allowed students equal exposure to the same content, VR allowed them to become hidden behind a mask and feel confident.

A 3D VR simulation in radiography education [131] and a study designing and evaluating adaptive interfaces for augmented reality workspaces [104] incorporated thematic analysis to HCI evaluations. Lages et al. [104] applied the thematic analysis to system logs, interview questions and observations, the research method involved talking to participants while they performed the study exercises conversationally about the information they found in the interface as a response to facilitator questioning. O'Connor et al. [131] applied thematic analysis to open-ended questions in a digitally administered post-study survey that asked participants open-ended questions about their experience using a virtual reality system for teaching radiography. The post-study survey also asked participants to rank functionality with Likert scales. The difference in materials coded by Lages et al.[104] and O'Connor et al. [131] illustrated that the thematic analysis process is flexible and could be incorporated into studies that also applied statistical metrics as part of their evaluation. Lages et al. [104] applied their coding method in two stages. The first stage incorporated Open Coding, Holistic coding, and Attribute coding. The second stage incorporated Axial coding, C-family coding, and pattern coding. O'Connor et al. [131] did not report exact coding methods. O'Connor et. al [131] found that students enjoyed using the VR but they felt they needed more feedback than provided by the tool. Student performance in assessments was statistically tested between students who used the VR and students who did not use the VR. Students using the VR to train performed better at patient positioning and beam centring in assessments.

2.5.5 Systematic Literature Review

In this section evidence from systematic literature reviews is analysed and compared to identify limitations within the existing literature. A systematic literature review can be applied to find areas suitable for new research, query the body of previous research to evaluate how well a statement is supported by other studies and to create an overview of existing studies [44]. A systematic literature review would allow software engineers to make better choices about the technologies needed for software development projects [99] and allow researchers to produce evidence through research that is directly applicable to the software industry.

In a systematic literature review, keyword searches collect a selection of research relevant to the field [26, 64, 137]. Keyword searching can be applied to one or more search engines to avoid limitations from the selection provided by one search. The literature review is systematic rather than comprehensive and the search criteria can be limited by refinements which remove literature based on publication timeframe [60, 64, 30, 26], publisher [64, 30] or number of references. Search engines such as Web of Science allow searches to be restricted by the research area [23] and Scopus allows literature to be excluded or included based on keyword terms which tag the search results [15]. After search terms have been chosen and results have been retrieved the results can be categorized based on criteria. This categorization can be performed by one person or coded in a rubric and applied by several coders.

Research on user evaluation in augmented reality published through IEEE Xplore and ACM Digital Library between 1993 and 2007 was systematically reviewed [64]. A search engine extracted publications based on keyword searches. Keyword searches were refined by adding and removing terms until the coverage was suitable, then the selection was filtered to remove papers not about augmented reality, or did not perform user evaluation. The publishers were chosen by analysing the literature retrieved from the search and identifying that ACM Digital Library and IEEE Xplore were two major publishers of research retrieved. The research papers were categorized based on the user evaluation technique applied. The review found that few collaborative AR papers were included in the sample. Also, the proportion of formal user evaluations between 2002 and 2007 was greater than the proportion of formal evaluations between 1995 and 2001. A limitation of restricting publications to ACM Digital Library and IEEE Xplore is that both these publishers specialize in computer science and engineering research. Since augmented reality research is interdisciplinary and spread throughout a large number of different fields, differences in the approaches of other science disciplines would not be captured in the sample if present. The keyword search was applied to PDFs directly that were extracted from publication databases, the disadvantage of this method is that the publications were not checked for keyword tags provided by the author. If other keywords were used by paper authors, these keywords would not be picked up by the search terms. The term "usability" is not in the search criteria, however, the Scopus search run for this research project found papers which were retried by usability and not by the other search terms.

A systematic literature review was performed which compared the usability study techniques applied to AR research papers published between 2005 and 2014 [60]. The research ranked the average number of AR papers reporting usability studies, the type of study performed, the proportion of user studies for different applications of AR, and recommended that more studies should be performed under more realistic conditions rather than in laboratory studies. The review found that only a small number of studies were performed outdoors. Heuristic evaluation was the least common evaluation technique applied by the user study papers surveyed. One limitation of the review was that only AR material was covered, however, this project is about immersive systems so the terms AR, MR (mixed-reality), XR and VR should be part of the criteria. Also, only venues indexed by the Scopus database were covered. There was a significant amount of literature published since 2014 which would be of interest and should be covered in a new systematic literature review.

A systematic review was performed on usability evaluation research published at the International Symposium of Mixed and Augmented Reality (ISMAR) [30]. The review covered publications that were published between 2001 and 2010 and contained 71 research papers. The criteria for the evaluation categorized the papers based on “task performance”, “human perception/cognition”, “collaboration” and “UX”. The review found that “error tolerance” was not frequently reported in usability evaluations. Evaluations of user experiences do not cover the long term effects of augmented reality and questions about the feelings of participants are focused on the participant’s immediate response.

Collaborative technologies for mixed reality were systematically reviewed [26]. The review covered literature published through Scopus, IEEE Xplore and ACM between 2013 and 2018 with the objective of categorizing the goals of the research publications and identifying future research areas. The review was performed by searching for keywords through a search engine and 259 papers were reviewed. The literature review identified that 89 of the papers surveyed utilized “annotation techniques” for transferring spatial information to another user via their visual display.

Learning theories, and evaluation techniques applied to virtual reality systems for higher education were systematically reviewed [137]. The review was performed on literature from Scopus, ProQuest, Web of Science and the IEEE Xplore Digital Library. Search terms were found by defining a search string which was adapted into a search for each database. Exclusion criteria were also developed for excluding false positives and checks on search samples were conducted to identify the terms in the exclusion criteria which should be applied. Filters were applied to the research papers that were identified by the search, firstly ‘semi-automatic’ then manual filters. The KH Coder 3 software package was used to pre-process the search terms. The analysis performed on the research papers retrieved was both qualitative and quantitative. A “concept matrix” was created to classify research papers based on “variables”, “theories”, “topics” and “methods”. Researchers coding papers filled out a questionnaire for each paper to classify them. The coverage of VR systems was limited to HMDs and CAVE systems were not considered as immersive. In this study, CAVE systems are considered immersive because they use large displays across several walls covering a large proportion of the users field of view, and respond to the users motion.

A review of Spatial 3D (S3D) and Spatial 4D (S4D) visualization techniques in was performed which identified the possibility of future research into the development of new S3D and S4D visualizations for VR [96]. The study reviewed literature to create a taxonomy from visualization techniques for spatial data in 3D and 4D. The authors identified that out of the 41 visualizations that were surveyed only 2 of these visualizations were specifically intended for virtual reality. Spatial visualizations were categorized based on whether they supported “juxtaposition”’, “interchangeable”, “superimposition”, or “explicit encoding”. The paper suggests that since virtual reality introduces additional concerns into the development of the visualizations such as a sense of presence, future research is needed to identify ways to incorporate the strengths of virtual reality in S3D and S4D visualization design. S3D and S4D visualizations could be potentially incorporated into designs for this visualization system through a user centred development process and evaluated.

2.6 Summary

This chapter discussed the literature surveyed for visualization techniques including immersive systems for geospatial data analysis, immersive visualization systems which included more general visualization techniques and visualizations used in presenting the results of ecosystem services analysis. This thesis adopted a user centred design process incorporating both interviews and focus groups for requirements gathering. The focus group expanded on the interviews by collecting information about the use of LUCI and the participant's response to visualization design ideas. User centred design is an iterative process so the rich data gathered was refined through consultancy during the development of the immersive visualization system. Evaluation included qualitative and quantitative usability testing adopting methods from Nielsen et al. [125] and questionnaires were included to measure effectiveness, and the users perceptions of the interface.

2.7 Extended literature review

An extended literature review of the practices for evaluating immersive systems for analysing geo-spatial data is presented. The objective of the review was to identify geospatial immersive visualization techniques in literature and identify differences in evaluation methods. Existing literature about immersive analytics was reviewed to investigate approaches to the evaluation of immersive visualization for ecosystem services and land use, discover differences in evaluation techniques applied to geospatial visualizations, and to investigate possible methods for the evaluation of the effectiveness and usability of the tool. Some systematic literature reviews were performed on evaluation methods in AR [117, 60]. However, limitations in the databases covered in previous literature reviews for geospatial visualization, and an absence of Systematic Literature Reviews (SLR's) for the evaluation of geospatial visualizations, suggest that an extended review would be beneficial for placing this thesis in context with the field.

2.8 Review method

Papers were reviewed to collect information on what results could be reported in an extended review[73, 172, 107]. Each paper provided definitions for concepts they used in their review. Two of the papers also categorized the objectives of the papers that they were reviewing [172, 107]. A taxonomy of methodologies and objectives was an objective for Willard et. al.[172], this taxonomy involved categorizing the literature. A categorization of literature was also created by Gonçalves et. al.[73].

The literature review of immersive geospatial visualization systems was performed following a systematic process to identify the most rigorous methods for case studies, user studies and other possible research methods for user evaluation and comparison with non-immersive systems. The extended literature review searched publications from Engineering, Computer Science, and Geographic Information Systems (GIS) to ensure coverage of as much published literature as possible. The literature was categorized based on evaluation method, visualization techniques applied, data set and the medium for visualization. The method for the extended literature review was based upon systematic literature reviews for software engineering and visualization [117, 60], as well as recommendations on the best practices for performing systematic literature review [44, 98].

2.8.1 Objectives

The literature review was performed to address the following objectives:

Q1 What immersive visualization techniques have been applied to geovisualization?
A categorization of the research goals and objectives could assist analysing the decisions for choosing different visualizations and evaluation techniques, This categorization could identify gaps in the visualization types and research goals, as well as identifying situations where different visualizations could be applied to geospatial data.

Q2 What differences exist in the evaluation techniques applied to geospatial visualization?
Categorizing evaluation techniques could identify differences in what research publications are measuring to evaluate geospatial visualizations.

2.8.2 Data Sources

The information sources chosen for the review were Scopus and Web of Science. Google scholar was used to check for research papers that were not covered by the search criteria and to expand to additional databases or adjust it. Literature sources from conferences and journals were considered as part of the review, however book chapters were not considered, as book chapters contain could contain research which has been published previously.

2.8.3 Criteria and search strategy

Criteria containing terms for filtering results from the literature sources were produced. Filtering based on these terms removed literature which was not relevant to the study objectives. The criteria contained four categories: evaluation terms, media terms, geospatial terms, and visualization terms. To satisfy the criteria, queried literature was required to contain a search term in all four categories. Lists of search results retrieved by search engines were manually inspected to identify additional relevant keyword terms and expand the search criteria.

Queries were logically structured with conjunction and disjunction operators and saved into the saved searches list for Scopus and Web of Science. Each search was run with a single query. After running each iteration of the search query the quality of the search results was inspected to identify the presence of literature which was not relevant to the search. For example, the abbreviation mR also means milli-Rads, so "mixed reality" was written in full.

Both Scopus and Web of Science were searched. The search criteria was produced for Scopus first then the search criteria were adapted for the Web of Science by searching through the topic (TS), title (TI), author keywords (AK) and abstract (AB). Scopus provides a list of keywords which are present in the search, and this keyword list was inspected to find relevant keywords for both inclusion and exclusion. The search results were then inspected to identify redundant search keywords to simplify the criteria. The keyword "spatial" was found to be unnecessary for the search criteria. Searching for keywords to match ecosystem services such as forest, carbon, flood, biodiversity made the search criteria unnecessarily complex without retrieving suitable readings so these keywords were not included in the final search criteria. Searches were performed in both Web of Science and Scopus then the results were combined in Zotero, where duplicates were removed by merging. The results of different search runs were compared to show which results were included or excluded changing search terms. The list of readings was exported as a RIS file to NVivo for analysis.

The following list of evaluation terms was adapted from the data extraction criteria specified by Merino et al. [118] and details the criteria for the evaluation search terms:

{([user| case] stud[y |ies], [user|heuristic] evaluation(s), user test(s),cognitive walkthrough(s), cognitive walk-through(s), [application|usage|analysis] example(s), survey(s), [controlled|user] experiment(s), demonstration(s), [example|user] scenario(s), usability, example(s) of use}

The media search terms:

{ [virtual | mixed | augmented] reality , immersive }

The media search terms were produced so that as much literature as possible for immersive systems was matched. The abbreviations AR,VR,MR and XR were not included as they produced too many false positives.

The geospatial search terms:

{ geo*, GIS, Geographical Information Systems, Geographic Information Systems, ecosystem service, ecosystem services, environmental, ecological}

The geospatial search terms captured the subject area being visualized. Geo* captured terms such as geography, geology, geophysics. After inspecting the results manually there was only a small number of results matched which did not relate to a geospatial visualization, and these results were filtered manually.

The following list details the criteria for visualization:

{data visualization,data visualisation}

The search criteria for “data visualization” ensured that unrelated terms such as “landscape visualization” and “surgical visualization” were excluded.

Geovisualization :

Geovisualization, Geovisualisation, Geo-Visualization, Geo-Visualisation, Geo Visualizations, Geo Visualisations, Geographic Visualization, Geographic Visualisation,

The criteria were combined using the formula:

evaluation AND media AND ((geospatial AND visualization) OR geovisualization)

2.8.4 Refining the search

The first search produced 1,437 results and the search query was adapted to improve the quality of the search and reduce the number of false positives. The search criteria were incrementally refined by inspecting the results of the search to check for false positives and inspecting the search results for papers which should be included to detect false negatives. The title, keywords and abstract were inspected for a selection of results. New search terms were discovered by inspecting other systematic literature reviews, and the keywords of documents which matched the search criteria. The final search of both databases collectively produced 336 results, 210 of these results were from Web of Science and 178 of these items were from Scopus. After filtering was applied there were 60 results remaining. A full list of the papers analysed is in § A.

2.8.5 Manual Filtering Criteria

The NVivo software [14] was used to collect literature for qualitative analysis. The metrics for the review were chosen so that the study could be compared with the results from systematic reviews [60, 117]. The filtering process was iterative: First, papers were scanned to ensure that an immersive VR system was used for the research, then checked for geospatial data visualization and the presence of an evaluation. Then the evaluation was checked to ensure that there were some findings about usability. The filtered research papers were manually filtered according to the following criteria:

Media Terms	To ensure that the terminology for immersion, Virtual Reality, Mixed Reality and Augmented Reality was within the scope of the research, the research papers were filtered according to the definitions in § 2.2.
Geospatial and Geovisualization Terms	Research with no geospatial component was removed.
Data Visualization Terms	Research without any data visualization was removed and research papers that contributed only rendering techniques were not considered to be data visualization e.g. 3D reconstruction of industrial equipment, buildings, or the modelling of terrain from mathematical techniques without real-world data. Research papers visualizing buildings but which also visualized additional geospatial data remained in the results.
Evaluation Terms	Research with no usability testing was removed. Some research papers contained only case studies which did not evaluate the usability of the application and these papers were removed from the sample. However, case studies which also reported on the usability of the tool were included. The remaining papers were categorized by tagging the papers with keywords based on the evaluation method for usability testing.

2.8.6 Metrics

The following metrics were collected about the research papers surveyed:

1. Research goals and objectives

2. Number of papers per dataset category.
3. Number of papers per type of user evaluation conducted. For example, case study, user study.
4. Number of papers per usability study type

To collect these metrics, papers were tagged with keywords to identify the medium used in the research, the type of user evaluation, the sense augmented, participant demographics surveyed, statistical tests, visualization methods/techniques, and the dataset.

2.8.7 Categorization of the Literature

Papers were coded into categories for media type, visualization type, evaluation, user demographic and geospatial data. The categories were then iteratively refined further into the following subcategories based on the media type, evaluation type and geospatial data. The visualization type was tabulated with the evaluation and visualization.

Evaluation Categories — The evaluation was categorized into case studies, heuristic evaluation, informal studies, performance testing and usability studies.

Dataset — The dataset was categorized as ballistic, environmental, geography, geology, planetary geoscience and WWW Traffic. Data geo-referenced for places, the movement of people, bathymetric surveys, and activities taking place on the earth's surface were categorized as geography. Data about processes occurring in the earth were categorized as geology. Data for environmental processes such as atmospheric datasets and flood risk management were categorized as environmental.

Media Media categories classified papers according to the technologies that were used in the research e.g CAVE, Mobile AR and VR HMDs

Visualization Technique Papers were coded by the visualization techniques which they used e.g isosurfaces, volume rendering, maps, scatterplot matrix.

Demographics Papers were coded by the users who participated in evaluation e.g soil scientists, geologists, geoscientists, engineers.

The lists of papers were exported from the categorization nodes into a spread sheet to verify that every paper had a data set, evaluation, media and visualization terms. A Sankey diagram was produced by exporting lists of papers, Figure 2.9.

2.9 Results from the extended literature review

In this section, the results of the extended literature review are discussed. The results cover the proportion of research papers in the dataset categories, evaluation categories and media categories. There were 60 research papers in total that were analysed.

2.9.1 Number of papers per dataset category

The most frequently occurring category of the dataset was geography (Figure 2.10). Geological data was the second most frequently occurring category and Environmental data was the third most frequent. These results identified that there was a limited number of evaluations measuring

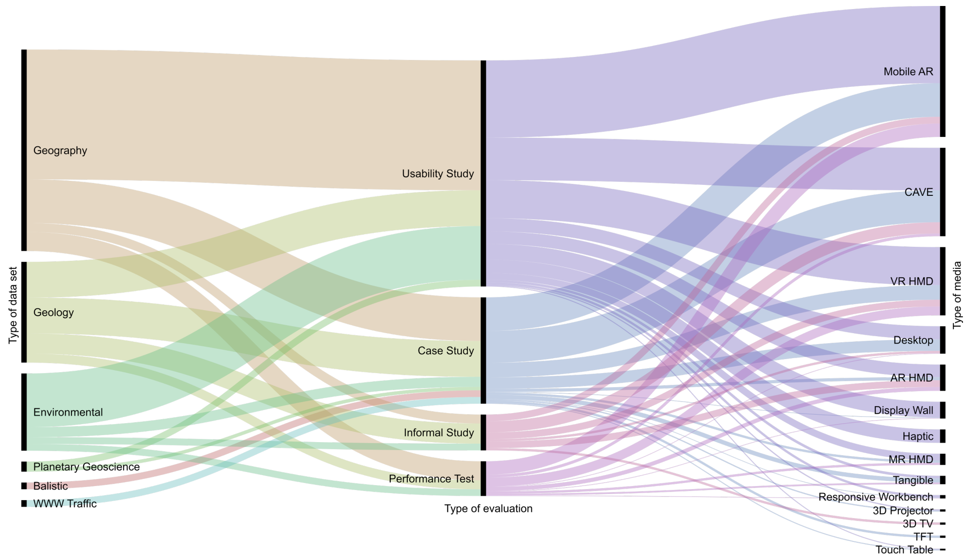


Figure 2.9: A Sankey diagram with the dataset categories (left), evaluation type (centre) and media (right).

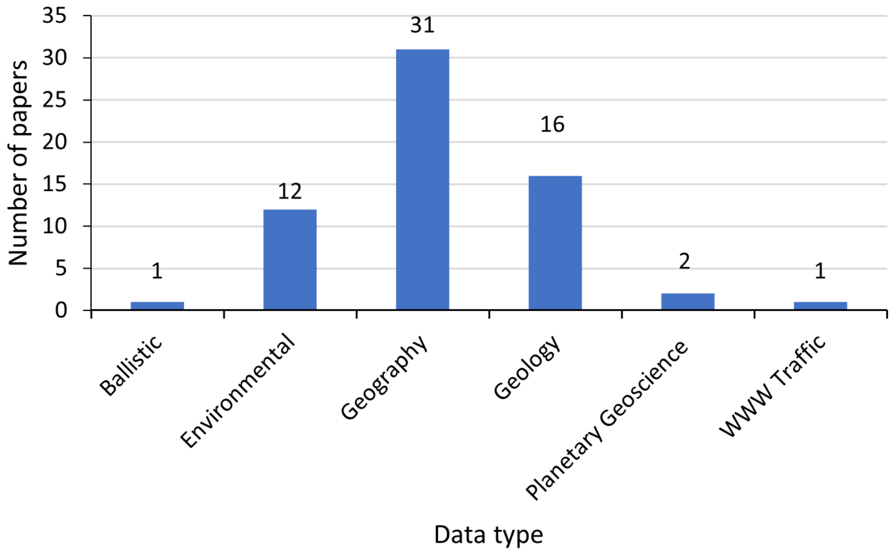


Figure 2.10: Number of papers per dataset category

the effectiveness of visualization for environmental processes. The small number of papers for the visualization of environmental data suggested that there were gaps where more research was needed. Geography is a broader category than geology or environmental data, so it was expected that there would also be more evaluated geographical data visualizations for immersive media. The categories are not entirely mutually exclusive, for example, the Adviser system [67] was classified as both geology and planetary geosciences because case studies at Antarctica and on Mars were presented. The BoreholeAR system [108] for borehole database visualization was classified as both geography and geology because the information visualized about boreholes was not entirely about rocks and processes occurring in the earth, it also contained project information and data about the drilling machine.

2.9.2 Number of papers per type of user evaluation

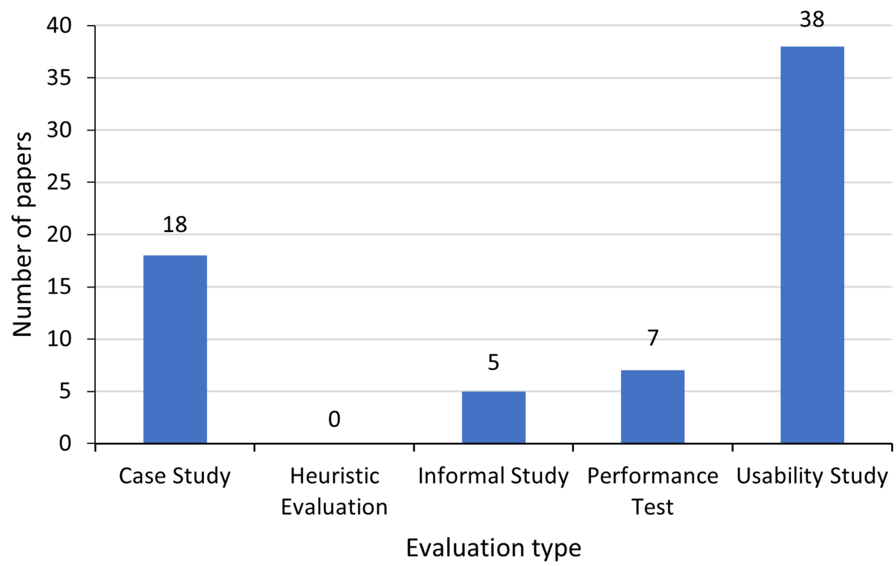


Figure 2.11: Number of papers per evaluation type

The most common method of evaluation involved running user studies on groups of participants (Figure 2.11). Papers which included a case study where a problem was solved with the tool and the usability was reported were less common than papers which conducted usability studies. 7 papers collected performance testing data about either load times or frame rates of the application and commented on how this affected the performance. The absence of performance test results indicates a gap, because the usability of VR systems and the sense of presence in the VR world is affected by performance. There were no papers which performed heuristic evaluations suggesting that there is a gap. There is a lack of known heuristics for analysing the usability of immersive VR systems.

2.9.3 Number of papers per type of usability study

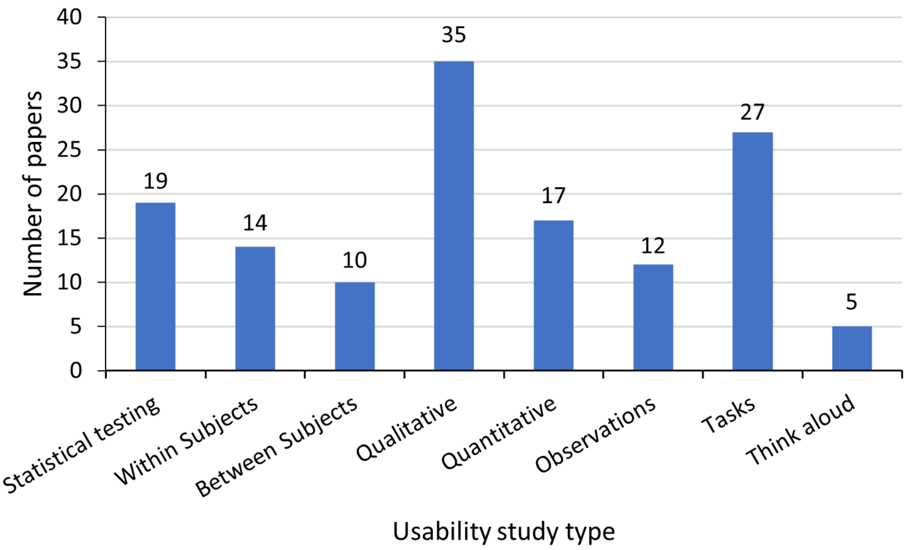


Figure 2.12: Number of papers per usability study type

The most usual method for evaluating the usability of software was based on qualitative evidence. Qualitative evidence was collected from users who interacted with the tool by filling out a questionnaire or by participating in interviews. Quantitative testing methods included testing completion time and the accuracy of participants using a software tool. In total, 38 papers satisfied the usability study criteria and 27 of these papers set formal tasks for users to complete. A think-aloud protocol was not frequently reported with only 5 papers reporting studies where the participant was required to articulate their actions while they were performing tasks. The statistical testing category contains both between-subjects and within-subjects tests. There were 19 papers applying either between-subjects or within-subjects testing techniques and within-subjects testing was more common than between-subjects testing.

2.9.4 Papers for datasets, evaluations and media

The Sankey diagram shows that the ranking of which evaluation methods are most popular is not affected by the type of dataset (Figure 2.9). Likewise, the popularity of different media is not affected by whether the evaluation method is a usability study or a case study.

In the above Sankey diagram Mobile AR and CAVE were most popular with four papers evaluated using each. VR HMD, and AR HMD were second most popular with 3 papers evaluating each. None of the papers visualizing environmental data performance tested their applications with the CAVE.

2.9.5 Discussion

The literature review identified that there is little published research visualizing environmental data in immersive environments which are also usability tested. There is an absence of heuristic evaluation as a testing method and evaluations are often performed in laboratory environments. However, only 5 of the evaluations incorporated think aloud protocols and only 12 incorporated observations. This identifies that observational information from these formal usability studies is often not reported, even

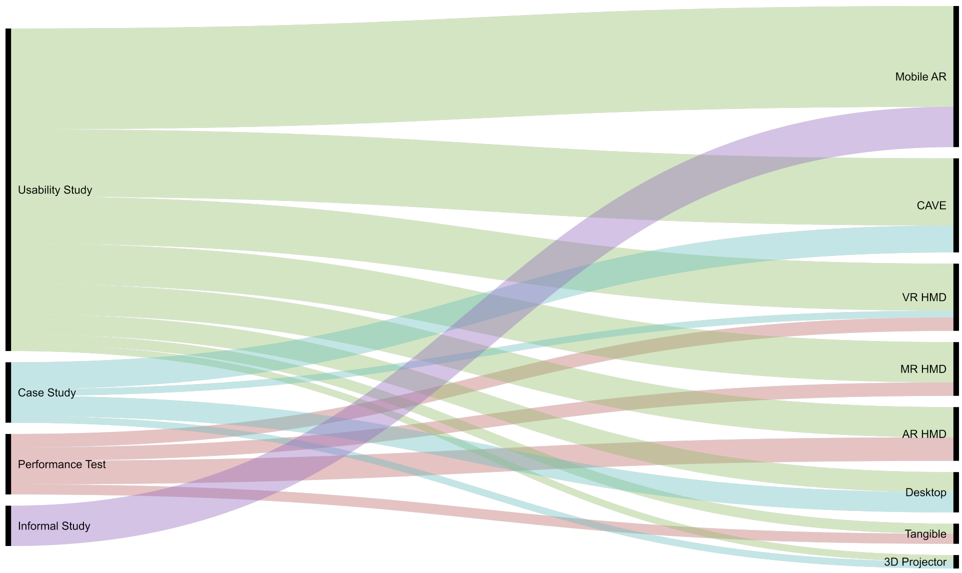


Figure 2.13: A Sankey diagram with the evaluation type (left) and the media (right) for environmental data visualization systems. The diagram shows that there are gaps for evaluation types in different media for environmental data visualization.

when participants have been set tasks to complete. The Sankey diagram of environmental data visualization identifies that there were no performance tests found for either CAVE or immersive systems which were also tested on the desktop (Figure 2.13). Since the performance of software affects usability, more research is needed publishing performance test results. Less research has evaluated VR HMDs compared to CAVE environments or Mobile AR and only 3 of the research papers that were found evaluated environmental data visualizations in VR HMDs. This identifies that there are some gaps in the literature evaluating VR HMDs for environmental data visualizations. Further deeper analysis is in progress for the literature review.

Chapter 3

Research Methodology

Contents

This chapter discusses the methods for requirements elicitation, and prototyping used for this research project. Section 3.1 discusses the User Centred Design process used for requirements gathering. Section 3.2 describes methods for interviews with users of LUCI. Section 3.3 describes methods for focus groups. Section 3.4 describes methods for pre-study questionnaires for the focus groups and the final evaluation. Section 3.5 describes prototyping methods for incorporating user feedback into design concepts.

The design of the visualization system in this thesis followed a User Centred Design process. An understanding of the work-flow, context and use cases was required to identify situations where visualization would be the most useful. There were different stakeholder groups using LUCI, so the experience of each stakeholder group was examined to create a tool suitable for as many different stakeholders as possible. Focus groups, interviews and questionnaires were considered as methods for collecting information. Different stakeholder groups may need to collaborate to complete their analysis, however, the perspective of individuals in these groups may identify communication needs which were not currently satisfied by LUCI. Interviews were used for requirements gathering in this thesis because information could be gathered from several different occupation groups and organizations (e.g. Business, and university students) who may be remote.

3.1 User Centred Design

User Centred Design (UCD) is a design philosophy which places users into a design process by incorporating their feedback throughout system development, rather than a specific method for designing a system [162]. User Centred Design relates all of the stages of system development to reflect the requirements and needs of the users by ensuring that the functionality is suitable, that the risk of human error is small, and that the users are fast and productive when applying the system to their goals [129].

User satisfaction and the emotional responses of users to design concepts are important in User Centred Design. Users should be consulted throughout the design process [46] and the system should be evaluated to ensure that it is efficient, effective, and that the user's requirements are met. Human Centred Design is often used in place of the term User Centred Design to emphasize that humans are affected by the system who may not be directly using it in addition to the users who are interacting with the interface [7]. In this thesis, an iterative development methodology was applied to the User Centred Design of an immersive VR Visualization system. Applying iterative development methodology to User Centred Design allows the design requirements to be adjusted based on data collection about the user groups and their experience using the prototype systems [46]. User Centred Design methods adopted by this thesis to incorporate the feedback from users into the system design included paper prototyping, interviews, focus groups and personas.

Personas are fictional characters which are representative of users for a system which is beingdeveloped [126]. A persona consists of a personal description of the user, the user's goals in using the system, and scenarios which describe system uses. A persona assists with User Centred Design by helping the developer to understand and empathize with the people who will be using their system [126]. A system with several different user groups can have multiple personas which describe differing user goals, scenarios and descriptions. The use of personas during the development of the system reduces the risk of the system being designed for the developer rather than the user group. In order to ensure that the personas accurately represented the users, the personas for this research project were created based on data about the users of the system. Personas created without data, based on the developer's perception of the user group, are less useful [136].

User Centred Design was applied in the published literature to the development of geospatial data visualization applications. For example, an immersive virtual reality application for visualizing 3D scans of prehistoric rock art on a multi-scale 3D terrain model of Valcamonica [103], a smartphone augmented reality application for urban tourism [177], and an application informing the general public about housing development in Wandsworth, London [77]. Data visualization systems have incorporated User Centred Design methods by involving users in requirements gathering [103], and evaluating designs with questionnaires, focus groups [116], or laboratory studies.

GIS experts may not have the same experiences and backgrounds so incorporating knowledge about the context of the user's work, and the abilities of the user into the development of user interfaces could help both GIS experts as well as novices [77]. The User Centred Design process provides information about how and why users were interacting with a system. A User Centred Design approach was applied to the Wandsworth application [77]. The researchers found that GIS assumes a background in cartography, geography or database management in order to use software tools [77]. More research into the visualization of spatial analysis could also assist non-experts in interacting with GIS by developing designs which assume less expertise. This thesis contributed towards the literature by applying User Centred Design to developing the requirements of a visualzation system to allow users with differing levels of expertise to analyse and visualize geospatial data in VR.

The following diagram describes the iterative process of developing the immersive VR visualization system for this thesis (Figure 3.1).

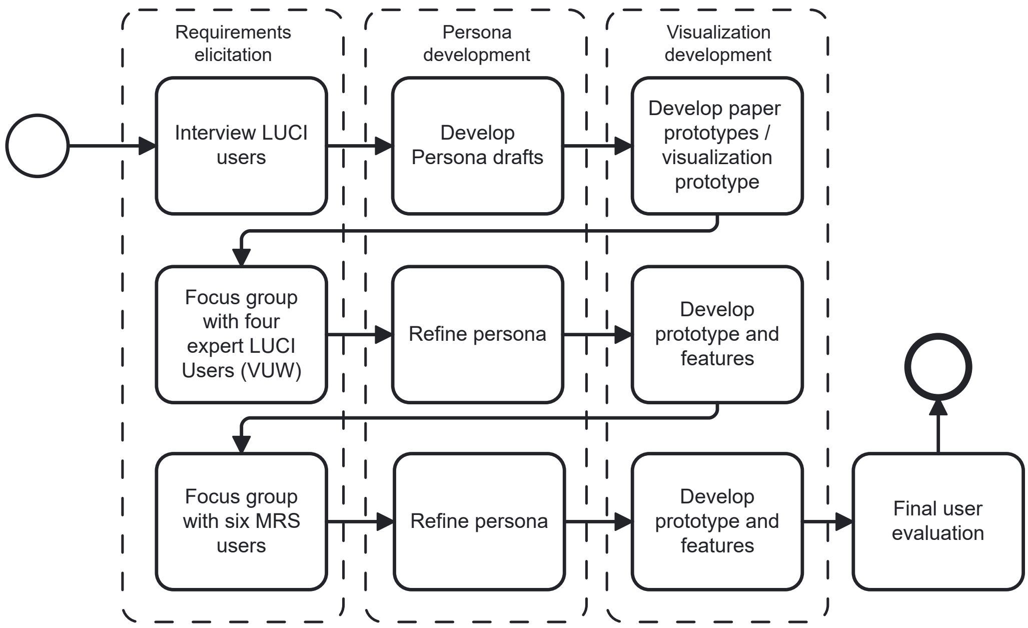


Figure 3.1: The UCD process for this thesis where requirements were elicited from participant groups. These requirements developed personas and informed the development of new visualizations and VR features.

The research in this thesis was approved by the Victoria University of Wellington Human Ethics Committee, application reference number #0000028871.

3.2 Interviews

Initial interviews were conducted with users of LUCI for modelling ecosystem services. Interviews were performed to gather information from a group of participants about the design of software systems [129]. The semi-structured nature of the interview questioning provided an advantage over questionnaire sheets where all of the questions must be written before the questionnaire starts and there are no opportunities to discuss subjects in further detail [25]. Semi-structured interviews were chosen for the requirements gathering to allow participants to go into depth about their experiences and discuss them in detail. Due to the small sample size of our study, interviews were a suitable option over questionnaires.

Interview participants were sourced through email. 11 semi-structured interviews were conducted according to a written interview protocol. Interviews were voice recorded and took approximately 30-45 minutes each.

The interviews for requirements gathering started by providing the background of the research project, introductions and providing participant information and consent as recommended by Cairns et al. [25]. The participant was given an opportunity to discuss their experiences with the LUCI tool to avoid responses to other questions in the questionnaire becoming framed by particular likes or dislikes which the participant would like to impart. The questions started with broad questions about their LUCI use first, then discussed details. The objective of each question was to start a discussion with the participants about the use of LUCI for their work. Lastly, the participants were debriefed about the study. The interview protocol is described below.

1. **Which tasks do you use LUCI for?**
   This question captured context of the participant's use of LUCI. Specifically, information about the following aspects of LUCI analysis tasks were collected: Any comparison of future scenarios to be performed by the participant using LUCI; analysis of current land use in the area of study (e.g farm land, riparian planting); the end users who would receive the result of the LUCI analysis; whether the analysis was performed for their own organization or as a presentation prepared for another organization; Whether there were any other tasks for which they used LUCI.

2. **What functionality provided by the LUCI toolbox are you particularly interested in?**
   This question identified features which could be visualized. Examples of functionality could be nitrogen retention or flooding.

3. **What information would you require when starting a new project with LUCI?**
   When designing the visualization tool, any information that was relevant to a LUCI session could be incorporated into visualizations, in addition to LUCI input data or generated outputs. Specifically, the following information was collected: Any datasets that the user incorporated into their analysis; any information or metadata that could be visualized to augment the analysis of LUCI input data.

4. **Which outputs generated by LUCI would you use during your analysis?**
   Collecting information about the outputs generated by LUCI allowed features to be designed which were effective for visualizing these outputs.

5. **Do you find any of the visualizations generated by LUCI to be particularly helpful during your analysis?**
   This question collected information about the tasks that the participant used visualization for, what data the visualization presented and how the visualization contributed toward an analysis.

6. **Is there any output generated by LUCI that you would like to visualize?**
   This question collected information about the tasks the participant was using data for, in particular: Any data the output was compared with; any trends in the output data.

Post-interview analysis protocol

Each participant was given a gift voucher for their participation (value of $20). All interviews were recorded and transcribed using Microsoft Word transcription software. The researcher then listened to the interview and corrected any mistakes or omissions in the transcription. Transcribed interviews were coded in NVivo [14]. These coding categories coded how many participants experienced similar problems or requested similar features from immersive visualization. The results of the analysis are presented in Section 4.1.

3.3 Focus groups

A focus group is a guided session with a small group of participants where moderators direct the topic of conversation [129]. Kuhn et al. suggested that focus groups can be good at creating ideas and suggestions during the design of products, describing use cases for how participants could use a product, communicating the requirements for usability to the developers and finding different user attitudes and responses to a system [102].

3.3.1 First Focus group with LUCI Users

As a follow up to the initial interviews, a focus group was conducted with four participants to gather in-depth information about how different users operated LUCI, and to gather feedback about preliminary visualization prototype designs. Participants were chosen who had already been interviewed, the participants were all analysts and three out of the four participants had written parts of LUCI as well as performing data analysis with LUCI.The focus group provided depth to the analysis by encouraging participants to discuss their experiences with using LUCI and compare similarities and differences. The differences between the participant's experiences and their requirements informed the development of personas by distinguishing differences between use cases.

The focus group was conducted in a room with equipment for demonstrating prototypes. Coffee and biscuits were provided and the focus group session was supervised. Four participants attended the focus group, two participants attended remotely over Zoom. The focus group session was voice recorded for transcription and a semi-structured method was followed for conducting the focus group where questions for the focus group were read from a sheet to start conversations about each topic. The focus group was introduced to the participants with a statement of the focus group rules, an overview of the project and motivation for the focus group. Participants were given information and consent forms about the process and data collection before the focus group started, participants were not provided with the questions.

3.3.2 Second Focus group with Mangatarere Restoration Society

The Mangatarere Restoration Society was chosen as a community group for the second focus group session because they were using LUCI to assist with their analysis of their catchment. The Mangatarere Restoration Society was formed in 2011 to address pollution issues with the Mangatarere stream [11]. The LUCI tool was being used to model different scenarios for land management and the mitigation of flood risk. LUCI can model natural solutions to flood mitigation.

MRS were end users of the developers interviewed in the initial interviews. In the initial interviews, 3 participants identified difficulties in their presentation of results to end users, so interviewing end users could identify ways to solve issues with the presentation (§ 4.2.4).

The focus group was conducted at the Carterton Courthouse community hub. An HTC Vive virtual reality headset and a PC were taken to the venue and set up in a room adjacent to where the focus group was conducted. Biscuits were provided to participants before starting the study. Voice recording equipment was in use during the focus group and the prototype demonstration and observational notes were taken. The pre-study questionnaire was administered first to collect participant background information (Appendix D), then the focus-group session started.

The objective of the MRS focus group was to collect information about how LUCI is operated and to gather information about visualization ideas. The information collected in the focus group included a discussion of the participant's experience gathering data, analysing data, experiences with the communication of LUCI output results, and ideas for the visualization of LUCI data.

The discussion was followed by a demonstration session where participants used a VR prototype individually with the researcher facilitating. A System Usability Scale (SUS) test [41] was administered after the participants completed the VR session.

After completing the focus group, screen shots from the demonstration prototype as well as concepts for further software development were discussed with the participants and four participants received a demonstration of the working prototype visualization system. The participants took turns with the demonstration one person at a time. The demonstration was screen recorded. Participants were instructed on how to use the VR system. Three oculus quests with a marine VR app and a Kauri dieback educational app were provided for their use while participants were waiting for a turn with the Immersive ESS Visualizer prototype system. Audio recordings were coded in NVivo for analysis and gift vouchers were provided ($20).

3.4 Questionnaires

Questionnaires contain written questions for a participant to complete, they can be presented digitally or on paper. Questionnaires allow a large number of participants to take part in a study as the distribution of the questionnaire is not costly, however, more participants take more time to process the results [25].

As recommended by Cairns et al. the pre-study questionnaire asked questions about how software and tools were used by participants [25]. In this research, questionnaires were chosen as a method for gathering information about the participant's background during the MRS focus group and for the final evaluation of the Immersive VR Visualization system. Questionnaires collected information about participant expertise with datasets, ecosystem services models, map reading, occupation and demographic information, software tools, and the use of VR (Appendix D).

3.5 Prototyping

When designing prototypes feedback from actual users is important so that the design has input from domain experts. Programmers and designers can misunderstand the tasks that the actual users are doing, so incorporating feedback about designs from actual users can ensure that the system better fits with what users require [125]. Paper prototyping is a method for integrating user experience into the development process by showing prototype designs of a system on paper [36] before programming them. When showing the designs to users, the users can be asked to step through what they would expect the design to do [36, 125], while another person takes the place of the computer. Paper mock-ups allow design problems to be discovered and fixed before programming starts. This reduces the usability issues in the completed design by ensuring that these usability issues are fixed earlier in the process. Fixing a paper mock-up is easier and less time consuming than fixing program code [125]. When drawing sketches of a design, higher fidelity mock-ups can give a misleading impression of which features are actually in the design and users can focus on details that the designer did not intend [91]. The level of fidelity for a mock up should match what the design is intended to communicate to users. Since this project was about visualizing data, the fidelity of the mock-up affects what data a user could read from each screen. When producing low fidelity prototypes, the designs ensured that data which the user would be expected to read in a finished visualization was on the prototypes. This was achieved by mocking up some designs with paper, and others with computer generated imagery which showed sample data. It was necessary for this project to show data that the users could read from each prototype visualization so that users could provide feedback if the level of detail was unsuitable or if the data being analysed was not suitable for the intended application of the tool.

In summary, this chapter described the research methods of the requirements gathering, interviews, focus groups, questionnaires and prototyping. Results of the requirements gathering are presented in chapter 4. The method for the final evaluation is presented in chapter 6.

Chapter 4

Requirements

Contents

This chapter presents the results from qualitative interviews and focus groups with users of the LUCI tool. These interviews and focus groups informed the requirements and design of an immersive visualization system, Immersive ESS Visualizer, and were conducted using earlier described methods (§ 3.1). The methods for implementing and evaluating a novel immersive geospatial analysis system are discussed. Section 4.1 describes the results of interviewing users of LUCI. Section 4.2 describes how interview participants with different background expertise used LUCI. Section 4.3 describes personas developed based on the result of interviews and focus groups. § 4.4 describes the results of a focus group with a subset of the participants from the interviews.

4.1 Interview Results

In this section, we present the results of the interviews. Firstly the background of the participants is presented, then reasons to use LUCI are described, followed by the interactions among users of LUCI and the software, issues that the participants identified with their use of LUCI, and any suggested potential features for the visualization system.

Participants were a convenience sample recruited through pre-existing contacts provided by my supervisor and by the LUCI group at Victoria University of Wellington. Table 4.1 shows the role, organizations, tasks, GIS experience, and LUCI experience of LUCI users who were interviewed. The role categorizes these users into developers, analysts, and students. Participants were numbered to preserve anonymity with their role as the prefix of their number, D was used for a developer, A for an analyst and S for a student. The developers have contributed code into the LUCI toolbox for ArcGIS. Analysts may have written scripts during their analysis with LUCI, however, they have not contributed code into the LUCI toolbox. The students interviewed used the LUCI toolbox during their studies. Students S3 and S4, were studying for PhD. D3 also identified as a student, they contributed to LUCI by developing a plugin and had more previous experience with GIS than the other students interviewed. Two businesses and three universities outside VUW were represented in the sample. The GIS experience of study participants ranged from 1.5 months to 15 years and LUCI experience ranged from 1.5 months to 12 years.

Experience can affect how software programs are used. Additionally, LUCI users in different roles could have different reasons for choosing LUCI and different tasks for their analysis which could affect their perceptions of their use. This section discusses the experience of LUCI users to contextualise their responses to their process of applying LUCI, and tasks for which they would use LUCI.

D1, D2, D3 and D4 were LUCI developers (Table 4.1). D3 used LUCI during PhD research however, this research also involved contributing developments to the LUCI ArcGIS toolbox. Developer D3 had eight years of experience with GIS prior to starting the project with LUCI, so was already a GIS expert. D4 developed visualization functionality for the LUCI toolbox as a research project, the project involved developing water wheel and spider diagram visualization functionality for LUCI. D4 used ArcPy to develop visualizations. S4 was also using LUCI for a research project at PhD level, however S4 had less prior experience with GIS and had previously worked in Architecture. Participant S2 was studying at PhD level and started using LUCI during that research.

Table 4.1: Participant backgrounds containing the participant id (PID), the participant's role in using LUCI, their organization, the type of tasks performed and the years of GIS experience. The prefix D, denotes the participant was a developer, The prefix A denotes the participant was an Analyst, the prefix S denotes the participant was a Student.

PID	**Role**	**Organizations**	**Tasks**	**GIS exp.**
D1	Developer	VUW	Coding, algorithm development	15 years
D2	Developer, Analyst	VUW	Report writing, analysis of data, coding components	6 years
A1	Analyst	VUW	Coordinating field work, interviewing people, social research, run LUCI, analysis of data, report writing	N/A
D3	Analyst, Student, Developer	VUW	Development of plugin, analysis of data, use LUCI	10 years
A2	Analyst	Business (B1)	Run LUCI, report writing, analyse mitigations, spreadsheet nutrient budget	12 years
A3	Analyst	Business (B2)	Analyse riparian planting, analyse flooding risk, run LUCI, write reports	Start of Ph.D.
S1	Student	University (Un1)	Analyse LUCI suitability for urban areas, run LUCI	1.5 month
S2	Student	University (Un2)	Use LUCI, Provide feedback on LUCI server, Analyse ecosystem services	4 years
D4	Developer	University VUW	Develop LUCI features	N/A
S3	Student	University (Un3)	Use LUCI, compare data, compare land uses	N/A
S4	Student	University (Un3)	Run LUCI	N/A

A2 and A3 were business users, they were both more experienced than the students S1 and S2 at using LUCI, with between 6 and 7 years of experience. A2 was analysing a farm to compare existing and future scenarios, and A3 was analysing a catchment to compare existing and future scenarios for changes in ecosystem services. S1 and S2 briefly used LUCI for student projects, S1 applied LUCI to an urban area to evaluate its suitability for analysis. S2 analysed two catchment areas used for high-intensity agriculture which experience waterlogging and flooding to investigate areas in the catchment for alternative land use.

The output provided to clients by participant A2 from their farm scale analysis was a written report with a recommendation of what land use changes to apply to reduce nitrogen emissions into rivers. The result of the catchment analysis for participant A3 was a report of how riparian planting affects ecosystem services on that catchment area.

Table 4.2 identifies that analyst A1 had programming skills in addition to their skillset as a geospatial analyst. Analyst A1 wrote python scripts separate to LUCI, features for the LUCI toolbox were written in python by LUCI developers. Visualizations were created in Python and R by analyst A1, these visualizations were customized specifically for a research project.

> *"I primarily used the underlying data. I actually produced my own maps and graphs."* - A1

LUCI's implementation included a Python toolbox for ESRI's ArcGIS and users of the toolbox also performed operations with the ArcGIS GUI. For example, they applied their GIS skills to add polygons or edit features when incorporating changes due to inaccuracies in nationally available data for land cover classification.

Table 4.2: Software used by participants, ✓ identifies the software used.

Participant	Software				
	R	Python	Excel	QGIS	Overseer
D1					
D2			✓	✓	
A1	✓	✓			
D3		✓			
A2			✓		✓
A3			✓		
S1					
S2					
D4		✓			
S3					
S4					

4.1.1 Reasons to choose the LUCI model

The following section discusses the reasons to use LUCI identified by participants. These reasons were categorized into geographical reasons and computational reasons.

Geographical

Comparative analysis Six participants were motivated to use LUCI to analyse the effect of land use changes on ecosystem services.

> *"Comparing the ecosystem services before and after loss of wetlands."*
> - A1

LUCI's high spatial resolution was an important reason for the usage of the tool, for three participants.

> *"I like that it's very spatially explicit, so it handles configuration of elements very well, so [is useful] in hydrological modelling."* - D2

LUCI is suitable for analysis over large landscapes, watersheds to smaller scale sites such as farms [29]. LUCI has previously been used to analyse the flow of nitrogen and phosphorus across the Lake Rotorua catchment and perform a tradeoff analysis with agricultural productivity [163]. Since ecosystem processes occur at particular scales, the resolution of the model affects its suitability for certain analysis problems.

Trade-off mapping was another important reason to use LUCI for four participants.

> *"One strength of LUCI is that they have a trade-off map that is very useful ."* - D3

Trade-off maps allowed comparison of different ecosystem services, and for the effect of a land use change to be evaluated based on the benefits from ecosystem services which were gained or lost.

Developer, D2, claimed that the trade-off mapping tool provided by LUCI had some limitations since the trade-off was shown with a traffic light colour scheme [90] and the interpretation of the trade-off map became difficult when more services were included. When talking about the traffic light colour scheme participant D2 made the following observation on visualizing tradeoffs with a larger number of services:

> *"If you're running just two services against each other, flood versus nutrients, that's quite easy for someone to visualize and see. But when you have five services that are trading off, it gets a bit harder."* - D2

Spatially explicit analysis The ability to analyse connections between locations and the effect of land use in those locations was important, according to one developer.

> *"It's actually got that connectivity and configuration. So you're really exploring not just what happens if you say, plant twenty hectares*

> *of trees, but where you actually put those twenty hectares worth has a big impact."* - D1

Connectivity was an important aspect of LUCI because it showed how small land cover changes affected the landscape in different spatial locations, thus allowing land cover changes to be carefully planned and positioned to maximise gains in particular ecosystem services.

Computational

The computational time for running hydrological models was important, according to one developer.

> *"Very efficient at moving mass, water, sediments and chemicals."* - D1

The size of the area that LUCI can analyse is bounded by computational time [29], so a fast execution time as a result of computational efficiency allows analysis to be performed on larger landscape areas than models which are not as performant. Efficiency is also important from the perspective of usability, as a long wait time can impact the users' perception of the tool and reduce their ability to perform analysis in an acceptable time frame.

Summary

Visual output was important in the analysis process for both trade-off mapping and the comparison of ecosystem services affected by a land use change. The most frequently identified reason for LUCI use was the ability to analyse land-use changes (6/11 responses). Visualizing tradeoffs between ecosystem services, and the high spatial resolution of LUCI was also important. The combination of efficient algorithms, high spatial resolution and the ability to analyse tradeoffs across multiple ecosystem services makes LUCI a suitable tool for decision making at the farm scale and at larger scales.

4.1.2 Applying LUCI

Applying LUCI to a land use application was a complex process which involved collecting data for analysis, processing the data to ensure that it was suitable for input to LUCI, running the LUCI model, then preparing a report based on the LUCI output. Interview participants reported different procedures for collecting data, processing the information according to the needs of their analysis, and delivering the results to the stakeholders. The process for using LUCI required complex interactions between roles and stakeholders which differed according to the context of the model's application, and the organizations involved. Participants D2, A3 and A1 discussed applying LUCI to catchment scale areas. Participant A2 both applied LUCI to a catchment scale area and to the farm scale. Figure 4.1 shows an example of how LUCI was applied to analyse ecosystem services for a client. There or two feedback loops, the first during the process of adjusting input data and the second collected feedback on the result of the analysis.

When collecting data, participants D2 and A2 reported consultancy with farmers and councils as part of the process of collecting data for a LUCI analysis.

> *" I try to consult with the farmer or the council."* - D2

Analyst A2 reported that consultants would communicate with farmers to calculate a nutrient budget before farmland was analysed using LUCI. Developer D2 reported that farmers were involved in reading maps and checking that data was correct.

Before running a LUCI analysis, D2, A1, and A2 stated that they needed to edit the land cover to model changes in the land use. Developer D2 also reported that due to inaccuracies in data provided for a national scale, editing was often required to correct land use classification. Participants D2 and A1 also reported that a reason for using LUCI was the high spatial

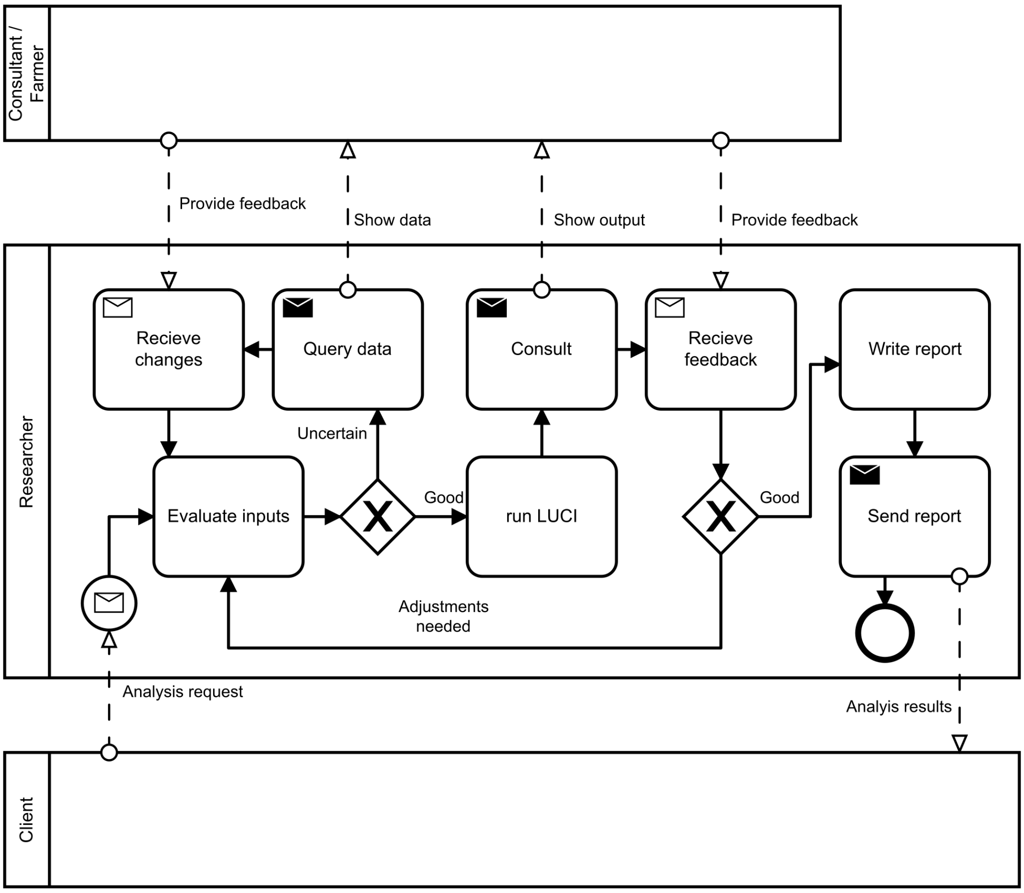


Figure 4.1: An example of the LUCI process discussed by participant D2. Data was gathered before running LUCI and writing reports for the client.

resolution provided by the model, and analyst A2 was applying the model to a farm-scale area, so the application required detailed data.

Analyst A3 reported that some input data describing the boundaries of riparian planting needed to be manipulated to align with a stream network and a DEM, because the input data was usually lined up with aerial photography which did not have the same projection. Participants D2 and A1 mentioned that they would use additional data about the area which was not inputted into the LUCI toolbox. Developer D2 used plans provided by the government for the area, and Analyst A1 used historical wetland maps. The process of editing data for input into LUCI demonstrates that setting up a LUCI project requires expert judgement.

Farmers were mentioned as recipients of the analysis by participants D1, D2, A1 and A2. Councils were mentioned as recipients of the analysis by participants D1, D2, and A3. Analyst A2 did not present the report output from LUCI to the farmers due to concerns about farmers' ability to correctly interpret the layers.

4.2 LUCI use

Examples of LUCI use discussed by developers, analysts, and students shared some end objectives. These included reporting on the state of ecosystem services before and after a known change has occurred, recommending a change to maximise or minimise ecosystem services and predicting the effect of a specific change on ecosystem services. Users all compared the quality of different data and evaluated the LUCI model for a given scenario.

4.2.1 Developers use of LUCI

Developers for LUCI were also end users of the LUCI model. The developers were involved in projects analysing how ecosystem services change with land use change.

> *"Look to see how the categories have changed."* - D2

LUCI developers also developed new plugins and features for the LUCI model and toolbox. The developers' personal experience in analysing their data informed design decisions which enhanced the tool. For example, one developer implemented a plugin for parametrizing LUCI models for a particular location to assist in their analysis of ecosystem services. Developer, D4, did not perform analysis as a part of their work on LUCI, and they instead interfaced with other developers with analysis experience while implementing visualization features for LUCI.

4.2.2 Analysts use of LUCI

Analysts using LUCI inspected how ecosystem services changed before and after land use change. The result of the analysis could either be a recommendation for changing land use or an analysis of the services altered. One analyst investigated how ecosystem services changed on farmland before and after mitigations were applied for nitrogen and phosphorus runoff.

> *"We would initially try to limit it to maybe two or three reasonably simple mitigations."* - A2

> *"What's the impact of just putting this first mitigation on? Maybe he wants to just do that and a couple of years later he wants to add this other thing in. So yeah, we would do that."* - A2

One analyst was investigating historical wetland areas and modelling ecosystem services.

> *"We modelled it for that area and then we also looked at the upstream contributing areas from wetlands."* - A1

One analyst was investigating how riparian planting changed ecosystem services at the catchment scale.

> *"[Client redacted] looking at a catchment in [location redacted] and that project was around whether the riparian planting that had been planted and proposed planting that was going to happen in the near future was going to affect flooding."* - A3

Analysts used LUCI to analyse ecosystem services at farm scale or at catchment scale, and analysed how services change with land use change.

4.2.3 Students use of LUCI

Students reported using LUCI to analyse land use benefiting catchment areas, estimating change to ecosystem services when changing farm management, and comparing land uses for different ecosystem services assessments. One student, S1, was evaluating the LUCI model for suburban areas. Another student, S2, was finding the land uses which benefit two catchments.

> *"Looking at two catchments that were used for predominantly high intensity agriculture."* - S2

> *"Best case scenario in terms of multiple ecosystem services, what land uses could I use to benefit?"* - S2

Students S3 and S4 were both comparing different land uses for their effect on ecosystem services.

> *"Estimate possible change to ecosystem services based on different grazing management, which I define by stock density and occupation period and occupation time in paddocks from these stations."* - S4

> *"There are several scenarios involved, and then it's it's just measurements of current status and then comparing the different land uses just to see what has a different ecosystem services assessment."* -S3

Students evaluated the models accuracy and compared land use with the effects of ecosystem services.

4.2.4 Problems encountered with LUCI

When applying LUCI to an ecosystem services analysis, participants encountered some issues which made their analysis more challenging. This section categorizes problems that were reported by participants.

Visualizing Data

Analysis of ecosystem services was a well-used software feature referenced by 6 out of 8 participants. Of the two participants who did not, one only developed features for LUCI, and the other evaluated the accuracy of LUCI rather than analysing the ecosystem services.

When visualizing ecosystem services some limitations were identified. One participant identified that the numerical values generated by LUCI were difficult to relate to a quantified course of action. Relating the LUCI results to a quantified action was challenging and required expert knowledge about the domain because uncertainty was introduced by the soil layer and resolution of the DEM [158].

> *"It took me a long time to figure out how to incorporate temporal change in that output. Because it didn't give me an actual amount of crops that could be created, there was no number. "* - A1

Another participant identified that ecosystem services outputs did not display the numerical result of the ecosystem service model and showed flood mitigation classifications on an ordinal scale instead.

> *"I think flood mitigation only gives you the area with the colour of traffic light, but actually, we want to bring inside the physical value."* - D3

Visualizing the values would assist with an analysis of the flood mitigation. Improving the visualization of the numerical data relating to LUCI outputs could improve the analysis of ecosystem services with LUCI by making the results easier to interpret. Since the LUCI input data has uncertainty, allowing the user to visually appraise the quality of the data by showing more information about the origins of the data, collection methods and accuracy, would allow users to more correctly interpret the results. Participant S2 identified that on low lying land, small changes in the height of the DEM caused speckled results for the nitrogen and phosphorous loading which were difficult to interpret, and these speckled results were passed through onto the tradeoff map.

Presentation of LUCI results

The following responses refer to the way that results are presented by LUCI. These responses are discussed with suggestions which could improve the presentation with immersive visualization. LUCI can generate output in the form of PDF files. The output PDF files generated by LUCI were both used during analysis and shown to end users.

In the current release of LUCI, the output is presented in several different PDF files rather than a single document. One participant suggested that separate PDF files were a disadvantage because several files need to be checked when inspecting the statistics. If the results were presented together in a single PDF it would improve the ordering and assist the analysis of the results.

> *"The problem with that is all the statistics get reported in separate PDF files."* - D2

Presenting the results together in a single PDF may help the analyst with their understanding of the PDF data. Participant A2 identified that the PDF outputs had visualizations that were difficult for farmers to interpret.

> *"The farmers found [it] hard to understand what the maps were telling them. Whereas we can tell them the same information using some numbers."* - A2

Developer D1 also indicated that the ordering of how results are presented could cause communication challenges with farmers.

> *"When my students went out and did studies with farmers and others to see their perceptions, they would still just present all of their information."* - D1

Since combining all of the PDF documents into a single PDF file would not necessarily improve the farmers' understanding of aspects of the analysis, supplying one PDF for both analysts and recipients of the analysis may not necessarily be the best solution.

In this research, an immersive system which allows the analyst to selectively present visual information in the correct order to different stakeholders based on the stakeholders' requirements could be developed. A guided immersive experience could fix issues both with the presentation ordering and the suitability of visualizations. Unlike PDFs, stakeholders using VR would be able to select the content they wanted to view, with the VR system ordering the information presented. An analyst could provide an explanation of the content as the stakeholder uses the system. Usability testing could determine if this approach improved the stakeholder's understanding of the results.

The responses to the traffic light colour scheme were mixed, with participant A3 liking the traffic light, and participants A2, A1, and D2 suggesting that different colour schemes could be applied.

> *I've always tried to go with purples or pinks because they're not quite so contentious they don't feel vilified.* - A1

4.2.5 Suggested Features

Features for adding visualization functionality to LUCI were suggested by participants and then discussed with the researcher during interviews. This section categorizes the suggested functionality and relates the suggestions to problems identified with LUCI and new possible applications of the LUCI toolbox.

Numerical visualization for ecosystem services and rivers

Two participants requested more numerical visualization for both rivers and ecosystem services. When analysing data some analysts look too much at the categories rather than the numerical outputs. Making the numerical outputs of the stream nutrient concentrations visually available could encourage analysts to look more deeply into the data.

> *"They don't dive into the numbers forecasted with the streams, so I think putting that out automatically would be really useful."* - D2

> *"I would prefer it to have to have numerical outputs for all of the ecosystem services."* - A1

Visualizing numerical information could allow users to better understand the data being visualized.

Spatial and Temporal visualization

Temporal visualization features could improve the analysis of data over different time periods. Two participants suggested features that could improve the visualization of temporal data. Visualizing how the magnitude of a land cover change affects the magnitude of an ecosystem service could improve the communication of results to other users.

> *"Anything that helps you understand the change, and how the magnitude of land cover change affects the magnitude of the ecosystem service change."* - A1

One participant suggested adding graphs to show how scenarios differ over different time periods. Graphs could assist a visual comparison of the land cover changes by providing more detailed numerical information.

> *" Some better displays of temporal changes in LUCI."* - A1

Two participants suggested that watersheds, sub-watersheds, blocks and the shape of the study area would be suitable area sizes when choosing a location inside the study area for the comparison of different scenarios over time. Blocks could be Māori land blocks [13], or legally recorded land boundaries [8].

> *" Blocks could be good, but I'm also wondering if it would be too complicated. You could potentially do whole watersheds, sub-watersheds would be another potentially useful way."* - A1

It is necessary to analyse ecosystem services over suitable area boundaries and model resolution for the particular processes which are being investigated [76]. Visualizing analysis within study area boundaries and over different time periods could assist with understanding ecosystem services data.

Scientific temporal visualization

The following possible features relate to the choice of data and natural phenomena for visualization.

Developer D1 suggested that showing algal blooms on rivers to indicate the water quality would be a useful feature. This feature would assist with showing the effect of land use changes categorically without visualizing the underlying numerical values.

The RE:PEAT system for interactively simulating ecological models for a Dutch peatland used thresholds to categorize water quality demonstrating the effect of environmental management decisions on a stream, however, it was not stated how the water quality was visualized [165]. Categorizing simulation data using thresholds could augment visualizing the effects of the water quality.

> *"Maybe you can see algal blooms as the water quality increases or decreases."* - D1

Similarly visualizing more numerical information about rivers could communicate changes in nitrogen and phosphorus in rivers with the magnitude of an ecosystem services change. However, numerically accurate data visualization over the river may not necessarily communicate the visual look of the river to the same extent as a visually realistic indicator of algal bloom. So both numerical indicators of the magnitude of ecosystem services changes and also visual indicators on a map could help to address both aspects. Six participants were comparing land use before and after a change, so an improved river visualization would help users to recognize changes in their land after river events.

> *"I'd love to be able to see new scenarios being rendered so people can be in there looking at how the landscape changes when the river changes."* - D1

Showing visualizations as a realistic rendering could assist users in understanding the effects of land use change, however, it would also require additional simulations and modelling to accurately render these effects based on land use change. Due to the additional simulation requirements, accurate rendering for the effect of land use change was out of scope for this research project.

Interactivity and design

The following features relate to the feedback on user interactions and design for visualization. One developer suggested movement over the landscape through flying and walking would assist with visualizing ecosystem services.

> *"I think it would be useful to be able to plant yourself in a landscape and be able to walk around but also fly over it."* - D1

One developer suggested directing the users' attention to parts of a visualization where changes were most significant between different scenarios. Focusing on parts of the visualization with significant changes would assist with walking the user through the findings in a way that assists with their understanding.

> *"Automatically focus in on the bits of the graph with the differences are most significant."* - D1

One developer, D2, suggested providing different colour schemes.

> *"I guess different colour schemes would be nice."* - D2

Automatically generating graphs could give the user an overview of the data.

> *"Having the graphs made automatically would be great."* - D2

Creating an interface which orders the analysis of LUCI data would improve the way that the results are presented and avoid the confusion of data being presented in the wrong order. The comparison to a hierarchical interface, suggested that an overview first then a method for filtering and finding details could assist with ordering the information consistent with the information-seeking Mantra suggested by Shneiderman [150].

> *"Almost a hierarchical thing where the first stuff came up and then if people wanted they then click up and you click on."*- D1

Allowing the user to navigate by flying or walking would assist with making the visualization feel like a virtual environment as well as a data visualization, Automatically focusing on the LUCI results which were most significant would require a way of ranking the importance, however, further research would be needed on how to do this, so ranking was out of scope for this project. Providing different colour schemes would be a possibility through an interface for customization. Automatically generating visualizations would provide an overview, but visualizations should also be interactive to facilitate filtering.

4.2.6 Summary

Frequent uses of LUCI included the analysis of tradeoffs between different ecosystem services at a given site, and the comparison of possible land use changes to mitigate negative effects of the current land use such as sediment, erosion, nitrogen, and phosphorus runoff. Users of LUCI often needed to make changes to data supplied for the analysis, and when making these changes, there was a need to communicate with different stakeholders who had an interest in the land use. Farmers, consultants, councils, land owners, catchment management groups, and environmental groups were all identified either as recipients of the final results, or as consulted groups during the analysis. There were differences in the way that organizations required the results of a LUCI analysis to be presented. In contrast to other participants, A2 identified that maps were not suitable for presentation to farmers. However, maps were presented in final reports by other participants. Users of LUCI typically present their results through reports, and the PDF's generated by LUCI are not directly presented as a final result. Due to the inclusion of an ArcGIS toolbox as part of LUCI's implementation, and users application of ArcGIS skills to process data prior to running the model, LUCI requires some experience with GIS to operate.

Problems encountered while visualizing LUCI outputs include temporal changes, inspecting numerical results, and speckling caused by small changes in the elevation of DEM input data.

Table 4.3 details features suggested for Visualization including features to filter and zoom. The spatial and temporal features suggested comparative analysis with multiple maps or layers could assist users in comparing the effect of land cover changes on ecosystem services.

4.3 Personas

For this research project, the User Centred Design process gathered information about the workplace context, the tasks that ecosystem service models were applied to solve, the background knowledge of the users, and the processes that the analysis was integrated into. The depth of qualitative information provided by user centred design processes was important for

Table 4.3: Features suggested in interviews with LUCI users.

Suggested features	
Numerical visualization	Showing numerical outputs
Spatial and temporal	Seeing how land cover change affects ecosystem services, adding graphs,
Scientific temporal visualization	River visualization
Navigation	Movement through flying or walking, Ordering the analysis
Filtering	Filtering for details
Colour scales	Colour schemes,

creating an immersive visualization system which can be integrated into a realistic real-world workflow to answer relevant questions for the user group. Interviews were conducted with 11 participants including developers, analysts, and students using LUCI. The qualitative results from the interviews were used as data for developing personas. Personas were created and updated throughout the research project at different stages of development. Personas were designed to be realistic, rather than created based on a stereotype.

4.3.1 Jane: Geospatial Analyst Persona

Jane is a geospatial analyst working for a university. She is 32 years old and has a Masters degree in Geographic Information Systems (GIS). Jane sees herself as productive at work and looks for new ways to present her analysis to be understood by farmers, or regional councils. She has some experience programming in the python language, but she does not see herself as a programmer. She uses python to automate the analysis of geospatial data.

Scenario 1 Jane analyses the risk of flooding after restoring the wetland in the Wairarapa. She would like an immersive visualization system to analyse the effect of wetland restoration on flow interception.

Scenario 2 Jane analyses ecosystem services tradeoffs for a riparian planting scenario. She would like to analyse the effect of riparian planting on nitrogen load, agricultural productivity, flow interception and erosion.

Goal 1 The riparian planting could have different position and extent. Jane wants to interactively visualize the effect of the planting on ecosystem services, and communicate to farmers how much alternate planting would reduce flow interception at different extents.

Goal 2 The riparian planting could have different effects on nitrogen load, erosion and agricultural production. Jane wants to compare the options and advise farmers on the best size and position for the land application.

Goal 3 The results of Jane's analysis need to be presented to stakeholders, such as local community groups and farmers. Jane would like to present the information about her analysis in an understandable way.

4.3.2 Paul: Local Community Member Persona

Paul lives on a lifestyle block near a stream in the Wairarapa and he has an interest in the flood risk for his property. He is 40 years old and has an interest in tramping, fishing, and the outdoors. Paul has an interest in the environment and lives on a lifestyle block with 3 cows. Paul does not have a background in data analysis. He would be interested in trying VR as a method to better understand the results that he is presented with. However, other than the occasional use of VR demo software he does not have experience with a VR system. Paul is proficient at using a desktop workstation as part of his management job at a local government authority.

Goal 1 Paul would like to evaluate the effect of wetland restoration on the flood risk of a stream.

Goal 2 Paul would like to talk collaboratively in a community setting and engage with the process of choosing restoration options informed by understandable data relating to the analysis.

Goal 3 Paul would like interactively investigate what-if scenarios for river flood management strategies.

A prototype visualization system was developed which showed a raster output from LUCI draped over a DEM of the study area. The study area covered the Mangatarere catchment area. The input data was provided by a LUCI analyst as an ArcGIS layer package and the data was only modified to clip to a boundary extent larger than the area of study. The input data to LUCI consisted of the landcover (LCDB5 polygon shapefile), soil FSL (polygon shapefile), gridded annual rainfall (raster), gridded annual evapotranspiration (raster), a stream network (polygon shapefile) and a 5m DEM (raster). LUCI generated a tradeoff map of agricultural production and nitrogen using the tradeoff tool with equal arithmetic weighting. Unreal engine read data exported by ArcGIS after running the model, and the rasterized image was draped over the DEM. The colour scale indicated the opportunity to improve the ecosystem services compared, where red areas showed that services could be improved and green areas indicate that the services are being provided. The user of the visualization would need to inspect the underlying data of the ecosystem services model to identify which services needed improving and by how much. The software developed for this research project could augment the functionality shown in the map to provide this additional information.

4.4 Focus Group Results

This section presents the results of a focus group with four participants, all expert users of LUCI model. The focus group was conducted according to the focus group method (§ 3.3).

The first part of the focus group collected information about the participants' experiences, or issues gathering data and processing data for analysis with LUCI. Then participants were invited to try a VR prototype which allowed them to glide above a tradeoff map in VR.

4.4.1 Issues Gathering and Processing Data

When gathering the data participants reported issues which included the availability of data or licensing restrictions, aggregation of the dataset, accuracy and consistency. Participants discussed the data quality in regions where they had used LUCI.

LUCI assisted with identifying which areas needed more data before running a model.

> *"I think one of the advantages of models like LUCI is that it can actually sometimes just say [that] here is where you need to go and collect the evidence and collect further data before we can actually have any kind of predictive certainty or bounded uncertainty."* - D1

The issues related to data differed depending on the area being analysed.

> *"I did a PhD in a site in [site redacted] and my issues are similar to [D3] about data quality, where I think back home they usually collect information about land use, and land cover for display purposes, but maybe not necessarily for modelling purposes."*-D2

When running the LUCI model, participant D3 needed to check the data for errors and inconsistencies. Participant D3 found that there was data missing, and they needed to visit areas where they were modelling.

> *"For the [site redacted] data and I think for anywhere where you're removed from the study area. You either actually have to go there and do some of your own ground truthing work, or you have to rely heavily on local contacts and local information."* - D2

When data was input into LUCI, there were automatic checks run on the data for inconsistencies such as overlapping polygons. However, a consistent dataset was not necessarily accurate.

> *"I faced a problem of data quality."* - D3

The categorization of agricultural data was discussed by D3. Aggregation of the dataset into categories could cause issues in processing the information when those categories were not suitable for the analysis which was being performed.

> *"So they might collect data about crops and then just call it agriculture, but the hydraulic properties of a pineapple field might be different from the properties of a cassava field or a rice field, especially because rice has standing water."* - D3

Depending on location, datasets would be incomplete due to a lack of knowledge about what data was being collected, and who to contact in order to get the data.

> *"I know that we have rain gauge data but when I talk to other scientists back home they only know of only a small subset of these rain gauges."* - D2

Some areas were better suited to the LUCI model than others.

> *"I think it's kind of interesting hearing [D3]. You know here are these problems with the data because she applied, or she's been applying and still applying LUCI in an area for which it was not originally developed [site redacted]. So really, really flat really, really wet. So one thing is checking the users, checking the data, and looking for inconsistencies."* - D1

Comparing multiple ecosystem services was identified as particularly difficult due to data concerns which could be due to differences in scales, availability of required data, and the complexity of making comparisons.

> *"I think the biggest problem I had is that we were trying to look at a lot of different things at once. So we're trying to figure out how we can know five ecosystem services, and then each of these ecosystem services has a scale and a quantity associated with it. So it's really difficult to get all of that information into one spot."* - A1

The accuracy of soil data and land cover data was identified as an issue for farm scale analysis. Participant D1 discussed checking the data with a local landowner to fix accuracy issues. Participant D1 identified that communication between stakeholder groups was part of the process of using the LUCI model.

> *"When I go in and show a landowner the soil map and the land cover map and the whatever, they go "Yep, Yep that all looks good". And then when we show LUCI results and it's. Uhm. No, that patch says it's boggy or it's dry, and actually, it's really the other way around. Then we go back to the soil data or the land cover data and realize there's a mistake in it."* - D1

The focus group responses indicated that when gathering and processing data for analysis with LUCI, participants encountered issues relating to error checking, consistency of data from different datasets, aggregation into categories, and incompleteness of information collected.

Visualization could help participants to see unexpected discrepancies in data, make comparisons more easily, and judge the accuracy of the model results. Three problems identified that could benefit from visualization were the detection of errors in the data, visualization of uncertainty, and interactive visualization for a large number of ecosystem services.

> *"Sometimes the model outputs show you areas where the model inputs or the data inputs to the model were wrong."* - D1

Visualizations could allow participants to fly over the landscape and identify errors in the data or in the model, which could assist with analysing uncertainties.

> *"And of course uncertainty. Just being able to visualize uncertainty is really important."* - D1

Interactive visualization of ecosystem services could assist participants in analysing multiple services simultaneously. Participant A1 indicated that having different scales makes analysis complex and that interactivity could assist with understanding.

> *"To have a summary map for example. You know with five items [ecosystem services] each with their own scale, which could be a continuous or discrete scale. That's really complicated. I think the best way to do that would actually be an interactive sort of visualization."*- A1

Solutions identified for visualizing ecosystem services tradeoff data included assisting participants to identify errors in the data or the model, allowing participants to fly over the landscape, visualize uncertainties in the model or data, and interactively visualize ecosystem services data or by providing a map to summarize ecosystem services data.

4.4.2 Prototype Visualization Responses

This section discusses participant suggestions for visualising ecosystem services data. Participants used the visualization system prototype. They also looked at paper prototypes of visualizations and commented on how visualizations could assist with their analysis based on their experiences. The feedback from the visualization prototypes included responses to visualizing map elevation, techniques for comparison between maps, labels and icons, navigation, and legends.

Elevation

Participant A1 suggested that the visualization of the DEM could make artifacts visible which would be useful for detecting errors in the DEM.

However, another participant suggested that the artefacts in the DEM could distract from the information that the participant should be reading.

> *"It's also making me think about the artifacts that might be in the DEM."* - D2

> *"Right, you can see pixels. Oh, you can see the artifacts in the DEM. Wow, so many artifacts."* - D1

> *"The first thing that was just jumping out to me was the artifacts and the digital elevation, which I knew were there, but just become so obvious when you're flying around in that landscape."* - D1

When discussing data quality, participant A1 had fewer data availability issues because the location they were modelling had higher quality information available, however, they did need to process 1m DEM data to a 5m resolution to manage the accuracy of the dataset.

> *"The main reason I would use that 3D rendering is to check my DEM, or to share with community groups."* - A1

One participant suggested that being able to see the faultlines in the elevation is good for the analysis.

> *"It's nice you can kind of like see some of the faulting. "* - D1

The navigation had some positive feedback for ease of use.

> *"It just feels easy to explore, especially, if you wanted to do planting or something."* - D2

Visualizing elevation could assist with understanding the model, and uncertainties in the data or in the model by allowing the user to compare layers in the ecosystem services data to the elevation.

Comparison between Maps

Two participants (D1 and D2) discussed comparisons between maps. Participant D1 suggested a map showing relative or absolute differences to assist with comparison.

> *"We do use scenarios, but then another map we would often then put is also one that shows the differences. So you'd actually have - here are two scenarios and then here would be also another map which actually just shows the relative and or absolute differences."* - D1

Participant D2 suggested that layers could assist with comparison by allowing the user to compare different data layers by turning layers on and off.

> *"I'm more used to the whole stacking thing where I get a bunch of tables and a bunch of layers, and I turned them on and off in GIS. But I can see [with] this one if I could have a look at this and practice with it more."* - D2

Side-by-side comparisons, stacking layers, and difference maps could assist with the comparison of ecosystem services data.

Labels and Icons

Labels were suggested to assist participants in navigating.

> *"I might need some things to help me orient myself like little labels saying like there's Carterton, or there's nitrogen."* -D2

One participant suggested that icons on the map would assist with the interpretation of what was underneath the land cover. The participant suggested that being able to inspect different services by looking around a virtual world would be beneficial rather than toggling between map layers.

> *"I think it'd be quite useful because then I could have a trade-off over here or a service over here, and then a biophysical variable over here like soil or land use, instead of just turning it, clicking it on and off and on and off."* -D2

One participant, D2, suggested representing the type of land use by icons.

> *"Land use represented by simple icons. We have this right [the landscape], and then you have tiny sheep on this area. And then I'm like, OK, that's the farmland. And then I go over to the other side of the mountain and I see erosion is dark red, I look and it's like a bunch of cut down trees and oh that's forestry."* -D2

The use of icons and labels could assist with communicating land use, and navigation.

Navigation

Aerial photography was suggested to assist with navigation across the map.

> *"That would be either a topographic map, yeah, or an aerial photo that would allow you to go OK, 'I know I am now looking at this area west of Carterton', or wherever it might be."* -D1

Aerial photography or a topographic map could help participants to position themselves and understand where they are looking. One participant suggested placing pin markers so that users could zoom into the marker positions could assist with navigation.

> *"Put a little pin there on the computer, put this on and then zoom in straight to that area would be actually really interesting."* - D2

Aerial photography and markers were suggested as methods to assist with navigation. The markers could have a feature to zoom in.

Menus and Legends

The legend confused one participant because it had a separate column for the colour and the label of the layer being coloured.

> *"I know what these columns [are] here, but I think someone who can actually use this wouldn't know that."* - A1

A key would be useful on an additional panel, as well as on the legend table. There were no colours listed on the legend prototype.

> *"I don't know how easy this is but if you could have a floating legend that would be great, on the top right or top left, wherever you end up putting it. Just telling me to remind the user that dark blue is two, or light blue is one like that. "* - D2

> *"So my feedback from them [stakeholders], when we were doing projects for them, was that satellite imagery was useful, but rivers, roads and railways were very useful on base maps."* - D2

When looking at the menu with the variables listed for a map layer, the participant commented that the variables would not be self explanatory to a non-expert.

> *"I think before you show it to someone you might need to cue them on to 'What does this button do?', 'What does that mean?"'* - D2

Participants suggested that clear information about metrics for example counts, was important for showing.

> *"Overall, I would expect more just like information about counts. How much of this landscape is two, for services? How much of this landscape is one, for some services that win."* - D2

Suggestions were made for drawing the immersive legend for areas, and pixel values on the area.

> *"This table where I can go over pixel by pixel, I think that would be more useful to me if I could just zoom into an area and start click pointing my wand or my controller at pixels. Then when I click the pixel it pops up saying: This is what services win, this is what services lose."* - D2

> *"I would want to look at the map, first and then zoom into one area and then get this kind of table."* - D2

4.5 Summary

The focus group with LUCI developers identified issues encountered when gathering and processing data, and features that could benefit analysing data with LUCI (Table 4.4). Features included the ability to fly or move around; visualize elevation and compare it to layers to check for errors; compare between different scenarios using side-by-side comparison, layers, or difference maps; view labels and icons on the map; zoom in to inspect data; counts for pixel values; colours and variable labels on a legend.
Issues gathering and Processing Data

- Data quality, missing data, uncertainty, check data for errors, Categorization of data, the accuracy of soil data, and landcover.
- Comparing multiple ecosystem services.
- Communication with stakeholder groups.
- Summary map are complex, interactive comparison was suggested.

The results of the focus group further informed the personas for Jane (§ 4.3.1) and Paul (§ 4.3.2). The features identified by users of LUCI informed the design and implementation that will be presented in Chapter 5.

Table 4.4: Table of feature suggestions for prototype visualization responses.

Prototype visualization responses	**Feature suggestions**
Elevation	Show artefacts in DEM, see faultlines in elevation,
Comparison between maps	Show relative or absolute differences, layers to turn on and off data layers, stacking layers, side by side comparisons
Labels and icons	Communicating land use and navigation with labels, icons
Navigation and zoom	Aerial photography, topographic map, placing pin markers for areas of interest, zoom to marker positions
Menus and legends	Colour key on a separate panel
Numerical	Counts, show details on demand for pixels

Chapter 5

Immersive ESS Visualizer

In this chapter, an immersive visualization system, Immersive ESS Visualizer, is presented. This system was designed to analyse and visualize ecosystem services. Immersive ESS Visualizer allowed geographic data layers to be compared and visualized across multiple hand-held maps and a landscape-size scenario map. The visualization system design and implementation are discussed in the context of the requirements from focus groups and interviews, as well as the system architecture.

5.1 Design

The following section presents the design of Immersive ESS Visualizer by describing the components and their integration into the system architecture. The integration of a game engine in the system design and the functionality provided by the game engine is described. The rationale for choosing visualization libraries and their use for visualizing maps is presented. A description of data formats chosen as input, the operations performed on data to preprocess, and integration of geoprocessing libraries with the system design are discussed.

5.1.1 Architecture

The system architecture describes the components of the software system. The architecture (Figure 5.1) was developed based on the features and requirements identified through interviews and focus groups (chapter 4), as well as previous immersive visualization systems [83, 140, 147]. The architecture contained visualization and geo-processing libraries, a game engine, plugins to interface the game engine with C++ libraries, visualization components, data storage, and configuration. The visualization system was designed incrementally, revising design decisions after interviews with expert analysts and two focus groups, one with expert analysts (Section 4.4), and another with a community group who were end users of LUCI outputs (Section 5.4).

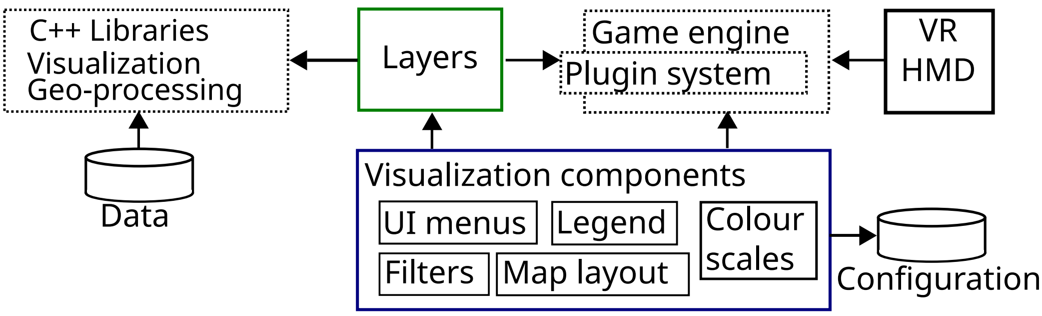


Figure 5.1: Architecture diagram of Immersive ESS Visualizer describing system components

5.1.2 Game Engine

The Unity game engine was used to assist with managing the scene layout, UI components, VR headset, input events, and shader pipeline. The immersive system developed in this project used UI widget components and the input system from the game engine to assist with implementing the user interaction. Unreal engine was previously applied to the visualization of geospatial data in VR [1], however, the Unity engine was chosen due to the availability of plugins from projects already interfacing VTK [35, 140, 83], and the ease of creating new plugins.

Shaders were written in HLSL (High-Level Shader Language) with Unity ShaderLab [17], and Unity Shader Graph to assist with the rendering of the categorical data and apply colour or filter based on the data. A shader was also written to render a smaller handheld map with per-pixel displacement. Unity added data to textures and HLSL shaders overlaid the layers onto either the mesh or the handheld maps based on extents, bounds and data spacing.

5.1.3 Visualization and geoprocessing libraries

Two libraries chosen were VTK (The Visualization Toolkit) [22] and GDAL (Geospatial Data Abstraction Library) [141]. VTK was chosen as a visualization library due to the use of VTK in other geospatial visualization projects [35, 83] and the support for geographical file formats and layers. VTK supported GeoTIFF format and other geospatial formats. The Mapbox plugin [10] was considered for visualizing maps, but this plugin required maps to be pre-processed and stored online. An advantage of using VTK over Mapbox was that VTK reads files without requiring a proprietary online service. Terrain meshes were generated with VTK, and parsed by Unity with a glTF (GL Transmission Format) [3] parser. Unity's native plugin interface was used to interface VTK and GDAL via a library written in C++ as part of this project. VTK and GDAL were both used to read in layers. The extent, bounds and data spacing were also parsed using GDAL. These layers were aligned onto the DEM using HLSL shaders to overlay based on extents, bounds and data spacing. HLSL shaders applied colour scales to data, filtered the layers based on data, and applied directional lighting to the terrain based on a Lambertian reflectance model (hillshade).

5.1.4 Data processing

LUCI's implementation included a toolbox which runs inside ArcGIS and models ecosystem services. LUCI generated raster data layers with the model output assigned to a specific coordinate system. LUCI also generated PDF files as a report. The raster layers were in ESRI ArcInfo Grid (binary) format [2]. These layers were converted to GeoTIFF format using a script. GeoTIFF format was chosen due to library support, and the ability to store large files. GeoTIFF also supported the formatting of pixels in both integer and float formats with multiple bands.

Stream data was supplied in Shapefile format with a vector attribute table containing data relating to the streams. In order to visualize streams as SDF, the streams were rasterized to GeoTIFF format with the streams ID (ArcID field) stored as a pixel value, then a Euclidean distance raster was calculated from the rasterized file. An R script using the EBImage library [132] generated a discrete Voronoi diagram [93] from the stream raster to store the ID of the streams.

Unity does not have built in support for ArcInfo files, GeoTIFF files, and ESRI shapefiles. Preprocessing the data manually before integrating it into Unity was considered as an option, however, this would create practical limitations for the datasets that the end users could inspect as pre-processing the data was found to be time-consuming. Aligning layers without game engine support for geo-referencing would be difficult and potentially lead to errors in placement. An advantage of integrating a library with support for geographical file formats is that the file format contains referencing information that can be used for layering. The files were kept in a format readable by QGIS, which allowed data to be inspected outside the Unity game engine when checking layers.

VTK provided functionality which can drape meshes over elevation rasters, and produced file formats which can be loaded by Unity. glTF is a file format which contains 3D mesh models, layers textures and optionally shaders. The glTF format was chosen for transferring meshes from VTK into Unity as it is supported by VTK and GLTF libraries are available for Unity.

Initially, VTK was used to read categorical data GeoTIFF layers, and convert them to R8G8B8A8 [18] format so that they could be rendered as textures. When GeoTIFF layers were read using VTK, the layers were processed to align with the digital elevation model based on the extents, bounds, and data spacing of the image. The RGBA data was stored in Unity Texture objects and rendered onto the mesh of the DEM. However, there were speed optimization issues with pre-rendering the textures with VTK due to the generation of lookup tables, and to reduce the transcoding overhead, the file reading was adjusted so that the GDAL library read data into Float32 Unity textures, which were projected with shaders which also applied the lookup tables. Raster attribute tables were extracted from the LUCI output files using GDAL_translate. These tables were read with an XML reader to build lookup tables for the shaders. Shaders were written in HLSL to filter categorical data, and apply sequential colour scales based on the raster attribute table.

5.1.5 User interface libraries

Libraries were chosen to enable the design of user interactions and assist with visualization. These libraries were SteamVR [16], VRTK [21], and uRaymarching [19]. SteamVR was chosen due to headset compatibility with the HTC Vive VR headset. VRTK was chosen due to its use in other research projects [100, 147], and support for implementing VR interactions with little or no programming through prefab components. SteamVR assisted with interfacing the VR headset with Unity game engine through a plugin. VRTK provided user interactions to assist with grabbing and triggering interface actions such as button presses. The handheld map terrain rendering shader used uRaymarching to raymarch. URaymarching was chosen for compatibility with Unity Engines URP rendering pipeline, and support for programming in HLSL.

5.2 User Interface

The following section discusses the implementation of map visualizations, map layers, user interface controls, map controls, and the user requirements for the interface.

The graphical user interface was based on a 3D immersive map that users could fly over (Figure 5.2). The size of the handheld maps was chosen to keep the width of the map at 1m. The User Interface was designed for use with HTC Vive game controllers. The advantage of the Vive controllers is that hand movement could be used to control objects in the VR world. The interface existed as objects inside the immersive world, and interface components also visualized data.

5.2.1 Map Visualizations

Two methods were used to visualize map data: The scenario map was implemented with a mesh and was positioned underneath the user's feet; handheld maps were smaller and could be repositioned by the user in a space near themselves.

Scenario Map

When the visualization system started, a scenario map showed an overview of the area of interest (Figure 5.3). The map was physically large compared to the user, and gliding close to the map allowed details to be inspected. The map could be draped with thematic maps, aerial photography, streams and roads. The Scenario map was a feature suggested in interviews with LUCI developers (Section 4.2.5). Mesh terrain was imported into the Immersive ESS Visualizer at the resolution of the user's data. In the Mangatarere catchment example, the mesh was generated at

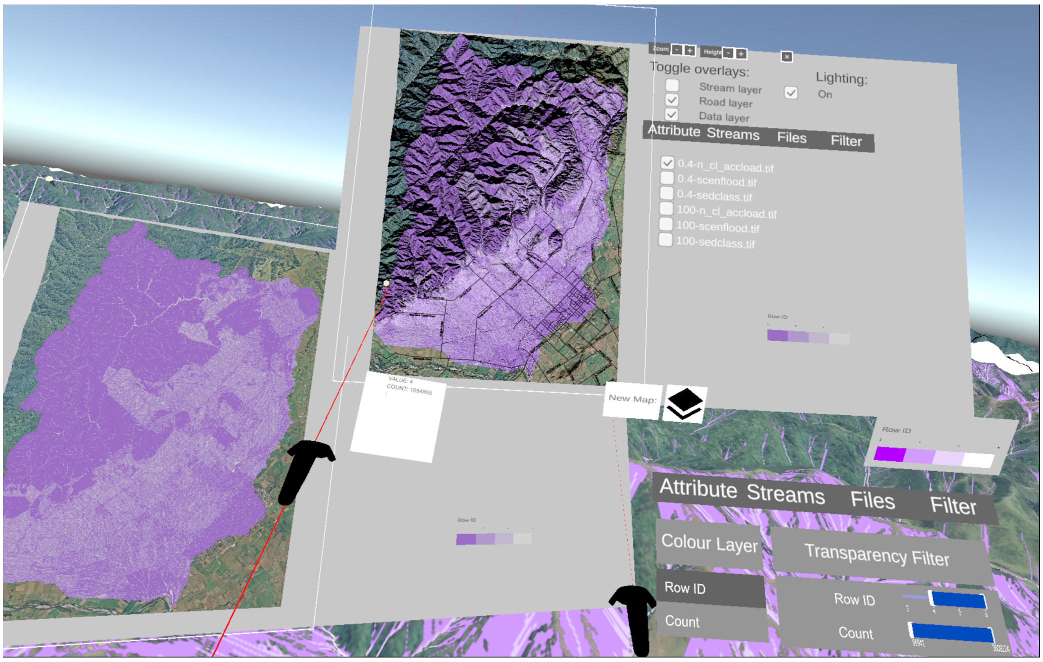


Figure 5.2: Two handheld maps float above the scenario map. A controller on the left points at the font map with a laser and picks the data value from the conical marker position. The front handheld map has a file menu open on the right panel, indicating file 0.4-n_cl_accload.tif is open, and the road layer, data layer, and lighting are toggled on. The right hand controller holds the controls for the scenario map below, with a filter making data on the lower quarter of the scale transparent to show aerial imagery.

the same level of detail as the input data without reducing the detail level. This detail level was chosen because users indicated that small changes to the elevation can affect the output of the ESS trade-off model. When a prototype was demonstrated (Section 4.4), the detail in the elevation allowed users to see faulting detail, and one user suggested that they would use this feature to look for problems in the DEM or present to groups (Section 4.4.2). A limitation of importing mesh maps at this resolution was that rending a large number of mesh polygons required high-performance graphics and had a high memory consumption. Though due to the size of the areas being investigated for this study additional optimizations did not need to be performed on the terrain to reduce the number of polygons. An alternative investigated was the Unity terrain tool. However, due to the requirement of using Unity terrain materials rather than custom materials (in Unity 2019.4), the terrain tool was not used. Additionally, the transition between detail levels caused visible imperfections when the terrain tool was tested.

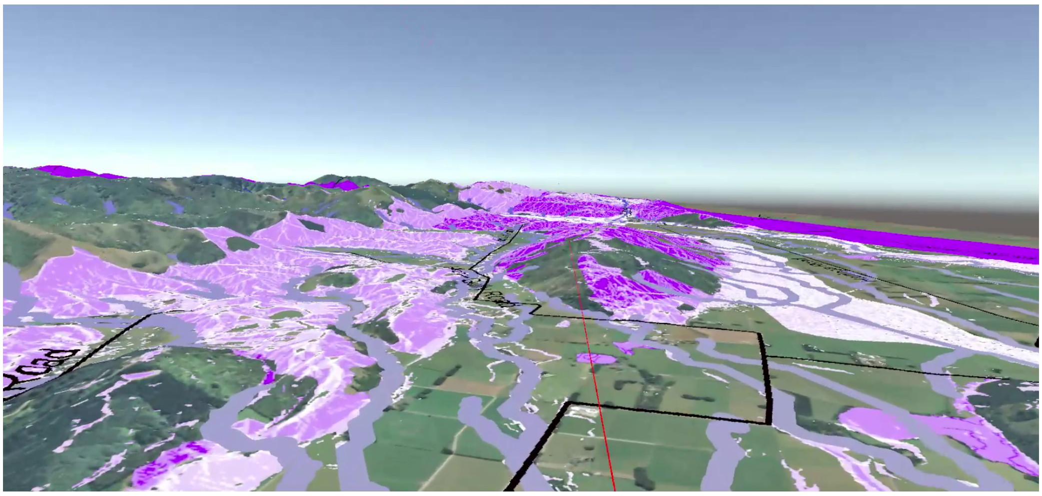


Figure 5.3: Scenario map in Immersive ESS Visualizer with a filtered data layer, roads and streams visible.

Handheld Maps

Multiple handheld maps (Figure 5.4) could generated by selecting an icon on the UI. As with the larger map, the handheld maps allowed the user to drape layers. Users could drape roads, and stream data onto the handheld maps, as well as place points of interest with the marker tool. The handheld map had Zoom and Height buttons (Figure 5.5). Zoom changed the scale of the map, and Height exaggerated the map elevation. The lighting option turned on the hillshade. LUCI developers indicated that comparing scenarios was part of the process of analysing data (Section 4.1). Immersive ESS Visualizer was designed to have multiple handheld maps to assist with their data comparison of scenarios.

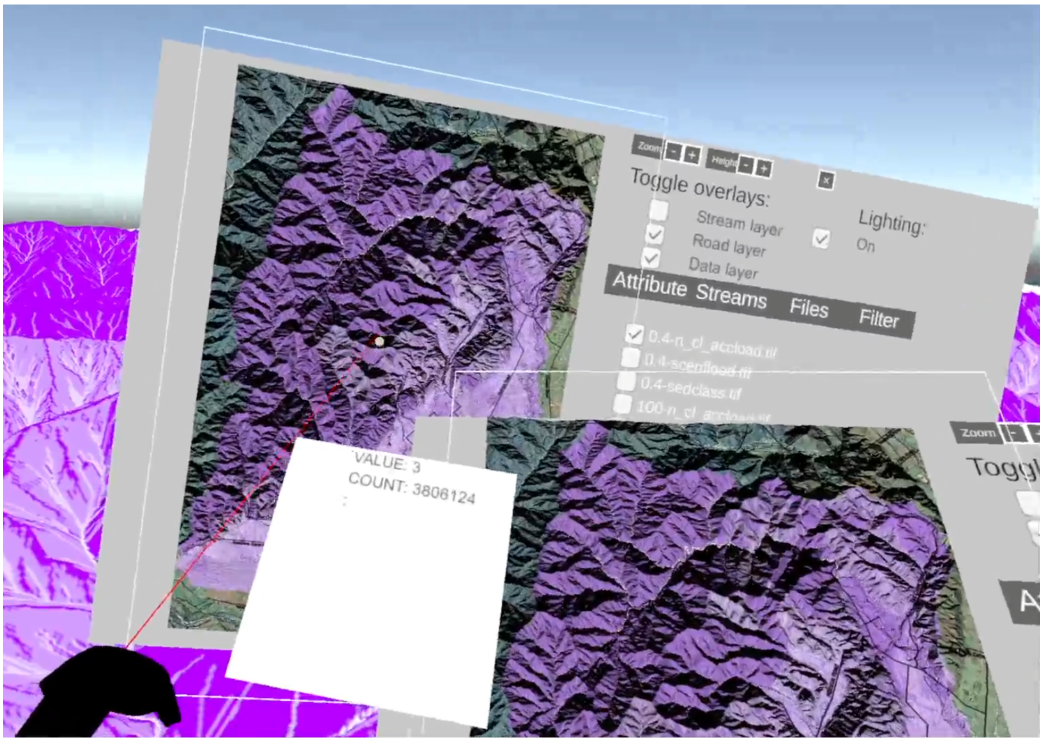


Figure 5.4: Multiple handheld maps with layer overlay, and lighting in Immersive ESS Visualizer.

5.2.2 Layers

Data could be overlaid onto the map in layers with opacity. Thematic data layers could be placed on top of an aerial imagery layer. Thematic maps could be filtered with range selectors. The stream data was also a thematic layer, and a threshold based on the Euclidean distance was applied to select the stream width. Layers containing different combinations of tradeoffs could be selected. Tradeoff maps contained several attributes and individual attributes could be shown for each layer through a linear UI menu. Each attribute had a legend held by the user.

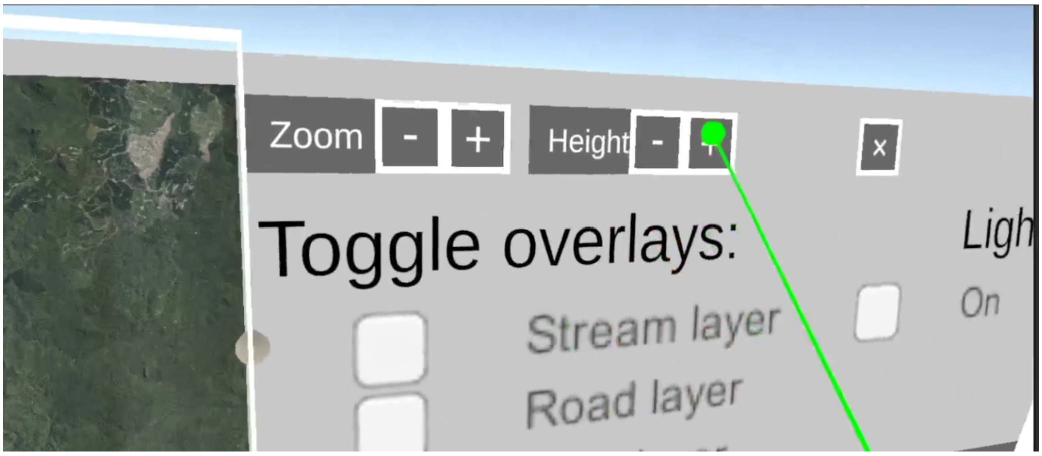


Figure 5.5: Height selection, zoom, overlays (stream layer, road layer, data layer), lighting on a panel attached to a Handheld Map in Immersive ESS Visualizer.

5.2.3 User Interface Controls

The tab panel, layer filter and attribute list are interface controls for layering and filtering data onto maps. The legend showed colour scales describing data displayed on the map.

Tab panel

The options across the tab panel are attribute, streams, files, and filter. Pointing at a tab with the right-hand controller, and pressing the trigger selected the tab (Figure 5.6).

Layer Filter

The Layer Filter visualization presents information from the Raster Attribute table of the layer that is selected. The Layer Filter is interactive and can filter layers draped over either the handheld maps or the mesh. Users can select a range of data with a selector (Figure 5.6) and make other data transparent that was not within the range of the selection for each attribute. Multiple ranges can be chosen to drill down through the dataset.

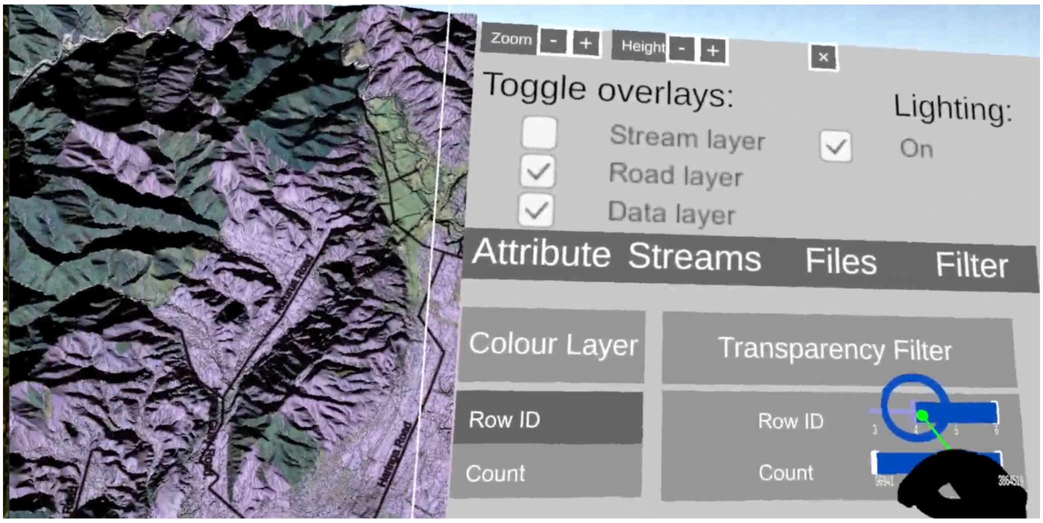


Figure 5.6: Tab panel and Layer Filter for selecting attributes, the right controller points to the Row ID scale selecting it and showing a blue circle.

Attribute list

The attribute list provided a linear menu listing layers similar to the layer filter, However, the filters were not shown providing a simplified view of the attributes available. One attribute could be selected at once, and interacting with the linear menu by pointing could change the layer selected.

Legend

The legend (Figure 5.7) showed the name of the attribute which was used to colour the map, or streams. The legend shows a colour scale with numbers chosen based on the number of values stored for the attribute. The range of the legend was set to colour between the maximum value, and the minimum value for the attribute.

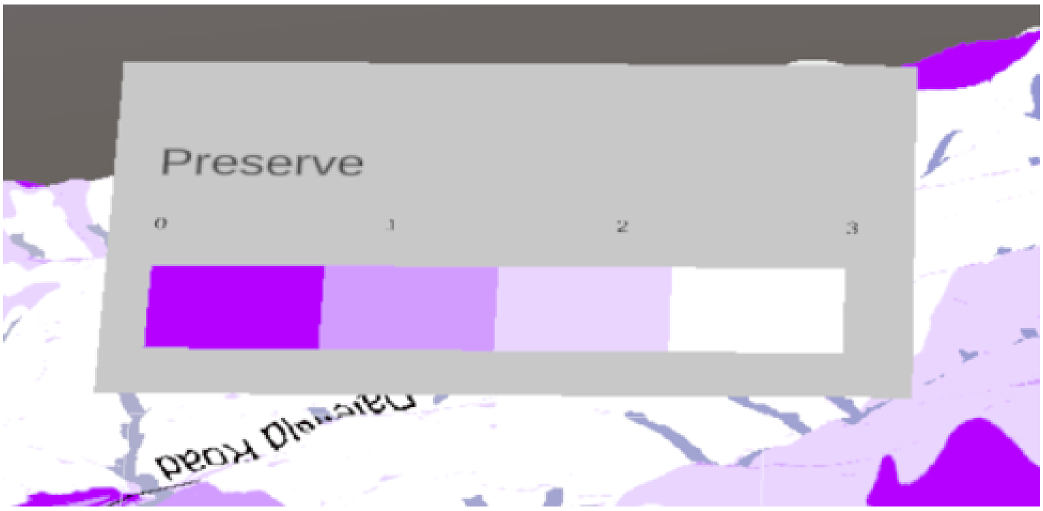


Figure 5.7: Legend showing a colour scale.

5.2.4 Map Controls

Map marker

A marker was shown when the user pointed the laser at the map (Figure 5.8). The marker was placed on the map, and it appeared across all handheld maps. The user could then select the marker to show the variables under that position. The marker allowed users to inspect exact values for every attribute on the layer. The map markers could also assist communication with a facilitator in a guided VR session, as the markers were also visible on the 2D monitor showing where the user is looking.

Distance grab

The distance grab feature brought the map closer to the user. The user pressed the grip button to show a blue marker and pointed the laser pointer at the marker then pressed the trigger(Figure 5.9).

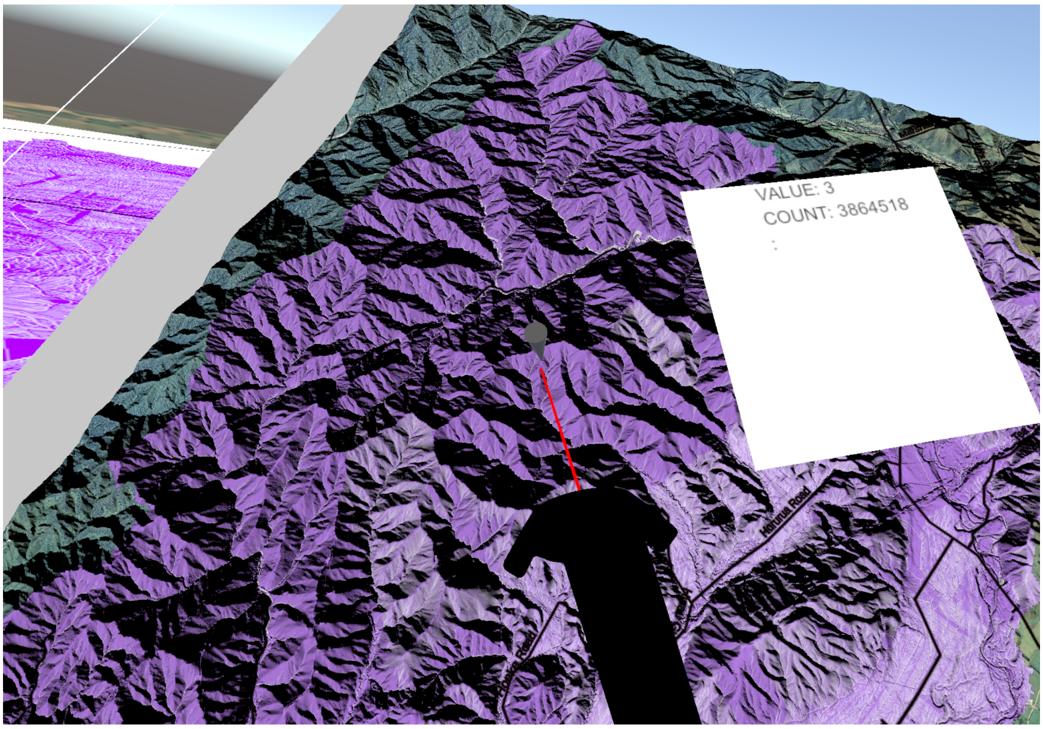


Figure 5.8: A map marker displayed on the map

5.3 Case studies

The visualization system was evaluated with two real-world case studies. The case studies were applied to develop walkthroughs to illustrate the application of the visualization system.

To demonstrate that Immersive ESS Visualizer was sufficiently general, two sites were chosen for the example tasks. The Mangatarere catchment area and Piako. The Mangatarere catchment was chosen due to the availability of both model data, and a report [34]. These resources were used to ensure that the tasks were representative of those a user may want to perform with the Immersive ESS Visualizer. The Piako site was chosen due to the availability of model data. The Piako site scenario was developed as a tutorial so that participants could learn how to use the functions of Immersive ESS Visualizer without looking at the data they analysed in

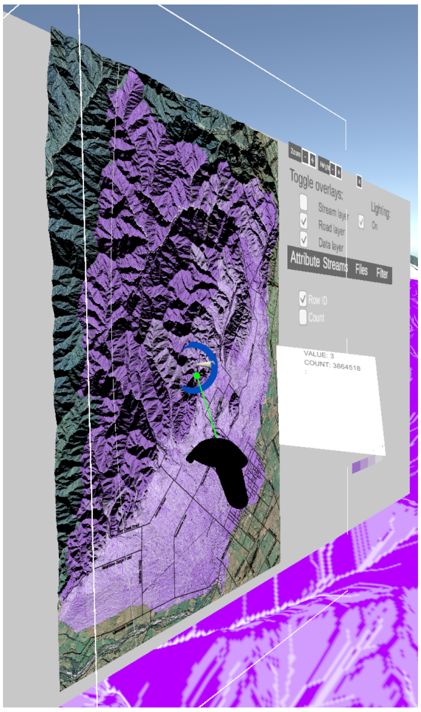


Figure 5.9: Grip button for pulling maps towards the viewer

the evaluation. Tutorial tasks were designed to guide the user through the features of the Immersive ESS Visualizer rather than provide realistic tasks.

The Mangatarere catchment area, Wairarapa, New Zealand, was analysed by Nature Braid for flow/flood mitigation to find locations where multiple benefits could be gained from interventions such as wetland restoration, and planting [34]. Data for both the Mangatarere catchment area and Piako was provided by Nature Braid.

The following features from the LUCI model were used in the analysis of the scenarios: Agricultural productivity, carbon, erosion, flow mitigation, habitat connectivity, nitrogen and phosphorus, trade-offs [34].

Dataset	Information	Source
DEM	5m raster resampled from 1m Lidar	LINZ
Land Cover	LCDBv5	Landcare Research
	Whaitua land use amendments	GWRC Nature Braid
Soil	FSL	Landcare Research
Rivers and streams	REC v2	NIWA ; Snelder et.al.

Table 5.1: Data sources as input into the Nature Braid model

5.3.1 LUCI model process for the Mangatarere case study

Nature Braid produced results from ecosystem services analysis which were presented to clients during a meeting session. End users collectively viewed maps on a large screen and also interacted with paper map copies so that they could draw areas of interest. Nature Braid incorporated the following activities to present the ecosystem services model results to clients.

- Showed input data layers, and showed results from running the model baseline (no changes)

- Allowed participants to draw a paper map to indicate areas of interest.

- Showed the scenario land cover shapefile layers, and asked clients for feedback.

- Asked clients to make suggestions relating to the input data for the scenario, for example, changing the width of riparian planting next to a road.

- The most interesting results were presented first, e.g. scenarios with the largest changes, or scenarios the clients would be most interested in.
- Gave clients the opportunity to comment on scenarios.
- Asked clients about which scenarios they would like to change.

5.3.2 Immersive ESS Visualizer walkthroughs

To illustrate the features of Immersive ESS Visualizer, the following two walkthroughs are provided with the two personas (Section 4.3.1, 4.3.2).

Inspecting flood mitigation for wetland restoration

Jane would like to compare two different wetland restoration for flood mitigation at a road in the right-hand corner of the map. Jane would like to analyse the effect of restoring the wetland at Tea Creek Road, she is particularly interested in flow mitigation. There are restoration options for 0.4% and 100% restoration to investigate. Her objective with using Immersive ESS Visualizer is to compare the flow mitigation at Tea Creek road between these two options.

When the visualization system starts, Jane is presented with a scenario map (section 5.2.1) showing an overview of the area of interest. Jane inspects the tab menu (section 5.2.3) attached to the left hand controller and reads across the list of options for the file menu. Selecting the files tab shows Jane the list of files available. Jane select the 0.4% restoration scenario flow interception layer from the file list, draping the layer onto the scenario map on top of the aerial imagery. Then, she creates a new handheld map with the new map button on the UI. Jane inspects the panel on the right hand side of the handheld map. The checkbox options on the map allow Jane to toggle roads on and off (Figure 5.6), as well as the stream and data layers. So she decides to toggle on the road layer to assist with her navigation. Using the handheld map as a navigational aid, Jane glides to Tea Creek Road to inspect the flow interception layer in detail. Jane grabs the handheld map by reaching out to touch it and pressing the trigger. Jane can position the map, moving around anywhere within the physical space allocated to the VR. Releasing the trigger places the map. Jane looks at the file tab of the handheld map (Figure 5.2), and drapes the 100% restoration scenario, "100-scenflood.tif", over the aerial imagery on the handheld map. Jane can now compare 0.4% wetland restoration and 100% restoration.

Jane selects the filter tab (Figure 5.6) and applies a filter to the scenario map which makes the flow mitigating land transparent showing the aerial layer underneath. The legend attached to the left-hand controller (Figure 5.7) shows the scale of the data with ordinal numbers showing the value of each colour on the map. Jane pans the handheld map with the laser pointer, and applies the zoom buttons on the handheld map to zoom the map into an area of the road that she is interested in so that she can see data layers in detail and inspect the elevation. Toggling the hillshade could make imperfections easier to see. Jane points with the right hand controller at the map, and places a marker (Figure 5.8) then points at it to read exact values from the map layer. The attribute list is attached to the tab menu and it shows a list of attributes that can be toggled to change the layer selected. Jane selects the attribute list tab and toggles between different attributes to make differences in the data flash on and off. The aerial layer is inspected through the filtered layer to see land cover which would become flood mitigating after a land use change.

Comparing ecosystem services tradeoffs between flood mitigation agricultural productivity

Paul would like to inspect an ecosystem services tradeoff analysis for the Wairarapa to analyse tradeoffs between agricultural productivity and flow mitigation. Paul is presented with a scenario map showing the overview of the area of interest. he is particularly interested in a road that he is familiar with so he glides close to the landscape and uses the file tab on the left hand controller to open a tradeoff map. Paul then decides to make a comparison with the handheld maps, he applies a filter option to inspect agriculturally productive land. Then he switches between inspecting the handheld map and inspecting the landscape.

Paul decides on an area of land where he would like to make a detailed comparison between agricultural productivity and flow mitigation. The cutaway zoom allows the user to create a zoomed-in version of the map on a separate handheld map, so it could help Paul with the comparison of layers at a point of interest. Paul points at an area of the map with the right-hand controller and presses the cutaway zoom button to cut out an additional handheld map. He grabs the new handheld map and places it side by side to perform a comparison. He presses the height exaggeration button (Figure 5.5) to bring out the elevation in the low-lying areas of the map allowing imperfections to be seen in greater detail.

The next section presents the focus group session with the MRS 5.4.

5.4 MRS Focus Group Session

In this section, we present the preliminary results of the focus group with the Mangatarere Restoration Society. The focus group was conducted using the study design presented in Section 3.3. The "Phase A" data was visualized when showing examples to participants in the focus group.

Firstly, the background of the participants is presented (Table 5.2), followed by the reasons to use LUCI. Similarities and differences between the requirements of the focus group participants and the expert users are analysed. The decision making process for users in the MRS is described, and suggested features for visualization that would assist with their use of LUCI.

Suggestions from inspecting their use of the system and a comparison with their SUS test results are presented.

5.4.1 Pre-Study Questionnaire

Participants were involved in activities in as part of their participation with MRS or workplace duties, including planting, education, facilitation of mapping, flood mapping, river management, river modelling. Participant qualifications included industry qualifications, tertiary qualifications at bachelors and masters level, and participants without tertiary education. 5/6 participants had used maps as part of their occupation. 3/6 participants were not living in the catchment area, however, they were visiting either weekly or fortnightly.

Two participants used maps daily, two used maps weekly, and two used maps this year. All participants were using digital maps, and 5/6 participants used paper maps. All participants reported using maps. Maps used include road maps, topographic, flood maps and soil maps. Tasks using maps included finding places, inspecting flooding, discussing flooding with the community, locating property elevations and finding locations (Table 5.3).

One participant reported having good experience using LUCI. Other participants either reported little experience or participation in a presentation where they had seen LUCI map outputs on a projector. Strengths of LUCI identified by participants was that it looked at multiple benefits, and was good for planning, however two participants reported that it was "high level" as a weakness.

Other land management and decision making software used included Overseer, MIKE, TuFlow, HEC-RAS/HMS, and SWAT. Two participants had experience with Oculus Rift, four participants did not have experience with VR, and both participants who had used VR reported that their last usage of VR was over 1 year ago.

Table 5.2: Table of MRS participant backgrounds for the focus group.

PID	Role	Organization	Tasks	GIS exp.
M1	Secretary / Coordinator	MRS	Holds- planting / education	GIS software
M2	flood mapping team	MRS	Facilitate mapping	ArcGIS
M3	project team	MRS	flood mapping	council websites
M4	GWRC officer	MRS	None	ArcPro, ArcGIS, QGIS, Mapinfo
M5	project team	MRS	Planting activities + river management	ArcGIS
M6	GW working group	MRS	River modelling project including catchment	No

Table 5.3: Which features of LUCI participants were most interested in

Feature	**Count**
Flooding	6
Water quality, Wetland restoration, Aquatic habitat	4
Community activities, Erosion, Sedimentaion	3
Recreational activities, biodiversity, cultural significance, terrestrial habitat	2

5.4.2 Focus group results

Focus group participants indicated interest in flood risk management activities and data collection. Group communication concerns were also discussed.

> *"Catchment management planning, and particularly around flood awareness and how we can communicate these flood hazards with the public so that they actually go, yeah, that's not gonna happen here, but, are able to visualize it for themselves." - M2*

Flood risk management activities included engagement with local farmers to collect knowledge about flood height.

Interest in flood risk

Participants M2, M6, M4, M1 and M5 all discussed their involvement in other activities relating to flood risk. These activities included planting, education of groups in the community, and mapping out flood locations. A citizen science exercise involving water monitoring was also discussed.

> *"So we basically planted, that's probably been our main thing." - M1*

> *"We really need to plant where the general public can get access to it." - M5*

Members of the group reported involvement with other groups. Activities with groups outside MRS included creating "living plans" for the Waiohine and Waipoua rivers.

Participant, M1, indicated involvement in nitrogen testing.

> *"We're doing all sorts of different tests nitrogen and all that kinds of stuff." - M1*

Participant M2 reported that their interest in LUCI was to find natural solutions for managing the risk of flooding, and they reported involvement in mapping out flood location in a flood hazard map.

> *"Developing flood hazard maps for Carterton, and then we'll look at what solutions we need to put in place, hopefully, some cool natural ones, which is where the LUCI tool comes in." - M2*

MRS received information about flood frequency in the form of reports prepared by hydrologists.

> *"Hydrologists will take that information and the records that GW hold, right and they'll present some sort of a report that we can have a look at so we can see what the flow frequency is." - M6*

Flood risk management activities included planting, nitrogen testing, citizen science, engagement with the local community and reading reports prepared by hydrologists.

Participant Involvement in Data collection

Participants M5, M4, discussed their involvement in data collection in previous MRS projects. Data was collected through the involvement of GWRC and the local community to inform decision-making around flood risk. The data collection incorporated local knowledge, LIDAR and aerial imagery collected from drones through GWRC, nitrogen testing and hydraulic modelling performed by GWRC with MIKE and TuFlow.

> *"So they we use Mike or TuFlow most of the time for that Yeah." - M4*

One participant, M5, had contacted farmers and asked them to draw on maps to collect local knowledge about flood height.

> *"We had that system where we went around all the farmers and got them to draw on maps where the floods came through on their land, and what years, and we calculated all that and then we went to the planners." - M5*

Participant, M5, indicated that after seeing flood maps local farmers appreciated flood risk more.

> *"When we went around the farmers with maps of the river. And they go, where are we? Yeah, I know, that's your house over there. And they go shit is it? And then when they see all the shading or where the flood could go, but they will say, God that's right round my house." - M5*

The GWRC was involved in collecting LIDAR data and aerial photography from drones.

> *"Every five years we do a volume or capacity analysis on each river, which is looking at sediment transport and movement. We will fly LIDAR down each river for that and also take a point survey every five years." - M4*

> *"We have here someone within our teams here that goes out and does all our LIDAR and drone photography as well." - M4*

> *"There's groundwater bores and ponds which also maybe come from Carterton and Masterton out here, and South Wairarapa Information that they have." - M4*

> *"It's just handwritten stuff. The model we don't actually have. I don't actually have any technical equipment as such." - M5*

> *"Most most of our stuff's like data for me is knowledge from the landowners."*

MRS participants were involved in data collection by contacting farmers to gather local knowledge, as well as nitrogen testing. Participants from MRS had involvement with GWRC collection of LIDAR and aerial photography.

Group Communication

Participants M6, M3, M2, discussed group communication. M6 indicated that data needs to be packaged to make it understandable.

> *"There's a few things that are a problem, but I guess here it is really how do you communicate everything to the community? First we have to understand it all, and then you've got to package it in a way that people can understand it and interpret it." - M6*

M3 discussed the need to show data for making group decisions.

> *"And that's having all those different things that you can show everyone to be able to make that final decision so to speak." - M3*

Participant M2 suggested that setting up VR in a community setting where members of the community could look at it would be useful.

> *"I think it would depend on the community we're talking to. So for some of the rural sort of communities, it might be hard to take this sort of equipment and things with us, so we would probably use them for that. But if we set up a display thing in town and people can come and have a look at it, this would be really useful." - M2*

Participant M2 stated that communication with the public could assist with the community's understanding of flood risk.

> *"And that mimics what I would like from a Council perspective, to be able to communicate with all of the public so they can fully understand. 'Oh my house is going to be under this much water'. When you look at a map, it's quite hard to visualize how deep the water would be at your place." - M2*

Previous media used in LUCI presentations with MRS included a TV screen and paper maps. MRS have both engaged with paper maps by asking farmers to draw flooded areas, and also engaged with analysts to use paper maps as a communication tool during presentations (Section 5.3.1).

> *"LUCI presentations that we've had have been on a TV screen and we've gone through lots of different scenarios of the different areas. LUCI showed us what our catchment area might look like with the various wetlands and so forth." - M3*

Participant M6 suggested that a benefit of using the VR would be the ability to interact with the system.

> *"We take some more refined information to help them understand what's going on, and then when we get to a point that we want to figure out what this project might finally look like, we can show the community that sort of stuff, but we can play with it." - M6*

Group communication was a concern for MRS, as communication needed to be suitable for the audience they communicated with, data was shown for group decisions, so presenting the data so that the group could use it in a group decision could be beneficial.

Interface feedback

This section discusses the feedback about the VR design concepts and demonstration. Suggested data to insert included landmarks, a flood layer, or base layer.

Landmarks

Participants M2, M4, M5 suggested landmarks for inclusion onto the map layer. Landmarks included road names, bridges, hospitals, police station, fire stations, or key landmarks.

> *"Road names and bridges are the major things that we put on maps for our community engagement. So we go and lay a massive map out, get people talk about them. Oh, and hospitals as well, hospitals and fire stations," - M4*

> *"Police station" - M5*

Participant M5 suggested ensuring that the road names were readable on map layers.

> *"So then, on a lot of the early maps, the road names are virtually unreadable. You need a magnifying glass. But now they're on a lot of the new stuff, the road names are really prominent and it's easily done. To track down where you're going." - M5*

Road names, and key features were suggested by participant M2 as suitable landmarks.

> *"Oh, the only other thing is, street names or a couple of key landmarks [so] that people can identify where they are in the system. We find that when we're talking about our flood maps, people want to know where they are in particular, like their house or something. If you've got just either the street names or a few key features, they can use that to orientate themselves." - M2*

Participant M2 has indicated that the presentation of layers for landmarks could be different depending on the audience, so it would be potentially useful to have layers stored outside the visualization system to make the experience customisable.

> *"I think, yeah that's just my perspective, then it would depend on the audience that you want and what you're trying to achieve in terms of sharing these stuff with people. So if we want to use this from an ecological perspective of restoring things, then people might want to see where existing wetlands or other things are. So, yeah, I think as the base layers, these are good and then when we take it to communities or whatever we do with it, that's where it would depend on what other layers you wanted to add to it." - M2*

One participant has indicated that they gravitated towards following the stream and found the experience emotive.

> *"Yeah, I can actually follow the whole river or the whole Mangaterere stream which is our catchment area. Very cool." - M3*

Adding landmarks to a layer could assist users to navigate and understand where they are in relation to the data.
Flood layer

Participant M2 indicated that having the ability to show their flood layers to community groups would be useful.

> *"Ah, from my own perspective having one with the floods like where the flooding goes would be quite useful from our perspective if we want to work with the community to figure out how we can mitigate those hazards. So if we had a flood layer I could sit next to it. And then I can kind of go 'Oh yeah, there's a big flooding piece in here'." - M2*

Since MRS has additional data which they would like to visualize, designing the system so that additional layers can be added could be beneficial.

Visualization responses

Visualization responses discussed the magnifying glass concept, the interactivity of Immersive ESS Visualizer, and additional instructional materials for assisting with the use of the visualization.

Participant M6 suggested that a magnifying glass feature could be useful.

> *"And also flood plain map. The floodplain, it's a reasonably big area. So if you're looking at that on an A3 page for example, or even on your computer screen. If you could have that magnifying glass out and just go and have look out over there, that would be useful." - M6*

The magnifying glass could provide an interactive zoom to assist with navigating a large area.

Instructional materials

One participant suggested improving the instructional materials and legends to help with the controls and interpretation of the data.

> *"And the only other thing would be having like a cheat sheet or something in front of you to start with, around what the different symbols mean. So you know how its FLO for flood. If we were to use it with a wider audience, they might not know what that means, So just some information around that." - M2*

Providing a cheat sheet would assist participants with learning to use the VR app.

Interactivity

Participants M2 and M6 commented on the interactivity of using Immersive ESS Visualizer for visualization. Participants liked having the ability to see changes instantaneously when using Immersive ESS Visualizer and drive the experience themselves to answer their own questions.

So when we hit the LUCI people, we would talk to them and they will change it on the screen and show us and talk to us about it. But here I can fiddle around myself, and look at it. - M6

Participant M6 liked the real-time interaction of applying changes and seeing them on the visualization.

"So if I know what all those things are, I can see what changes just literally instantaneously in real time." - M6

Participant M2 liked zooming with the controllers and identified that zoom was an advantage over paper.

"I think it's a good way for, like if we come to talk to people about things, it's a really good way that they can visualize and see the data, rather than [printed maps]. And particularly because you can zoom in a bit like that, I can then kind of get even further in, whereas when we have them printed, it's often quite hard to see little bits and pieces." - M2

Participant M2 has suggested changing the colour scheme to make the colors less bright.

"Maybe just the colours, the purple, and this might just be my personal preference. From what we've had before is like it's quite hard to sort of see where there's good trade-offs and bad trade-offs. I can just see mainly the bad ones because they're brighter in the face. So I don't know whether there's different colour scales, you can use or how that works?" - M2

Use cases for Immersive ESS Visualizer

Suggestions for potential use cases included the communication of flood risk, and planning mitigations for managing river flooding.

Flood level
Participants M3, M4, and M6 suggested that Immsersive ESS Visualizer could be used for visualizing flood risk and communicating it to the public. Participants M3, and M5 suggested communicating flood risk to farm owners.

> *"To be able to go out to a farm owner, and for them to be able to put on a headset and to be able to visualize the flood, it would be far easier than trying to work it out on the map to me. That would be gold." - M3*

> *"For Waiohine where there is some public land, so the public can access it. Because how do you communicate a flood and the size of a flood and when it might be coming, in a flood warning?" - M6*

Participant M4 suggested that informational graphs would be a useful tool to assist with flooding and communicate the impact visually.

> *"Informational graphs, to have both the horizontal and vertical looking at something that is far easier to see it. To see the graph, to help what you were saying. People say it's 4 meters now, and so you could say, alright let's put the graph up to four meters and then you can see the hydro-graph and then also see where it's flooding. Would be pretty useful to get that." - M4*

- referring to streams visualization.

Scenario planning
Participants M2 and M6 suggested that Immersive ESS Visualizer could assist with planning catchment management scenarios. Participant M6 suggested planning flood mitigations for the river using interactive visualization to explore potential options.

> *"If you're listening to government and other people talking, there's there's a philosophy of 'give the river more room'. There's the hourglass shape, there's slow the river down, hold more water up in the*

> *catchment. So you attenuate the peaks and things like that. So I'm sure those are things that through LUCI and through whatever you can do, that it would be much easier to start to show the effects of what that could be. If you could do some scenario planning and you say, what if we did this?" - M6*

M2 suggested that interactive visualization could help people to find good tradeoffs.

> *"Yeah, from our perspective, I think when we come to look at catchment management planning this would be really convenient. People can look at these maps and work out where the good trade-offs are, and this is a lot more interactive than traditional [methods], just having paper maps in front of you. People can really interact and understand where the stuff is." - M2*

5.4.3 Discussion of the Focus Group

The focus group collected responses about visualization design ideas, the experience of using immersive visualization, potential uses for Immersive ESS Visualizer, the collaborative nature of decision making around catchment management, the groups interest in flood risk and the types of data collection and modelling participants have been involved with. Responses to visualizations included the discussion of features to zoom, instructional materials, interest in flood risk, interactive features to control experience, landmarks, and flood levels (Table 5.4).

Based on the responses from the focus group, the Immersive ESS Visualizer prototype was updated. The visualization changes include merging the handheld maps and the scenario maps into the same scene so that users could visualize data and compare both simultaneously. During the focus group, the potential use cases identified included visualizing flood risk, and scenario planning, so improvements to the handheld maps could

Table 5.4: MRS focus group suggested features

Visualization responses	**Suggestions**
Magnification/Zoom	Magnifier feature, interactive zoom
Instructional materials	Cheat sheet
Interactivity	Fast changes, ability to control the analysis
Flood level	Flood risk communication, informational graphs
Scenario planning	Plan flood mitigations interactively, finding trade-offs
Landmarks	Roads key landmarks

Table 5.5: MRS focus group reported concerns.

Key issues	**Activities**
Interest in flood risk	Planting, mapping out floods nitrogen testing, citizen science
Involvement in data collection	Data collection, LIDAR, aerial imagery, contacted local farmers, sediment transport
Group communication	Communication to the community, communicating with analysts.

make the experience more interactive during scenario planning and make different options comparable with multiple maps.

Due to the interest in stream data, a stream visualization feature was prototyped. Layer visualization for tradeoff maps and ecosystem services was prioritized due to the balance of interest in the interviews, the first focus group, and restoration tasks which involve ecosystem service analysis.

Zooming with the handheld maps was added to allow users to see a zoomed out view of the entire catchment area, or zoom in to inspect details. The addition of the zoom feature allowed users to apply handheld maps like the magnifying glass concept (Section 5.4.2). Features for filtering data on the handheld map interactively were added. Instructional materials were added inside Immersive ESS Visualizer, so that users could refer to slides and panels attached to controllers showing how to use the system. Options to add road layers were added to handheld maps to assist with finding landmarks. Data layers could also be toggled on and off so that users could inspect the aerial imagery while looking at the data. An option to toggle the hillshade on the handheld maps was added. Close buttons and a map generation button were added to the controls so that users could add and remove handheld maps. Handheld maps and the scenario map were merged into the same scenario, so that users can visualize data with both simultaneously.

Features which are in common with the first focus group include, analysing tradeoffs, planning mitigation scenarios, landmarks, interactive exploration of the data, zoom magnification and communication requirements with different groups.

Chapter 6

Evaluation

Contents

A user study was performed in order to evaluate Immersive ESS Visualizer. The first objective of the user study was to test the effectiveness of immersive visualizations for improving the comparison of the impact of land-use change for multiple ecosystem services (RQ1). The second objective of the study was to investigate the effectiveness of immersive visualization for communicating with a stakeholder for ecosystem services analysis (RQ2). The rationale for the study design and data preparation is described in Section 6.1. The process for the task design and the tasks participants perform in the study are then described in Section 6.2. The participant sampling and expertise is described in Section 6.3. The method for the user study is discussed in Section 6.4 with a description of the study procedure. The features tested are listed and discussed in Section 6.4.1.

6.1 Design

The usability study compared participant use of the media conditions, 2D Screen, VR, and paper maps, in each of the three different scenarios, wetland restoration, tradeoff analysis and riparian planting (§ 6.2). The study tasks that users completed was informed by interviews and focus group sessions about how visualization could assist with an ecosystem services analysis with the LUCI model (§ 4.1, 4.4, 5.4.2). These interviews and focus groups identified that comparison of ecosystem services between land use scenarios, and comparison of tradeoff maps were realistic tasks as part of an analysis of ecosystem services. Paper maps and 2D screen were chosen as media for comparison with Immersive ESS Visualizer because paper maps and 2D screens were already commonly used for analyzing LUCI model results. Analysts currently incorporated paper maps into their process for communicating with clients, in addition to providing reports in PDF format. The LUCI toolbox provided functionality to generate output in PDF format. A 2D screen could be used by LUCI users to view PDF output. The study design had both between-subjects and within-subject conditions. Expertise categories for study participants (§ 6.3.1) were between-subjects conditions, and media conditions were within-subjects conditions. The study for users who were not local to the Mangatarere Catchment area was conducted at Victoria University of Wellington, and the study for users local to the Mangatarere Catchment area was conducted at the Carterton Events Centre.

Benavidez et al. [34] described an ecosystem services analysis using LUCI at the Managarere Catchment area. The objective of that analysis was to find locations for flow mitigation which also provided benefits for multiple other services. Soft solutions for flow mitigation such as wetlands and planting were preferred [34]. Benavidez et al. [34] made recommendations about which land use scenarios resulted in environmental improvements. In order to make the user study applicable to the analysis, the user study tasks were designed around inspecting the results of ecosystem services analysis for soft flow mitigation solutions and comparing the effects of the land use change across multiple services. This goal ensured that the study tasks were realistic. Expert analysts identified they used LUCI for comparison of the impact of land use changes (§ 4.1.1). Two mitigation solutions presented by Nature Braid were wetland restoration and riparian planting scenarios. These scenarios were used to create study tasks from data provided by Nature Braid. Nature Braid also provided tradeoff maps for the baseline with no mitigations [34], so tradeoff map comparison was a study task. Basing the usability study tasks on real data from ecosystem services tradeoff analysis ensured that the study tasks were realistic, and the comparison tasks were suitable for answering RQ1.

Experts identified that communicating with stakeholders such as community groups through group presentation sessions and by providing PDF reports to their clients was part of their work process (§ 4.1.2). When using VR with the guidance of an expert analyst, it would be necessary for the analyst to have a conversation with the user inside the headset. The report of the analysis for the Mangatarere Catchment area identified that land use analysts iteratively consulted with the Mangatarere Restoration Society for feedback in group sessions [34]. So a potential use case for Immersive ESS Visualizer would be to assist a land use analyst in communicating potential restoration scenarios to an individual stakeholder during a group session where stakeholders take turns using VR. The communication between the facilitator and the study participant models the communication to stakeholders through a VR presentation as only one participant can be in the VR headset at once. So participant feedback and researcher observation from the communication aspects of completing study tasks in VR was suitable for answering RQ2.

The study aimed to collect qualitative information about the use of the VR system and compare the usability of the VR with maps provided on paper, and analyzing PDF maps on a 2D screen.

6.1.1 Data preparation

This section describes data preparation for the study areas, Tea Creek Road (Figure 5.2) and Piako (Figure 6.1) which were used in the evaluation. The tasks and areas of study were informed by the walkthroughs (§ 5.3.2) developed with the personas (§ 4.3).

Tea Creek Road

The data layers for flow interception classification, nitrogen accumulated load, and sediment delivery were provided by Nature Braid, they were categorical data generated by the LUCI model from input data. The input data consisted of a 5m DEM (Table 5.1), LCDB v5.0, Whaitua land use dataset, manual amendments by Nature Braid, FSL, REC v2, Rainfall and evapotranspiration.

The DEM was provided by Nature Braid [9, 34]. Aerial photography was sourced from LINZ [24], this aerial imagery was downsampled to 2.4m resolution and converted into a GTIFF file. The DEM was preprocessed into a mesh, and aerial photography was draped onto the mesh.

Piako

The 15m input DEM used for visualization was provided by Nature Braid. The DEM was infilled with additional elevation data outside the area of interest to make the DEM rectangular to ensure that the rendering algorithm for the handheld maps did not create edge artefacts around the study area. The NZ 8m Digital Elevation Model (2012) was used to infill missing data as this data was only required for visualization purposes, and participants did not need to analyze the elevation outside the area of interest.

6.2 Study Tasks

The tasks that users could perform with the Immersive ESS Visualizer were planned by inspecting the report by Benavidez et al. [34] and identifying specific scenarios and trade-offs to compare with features from Immersive ESS Visualizer, Since the tasks were designed to realistically describe the analysis that participants may want to perform. The ordering of tasks was not graded according to difficulty level.

This section describes the tasks that users were required to perform for each medium and evidences the rationale with interviews, focus group sessions and background literature. The tasks are presented in detail with a discussion of how task completion was suitable for answering the research questions (RQ1, RQ2). There was one task performed for each scenario, and the task was performed for each medium. The study tasks were piloted to ensure that they could be completed in time and that the tasks were suitable for answering the research questions. Results from the pilot studies informed the design of the study tasks.

Before using VR software, the participants were provided with instructional slides describing how to use the VR tool. Participants were asked to complete a tutorial presented inside the VR headset on a panel attached to the controller. Instructional slides were available inside VR on a panel attached to one of the controllers so that they could be navigated as a reference (§ 6.1a). The use of instructional materials minimised the need for participants to receive assistance during their use of VR in tasks 1-3.

Participants were informed of the risks of cybersickness and that they could stop at any time. Cybersickness can be caused by a number of factors such as optical flow, movement speed, acceleration and the type of content. Movement initiation and speed was controllable by the user, and since cybersickness could be affected by movement speeds [159], users could potentially choose speeds which did not make them feel cybersick. Movement was only in the direction of the HMD avoiding horizontal or vertical panning. Since participants were asked to remove the headset in-between each of the VR tasks, it was possible for the participants to indicate if cybersickness was an issue and withdraw from the study at any time. Participants had the option of standing or sitting, seating space was available if participants needed to sit outside of the VR.

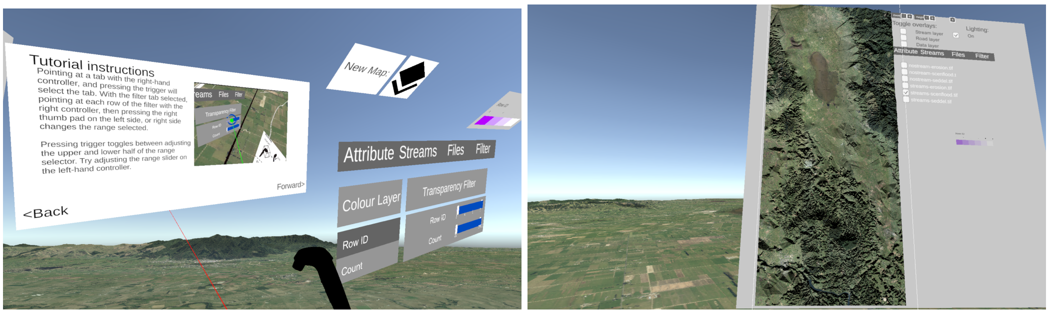
The following tasks were identified:

Tutorial. Analysing streams at Piako.

The tutorial exercises walked participants through using each feature of Immersive ESS Visualizer. The VR software contained a tutorial which the participants were required to complete before they a their knowledge to the scenarios. The tutorial scenario contained the Piako catchment, and the participants experimented with the data in the baseline scenario. The Tasks for the scenarios used for the evaluation of the VR system were designed so that the data in the tutorial was not required for completion.

Task 1. Comparing 0.4% restoration, and 100% wetland restoration scenarios.

Instruction: The provided map layers in the file tab are for two restoration options: 0.4% restoration, and 100% wetland restoration. Use any or all of the features described in the VR tutorial to compare these restoration options at Tea Creek Road.



(a) Tutorial slides in the Piako scenario. (b) A handheld map showing elevation, aerial imagery, and a hillshade at Piako.

Figure 6.1: Two images showing the Piako tutorial.

Areas of wetland restoration showed a prominent change in colour where the wetland was restored. The participants had access to flow interception classification, nitrogen accumulated load, and sediment delivery. Areas that showed change were large enough to see without magnification and appeared block coloured e.g on the Flow interception classification map. The task required two scenarios to be compared, each with several layers which could be filtered and zoomed in with features of the VR system. Though it would be possible to observe changes in the maps without zooming. It was anticipated that users would detect differences in the colour between layers by either switching between files in the file menu or comparing maps side by side with the handheld maps. Since the features of interest were at Tea Creek Road, the road layer could assist participants to find places of interest, and the gliding movement could allow participants to inspect the area on the large scenario map, by moving themselves to the location.

The areas affected by the 0.4% restoration and 100% restoration included both larger areas across the top right corner of the study area, as well as smaller speckle features. The size and shape of these features were different to the riparian planting, so it was hypothesized that some participants would be able to apply different visualization features to inspect.

Though the size and shape of the areas being restored was unique to the task, wetland restoration was a realistic use-case for Immersive ESS Visualizer which could be of interest to other community groups or regional councils.

Task 2. Comparing tradeoff maps for the baseline scenario.

Instruction: The file tab provides two map layers. The first map is a tradeoff between flow mitigation, nitrogen, and phosphorus. The second map is a tradeoff between agricultural productivity, carbon, flow mitigation, habitat, nitrogen, phosphorus, and erosion. Use any or all of the features described in the VR tutorial to compare two of these two tradeoff map layers.

The tradeoff maps had multiple variables on each map, and the VR prototype visualization system had attribute selection, and filtering features which it was anticipated that participants would use to inspect data on these maps. There were two tradeoff maps provided, and they were tradeoffs between multiple attributes, flow mitigation, nitrogen, phosphorus and agricultural productivity, carbon sequestration, flow mitigation, habitat connectivity, nitrogen, phosphorus and erosion. Both of the tradeoff maps contained model output for the number of services to preserve, the number of services with an opportunity for change, and the number of services where change did not make a significant difference. The tradeoff scenario was chosen because the tradeoff maps had multiple attributes, so users could apply the attribute chooser and filters to inspect data in attribute layers.

Analysing the differences in the tradeoff maps involved reading both speckled areas of the map as well as larger filled areas. The tradeoff maps in the VR system had multiple services which were available as layers, and users could turn these layers on and off to inspect the data or apply filtering criteria.

Task 3. Comparing riparian planting scenarios for 5m, 15m and 30m

distances from streams.
Instruction: The provided map layers in the file tab are for three riparian planting options at 5m, 15m and 30m widths from streams. Use any, or all of the features described in the tutorial to compare these three scenarios.

The data were ordinal categorical classifications of the flow interception classification and nitrogen accumulated load. The flow interception classification map exhibited differences around the stream riparian planting areas, where planted areas were visible as reducing flow. In order to read the flow interception classification map on each medium, participants would need to observe line features around the streams, which were thin. The riparian planting scenario was chosen because riparian planting is a comparative task which users could be interested in [34].

This task was chosen because the riparian buffer sizes are long, thin features which may require zooming, or careful inspection. The task of comparing riparian planting was realistically applicable in general to other areas, rather than a mitigating feature unique to the Mangatarere catchment area. So demonstrating that Immersive ESS visualizer could be applied to riparian planting comparison suggested that riparian planting in other areas could also be compared. Features in the nitrogen-classified accumulated load map were speckled rather than solid.

Data provided by Nature Braid was inspected to find map layers relevant to each task, and task questions were designed which required the user to perform the task with the provided layers. Tasks were defined for VR, Paper Maps, and 2D Screen.

6.3 Participants

Participants were recruited by email from pre-existing contacts, and contacts provided by supervisors. Ethical approval was granted by Victoria University of Wellington human ethics committee, approval number 0000028871 (v3).

Participants were invited based on their domain expertise in reading maps, knowledge of the ecosystem services, and/or the study area (Mangatarere catchment). The study was run with a combination of participants who had previously encountered the VR system and new participants. Participants were recruited in rounds with convenience sampling. Due to our initial estimate of a very small sample size, the first six participants were presented with media in a different order to ensure that each order was represented in the study. Fortunately, a much larger sample size was obtained, so after the first six, the sampling method switched to randomising the order in which different media were presented.

In order to ensure the difference in media order did not impact statistical results, any statistical analysis was repeated twice: the first analysis included all participants, and the second analysis excluded the first six participants. Results were reported from the first analysis unconditionally, and the second analysis did not yield significantly different statistical results from the first.

24 participants (See, Table 6.1) were recruited. Questions 1-5 of the pre study questionnaire describing the participant's background are shown in the table. Q2 organization names / role is redacted to the type of organization for privacy. Participants were from private companies (7 participants), universities (8 participants), government departments (5 participants), and a council (1 participant). Experience ranged from 6 weeks to 21 years. GIS analysts, research fellows, scientists, university teaching, planners, and software engineers were represented. 12 of the participants had PhDs and 19 had university qualifications, indicating a highly qualified sample. It was not possible to know the participant's level of expertise before choosing the study condition. Deciding on participant expertise for each category involved a group discussion with supervisors, and a detailed analysis of the pre-study questionnaire sheet, which would not be possible within the time constraints of the user study session while the participant was present.

Table 6.1: Table of participant backgrounds.

PID	Q1) Occupation	Q2) Organization/role	Years in role	Q4) Projects/activities	Q5) Academic, industry qualifications
EV1	Environmental / Geospatial scientist	Private company	1.5	Ecosystem service modelling, geospatial analysis	PhD Physical geography
EV2	Biophysical / Geospatial/Environmental Scientist	Private company	2	Environmental modelling, GIS analysis, research	PhD Physical geography
EV3	Research fellow	University	5	Development of VR for volcano monitoring data. Geospatial analysis of geological/geophysical data	PhD Geophysics
EV4	Research assistant/research fellow	Geography/Earth sciences University	2	Teaching tools creation, VR, video production, GIS	PhD Science
EV5	Data/insights manager	Government department	1.5	Developing dashboards, GIS solutions	BE (Computer systems) Mcom
EV6	Data analyst/manager	Private company	4.5	GIS related choropleth maps, boundary maps, data engineering	PhD Logic and computation
EV7	GIS technician	Private company, Georeference maps/data entry	0.5	Historical data compilation	Grad Dip sci (maths)
EV8	GIS Analyst	Government department	3	Topography mapping, GIS, LiDAR	BSC Geology
EV9	PhD candidate/teaching fellow	University teaching/research	4	Research, teaching environmental science	PhD Environmental Science
EV10	Professor of Physical geography	University	11	Teaching, research	PhD Atmospheric Science
EV11	Professor	University	~5	Teaching, research	PhD Geography MSc GIS
EV12	GIS Analyst	Private company	4	Cartography, Field-based activities, web app development, data / spatial analysis	MSC GIS, BSC Geography
EV13	Spatial intelligence analyst	Government department	7mth	Mapping	PhD, Forest and Conservation Sciences
EV14	Data/information lead	Government department	4	Analysis of environmental damage[location redacted] (social, environmental economics)	BSc Computer science
EV15	Assoc. professor in Ecology/ecological restoration	University teaching/research	21	Ecological field work, data analysis, spatial ecology, Wairarapa region	PhD Ecology
EV16	Lecturer Human Geography	University	4	Urban Modelling, GIS analysis, teaching spatial data analysis	PhD Geography
EV17	Strategic planner	Private company	13	Drafting urban plan,[redacted location] digital twins	not answered
EV18	Freelance planner / researcher	University	1	Research, Carbon Sequestration	M. Arch (urban planning /design)
EV19	Retired	n/a	n/a	n/a	not answered
EV20	Retired	n/a	n/a	n/a	not answered
EV21	Software engineer	Private company	3	Software development	not answered
EV22	Business intelligence specialist/GIS analyst	Government department	1	ArcGIS Enterprise administrator, web-app development, cartography, ETL pipeline construction, data engineering	B.Sc. Geography
EV23	Planning/regulatory manager	Council	15.5	Wairarapa Combined district plan review	not answered
EV24	Lecturer hydrology	University	6 wks	Spatial data collection, GIS, analysis, visualization,	PhD Geography

6.3.1 Participant expertise analysis

Expertise of participants were categorized based on Map reading, data, geospatial analysis tools, VR and location. Experts and non-experts had different methods for interacting with software [48], and using the Immersive ESS Visualizer to analyse ecosystem services data incorporates knowledge from multiple disciplines: Map reading skills, experience with other geospatial analysis tools experience with datasets, experience with VR, experience with 3D software, and experience with analysing ecosystem services. These all influence how the participant decided to use the software. Expertise was consequently categorised with three categories: Novice, competent, and proficient. Some participants discussed their past experiences while completing tasks. However, the categorization was performed based on their questionnaire responses rather than discussion during the study to ensure consistency in the categorization.

The criteria for what defines expertise was informed by the characteristics suggested by Cifter et.al [48]. Cifter stated, that experts understand terminology specific to the domain, are more likely to follow instructional documentation, have more training, can overcome problems and have more confidence using new products. Additionally, professional users have more knowledge of the tasks performed compared to non-professional users of products. Since the Immersive ESS Visualizer was a system developed for this research project, most participants had little familiarity with it. However, experts could still draw on their expertise to assist them with the completion of tasks.

Dreyfus et. al. [62] presented a 5 stage model of knowledge acquisition which categorized skills as novice, advanced beginner, competence, proficiency and expert. There are tools for measuring the Dreyfus model, however, the task may involve measuring knowledge that the participant cannot explain themselves, and tests such as [5] which use the Dreyfus model involve assessment from a supervisor who works with the person in addition to self assessment. Such an approach was not adopted as our questionnaire needed to be administered within the time constraints of a user study and needed to be compatible based on the information provided by the participant.

We were unable to find literature relating to the categorization of different levels of expertise specifically for the design of software in the geospatial domain. However, Walsh et.al. [168] categorized users based on prior categorizations of digital cultural heritage users. The categories were simplified, ranking users by their motivation, technical expertise, and domain expertise. With each of technical expertise and domain expertise ranked as high, medium, and low. Matthews et.al. [114] categorized expertise based on self reported data relating to role, number of years of experience. The method of tabulating self reported expertise allowed differences in the opinion towards personas to be qualitatively analysed without measuring expertise. Raymond et. al. [138] presented a categorization of local and scientific knowledge into categories for environmental management.

A potential limitation to measuring expertise by ranking questionnaire responses was that the participants would need to be ranked based on the information that they provided. Dreyfus et al. [62] suggested that experts have tacit knowledge that they may not impart, so the method of ranking may not be able to detect advanced expertise. In this thesis, it was not practical to set a test to measure the extent of their expertise in each subject area. So the categorization applied in this thesis was based on data which was self reported, rather than inferred from a test.

Rather than evaluating experts to separate them from non experts, this research identified groupings relating to specific data knowledge, geospatial software, VR software, and 3D navigation skills which were self reported. These groupings were then tested for significance. The advantage of this approach was that differences in the way that users interacted with each medium could be tested based on the responses of a questionnaire sheet and data provided during the study session.

The users were required to fill out a pre-study questionnaire (Appendix D) before the study started. Questions 1-5 were for the participant's background and were not ranked as part of expertise scoring.

6.3.2 Expertise Scoring

When scoring expertise, each question of the post-study questionnaire was grouped into experience categories for map expertise, dataset expertise, technology expertise, and VR software expertise. The questions and groupings are described in Table 6.2. Expertise was ranked on whether they had novice, competent, or proficient expertise. Then questions which were binary were classified as either novice or proficient. After classifying every individual question, an overall expertise ranking for each category was calculated by taking the median. The median was chosen because unlike the maximum and the minimum, the median calculates a middle value. If the mean was chosen, then extremes would have a greater influence over the calculated middle value. The median reduces the effect of outlier values on the calculated category [49].

Map Reading

Map reading questions related to both digital and paper map experiences. Participants who read maps more often (Q6) and used maps as part of their occupation (Q7) may be more likely to have higher map reading expertise than users who used maps infrequently for recreation or for navigation. The type of maps reported (Q8, Q9) and associated tasks (Q10) were compared to the data used in the user study. Participants who had experience with similar data types, e.g raster data, as well as experience with the visualized layers may be more likely to have higher expertise. Data experience may allow participants to rely on their existing knowledge, or tacit knowledge to find places of interest and answer the questions. Questions 6-10 were scored for Map expertise according to Table 6.2.

Location expertise

Questions 11 and 12 were scored for location expertise. The participant was asked if they were a resident (Q11), or how often they visited the catchment area (Q12). Participants with local knowledge may also draw on their area expertise, for example, by referring to road names, or places of interest known to be on the map, rather than by inspecting the road layer provided, participants with local knowledge could possess an understanding of additional information relevant to the analysis relating to the land use which may not be encoded by the layers which are input into the LUCI model, or the data layers provided. Questions 11 and 12 were scored for location expertise.

Datasets

The dataset expertise section asked for the participant's experience of LUCI (Q14), datasets (Q17), and land management decision making tools(Q18) which were relevant to the data shown by Immersive ESS Visualizer. This data formed part of the categorisation of the participants' expertise, as users who had experience with datasets and models as part of their job may be more likely to have an understanding of data limitations and an interest in particular features which could be present inside the datasets.

Participants were asked to identify the aspects of LUCI which they were most interested in (Q13), This information was analysed qualitatively by relating the features that they were interested in, to the data in the ecosystem services data which they were analysing, and experiences using Immersive ESS Visualizer.

It was expected that participants with higher expertise in geospatial data analysis would likely possess more knowledge about aspects that they were the most interested in, which could guide the way that they use the tool, and the types of questions that they would like to answer with it.

The participants were asked about which LUCI outputs they have previously used (Q15), as knowledge of the outputs which are visualized by Immersive ESS Visualizer, could affect how reliable participants perceive the data to be, and which features or patterns they were attracted to analysing in the data layers. The analysis of this question was combined with the information that they provided on the strengths and weaknesses of LUCI (Q16), as users could have varying degrees of trust in model outputs. Participants with an in-depth understanding of strengths and weaknesses may be more likely to be expert users, compared to users who have little or no knowledge of the underlying model. Questions 14-18 were scored to calculate dataset expertise, Q13 was analysed qualitatively as being interested in features of LUCI is not a measure of expertise with those services.

Technology

Participants were asked about their experience with land management decision making tools (Q19) as well as GIS software such as ArcGIS, QGIS, and MapInfo. Expert users could have a process which they already use to analyse data with GIS software, that translates either consciously or implicitly when analysing geospatial data in virtual reality. Participants who already have experience with land management decision making tools could be expert users and have a higher level of domain knowledge in the domain associated with the specific tool that they had expertise with. Question 19 was scored to calculate technology expertise.

VR

The expertise score for VR was based on the frequency of use. Batch et al. [33] measured the regularity of computer games, and whether or not participants had VR experience. Satriadi et al. [147] measured the amount of VR experience; less than 5 hours, 5-20 hours, or more than 20 hours.

However, 20 hours of experience is short, and may not be enough time for any long-term effects of VR use to emerge.

Gardony et. al. [68] measured video game experience with a video game experience questionnaire self-categorizing frequency of use as N/A, occasional, frequent, and expert. However, there were no significant effects detected, and Gardony et al. did not measure the type of video games played.

Richardson et al. [139] calculated a score based on the frequency of video game use, the frequency of game use when participants first started gaming and the highest frequency of game use in their lifetime. They found a relationship between VR navigation performance in hallways, "multi-target learning in a campus environment", and game experience also affected desktop VR pointing error and response time.

In this study, a score was calculated based on the frequency of use for an HMD (Q21), frequency of use for video games (Q24), frequency of use for VR navigation (Q3), and frequency of navigation in 3D-worlds (non-HMD) (Q26).

Immersive ESS Visualizer required participants to physically move around while they used the software, users more accustomed to physical movement while wearing a headset could potentially interact with software differently to other users. When Immersive ESS Visualizer started up, the participant was positioned hovering over a large scenario map. This map could then be used as part of the participant's data analysis. However, users who were less accustomed to movement in VR may find that interacting with features like the handheld maps was more difficult without the confidence to step out and physically walk around. The participant was required to handle an HTC VIVE controller when they were interacting with the VR. If participants were not accustomed to using handheld controllers like HTC Vive or similar, then it is possible that they would be under more cognitive load than users who could apply the physical interface fluidly, and already have the experience with it. Cifter et. al. [48]

suggested that users who are novices are less confident with the use of new devices. Navigation in a Virtual world was provided as a separate question to navigation inside an HMD, as some virtual reality experiences may not present themselves as a virtual world which required the user to apply a navigation technique. Specifics of the software used were requested so that the software could later be searched for relevant navigational techniques, for example, whether the software uses navigation by teleportation, or navigation by flying.

3D software including non-VR videogames may require a user to navigate in a virtual world, this experience with navigation could have an effect on how easily the user could pick up the interface and use it. So the background questionnaire incorporated experience with 3D worlds (Q26) / video games (Q24) to provide data for evaluating the user's expertise.

Qualitative information about which AR/VR software programs, which HMD VR programs with navigation in a virtual world, and which non-HMD programs require 3D navigation was collected. However, programs were not ranked and included into the statistical score as more software programs would not necessarily increase performance with navigational tasks, over using the same programs more frequently. The type of HMD was also not ranked and included in the score, as navigational skills may not depend on the number or exact type of HMD.

Asking exactly how long participants had used each dataset or software package was considered. However, these questions were not included due to the difficulty of answering if the participant has worked with datasets intermittently, or over several years. It would be impractical to test participants knowledge during the study conditions, so ternary classification was chosen for convenience due to the difficulty of being able to form a judgement which was not directly related to the data provided. Additionally, the number of years of experience in a particular role did not necessarily mean that a higher level of understanding was achieved through practice [62]. But, if the user's time in the role was particularly short, and they have not had prior experiences with using data/ software, then they could be more novice than a user with more extensive experience. Questions 21, 23, 24, and 26 were scored to calculate VR expertise.

6.4 Procedure

The study was designed to test three media, VR, Paper and 2D Screen. The media order was chosen to systematically test with a different permutation of the VR/ Paper Maps and 2D screen conditions. Each participant performed the same three tasks in each of the three media and each participant was presented with the media in one of the six possible orders. The ordering of the media presentation for participants is discussed in § 6.3. The following section describes the method for conducting the experiment.

6.4.1 Features of Immersive ESS Visualizer

Immersive ESS Visualizer features that were evaluated against the tasks are presented in Table 6.3.

6.4.2 Study-protocol

Following an introduction about the study participants signed a consent form, then a pre-study questionnaire collected information about the participant's demographic, background and experience with VR and ecosystem service trade-off analysis (Appendix D).

The same three tasks were provided for each of the three media VR, Paper maps and 2D Screens. They were provided with the three tasks for each media immediately before using that media. After the user completed the tasks for each medium, questionnaires were administered.

Table 6.2: Pre-study questionnaire ranking criteria for participant expertise, Q6-10 categorizes Map expertise, Q11-12 categorizes location expertise, Q14-18 categorizes data expertise, Q19 categorizes Geospatial Technology expertise, Q21,23,24,26 categorizes VR expertise.

Question	**Novice**	**Competent**	**Proficient**
Q6) How often do you read maps?	> 1 month	Monthly	Weekly/Daily
Q7) Have you ever used maps as part of your occupation?	No		Yes
Q8) Do you use digital maps, paper maps or both?	None	Either	Both
Q9) What type of maps? e.g topographic, soil maps geographical, road maps	road maps/none	One other map	Two or more other maps
Q10) What types of tasks would you use maps for	navigation /non-relevant tasks	Visualization /looking at data	analysing, manipulating data, teaching geospatial analysis
Q11) Are you a resident of the Mangatarere catchment area?	No		Yes
Q12) If you are not a resident, how often do you visit the Mangatarere catchment area?	Never/Yearly or longer	Monthly	weekly/Daily
Q14) Describe your experience with LUCI in this project or other projects,	None		Any
Q15) Which LUCI outputs have you used e.g Diagram, charts, reports, please describe	None	One output	any outputs
Q16) What do you think strengths and weaknesses of LUCI are?	None		Any
Q17) Have you used any of the following datasets	None or one,	two excluding rainfall and evapotranspiration, road layers	three or more
Q18) Have you ever worked with any land management decision making tools other than LUCI. E.g overseer, ARIES, MIKE? Please specify	None		Any
Q19) Have you used any of the following, Geographic information systems (GIS) software? E.g ArcGIS, QGIS, MapInfo ?please specify	None	One GIS System	Many
Q21) How often do you use a head mounted display	Never / a few times / yearly	Monthly	Weekly/Daily
Q23) How often do you navigate in a virtual world inside an HMD	Never	Monthly	Weekly/Daily
Q24) How often do you play video games	Never/ a few times / yearly	Monthly	Weekly/Daily
Q26) How often do you navigate in 3D worlds (non-HMD)	Never / a few times/ yearly	Monthly	Weekly/Daily

Table 6.3: Features of Immersive ESS Visualizer

Feature	Use	Task
Colour scales	Colour scales show the trade-offs and categorical data in comparison exercises.	1,2,3
Elevation	Tradeoff maps are overlaid onto elevation.	1,2,3
Rivers	Rivers are visible on both handheld and the scenario map.	1,3
Colour filters	Map comparison exercises have a filtering component.	2
Navigation	Users can glide around the scenario map.	1,2,3
UI menus	UI menus are used to filter/show and hide maps or generate additional handheld maps.	1,2,3
Colour scale legend	Colour scale legend shows numerical values for colour scales.	1,2,3
Marker	Marker selects data from handheld maps.	1,2,3
Zoom/magnifier	Handheld maps can be zoomed to look closely at details.	1,3
Landmark/ text layers	Layers for landmarks and text can be hidden and shown during tasks.	1,2,3

Experimental sessions were conducted with one facilitator. Figure 6.2 shows the experimental setup. Participants were introduced to the study, and given a background questionnaire. Then participants were required to complete the tasks in the order assigned while thinking aloud. A post-study questionnaire was given to the participants after completing the questions for each medium, then a SUS test [41] with the adjective measure [31] was used to collect statistics about usability, and the NASA TLX [81] collected statistics about workload and performance. Participants were audio recorded and sessions with the 2D screen and VR were screen recorded.

Immersive ESS Visualizer Participants were provided with the list of tasks before entering the VR, they were permitted to ask the facilitator to read out the question while they were in the VR headset. Before each participant entered VR, they were given a demonstration on the use of the controllers, they were also given instructions on how to use the slides. After they read the tasks, they were placed into VR and asked to complete

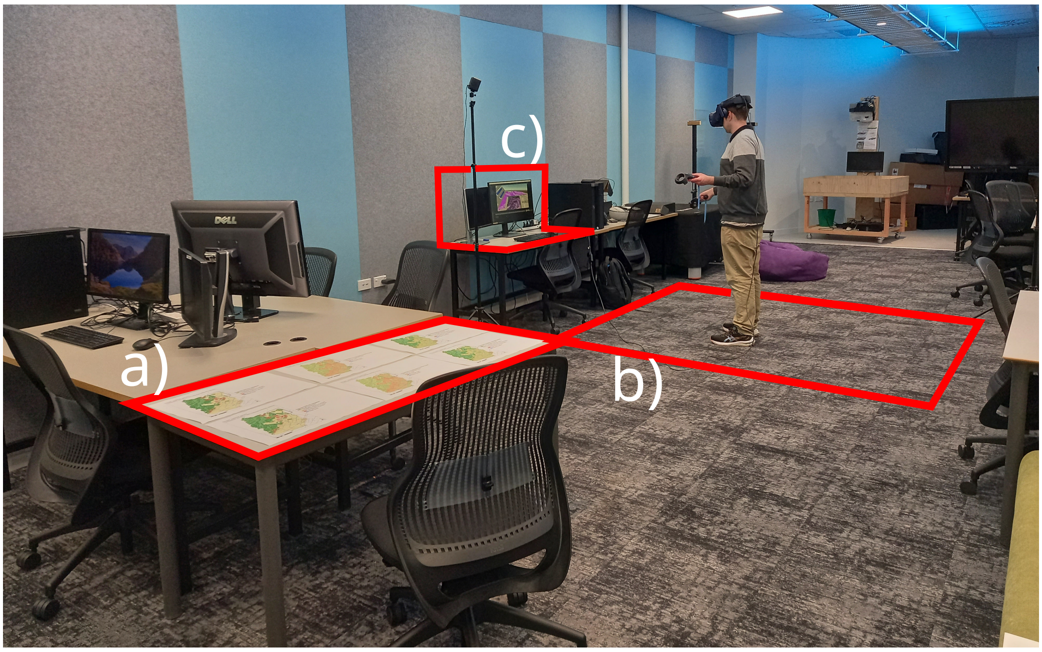


Figure 6.2: User study setup, a) is the table where participants use paper maps, participants recieved the maps in a pile provided by the facilitator. b) shows the VR area where the participant was guided through the VR. c) shows the monitor where the facilitator could see the participant's VR session, this monitor was also used by the participant in the 2D screen exercise.

the instructions on the tutorial slides. Participants were asked to think aloud [125], and they were permitted to ask questions. After completing the tutorial, each task on the instruction sheet was in a separate scenario. Participants came out of the VR headset before starting each task and read the task on paper. After completing the study tasks participants were given a post-study questionnaire about their use of the system and their perceptions of usability, effectiveness scales for VR, questions about communication in VR, NASA TLX, and then a SUS test.

Paper maps Participants were provided with the list of tasks before using the paper maps and asked to think aloud, participants were permitted to ask questions. After looking at the paper maps, they were given a post-study questionnaire, a NASA TLX, and then a SUS test.

2D screen Participants were provided with the list of tasks before using the 2D screen, participants were asked to think aloud and were permitted to ask questions. After looking at the 2D screen, they were given a post-study questionnaire to complete, then a NASA TLX, and then a SUS test.

After completing all media, participants were given a post-study questionnaire sheet and interviewed about their experiences in each medium questions asking them to compare their experiences in each medium.

6.5 Study Analysis

When analysing the post-study questionnaire, Likert scores for the effectiveness of VR features from the post-study questionnaire were analysed qualitatively. Linear mixed effects models were run on the TLX score data, and SUS score data, to test for correlations among expertise measures within media conditions (VR, paper maps, 2D Screen). The audio recordings and post-study questionnaires were analysed in NVIVO to find common themes between different users. A summary of the questions is listed below in Section 6.5.1.

6.5.1 Analysis of Post-study Questionnaires

Features and Techniques

The questionnaire sheet for each medium asked participants to describe how they completed each task. These questionnaire sheets were tabulated and qualitatively analysed in NVIVO to categorize the responses and find common themes in how participants reported that they approached each task.

We will now ask you questions about your experience analyzing data with [media].

Q1 When analyzing data [with media] describe how you completed each task:

1. Wetland restoration at Tea Creek Road.
2. Comparing tradeoffs in the Wairarapa.
3. Riparian planting in the Wairarapa.

Q2 What features of the [Media] did you find useful for completing each of these tasks?

1. Wetland restoration at Tea Creek Road.
2. Comparing Tradeoffs in the Wairarapa
3. Riparian planting in the Wairarapa

Comparison of 2D screens, VR and paper maps

Participants were asked to compare their experiences with VR, paper maps, and 2D Screen by answering the following questions. Each question was analysed qualitatively by coding their comparative experiences to find statements in common.

Q1 Compare your experiences with VR, Paper Maps and 2D Screen, while completing Task 1 Wetland restoration at Tea Creek Road.

Q2 Compare your experiences with VR, Paper Maps and 2D Screen, while completing Task 2, Comparing Tradeoffs in the Wairarapa.

Q3 Compare your experiences with VR, Paper Maps and 2D Screen, while completing Task 3, Riparian Planting in the Wairarapa.

Communication

Q1 When discussing your findings for the wetland restoration scenario. Which features in VR did you find effective for assisting your discussion?

Q2 When discussing your findings for the scenario comparing tradeoffs in the Wairarapa. Which features in VR did you find effective for assisting your discussion?

Q3 When discussing your findings for the riparian planting scenario, Which features in VR did you find effective for assisting your discussion?

Q4 When discussing your findings for analyzing streams at Piako, Which features in VR did you find effective for assisting your discussion?

Q5 Describe your experience in communicating your findings to the Researcher.

Q6 If you wished to communicate your findings to someone outside the application, what features of the VR system would be the most effective in assisting your communication?

6.5.2 Qualitative data analysis

Thematic analysis was applied to this research project by analysing audio recordings and post-study questionnaires from the user study. The methods for the thematic analysis were similar to Braun et al. [40]. An advantage of thematic analysis was that the process was an analysis method which can be applied to data, and did not constrain data acquisition methods, or place requirements on the coding process which could not be satisfied by a single researcher [40]. For this research project, the researcher coded qualitative information. In this study, codes are short blocks, individual sentences or words. The coding was chosen based on the context required to form an understanding. Complete coding [40] was used for interview transcripts and post-study questionnaire qualitative feedback. Thematic analysis involved the following steps [39, 40, 42, 142]:

1. The user study audio was transcribed and added to NVivo.
2. Transcriptions and post-study questionnaires were read to identify information of relevance.
3. The complete coding process was followed.
4. Themes and categories were identified.
5. Themes and relationships were defined and iteratively reviewed.
6. Named and defined the final themes
7. Write-up.

6.6 Summary

In this section, the design of the final evaluation was presented, and the data preparation was discussed and referenced to the walkthroughs for personas. The three study tasks were defined that were based on LUCI use for the analysis by Benavidez et al. [34]. The tutorial information was described. The participants and method for coding the participant expertise were developed with a novel scoring method to assist statistical analysis of results, including thematic analysis and coding methods. The procedure for running the study was presented. Qualitative and quantitative evaluation methods were described. In the next chapter results from the user study will be presented.

Chapter 7

Results

Contents

The participant feedback from the user study described in § 6 is analysed. § 7.1 describes the categorization of participant expertise based on the method in § 6.3.1. § 7.3 describes the coding method of the user study, grouping the codes into categories. § 7.4 describes the qualitative analysis of participant responses and extracts themes based on the qualitative research method in § 6.5.2. § 7.2 describes a statistical analysis of the SUS, and TLX scales, then discusses the effectiveness scales for Immersive ESS Visualizer features. § 7.5 describes a summary of the results. The discussion connects the research questions to results of the user study. RQ1: How can Immersive visualizations affect the comparison of the impact of land-use change for multiple ecosystem services? RQ2: How effective is immersive visualization for facilitating communication to stakeholders analysing the impact of land use change on ecosystem services?

7.1 Participants Expertise

Expertise was categorized as Novice, Competent or Proficient according to the categorization method in § 6.3.1. The expertise ranking criteria is tabulated in Table 6.2, an overview of the median expertise for each category ranked based on the criteria is tabulated in Figure 7.1, and the expertise for each question ranked based on the criteria is tabulated in Figure 7.2.

Median expertise levels in Figure 7.1 are ranked 1,1.5,2 and 3. The expertise level 1.5 arises from the decision to use the median as the method for calculating categorization prior to data collection and analysis. Participant expertise is grouped into map expertise, location expertise, data expertise, spatial technology expertise and VR expertise which are described in this section. A table of participant background information (Q1-Q5) is provided in Table 6.1.

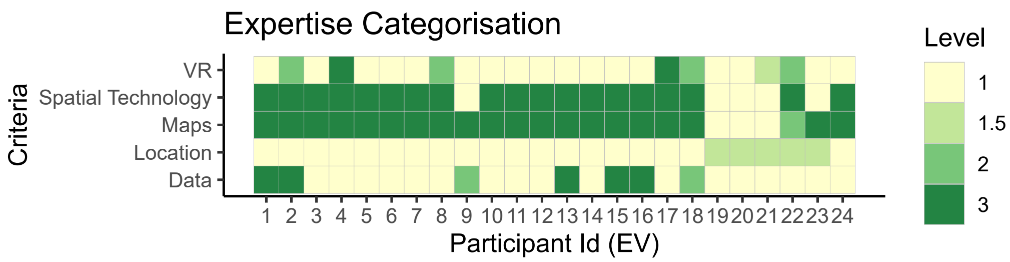


Figure 7.1: Participant expertise for each category. Levels: 1 = Novice, 2 = Competent, 3 = Proficient. Some expertise criteria are ranked as 1.5 due to the median being calculated from an even number of questions.

7.1.1 Map expertise

The participants who were ranked as proficient or competent with using maps as part of their occupation (21 participants, EV1-18 and EV22-24 in Figure 7.2 Q7) were also proficient in the spatial technology expertise categorization (Figure 7.2 Q19)), except for EV9 and EV23. The similarity in responses between Q7 and Q19 indicates that spatial technology had high workplace adoption for participants. None of the participants used only paper maps. 12/21 participants who had used maps as part of their occupation were also using paper as well as digital maps. The high use of paper maps indicated that testing with paper maps was a realistic scenario. The map expertise of the participants closely matched the experience of the persona Jane 4.3.1, indicating that the expert participant group was a close match to the group that was used to create the persona. Participants using paper maps generally used digital maps as well.

Three participants' map expertise did not match their spatial technology expertise, EV9, EV22, and EV23 (Figure 7.1). The map expertise was a relatively good predictor of spatial technology expertise. EV9 and EV23 had higher map expertise than spatial technology expertise. Both EV9 and EV23 used only digital maps and not paper maps, but they did not use GIS software to view the digital maps. EV22 had competent map expertise with proficient spatial technology expertise. The close similarity between map expertise and spatial technology expertise indicated that most participants who were using maps were also using GIS software, such as ArcGIS and QGIS, when they interacted with maps.

7.1.2 Location expertise

Four participants were residents and lived in the Mangatarere catchment area. These participants did not need to answer how often they visited the area. Participant EV22 did not live in the Mangatarere catchment area, but they visited monthly.

7.1.3 Data expertise

11 participants were sufficiently familiar with the LUCI tool to be able to discuss the strengths and weaknesses of LUCI. 7 participants were ranked Competent or Proficient with data expertise. All of the participants ranked as competent or proficient with data expertise also described some strengths and weaknesses of LUCI. Four participants (EV8, EV10, EV11 and EV14) described the strengths and weaknesses of LUCI, but did not have data expertise. Four participants (EV1, EV2, EV13 and EV18) who were ranked as competent or proficient with data expertise were able to describe their experiences with LUCI. EV16 was the only participant ranked as either competent or proficient with data expertise who neither described a personal

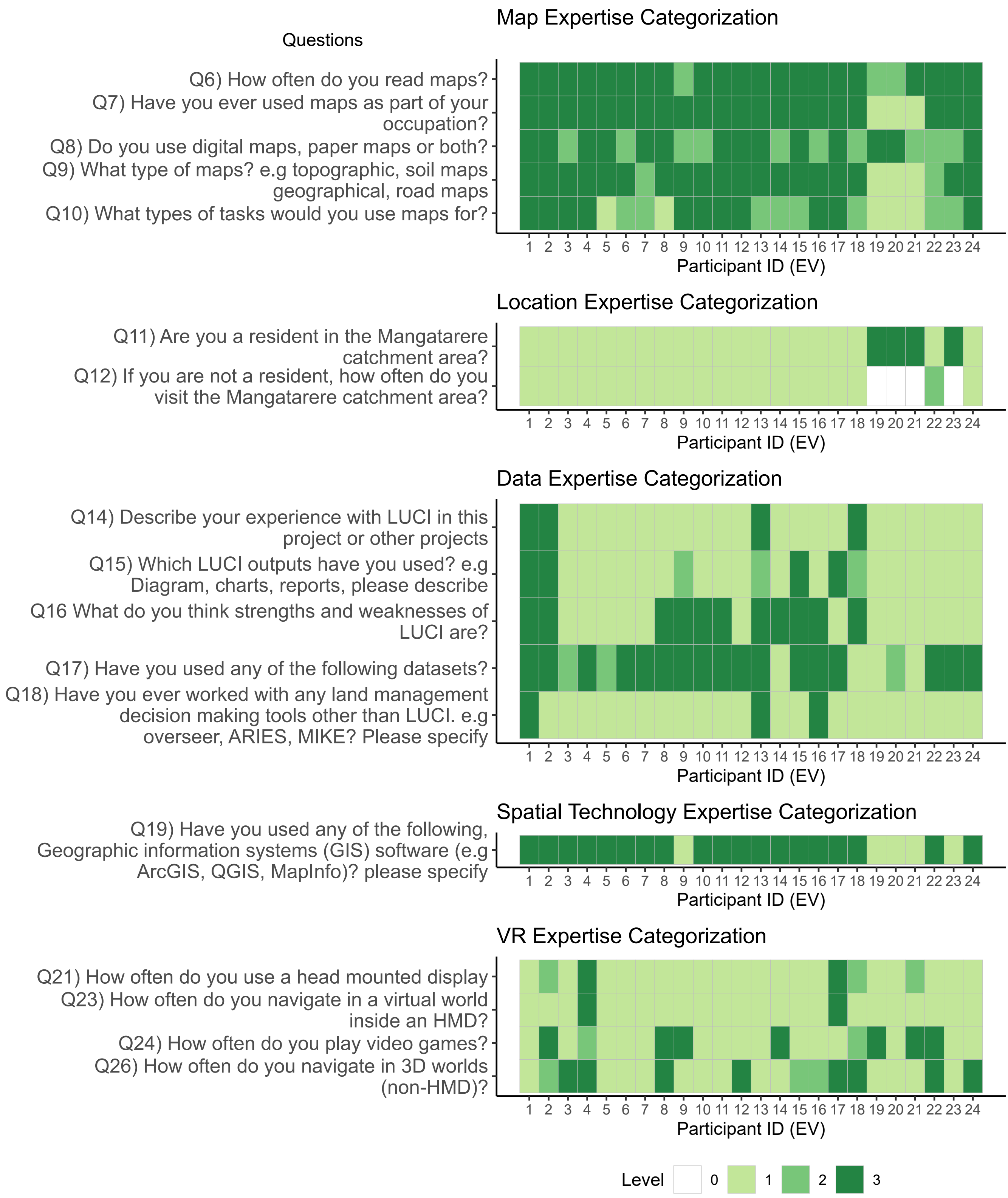


Figure 7.2: Categorized expertise for Map, Location, Data, Spatial Technology and VR. Levels: 0 = N/A, 1 = Novice, 2 = Competent, 3 = Proficient

experience with LUCI, nor used any outputs of LUCI. However, they were able to discuss strengths and weaknesses, as they had viewed demonstrations of LUCI. Two participants (EV9 and EV15) did not describe personal experiences with LUCI, but they had used data outputs.

7.1.4 VR expertise

6 participants were ranked competent or proficient with their VR expertise. EV21 ranked 1.5, between novice and competent, all other participants were novice. There were an even number of questions for VR expertise, and the median of the scores for participant EV21 was 1.5. Two participants had greater than novice expertise with VR and were also either competent or proficient with data expertise. Other participants were either a novice with data, or a novice with VR. All participants who were not novices with VR also had competent or proficient map expertise.

5 participants used VR with medium or high expertise, indicating that they used HMDs at least once a month. 11 of the participants were Competent or proficient at navigating 3D worlds (non-HMD), and 9 were competent or proficient at playing video games. Four participants (EV21, EV19, EV14 and EV9) were competent or proficient at videogames and were novices at navigating 3D worlds (non-HMD). EV21 ranked 1.5 overall for VR Expertise, and EV19, EV14, and EV9 ranked novice overall, indicating that experience in video games without 3D navigation had little effect on their overall score for VR expertise.

7.2 Quantitative results

In the following section the quantitative results from the SUS test, TLX test, and VR effectiveness likert scales are analysed. The SUS test, TLX test and effectiveness scores were administered according to the protocol in § 6.4.2.

Linear mixed effects models can find correlations among multivariate data, and account for differences in individuals which cause multiple samples from the same individual to be non-independent [174]. The user study collected SUS score and TLX responses from each individual for three different media, so a random effect was added to each of the linear mixed effects models for SUS and TLX analysis to account for random variation in how different individuals respond. Hewitt et al. applied linear mixed effects models to the analysis of TLX scores for website usability [85].

7.2.1 Task Load Index (TLX) scores

Raw TLX provides a measure of difficulty in completing tasks with each system [80]. The raw unweighted TLX was calculated by adding the TLX score for each of the 6 scales.

The mental demand, effort and frustration scores were higher for VR compared to paper and 2D screen conditions (Figure 7.3). The physical demand for VR had a wide distribution of scores compared to 2D screen and paper. The performance score for VR appeared bimodal with 14 responses on the perfect side of the scale (Figure 7.3), and 8 responses on the failure side (EV5, EV6, EV7, EV10, EV11, EV13, EV21 and EV23). Out of the participants reporting failure score above 11, EV21 did not score high map expertise (score 1), others had proficient map expertise (score 3). EV13 was the only participant from this group with proficient data expertise (score 3) and the other participants had a score of 1. EV21 had a VR expertise score of 1.5, other participants from this group had a score of 1 (Novice). Participants with a VR expertise score of either 2 or 3 all reported a performance score between 3 and 10 inclusive on the VR TLX indicating that participants with competent or proficient VR experience reported that their performance was on the perfect side of the scale.

The raw unweighted TLX scores (Figure 7.3) indicated that VR was more difficult to use than either paper maps or 2D screen, the VR median (IQR) was 71 (54.25-76.75), the 2D screen median (IQR) was 33.00 (26.75-45.50) and the paper maps median (IQR) was 42 (26.25-51.50).

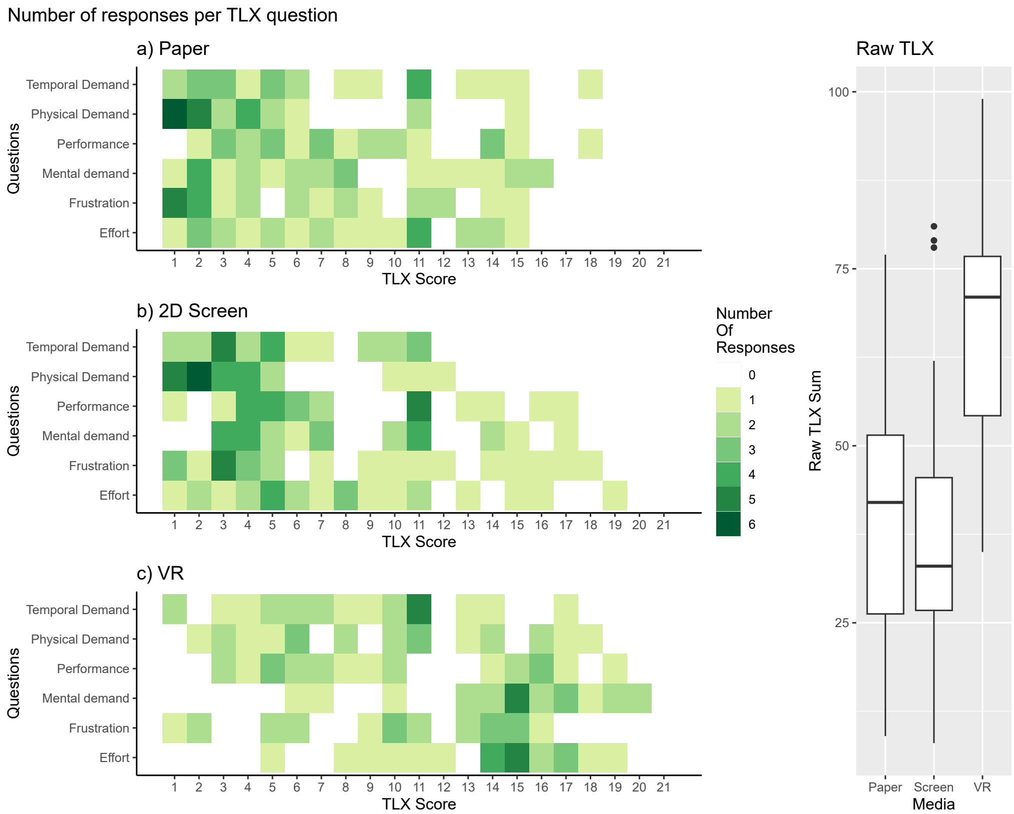


Figure 7.3: Responses for each TLX question for a) Paper, b) 2D Screen, and c) VR. Temporal Demand, Physical Demand, Mental demand, Frustration and effort are ranked from very low (1) to very high (21). Performance is ranked from perfect (1) to failure (21).

A linear mixed effects model was run on the TLX score data in order to test for correlations among map expertise, location expertise, data expertise and VR expertise within the media conditions, and to test for differences in the TLX score among media. The fixed effects were map expertise, location expertise, data expertise, VR expertise, media condition and media order. The spatial technology expertise was not included in the model, due to the similarity with the map expertise. The model had an intercept for ID as a random effect to group the three TLX scores per participant, one for each of the three media conditions. Residual effects were plotted to check normality and homoscedasticity assumptions for the linear mixed effects model. There were no visual discrepancies to suggest that assumptions were violated. A Shapiro-Wilk normality test was performed indicating that the null hypothesis of normally distributed residuals should not be discarded (W = 0.98617, p-value = 0.6369). P-values to test the significance of the fixed effects were reported in a Type III ANOVA summary table(Table 7.1).

After adjusting for expertise and media order, the Raw TLX significantly differs between media ($p < 0.0001$) indicating that the null hypothesis of no correlation between media and raw TLX should be discarded in favour of the alternative hypothesis that a correlation exists between media and raw TLX score (Table 7.1).

After adjusting for expertise and media, the Raw TLX significantly differs between media order (p = 0.0336133) indicating that the null hypothesis of no correlation between media order and raw TLX should be discarded in favour of the alternative hypothesis that a correlation exists between media order and raw TLX score (Table 7.1). The coefficient estimates table indicates that for each subsequent media task the Raw TLX score decreases by 4.2696620 units. So as a participant interacted with each media condition, they were placed under less workload by subsequent media conditions.

Pairwise comparisons of estimated marginal means of the Raw TLX

Table 7.1: The ANOVA table for testing the significance of correlations in the linear mixed effects model for Raw TLX scores.

	Chi sq.	**Df**	**p-value**
(Intercept)	11.8888875	1	0.0005647
Map expertise	0.3464864	1	0.5561089
Location expertise	0.1269853	1	0.7215785
Data expertise	0.9407401	1	0.3320876
VR expertise	2.1307038	1	0.1443745
Media condition	62.5992011	2	<0.0001
Media order	4.5142644	1	0.0336133

Table 7.2: Table of coefficients for the Raw TLX linear mixed effect model.

	Estimate	**Std. Error**	**df**	**t-value**	**p-value**
(Intercept)	67.5244558	19.583508	19.57878	3.4480266	0.0026046
Maps	-5.0911507	8.649139	17.35792	-0.5886309	0.5636909
Location expertise	-10.3527138	29.052094	16.92183	-0.3563500	0.7259828
Data expertise	-3.9842527	4.107826	17.39531	-0.9699176	0.3453814
VR expertise	-7.4495815	5.103526	16.96469	-1.4596931	0.1626444
Screen	-0.9695692	3.951569	41.16669	-0.2453631	0.8073944
VR	27.7346708	4.081678	41.72113	6.7949194	<.0001
Media Order	-4.2696620	2.009555	41.47282	-2.1246798	0.0396181

scores were run with the R emmeans package. The Bonferroni correction was applied. Test results indicated that the Raw TLX for VR was significantly higher than for Paper and 2D screen (both $p<.0001$). However, no significant difference was indicated for the Paper-Screen pair ($p=1$) (Table 7.3). The p-value of 1 indicated that the means were likely to be similar. The estimated means for the TLX score indicated that VR and Paper differ by 27.73, the means of Screen and VR differ by 28.70, and the means of Paper and Screen differ by 0.97 (Table 7.3).

The estimated marginal means for paper (39.02) and screen (38.05) were

Table 7.3: The difference in estimated marginal means of the Raw TLX score for each pair of Paper, Screen, and Immersive ESS Visualizer (VR) averaged over all types of expertise and media order.

Contrast	Estimate	SE	Df	t-ratio	p-value
Paper - Screen	0.9695692	3.951570	43.01678	0.2453631	1
Paper - VR	-27.7346708	4.085122	43.54406	-6.7891896	<.0001
Screen - VR	-28.7042400	4.079733	43.53264	-7.0358143	<.0001

lower than the estimated marginal means for VR (66.76) indicating that VR was more difficult for participants in this study compared with either Paper or Screen (Table 7.4).

Table 7.4: Table of estimated marginal means for Raw TLX score for each of Paper, Screen and Immersive ESS Visualizer (VR) averaged over all types of expertise and media order.

Media	EMMean	SE	Df	Lower CL	Upper CL
Paper	39.02429	5.846585	25.65376	26.99857	51.05002
Screen	38.05472	5.845545	25.63724	26.03076	50.07869
VR	66.75896	5.916853	26.62201	54.61051	78.90742

7.2.2 System Usability Scale (SUS) Scores

The SUS scores for paper maps, 2D screen, and VR indicated that the VR was more difficult to use than 2D screen or paper maps (Figure 7.4),

13 participants stated that they agreed or strongly agreed that they would need the support of a technical person to use the system compared to 1 participant agreeing with the statement for paper, and 2 agreeing or strongly agreeing for the 2D screen (Figure 7.5).

Participants generally felt confident with the Immersive ESS Visualizer, with 10 people agreeing or strongly agreeing, that they felt confident, 7 neutral, and 5 disagreeing, or strongly disagreeing. Participants also generally felt confident using the 2D screen and the Paper.

When asked if the functions in the system were well integrated. Responses between the 3 systems were similar with 11 participants stating that they either agreed or strongly agreed for VR, 11 participants also agreed or strongly agreed that functions of the screen were well integrated, and 10 participants agreed that the functions of the paper maps were well integrated.

A linear mixed effects model was run on the SUS score data in order to test for correlations among map expertise, location expertise, data expertise and VR expertise within the media conditions, and to test for differences in the SUS score among media. The fixed effects were map expertise, location expertise, data expertise, VR expertise, media and media order. The Spatial technology expertise was not included in the model, due to the similarity with the map expertise. The model had an intercept for ID as a random effect to group the three SUS scores per participant, one for each of the three media conditions. Residual effects were plotted to check normality and homoscedasticity assumptions for the linear mixed effects model, however, there were no visual discrepancies to suggest that assumptions were violated. A Shapiro-Wilk normality test was performed indicating that the null hypothesis of normally distributed residuals should not be discarded ($W = 0.98351$, p-value = 0.4873). P-values to test the significance of the fixed effects are reported in a Type III ANOVA summary table (Table 7.5).

After adjusting for expertise and media order, the SUS score significantly differed between media ($p < .0001$, see Table 7.5) indicating that the null hypothesis of no correlation between Media and SUS scores should be discarded in favour of the alternative hypothesis that a correlation exists between Media and SUS score (Table 7.5).

The level of VR expertise for a participant had a significant effect on their SUS score ($p=0.04576$, see Table 7.5), indicating that the null hypoth-

Table 7.5: The ANOVA table for testing the significance of correlations in the linear mixed effects model for SUS score.

	Chi sq.	Df	p-value
(Intercept)	12.9984161	1	0.0003118
Maps	3.1551963	1	0.0756856
Location.expertise	0.4901956	1	0.4838401
Data.expertise	0.0016963	1	0.9671472
VR.expertise	3.9902631	1	0.0457639
Media condition	92.0822928	2	$<$0.0001
Media order	3.0577655	1	0.0803521

esis of no correlation between VR expertise and SUS scores should be discarded in favour of the alternative hypothesis a correlation exists between VR expertise and SUS score (Table 7.5). The coefficient estimates table indicates that for every one unit increase in VR expertise, the SUS score increased by 7.2012 units (Table 7.6).

The correlation between Map expertise and SUS score was near statistical significance (p=0.07569) indicating that the null hypothesis of no correlation between Map expertise and SUS scores cannot be discarded in favour of the alternative hypothesis (Table 7.5). The coefficient estimates table indicates that for every one unit increase in Maps expertise SUS score increases by 10.8840 units (Table 7.6).

Pairwise comparisons of estimated marginal means of the SUS scores were run with the R emmeans package. The Bonferroni correction was applied. Test results indicated that the SUS score was significantly lower for VR than for Paper and 2D screen (both $p<.0001$). However, no significant difference is indicated for the Paper-Screen pair (p=1). The estimated means indicate that VR and Paper differ by 31.31, the means of Screen and VR differ by 28.84, and the means of Paper and Screen differ by 2.48 (Table 7.7).

Table 7.6: Coefficients for the linear mixed effects model for SUS scores.

	Estimate	Std. Error	Df	t-value	p-value
(Intercept)	50.7975505	14.089564	21.84696	3.6053316	0.0015844
Map expertise	10.8840444	6.127413	18.28150	1.7762872	0.0923316
Location expertise	14.3634494	20.515119	17.64705	0.7001397	0.4929679
Data expertise	-0.1198875	2.910845	18.32177	-0.0411865	0.9675927
VR expertise	7.2012423	3.605011	17.70841	1.9975643	0.0613638
Screen	-2.4750768	3.487046	42.14424	-0.7097919	0.4817422
VR	-31.3134977	3.596045	42.90884	-8.7077603	<.0001
Media Order	3.0981578	1.771746	42.56338	1.7486468	0.0875616

Table 7.7: The difference in estimated marginal means of SUS scores between each pair of media averaged over all types of expertise and media order.

Contrast	Estimate	SE	Df	t-ratio	p-value
Paper - Screen	2.475077	3.487047	43.03704	0.7097917	1
Paper - VR	31.313498	3.600120	43.78212	8.6979048	<.0001
Screen - VR	28.838421	3.595473	43.76605	8.0207577	<.0001

The SUS scores for Paper (81.80) and Screen (79.32) are both higher than the SUS score for VR (50.49), indicating that Paper and Screen were perceived to have higher usability than VR (Table 7.8).

Table 7.8: Table of estimated marginal means for SUS score for each of Paper, Screen and VR media averaged over all types of expertise and media order.

Media	EMMean	SE	Df	Lower CL	Upper CL
Paper	81.79951	4.301811	29.45653	73.00724	90.59178
Screen	79.32443	4.300713	29.43115	70.53408	88.11478
VR	50.48601	4.372803	30.74894	41.56467	59.40735

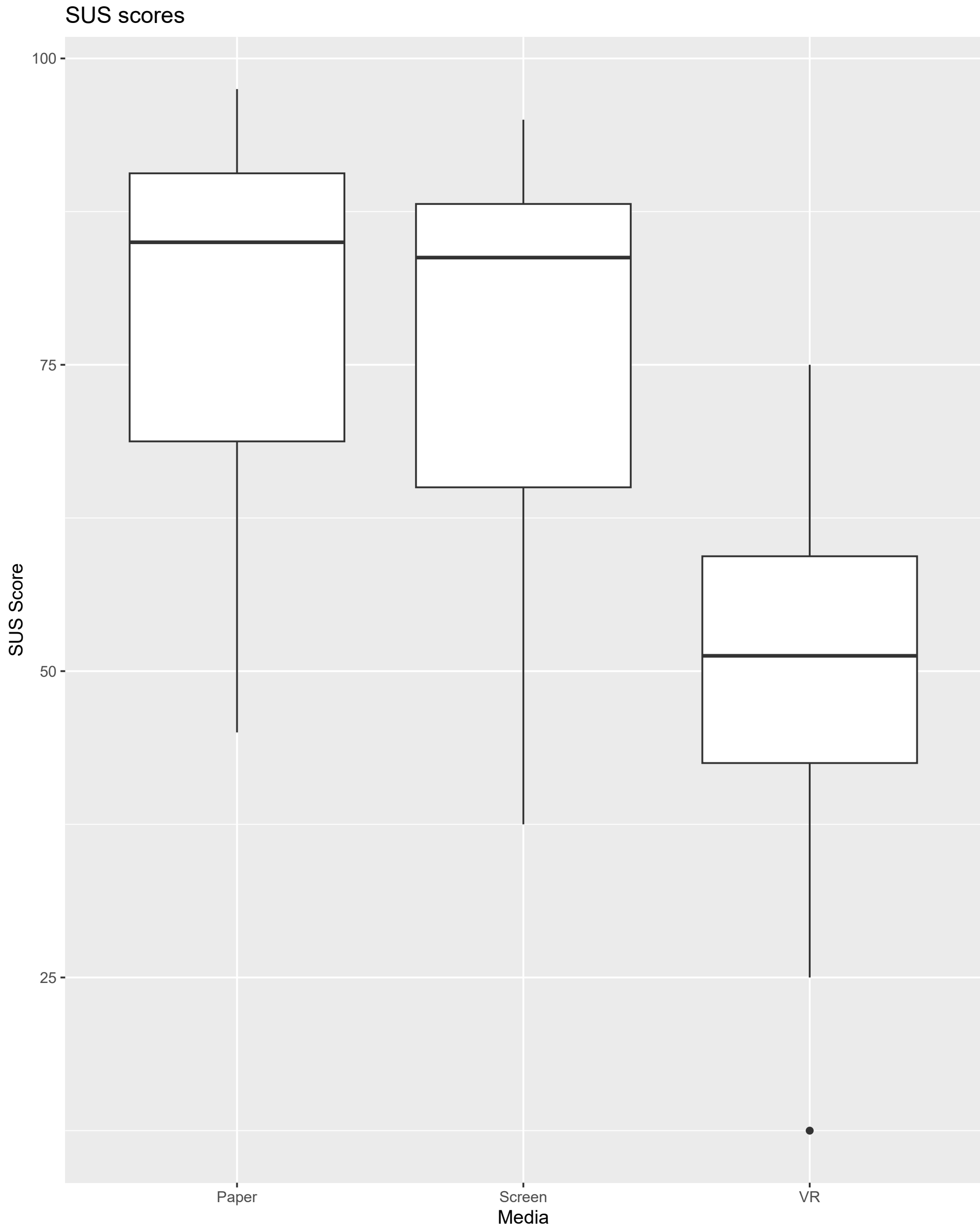


Figure 7.4: SUS scores for VR, 2D Screen, and Paper maps

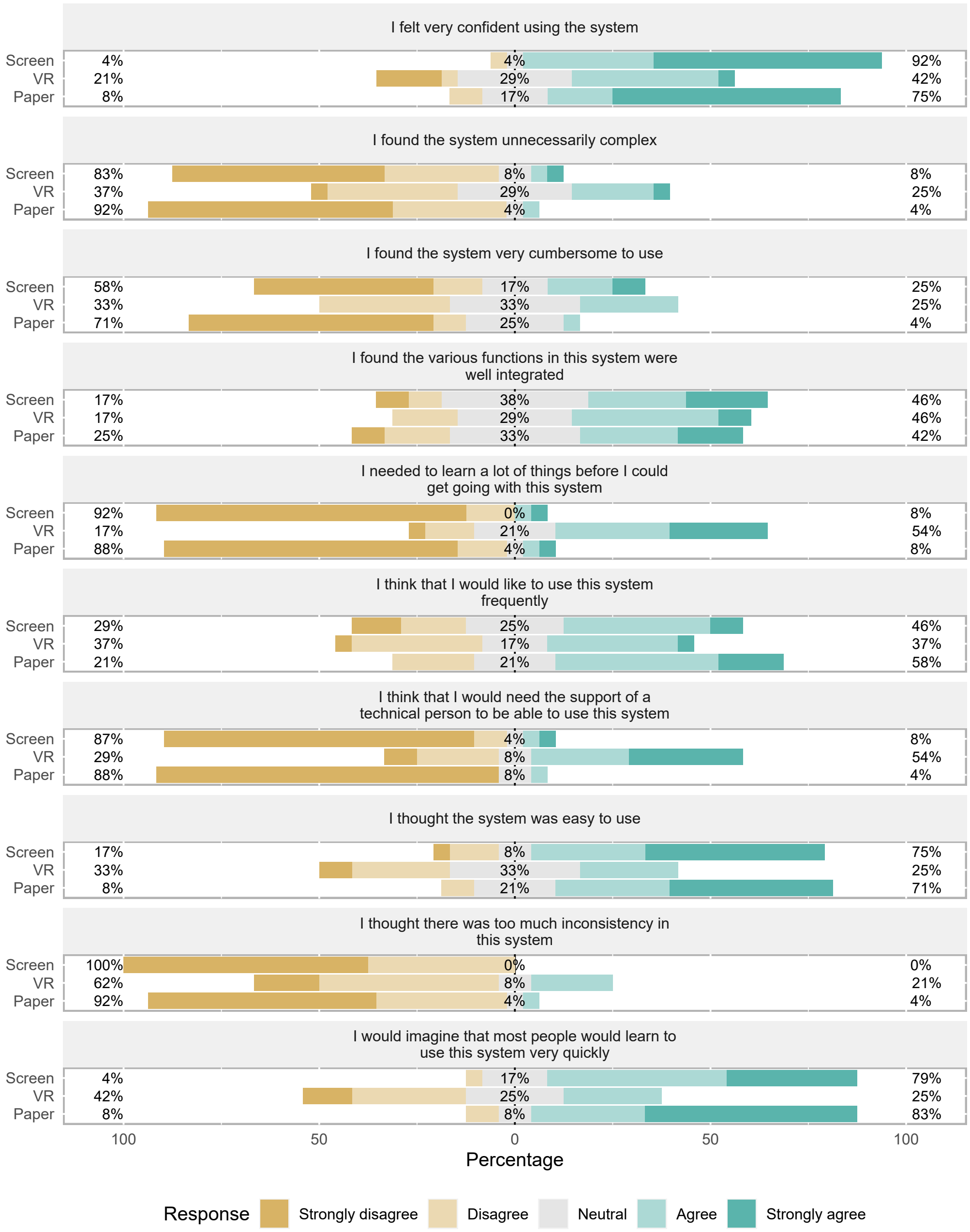


Figure 7.5: Likert scales for individual SUS score questions for each media.

7.2.3 Effectiveness scales for Immersive ESS Visualizer features

Effectiveness scales for the VR features indicate that the file list, tab menu, handheld map, and zoom buttons were most effective (Figure 7.6). The file list was the highest ranked recieving 19 responses indicating either effective or very effective. The tab menu received 17 responses indicating effective or very effective. All features were ranked positive other than the legend. The handheld map data layer was ranked higher than the scenario map data layers. The scenario map data layer has 11 participants ranking effective or very effective. The map lighting button received 4 negative responses, 4 neutral responses and 13 positive responses. Further discussion of these rankings is discussed in Section 7.6.

7.3 User study coding

Participant responses for the user study were coded according to a complete coding method [40] with user study transcripts, post-study questionnaire forms and observational notes coded. Three top-level categories were Background, Observations, and Sentiment (Figure 7.7). Initial background categories were created by inspecting the structure of the background questionnaire since coding the top levels according to the background would make analysis easier by facilitating a direct comparison. These top-level categories were then broken down into sub-categories, then codes. "Observations" comprised statements made by participants about data, visualization techniques, potential use cases, questionnaires, questions or suggestions relating to the data.

The positive and negative categories grouped the sentiment of statements. These categories were kept separate from the visualizations as the statements could be positive, negative, neutral or informational. The location category contains statements made that required local knowledge

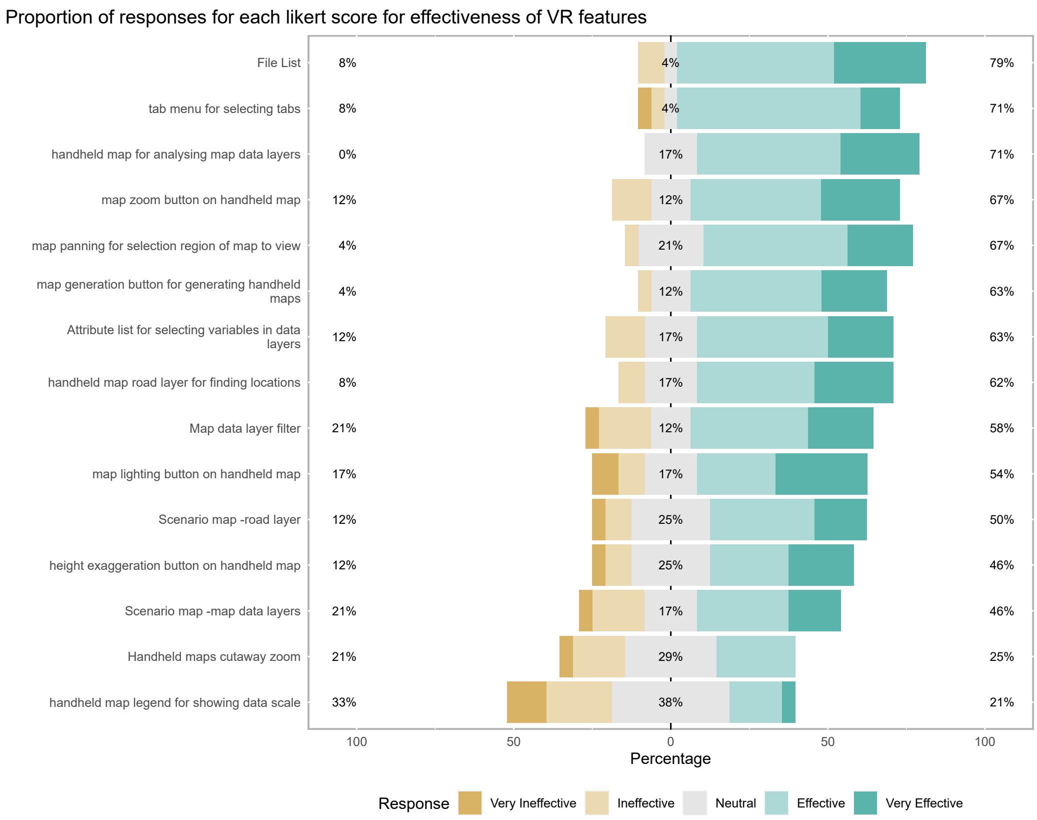


Figure 7.6: Effectiveness scales for features

about the Mangatarere catchment area, such as references to landmarks made without the map layer, or references to roads and other geospatial data. The Dataset category coded statements made about the data which relied on knowledge of variables, such as nitrogen and phosphorus, hydrology or soil science. The GIS category was subdivided into constraints with past experience, Familiarity with GIS Systems, and Spatial literacy. The Constraints with past experience category coded statements where participants viewed past experience with GIS systems as a limiting factor to their ability to learn or use the VR system. The Familiarity with GIS systems category coded statements where the participant refered to their knowledge of GIS systems or compared their experiences in a medium to

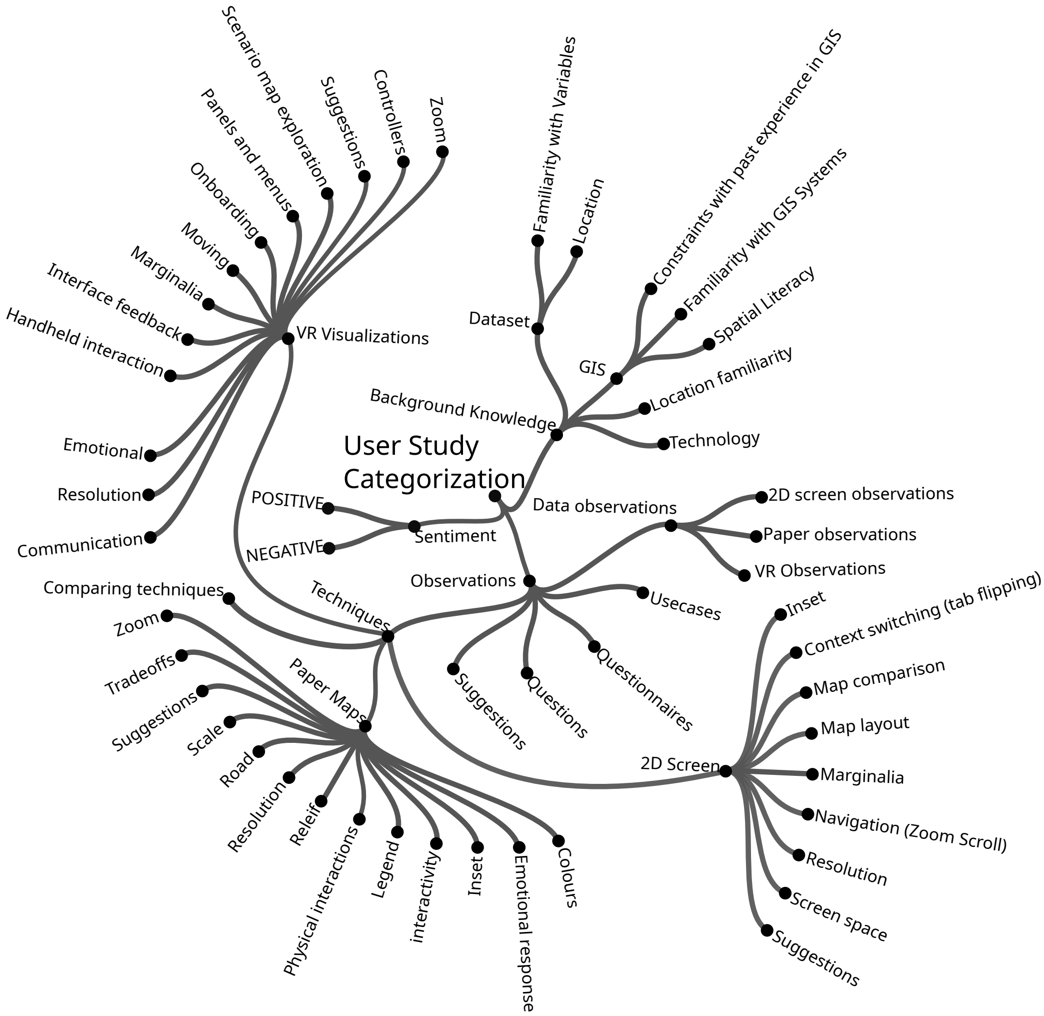


Figure 7.7: Categories used to code the evaluation user study

their past experiences using GIS Systems. The Spatial literacy category coded statements relating to the participant's knowledge of spatial concepts relating to GIS. The technology category contained statements relating to familiarity with video games, software requiring 3D navigation, game engines, hardware, other VR software, or specifics of GIS software.

The data observations category coded the participant's observations of the dataset which they made when they use each media. The techniques category coded the participant's statements relating to each visualization media and features. The comparing techniques category coded observations made by participants about their discussions when they self-reflected on similarities or differences between their completion of the task in different media, or their own discussion comparing the experience of using each media.

The paper maps category coded responses to features and interactions with the paper maps. The Colours category coded responses to colours on the paper maps. The inset category coded participant responses to the insets inside the wetland restoration maps shown for Task 1 of the paper maps questions. The interactivity coded participant responses to their ability to interact with the paper maps. The Legend category coded responses to the legends provided with the paper maps. The physical interactions category coded interactions that involved participant movement such as arranging the maps in a grid or switching between them. The tradeoffs category coded responses relating to the tradeoff maps. The scale category coded responses to the paper maps physical size. The resolution category coded responses to the resolution of the paper maps.

The VR Visualizations category was subdivided into categories for individual features that participants discussed when they were in the study session as well as the following categories. The communication category coded statements made by participants about the experience of communicating while in VR or in other media. The resolution category coded the participant's responses to the level of detail. The Emotional category coded the emotional responses to the visualization. The Handheld Interaction category coded interactions with the handheld map, generating handheld maps. The marginalia category coded the participant's interactions with map marginalia such as the legends, colour scale, and markers. The Moving category coded the participant's responses to the positioning of handheld maps, discussion about their positioning of themselves in relation to the scenario map, physical movement and gestures. Scenario map exploration coded responses to the exploration of the data with scenario maps. The Suggestions category coded visualization ideas that are suggested by participants to either augment the VR with functionality or apply fixes to perceived defects. The Zoom category coded responses relating to zooming while in VR, the participants could refer to the movement towards and away from the scenario map as a form of zooming as well as using the zoom button features.

The 2D screen category was subdivided into categories for features of the 2D screen such as navigation with Zoom and Scroll features, layout of maps on the 2D screen, marginalia. Context switching coded participant responses to flipping between different tabs.

7.4 Qualitative results

This section discussed themes extracted from coded questionnaires and user study audio recordings by inspecting codes and concepts then relating them to the research questions. Figure 7.8 is a thematic map, describing conceptual connections between themes and subthemes extracted from the user study and connecting them to RQ1 and RQ2. RQ1 was addressed by answering two sub-themes: Effectiveness of map navigation for each media; Effectiveness of data comparison for each media (Figure 7.8). RQ2 was addressed by examining how features of VR assisted communication. Effectiveness of communication was broken down into the use of the 2D display and the use of map pointers in Immersive ESS

Visualizer.

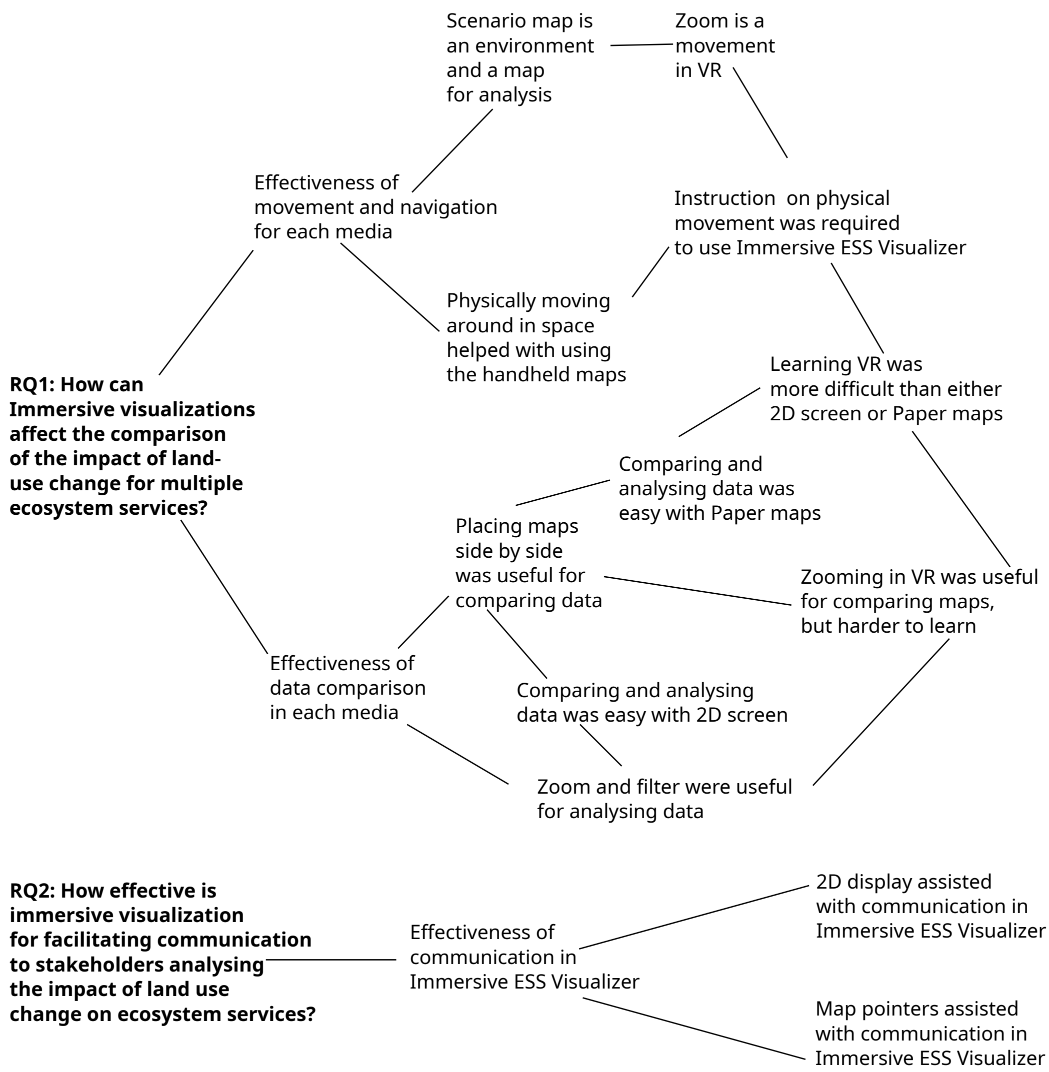


Figure 7.8: Themes extracted from user studies

7.4.1 Overview of subthemes in relation to interactions

The analysis of geospatial data involved inspecting the map, map navigation/finding a location of interest, zooming, filtering, reading and comparing data to extract results. Zooming was used as a method for navigating and finding locations in the 2D screen and in the VR media. The effectiveness of navigation in each media and the effectiveness of data comparison in each media were both broken down into subthemes which relate to the features of each media.

Effectiveness of comparison in each media

For reading and comparing data, participants used layer/tab switching (VR and 2D screen), side-by-side views (VR, 2D screen and paper), scrolling (2D screen), and moving maps around in VR. With paper maps, participants had more freedom over how the maps were positioned, as they had a larger surface and could place all of the maps provided simultaneously on the table. Since zooming and filtering both reduced the amount data shown, either spatially or based on a variable, they were grouped together. Zooming filters data spatially.

Subthemes of the effectiveness of data comparison in each media included: Zooming and filter were useful for analysing data; placing maps side-by-side was useful for comparing data; comparing and analysing data was easy with 2D screen; comparing and analysing data was easy with paper maps; and zooming in VR was useful for comparing maps but harder to learn.

Effectiveness of movement and navigation for each media

Movement in Immersive ESS Visualizer was used to navigate to places of interest, position handheld maps, and act as a zoom. Movement could be categorized as either physical movement or virtual movement, where physical movement required the user to interact with VR by moving themselves physically. Actions, such as walking inside the study room and grabbing maps, were examples of physical movements whereas actions, such as pulling a map from a distance and gliding, were virtual movements. Zooming and gliding are discussed in § 7.4.2. In VR, moving closer or further away with the glide function was a zooming method, whereas moving the handheld maps physically was a comparison method for arranging maps to make comparison easier, so movement was separated into two categories in order to analyse the participant responses. The handheld maps showed a map overview of the area of interest, and zooming out on the scenario map by gliding high above the surface, also provides an overview of the area of interest.

Subthemes for the effectiveness of navigation include: Physically moving around in space helped with using the handheld maps, the use of the scenario map as an environment as a map, Zoom is a movement in VR, and instruction on physical movement was required to use Immersive ESS Visualizer.

Effectiveness of communication in Immersive ESS Visualizer

Participants communicated with the researcher while they performed tasks with Immersive ESS Visualizer. Features of Immersive ESS Visualizer were used by participants to assist with their communication. Map pointers assisted with communication, and particiants incorporated the 2D display connected to the VR as a tool to show the researcher what they were looking at.

7.4.2 Effectiveness of movement and navigation for each media

This theme discusses navigation by zooming in VR and in the 2D Screen condition. The paper maps did not support zooming and participants needed to physically move maps to interact with paper, so paper is discussed in § 7.4.3 with regards to physical movement.

Movement through zooming Physical movement and virtual interactions with zooming in VR assisted participants to navigate to and analyse areas of interest when visualizing ecosystem services data.

Zooming to enlarge maps was supported in VR in three different ways. Zoom buttons were attached to the handheld maps, handheld maps could be grabbed and pulled close to a participants's face, and participants could glide (zoom) across the scenario map. participants could physically walk inside the room to move close to the virtual handheld maps as an alternative to zooming.

Scenario map is an environment and a map for analysis

Zoom and movement features in Immersive ESS Visualizer support data analysis at both catchment scales and across more localised scales. Two participants liked the benefit of being able to work with maps at two different scales in the VR medium. Participants could see a smaller map by either zooming out from the scenario map or interacting with the handheld maps.

Reasons to glide (zoom) included both inspecting data close up and also for feeling present in the location. Participant EV5 liked the ability to treat the scenario map as either an environment or a map, so they glided across the map as a zoom.

> *"I'm the sort of person that likes feeling like I'm in a virtual environment, but having the option to zoom away from it. So it's that real-time choice between am I treating it as an environment or as a map." - EV5*

Participants EV4, EV7 applied strategies which incorporated the use of both handheld maps and scenario maps simultaneously. They zoomed out far from the scenario map so that it could be used as a smaller map, but participant EV22 felt too far away to see the information.

> *"Ah and you can go back as well and you can zoom right out. Yeah. Amazing. Ohh that's cool. Oh, that's neat. That's awesome. Can you go side to side?" - EV7*

> *"I find myself using the big environment almost like one of these maps*

> *sometimes and then, but it's nice having the kind of [the ability to] jump around between different ones." - EV4*

> *"My gut instinct must be to do that. Always feels like I'm too far away for me to really see what's going on. " - EV22*

Participants EV11 and EV15 both compared movement and zooming. Participant EV11 reported feeling that movement and zooming were different.

> *"There's this kind of strange disconnect between zooming a map and moving it closer to you. It is two different things." - EV11*

The use of the scenario map as either an environment or a map demonstrated an advantage of Immersive ESS Visualizer over paper maps or the 2D screen. Both paper maps and the 2D screen are non-immersive, so participants were not able to inspect the landscape as an environment, and incorporate that perspective into their analysis strategy in either paper maps or the 2D screen condition.

Movement and zooming with handheld maps

Participants could zoom with the handheld maps either by using the zoom buttons, or by physically moving close to the handheld maps. Zooming with the handheld maps received positive responses because the zoom allowed participants to inspect details close.

> *"So I do like that. Without the zoom function, you'd have the same problem again as the paper." - EV4*

> *"I was able to uncheck and check the layers more, and I was able to zoom in as much as I wanted so those aspects of the interactivity were good, and there's a thing that I was frustrated about with the paper and the 2D." -EV24*

Participant EV15 compared the ability to walk close to the map as a substitute for zooming.

> *"Didn't really zoom into the map, I just walked up close to it and then walked back again. " - EV15*

One limitation of having zoom buttons for the handheld map was the size of the buttons, and attempting to hit small buttons at a distance. Two participants compared the zoom function favourably with the paper maps and the 2D maps. There were concerns that the paper maps and the 2D maps had insufficient resolution for the zoom functionality.

Physically moving around in space helped with using the handheld maps in VR Participants commented on the action of moving the map in VR. However, some assistance was required when instructing the participants to reach out and grab the handheld maps with the controller. Two participants reported that after gaining their confidence to physically walk, their self-reported feeling of success improved when using VR (EV11, EV23).

When participant EV23 commented on learning to use the VR they found that walking around helped in relation to using the handheld maps.

> *"Once I realized I can use my feet everything became easier, yeah." - EV23*

Participant EV11 discussed placing handheld maps in VR and arranging them as becoming easier after they started physically walking around in the VR space .

> *"When I got to the third task where I wanted to see the three, five metre, ten metre, fifty metre, knowing that there was a difference to be seen because of doing it previously, I did just about get to the point where I could put these three things [handheld maps]. I can kind of arrange them and then start looking, and I think at that point I was moving around in the space a bit more than I had been before." -EV11*

Participant EV10 was awestruck by the feeling of being able to reach out and grab a map to move it around.

> *"Ok and then you can put it there, I've got it. And then, OK, wow, that's incredible. Yeah, and then I could go back. I could do that again I suppose. OK, I'm moving the whole thing." - EV10*

One participant reflected on learning to physically move while in the headset. Another participant also reported that they lacked the confidence to walk while wearing the headset.

All participants except two chose to stand up if they had started sitting down. It was possible for participants who chose to sit to move around in a chair with wheels. However, due to the positioning of the handheld maps, and their size, standing participants appeared more mobile and able to reach around maps.

Participants could either walk/wheel forward to grab a map that was out of reach or use the grip button to bring up a blue circle and press the trigger to pull the map closer. Two participants commented on maps appearing to come too close when using the blue circle feature to summon a map from a distance.

Users required instruction on physical movement to use Immersive ESS visualizer.

Three participants did not find the Zoom helpful for the 2D screen due to insufficient resolution (EV7, EV12, EV17), while three participants (EV2, EV11, EV24) did.

Participant EV2 found zooming was helpful with the 2D screen.

> *"I can see some nuances now at this scale. When I zoom in I see that this is all green." - EV2*

In the VR, the handheld maps were larger, and participants EV2, EV4, EV12, EV13 indicated that they found working with the handheld maps was too close. EV12 suggested a feature for moving maps further away.

One participant indicated that the provided data layer for the paper maps was only showing places where the flow was being reduced rather than showing the amount of water that would be flowing.

"I don't know how much, I find it a difficult, slightly difficult ecosystem service to conceptualise. It's just either flow mitigating or not, you want to know like how much water, or is it stopping a flood in an important place? So I guess that doesn't really tell you, that just shows the buffers. Basically, this almost looks like a restoration scenario map I would say. " - EV13

"OK. I guess if I were to critique my only use of the VR, I think I didn't use a 3D part of it that much, I guess. I think maybe that's from being used to using 2D maps and that's how I use this data set. Usually, I used it as a 2D map so I would create static visualizations. We know it's supposed to be a reality scenario where you can interact, but I actually think the static 3D maps would also be useful."

[Researcher]: "So you mean placing maps into the VR, but not necessarily having them interactive? Is that what you mean by static?"

EV13: "Yeah, having seen views of the targeted areas, I could see myself thinking that helps me understand this scenario a little bit more. So I think sometimes it's hard to visualize the way the valleys look." - EV 13

7.4.3 Effectiveness of data comparison in each media

Placing maps side by side was useful for comparing data

When using paper maps, participants were able to move maps around. One of the perceived advantages of having physical media for one participant was the ability to see all of the information at once without the constraint of zooming where map data outside the area of the screen was not visible.

Participants EV9, EV17, EV21 and EV24 applied an analysis method where they positioned maps close to each other side by side to look at them in VR. The ability to look at the maps side by side was perceived by EV24, and EV9 as a useful feature for assisting with the analysis.

> *"Comparing trade-offs. Trying to compare maps and riparian planting. I think my approach was the same to get the two maps visible. The approach was to get two maps side by side and look at them in the VR." -EV21*

> *"Yeah, it's handy to have them in a side by side." -EV24*

> *"So this would be quite good then. You can put them side by side." -EV9*

Matching up Zoom levels for side-by-side maps was a method that EV12 was observed applying to both the 2D screen tasks and the VR handheld maps.

> *"I'll put zoom map so I can see both sides both in the same view. And I can looking over the key." -EV12*

One participant suggested that the arrangement of the handheld maps in the VR was good for analysing data because they were able to see two maps at once. Though another participant found that maps were too far apart when they were positioned. Participants had different styles for positioning the maps, and some were observed attempting to line up the maps without intersecting them or obscuring the control panel, where another participant created an intersected arrangement of maps.

> *"Yeah, combination of zooming in and hovering over the area. And then, but it's nice to have, to be able to do two up displays and choose the equivalent data at the two different things." - EV4*

> *"It's quite hard to move them, because they keep coming closer. Do you know? I mean like, I want them to be in my visual range, so I have to turn my whole head." - EV13*

There were also participants who predominantly focused on the hand-held maps rather than on the scenario maps

Paper maps were provided in a pile to participants for each question. When analysing data with the paper maps, the participants were observed flipping through paper maps, arranging them side by side, arranging them with legend overlapping, arranging into a grid layout, or arranging them in groups of three. One participant, EV21, folded and asked to staple the wetland restoration maps to organise them so that the inset boxes were closer together.

An advantage of the paper maps was being able to arrange them and see everything at once.

> *"Yeah, it's nice on these printed maps because you can put them all up in front of you and compare different aspects of the story." - EV10*

> *"It's more than moving them, it's arranging them. So being able to arrange them according to dimensions. Seeing them all at once." - EV5*

Participants were also able to draw on the paper maps, to indicate locations to the researcher. One participant commented that drawing on the maps was helpful.

> *"So being able to draw them is quite nice and it helps me actually engage in them. So now I know what I'm doing." - EV5*

The 2D screen tasks required participants to use a PDF reader to visualize data. Features used by the participants included placing windows side by side, tabbing, flicking between tabs rapidly to make differences flash, and scrolling. When analysing data with the 2D screen, the participants were observed, scrolling, placing PDFs in different tabs and flicking between them, placing maps side by side in different windows. When arranging maps on the 2D screen, users could place two maps side by side, however, unlike paper the users were not able to view six maps all at once on one display screen.

EV3, EV4, EV6, EV16, EV18, EV19, EV22, EV23, and EV24 reported that positioning maps side by side helped with analysis when using the 2D screen. However, EV14 reported that flicking between maps was difficult. EV13 reported that it was difficult to get the maps close enough. EV5, EV6 and EV11 reported that placing two maps on one page was not helpful as the arrangement was vertical. However, EV24 found that placing 2 maps on a page did help.

When discussing the 2D screen analysis:

> *"But the advantage of using this medium, I would say is you know, I can put them parallel and then zoom into an exact area that I want to compare and then read much more clearly than a paper medium" - EV 18*

The physical size of the screen was identified as a limiting factor to the map comparison by participant EV5.

> *"When the maps are laid out, I just don't have as much screen real estate." - EV5*

Context switching

One participant, EV4, commented that tabbing between maps to toggle on and off in the 2D screen, like in the VR had an advantage over paper as they could indicate differences through switching.

> *"I find that the toggling and this is what I was doing in the VR, like just being able to turn things on and off so much easier to notice the differences between things." - EV4*

One participant EV21 indicated that they needed to line up the PDF's in the same spot in order to flick between them. A disadvantage of the 2D screen was that users needed to adjust the size of the maps individually to compare maps which were the same size.

Participant EV4 commented that switching between maps was a disadvantage because they needed to make a mental switch. Participant EV13 commented that they could not get the maps close enough and zoomed simultaneously.

> *"One of the big advantages of the VR was being able to turn the layers on and off individually, to try and to clean the trade-offs, to try the component layers. It didn't need to be 3D to be able to do that. That could have been achieved on the 2D so I feel like the 2D version was very much just a screen version having two paper maps. So I think there's another option more like a traditional GIS where you can manipulate 2D maps." - EV 13*

Lining up the zoom levels so that maps on the 2D screen had the same scale was problematic for Participant EV13.

> *"What's harder about this one is I can't really get the maps very close together easily, you could do it very easily with the paper, but probably, I don't know if it's just me comparing but I think I find this one a little bit harder to do than the paper maps, just because I can't get them close and to be zoomed at the same time." - EV13*

Five participants (EV9, EV12, EV19, EV22 and EV24) used scrolling functionality to switch context between maps on the 2D Screen. EV9 and EV24 indicated that applying scroll to switch context between different maps was difficult.

> *"It's difficult. Yeah, it's difficult to see if you're just scrolling backwards and forwards between them." - EV9*

> *"I find it actually a little more difficult because I'm scrolling between the two maps." - EV24*

One participant had difficulty with the 2D screen because they were not able to see maps simultaneously, and were not able to toggle between them in layers, though participant EV4, EV21 used tabs to flick between map layers. The disadvantage of the tabs was needing to line up maps to flick between them.

Participant EV5 commented that PDF maps were hard to see on the screen at once, compared to using GIS software. However, the task for paper maps was about reading the results of an analyst's PDF report. In order to test with a GIS software platform, participants without domain expertise would also need to use the GIS platforms designed for experts.

> *"So it's really hard. You can't see the maps on the screen at the same time. If I was using a Geo platform, I would expect to be able to toggle layers on. " - EV5*

When comparing the 2D screen to the VR:

> *"It almost feels simpler in the sense that it's less. You're probably taking in less information because it's 2D where potentially in the VR environment I'm looking for specific things, but I'm also quite interested in looking around and I'm taking more in. This feels a little bit more flat and specific, which might be useful in some cases, but yeah, I think I lose that ability to quickly check." - EV 14*

> *"I found the Tea Creek Rd. exercise easiest on paper because of the comparison aspects. I found task 2 most useful on VR because I could get around the scale issues of paper and screen." - EV 17*

Immersive ESS Visualizer could assist with relating data across different maps by making it easier to line up layers and switch between them, as changing layers with the handheld maps does not require the user to line them up like with separate windows on the 2D screen condition.

Emotional Responses Emotional reactions included the fear of falling, feeling weird, and feeling like the researcher could see everything.

Participant EV15 reported fear of falling.

"It's alright as long as I don't look down and I think I'm about to step off the edge of a cliff and fall down into space. It's fine looking at the thing, yeah." - EV15

Participants EV9, and EV15 reported weird feelings associated with being in VR.

"It's daunting because you're looking at a weird, like, with the headset on and everything as well, it feels very unreal. So you've also got this your brains is trying to compute having something in 3D around you looking at a map like that. As well as different colours at the same time." - EV9

"Quite weird I gotta tell you." - EV15

VR was more difficult to learn than either 2D screen or Paper maps Two participants discussed the complexity of learning VR and getting practice with the tool to become familiar. The VR software was identified as more difficult to learn than the 2D Screen or the paper maps.

"I need to spend more time getting used to it. I mean, that's neat, and obviously what I'm trying to do here is in the real world sort of. So it's a very cool way to visualise what's going on. I think I'd need quite a bit more practice just to become familiar enough with it to get more out of it than I would get from just looking at a hundred maps or, you know, static maps on the screen. But I can imagine the power of this. I just feel like I'm a bit of a bunny and don't quite how to how to tap into it right now, but it's very neat, it's really amazing." - EV10

"I mean, I think within the time frame of the session. It's quite hard to, I mean, maybe people who played more video games or whatever would be more immediately in there and understand the possibilities better than me." -EV11

> *"It's hard till you figure it out, and it's very easy to feel overwhelmed, but then once you've figured it out and you know the thing that's massive in your face, you've grabbed it and pushed it back and you realise you got control over it then it's just trying to answer the questions." - EV8*

Suggested Improvements for VR Features to augment the handheld maps suggested by participants included vectorization (EV5), linked settings (EV12, EV17), a clone tool (EV17), and linked zooms (EV17). Vectorizing the map layers would avoid pixelation. Linking settings of the handheld maps, linking zoom levels, and supplying a clone tool would reduce the need to apply settings to several different handheld maps by providing a way to synchronize them, or copy settings between maps.

Participant EV13 suggested a difference raster as a method for comparing layers by visualizing the difference between them.

Change maps were suggested as a possible way to assist with showing differences between layers.

> *"This one. It's really difficult to see the differences. I would say a change map would probably be the most would help with that." - EV13*

Differences in the scale of the areas of observation were also commented on by one participant.

> *"Yeah, this particular analysis is focused on the whole landscape in a different way than the other one was but you could presumably do the same thing if you wanted to zoom into a box but it's not telling us do that. I don't know why is that it's just a very different feel. You can see the same things as it's more homogeneous in terms of its usability or its importance. Whereas this one, some core areas come out because more services have been added." - EV13*

When inspecting data with the 2D screen participant EV4 suggested vectorization to improve zoom capabilities.

> *"Yeah, so the zoom would be, you know, if this was fully vectorized, obviously you could zoom in. But you do have that same limitation as the printed maps, but it's definitely easier in this view." - EV4*

EV5 disliked the pixelation of the paper maps and suggested vectorization.

> *"I found that. I could see the pixelation and that bugged me." - EV5*

Colour schemes and legends

The responses to the colour scheme of each media were mixed. The paper maps and the 2D screen had a red-green colour scheme, and the VR had a sequential white/purple colour scheme. One participant indicated that they did not like red-green colour schemes (EV11), and one participant had difficulty with the red-green colour scheme as they identified that they were colour blind (EV6). One participant indicated that red stood out and made the red easy to identify, but changes in the greens were more difficult to identify as the differences between the greens were more subtle (EV10).

> *"I suppose in the colours, [homogentity] significantly enhance, stand out because the red is the obvious thing. I don't know, I can see changes in that more obviously, than I can in some of the others. Greens, light greens model services. When you look closely, you can see the differences, but it's not so obvious." - EV10*

The legends for the paper maps were liked by participants EV2, EV5. However, participant EV5 also indicated that they were unsure of how extreme the red side of the scale was for the data compared to national levels.

> *"I think for me the single colour. The one advantage of the paper maps, I think was probably the heat map colour ramp, compared to a single colour." - EV5*

> *"The legends are a lot more clear here." - EV2*

> *"There's a sense that if it lights up as red, that you go, well, this is the highest in the current data set, but there's no sense of whether that's actually within a normal range for the whole country, for example. So it might be leading saying, oh, this is a potentially a problem area but actually well within what you would expect?" - EV5*

Another participant liked the red-green colour scheme for the 2D screen.

> *"Yeah, that box is really useful actually. The colour scheme is very useful I know exactly what's going on." - EV2*

2D display and the laser pointer assisted with communication in VR. Communication in Immersive ESS Visualizer involved conversing with the facilitator while using the system to perform tasks. Features used for communication included the laser pointer attached to controllers, zooming in or out from maps, the 2D screen attached to the VR system for the facilitator, the handheld maps, side-by-side comparison, and road labelling.

> *"A lot of just the toggling between maps. Yeah, that's what I mainly used." -EV13*

11 of the 24 participants (EV3, EV5, EV6, EV7, EV11, EV13, EV15, EV17, EV18, EV21, and EV24) commented that the laser pointer assisted with communication. The laser pointer was observed being used to gesture, circle and point at areas on the handheld maps.

> *"Well actually I found the communication all right because you could understand what I was saying. You could clearly see what was good, which features in the system. So like. I mean, like me, pointing the laser pointer. That was cool." - EV7*

10 participants (EV2,EV3, EV12, EV15, EV22, EV24, (hillshade), EV4, EV5 (height exageration), EV8, EV9) found the handheld maps effective for communication. The handheld maps were observed being used as a prompt, or a target for the laser pointer. EV3 discussed road labels as a communication tool for describing locations. EV17, EV2 found the large scenario map effective for communication.

The handheld maps in VR were able to be zoomed and 9 participants (EV2, EV3, EV4, EV6, EV8, EV9, EV10, EV12, EV15) found that zooming was effective for communication.

4 participants (EV3, EV9, EV12, and EV15) specified side-by-side comparison as effective.

3 participants (EV4, EV7, and EV24) commented that the external 2D screen connected to the VR was effective for communication. Two participants, (EV7 and EV13) discussed their experience with using the VR made them feel like the conversation was understood. Participants indicated that they felt like the researcher knew what they were talking about when referring to map data in the VR. The VR laser pointer tool ranked as useful to assist with communication by circling points of interest on the handheld maps so that the researcher could see the laser pointer on the screen, as the point was under discussion using the laser pointer.

Participants were able to converse with the researcher about data while in the VR, as the screen was showing the researcher what data the participant was referring to. Participants reported an awareness that the researcher was able to see what they were seeing.

> *"It was good I guess I felt like what I was describing to you more was my experience using the VR, less than the findings of the things. Good, I thought it was good, I felt like you understood what I was talking about. I think you understood what I was saying, you knew what I was talking about." - EV13*

> *"Sweet, I can just look over there and [the researcher] knows exactly what I'm looking at, even though well, I was up on the screen." - EV8*

Participant EV8 found that Immersive ESS Visualizer did help communicate the results of ecosystem services analysis.

> *"Yeah, people are engaged. So if you wish to communicate for some outside application, the system of communication, as I said before, just the whole system really, like just telling someone to go into VR to look at something or whatever. It's pretty effective." - EV8*

Participant EV8 reported feeling like communication was easier with the headset on.

> *"For some weird reason I felt like it was easier for me to communicate my findings to you as the researcher when hidden behind a mask, so to speak. I felt like I could, OK, maybe that's because this is your project or whatever, but I felt like wearing it, I could just say anything, whatever. I weirdly thought that you were seeing exactly the same thing that I was seeing, even though you weren't if that makes sense." - EV 8*

7.5 Discussion

Thematic analysis was used to qualitatively analyse the data, identifying themes and sub-themes from the categorization of codes (Figure 7.7). These themes were: How effective is navigation for each media? How effective is data comparison in each media? How effective is communication in Immersive ESS Visualizer? This section discusses the results in the context of published literature.

7.5.1 Effectiveness of movement and navigation for each media

In VR navigation can be performed by gliding (zooming) across the scenario map, or by zooming and panning the handheld maps. Participants referred to the glide across the scenario map as a zoom and they used the glide to bring the scenario map closer and inspect details. Navigation in the 2D screen had scrolling and zooming available. It was not possible to zoom in and out with paper. Participants required instruction to assist them with learning how to physically move and place maps. Participant responses to Immersive ESS Visualizer suggest that physical movement was more difficult in VR than in 2D Screens or Paper maps. However, this was expected because paper maps required less movement to position on a table compared to moving around in the room with VR, and the 2D screen was a sedentary task.

Comparing movement through zooming and gliding with VR systems in literature

The zoom feature in VR received positive feedback. In Immersive ESS Visualizer the zoom function was reported as useful by 13 participants for analysing data, also 9 participants found it useful for communication. Handheld maps were provided in front of the user when the VR application started. The handheld maps had road layers available as a tab menu option. The handheld map was in a vertical orientation. A study of interaction strategies for augmented reality geo visualizations, allowed participants to inspect a 3D model of a city with a planned route before asking them to navigate a route in a first person Cave environment. Gardony et al. [68] provided the 3D city model in a horizontal orientation, like a table top model. Gardony et al. found that participants who zoomed first rather than changing the orientation of the city model to top-down were less able to navigate the visualized route in the cave environment. Immersive ESS Visualizer provided a vertical orientation to ensure that users saw an overview first which may have contributed to the positive qualitative responses for zooming by removing the need to reorient to see an overview. The vertical configuration of Immersive ESS Visualizer assisted with user navigation when finding Tea Creek Road by providing an overview.

Comparing physical movement for map placement in literature

Moving around in physical space helped participants to reach out and grab the handheld maps in the VR system. In Immersive ESS visualizer, participants were observed comparing a small number of maps side by side. Layouts created by participants while using Immersive ESS Visualizer also generally avoided occluding maps, though seven participants were observed allowing maps to overlap when reading parts of the maps that they were interested in. When using Immersive ESS Visualizer, Fifteen participants were observed with map layouts that partially occlude controls which indicates that moving maps close together to cover map controls was one strategy frequently used by participants. Most participants did not position maps so that they overlapped. More participants allowed controls to be occluded compared to the number of participants who allowed the maps to become occluded. Six participants applied tilting techniques (Figure 7.9 a),b),h)) to angle maps towards or away from themselves. Frequently used positioning techniques in Immersive ESS Visualizer included positioning maps around the user at a 90-degree angle to other maps, or a more obtuse 120-degree angle. Users generally compared either two maps or three maps. Participants tended to move their heads less to compare when maps are closer together, so tilting and occluding maps seemed good strategies for comparison. EV2, EV4, and EV7 applied strategies which used both the scenario map and handheld maps, where the scenario map became an overview. However, generally, the handheld maps were used more in Immersive ESS Visualizer than the scenario map. Handheld maps were highly regarded for analysing data in the effectiveness scales with 4 neutral and 17 positive responses However, the scenario map was less highly regarded for analysing data with 5 negative, 4 neutral, 11 positive responses.

Qualitative observations for the arrangement of handheld maps in Immersive ESS Visualizer, seemed different to responses reported by Satriadi et al. [147] for map arrangement. They found that users in VR avoided oc-

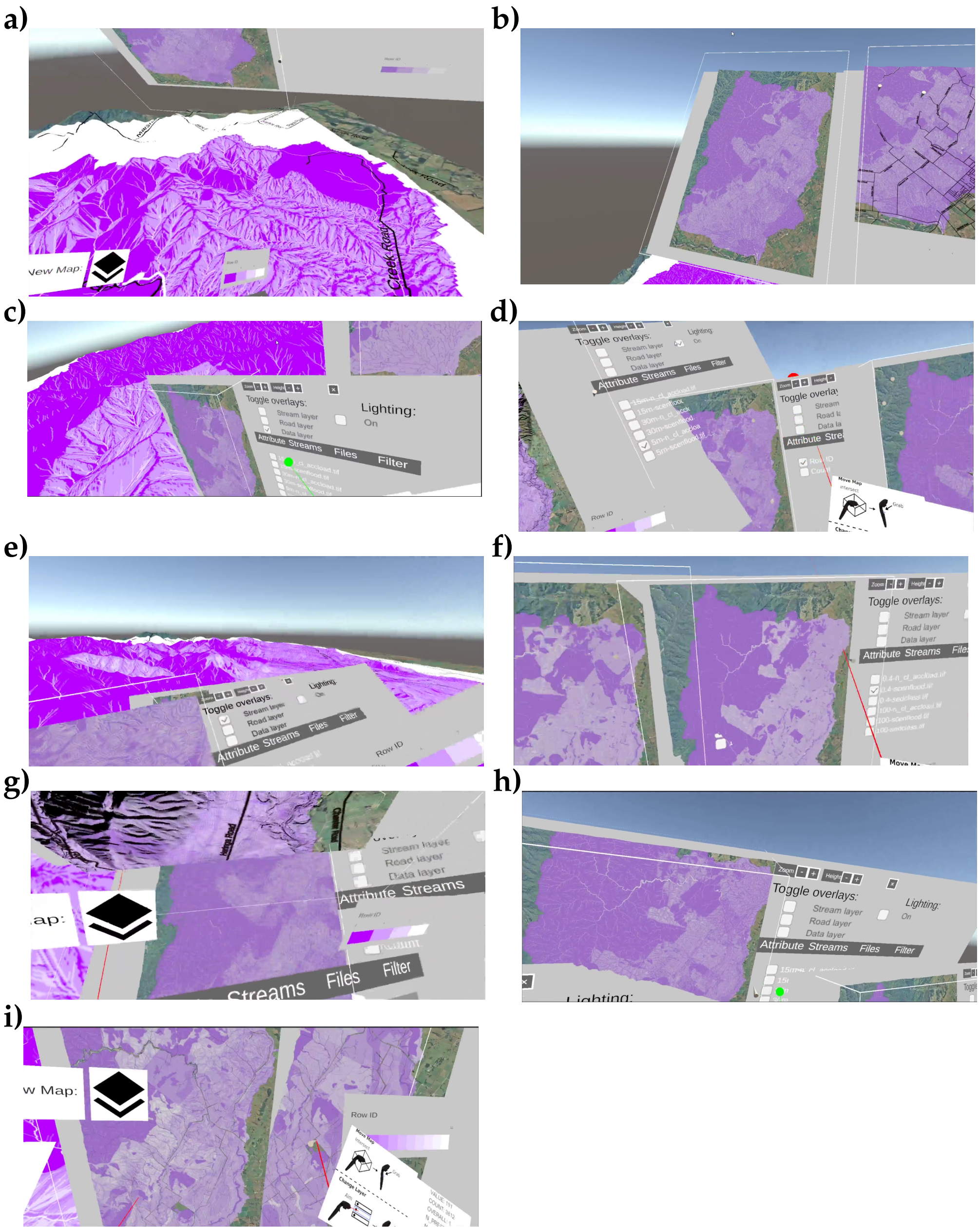


Figure 7.9: A selection of map arrangements created in Immersive ESS Visualizer by participants. a) Two handheld maps were being used, they were both facing each other, so only one handheld map is shown. The user was glancing up to the handheld map and down at the scenario map below to make comparisons. b) Two handheld maps were next to each other in the same orientation, The right map was zoomed in showing roads and controls on the left map are occluded. The left map was zoomed out. Both maps were tilted forward adjusting the viewing angle. c) Two handheld maps were being compared, panels were unobstructed. d) One handheld map was to the left, two in front at a 90 degree angle to the left map, the tab menu of the centre handheld map was obscured. e) Two handheld maps, one in front, one behind, the map in front was tilted down to reveal the scenario map underneath for comparison. f) Two handheld maps were next to each other in the same orientation, the map on the right was obscuring the controls for the map on the left. g) Two handheld maps composited together for a comparison by looking up and down. h) Three handheld maps were next to each other, the map in the centre was pulled through to the front by tilting the top towards the user, revealing the file list. i) Two handheld maps were next to each other, with the left map clipping into the right map intersecting.

cluding maps and that participants preferred the largest map size of 80x80 cm. In Immersive ESS Visualizer maps were a fixed size of 100cmx150cm. Immersive ESS Visualizer allowed users to pan and zoom handheld maps, however, Satriadi et al. [147] did not provide map controls to do this. The availability of zoom controls and map panning could account for a lesser need to use a larger number of maps in Immersive ESS Visualizer. In Satriadi et al. the zoom levels of maps were fixed. One difference between Immersive ESS Visualizer and Satriadi et al. [147] was that the participants were a convenience sample recruited from a university and information was collected on familiarity with VR and reading maps. The data tasks were route finding and shape comparison. However, these tasks do not require expert knowledge to complete. When comparing ecosystem services with Immersive ESS Visualizer, the participants were recruited from users with expertise in GIS and community members with knowledge of the Mangatarere catchment area. So differences in the participant expertise and the analysis task could affect the types of comparisons that participants wanted to perform, and how participants incorporated existing knowledge into the completion of the tasks.

One participant, EV7, suggested designing the interface of Immersive ESS Visualizer so that the user could walk around the scenario map. Using a virtual map table could allow the user to walk around the scenario, however, an advantage of flying was gliding to zoom out for an overview or zoom in to view details and experience the world as an environment. Lochhead et al. [110] incorporate the ability to grab and position maps in VR, IVEVA has a VR room design with a map table, and smaller displays that could be positioned. However, usability testing of IVEVA was not reported.

7.5.2 Comparison of Data in VR

Qualitative results suggested that placing maps side-by-side helped with comparing data in all media, however, VR was perceived as more difficult to learn and use than either the paper maps or the 2D Screen. Effectiveness scales suggested that the handheld map was considered more effective than the scenario map for comparing data.

Placing maps side by side was useful for comparing data

In Immersive ESS Visualizer both layer switching and side-by-side comparison were supported through the use of map placement and layer switching. Placing maps side by side in the 2D screen and VR was useful for comparing data. Participants were able to flick between layers in the VR and this helped their analysis. Some participants using the 2D screen suggested layers would have helped with analysis. Mapstack [155] supports side-by-side comparison through grid layouts and stacking. The study found that map blitting was preferable to users with low peak saccade velocities, low saccade amplitudes and long fixation duration. Users who preferred grids had fast peak saccade velocities. Some users of Immersive ESS Visualizer reported feeling that they could not get maps close enough together. However, side-by-side comparison was reported as a feature beneficial for communication. Meva [83] provided side-by-side visualization for simulation runs through split-screen displays. However side-by-side comparison through split screen would require displaying through a medium which would support this method of drawing. An advantage of having floating maps is incorporating a landscape-size scenario map with smaller maps for multi-scale comparison.

In Immersive ESS Visualizer, 3D navigation experience was collected as a sub-component of VR expertise and VR expertise had a marginally significant correlation with the SUS scores of participants. In evaluating MapStack [155] researchers found that users with 3D game experience had a preference for the grid layout over the stacking layout or the map blitting.

7.5.3 Emotional reactions

Positive emotional reactions were reported by participants EV10, EV20, EV21, EV23, EV5, EV7, EV8, EV24.

> *"It's brilliant. I can see why people get hooked on this." - EV20*

When picking up and grabbing a map participant EV10 responded with the following remark.

> *I've got it. And then OK, wow, that's incredible. Yeah So and then I could go back. I could do that again, I suppose, OK I'm moving the whole thing. - EV10*

> *"I could play with this all day." - EV24*

EV8, EV9, and EV15 reported emotional reactions associated with being in the VR world, including weird feelings, or the fear of falling. Hruby et al. [87] suggest that testing 1:1 spatial presence in geo-visualization could be a different scenario to testing 1:x scale geo-visualizations, as looking at a virtual globe on a screen has a different perspective to looking at the world from the perspective of being there. EV5 reported having the choice between treating the scenario map as an environment or a map. Participant EV5's response suggests that they were experiencing a difference in perspective and how they were interpreting the Scenario map depending on where they placed themselves in VR. When evaluating Immersive ESS Visualizer spatial presence was not tested, however, qualitatively. Though participants EV7 and EV4 incorporated both the scenario map and the handheld maps into their analysis, participants generally used one or the other at once. So participants treated these tools differently.

7.5.4 The VR laser pointer and the connected monitor assisted with communication

Participants could communicate with the researcher in VR, and participants could use the VR laser pointer to communicate what to look at on the monitor connected to the VR. 11 participants commented that the laser pointer assisted with communication. Zooming and handheld maps were also beneficial for communication, and a larger number of participants were assisting their communication with the handheld maps, rather than the scenario map.

In Immersive ESS Visualizer only one user had the VR headset and the facilitator was able to talk to them and see what they were pointing at on the 2D screen. However, participants commented that the 2D monitor showing the VR assisted with their communication with the facilitator. A study of a Soil boundary mapping system in a CAVE environment allowed soil scientists to collaboratively visualize soil maps and draw boundaries [78]. The system used a tablet as control input and a head tracking device. Soil scientists could draw onto the tablet and see changes on the CAVE environment. In the CAVE environment soil scientists could talk to each other about the data and scientists could see the results in stereoscopic 3D. An advantage of VR over the CAVE environment is the reduced cost, the ability to transport VR to an area of interest to engage local participants, and high-quality stereoscopic rendering without light from the room entering the HMD and the 2D screen did provide sufficient feedback to the facilitator to answer questions and have a discussion, so in the context of presenting results to a user, the communication was effective. In future work multiple VR headsets could be investigated for allowing more than one participant simultaneously, however for demonstrating to users when there is one person using the VR at a time, the 2D screen monitor provides an interface where the facilitator can be fully aware of surroundings while interacting conversationally. Forsberg et al. [67] suggested that the Adviser system for geo-visualization in a CAVE environment could assist with communication between engineers and geologists with users sketching on a tablet while other users can see what they sketch in the CAVE environment, e.g sketching waypoints, and planning routes with a Mars rover [67]. Immersive ESS Visualizer could potentially facilitate similar collaboration with a user in VR explaining features in VR and showing them with a laser pointer on a 2D screen for users who are in the room, and users could take turns with the headset.

Handheld maps and communication The scenario map was used for both comparing layers and as an environment, however in the post-study questionnaire more participants identified that handheld maps were more helpful for communicating their results than the scenario map. 10 participants specified that handheld maps were helpful, and 2 participants specified that the scenario map was helpful, but Batch et al. [33] performed a user study asking users to first explore economic data in the visualization system ImAxes, and then arrange the visualizations for presentation to a third party. The presenter used the monitor to view presentations that were prepared in VR by the participant while the participant talked about what they found while using the VR system. In Immersive ESS Visualizer a think-aloud protocol was followed [125] rather than asking the participant to perform a separate presentation phase. Batch et al. found that participants who did not have experience with VR experienced difficulty with navigating, and that participants physically walked more when presenting to the facilitator than when presenting their data. Participants using ImAxes stayed in the same place and placed visualizations in the nearest available space rather than walking. An advantage of VR was the sense of immersion. The arrangement of the Handheld maps suggests that improvements to how maps could be moved at a distance could make map layout easier. SUS score and TLX results from Immersive ESS Visualizer suggest that participants with more VR expertise found the system more usable. In Immersive ESS Visualizer video game expertise is a subcomponent of the VR expertise, and Batch et al. did not find evidence that video game expertise assisted users who did not have experience with VR systems.

The qualitative responses from Immersive ESS Visualizer suggest that participants found that it was effective for communicating their findings to the facilitator, so could potentially be a presentation tool. Qualitative responses from participants using ImAxis reported by Batch et al. [33] suggest that participants could use ImAxis for preparing presentations.

7.6 Strengths and weaknesses in each media

A strength of VR was the ability to inspect fine details of the data. Immersive ESS Visualizer allowed users to apply a combination of techniques, zooming, comparison between data layers, filtering and the hillshade to inspect fine details.

Participants EV1, EV3, and EV4 commented that VR assisted them in looking at fine details

> *"Helps me look closer to the beneficial areas that are difficult to see in the 2D maps /screen." - EV1*

The hill-shading in VR received positive feedback from participants. Zooming in on data layers was possible in the 2D Screen environment. However, VR allowed users to turn on and off the hillshade, which could identify topology.

12 participants (EV3, EV7, EV8, EV12, EV13, EV14, EV15, EV17, EV18, EV21, EV22, EV24) provided positive comments about the hillshade. The hillshade received four negative responses in the effectiveness scales (EV2, EV5, EV6, EV15). Participant EV15 suggested that the map lighting button wasn't required because the stereoscopic 3D was already showing the relief. However, EV18 found that the map lighting button made the elevation more realistic.

> *"Hillshade/lighting very useful for identifying topography." - EV3*

> *"Very localised zoom/flying options in map environment. [It] was possible to see changes on the banks of individual streams." - EV4*

The communication capabilities of Immersive ESS Visualizer received positive feedback. Participant EV8 suggested that VR could be effective for communicating to people.

> *" Telling someone to go into VR and look at something would be effective." - EV8*

> *" Could change perspectives in tools in real time as I talked." - EV4*

Filtering was discussed as an advantage of the VR over paper maps, as the VR system was interactive.

> *"This one has the disadvantage of me not being able to interact with the results and I can't just filter, just show me this for example." - EV2*

VR allowed users to rapidly open and close layers to view on the handheld maps. In the 2D screen files were in a separate file browser, and users could tab between files they had open, however lining up layers on tabs to flick between them was more difficult than having the ability to flick between them on the handheld maps.

The disadvantages of the VR were the Legend and colour scale, the physical demand of using VR. Difficulty of learning physical movement. With paper maps it was also possible to switch between maps, but as the number of maps increases. The difficulty of printing could be a limiting factor.

Paper maps strengths and weaknesses

Physical layout, drawing on them, and Familiarity Paper maps had the advantage of a physical layout on a table to see the maps. Users could inspect them all at once on the table. However, if the number of maps was much larger it could get more difficult. Paper maps could be drawn on, and some users annotated the maps while communicating with the researcher. It was possible to use the VR laser pointer as a communication device, and the use of annotation for the paper maps was similar to the use of the VR pointer. Further research may be needed to establish whether marking the page is as important as the gesture, as Immersive ESS Visualizer had markers available, but the laser pointer was used more frequently than markers.

15 participants gave positive comments about positioning paper maps (EV5, EV6, EV7, EV9, EV10, EV11, EV12, EV14, EV15, EV16, EV17, EV21, EV22, EV23, EV24). Paper maps had the advantage of familiarity participant EV23 stated that

> *"Paper is super easy to use as this is what we know, we don't have to think to be able to make a quick assessment" - EV23*

Comparing and analysing data was effective with Paper maps Paper maps were effective for making comparisons between scenarios for ecosystem services as evidenced by the median SUS score of 85 compared to the score of 51.2 for Immersive ESS Visualizer (Figure 7.4). The median TLX score of 42 was smaller than the VR TLX score of 71 (Figure 7.3) indicating that the paper maps had a lower workload than the Immersive ESS Visualizer. However, a disadvantage of the paper maps was that the system was not interactive, so it was not possible to filter data or zoom to make the same highly detailed observations as in the VR.

2D Screen strengths and weaknesses

The 2D screen had the advantage of being able to zoom. However, participants indicated that Zooming in VR was more effective than zooming with the 2D screen. Neither the 2D screen nor the paper elicited the same emotional reactions as VR when inspecting data. Neither the 2D screen nor the paper maps had a scenario map which functioned as an environment as well as a map. A disadvantage of the 2D screen was that participants could not draw on the maps. The size of the 2D screen was suggested as a limitation by participant EV5, as there was less space to position maps.

> *"When the maps are laid out, I just don't have as much screen real*

estate." - EV5

Comparing and analysing data was effective with 2D screen

The 2D screen was effective for making comparisons between scenarios for ecosystem services as evidenced by the median SUS score of 83.8 compared to the SUS score of 51.2 for Immersive ESS Visualizer (Figure 7.4). The median TLX score of 33 for the 2D screen compared to the TLX score of 71 for the Immersive ESS Visualizer (Figure 7.3) indicates that the 2D screen had a lower workload than Immersive ESS Visualizer. However, a disadvantage of the 2D screen was that the system did not have the data filtering capabilities of Immersive ESS Visualizer, or the ability to inspect details with stereoscopic shaded elevation.

7.6.1 Summary

This section summarises findings from analysing the evaluation of Immersive ESS Visualizer. The paper maps and the 2D screen were perceived as more usable in general than VR based on statistically significant TLX and SUS Scores. However, the VR system had the following advantages over 2D screen and paper maps:

Strengths of VR:

Zooming, and glide movement help data comparison

The zooming function was beneficial for data comparison as evidenced by its high effectiveness score, and positive qualitative feedback. The vertical configuration of how maps were presented to participants may have assisted them with their use of the zooming function as a navigational aid.

Zooming helps with communication

The zooming function was beneficial for communication as evidenced by qualitative responses to the post-study questionnaire about features that assisted with communication. Zooming assisted participants in using the handheld map while talking to the researcher about the data displayed on the map.

2D display and the laser pointer helps with communication.
The 2D display and the laser pointer were both considered useful by participants as communication tools. Participants could point at areas on the handheld maps while looking where they were pointing and knowing that the researcher could see their gesture on the 2D display plugged into the VR. Feedback from post-study questionnaires shows that the 2D screen and the laser pointer were often used by participants as a communication tool.

Participants communicate easily with the researcher.
Qualitative feedback from participants indicated that they felt like the researcher could see what they were seeing, which assisted with their communication. The 2D screen assisted the researcher with understanding what the participants were referring to when they were talking. The researcher could not see the elevation of the maps in stereoscopic 3D, though for the purposes of Immersive ESS Visualizer this was not a significant disadvantage as the researcher had sufficient knowledge to provide necessary assistance. Future research could investigate integrating more users into the same virtual world.

Scenario map is both an environment and a map.
The scenario map was used as an overview by zooming out, or as an environment by gliding around, or close to the map. Gliding was referred to as zooming in and out, suggesting that participants could use the glide to focus on areas of interest as well as for movement.

3D layouts are possible with map tilting in VR
Observation of screen recordings for participants in VR indicates that participants positioned handheld maps in configurations that were three-dimensional as well as in side-by-side configurations. Three-dimensional layouts incorporating map tilting reduced the distance required for map comparisons,

which would be beneficial to the usability of the VR for participants adopting tilt, such as in Figure 7.9 a),b),h).

Weaknesses of VR:

VR was more difficult to use, However, participants with more VR expertise ranked the system more usable

VR was ranked more difficult to use based on the SUS and TLX scores compared to paper maps, and the 2D screen. The TLX scores for how successful the participant ranked their performance also indicated that people ranking their experience as successful had competent or proficient VR expertise. Participants suggested that they would get better with further training, and observations indicated that participants gained confidence with the system as they progressed through the tasks. TLX scores indicate that participants ranked the mental demand of the VR system higher than the 2D Screen or Paper maps. However, there were a large number of features that participants needed to learn in order to use the system fully. The TLX scores for VR suggest that VR was more physically demanding than paper maps or 2D screen, however, this was expected as the VR system involves the physical actions of wearing a headset and using controllers. Physical movement could also have helped to position objects rather than relying on button presses for object rotation. Users were generally able to position handheld maps after learning that they could reach out and grab them. However, the TLX score assumes that physical movement is always a disadvantage.

The TLX score suggests that more physical demand is a negative. However, being physically active can also be beneficial. VR software that requires or promotes physical activity would get marked negatively on the physical demand TLX scale.

The SUS test scores suggest that as VR expertise increases participants had less difficulty using the VR system. Providing a longer training session could potentially reduce some usability issues associated with learning to use Immersive ESS Visualizer. However, due to time constraints and the sampling of working professionals as participants, the training needed to be kept short so that the study could be completed within a couple of hours. Incorporating more interactive elements into the process of training to use the system could potentially encourage physical movement and reduce the difficulty of learning to grab and move handheld maps.

RQ1 How can immersive visualizations affect the comparison of the impact of land-use change for multiple ecosystem services?
Users found that Zoom helped with their comparison of data in VR, and being able to zoom in to compare data was an advantage of the VR system over paper maps. Users were able to inspect fine details in the VR and use hillshade interactively as part of their analysis. In Immersive ESS Visualizer the file list, tab menus, handheld map, and zoom buttons were the most highly-ranked features of the VR system based on effectiveness scales (Figure 7.6). The legends, and scenario map were less effective. The colour scale received mixed responses. Users could incorporate 3D layouts to compose maps together and compare. Users had the option of using the scenario map as either an environment or a map, which was an advantage over 2D screens or paper maps which did not provide an immersive scenario map. Handheld maps allowed users to create layouts with multiple maps, and users often used 2 or 3 maps when performing their analysis. The file list was ranked the most effective. Users could flick layers on and off to compare data. Layers with Immersive ESS visualizer had an advantage over layers with the 2D screen they were automatically aligned with the map elevation, and tilting was applied to assist with layout and also to inspect 3D terrain. Layers with the 2D screen could not be tilted. The paper maps allowed users to see all of the maps at once, however with a large number of maps, the physical printed maps could become more difficult to use. Immersive ESS Visualizer provides the benefit of immersion and allows users to zoom in and see details that they were not able to see with

the 2D screen and paper maps. However, Immersive ESS Visualizer was more difficult to use, with a lower SUS score (median 51.2) compared to paper maps and 2D screen, and a higher workload indicated by the raw TLX (median 71). Users did need to move more physically to use the Immersive ESS Visualizer. However, more physical movement was expected and physical movement is not necessarily a disadvantage when users have learned how to grab and place maps in the VR world. Since users were learning how to use Immersive ESS Visualizer as they were completing tasks, the workload may decrease as users become more accustomed to the tool.

RQ2 **How effective is immersive visualization for facilitating communication to stakeholders analysing the impact of land use change on ecosystem services?** When using Immersive ESS Visualier participants used the laser pointer, and the connected 2D display to communicate with the researcher. 11 participants commented that the laser pointer assisted with communication. 10 participants found handheld maps effective for communication. Side-by-side comparison and zooming were both features reported as beneficial for communication. Communication received positive feedback from participants indicating that they could easily communicate while inside the VR headset and indicate to the researcher what they were seeing. Immersive ESS Visualizer could potentially be used in a group setting as a communication tool.

Chapter 8

Conclusions

Contents

Ecosystem services are the benefits provided to humans by ecosystems through their naturally occurring processes. Land use is how humans manage, alter, and conserve the ecosystem services and goods provided by the land [59]. Modelling ecosystem services can assist with analysing and predicting the effects of land use change so that land use change results in the best outcomes for stakeholders by helping to identify which land is best preserved, and which land should be changed. Interviews and focus groups with users of LUCI identified the need to compare ecosystem services among land use scenarios, and communicate the results of an ecosystem services analysis to stakeholders. These requirements motivated the research questions of this study.

- **RQ1: How can Immersive visualizations affect the comparison of**

the impact of land-use changes for multiple ecosystem services?

- **RQ2: How effective is immersive visualization for facilitating communication to stakeholders analysing the impact of land use change on ecosystem services?**

Better tools are needed for analysing data from ecosystem services analysis, so a visualization system (Immersive ESS Visualizer) was designed and implemented as part of this research project. To answer the research questions, we evaluated Immersive ESS Visualizer with 24 participants with different levels of expertise and experience.

8.1 Overview

When developing and evaluating Immersive ESS Visualizer(§ 5), a user-centred design process was followed (Figure 3.1). The process was iterative and involved gathering user requirements through focus groups and interviews, responses to requirement gathering informed the development of personas, and designs were developed to show participants as part of the requirements gathering. A selection of features was implemented in the first prototype and demonstrated to land use scientists. Then the prototype was further developed and shown to members of a conservation community group in the Mangatarere catchment area of the Wairarapa region, New Zealand.

The effectiveness of Immersive ESS Visualizer compared to a 2D screen and paper maps for analysing data was evaluated by a user study. When analysing the results (§ 7) of the study, the user's expertise was categorized based on the results provided in a pre-study questionnaire using the method in § 6.3.1. The criteria for measuring expertise were developed for this thesis, and categorised based on map reading, data, geospatial analysis tools, VR and location. The method of calculating location expertise necessarily ranked participants between novice and expert. However, because the catchment area was the cutoff, participants living near to Carterton (e.g Greytown or Masterton) would not be counted as having location expertise unless they were visiting the catchment area frequently. Historically living in the catchment area was not factored into location expertise (e.g several years ago); since living experiences are unique and personal, they could develop different knowledge through being in the area. Qualitatively, users who had location expertise used local knowledge to provide explanations data which they were inspecting. However, the sample size of users with location expertise was small. The availability of people with knowledge of the location was limited by COVID-19. So, this could have impacted the balance of expertise the final design required to use effectively.

The level of VR expertise for a participant had a significant effect on their SUS score (p=0.0457639, see § 7.2), so the method of ranking VR expertise was useful for detecting differences and further research could develop techniques for ranking VR expertise and understanding the effect of VR expertise on user study results in immersive analytics.

The level of Map expertise was not found to have a statistically significant effect on either SUS or TLX scores for the application, though a positive correlation was found in the SUS scores. The choice of questions was designed to be completable by both map experts and non-experts, and the choice of questions could affect perceptions of workload or usability. Further studies on more technical questions could be investigated further to find out if experts and non-experts have differences in their approaches to analysing data.

The personas were useful for choosing features and working through the process of completing analysis and visualization tasks. The personas had goals representing participant requirements for these expertise groups using ecosystem services models.

When investigating RQ1, the user study found that Immersive ESS Visualizer was effective for inspecting details in the ecosystem services data; participants adopted 3D layouts which would not be possible in the 2D screen or paper map media, zooming and the handheld maps were reported as useful features, and users found the experience emotive.

The use of 3D layouts gives users the advantage of being able to place and store information in a virtual environment which they can refer to by manipulating the interface.

Emotional reactions can affect self-presence [63]. Qualitative analysis of the user study suggested that participants found the experience emotive and further research could determine how emotional reactions affect the analysis of the data. Emotional reactions were generally positive, and positive emotional reactions could give users engagement with the material [63]. Qualitative responses of participants within Immersive ESS Visualizer suggested that VR was useful for the participants communicating their analysis to the researcher.

Immersive ESS Visualizer was less usable on the SUS scale and had a higher workload measured by the NASA TLX compared with either the 2D screen or paper maps. These results indicate that Immersive ESS Visualizer could be harder for inexperienced users to pick up and use immediately. Participants who practice more with VR technologies could have less difficulty with using Immersive ESS Visualizer. Further research into tutorial materials and onboarding for users with less expertise could reduce the difficulty with learning to use Immersive ESS Visualizer.

When investigating RQ2, the study found that Immersive ESS Visualizer was effective for participant communication with the researcher. Communication features included virtual laser pointers and 2D display showing the facilitator what the participant was looking at in VR. Participants reported that they found the facilitator's 2D display and the virtual laser pointer useful for communicating results to the facilitator. The laser pointers were used to indicate areas on handheld maps while participants discussed them with the facilitator. Participants reported that the zooming feature was effective for assisting with communication. Zooming was used with the handheld maps to show areas on the handheld maps to the facilitator for discussion. The communication features in Immersive ESS Visualizer received positive responses. Research questions RQ1 and RQ2 are further discussed in (§ 8.3).

8.2 Contributions

This thesis makes the following research contributions:

- **Requirements for an Immersive visualization tool for ecosystem services analysis.**
  Interviews and focus groups collected information about the expertise of users of ecosystem services modelling tools (§ 4.1, 4.4, 5.4). Users interviewed had experience with the LUCI ecosystem services model or had local knowledge about the Mangatarere catchment area. The requirements could help to inform the development of similar VR visualization systems about what features could be helpful for similar users. The interviews and focus groups also helped to inform the development of personas in this research project, which could assist with further immersive VR software development. Features suggested by participants are in Table 4.3, Table 4.4 and Table 5.4. The requirements had some features in common which were liked by all groups: Zooming, interactive controls, the ability to change layers, the ability to generate visualizations, road layers, and features for comparative analysis. The MRS group also requested instructional materials.

- **An immersive VR visualization system for analysis of ecosystem services.**
  Immersive ESS Visualizer (§ 5) provided the following features: Scenario map, handheld maps, data layers for scenario map/ handheld

maps, tab panel, layer filter, attribute list, legend, map marker, and distance grab. The visualizations were provided in an Immersive VR environment, where users could navigate by gliding around the scenario map or zoom/pan the handheld maps to find locations of interest. Handheld maps could be grabbed by moving physically and pressing the trigger.

The adoption of 3D layout strategies in Immersive ESS Visualizer demonstrated an advantage over 2D screen and paper maps where content could not be positioned spatially. Three-dimensional content positioning techniques in VR took advantage of the ability to store content inside the virtual space, and created compositions which partially occlude to assist with comparison.

Panels were attached to the controllers or to handheld maps in the world then interacted with through a laser pointer and button presses on the controller.

- **Evaluation techniques for the user evaluation of geospatial immersive visualization software were extended through developing a categorization for relevant expertise.**

  The analysis of interviews and focus groups was used to inform the development of a questionnaire for ranking the expertise of users in the final evaluation. Evaluation techniques were extended through a method for ranking expertise. Participants were categorized according to their VR expertise, data expertise, spatial technology expertise, map expertise and location expertise according to the responses provided in a pre-study questionnaire. This novel categorization for expertise allowed statistical tests to be performed with linear mixed effects models to determine how differences in expertise related to differences in workload and usability. The Handheld maps received a high ranking on the effectiveness scales.

A user study evaluated the effectiveness of Immersive ESS Visualizer compared to paper maps and 2D screen. The user study results were statistically analysed, and a thematic analysis was performed on user study feedback recording transcripts and post-study questionnaire responses. The results of the user study were analysed to determine the effectiveness of Immersive ESS Visualizer compared to paper maps and the 2D screen for data comparison (§ 7). The participant experiences and researcher observations of communication in Immersive ESS Visualizer were analysed and compared to relevant literature to determine whether Immersive ESS Visualizer could be an effective tool for communicating analysis results to users while supervised by an expert.

The linear mixed effects model for statistically testing SUS scores with expertise found that participants with more VR expertise generally found the system easier to use as evidenced by the increase in SUS score with VR expertise. The expertise ranking allowed statistical testing with expertise relevant to the geospatial study domain which would not have been possible without expertise ranking. Research into statistically analysing participant expertise could be adapted to other research projects to enable an in-depth analysis of participant backgrounds.

An immersive VR Visualization system was implemented based on requirements developed from interviews and focus groups, then evaluated in a user study. The requirements developed from interviews and focus groups satisfy Objective OB1: To develop the requirements for an immersive visualization system for comparing the impact of land-use changes for multiple ecosystem services. Feature suggestions from participants were described in Table 4.3, Table 4.4 and Table 5.4. Navigation by zooming, changing layers to compare ecosystem services, comparing maps side-by-side, filtering, placing markers, zooming and gliding over maps were all features suggested. The immersive visualization system satisfied Objective OB2 : Develop an immersive geospatial visualization system based on the requirements gathered in OB1. Participants were able to use Immersive ESS Visualizer to analyse land use changes and were able to complete tasks set in a user study. Participants could communicate with the researcher while in the VR headset, features that helped with communication were the laser pointer, the handheld maps, and the researcher's 2D display to point out and discuss features of interest. Objective OB3 was satisfied by evaluating the effectiveness of VR in a user study. While participants rated the 2D screen and the paper maps as being easier to use, the VR had the advantage of being able to Zoom, examine details, inspect hillshade, and position maps in virtual space to compose together layouts.

8.3 Research Questions

Participants explored data from an ecosystem services analysis of the Mangatarere catchment area using three different media: Immersive ESS Visualizer, paper maps, and 2D screen. The following research questions were investigated:

RQ1 How can immersive visualizations affect the comparison of the impact of land-use change for multiple ecosystem services?
Handheld maps were ranked as effective (Table 7.6), physically moving around in space helped with using the handheld maps in VR, but participants required instruction on physical movement to use Immersive ESS Visualizer. VR was more difficult to learn and use than either 2D screen or paper maps (§ 7.5). However, users with more VR expertise gave higher SUS scores for Immersive ESS Visualizer. Participants found that zoom helped with their comparison of data in VR, and being able to zoom to compare data was an advantage of the VR system over paper maps. Immersive ESS Visualizer was good for inspecting the hillshade.

In VR, placing maps side by side was useful for comparing data, and participants were observed adopting positioning techniques that incorporated the 3D nature of the handheld maps to compose maps together and assist with their comparison such as tilting maps forward or backwards and placing maps with menu controls overlapping. Layout techniques included angling the maps around the user's position, or layouts that tilt or occlude (§ 7.5.1). The file list was ranked as the most effective feature on the effectiveness rankings for VR. The file list was used to select different layers to show on the handheld map or on the scenario map. The scenario map could be both an environment and a map, and could be used either as an overview or for inspecting details and being in the world.

Paper maps were good for inspecting ecosystem services because all the maps could be viewed at once and organized on the table, paper maps could also be drawn on, but paper maps were not interactive and did not allow data filtering. The 2D screen was good at making comparisons between scenarios. However, the paper map zoom was not as effective as Immersive ESS Visualizer, the maps on the 2D screen could not be drawn on, and toggling between maps was more difficult.

The SUS test and the Raw TLX score both reported significant differences between two pairs of media: VR and 2D screen; and VR and paper maps. However, no significance was reported between 2D screen and paper maps (§ 7.2). The SUS score and Raw TLX for VR indicated that it was more difficult to use generally. However, people with more VR expertise generally found the system easier to use as evidenced by the increase in SUS score with VR expertise. Participants frequently gave emotional responses to being in VR. Then emotional responses were generally positive.

RQ2 How effective is immersive visualization for facilitating communication to stakeholders analysing the impact of land use change on ecosystem services?
Immersive ESS Visualizer was effective for communicating ecosystem services analysis. The facilitator's 2D display showing the participant's view of the VR, and the pointer both assisted participants in communicating in Immersive ESS Visualizer (§ 7.5.4). Participants used the handheld maps for communication and pointed at the handheld maps with the laser pointers while they discussed findings with the researcher who was looking at the display. Qualitative responses from participants indicated that they could easily communicate while inside VR and they indicated that they felt that the researcher could see what they were seeing. The positive responses for communication in VR indicated that Immersive ESS Visualizer could be used by an expert to present results in a guided session. Visualization in VR could assist with communicating the results of ecosystem services analysis.

The main takeaway from this thesis was that although there were some difficulties with using Immersive ESS Visualizer, the benefits of spatially arranging maps, inspecting fine details, Zooming, and the emotional response to the VR provided sufficient benefits for VR to be useful to analyse ecosystem services data. As users get more practice, the usability issues with physical movement could become less of a concern and they could become more proficient with the tool.

Future VR tools for geospatial data should include the following features: Zooming features, features for spatial map arrangement, map comparison, layers, and features for hillshade. Participants indicated that they would like legend colour scale options.

8.4 Limitations

There were some limitations to this research.

The procedure of getting feedback from participants involved intermittently testing a prototype. Due to the remote location of some research participants, constraints on participant time, and COVID-19 restrictions, it was not possible to test as frequently as we would have liked with lower-fidelity prototypes. Community focus group participants saw a later version of the Immersive ESS Visualizer, rather than very early designs.

Due to the logistical issues associated with giving experts the application to administer themselves, it was not practical to give land use scientists a copy of the software to incorporate into their process for communicating results to non-experts in an in-the-wild study. Asking land management scientists to apply the visualization tool would also make it more difficult to collect detailed information on how effective visualizations were for participants inside the VR, as it would instead collect information on the perceptions of land management scientists incorporating it into group sessions. So an in-the-wild study was beyond the scope of this research.

Recruiting domain experts who analyse environmental data relating to ecosystem services, and people with local knowledge was challenging as the expertise was highly specialized. Due to the difficulty of recruitment, four of the participants lived in the Mangatarere region, and one participant was visiting monthly. The low representation could be a limitation, as there could be potential users from the Mangatarere region with views not represented in the sample. Due to the scope of this thesis, the recruitment of participants was limited to one user study.

Due to group presentations requiring a domain expert to facilitate, it was not possible to run a usability study in a group environment with Immersive ESS Visualizer. So tasks with paper maps and the 2D screen were representative tasks of what a user could perform with these media, based on the requirements identified in interviews and focus groups. A group study design was considered, however, due to the difficulties of separating what tasks different individuals perform to understand the effect of each media, and the requirement for domain experts to run group sessions administering the study, a usability test with individuals and a facilitator was chosen. An in-the-wild study incorporating an Immersive ESS Visualizer into a group environment could be performed as future work. Extending Immersive ESS Visualizer's data capabilities to work with larger geospatial datasets could involve applying level-of-detail algorithms to optimize performance.

Due to the accuracy required for visualizing the terrain data, a high-end machine was required. In order to run studies, a desktop computer and HTC Vive VR headset were taken to the Carterton Events Centre for testing in person. The hardware requirement was a limitation as participants may not have hardware capable of running Immersive ESS Visualizer, so an in-person testing method was chosen rather than a remote testing method, which could have made participants more difficult to source especially during COVID-19 restrictions.

Difficulties with COVID-19 COVID-19 had an effect on the ability to contact local groups who would be suitable for participating in the study. I started the research project before COVID-19 lockdown restrictions and finished after the lockdown restrictions were lifted. The effect of COVID-19 changed how groups interacted and the availability of participants even after COVID-19 restrictions were lifted. So COVID-19 had a significant impact on the ability to conduct focus group sessions and the ability to contact participants and arrange user study sessions at the time that focus group sessions and user study sessions would have been most beneficial.

8.5 Future work

Multi-user system Immersive ESS Visualizer could be extended into a multi-user system and a further study of communication in Immersive ESS Visualizer could be conducted to create a visualization tool for remote collaborative work. New techniques for developing VR tutorials could be investigated to make onboarding easier for users who were less experienced with VR. A more interactive tutorial could assist less expert users to perform the correct physical movements, by telling them when they have performed each action correctly, rather than passively showing instructions on a slide show.

More data Immersive ESS Visualizer could be further extended for visualizing more detailed local knowledge by providing navigation strategies for precise movement at the surface, and applying improving visualization techniques for surface details such as walking tracks, buildings, roads and landmarks.

Immersive ESS Visualizer could be applied to other geospatial domains, such as visualizing geological maps, or sub-surface details such as faults, undersea volcanoes or flooding risk models. A potential use case for Immersive ESS Visualizer would be to augment other methods for presenting data. Extending the datasets to other geospatial data would help to test if Immersive ESS Visualizer is more generally applicable to other models (such as MESH [12], InVEST [6]), and similar domains with the same data types.

Evaluation After further development, it would be possible to incorporate Immersive ESS visualizer into an in-the-wild study to collect the perceptions of land management scientists applying it in a group scenario.

In the user study, participants were able to communicate with the facilitator while they were performing the exercises. The researcher was able to guide the participant through picking up the handheld maps in the tutorial by describing the action. Further research could incorporate

Immersive ESS Visualizer into an in-the-wild study with a domain expert in ecosystem services administering VR to non-expert users.

A longitudinal study could be performed to analyse the effect of using Immersive ESS Visualizer over a longer time period. The study method could be extended to other regions and conservation groups with the objective of developing the system further and extending the geospatial data visualization capabilities. Longitudinal studies and in-the-wild testing would help to understand how Immersive ESS Visualizer would be applied in an organizational environment over longer time frames.

Suggested features Suggested features for Immersive ESS Visualizer included more visualizations of a wider range of geospatial data, adding markers onto the scenario map for landmarks or variables, adding icons relating to the type of land cover, multiple connected views for hand-held maps, connected zoom levels, ability to take screenshots, vectorized elevation contours, a north arrow, changes to the legends, and a difference raster showing ecosystem services changes before and after land use change. Suggested features could be implemented and tested with further development of Immersive ESS Visualizer.

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Appendices

Appendix A

Extended Literature Review References

Id	Title	Author	Year
P1	Real-time geographic visualization of World Wide Web traffic	Lamm, S. E. *et al.*	1996
P2	Application of virtual reality in the interpretation of geoscience data	Lin, C. R. *et al.*	1998
P3	Virtual reality for geosciences visualization	Lin, C. R. *et al.*	1998
P4	Immersive data visualization with the VisionDome	Francine E. *et al.*	2000
P5	A comparative study of user performance in a map-based virtual environment	Swan, J. E. *et al.*	2003
P6	Adviser: Immersive field work for planetary geoscientists	Forsberg A. *et al.*	2006
P7	A reliable new 2-stage distributed interactive TGS system based on GIS database and augmented reality	Kim, S. *et al.*	2006
P8	Visualization of spatial sensor data in the context of automotive environment perception systems	Tönnis, M. *et al.*	2007
P9	A geoscience perspective on immersive 3D gridded data visualization	Billen, M.I. *et al.*	2008
P10	Evaluation of an augmented photograph-based pedestrian navigation system	Walther-Franks, B. *et al.*	2008
P11	Geospatial visualization using hardware accelerated real-time volume rendering	Berberich, M. *et al.*	2009
P12	Integration of regional to outcrop digital data: 3D visualisation of multi-scale geological models	Jones, R. R. *et al.*	2009
P13	Evaluating User Experience of Experiential GIS	Paddington H.	2009

P14	Handheld Augmented Reality for underground infrastructure visualization	Schall, G. *et al.*	2009
P15	Interactive editing of digital fault models	Van Aalsburg, J. *et al.*	2010
P16	Geocollaborative Soil Boundary Mapping in an Experiential GIS Environment	Harris, T. M. *et al.*	2011
P17	Immersive visualization and interactive analysis of ground penetrating radar data	Sgambati, M. R. *et al.*	2011
P18	Evaluation of effectiveness of the stick-grip device for detecting the topographic heights on digital maps	Evreinova, T. V. *et al.*	2012
P19	Haptic visualization of bathymetric data	Evreinova, T.V. *et al.*	2012
P20	MetaTree: Augmented Reality Narrative Explorations of Urban Forests	West, R. *et al.*	2012
P21	Comprehensible and Interactive Visualizations of GIS Data in Augmented Reality	Zollmann, S. *et al.*	2012
P22	Visualization of Solar Radiation Data in Augmented Reality	Carmo, M. B. *et al.*	2014
P23	Using and evaluating augmented reality for mobile data visualization in real estate classified ads	De MacEdo, D.V. *et al.*	2014
P24	Parallel processing and immersive visualization of sonar point clouds	Febretti, A. *et al.*	2014
P25	Concept and workflow for 3D visualization of atmospheric data in a virtual reality environment for analytical approaches	Helbig, C. *et al.*	2014
P26	A Novel System to Display Position of Explosion, Shot Angle, and Trajectory of The Rocket Firing by Using Markerless Augmented Reality ARoket : Improving safety and quality of exercise anytime, anywhere, and real time	Infantono, A. *et al.*	2014

P27	Visualization of Climate Change in situ	Liestol, G. *et al.*	2014
P28	Mobile device visualization of cloud generated terrain viewsheds	Mangold, C.	2014
P29	Empirical evaluation of smartphone Augmented Reality browsers in an urban tourism destination context	Yovcheva, Z. *et al.*	2014
P30	MEVA - An Interactive Visualization Application for Validation of Multifaceted Meteorological Data with Multiple 3D Devices	Helbig, C. *et al.*	2015
P31	BoreholeAR: A mobile tablet application for effective borehole database visualization using an augmented reality technology	Lee, S. *et al.*	2015
P32	Immersive 3D geovisualization in higher education	Philips, A. *et al.*	2015
P33	Smart maintenance of riverbanks using a standard data layer and Augmented Reality	Pierdicca, R. *et al.*	2016
P34	An immersive approach to the visual exploration of geospatial network datasets	Zhang, M. J. *et al.*	2016
P35	An immersive virtual environment for collaborative geovisualization	Doležal, M. *et al.*	2017
P36	Hybrid three-dimensional representation based on panoramic images and three-dimensional models for a virtual museum: Data collection, model, and visualization	Hu, Q. *et al.*	2017
P37	Augmented reality based bee drift analysis: A user study	Nguyen, H. *et al.*	2017

P38	Evaluation of scientific workflow effectiveness for a distributed multi-user multi-platform support system for collaborative visualization	Banic, A. *et al.*	2018
P39	System satisfaction survey for the App to integrate search and augmented reality with geographical information technology	Chiu, C. *et al.*	2018
P40	Mobile Augmented Reality for Flood Visualisation	Haynes, P. *et al.*	2018
P41	VRGE: An immersive visualization application for the geosciences	Hyde, D.A.B. *et al.*	2018
P42	Support collaboration across geographically distributed users using heterogeneous virtual reality systems	Khadka, R. *et al.*	2018
P43	Sino-InSpace: A Digital Simulation Platform for Virtual Space Environments	Lyu, L. *et al.*	2018
P44	Indirect Augmented Reality Browser for GIS Data	Skinner, P. *et al.*	2018
P45	Combining IoT Deployment and Data Visualization: Experiences within campus maintenance use-case	Yasmin, R. *et al.*	2018
P46	Visual Exploration of 3D Geospatial Networks in a Virtual Reality Environment	Zhang, M. *et al.*	2018
P47	Comfortable immersive analytics with the virtualdesk metaphor: Case studies and perspectives	Filho, J.A.W. *et al.*	2019
P48	Understanding citizen perspectives on open urban energy data through the development and testing of a community energy feedback system	Francisco, A. *et al.*	2019

P49	Immersive interaction design based on perception of vector field climate data	Lu, S. *et al.*	2019
P50	Improving information sharing and collaborative analysis for remote geospatial visualization using mixed reality	Mahmood, T. *et al.*	2019
P51	Exploration of large omnidirectional images in immersive environments	Mirhosseini, S. *et al.*	2019
P52	Making the Invisible Visible-Strategies for Visualizing Underground Infrastructures in Immersive Environments	Ortega, S. *et al.*	2019
P53	Retrofitting Realities: Affordances and Limitations in Porting an Interactive Geospatial Visualization from Augmented to Virtual Reality	Richardson, M. *et al.*	2019
P54	GeoGate: Correlating geo-temporal datasets using an augmented reality space-time cube and tangible interactions	Ssin, S.Y. *et al.*	2019
P55	Comparative Study for Multiple Coordinated Views Across Immersive and Non-immersive Visualization Systems	Su, S. *et al.*	2019
P56	Harnessing the power of immersive virtual reality - visualization and analysis of 3D earth science data sets	Zhao, J. *et al.*	2019
P57	Augmented Reality Geovisualisation for Underground Utilities	Stylianidis, E. *et al.*	2020
P58	Architectural visualization in the age of 5g: A mixed method pipeline for architectural design communication	Villa, D. *et al.*	2020
P59	Evaluating an Immersive Space-Time Cube Geovisualization for Intuitive Trajectory Data Exploration	Wagner, F. *et al.*	2020

P60	An efficient flood dynamic visualization approach based on 3D printing and augmented reality	Zhang, G. *et al.*	2020

Appendix B

Information Sheet for interviews

Exploring Immersive and Non-Immersive Techniques for Geographic Data Visualization

INFORMATION SHEET FOR PARTICIPANTS

You are invited to take part in this research. Please read this information before deciding whether or not to take part. If you decide to participate, thank you. If you decide not to participate, thank you for considering this request.

Who am I?

My name is Benjamin Powley and I am a PhD student in Computer Science at Victoria University of Wellington. This research project is work towards my PhD thesis.

What is the aim of the project?

This project collects information for the design of a software tool for interactively displaying data which augments analysis with the LUCI toolbox. Your participation will support this research by helping to identify the necessary functionality of the tool. This research has been approved by the Victoria University of Wellington Human Ethics Committee #0000028871.

How can you help?

You have been invited to participate because you have experience using LUCI. If you agree to take part, I will interview you at your workplace, Victoria University of Wellington, or remotely over Zoom. I will ask you questions about your workflow and experiences with LUCI. The interview will take up to one hour. I will audio record the interview with your permission and write it up later. You can choose to not answer any question or stop the interview at any time, without giving a reason. You can withdraw from the study by contacting me at any time before 31/07/2021. If you withdraw, the information you provided will be destroyed or returned to you.

What will happen to the information you give?

This research is confidential. This means that the researchers named below will be aware of your identity but the research data will be combined and your identity will not be revealed in any reports, presentations, or public documentation. However, you should be aware that in small projects your identity might be obvious to others in your community.

Only my supervisors, the transcriber (who will be required to sign a confidentiality agreement) and I will read the notes or transcript of the interview. The interview transcripts, summaries and any recordings will be kept securely and destroyed on 01/10/2024.

What will the project produce?

The information from my research will be used in my Ph.D. dissertation, academic publications and conferences. A software tool will be produced based on information collected from this research.

If you accept this invitation, what are your rights as a research participant?

You do not have to accept this invitation if you don't want to. If you do decide to participate, you have the right to:

- choose not to answer any question;
- ask for the recorder to be turned off at any time during the interview;
- withdraw from the study before 31/07/2021;
- ask any questions about the study at any time;
- receive a copy of your interview recording;
- receive a full transcript of your interview and given an opportunity to provide comments;
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to contact either:

Student:
Name: Benjamin Thomas Powley
University email address: Benjamin.Powley@ecs.vuw.ac.nz

Supervisor:
Name: Dr Craig Anslow
Role: Senior Lecturer
School: Engineering and Computer Science
Phone: 04 463 6449
Email: craig.anslow@vuw.ac.nz

Supervisor:
Name: Dr Mairéad de Róiste
Role: Senior Lecturer
School: Geography, Environment and Earth Sciences
Phone: 04 463 6431
Email: mairead.deroiste@vuw.ac.nz

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University of Wellington HEC Convenor: Associate Professor Judith Loveridge. Email hec@vuw.ac.nz or telephone +64-4-463 6028.

Exploring Immersive and Non-Immersive Techniques for Geographic Data Visualization

CONSENT TO INTERVIEW

This consent form will be held for five years.

Researcher: Benjamin Powley, School of Engineering and Computer Science, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in an audio recorded interview.

I understand that:

- I may withdraw from this study at any point before 31/07/2021, and any information that I have provided will be returned to me or destroyed.
- The identifiable information I have provided will be destroyed on 1/10/2024.
- Any information I provide will be kept confidential to the researcher and the supervisor and the transcriber.
- I understand that the findings may be used for a PhD dissertation, academic publications and presented to conferences.
- I understand that the recordings will be kept confidential to the researcher, the supervisor and the transcriber.
- My name will not be used in reports and utmost care will be taken not to disclose any information that would identify me.
- I would like a copy of the recording of my interview: Yes o No o
- I would like a copy of the transcript of my interview: Yes o No o
- I would like to receive a copy of the final report and have added my email address below. Yes o No o

Signature of participant: ________________________________

Name of participant: ________________________________

Date: ______________

Contact details: ________________________________

Appendix C

Information Sheet for focus groups

Focus Group Study Protocol

The objective of the focus group is to collect data about the way that the LUCI tool is operated, and to gather participant feedback on visualization design ideas that were produced as a result of the interviewing.

1. **What are your experiences of gathering data for LUCI analysis.**
   The objective of this question is to contextualize the LUCI toolbox in the wider system of providing data analysis service where consultants, farmers and council are involved in the process of data collection. The question also discusses which interested parties are processing input data for inclusion into a LUCI analysis?

   (a) How do you gather data for your LUCI analysis e.g do you inspect the land directly?
   (b) How do you interact with other parties to collect data, for example farmers, consultants, council?
   (c) How is the data processed prior to the LUCI analysis, are other parties responsible for processing the data?
   (d) Are there any problems or issued that you have encountered while gathering or processing data for your analysis? If so what are they?
   (e) If there have been problems encountered then how could a visualization system solve these issues?

2. **What are your experiences of communicating LUCI output results to other interested parties**
   This question will collect information on which interested parties are receiving which outputs from LUCI, and whether the results are validated with the input of other parties.

   (a) How do you interact with other parties to present results from your analysis?
   (b) Would you communicate with other interested parties to validate the results of your analysis. Which parties would be involved in this process?
   (c) Are there any problems or issues that you have encountered when producing output from LUCI? If so what are they?
   (d) If there are problems that have been encountered then how could a visualization solve these issues?

3. **What other software or processes do you use during your data analysis.**
   This question discusses any other software that is required during the process of performing analysis with LUCI.

   (a) How do you use this software and at what stages of the analysis process?
   (b) Are there any problems or issues that you solved by applying different software? If so what are they?
   (c) How would visualization assist with solving these issues?

4. **Explain potential ideas for visualizing LUCI data and request feedback about how they could possibly use these visualizations in future analysis.**
   If a participant could not use the visualization then request feedback on fixing the visualization or other suggestions
   For this question the prepared stimulus should be shown to participants with a walk through of how to use visualization ideas which were created as a result of the previous interviewing.

5. **Are there any other needs or ideas that have not been covered?**

Exploring Immersive and Non-Immersive Techniques for Geographic Data Visualization

INFORMATION SHEET FOR PARTICIPANTS

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Who am I?

My name is Benjamin Powley and I am a PhD student in Computer Science at Victoria University of Wellington. This research project is work towards my PhD thesis.

What is the aim of the project?

This project collects information for the design of a software tool for interactively displaying data which augments analysis with the LUCI toolbox. Your participation will support this research by helping to identify the necessary functionality of the tool. This research has been approved by the Victoria University of Wellington Human Ethics Committee #0000028871.

How can you help?

You have been invited to participate because you have experience using LUCI. If you agree to take part you will be part of a focus group at Victoria University of Wellington, or remotely over Zoom. I will ask you and other participants questions about your workflow and experiences with LUCI, as well as your views on possible software designs, and applications of the software tool. The focus group will take up to one hour. I will audio record the focus group with your permission and write it up later.

The information shared during the focus group is confidential. That means after the focus group, you may not communicate to anyone, including family members and close friends, any details about the identities or contributions of the other participants of the focus group.

You can withdraw from the focus group at any time before the focus group begins.

You can also withdraw while the focus group it is in progress. However it will not be possible to withdraw the information you have provided up to that point as it will be part of a discussion with other participants.

What will happen to the information you give?

This research is confidential. This means that the researchers named below will be aware of your identity but the research data will be combined and your identity will not be revealed in any reports, presentations, or public documentation. However, you should be aware that in small projects your identity might be obvious to others in your community.

Only my supervisors, the transcriber (who will be required to sign a confidentiality agreement) and I will read the notes or transcript of the focus group. The focus group transcripts, summaries and any recordings will be kept securely and destroyed on 01/10/2024.

What will the project produce?

The information from my research will be used in my Ph.D. dissertation, academic publications and conferences.

If you accept this invitation, what are your rights as a research participant?

You do not have to accept this invitation if you don't want to. If you do decide to participate, you have the right to:

- choose not to answer any question;
- ask for the recorder to be turned off at any time during the focus group;
- withdraw from the focus group while it is taking part however it will not be possible to withdraw the information you have provided up to that point;
- ask any questions about the study at any time;
- read over and comment on a written summary of the focus group;
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to contact either:

Student:
Name: Benjamin Thomas Powley
University email address: Benjamin.Powley@ecs.vuw.ac.nz

Supervisor:
Name: Dr Craig Anslow
Role: Senior Lecturer
School: Engineering and Computer Science
Phone: 04 463 6449
Email: craig.anslow@vuw.ac.nz

Supervisor:
Name: Dr Mairéad de Róiste
Role: Senior Lecturer
School: Geography, Environment and Earth Sciences
Phone: 04 463 6431
Email: mairead.deroiste@vuw.ac.nz

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University of Wellington HEC Convenor: Associate Professor Judith Loveridge. Email hec@vuw.ac.nz or telephone +64-4-463 6028.

Exploring Immersive and Non-Immersive Techniques for Geographic Data Visualization

CONSENT TO PARTICIPATE IN FOCUS GROUP

This consent form will be held for five years.

Researcher: Benjamin Powley, School of Engineering and Computer Science, Victoria University of Wellington.

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in an audio recorded interview.

I understand that:

- I acknowledge that I am agreeing to keep the information shared during the focus group confidential. I am aware that after the focus group, I must not communicate to anyone, including family members and close friends, any details about the identities or contributions of the other participants of the focus group.
- I can withdraw from the focus group while it is in progress however it will not be possible to withdraw the information I have provided up to that point as it will be part of a discussion with other participants
- The identifiable information I have provided will be destroyed on 1/10/2024.
- I understand that the findings may be used for a PhD dissertation, academic publications and presented to conferences.
- I understand that the observation notes/recordings will be kept confidential to the researcher, the supervisor and the transcriber.

- My name will not be used in reports and utmost care will be taken not to disclose any information that would identify me.
- I would like a summary of the focus group: Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: ________________________________

Name of participant: ________________________________

Date: ______________

Contact details: ________________________________

Focus Group Rules

The objective of the focus group is to collect data about the way that the LUCI tool is operated, and to gather participant feedback on visualization design ideas that were produced as a result of the interviewing. The following list details the rules which will be discussed with the participants before the focus group session starts:

1. The information shared in this meeting is confidential. You should not discuss the opinions and comments made by other focus group participants with anybody outside this room. We would like you and others to feel comfortable when sharing information.
2. You do not need to agree with others, but you should listen respectfully as others share their views.
3. We would like to hear a wide range of opinions: please speak up on whether you agree or disagree.
4. There are no right or wrong answers, every person's experiences and opinions are important.
5. The meeting is audio recorded.
6. Only one person should speak at a time.
7. Please turn off your phones.
8. Should any thoughts occur after the focus group session, please get in contact to share your thoughts.

Greetings,

I am a PhD student in Computer Science studying at Victoria University of Wellington. My research is about designing and evaluating a software tool for interactively displaying data. I would like to invite you to participate in a focus group session about your experiences with the LUCI toolbox. You have been invited to this focus group session because you have previously participated in an interview, and the focus group will discuss some topics and ideas which resulted from these interviews.

The results of these focus groups will be used to inform the design of the software tool which will augment LUCI.

The focus group will take between 45-60 minutes. If you wish to participate in the study please contact one of the following for more information:

Benjamin Powley, Student, Benjamin.Powley@ecs.vuw.ac.nz
Dr Craig Anslow, Supervisor, craig.anslow@ecs.vuw.ac.nz
Dr Mairéad de Róiste, Supervisor, mairead.deroiste@vuw.ac.nz

This research has been approved by the Victoria University of Wellington Human Ethics Committee, Application reference number #0000028871.

Kind Regards,

Ben

Appendix D

Final Evaluation User Study Questionnaire

Table D.1: Pre-study questionnaire for the final evaluation

	Question
Q1)	What is your current occupation?
Q2)	What is your current role within [organization]?
Q3)	How long have you been a member of [organization]?
Q4)	What projects or activities have you participated in with [organization]?
Q5)	Do you have any academic or industry qualifications, If so, please specify: (e.g B.Sc. Environmental Science; New Zealand Certificate in Business Administration and Technology,Level 3)
Q6)	How often do you read maps?
Q7)	Have you ever used maps as part of your occupation?
Q8)	Do you use digital maps, paper maps or both?
Q9)	What type of maps? e.g topographic, soil maps geographical, road maps
Q10)	What types of tasks would you use maps for
Q11)	Are you a resident of the Mangatarere catchment area?
Q12)	If you are not a resident, how often do you visit the Mangatarere catchment area?
Q13)	What aspects of LUCI are you most interested in?
Q14)	Describe your experience with LUCI in this project or other projects
Q15)	Which LUCI outputs have you used e.g Diagram, charts, reports, please describe:
Q16)	What do you think strengths and weaknesses of LUCI are?
Q17)	Have you used any of the following datasets?
Q18)	Have you ever worked with any land management decision making tools other than LUCI. E.g overseer, ARIES, MIKE? Please specify:
Q19)	Have you used any of the following, Geographic information systems (GIS) software? E.g ArcGIS, QGIS, MapInfo ?please specify: (e.g HTC Vive, Oculus Rift, Google Cardboard, Microsoft Hololens)
Q21)	How often do you use a head mounted display
Q22a)	Do you have any experience using VR?AR software?
Q22b)	Do you use any software programs for an HMD that require navigation in a virtual world, Please specify:
Q23)	How often do you navigate in a virtual world inside an HMD?
Q24)	How often do you play video games?
Q25)	Does any of the software you use (non-HMD) require 3D navigation, please specify:
Q26)	How often do you navigate in 3D worlds (non-HMD)?

Appendix E

Final Evaluation User Study Questions

Restoration at Tea Creek Road

*You have already been asked the mid study questions **Task 1** and **Task 2** inside the VR, paper and 2D screen tasks, they are reprinted here for reference to assist with answering the post study questions.*

Mid Study:

VR

VR **Task 1)** The provided map layers in the file tab are for two restoration options: 0.4 % restoration, and 100% wetland restoration. Use any, or all of the features described in the VR tutorial to compare these restoration options at Tea Creek Road.

VR **Task 2)** Choose a location of interest to inspect , and discuss any notable similarities and differences among **map data layers** provided.

Paper Maps

Paper **Task 1)** The provided maps are for two restoration options: 0.4 % restoration, and 100% wetland restoration. Compare these restoration options at Tea Creek Road.

Paper **Task 2)** Choose a location of interest to inspect , and discuss any notable similarities and differences among maps provided.

2D Screen

Screen **Task 1)** The provided maps are for two restoration options: 0.4% restoration, and 100% wetland restoration. Compare these restoration options at Tea Creek Road.

Screen **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among maps provided.

PostStudy:
We will now ask questions about your experience analyzing Wetland at Tea Creek Road .

Q1) When analyzing Wetland at Tea Creek Road describe how you completed **Task 1** with each of these systems.

a) VR

b) Paper

c) 2D Screen

Q2) Compare your experiences with **VR, Paper Maps and 2D Screen**, when completing **Task 1,** while analyzing **Wetland restoration at Tea Creek Road.**

Q3) When analyzing **Wetland restoration at Tea Creek Road**, describe how you completed **Task 2** with these systems.

a) VR

b) Paper

c) 2D Screen

Q4) Compare your experiences with **VR, Paper Maps, and 2D Screen,** when completing **Task 2,** while analyzing **Wetland Restoration at Tea Creek Road.**

Q5) What features of each system (**VR, Paper Maps, 2D Screen**) did you find useful for analyzing **Wetland restoration at Tea Creek Road,** in **Task 1** and **Task 2?**

Riparian Planting

*You have already been asked the mid study questions **Task 1** and **Task 2** inside the VR, paper and 2D Screen tasks, they are reprinted here for reference to assist with answering the post study questions*

VR

VR **Task 1)** The provided map layers in the file tab are for three riparian planting options at 5m, 15m and 30m widths from streams. Use any, or all of the features described in the tutorial to compare these scenarios.

VR **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among data layers provided.

Paper Maps

Paper **Task 1)** The provided maps are for three riparian planting options at 5m, 15m and 30m widths from streams. Compare these riparian planting options.

Paper **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among maps provided.

Screen 2D

Screen **Task 1)** The provided maps are for three riparian planting options at 5m, 15m and 30m widths from streams. Compare these riparian planting options.

Screen **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among maps provided.

PostStudy:
We will now ask you questions about your experience analyzing Riparian Planting at Tea Creek Road.
Q1) When analyzing **Riparian Planting** describe how you completed **Task 1** with these systems.

a) VR

a) Paper Maps

b) 2D Screen

Q2) Compare your experiences with **VR, Paper Maps and 2D Screen**, when completing **Task 1**, while analyzing **Riparian Planting**.

Q3) When analyzing **Riparian Planting**, describe how you completed **Task 2** with these systems.

a) VR

b) Paper Maps

c) 2D Screen

Q4) Compare your experiences with **VR, Paper Maps, and 2D Screen**, when completing **Task 2**, while analyzing **Riparian Planting**.

Q5) What features of each system **(VR, Paper Maps, 2D Screen)** did you find useful for analyzing **Riparian Planting** in **Task 1** and **Task 2**.

Analyzing streams at Piako

You have already been asked the mid study questions Task 1 and Task 2 inside the VR, paper and 2D screen tasks , they are reprinted here for reference to assist with answering the post study questions

VR

VR **Task 1)** The provided map layers in the file tab are for analysis with and without streams. Use any, or all of the features described in the tutorial to compare these scenarios.

VR **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among data layers provided.

Paper Maps

Paper **Task 1)** The provided maps are for analysis with and without streams. Compare these two analysis scenarios.

Paper **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among maps provided.

Screen 2D

Screen **Task 1)** The provided maps are for analysis with and without streams. Compare these two analysis scenarios.

Screen **Task 2)** Choose a location of interest to inspect, and discuss any notable similarities and differences among maps provided.

Post Study:
We will now ask you questions about your experience analyzing **Streams at Piako**
Q1) When analyzing **Streams at Piako** describe how you completed **Task 1** with these systems.

a) VR

b) Paper Maps

c) 2D Screen

Q2) Compare your experiences with each **VR, Paper Maps, 2D screen,** when completing **Task 1,** while **Analyzing streams at Piako.**

Q3) When **Analyzing streams at Piako**, describe how you completed **Task 2** with these systems.

a) VR

b) Paper Maps

c) 2D Screen

Q4) Compare your experiences with **VR, Paper Maps, and 2D Screen**, when completing **Task 2**, while **Analyzing Streams at Piako.**

Q5) What features of each system, **(VR, Paper Maps, 2D Screen)** did you find useful for **analyzing Streams at Piako** in **Task 1** and **Task 2.**

Effectiveness measures

Answer each question by placing a circle around the number of your choice. Please circle only **one** *number per question.*

	Not Very Effective				Very Effective
How effective was the **Scenario Map** for analyzing **Map Data Layers**?	1	2	3	4	5
How effective was the **Scenario Map Road Layer** for finding locations?	1	2	3	4	5
How effective was the Scenario Map **Stream Layer** for viewing streams?	1	2	3	4	5
How effective was the **File List** for selecting files?	1	2	3	4	5
How effective was the **Tab Menu** for selecting tabs?	1	2	3	4	5
How effective was the **Attribute List** for selecting variables in data layers?	1	2	3	4	5
How effective was the **Map Data Layer Filter**?	1	2	3	4	5
How effective was the **Map Lighting** button on the Handheld Map?	1	2	3	4	5
How effective was **Map Panning** for selecting a region of the map to view?	1	2	3	4	5
How effective was the **Map Zoom button** on the Handheld Map?	1	2	3	4	5

Effectiveness measures

Answer each question by placing a circle around the number of your choice. Please circle only **one** *number per question.*

	Not Very Effective				***Very Effective***
How effective was the **Height Exaggeration** button on the Handheld Map?	1	2	3	4	5
How effective was the **Handheld Map** for analyzing **Map Data layers**?	1	2	3	4	5
How effective was the Handheld Map **Road Layer** for finding locations?	1	2	3	4	5
How effective was the Handheld Map **Stream Layer** for viewing streams?	1	2	3	4	5
How effective was the Handheld Map **Legend** for showing the data scale?	1	2	3	4	5
How effective was the **Map Generation button** for generating handheld maps?	1	2	3	4	5
How effective was the Handheld Maps **Cutaway Zoom**?	1	2	3	4	5

Assistance measures

Answer each question by placing a circle around the number of your choice. Please circle only **one** *number per question.*

	Very Much				Very Little
How much did you feel like you needed assistance with the **scenario map data layers**?	1	2	3	4	5
How much did you feel like you needed assistance finding locations with the **map road layer**?	1	2	3	4	5
How much did you feel like you needed assistance viewing the scenario **map stream layer**?	1	2	3	4	5
How much did you feel like you needed assistance to **analyze map data layers** with the handheld map?	1	2	3	4	5
How much did you feel like you needed assistance with the **file list for selecting files**?	1	2	3	4	5
How much did you feel like you needed assistance with the **tab menu** for selecting tabs?	1	2	3	4	5
How much did you feel like you needed assistance with the **attribute list** for selecting attributes?	1	2	3	4	5

Assistance measures

Answer each question by placing a circle around the number of your choice. Please circle only **one** *number per question.*

	Very Much				Very Little
How much did you feel like you needed assistance with the **attribute list filter**, for filtering data based on attributes?	1	2	3	4	5
How much did you feel like you needed assistance with the **map lighting button**?	1	2	3	4	5
Assistance measures How much did you feel like you needed assistance with **panning the map**?	1	2	3	4	5
How much did you feel like you needed assistance with the **map Zoom button**?	1	2	3	4	5
How much did you feel like you needed assistance with the **height exaggeration** button?	1	2	3	4	5
How much did you feel like you needed assistance using the **handheld map road layer**?	1	2	3	4	5
How much did you feel like you needed assistance with the **handheld map stream layer**?	1	2	3	4	5
How much did you feel like you needed assistance reading the **legend**?	1	2	3	4	5
How much did you feel like you needed assistance generating new maps with the **map generation button**?	1	2	3	4	5
How much did you feel like you needed assistance using the **Cutaway Zoom** ?	1	2	3	4	5

Communication

Q1) When discussing your findings for the wetland restoration scenario. Which features in VR did you use to assist your discussion?

Q2) When discussing your findings for the riparian planting scenario, Which features in VR did you use to assist your discussion?

Q3) When discussing your findings for analyzing streams at Piako, Which features in VR did you use to assist your discussion?

Q4) Describe your experience in communicating your findings to the Researcher.

Q5) If you wished to communicate your findings to someone outside the application, what features of the VR system would be the most helpful in assisting your communication.