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Immersive Analytics for Understanding Ecosystem Services Data

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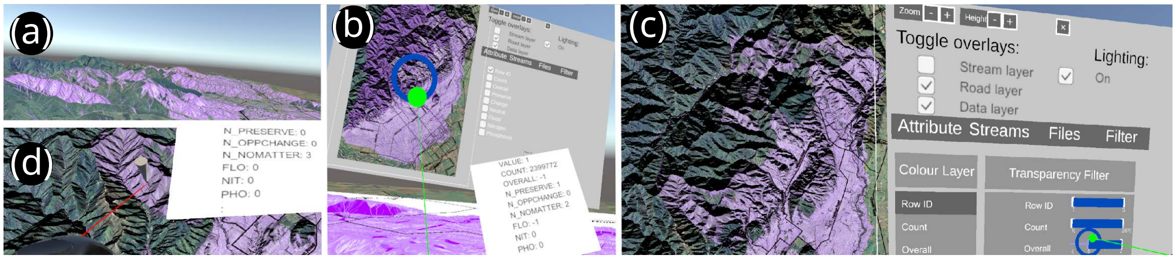

Figure 1: Immersive ESS Visualizer, showing visualization features: a) A scenario map with a data layer filtered. b) A handheld map with the blue circle for grabbing at a distance, the white panel shows values under the pointer, the handheld map control panel has an attribute list showing a linear radio menu with variables for selecting the layer visualized as a purple overlay. c) A handheld map showing a three-way tradeoff among flood, nitrogen and phosphorus. The filter tab is selected indicating a filter is applied to the overall score of the 3-way tradeoff. d) A close up view of the marker showing variables on the layer. Data credit: DEM 5m [11], NZ LCDBv5.0 [4], Whaitua land use dataset GWRC (2021), FSL [1], RECv2 [8], Rainfall and evapotranspiration NIWA (2018).

ABSTRACT

Planning land use changes requires input from experts across several domains with diverse expertise. Currently available tools were not designed for analysing the required ecosystem services before and after land use changes, or for analysing tradeoffs. Our study is motivated by the need for better tools designed for expert analysts and location knowledgable stakeholders to analyse data relating to land use planning, such as ecosystem services data. The effectiveness of an immersive VR visualization system (Immersive ESS Visualizer) for analysing and visualizing ecosystem services data, is evaluated and compared to existing methods of analysis, paper maps and a 2D screen. Although VR presented some difficulties, the benefits of spatially arranging maps, inspecting fine details, navigation by zooming, and inspection of hillshades provided sufficient advantages to make VR an effective tool for ecosystem services analysis. Participants using Immersive ESS Visualizer arranged handheld maps into 3D layouts, which would not be possible with paper or on the 2D screen. Our research demonstrates that geospatial analysis can be supported by comparative visualization in VR.

Index Terms: Ecosystems Services, Visualization, Virtual Reality

1 INTRODUCTION

Ecosystem services (ESS) provide direct and indirect benefits to humans. For example, agricultural farmland provides ecosystem services directly by producing goods [39]. Farming increases agricultural production but can negatively impact other ecosystem services by reducing biodiversity and producing runoff containing nitrogen and phosphorus [39]. Elevation makes the analysis problem a good candidate for VR, as a Digital Elevation Model (DEM) is 3D. VR headsets are stereoscopic, allowing interaction with 3D content through physical movement. Our research question is: How effective is immersive VR visualization for analysing ecosystem services? This research fits a gap in the reviewed literature by visualizing ecosystem services data and tradeoffs in VR including multiple maps with elevation. The main contribution of our paper is the development and evaluation of a VR system to compare ESS. Contributions are:

1. An immersive VR visualization system

Following a user-centred design method, Immersive ESS Visualizer was designed and implemented to support experts analysing ecosystem services and stakeholders with an interest in their analysis. The novelty of Immersive ESS Visualizer is the ability to compose multiple maps with elevation into complex 3D layouts, intersecting and arranging maps.

2. Requirements

The requirements were developed through working with expert land management scientists and participants from a catchment group.

3. Evaluation

The VR system was evaluated through a user study with data from an ecosystem services analysis with the Land Utilization Capability Indicator (LUCI) model [5] performed on the Mangatarere catchment in New Zealand. The data from the analysis was provided by NatureBraid. Our evaluation required participants to perform realistic tasks on each of three media, paper maps, a 2D screen, and VR. The 2D screen, and paper maps media were chosen based on interviews and focus groups because they are representative of the media already being used for analysis. The tasks were designed based on interviews and focus groups. 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 results, to test for correlations among expertise measures within media conditions.

2 RELATED WORK

Immersive analytics systems use hardware interfaces to enhance the immersive nature of the experience when analysing data [44]. Immersive analytics systems could improve engagement with data analysis, understanding of data, and assist with collaboration [20].

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This research followed a user centred design methodology [36, 35].

Ecosystem services data The LUCI ecosystem services model includes flood risk mitigation, agricultural production, carbon sequestration, diffuse pollution, and erosion data [27]. LUCI has been applied to an analysis of ecosystem services tradeoffs in catchment areas [47], an analysis of the differences between ecosystem services in wetlands at a catchment scale [46], and the calculation of habitat diversity metrics [33]. The model can run at high resolutions e.g. 5m, or 1m resolution. Quality of the Digital Elevation Model (DEM) can cause differences in the output results of ecosystem services such as nitrogen and phosphorus calculated by the LUCI Model. Metrics such as the topographic wetness index [51] are affected by elevation, so showing the DEM data which is input to the model would assist users to evaluate the quality of the output results. Methods for processing DEMs were shown to affect the quality of the data [38, 51], so substituting layers 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 [21]. Our literature review found no examples of immersive stereoscopic visualization applied to analysing maps of tradeoffs among ecosystem services.

Maps and Terrain Layers Examples of systems for analysing geospatial data in VR are MEVA and OpenGEOSys. MEVA and OpenGEOSys were applied to visualizing the Weather Research and Forecasting model (WRF) [25, 26]. OpenGeoSys was applied to environmental and hydrological data. OpenGEOSys, VRGS, Visualizer [14] and MEVA have previously visualized terrain in VR as a 3D model. OpenGEOSys and MEVA visualize terrain with surface meshes. VRGS [10] could visualize LIDAR and structure from motion data for digital outcrops as point clouds, tiled models (terrain) or textured mesh. Immersive ESS Visualizer visualizes the surface of the terrain, as the data is 2D rasters draped over elevation. Since multiple raster layers need to be compared with the elevation, MEVA, Visualizer and OpenGeoSys were not used for our study.

Layout techniques No existing systems that we reviewed allow the users to pick up the multiple maps with elevation to interact with them, and compare them to a larger scenario sized model of the terrain. Previous studies evaluated layout techniques incorporating multiple maps in VR [41, 45, 30]. Multi-view map layouts [41] were evaluated for visualizing geospatial data in VR, and received positive responses, however these maps did not have 3D terrain elevation. In Immersive ESS Visualizer. The mapstack technique [45] was considered for map layouts. However, in mapstack, the maps are tilted away from the viewer when drawing the layout which may occlude the data if elevation was added. The multi view map layout technique was chosen for comparing maps with elevation over grid layouts [30] because there are a small number of multiples for the number of maps being compared at once (e.g 2-3 maps), grabbing and dragging allows the user to choose their own layout.

IVEVA [31] was designed with a virtual room containing a map table, and smaller maps that could be grabbed and positioned. However, usability testing of IVEVA was not reported. Immersive ESS Visualizer has multiple maps with elevation in VR, which users can position, and a large environment sized map that users can glide over, much larger than the table sized map provided by IVEVA.

Markers Mapping polygons could be textured with an image to annotate a map with tactical symbology [28]. Tactical symbols contained text, an icon, a number, a frame, a fill, and a graphic modifier. Concentric rings [53] were considered for label placement. Concentric rings could place labels on rings positioned around the outside of an object however they were not used due to the size of the maps that needed to be annotated. Positioning symbols in world space ensured that the symbols were positioned at the same place for both eyes. However, a disadvantage was that the symbols could occlude each other if they were positioned close together. In Immersive ESS Visualizer, the markers are conical, so that the users can see precisely where the cone meets the terrain. Users are also able to move the map, and their view position to see the terrain from any angle.

Moran et al. [34] displayed details on demand by showing a bubble next to 3D markers in a VR environment, however in Immersive ESS Visualizer, details are shown on a panel attached to the controller, so that users can position and move the panel with the controller.

Zooming Gestures for Zooming maps [52] and map navigation buttons [6] were considered for implementing the map Zoom. DiveZoom [42] is a gesture technique designed for horizontal map zoom, however the map's in immersive ESS Visualizer could be positioned in any arbitrary direction. The zoom buttons were chosen because during interviews and focus groups, participants identified that they had experience with map software. The use of zoom buttons for map navigation is a familar design to avoid learning new gestures, also the map buttons are usable with only one controller.

Evaluation Evaluation methods are reviewed which compare methods for evaluating different media. User studies have compared interactions in different media with VR. Weerasinghe et al. [49] compared VR, paper floor plans and renderings, and a 3D virtual environment for experiencing future office spaces. Weerasinghe et al. found higher engagement and sense of presence scores in VR compared to either desktop or paper conditions. Batch et al. [12] performed a study with a think aloud protocol asking participants to explore economic data in a VR visualization system and then arrange the visualizations for presentation to a third party. Our research applies a think aloud protocol while using Immersive ESS Visualizer, then post-study interviews with participants to collect their experiences while in VR, using paper maps and a 2D screen.

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. Approaches for ranking expertise could involve collecting self reported information [48, 32] or assessment from a supervisor [2]. Matthews et.al. [32] categorized expertise based on self reported data relating to role, number of years of experience and training. In this study expertise ranking is based on self reported data, so that the study can be administered in the study time constraints. Dreyfus et. al. [19] presented a 5 stage model of knowledge acquisition and claims that experts and novices have differences in the way that they approach solving problems, experts have an intuition for knowing how to problem solve, however beginners follow a set of rules without having the deeper understanding to adapt to similar situations. Walsh et. al. categorized skills as novice, advanced beginner, competence, proficiency and expert. However, Walsh et.al. [48] categorized digital cultural heritage users based on motivation, technical expertise, and domain expertise, with each of technical expertise and domain expertise ranked on a three point scale. Similarly, in our research three expertise levels were considered sufficient for ranking questions, then expertise for questions was averaged with the median.

We were unable to find an example of thematic analysis applied to previous geospatial VR immersive analytics systems. However, thematic analysis has been effectively applied to the use of virtual reality, for example analysing student perspectives for VR in nurse education [40] and to develop design requirements for family communication technologies [17]. Both Saab et.al. [40] and Brown et.al. [17] followed a 6-step process. Thematic analysis can be applied to interviews [17, 40] and focus groups [40]. A 3D VR simulation in radiography education [37] and a study designing and evaluating adaptive interfaces for augmented reality workspaces [29] incorporated thematic analysis to HCI evaluations. Thematic analysis was chosen for this project because it allows rich qualitative information to be extracted from data sources such as audio transcriptions, and questionnaire sheets in relation to Human Computer Interaction.

3 IMMERSIVE ESS VISUALIZER

3.1 Requirements

Requirements were gathered to identify tasks that users would need to perform with the system, and the features required to complete these tasks. 11 interviews were conducted with land management scientists, followed by a focus group with 4 of these interview participants, and a second focus group with 6 participants from a catchment group local to an area being analysed. The participants identified the following requirements:

R1 Compare maps showing ESS model data. Examples of comparison include toggling between map layers and/or side by side comparisons of ecosystem services data (e.g flood mitigation, nitrogen). Analysing tradeoffs among ecosystem services.

R2 Compare ESS model output to elevation. Elevation affects services like nitrogen, phosphorus, flood mitigation. So users would like to compare services to elevation.

R3 Visualize artefacts in the digital elevation model. Identify how imperfections in elevation could affect model output for services such as nitrogen, phosphorus, erosion, flood mitigation.

Features requested also included pin markers, the ability to read numerical values, and navigation through flying and walking. Tasks required included: Analysing tradeoffs among ecosystem services; comparison among land use scenarios; planning mitigation scenarios for land use; visualization of how elevation affects ecosystem services; and interactive data exploration of analysis results.

During the requirements gathering, participants identified that PDFs viewed on a 2D screen, and paper maps were already being used for analysing the model results.

3.2 Design

Immersive ESS visualizer's system architecture comprised of a game engine (Unity 2019.4 [9]), a native plugin to read geospatial data, libraries for geospatial data processing, data storage in geotiff files, configuration, and visualization components. The graphical user interface was based on a 3D map that users could fly over (Figure 1 a)).

The size of the handheld maps were chosen to keep the width of the map at 1m. This size was chosen based on the tradeoff between locality and size presented by Satriadi et. al. [41]. The maps are highly detailed, and there are a small number of maps. The user interface was designed for use with HTC Vive [3] game controllers. In order to support the tasks identified during requirements gathering the following features were implemented.

Scenario map was a mesh positioned underneath the user's feet (Figure 1 a)). It was large compared to the user, and gliding close allowed details to be inspected. The size was chosen so that users could glide around the map as an environment, and inspect how small differences in elevation could affect the results of layers such as nitrogen load and phosphorus load.

Handheld maps were smaller than the scenario map and could be re-positioned. Multiple handheld maps could be grabbed, dragged, and positioned into layouts in VR so that multiple variables, such as total nitrogen load, could be compared across maps.

Layers Participants wanted to visualize data layers containing attributes (variables). Aerial photography, streams and roads were draped so that participants could compare the data layers with elevation. Attributes were coloured purple (Figure 1). The color purple was chosen to avoid confusion with colours on the aerial imagery.

Attribute list was a linear menu where attributes could be individually selected. Interacting with the menu by pointing could change the attribute on each layer (Figure 1 b)). Attributes could be rapidly toggled to flick between layers when comparing data.

Elevation Participants needed to inspect detailed elevation data and analyse the effect of elevation on ecosystem services data. DEM was visualized on both the handheld maps, and scenario maps, by extruding the elevation in 3D.

Navigation Participants could fly over the landscape, gliding in the direction their head pointed by pressing the controller trackpad to control speed.

Layer filters directed attention toward information by filtering data on layers draped over handheld maps or the scenario map. Range selectors set multiple filter criteria (Figure 1 c)), only data which satisfies the criteria selected is rendered onto the overlay, the aerial imagery is visible where the data layer did not match the filtering criteria. Filters could be interacted with using the controllers, by pointing at a filter, and pressing the trackpad to adjust the selected range. The upper and lower range could be toggled with the trigger button.

Zoom The user could glide towards the scenario map to zoom. Zooming allowed users to inspect small details of the ecosystem services data, and inspect how aberrations in the elevation could affect the layers. The handheld maps could be zoomed by pointing at the zoom button on the attached panel and pressing trigger.

Pin markers were placed on handheld maps with the laser pointer by pressing trigger (Figure 1 d)). Each marker was shown on all handheld maps. Hovering on the marker allowed users to inspect numerical values on a panel attached to the controller, the panel shows a list of values for all attributes on the layer.

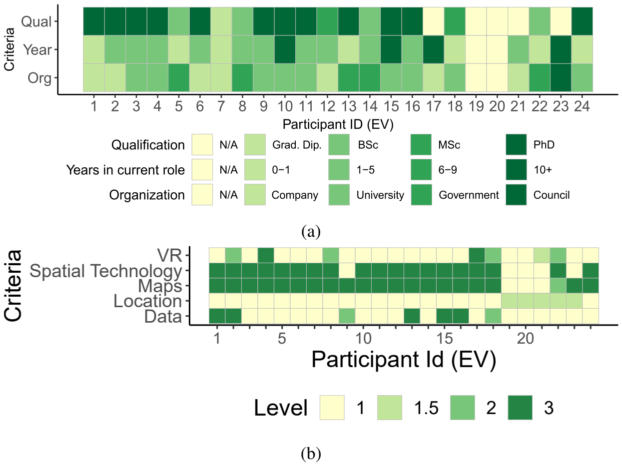
Instructional materials Tutorial slides were provided to participants on a panel attached to a controller which they could inspect in VR. The ability to arrange multiple maps with elevation and drape raster data is a novel feature of Immersive ESS Visualizer. The handheld maps could be dragged and placed anywhere around the user, and intersected together. The user could glide around the scenario map to compare detailed elevation features and see an overview. Layers could be viewed at different magnifications and compared by positioning multiple maps with elevation in 3D layouts.

4 USER STUDY

A user study was performed to evaluate the effectiveness of paper maps, 2D screen and VR for completing ecosystem services analysis tasks. Paper maps and 2D screen were chosen for comparison with the VR system due to their use by analysts interviewed for requirements gathering. In our study, the paper maps were printed A3 maps showing the results of ecosystem services analysis (Figure 3). PDFs were interacted with through the google chrome web browser so that participants could use multiple windows and tabs to view them. Both the 2D screen and paper maps were rendered flat with a hill-shade. The VR headset used during the study was an HTC Vive Pro. The desktop PC running Immersive ESS Visualizer had the following specification: Intel Xeon-W 2235 CPU (6 Cores 3.8GHz, 4.6GHz Turbo), EVGA GeForce RTX 3080 10GB Graphics Card, and 64GB RAM. The study was a mixed factorial design with both between-subjects and within-subject conditions [50]. Ethical approval was granted by Victoria University of Wellington human ethics committee, approval number 0000028871 (v3). Written consent was provided from all participants.

4.1 Participants

Participants were recruited by email from contacts provided by coauthors, invitations were based on their domain expertise in reading maps, knowledge of the ecosystem services, and/or the study area. Participants were sampled for the user study who either have experience with geospatial data, or expertise with the location being analysed. These sampling criteria were chosen because land use decisions could involve regional councils, or catchment groups who generally have knowledge of the location, which could guide their analysis of the data or decision making. A combination of focus group participants and new participants were recruited in rounds with convenience sampling. 7 participants were from companies involved in geospatial analysis, 9 from universities, 5 from government departments, 1 from a regional council, 2 did not report an occupation (Figure 2 a)). Experience ranged from 6 weeks to 21 years. 12 of the participants had PhDs and 19 had university qualifications, indicating a highly qualified sample.



(a)

(b)

Figure 2: a) Participant background experience. b) Categorized median expertise for study participants, ranked: 1 = Novice, 2 = Competent and 3 = Proficient

4.2 Expertise categorization

Expert analysts and stakeholders in land use decision making may have different methods for interacting with software [18]. Using Immersive ESS Visualizer to analyse ecosystem services data incorporates knowledge from multiple disciplines. Expertise was categorized based on map reading, data expertise, spatial technology, VR experience and familiarity with the location (Figure 2 b)). Expertise questions were categorised into three levels: novice, competent, and proficient. The median of questions in each expertise category was calculated. The advantage of this approach was that differences in the way that participants interacted with each media could be tested based on the responses of a questionnaire sheet and data provided during the study session.

4.3 Procedure

Following an introduction to the study, a pre-study questionnaire collected information about the participant's demographic, background and experience with VR and ecosystem service trade-off analysis. The same three tasks were provided for each of the three media; paper maps, 2D screens and VR. Participants were provided with the tasks for each media, immediately before using that media. Sessions were conducted with the researcher as a facilitator. Figure 3 shows the experimental setup. Participants were required to complete the tasks in the order assigned while thinking aloud [35]. Before each participant started the VR condition, they were instructed on the use of the controllers, and how to use the tutorial slides. They were assisted into the VR headset and asked to follow the slides. Participants removed the VR headset before starting each task and read the task on paper. Sessions were audio recorded, the 2D screen and VR conditions were screen recorded. A post-study questionnaire was given to the participants after completing all of the questions for each medium.

Due to initially estimating a very small sample size, the first six participants were presented with each of three media in a predetermined order to ensure each order was represented. Fortunately, a much larger sample size was obtained, so after the first six participants, media were presented in random order. Following advice from an independent statistical consultant, analysis was repeated to ensure statistical validity by first including, then excluding the first six participants. Results are reported from the first analysis, as the second did not yield significantly different results.

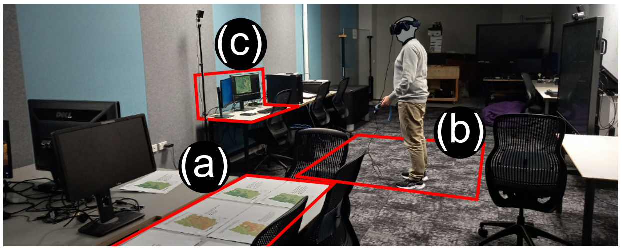


Figure 3: User study setup, a) Paper map table b) VR area c) 2D screen

4.4 Study Tasks

Realistic ecosystem services data analysis tasks were created for participants by inspecting an ecosystem service report produced by Benavidez et al. [13] and identifying specific tasks and trade-offs to compare. The study tasks were developed from ecosystem services analysis tasks that had been perfomed by experts and documented in the report, they are therefore realistic because they represent use-cases of the LUCI model. The study tasks were piloted to ensure suitability. In VR, participants were asked to use any or all features described in the tutorial to complete the task. The following tasks were performed:

Task 1. Compare 0.4% restoration, and 100% wetland restoration scenarios. The participants were provided with map layers for 0.4% and 100% wetland restoration options for a wetland area. Variables include flow interception classification, nitrogen accumulated load, and sediment delivery.

Task 2. Compare tradeoff maps for the baseline scenario. Two maps were provided showing tradeoffs between multiple attributes. One tradeoff map had 3 attributes: flow mitigation, nitrogen, and phosphorus. The other tradeoff map had 7 attributes: agricultural productivity, carbon, flow mitigation, habitat, nitrogen, phosphorus, and erosion. Model output results rank areas of the landscape, and individual services as preserve, change or neutral.

Task 3. Compare riparian planting scenarios for 5m, 15m and 30m distance from streams. Three riparian planting options were provided at 5m, 15m and 30m widths from streams. The data were raster maps of classifications for flow interception and nitrogen accumulated load. The flow interception classification map exhibited differences around the stream riparian planting areas, where planted areas reduced flow.

4.5 Data Collection and Analysis

A SUS test with an adjective measure was used to collect statistics about usability [16]. The NASA TLX collected statistics about workload and performance [7], and effectiveness scales collected Likert rankings for each feature in VR. Audio recordings and post-study questionnaires from the user study were analysed through thematic analysis similar to Braun et al. [15].

5 RESULTS

In the following section the results from the SUS test, TLX test, and VR effectiveness Likert scales are analysed. Two linear mixed effects models were run, one for SUS data, and one for the TLX data. The models test for correlations among map expertise, location expertise, data expertise, and VR expertise within the me-

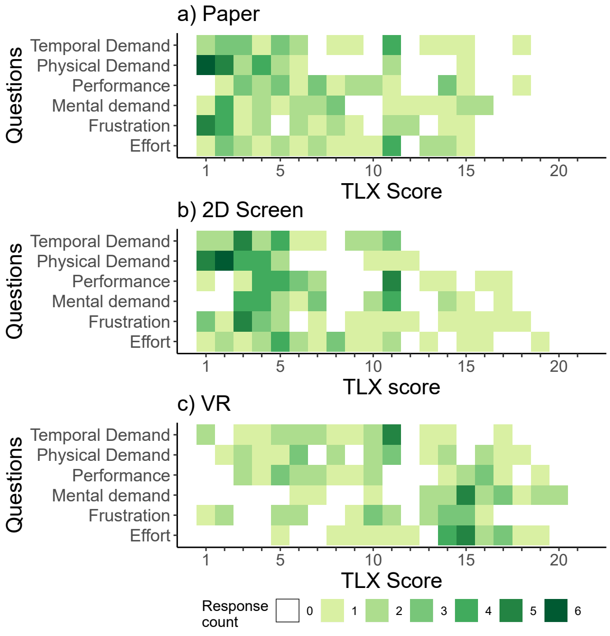


Figure 4: Number of responses for each TLX Question score. Lower scores are better.

dia conditions, and to test for differences in SUS score/TLX score among media. The fixed effects were map expertise, location expertise, data expertise, VR expertise, media condition, and media order. Media order is the order each media was presented to the participant, including media order allowed for analysis of the learning effect. The spatial technology expertise was not included in the model, due to the similarity with the map expertise. The model had an intercept for participant's ID as a random effect to group the three scores per participant, one for each of the three media conditions. Residual effects were plotted for both models to check normality and homoscedasticity assumptions for the linear mixed effects model, however, there were no visual discrepancies to suggest that assumptions were violated. P-values to test the significance of the fixed effects for the SUS, and TLX models are reported in Table 1.

5.1 TLX Results

Raw Task Load Index (TLX) provides a measure of difficulty in completing tasks with each system [24](Figure 4). The physical demand for VR had a wide distribution of scores compared to 2D screen and paper. The performance score for VR appears bimodal with 14 responses on the perfect side of the scale, and 8 responses on the failure side. Participants ranking their performance as worse than the mid point (score > 11) had high map expertise other than participant EV21 (median expertise 1) (Figure 2 b)), others have proficient map expertise (median 3). Participants with competent or proficient VR experience all reported that their performance was on the perfect side of the scale (score < 11). More participants found VR physically demanding (7 with score > 11), compared to 2D Screen (2 participants) or paper maps (1 participant). It was expected for VR to be more physically demanding as VR is active while both the 2D screen and the paper tasks are sedentary activities. The raw TLX scores indicate 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).

After adjusting for expertise and media order, the Raw TLX significantly differs between media ($p < 0.0001$) indicating that a correlation exists between media and raw TLX score (Table 1). After adjusting for expertise and media, the Raw TLX significantly differs between media order ($p = 0.0336$) 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 1). The media order correlation suggests a learning effect.

Table 1: ANOVA tables testing the significance of correlations in the linear mixed effects model for Raw TLX, and SUS. Exp.=Expertise, Cond.=Condition

	TLX			SUS		
	Chi sq.	**Df**	**p-value**	**Chi sq.**	**Df**	**p-value**
Intercept	11.8889	1	0.0006	12.9984	1	0.0003
Exp.						
Map	0.3465	1	0.5561	3.1552	1	0.0757
Location	0.1270	1	0.7216	0.4902	1	0.4838
Data	0.9407	1	0.3321	0.0017	1	0.9671
VR	2.1307	1	0.1444	3.9903	1	0.0458
Media						
Cond.	62.5992	2	<0.0001	92.0823	2	<0.0001
Order	4.5143	1	0.0336	3.0578	1	0.0804

Table 2: The difference in EMMs of Raw TLX and SUS, for media pairs averaged over all expertise and media order. P=Paper, S=Screen, V=VR

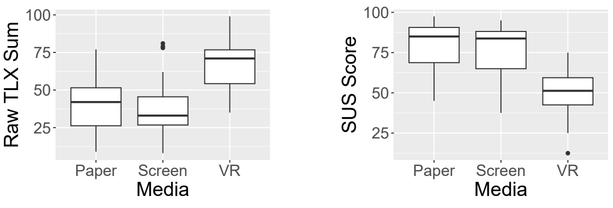
	Est.	**SE**	**Df**	**t-ratio**	**p-value**
TLX					
P-S	0.9696	3.9516	43.0168	0.2454	1
P-V	-27.7347	4.0851	43.5441	-6.7892	<.0001
S-V	-28.7042	4.0797	43.5326	-7.0358	<.0001
SUS					
P-S	2.4751	3.4870	43.0370	0.7098	1
P-V	31.3135	3.6001	43.7821	8.6979	<.0001
S-V	28.8384	3.5955	43.7661	8.0208	<.0001

The estimated marginal means (EMMs) for paper (39.02) and screen (38.05) are 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. Pairwise comparisons of TLX Score estimated marginal means for pairs of media indicate Raw TLX for VR was significantly higher than for Paper and 2D screen (both p<.0001) (Table 2). However, no significant difference is indicated for the Paper-Screen pair (p=1).

5.2 System Usability Scale (SUS) Scores

The SUS scores for paper maps, 2D screen, and VR indicate that VR was more difficult to use than 2D screen or paper maps (Figure 5 b)), 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 6), thus supporting TLX results.

After adjusting for expertise and media order, the SUS score significantly differs between media ($p < .0001$, see Table 1) indicating that a correlation exists between Media and SUS score. The level of VR expertise for a participant had a significant effect on their SUS score (p=0.0458), indicating that a correlation exists between VR expertise and SUS score. The correlation between map expertise and SUS score was near statistical significance (p=0.0757) indicating that the null hypothesis of no correlation between Map expertise



(a) (b)

Figure 5: TLX and SUS scores for each media

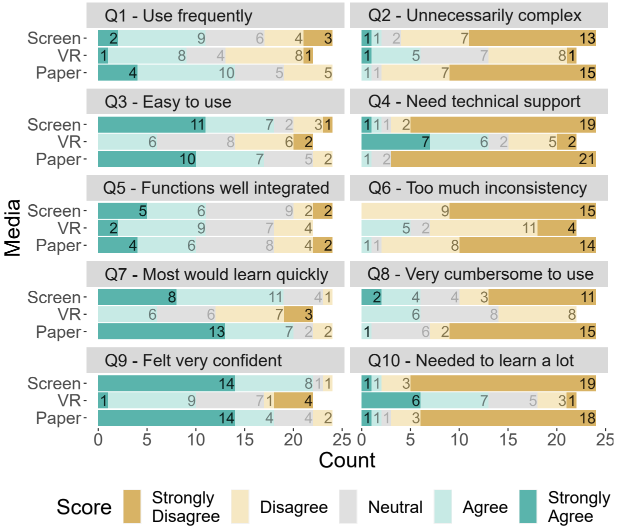


Figure 6: Likert scales for each SUS score questions

and SUS scores cannot be discarded in favour of the alternative hypothesis. The SUS score Estimated Marginal Means (EMMs) for paper (81.80) and screen (79.32) are both higher than VR (50.49), indicating that paper and screen were perceived to have higher usability than VR. The EMM SUS score was significantly lower for VR than for Paper and 2D screen (both p<.0001) (Table 2). However, no significant difference is indicated for the paper-screen pair (p=1).

5.3 Effectiveness

Effectiveness scales for the VR features indicate that the file list, tab menu, handheld map, and zoom buttons were most effective (Figure 7). The file list was the highest ranked receiving 19 responses indicating either effective or very effective. Participants could open files with the file list for each map to inspect layers. The tab menu received 17 responses indicating effective or very effective, indicating that participants could change tabs to access the layer filter, file menus or attribute lists. All features were ranked favourably, other than the legend. The handheld map data layer was ranked higher than the scenario map data layers. Participants were observed to have a strong preference for using the handheld maps over the scenario map for analysis. 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.

5.4 Qualitative analysis

Themes were extracted from coded questionnaires and audio recordings (Figure 8), the themes were: Effectiveness of map navigation for each media; Effectiveness of data comparison for each media;

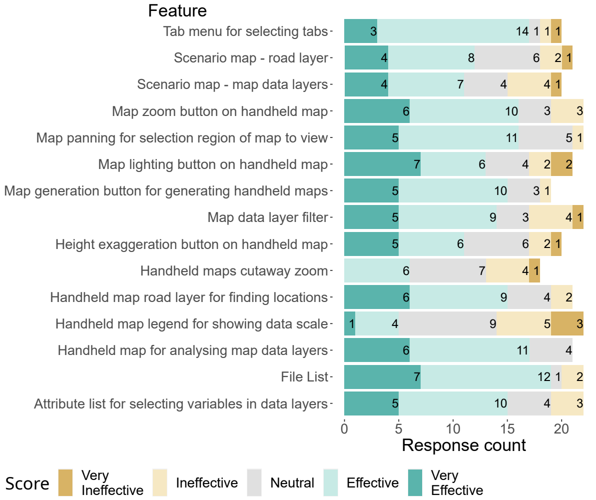


Figure 7: Effectiveness scales for features of Immersive ESS Visualizer, totals differ because some questions were not answered.

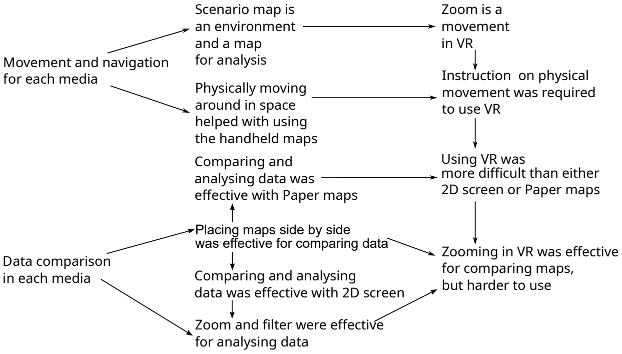


Figure 8: Themes extracted from user studies

Geospatial data analysis follows the information seeking mantra; inspecting the map, navigation/finding a location of interest, zooming/filtering, reading and comparing data to extract results [43]. Zooming was used for navigating and finding locations in the 2D screen and in VR. The effectiveness of navigation in each media and the effectiveness of data comparison in each media are subthemes which relate to the features of each media. Zooming is also grouped with filtering as it filters the area under inspection.

5.4.1 Movement and navigation for each media

This theme discusses navigation in VR and with the 2D screen. Paper maps could not be zoomed, and participants needed to physically move to interact with the maps. In VR participants moved to navigate to places of interest, positioned handheld maps, and zoomed. Physical movement in VR required the user to interact through actions such as walking inside the study room and reaching out to grab maps. Virtual movements such as distance grab and gliding were performed with the controller. In VR, moving closer or further away with the glide function was a zooming method, whereas moving the handheld maps physically was a method for arranging maps to make comparison easier. The handheld maps showed a map overview of the area of interest, but zooming out on the scenario map by gliding high above the surface also provided an overview.

Movement through zooming was supported in VR in three ways: Zoom buttons were attached to the handheld maps, handheld maps could be moved pulled closer, and participants could glide (zoom) across the scenario map. The VR zoom function was reported as useful by 13 participants for analysing data. Two participants compared VR zoom function favourably with the paper maps and the 2D screen. Zoom in VR allowed participants to look at elevation in close detail at any magnification with a stereoscopic 3D effect. Handheld map zooming received positive responses. *"So I do like that. Without the zoom function, you'd have the same problem again as the paper." - EV4*

Participants could zoom on the 2D screen interface. Three participants did not find the zoom helpful for the 2D screen due to insufficient resolution (EV7,12, 17), while three participants (EV2, 11, 24) did. The resolution of the data was a limitation in ecosystem services modelling at a catchment scale, rather than a limitation of the media as the resolution was the same in each of the three media, as a 5mx5m DEM was provided as input data.

Instructions on physical movement to use VR Participants commented on the action of moving the map in VR and some assistance was required when instructing the participants to reach out and grab the handheld maps with the controller. Two participants with low VR expertise and high map reading ability reported that after gaining their confidence to physically walk in VR, their feeling of success improved (EV11, 23). Both of these participants reported that they never use an HMD. They were learning to use the VR equipment for the first time during the study.

Physical movement helped with VR handheld maps Participant EV10 was impressed 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, ... 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*

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*

In VR, the handheld maps were large, and three participants EV2, 4, 12, and 13 indicated that they found working with the handheld maps too close. EV12 suggested a feature for moving maps away.

5.4.2 Comparison in each media

Zooming and filter were effective for analysing data; placing maps side-by-side was effective for comparing data; comparing and analysing data was effective with 2D screen; comparing and analysing data was effective with paper maps; and zooming in VR was effective for comparing maps but harder to use. For reading and comparing data, participants used layer/tab switching (VR and 2D screen), side-by-side views (Paper, 2D screen, VR), scrolling (2D screen), and moving maps in VR.

Scenario map is an environment and a map for analysis The use of the scenario map as either an environment or a map demonstrates an advantage of VR 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.

Zoom and movement in VR support data analysis at catchment scales and localised scales. Two participants liked being able to work with maps at two different scales in VR. Participants could see overviews by zooming away from the scenario map or using handheld maps. This unique novel feature of Immersive ESS Visualizer allows participants to compare the scenario map as an overview while analyzing elevation details on handheld maps. Placing markers on handheld maps provides details on demand while having an overview simultaneously visible. Other systems such as IVEVA [31], and Maps around me [41], do not allow users to simultaneously compare elevation overviews with elevation details. Reasons to glide (zoom) included close data inspection, and feeling present in the location. Participant EV5 liked treating the scenario map as an environment or a map, so they glided across the map to zoom. Participants EV4 and 7 applied strategies which incorporated the use of both handheld maps and scenario maps simultaneously, they zoomed away from the scenario map to view it smaller, but participant EV22 felt too far away to see information. Participants EV11 and EV15 both compared movement and zooming, however EV11 indicated that movement and zooming were different.

Placing maps side by side was effective for comparing data Participants had sufficient space to position all of the paper maps on the table and move them around. One of the perceived advantages of paper maps for one participant was the ability to see all of the information at once without zooming. Participants could indicate locations to the researcher by drawing on paper maps.

In VR four participants (EV9, 17, 21 and 24) 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 9 as a useful feature for assisting with the analysis. *"The approach was to get two maps side by side and look at them in the VR." -EV21*

A strength of VR was the ability to inspect fine details of the data. VR allowed participants to apply a combination of techniques, zooming, comparison between data layers, filtering and the hillshade to inspect fine details. The hill-shading in VR received positive feedback. 12 participants (EV3, 7, 8, 12, 13, 14, 15, 17, 18, 21, 22, 24) provided positive comments about the hillshade. The hillshade received four negative responses in the effectiveness scales (EV2, 5, 6, 15). Zooming in on data layers was possible in the 2D Screen environment. However, VR allowed participants to turn on and off the hillshade, which could identify topography.

Hillshades have previously been applied in 2D and 3D [38], as well as in the Adviser system [21]. Adviser has a single large map rather than handheld maps, so participants could combine compositing layouts in Immersive ESS Visualizer which were not possible in Adviser. Participants using the 2D screen interacted with desktop features such as placing windows side by side, tabbing, flicking between tabs rapidly to make differences flash, and scrolling.

Nine participants (EV3, 4, 6, 16, 18, 19, 22, 23, and 24) reported that positioning maps side by side helped with analysis when using the 2D screen. EV14 reported that flicking between maps was difficult. EV13 reported that it was difficult to get the maps close enough. EV5, 6 and 11 reported that placing two maps on one page was not helpful as the arrangement was vertical. EV24 found that placing two maps on a page did help. When discussing the 2D screen analysis:

> *"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. Five participants (EV9, 12, 19, 22 and 24) 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.

Emotional Responses Positive emotional reactions were reported by eight participants for VR (EV10, 20, 21, 23, 5, 7, 8, 24). Two participants reported negative emotional reactions including the fear of falling (EV 15), and feeling weird (EV 9, 15).

VR was more difficult to use than 2D screen or paper maps Two participants discussed the complexity of learning VR and getting practice with the tool to become familiar. Our study identified issues with the use of VR, however in working with expert users with high map expertise, their familiarity with both paper and digital (2D screens) maps means learning to use these methods is substantially reduced in comparison to their lower exposure to VR systems.

> *"So it's (VR) 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 ... I can imagine the power of this."* - *EV10*

6 DISCUSSION

Movement and navigation for each media In VR, navigation can be performed by gliding (zooming), or by zooming and panning the handheld maps. physically moving around in the VR space helped with using the handheld maps, but participants required instruction on physical movement and map placement to use VR. Navigation on the 2D screen consisted of scrolling and zooming. It was not possible to zoom in and out with paper. Participant responses suggest that physical movement was more difficult in VR than with the 2D screens or paper maps. This is expected because paper maps require less movement to position compared to physically moving in VR, and the 2D screen is a sedentary task.

The handheld maps were provided in front of the user in a vertical orientation. A study of interaction strategies for AR geovisualizations, allowed participants to inspect a 3D model of a city, then navigating a planned route in a first person Cave environment. Gardony et al. [22] provided a 3D city model in a horizontal orientation and found that participants who zoomed first rather than changing the orientation to top-down were less able to navigate. In VR, vertically orienting the handheld maps ensured that participants saw an overview first which may have contributed to the positive responses for zooming, since participants did not need to change the orientation. Participants found that zoom helped with their comparison of data in VR. Being able to zoom to compare data was an advantage in VR over paper maps. Immersive ESS Visualizer was effective for inspecting the hillshade, satisfying requirement R3 since hillshade allowed fine details to be observed. Participants were observed comparing a small number of maps side-by-side (e.g. two or three). Handheld map layouts created by participants 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. 15 participants were observed with map layouts that partially occlude controls, indicating that participants covered map controls to move maps closer together. Map controls were more frequently occluded compared to maps. Six participants tilted maps towards or away from themselves. Frequently used map positioning techniques in VR included placing maps at 90-degree angles to other maps, or a more obtuse 120-degree angle, suggesting that the ability to re-orient the terrain is beneficial compared to visualising the terrain attached to a flat surface such as a table. Participants tended to move their heads less when maps were closer together, so tilting and occluding maps seem good strategies for comparison. Three participants (EV2, 4, and 7) applied strategies which used both the scenario map and handheld maps, where the scenario map became an overview. Qualitative observations for the arrangement of handheld maps in VR, seem different to responses reported by Satriadi et al. [41] for map arrangement. They found that participants in VR avoided occluding 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 participants to pan and zoom handheld maps, however, Satriadi et al. [41] 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. zoom levels of maps were fixed, unlike Immersive ESS Visualizer.

Comparing each medium The adoption of 3D layout strategies in VR demonstrates an advantage over 2D screen and paper maps where content cannot be positioned spatially. Observed positioning techniques incorporated the 3D nature of the handheld maps to compose maps together and assist with comparison such as tilting maps forward or backwards, partially occluding maps, and placing maps with menu controls overlapping. The ability to zoom out from the scenario map allows users to view it as either an environment or a map, unlike IVEVA [31] which provides the 3D landscape on a virtual table. Content could be stored inside the virtual space. The Handheld maps received a high ranking on the effectiveness scales. In VR, placing maps side by side was effective for comparing data. Users often created layouts with 2 or 3 handheld maps when performing analysis. The ability to create complex 3D layouts with handheld maps make the VR satisfy requirement R1. The ability to zoom in VR and look at elevation details when inspecting the data made the VR system satisfy requirement R2.

Evaluation One difference between the evaluation of Immersive ESS Visualizer and Satriadi et al. [41] was that participants in the study by Satriadi et al. 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. GIS experts and novices may have different experiences and backgrounds [23], 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. VR was more difficult to use than 2D screen or paper maps. However, participants with more VR expertise gave higher SUS scores, so they found VR more effective. The TLX performance score for the VR condition appears bimodal, more experienced VR users tended to rank performance higher. 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. The method expertise ranking could be adapted to other research to enable in-depth analysis of participant responses based on different expertise domain areas. Participants frequently gave generally positive emotional responses to being in VR.

Effectiveness scales indicated the file list was ranked most effective feature for VR. The scenario map could be 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 maps could be viewed simultaneously and arranged 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 maps on the 2D screen could not be drawn on, and toggling between maps was more difficult.

Suggested Improvements for VR Features to augment the handheld maps suggested by participants included vectorization (EV5), linked settings (EV12, 17), a clone tool (EV17), and linked zooms (EV17). Vectorizing the map layers would avoid pixelation. Handheld map improvements suggested include linking settings among maps, linking zoom levels, and a clone tool for map settings. Participant EV13 suggested a difference raster as a method for visualizing difference between layers.

Limitations A potential limitation to measuring expertise was that the participants were ranked based on self reported information. Dreyfus et al. [19] suggested that experts have tacit knowledge, so this method of ranking may not detect advanced, or unreported expertise. Land use analysts, and participants with local knowledge and/or interest in ecosystem service planning were challenging to recruit due to their expertise being highly specialised. Four of the participants lived in the study area, and one participant was visiting monthly. Sample size could be a limitation, as users with local knowledge could have views not represented.

7 CONCLUSION

Expert land use analysts and stakeholders require tools which allow them to analyse the effect of land use change on ecosystem services data. The effect of elevation on ecosystem services data was a concern for analysts as it could affect model results. Current available VR visualization tools were not specifically designed for ecosystem services analysis. Immersive ESS Visualizer was implemented, and evaluated in a study comparing VR with paper maps, and a 2D screen. SUS scores indicate participants with more VR expertise ranked VR more effective than those with less VR expertise.

Zoom and gliding features were effective in assisting users to navigate and inspect fine details for data comparison in VR. The VR hillshade was effective for inspecting fine topographic details. 3D map layouts composing handheld maps together were effective for the comparison of data in VR because they allowed users to tilt, overlap, store content in the virtual space, and position maps to assist their analysis. Participants had a preference for using the handheld maps over a large scenario map. Responses to handheld maps, hillshades and the zoom suggest that participants found the novel feature of comparing multiple maps with elevation was effective. Our research recommends the following reasons to use Immersive ESS Visualizer: The ability to spatially arrange maps with elevation to compare data, stereoscopic inspection of fine details, interactive zooming, and emotional responses to VR. The correlation with VR expertise and effectiveness suggests that as participants get more practice, issues with VR unfamiliarity could become less of a concern.

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