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RESEARCH ARTICLE

Comparative usability of an augmented reality sandtable and 3D GIS for education

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ABSTRACT

Augmented Reality (AR) sandtables facilitate the shaping of sand to form a surface that is transformed into a digital terrain map which is projected back onto the sand. Although a mature technology, there are still few instances of sandtables being used in surface analysis. Fundamentally there has not been any reported formal assessment of how well sandtables perform in an educational context compared to other conventional learning environments. We compared learning outcomes from using an AR sandtable versus a conventional 3D GIS to convey key concepts in terrain and hydrological analyses via usability and knowledge testing. Overall results from students at a research-intensive New Zealand university reveal a faster task performance and more learning satisfaction when using the sandtable to undertake experimental tasks. Effectiveness and knowledge quiz results revealed no significant difference between the technologies though there was a trend for more accurate answers with 3D GIS tasks. Student learning wise, the sandtable integrated core concepts (especially morphometry) more effectively though both technologies were otherwise similar. We conclude that sandtables have high potential in geospatial teaching, fostering accessible and engaging means of introducing terrain and hydrological concepts, prior to undertaking a more accurate and precise surface analysis with 3D GIS.

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Tertiary teaching; efficiency; effectiveness; satisfaction; terrain analysis

1. Introduction

Technology offers tools and methods that can collect, manipulate, analyse and visualise spatial data, with increasing proliferation and performance precision (e.g. GIS, GNSS). Augmented Reality (AR) and Virtual Reality (VR) in particular, have increasingly attracted the public imagination with their novelty, ability to entertain and scintillate and have become two groups of visualisation technologies that can justifiably be added to the core geospatial toolset. More specifically, AR combines real and virtual elements, in interactive real-time and registers them in 3D reality while VR technology immerses the user completely inside a synthetic environment (Azuma 1997). Both VR and AR are

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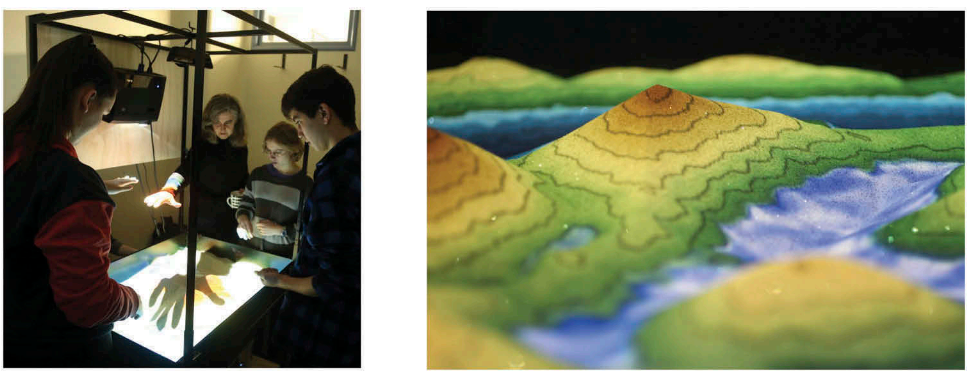
inherently spatial (e.g. Arvantis *et al*. 2009). Their popularity means that they are used for many applications, but little effort has been made to determine how well AR and VR perform as educational tools. This is often the case when tools are used for teaching and learning. Evidence of the effects of AR, as an example, are characterised as 'shallow' due to studies having a simple experimental design for one, leading to a need for controlled and comprehensive evaluation (Wu *et al*. 2013, p. 47).

This need applies equally to AR sandtables, which by their nature are a visually rich tool with great potential to contribute to the efficacy of teaching and enriching student learning outcomes. A number of educational institutions have implemented AR sandtables to enhance teaching outcomes in the areas of earth science and computer visualisation (Ratti *et al*. 2004 – the first sandtable – Sandscape; Mitasova *et al*. 2006 – coupling of sandtables and GIS, and, Kreylos 2018 – making the sandtable open source, with code and explanatory materials).

An AR sandtable (Figure 1(a)) comprises a frame (either constructed from wood or metal) that houses a box that is filled with sand. Overhanging the box is a support to which is attached a 3D camera sensor (e.g. Microsoft Kinect) and a digital colour projector. The sensor measures the distance to the sand surface through active sensing, using a near-infrared camera to measure the distortion on a transmitted and calibrated light pattern once it encounters the surface. This information is translated into depth images at a rate of 30 frames per second (see section 3a). The computer constructs and renders a topographic surface (e.g. as hypsometrically coloured contours, e.g. Figure 1(b)) and feeds this to a colour projector, which displays it onto the surface of the sand. This whole process takes place in real-time, but a short delay is introduced so that transient changes, such as hands moving in the scene, are not incorporated into the model.

1.1. Research challenges

In general, the goals of AR projects are to implement useful tools in a variety of settings. Sandtables in particular, have matured as a technology and have become prevalent over the years. However, there has been limited formal analysis of AR sandtable effectiveness in enhancing teaching and improving learning outcomes.



(a) (b)

Figure 1. (a) Users and the Otago sandtable; (b) Coloured contours and surface water.

Broadly speaking, AR technologies can be used to teach abstract and fundamental concepts in geoscience that involve spatial thinking. Spatial thinking includes approaches to space (i.e. relative and absolute), representation tools such as maps (and by extension, AR displays), and ways of reasoning about a spatial scenario (National Research Council 2006, Scholz *et al*. 2014). A recommendation from a US national report on 'Learning to Think Spatially' advocates broadening 'sensory input', overcoming 3D 'visualisation limitations' and using more intuitive interfaces (National Research Council 2006, p. 9). These are all attributes that the sandtable possesses. As a component of the fundamental skill of spatial thinking (integral to success in STEM: Wai *et al*. 2009), the teaching of terrain principles is an important yet difficult undertaking. For example, a commonly used method for interpreting relief is to create series of cross-sections from an elevation contour surface. This requires mentally challenging tasks to relate the 2D cross-section visualisations to the corresponding 3D elevation surface.

The pioneering sandtable implementation at the Massachusetts Institute of Technology (MIT) described the implementation and user experience aspects of an AR sandtable but offered no formal evaluation in an educational setting (Ratti *et al*. 2004). Comparatively, the research reported by a group from the University of North Carolina included an informal evaluation through anecdotal observations (Tateosian *et al*. 2010), while the stated goal of the UC Davis, California project was to develop a real-time integrated augmented reality system to physically create topographic models that can be used as backgrounds for simulations (Kreylos 2018). Although there is evidence that educational studies are underway, they are in a public science setting (Reed *et al*. 2014) with very different learning objectives to the more formal university setting. Interestingly, many of the installations to date appear to be located in schools and museums, known to be bridges between formal and informal learning (Hofstein and Rosenfeld 1996). In summary, the sandtable appears generally to be presented as a technological marvel, in some cases extended as a directed teaching tool in university settings, but without rigorous evaluation of effect on learning outcomes. Thus, there is a clear need for a study that assesses the effect of the sandtable on learning strategies, satisfaction, task efficiency and task completion correctness.

1.2. Research objectives

Such an initiative was undertaken at the University of Otago (Dunedin, New Zealand) in 2016. A comparative usability study was designed to assess the impact of AR sandtable and 3D GIS technologies on the teaching of terrain and hydrological concepts to 2nd year university students enrolled in an introductory GIS course. These concepts are conventionally taught using (non 3D) GIS technology. The usability study was particularly guided by the following questions:

- Will the sandtable facilitate faster completion of tasks than a GIS?
- Will the sandtable enable tasks to be completed more correctly than a GIS?
- Will the sandtable user experience greater satisfaction relative to a GIS?
- Will the sandtable foster beneficial learning strategies?
- Will the sandtable improve domain knowledge in the short term?

The research project was supported by an internal university teaching development grant that funded the design and construction of a new AR sandtable, as well as the design and operation of the usability study.

A short review follows this introduction, covering AR applications for teaching and learning, sandtable AR and usability testing. Background to the Otago sandtable study is provided, followed by an outline of the comparative sandtable vs. 3D GIS usability experiment. Following this is a presentation of the study's results, analysis, discussion and concluding statements.

2. Related research

AR affords many opportunities for education, particularly in a spatial sense, where the co-existence of computer-generated objects in a real context facilitates the expression of complex spatial and abstract concepts (Arvantis *et al*. 2009), being more effective than conventional technologies (Rosenbaum *et al*. 2007, El Sayed *et al*. 2011, Wu *et al*. 2013). However, AR technology needs deep integration into educational programmes to be effective. AR has many characteristics that make it valuable in education, including enabling collaborative, 3D-interactive use coupled with intuitive interaction and an ability to reveal the invisible in an immediate, compelling way. It is the latter characteristic in particular that affords a more effective, informal method of learning that can blend effectively with conventional, formal education (Hofstein and Rosenfeld 1996, Cuendet *et al*. 2013, Wu *et al*. 2013). However, an inflexibility of content within the lesson flow, cognitive overload (Sotiriou and Bogner 2008), multi-user and self-imposed physical limitations (Jermann *et al*. 2009, Arvantis *et al*. 2009) and difficulty in obtaining controlled experiment conditions in the 'chaotic' classroom (Cuendet *et al*. 2013) have to be overcome. The AR sandtable has the promise to address these drawbacks, possessing the desired characteristics of tangibility, collaboration in 3D space and immediacy of interaction to make it a highly effective teaching and learning tool.

Wu *et al*. (2013) echo a call for a controlled and comprehensive evaluation of AR in a learning context. Dias *et al*. (2003) approached the level of complexity required, testing efficiency, effectiveness and satisfaction for their marker-based AR authoring tool, MixIt, but on a small cohort of 16. A more recent example compared marker-based AR finger gesture manipulation of Digital Elevation Models (DEM) to traditional 2D interpretation (Carrera and Asensio 2017a, 2017b). Both assessments made use of five displays: a) contour lines, b) orthophotos, c) hypsometric colouring, d) hypsometric colouring and contours, and e) hypsometric colouring, contours and shading. The student participants were split into a group of 73 performing tasks with both tools (2D then AR), and a control group of 22 using 2D interpretation only. A questionnaire template (Topographic Map Assessment – TMA; Newcombe *et al*. 2015) was applied before and after the AR tasks, testing path (easiest), stream/waterflow, slope (steepest), visibility, elevation points, photo interpretation and profile. The AR group performed better (students' paired t-test) than the control group, improving questionnaire results significantly post-AR. An ANOVA analysis found an enhanced development of stream/waterflow skills, with slope, visibility and profile improving weakly.

Specific to the sandtable, the early continuous TUIs (e.g. Sandscape and Illuminating Clay – IC – developed at MIT, Shamonsky 2003, Ishii *et al*. 2004) have been subject to low-level usability testing, based on interviews with participants. There was positive evidence of benefits from using IC to teaching and professionally, provided an easy 'roughing process' and fast evaluation of 'what-if' scenarios, leading to more confident decision-making with enhanced communication and presentation. However, in a proposal for a 'plural' approach, it was acknowledged that for deliberate, precise tasks, conventional GUI tools would also need to be used.

Mitasova *et al*. (2006) explored the coupling of the continuous TUI and GIS in particular (an aspect that Sandscape pioneered), with a specific emphasis on terrain analysis (including surface feature identification, watershed, solar irradiation and querying). For their TanGeoMS clay interface (Tateosian *et al*. 2010), anecdotal observations revealed creative yet background-specific use of the environment (e.g. hydrologists making hydrology-led interactions). They also found that all participants were generally engaged, though some participants were initially hesitant and only encouraged to engage with the technology by observing others interact with the interface. Their most recent research centres on the sandtable-based Tangible Landscape, which features laser pointer input (for viewshed point and linear route, for example), first-person immersive VR interaction (Tangible Landscape Immersive Extension) (Tabrizian *et al*. 2016), contour-guided sand and clay sculpting (Petrasova *et al*. 2015) and earthmoving cut and fill volume overlays (NCSU GeoForAll Lab 2016), enabling physical approximation of real-world surfaces. Finally, in another recent development, UC Davis deployed the software driving the sandtable set-up as open source (e.g. see Kreylos 2018). When applied to an existing physical sandtable with supporting hardware, the installed software can generate on-the-fly contour maps of the current sand surface, along with virtual water flow, with potential for further functionality to be added.

3. The Otago AR sandtable study

The aims of the Otago AR sandtable study were to:

- construct a mobile AR sandtable for teaching and learning geospatial and engineering concepts (additionally for community outreach), supported by free and open-source software;
- develop and implement a teaching plan that incorporates the AR sandtable into GIS and civil engineering undergraduate papers taught at the University of Otago;
- assess the usability (efficiency, effectiveness, satisfaction) of the system in its educational context, and;
- analyse the impacts of this intervention on teaching outcomes (reported elsewhere).

Addressing previous experiences with AR testing outlined in the previous section, the following study considerations emerged. The proposed experimental conditions (set tasks, smaller numbers) isolate sandtable use from the unstructured and unpredictable full class situation, including issues like monopolisation in collaboration. Secondly, the proposed augmenting content (contour maps of the sand surface) is well integrated with the physical and not of a magnitude so as to be overwhelming. Lastly, the augmented contour map is flexible enough (coloured and uncoloured) to blend with the malleability of the medium to support a large range of terrain-based and hydrological descriptors, as foundations of knowledge in those two domains.

The project plan was implemented in three phases: development and construction; experimentation and testing; and assessment and dissemination. In the first phase, the sandtable design was first developed by a team of researchers at the University of Otago and then constructed by Metalon, a commercial furniture manufacturer. It took the form of a custom-made, mobile 1000 mm x 700 mm sandbox on a trolley with overarching frame (Figure 1(a)). Development was based on existing open-source software (Kreylos 2018) that was linked to a Microsoft Kinect v1 sensor for surface data collection and a short-throw projector for map display – both sensor and projector were mounted on the frame.

Subsequent development implemented visualisation tools tailored to the planned learning activities, including coloured contour maps similar to those in the original UC Davis system. Keys were mapped to developed software that switched between coloured contour hue schemes, including uncoloured contours for test conditions (and also for adjusting the height at which colours are seen), different contour separations, freeze contours (to minimize displayed instability due to sensor variations), controlling the water function (on/off and global/local flood/dry), and exporting the sand surface in text XYZ format (for easy import into a GIS). See Figure 1(b) for an illustration of coloured contours and surface water. Finally, documentation for the sandtable operation and calibration process was developed for future management.

The experimentation and testing phase focussed primarily on undertaking usability and knowledge evaluations to gain better insight into how university students interact with an educational interface and AR. It was anticipated that outcomes from the assessment phase would have the potential to inform future design and development of AR for educational purposes and open further research inquiry into how this form of novel technology can be fully utilised and optimised for learning and teaching in Higher Education. Ethical approval was obtained for the testing phase, which included assessing student performance in such areas as measuring efficiency (time taken), effectiveness (correctness of completed task) and satisfaction (user opinion of the technologies).

3.1. How the AR sandtable works

The AR sandtable consists of four main components: The sand tray itself, an integrated depth sensor and camera, a projector, and a controlling computer, as illustrated in Figure 2.

The integrated depth sensor and camera is a Microsoft Kinect v1 sensor (Zhang 2012). This version of the sensor uses a near-infrared (NIR) structured light system to create a depth map of the scene in front of the camera. The use of NIR for the structured light system means that the projected pattern is not visible to the human eye, but normal cameras with suitable filters can be used to image the projected pattern and determine depth from the distortion caused by the shape of the surface. The Kinect also has a colour camera, although this is not used in the normal operation of the sandtable. This combination of a colour (RGB) camera and depth is often referred to as an RGB-D sensor.

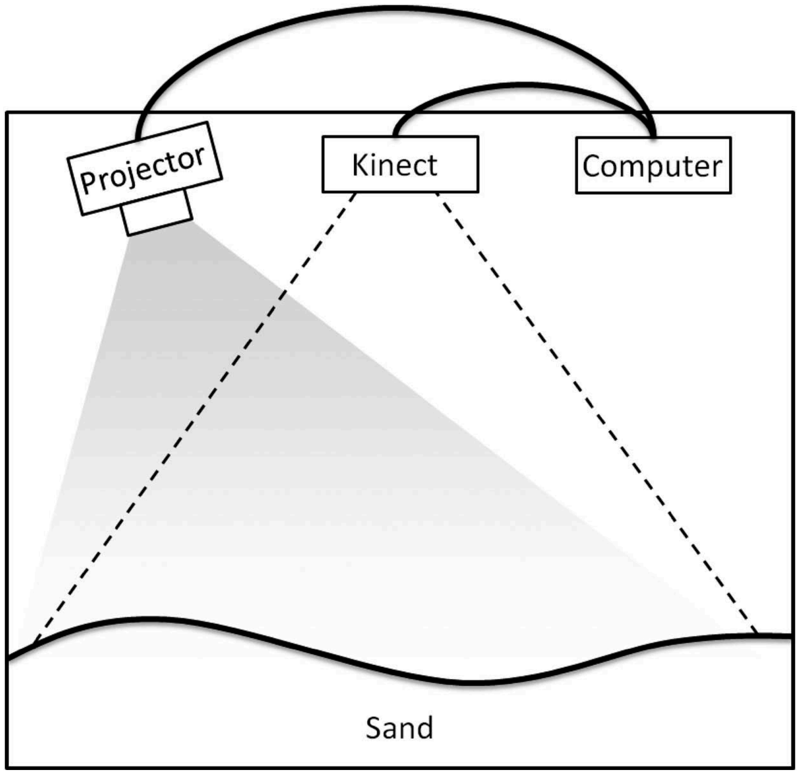


Figure 2. Schematic of the AR sandtable.

Once the shape of the surface is known, the desired texture to project onto the surface can be computed. This might be hypsometric colour gradients, a set of contour lines, or any other function of the sandtable's surface shape. In order to project the texture onto the surface, it is necessary to account for the different locations and orientations of the projector and the Kinect sensor. This relationship is established as a six degree of freedom transformation (rotation plus translation) between 3D co-ordinate frames centred at the projector and depth sensor's optical centres, estimated by a calibration process (Appendix).

4. Experimental design and methods

As part of an introductory GIS course taught at the University of Otago, a comparative study was conducted. The overarching theme was assessing the use of GIS versus the sandtable for terrain analysis and hydrological modelling, e.g. the modelling of the flow of water over a digital surface (i.e. DEM) and the products arising from this (slope, aspect, flow direction, basins). The study took the form of a laboratory exercise undertaken during the regularly scheduled laboratory period. Consenting students drawn from the course were assigned to one of four streams. Each student had completed eight weekly labs on other GIS topics prior to the one in this study. Each lab stream was divided into six groups of up to four students.

During the session (just under 2 h long), each within-subjects group completed sandtable tasks and GIS tasks for up to 20 min each. To avoid finding only a learning effect, half of the participants encountered the sandtable first, the other half, 3D GIS first. Furthermore, the sandtable surfaces were exported and used as the basis of the GIS test for a later, different group, enabling surface-to-surface comparison (acknowledging that visually, the GIS rendering of the surface is scaled down to fit within the monitor display). Same-group comparison across the two technologies was also enabled, albeit with different surface configurations. This was important as we wanted each group to encounter any given surface configuration for the first time when being tested, so that there was no chance of remembered surface information affecting the results of the experiment.

The GIS analysis tasks were performed using ArcGIS 10.3.1. The sandtable was installed in a small room adjoining the GIS lab in such a manner that students could interact with the table via three of its four sides. The general structure of the experiment for any given student was Task 1 (sandtable or GIS: 20 min) – Knowledge Testing (20 min) – Task 2 (sandtable or GIS: 20 min) – Knowledge Testing (20 min) – Reflections (30 min), for a total time of 110 min. This process was staggered so one group each of GIS and sandtable students started at the beginning of the experiment period, the second set of groups 20 min in, the third set of groups 40 min in, and so on.

During the experiment, the following tasks were performed using both the sandtable (recorded through flag and string objects then photographed, see Figure 3) and 3D GIS (recorded and labelled through 3D graphics then saved, see Figure 4(b)) conditions. The captured surfaces used as the basis for the 3D GIS had edge artefacts (the tall, thin and sharp peaks in Figure 4), which the participants were told to ignore. Both the sandtable surface and digital equivalent in 3D GIS were considered to be at 1:1 scale for their respective experiments, to facilitate error measurement of experiment tasks. However, in practice the 3D GIS afforded a range of scales through zoom functionality – practically this ranged from approximately 1:4 relative to the sandtable (the whole of the 3D GIS surface filling the monitor display) to scales larger than 1:1 when zoomed in.

In terms of spatial granularity, whereas the sand surface was physically continuous, all surface calculations (e.g. for the contour map) were based on a 640 × 480 point capture from the Kinect sensor. The same density of sampling was used for the surface point

(a) (b)

Figure 3. (a) The flags, arrow and string used for sandtable annotation. (b) The sandtable surface ‘annotated’ with task answers.

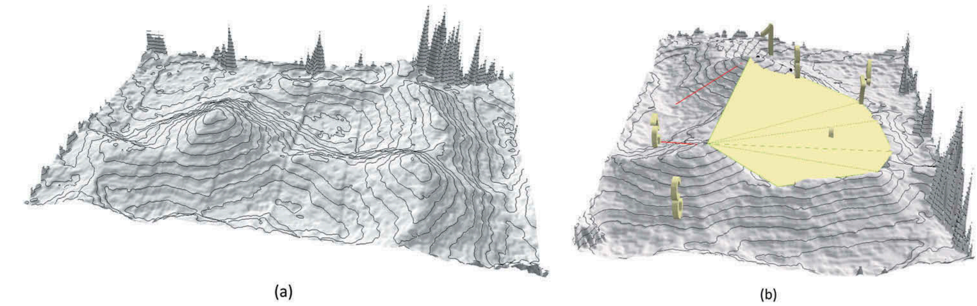


Figure 4. (a) The surface interpolated from captured sandtable surface points in ArcGIS ArcScene. (b) Another surface (view corresponding with Figure 3(b)) with 3D graphics annotation.

data export from the sandtable that was interpolated to form the surface tested in the GIS. The GIS surface itself also appears to be physically continuous though it is a raster (resolution 1.75 mm).

Initially, the map display was setup in non-colour mode (i.e. just contours). Participants were first given the opportunity to 'play around' with the interface in order to gain an appreciation for its functionality (2 mins). At the end of the play period, the experimenter either:

- in the case of the sandtable, sets up a terrain landscape with the following features: Two hills of similar yet different height; One large basin between the two hills, of medium depth; One smaller basin, of maximum depth; A small flat area, and, if possible; A slope that is demonstrably steeper than any other slope.
- in the case of the 3D GIS, loads and symbolises a 3D surface that has been captured and exported from a previous sandtable session.

The final stage in the experiment induction involved participants being shown the 'northern' edge of the display.

The main part of the experiment referenced the Topographic Map Assessment (TMA) (Newcombe *et al.* 2015), though the extent of functionality and limited time available for testing necessitated a prioritisation on testing of on-surface features (basin and associated pour point), characteristics (highest/lowest point) and morphometric-related measures (slope, aspect, water flow). An experimenter prompted the students to undertake 8 tasks in the following order (16 mins):

- Visually identify the highest point on the terrain (point)
- Visually identify the lowest point on the terrain (point)
- Visually identify the steepest slope (point)
- Visually identify the flattest topography (point)
- Visually calculate the catchment of a single hydrological system (area)
- Visually predict the pour point of the large basin (point)
- Visually predict the direction of flow of water for a chosen slope (line)
- Visually identify a slope with a northerly aspect (point)

The experimenter timed each task (efficiency data) and recorded the participant task results for post-experiment assessment of effectiveness or accuracy. The latter was conducted for attribute and spatial accuracy (see Figure 5 for an example solution dataset for the 3D GIS exercise) for:

- highest point, lowest point and basin pour point; difference in elevation from the nominated elevation to the actual one (also x,y difference in location).
- steepest and flattest slope; difference in slope from the nominated slope location to the actual one (also x,y difference in location).
- flow of water and northerly aspect; difference in bearing from nominated flow direction to the actual one, also difference in aspect angle from North.
- basin; difference in total areal error (difference in basic area) and visual area calculated as:

Visual area = (positive areal error + negative areal error)/calculated area

Positive and negative areal error are defined as per Alani *et al*. (2001) with positive area error being any area within the estimate but not in the calculated area and negative areal error being any area within the calculated area but not the estimate.

In the final stage of the exercise, the experimenter visually demonstrated some of the correct answers, e.g. through display of coloured terrain (highest and lowest points) (2 min). An observer made notes on learning strategies used through the entirety of the experiment.

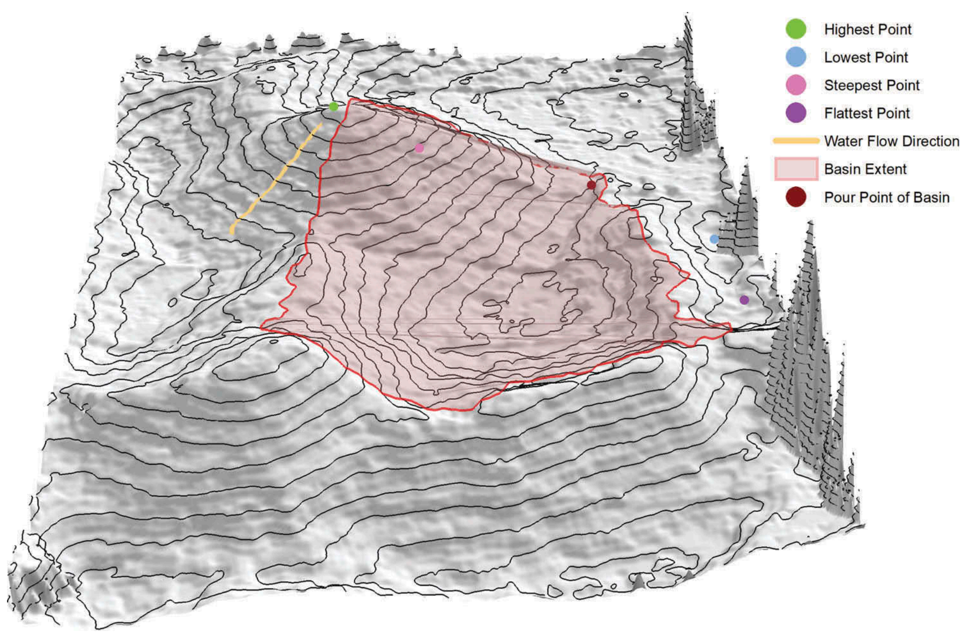


Figure 5. GIS-calculated solution dataset corresponding to the sandtable arrangement in Figure 3(b) and the 3D GIS arrangement in Figure 4(b).

To ascertain satisfaction with the two technologies, some statements and questions were posed to the study's participants via the University of Otago Blackboard Learning Management System (LMS). Table 1 lists the questions asked. There were Ease of Use, Usefulness and Software Contribution to Learning categories. The first five questions in the Ease of Use category required Likert-scale responses, with the remainder open answer.

Immediately after the session, there was a quiz delivered through the university LMS to test terrain and hydrological principles (short-term knowledge). The participants were given a random choice of five questions out of a question pool (see Table 2).

The answers were marked independently by two domain experts, with all identifying information for which of 3D GIS and sandtable technologies the quiz came after, removed. The marks, which could range from 0 to 5, were averaged, except in isolated cases where the difference between marks was greater than 2. In these cases, the two markers discussed the adjustment of their mark(s) so that the difference between them reduced to at most 2.

Table 1. Questions to ascertain satisfaction with the sandtable and 3D GIS. Statements eliciting Likert-scale answers italicised, the rest are open answer.

EASE OF USE	*I have used [augmented reality technologies such as the Sandbox/3D GIS] before.*
	The [Sandbox/3D GIS] technology was easy to use.
	The [Sandbox/3D GIS] technology was engaging.
	I found completing the [Sandbox/3D GIS] tasks entertaining.
	The [movement of sand and gestures/commands and actions] used to operate the [Sandbox/3D GIS] were intuitive and easy to master.
	Was there anything in the technology that you missed but was expecting to see?
	Did you encounter any problem using the system?
USEFULNESS	What were the three main things you liked about the technology.
	What were the three main challenges (if any) you encountered using the technology?
	Would you recommend your peers to use the system … briefly explain.
	Did the system work the way you wanted it to work?
	Would you use this interface recreationally if given the chance?
	Were you able to complete the task using this interface?
SOFTWARE CONTRIBUTION TO LEARNING	Briefly tell us how the use of the technology contributed to your learning
	Briefly what were the challenges if any in using this piece of technology for learning?
	Are there any specific examples of learning experiences you would like to share with us resulting from the use of the software?
	Were there any difficulties you encountered in using the technology to support your learning?

Table 2. Pool of questions and statements to ascertain hydrological and terrain knowledge.

Define a watershed in a hydrological system.
Define what flow direction is.
Give a definition of hydrological modelling.
Give two reasons why you would encounter a pit in terrain data.
Give two solutions for removing pits from terrain data.
In your own words, define what a sink is in a hydrological system.
In your own words, what is the aim of hydrological modelling?
Name three types of digital elevation data (i.e. DEMs) that could be used for hydrological modelling.
What factors define the direction of water flow on a surface?
What is a basin in a hydrological system?
What is a catchment in a hydrological system?
What is a 'pour point' in relation to a basin or catchment?
What is the difference between a catchment and a basin?
Why would you do hydrological modelling?

During all the tasks, observations were made by lab personnel and investigators of how the students interacted with the sandtable, GIS and each other in order to strengthen the learning process. Looking at lecturer/course evaluations for the Introductory GIS course that year (these are questionnaires that are completed anonymously by students, for the most part with Likert-scale responses), the free comments fields were scrutinised for any unprompted mention of the sandtable in the context of the entire paper. All student grades were also factored into the analysis. The disparate sources of data were linked by student ID code to enable management and analysis, though all reporting of results and analysis was anonymous.

A Kolmogorov–Smirnov (one sample) test was run to check for normal distribution of efficiency, satisfaction, effectiveness and knowledge data. As non-normality was found in most cases for the effectiveness and satisfaction data, the following non-parametric statistical analyses were applied. A Mann–Whitney test was used to establish significance in the effectiveness of the results. For the matched analysis (surface in sandtable vs. same surface in 3D GIS; same for participants), Wilcoxon matched pairs were used. For the satisfaction Likert-scale data, Kolmogorov–Smirnov (2 sample) tests were used to establish significance.

As normality was found for the efficiency and knowledge data, the following statistical analyses were applied: ANOVA tests for comparative analysis with paired sample t-tests being used for the matched analysis (matched surfaces and groups, as above) of knowledge quiz results. However, due to the presence of outliers in the efficiency data, Wilcoxon matched pairs were used in that case.

For both parametric and non-parametric tests (i.e. covering all of efficiency, effectiveness, satisfaction and knowledge), the analysis compared the sandtable and 3D GIS conditions, and further compared participants that encountered a specific technology first in the experiment to those that encountered that technology second (e.g. those that encountered the sandtable as their first test vs. those that encountered the sandtable after their 3D GIS test). In addition, Pearson's correlation was calculated to compare knowledge results with overall performance in the Introductory GIS course. Correlations were also performed with examination/midterm test marks (as the closest equivalent to the experiment knowledge tests; 30% + 16% = 46% of total assessment), the practical lab mark total (out of 9 labs, * 6% = 54% of total assessment), and the specific DEM practical lab mark (completed the week before the experiment) forming part of that overall grade.

5. Results

In all, 54 students took part in the usability study, organised as 18 groups of 2–4 people. Efficiency-wise (Figure 6, Table 3), all eight tasks were performed significantly faster with the sandtable than with the 3D GIS ($F_{1,34}$: $p < 0.01$ apart from highest point and basin definition; $p < 0.05$). Matched pairs analysis revealed similar results, with the same participant generally faster with the sandtable, a trend that continued when comparing the pairs of tests with the same surface configuration. Analysis of the data revealed a significantly faster performance for the lowest point, steepest slope and water flow ($F_{1,16}$: $p < 0.05$) in 3D GIS when expressly done after the sandtable task (Figure 6(b)).

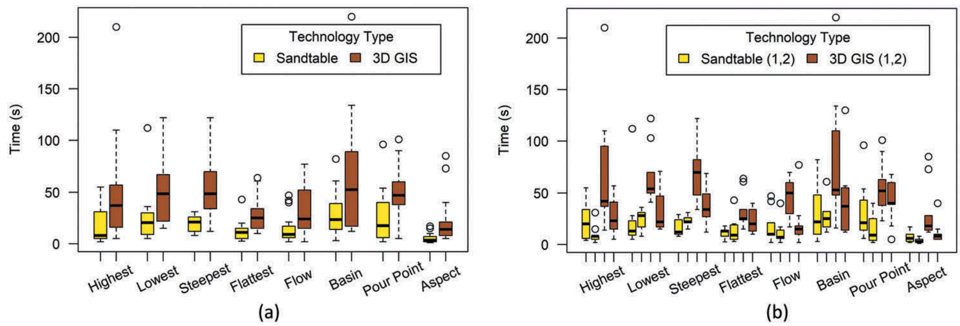


Figure 6. (a) Box plot of efficiency results for the eight tasks comparing sandtable and 3D GIS technologies. (b) The results accounting for whether either technology was encountered first or second. Numbers in the legend indicate whether a technology was encountered first (lefthand bars) or second (righthand bars).

Table 3. Efficiency results (ANOVA *F*-statistics for Sandtable vs. 3D GIS, Wilcoxon matched pair *t*-values for matched analysis; *$p < 0.05$, **$p < 0.01$).

	Sandtable vs. 3D GIS (F)				
Task	All	Sandtable first	3D GIS first	Matched Group (t)	Matched Surface (t)
Highest	7.28*	4.28	3.54	17**	9**
Lowest	8.25**	6.98*	0.001	19**	27.5*
Steepest	23.19**	8.29*	4.47	5**	7**
Flattest	14.37**	2.15	0.27	11**	5.5**
Flow	8.11**	6.56*	1.00	17.5**	14**
Basin	6.27*	2.74	0.24	25*	28.5*
Pour Point	9.13**	1.00	2.95	27**	21**
Aspect	8.52**	3.81	3.78	17**	4.5**

For satisfaction results (Figure 7, Table 4), while participants were generally inexperienced with AR as opposed to 3D GIS, they were significantly more satisfied with the sandtable (p < 0.01). As for accounting for what technology was encountered first in the

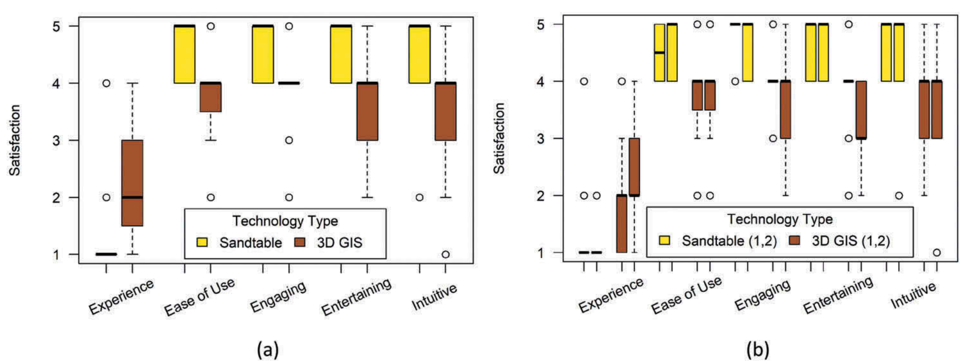


Figure 7. (a) Satisfaction results for the five Likert-scale questions on experience ease-of-use, engagement, entertainment and intuitive interface. (b) The results accounting for whether either technology was encountered first or second. Numbers in the legend indicate whether a technology was encountered first (lefthand bars) or second (righthand bars).

Table 4. Satisfaction results (Kolmogorov–Smirnov 2 sample *d*-values for sandtable vs. 3D GIS; **p* < 0.05, ***p* < 0.01).

	Sandtable vs. 3D GIS		
Statement	All	Sandtable first	3D GIS first
Experience	0.61**	0.06	0.25
Ease of Use	0.51**	0.09	0.04
Engaging	0.69**	0.09	0.28
Entertaining	0.56**	0.09	0.39*
Intuitive	0.42**	0.03	0.12

experiment, those who saw the 3D GIS first were significantly ($p < 0.05$) more positive about the 3D GIS than those who saw the sandtable first, for the statement 'I found the 3D GIS tasks entertaining'.

The results of the effectiveness measures included attribute accuracy (Table 5). Although GIS mediated estimates were on average more accurate, this trend was not significant (though highest point was significant at $p < 0.1$). No significant difference could be found when considering what technology was encountered first.

For spatial accuracy (Table 5), GIS-based estimates were again more accurate, though only lowest point was significant (at $p < 0.05$; closely followed by highest point at $p < 0.1$). When considering order in which the technology was encountered, only highest point task results were significantly more accurate if performed in a 3D GIS before experiencing the sandtable ($p < 0.05$).

Matched pairs analysis revealed a significant increase in attribute accuracy ($p < 0.01$) for the same group when using GIS to estimate the highest point (though matched surface did not elicit any significant differences). Using GIS resulted in significantly improved spatial accuracy for the same group estimating lowest point ($p < 0.01$), highest point and pour point ($p < 0.05$). Matched surfaces also led to enhanced spatial accuracies when using GIS, in placing the pour point ($p < 0.01$) and lowest point ($p < 0.05$). Finally, for basin estimation, no significant improvement was found in the use of the sandtable, as defined by difference in total (basic) area and visual area.

For the knowledge quiz results (Table 6), no significant difference could be detected in performance when experiencing either technology, even when taking into account which technology was encountered first (same for matched analysis of participants). There was also limited correlation (mostly positive) of each technology's quiz results with overall grade and constituent score performance (Table 7) in the Introductory GIS course as a whole (the highest was a 0.24 correlation of the post-GIS quiz results and the overall practical lab performance, 0.11 correlation with the DEM lab alone; also a correlation of 0.25 of post-sandtable quiz results and theory test results). Finally, a general observation from the quiz answers was that in a few cases, after the sandtable experiment, the sand medium was specifically mentioned (e.g. in filling hydrological pits with sand) whereas there was no such demonstrable influence of technology in the post-GIS answers.

Table 5. Effectiveness results (Mann–Whitney *U*-values for sandtable vs. 3D GIS, Wilcoxon matched pair *t*-values for matched analysis; $^{*}p < 0.05$, $^{**}p < 0.01$).

	Attribute effectiveness					Spatial effectiveness				
	Sandtable vs. 3D GIS					Sandtable vs. 3D GIS				
Task	All (U_S, U_G)	Sandtable 1st (U_{S1}, U_{S2})	GIS 1st (U_{G1}, U_{G2})	Matched group	Matched surface	All (U_S, U_G)	Sandtable 1st (U_{S1}, U_{S2})	GIS 1st (U_{G1}, U_{G2})	Matched group	Matched surface
Highest	95, 194	46, 26	26, 46	14**	31	94, 195	39, 33	15*, 57	24*	37
Lowest	99, 190	33, 39	46, 26	41	30	74*, 215	26, 47	41, 31	18**	24*
Steepest	108, 181	30, 42	45, 27	32	51	99, 190	45, 28	34, 38	42	43
Flattest	146, 144	35, 37	22, 50	48	59	114, 175	41, 31	27, 45	49	48
Flow	164, 125	40, 32	34, 38	58	52	N/A	N/A	N/A	N/A	N/A
Basin	158, 131	30, 42	40, 32	50	59	141, 148	26, 46	30, 42	66	61
Pour Point	103, 186	24, 48	39, 33	36	41	99, 190	27, 45	33, 39	26*	17**
Aspect	109, 180	33, 39	20, 52	51	40	N/A	N/A	N/A	N/A	N/A

Table 6. Knowledge quiz results (ANOVA *F*-statistics for sandtable vs. 3D GIS, paired *t*-test values for matched analysis).

	Sandtable vs. 3D GIS			
Task	All	Sandtable first	3D GIS first	Matched Student
Average mark	1.17	0.20	0.87	−1.82

Table 7. Correlation of knowledge quiz results (quiz taken after either sandtable or 3D GIS tasks) with GIS course performance (Pearson's *r*).

Task	Sandtable correlation	3D GIS correlation
Course percentage	0.12	0.20
DEM lab mark	−0.05	0.11
Total lab mark	0.06	0.24
Test mark	0.25	0.10
Exam mark	0.08	0.15
Total test and exam mark	0.16	0.14

6. Discussion

The use of the AR sandtable in education is part of a widespread trend of integrating new technology into teaching (e.g. Carrera and Asensio 2017a, for marker-based AR). A usability evaluation of the sandtable for terrain and hydrological teaching in a tertiary setting was much needed and this study has yielded valuable results in this regard. Overall, all sandtable tasks were performed more efficiently (i.e. took less time) than for 3D GIS. These results held for individual efficiency performance, as well as when considering the same surface in the sandtable and 3D GIS. Overall, this outcome provides strong support for continued use of the sandtable in geospatial teaching. The satisfaction results are possibly aligned with an increase in motivation, in turn leading to more efficiently completed tasks. The number of participants is sufficient for these results to be considered robust. They represent the majority of a tertiary GIS class, so testing more participants is unlikely to alter the results significantly.

Even so, such a group is likely to include students with relatively limited spatial ability, with evidence coming from the variability in performance between individuals. Future testing should ascertain whether this is in fact the case, and measure whether it is these students that benefit most from using the sandtable for teaching, with associated assessment of increased motivation for sandtable use.

In hindsight, these results are not surprising since the sandtable interface is inherently offering the affordance of physical three-dimensional interaction. In other words, the 'pickup properties' within the 'optical flow array' in J.J. Gibson's (1979) framework on ecological perception is a direct mapping of 3D spatial properties. Also, the congruence principle is at play here, with a 3D display facilitating the construction of a 3D mental model.

For certain tasks, the order in which the technologies were encountered was found to be significant. For the lowest point, steepest slope, water flow and aspect tasks, more efficient results were achieved if the sandtable was encountered first as opposed to the reverse case (3D GIS first). Carrera and Asensio (2017a) also measured strong improvement in performing water and stream flow tasks (also weak improvement in visibility, slope and profile tasks) with their marker-based AR.

The tasks that saw improvement (slope, aspect, flow) are mostly morphometry-based tasks and the results suggest that the sandtable helped the participants integrate core concepts into their learning in this domain. However, this insight was not significantly backed up by the results of the knowledge quizzes, with students attaining similar marks whether they took the quiz immediately after experiencing the sandtable or GIS technology.

Despite being a technology that the participants were initially less familiar with, they were significantly more satisfied with the sandtable than the GIS (in terms of ease-of-use, engagement, being entertained and intuitive controls) – again, the interface afforded a direct manipulation of a 3D subject matter and therefore the sandtable is ideally suited for 3D spatial tasks. This result was accentuated by significant improvement in the perception of being entertained by 3D GIS in those that encountered that technology first as opposed to those that encountered the sandtable first. This suggests that for the second group, the GIS was a bit of a 'comedown' after the more entertaining sandtable, providing further strong support for use of the sandtable. The pedagogical benefits of having increased motivation and interest have already been established in previous studies (e.g. Sotiriou and Bogner 2008).

From observation, a few technical problems were noted during the setup of the sandtable learning environment, though the issues did not significantly impact on students' interactions with the sandtable. Throughout the experiment, it was observed that participants were slightly more engaged with the sandtable. During the short debriefs after sessions, participants mentioned that interacting with the sandtable fostered better engagement as the activities were more hands-on compared to the 3D GIS, and that they were able to discuss issues with their peers during the tasks. It is possible that this discussion may be a factor in the sandtable's superior performance in efficiency and satisfaction experiments.

The effectiveness (correctness of practical tasks) results were not as unequivocal as the efficiency and satisfaction findings, but the significant improvements found (e.g. in placing the highest point or lowest point) favoured the GIS over the sandtable. It seems that GIS offers a more refined and sophisticated manner of control over analysis than the sandtable, which, while immediate and intuitive, is constrained by coarseness of hand interaction and limitations of the sand medium. With the direct physical viewing but coarse-grained ability to measure offered and afforded by the sandtable, the fine-grained, mediated controllability of the GIS interface is sacrificed. Overall these results point to recommending the sandtable as a user-friendly 'gateway' learning technology prior to using the more complex and rigorous GIS. By design, a sandtable can be used as a collaborative learning environment, where novice students can engage in dialogue with each other while learning fundamental concepts. It is better suited for learning through exploration, discovery and improved spatial awareness. Moreover, the 3D GIS results reveal greater individual differences, so a way to mitigate would be to introduce the AR sandtable first, and take advantage of its revealed property to elicit good performance in most students. This outcome is considered a fundamental finding of the study that resonates with the stated purpose of the first sandtable (Ishii *et al*. 2004). Sandscape was originally presented as a way of bridging two design phases in landscape architecture. This is an initial 'upstream' phase with emphasis on exploratory, physical and rapid development of form (sculpting), followed by a 'downstream' phase of analytical design, digital and more quantitative, precise. Indeed, the authors say 'the promise of these new tools may be in shaping a plural planning process' (p. 297).

Given the proposed dual role of AR sandtable and GIS technologies in geospatial teaching, research efforts to combine both, such as Tangible Landscape's coupling of sandtable and GRASS GIS functionality (Tabrizian *et al*. 2016), warrant more attention and development. Indeed, in further development by that group, an infectious tree disease scenario has allowed for the addition of a spatially explicit spread model, space and time-dependent interaction and the addition of a graphic dashboard to the Tangible Landscape set-up (Tonini *et al*. 2017). Such a hybrid system could very well provide a single platform that combines the accessibility and efficiency of the sandtable with the effectiveness and precision of the GIS. Since the initial AR experiment, a software component was developed for the Otago AR Sandtable that relates the sand surface heights to heights from a real-world Digital Elevation Model (DEM) (similar to the cut-fill symbolisation enabled for Tangible Landscape – NCSU GeoForAll Lab 2016). This appears on the sand surface as a projected colour-coded display that shows red where the sand is too high relative to the DEM and blue where the sand surface is too low. The user can move sand from red areas into blue areas until the occurrence of both colours is minimised. The resulting surface approximates to the DEM (South Dunedin, Wanaka, Christchurch Peninsula and Auckland Harbour DEMs are currently accessible for this function). It is planned to use this function to test the sandtable's value in communicating critical issues (e.g. climate change and sea-level rise in low-lying areas such as the aforementioned South Dunedin scenario).

An immediate next step identified in this study in the assessment of AR sandtable technology in university education is to evaluate its impact on other subject domains. To this end, a civil engineering experiment has subsequently been run with Bachelor of Surveying students at the University of Otago to assess the comparative usability of AR sandbox technology with conventional technology, here paper contour plans with dammed water volume estimation. A long-term possibility is to examine the scope of using the AR sandtable to teach terrain and hydrology concepts to school students at all levels (i.e. primary and secondary education as well as the tertiary example featured here).

Finally, the existing software will serve as a basis for developing a revised version that supports a more current sensor, such as the Intel RealSense Depth Camera (D415). This sensor has a higher output resolution (1280 x 720, Intel 2019), as well as potential for skeleton tracking modules (currently implemented commercially for up to six people, e.g. Nuitrack 2019). This could enable co-operative interaction, though further development and interaction design would be needed to shift the emphasis from the featured full-body tracking to the hand tracking that the sandtable requires. This could form the basis of an enhanced system of interaction that features better gesture integration (including pointing and drawing) as well as other developments such as assimilating physical objects in the sandtable environment (e.g. model buildings). These advancements would maintain the valuable simplicity of sandtable use but could be extended through the introduction of ancillary interaction technologies (smartphone apps, hololens). The addition of virtual reality (VR) in particular would afford a first-person insight that may foster understanding of terrain and hydrology yet further.

7. Conclusion

This study assessed the impact of sandtable-based AR on student learning. The usability testing included the usability dimensions of efficiency (time taken for set tasks), effectiveness (correctness of completed task) and satisfaction (user opinion by Likert-like scale statements and open questioning). Combining quantitative performance measures (efficiency and effectiveness tests) with qualitative data (satisfaction survey, observations) allows one to establish relationships between the use of AR to particular student learning outcomes (grades) as well as improve understanding of particular ways in which AR supports authentic student learning (learning experience).

Students indicated that they enjoyed the sandtable environment much more than the 3D GIS environment. This is reinforced by the efficiency results: they performed terrain and hydrological tasks faster with the sandtable. From observation, the student learning experience in the sandtable and the 3D GIS seems to be similar. However, the sandtable environment helped students integrate core concepts into their learning – this was particularly true with morphometric tasks. It should be underlined that the sandtable environment encourages more practical hands-on visualisation of the subject domain. Although there was no demonstrable improvement in knowledge performance from the post-experiment quizzes, there was evidence in the quiz answers that the practical tasks the students undertook in the study reinforced answers to the theoretical questions. Finally, the effectiveness experiment yielded better results with GIS, though evidence of significant improvement was sparse. Therefore, it can be seen that there are complementary roles for the two technologies in teaching about terrain and hydrology – with the sandtable being used initially for its accessibility and for fostering swift engagement with the subject matter. Facilitating early engagement with STEM subjects is critically important to attracting future students into these disciplines. This, along with the increased affordance of AR interaction has the potential to form a solid platform from which deeper and more accurate analysis can be undertaken with the GIS.

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Appendix Calibration for transformation between projector and depth camera

To estimate the transformation between projector and depth camera, a calibration process is required. This involves projecting a cross hair into the scene and placing a target with an easily recognised shape (a disk, in the usual case) at the cross hair. Each such placement establishes a correspondence between a 2D point in the projector image (the cross-hair coordinates in pixels) and a 3D location in the world (the location of the target). With sufficiently many such correspondences the projector's field of view and pose (location and orientation) in the Kinect's coordinate frame can be computed using standard camera calibration routines. The UC Davis

SARndbox software solves this using at least 12 points to form a linear least-squares fit for the elements of a 3×4 projection matrix, P, which maps 3D world (Kinect-space) co-ordinates (x, y, z) to 2D projector coordinates (u, v) as:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \equiv P \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix},$$

where the equivalence indicates equality up to an unknown scale factor. Having established the matrix P it is easy to take any 3D location from the depth sensor and identify the corresponding pixel in the projector. Thus, the desired texture on the 3D surface can be converted to a 2D image which can be projected onto the sand.