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***Flash Flood!* – A SeriousGeoGame combining science festivals, video games, and virtual reality with research data for communicating flood risk and geomorphology.**

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Abstract

The risk of flooding around the world is large and increasing yet in many areas there is still a difficulty in engaging the public with their own flood risk. Geomorphology is a science which is linked to flooding and can exacerbate risks but awareness of the science with the public is low, and declining within academia. To increase awareness it is important to engage the public directly with the science and those who are working to reduce flood risks – this starts by inspiring people to seek out further information through positive experiences of the science and researchers. Here, a new framework is presented to engage the public with specific research projects by using the best components offered by the popular mediums of games, virtual reality, and science festivals, to allow the public to get 'hands on' with research data and models – SeriousGeoGames. A SeriousGeoGame, *Flash Flood!,* was developed around real geomorphology survey data to help engage the public with a flood risk related research project by placing them in a river valley as it undergoes a geomorphically-active flooding from intense rainfall event. *Flash Flood!* was exhibited at science festivals and similar events in the UK by scientists on the project, and supported with online content including videos. Through event feedback it was shown to create positive experiences for participants and inspired curiosity as seen through online analytics. This is hoped to inspire more fruitful engagements with relevant agencies in the future when it matters most.

1. Introduction

Flooding is a first-order risk around the world, and the UK is no exception. The UK's Environment Agency estimate that 5.2 million homes are at risk of flooding, yet less than 10 % of those consider themselves at risk (Curtin, 2017). Curtin (2017) goes on to compare this to a YouGov poll (Smith, 2017) suggesting that more than 11 % of the UK's 27.2 million households (Office for National Statistics, 2017) have made plan in case of a zombie apocalypse. It is astonishing that the public seems better prepared for an entirely fictional risk than they are for something which poses them the greatest risk, but this is the environment practitioners find themselves in.

Geomorphology is the science of how planetary surfaces form and is an often-underappreciated facet of flood risk. It can increase the impact of flood events through erosion of the channel and banks, including scouring around infrastructure such as bridges and the transport of material which can make flood waters more damaging. Clean up of deposited material, sometimes contaminated, increases the post-event cost. Geomorphology also contributes to the likelihood of flooding with erosion and deposition altering a river channel's capacity to hold water, or even change the course of the river itself. Presently geomorphology is not considered an important component of present flood forecasting and considered a minor source of uncertainty (Flack et al., 2019), yet some evidence suggests that the flood-related geomorphology is likely to be exacerbated by climate change due to the non-linear relationship between river discharges and sediment yields (Coulthard et al., 2012). Even though geomorphology is set to become more prominent in the future, and the science behind geomorphology being well reported, the term itself as a distinct discipline is declining within academia, and virtual unheard of with the public, in curricula, and in media reporting of geomorphic events (Clarke et al., 2017).

With climate change due to increase the risk of flooding and the geomorphic impact of flooding, it is unfortunate that practitioners already find themselves playing catch up in the communication of even present day risks. Resilience to hazards is borne out of preparedness, and preparedness is built on knowledge, so the first step in building societal and individual resilience to geomorphic-flooding hazards is by making people aware and more curious the topic. As Clarke et al. (2017) asserts, the responsibility is with geomorphologists, and by extension flood management practitioners, to inspire this curiosity.

This paper presents a case study of the *Flash Flood!* application, a game-based virtual reality (VR) activity designed to highlight the geomorphic risk posed by flooding from intense rainfall, more commonly known as flash flooding. It highlights the SeriousGeoGame model of using science festivals, video games, and VR to allow the public to interact 'hands-on' with scientific data to promote enjoyment and curiosity in flooding and geomorphology. In Section 2, the specific research context for *Flash Flood!* is described, followed by a description of the development of the application in Section 3. The evaluation of the application against its stated objectives is shown in Section 4, and discussed in Section 5, before conclusions in Section 6.

1.1 The SeriousGeoGames Model

The SeriousGeoGames Lab (SGG) was established in 2014 to explore the use of games, and gaming technology, in enhancing the research, teaching, and communication of geosciences. The first SeriousGeoGame produced was *Humber in a Box* (Figure 1), a novel dynamic merging of a research-grade hydraulic model - CAESAR-Lisflood - (Coulthard et al., 2013) with a gaming engine – UNITY-3D. Users viewed a 3D model of the Humber Estuary on top of box in a museum style space, and tidal flows were calculated using the CAESAR-Lisflood code and animated within UNITY-3D. Users could then simulate past and future scenarios by altering the base sea level giving them an idea of future flood risk with rising sea levels. The scene was viewed using immersive VR via an Oculus Rift Developer Kit 2 Head Mounted Display (HMD).

Humber in a Box proved a popular exhibit at events and festivals across the UK before becoming obsolete in 2018. The experiences of what worked well provide a framework for a simple model to design future SeriousGeoGames from – A SeriousGeoGame should look and feel like a video game and exploit VR as the medium of interaction with the application. It should be optimised for use in a science festival setting where interactions may be short, a few minutes at most, and turn over of users is high. Fundamentally, a SeriousGeoGame should afford the user a first-hand experience of interacting with research and therefore should feature research models and/or data at its core (Figure 2).

A successful SeriousGeoGame will achieve two objectives –

1. To create a positive experience for the user with scientists and the research topic (fun)
2. To increase interest for the user in the research topic (curiosity)

It is tempting to include a third objective, to try and increase the understanding of the research topic, but from experience this is difficult to achieve/evaluate within the busy science festival setting. To use an analogy borrowed from religious evangelism, the purpose is to 'plant a seed' with the user which might 'germinate' with future interactions with science, scientists, or relevant practitioners in the future. Whether the positive interaction does in fact plant this seed is a matter of trust and something exhibitors will never be able to view come to light. When knowledge transfer does occur it will likely not be through interaction with the SeriousGeoGame but through the interaction with the scientists exhibiting it (Jensen and Buckley, 2014), and in particularly through a debrief with the user afterwards (Crookall, 2010). Through this model it is feasible to engage people with both objectives without them trying the SeriousGeoGame itself, for example, a child might be engaging with the SeriousGeoGame whilst their parents are interacting with the scientist. Interaction with the activity is not limited to the time and space of the science festival hall but supported by ancillary activities, such as websites, social media, and videos.

With the model established, below we investigate each of the three elements – science festivals, video games, and virtual reality – to see what advantages they give for meeting the two objectives.

1.2 Science Festivals

The science festival is a common feature of the public engagement with science landscape and for many researchers the local annual science festival is likely one of their few interactions with members of the public. The vibrant UK scene, for example, boasts 11 large annual science festivals which can attract between 6,000 and 50,000 visitors (Jensen and Buckley, 2014), and the UK Science Festival Network has 45 member festivals (Science Festivals Network UK, 2019). The US scene is also growing, with the Science Festival Alliance growing from just four member festivals in 2009 to around two dozen in 2012 (Durant, 2013), and in 2017 47 member festivals shared science and research with over 2 million members of the public (Science Festivals Alliance, 2018).

Traditionally, a science festival will be focussed on a central exhibition space, populated by stands and exhibits, focussing on interactive demonstrations highlighting either basic science principles, or more bespoke demonstrations for research projects. Science festivals also usually feature talks and panels by scientists on contemporary issues, and workshops which take people into more detail. Many festivals encourage more creative methods of engaging audiences, including café crawls, story-telling events, improvised comedy, orchestral performances, and films (Durant, 2013).

The goal of a Science Festival is usually to celebrate science and research (often that performed or funded by the organisers) and to engage non-specialists (Bultitude, 2014). As such, they have become a core method used to engage the public with the latest research (Jensen and Buckley, 2014). The true power of Science Festivals is their ability to bring the public and scientists together, and the successful engagements emerge from the conversations engendered (Jensen and Buckley, 2014).

Science Festivals could be described as niche in their nature, appealing to a small sub-set of the population. In a 2011 MORI poll showing that only 3% of the UK population attended a Science Festival in the previous year (Jensen and Buckley, 2014). A criticism of Science Festivals is that they only attract those who are already ‘science interested’ who tend to be well-educated, meaning that there is little socio-economic diversity (Bultitude, 2014). However, evaluations of events which have targeted under-represented groups have seen the same success by facilitating interactions between scientists and the public (Jensen and Buckley, 2014).

1.3 Video Games

Video gaming is big business, with retail sales of video games accounting for 51.3 % of the UK's entertainment retail market (included music, video and games), and worth £3.84bn (Entertainment Retailers Association, 2018). It is forecast that there are 2.3 billion people using video games worldwide, with a global market of US$137.9bn (Wijman, 2018). The popularity of videogames has not gone unnoticed by educators, with dedicated educational versions available of popular games such as Minecraft, Roblox, Assassin's Creed, and SimCity, and the educational games market is expected to reach US$17bn by 2023 (Adkins, 2018).

Video games are powerful tools for engaging people with science as they provide a first-hand experience which can inspire an emotional response (Mendler De Suarez et al., 2012; Squire, 2003; Wu and Lee, 2015). In addition, games are fundamentally fun (Wu and Lee, 2015), and as such they are naturally engaging and motivating for the user (Ryan et al., 2006). Video games are popular, with 64 % of US households owning a gaming device and an average of two gamers per household (Entertainment Software Association, 2018).

The flexibility and complexity which can be afforded by video games has made them an attractive tool for engaging people with complex issues such as Climate Change (Porter and Córdoba, 2009; Reason, 2007; Warburton, 2003). This has led to the development of 'serious games', games where learning is a core objective without losing sight of the entertainment element (Abt, 1987; Charsky, 2010; Crookall, 2010), and there are several studies showing that serious games have been effective in delivering the intended learning outcomes (Bellotti et al., 2013; Chin et al., 2009; Coleman et al., 1973; Connolly et al., 2012; Gosen and Washbush, 2004; Mani et al., 2016; Mitchell and Savill-Smith, 2004; Vogel et al., 2006; Wilson et al., 2009).

1.4 Virtual Reality

Virtual reality (VR) can be used to refer to any computer-based simulation featuring a virtual world (e.g. Markowitz et al., 2018; Merchant et al., 2014; Mikropoulos and Natsis, 2011), however it is used here to refer specifically to 'immersive' VR where a user will typically use a HMD to view the virtual world. It is currently regarded as an emerging technology, but VR has been around since the 1960s (Sutherland et al., 2003) and has seen various phases of development, particularly in education (e.g., Bricken and Byrne, 1993). It has only been recently, with the development of HMDs such as Oculus Rift, HTC Vive, and Playstation VR, that the technology has enabled mainstream use of VR.

VR simulations often share features with video games and thus share many of the same learning advantages, such as being engaging and motivating (Abulrub et al., 2011; Psotka, 2013). However, the immersivity and presence (the feeling of physically being in the virtual world) produce experiences which are highly engaging allowing the user to focus more on the learning outcomes (Bricken and Byrne, 1993; Markowitz et al., 2018; Salzman et al., 1999). Furthermore users consider the virtual environment as real (Blascovich and Bailenson, 2011) and can develop a strong attachment and internalisation to them (Clark, 1997; Weisberg and Newcombe, 2017). A particular advantage of VR is that it can allow users to feel closer to otherwise abstract or distant ideas (Trope and Liberman, 2010), for example in Markowitz et al. (2018) users were shown 'first-hand' (via VR HMD) the impacts of ocean acidification and reported increase knowledge gain and interest in the subject as a consequence.

2. Flooding from Intense Rainfall

2.1 The Research Context

Flash Flood! was conceived as an engagement activity to support the Flooding from Intense Rainfall (FFIR) research programme, funded by the Natural Environment Research Council UK (NERC). The FFIR programme described itself as "A five year NERC funded programme aiming to reduce the risk of damage and loss of life caused by surface water and flash floods" (Flooding from Intense Rainfall, 2019). The UK based and focussed programme brought together experts from several Universities, environmental consultancies, the Met Office, the Environment Agency, and the British Geological Survey to better understand the role intense, localised rainfall events had on both rural and urban flooding, with a strong focus on end-to-end forecasting on events (Dance et al., 2019; Flack et al., 2019). Thunderstorms, driven by strong convection in summer months, form and dissipate rapidly and can be highly localised covering just 1-3 km wide. Despite good understanding and being able to forecast the conditions in which they form, it is presently not possible to provide accurate forecasts of when and where the storms themselves will form.

The focus on the simulation would be on a sub-section of the programme concerning the modelling of the geomorphic impacts of flash flooding. For most flood events in the UK changes to the river bed, channel and surrounding flood plain through processes of erosion, deposition, and transport (i.e. geomorphic activity) are negligible to resulting flooding. This is reflected in the current flood forecasting situation in the UK where geomorphic activity is considered as a source of uncertainty which influences model results to a much lesser extent to other sources, such as the rainfall input (Flack et al., 2019). However, there are rare and extreme examples where flood events induce significant geomorphic activity, with recent high-profile examples including Boscastle (2004), Cockermouth (2009), Glenridding (2015), and Coverack (2017).

The geomorphic activity induced by flash flooding can make the flooding even more devastating to communities who can find their properties inundated with mud and debris as well as water. Transported material in flood water increases its power and ability to erode, making it able to destroy and wash away infrastructure, such as bridges. It can also have a profound effect on the river valleys themselves, with some floods inducing so much geomorphic change that they fundamentally change the behaviour of the river for several years. These flood events have been referred to previously as threshold events (BULL, 1979; Chappell, 1983; Fryirs, 2016; Milan, 2012; Schumm, 1979).

Threshold events relate to a concept in geomorphology science called river sensitivity, a concept described by Kristie Fryirs as 'lost' but of increasing significance for landscapes under a changing climate in her medal winner address to British Society for Geomorphology in 2015 (Fryirs, 2016). The concept can be summarised by the equation below –

$$River\ Sensitivity = \frac{\text{Recurrence of Threshold Events}}{\text{Time Required to Recover}}$$

The equation assumes that every river has a stable behaviour, with it displaying consistent responses to similar events. This stability is maintained by mature vegetation cover and a paucity of sediment which can be moved by the river. However, there exists a threshold magnitude of flood event which will disturb this stability by removing the vegetation cover, exposing sediment and transporting it elsewhere in the channel. After the event, the channel begins recovery (or relaxation) through a period of enhanced dynamism in the geomorphology until new vegetation has matured and sediment sources exhausted. The balance between how often these events occur and how long it takes a river channel to recover is the river's sensitivity. During the threshold event and the river's recovery the amount of sediment delivered downstream in the system is greatly increased, and this in turn may influence the flood risk in those areas (Lane et al., 2007; Slater, 2016). Predictions of climate change for the UK suggest flood events will become more likely and more extreme (Dankers and Feyen, 2008; Ekström et al., 2005; Feyen et al., 2012; Fowler and Ekström, 2009; Pall et al., 2011; Prudhomme et al., 2003) disrupting the balance determining river sensitivity – the impacts of this on rivers and future flood risk is not known but is likely to be negative.

2.2 The Research Data

The case study at the heart of *Flash Flood!* is the 2007 flood event in the upland valley of Thinhope Burn, Northern England, as detailed by Milan (2012). The event was an FFIR event which could be described as a threshold event for the system. During a six-hour period a highly localised yet intense convective storm precipitated 82 mm of rainfall on the upper catchment (Met Office, 2003) resulting

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in flood event – those who witnessed the event described a wall of water and the sound of boulders crashing along the river bed (Milan, 2012). The valley floor was fundamentally changed by the event which saw large geomorphic changes during the event (see Figure 3) and increased mobility of material subsequently (Milan, 2012).

The usefulness of this case study for the development of *Flash Flood!* was the availability of ground survey data of the stable river valley just three years prior to the flood, and repeat surveys afterwards, which were used by Milan (2012) and provided for this work. To have detailed surveys before a geomorphically active event such as this is rare and cannot be planned for so provided an exciting opportunity. This survey was captured in the summer of 2003 using a back-pack Global Positioning Satellite (GPS) system across a 500 m reach section. Although similar surveys were available for after the flood, it was decided to recapture the same 500m in more detail using a Terrestrial Laser Scanner (TLS) in the summer of 2014. Although this survey was conducted 7 years after the flood the channel had still yet to recover and largely reflected the immediate post-flood environment.

To give an indication of the height of the peak flood extent, simple modelling was performed within the CAESAR-Lisflood software (Coulthard et al., 2013), using elevations derived from the 2003 GPS survey and the estimated peak discharges from Bain et al. (2010) to drive the model hydraulics.

3. Development

The Flash Flood! application was designed by the SeriousGeoGames Lab and developed by indie-games developers BetaJester using the Unity-3D gaming engine. There have been two iterations of the VR-based software with the second being optimised based on the experiences exhibiting the original version.

3.1 The original *Flash Flood!*

The original *Flash Flood!* was developed in 2015. The 3D environment was built using the popular gaming engine UNITY-3D. The before and after flood scenes were constructed from the DEMs using the data described in Section 2.2, each converted into a point cloud. A sample of each point cloud was extracted, converted to a mesh, and imported into UNITY-3D. The scenes were populated using textured renders and 3D objects (known as assets), with the scene being more heavily populated with trees than in real life to help blur edges and create a more interesting 3D environment for the user to explore.

The exhibit used the Alienware X51 R3 (Intel Core i5 6400 CPU @2.71 Ghz – 16Gb RAM – NVIDIA GeForce GTX 970), which was labelled as "Oculus-ready", and the consumer model Oculus Rift. The application was optimised to a lower standard than the equipment specification afforded to allow a desktop-only version of the software to be released. Graphics were kept simple (see Figure 4) and the representation of water kept to an animated plain which was angled down in the direction of the river and would rise and fall given the impression of rising and falling water levels as it intersected the landscape. Users explored the scene using the two joysticks on an Xbox controller and needed to use no other buttons or d-pads.

The user began the simulation within the river valley viewing it from a first-person perspective. The user was free to explore the whole scene with movement restricted at the edges by hills or invisible barriers. The flood animation timeline did not begin automatically and only started when the operator pressed the P button on the keyboard.

The simulation moved along a 6 hour timeline which took 30 seconds per hour timestep, for a total of 3 minutes. It began at 15:00 and on-screen prompts described the scene at each step –

15:00 – "Clouds begin to gather"

16:00 - "A storm is brewing"

17:00 – "The storm intensifies"

18:00 – "Intense rainfall falls on the uplands of the river"

19:00 – "Rain water from the uplands swells the river level. A flash flood in coming!"

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20:00 – "The flood has reached its peak"

21:00 – "The flood has receded leaving a scene of devastation"

During 19:00 the eponymous flash flood wave passed through the scene – this was produced using two shapes, a box and wedge (as the flood toe), textured in the same way as the water, to give an impression of the "wall of water" described by witnesses (Milan, 2012). Throughout the timeline the water turned increasingly brown to represent the debris within the water. As the simulation transitioned between 20:00 and 21:00 the before the flood scene was switched for the after the flood scene. Most of the changes were obscured under the height of the water as this was the peak of the flood, but it still required a respawning of the user resulting in some sudden, unrealistic changes.

The limitations of time and funding meant that there was no sound incorporated into the original version and narration was provided via a one-to-one interaction with an operator – usually a scientist within a relevant research area, or a science communication generalist. This had the advantage of being able to tailor the message based on the operator's research field and the age and responsiveness of the user.

3.2 *Flash Flood! Vol.2*

In 2018 an opportunity arose to redevelop the original *Flash Flood!*. Where the original had been limited in its graphics and representation of river flow due to the release of a desktop-only version, there were no such limitations for *Vol.2*. Instead, the new development was optimised for a new set of equipment using the Alienware 17R5 Oculus-Ready laptops (Intel i7-8750H @ 2.20GHz – 8GB RAM – NVIDIA GeForce GTX 1070), with an aim of achieving a look and feel of a AAA-game. This was partly in response to an increasing number of comments on the basic level of the original graphics and users becoming more accustomed to ever more sophisticated VR experiences. Photo-realistic assets were used for textures and 3D objects, and the scene was made wooded like the original to make a more interesting scene. The transitions at the edges of the scene were significantly improved by removing the hills and replacing these with an unexplorable extended landscape and hiding the edges using stone bridges (see Figure 5). The basic horizontal plain of water was replaced by the more sophisticated River Auto Material (R.A.M. by NATUREMANUFACTURE) asset, with customisation from the developers for the representation of the flash flood showing a rapidly rising water level with debris in the form of rocks and logs. *Vol.2* uses the same data and flood timeline as the original version.

From an exhibitor point of view the main limitation of the original version was the staffing resource required due to the one-to-one narration provided by the operator – this interaction was exhausting, and a single operator could manage around four or five demos before requiring a rest during busy periods. This means each set up required a minimum of two operators rotating regularly, and an extra operator for every two sets to allow for breaks and control of the crowd. This limited the number of demonstrations which could be achieved and size of exhibits which could be supported. To overcome this limitation *Vol.2* uses a soundtrack with narration. The user chooses between two narrators – Chris (voiced by Dr Chris Skinner) and Jess (voiced by Dr Jess Moloney) – defaulting to Jess. The two narrations follow slightly different scripts with Chris's being more general and Jess's drawing more on Dr Moloney's research into dating past flood events (Moloney et al., 2018). The choice of a single male and female voice was a starting point and allows for an increased representation of voices with future developments.

3.3 Ancillary developments

The two iterations of VR software are not the only developments relating to Flash Flood! nor is the achievement of the two objectives limited to the time and space within the science festival hall. The activity was promoted and supported by the SGG social media accounts (Facebook and Twitter) and the SGG website. At times this was enhanced by support from the University of Hull Marketing and Communication team, plus other colleagues at the University of Hull, other Universities (particularly Reading and Newcastle), and the Natural Environment Research Council.

To support the original version of *Flash Flood!* a handout was produced. The handout included brief descriptions of the event, links to the SGG website and social media accounts, and an activity which could be done alongside the simulation. The intention was to mimic the taking of field notes performed by geomorphologists, before and after the flood. At events the handout was given out along with a "I survived the Flash Flood!" badge and was also free to take from the table. It was also used for those waiting to have a turn on the simulation or watching others to occupy them and was used with a clipboard and pencil to fit the fieldwork image.

To make the application more accessible a desktop-only version was made available via SourceForge which could be controlled using a mouse and keyboard. This was free to download and would operate on any reasonably modern windows machine. However, several schools reported they wished to use the software but were unable to due to networking restrictions on school machines – in response a 360 video version was produced and made available via YouTube. This version allowed headtracking but not free movement. It included sound and two versions were available, one with narration and one without. To support both the desktop and 360 versions a manual was produced, and articles aimed at students and teachers published (Skinner, 2018; Skinner and Milan, 2018).

4. Evaluation

4.1 Objective 1 – Fun

Through demonstration of *Flash Flood!* at events it is obvious that most participants enjoy the activity. Verbal feedback has included words describing the activity as "epic" or "sick", both meant as a positive. The most common word received as feedback has been "weird" most often delivered with a smile on their face – it is obvious that it is meant as a positive, that the uncanny experience of immersion in a virtual world is exciting, yet out of the ordinary.

Flash Flood! has been highlighted in the feedback obtained by events, usually via comment walls. At NERC Into the blue comments under the "Things I loved about Into the blue" included "the gogls"

(Goggles = VR headset) and "flash flood", and under "Things I learned at Into the blue" was "Rivers are fantastic!". Into the blue also ran a public vote for most popular stand, for which *Flash Flood!* was awarded joint-3rd out of 40 exhibits and events.

Not all feedback has been positive and there have been a few negative comments received during exhibits. Mostly these are to do with issues relating to VR, for example it makes them feel dizzy or nauseous, or simply that they did not like it. Other comments have been around dissatisfaction with the graphics of the game or wanting more game-like objectives. On this latter point, "What am I supposed to do?" is a common question at the start of demonstrations.

In conversation, it is often commonly asked of participants what they might like to see included in *Flash Flood!*. Common suggestions include better graphics, being able to explore a wider space, or wildlife such as sheep, wolves, bears, or dinosaurs. Others would like more game like elements like something to shoot, such as zombies (see Curtin, 2017). With *Vol.2* where more sets available to do multiple simultaneous demos, several have commented that they would like to have them linked and being able to explore the scene together with their friends.

At the 2018 Hull Science Festival, at the University of Hull, *Vol.2* was used as part of an Earth Arcade. The Earth Arcade is a room of game-like activities all designed to communicate key global environmental issues in a non-intrusive way. The games range in style and complexity so that a family audience can engage with it effectively. Games included were –

- *Flash Flood! Vol. 2* – five sets
- *Plastic Fishing* – a game aimed at pre-school children using magnetic fish to highlight ocean pollution and plastic waste (see seriousgeo.games/eartharcade/eartharcade_9)
- *Flood City: Hull* – A PowerPoint game showing the impacts of sea level rise on coastal flooding in a city
- *River in a Box* – An EmRiver stream table (see seriousgeo.games/eartharcade/eartharcade_3)
- A table with relevant Top Trump cards and colouring pens and paper (

The Earth Arcade was situated in its own space, like a mini-festival within the festival, and this space was used to provide evaluation boards for participants to leave comments with four questions offered –

1. What did you enjoy?
2. What did you learn?
3. What will you do?
4. What would you like to see?

In total 69 responses were posted on the board, 42 of which related to *Flash Flood!,* either directly or using an appropriately descriptive term (such as Virtual Reality) or as part of the whole Earth Arcade exhibit. Figure 6 shows the division of these 42 responses.

The majority of the responses were describing what they liked, with all answers positive. 26 of the responses were generic, for example "The flud computers" or "I enjoyed everything", whilst 9 were more descriptive in what they enjoyed –

"I like the VR river flood it was like I was really there"

"I liked the VR river experiment. I was very interesting and educational"

"The flash flood was very exciting and cleverly made, it was fun"

"It felt real"

"What a fun way to learn some serious stuff. And all the people helping us were so friendly! :)"

"I enjoyed seeing what is like in the middle of a flood"

"I liked the forest – it was great! I got caught in a tree!"

"hid in the chrees"

"I loved to find out about how flood changes river and all around"

The only negative comment received was under "What would you like to see?" and stated "I liked it mostly apart from the graphics". Other comments in that section were –

"Can you make the VR flood simulation interactive? Ie you get washed away or can build dams etc."

"Flash Flood sim was very good. Multiplayer with local other PCs?"

"2 very excited boys on the flood VR. Suggestions: Allow bridge access? Gurgling voices if in the riverbed when the flash flood arrives?"

Four comments were posted under "What did you learn?", there were –

"I lerned about floods"

"I learn a lot about flash floods"

"I enjoyed the experience and larnt about the havoc these floods can create"

"I learnt about what happens during flash floods"

4.1 Objective 2 - Curiosity

To fulfil the first objective, it is important to keep interactions between the public and scientists as informal and as natural as possible, avoiding anything which might be intrusive to this. Therefore, in a science festival setting methods of formally and quantitatively assessing the publics' response, for example using questionnaires, is not appropriate nor helpful. This is especially true when considering individual exhibits within a festival hall where each exhibit may wish to conduct their own evaluations – this would become tiresome for the public who only wish to have fun, exciting, and interesting engagements.

To assess the success of *Flash Flood!,* and other SeriousGeoGames, against Objective 2 users are signposted to online media relating to SGG. Figure 7 shows the total views for the SGG website and YouTube channel, with each accumulating a remarkably similar total since September 2015, and both have been growing at a similar rate of around 200 views per month since the beginning of 2018.

There are three *Flash Flood!* related videos on the SGG YouTube channel (out of a total of 51 videos) – a preview demo for the original version, and the two 360 versions. The growth of aggregated views for all these videos is also shown in Figure 7. As a share of overall views on the SeriousGeoGames channel, the *Flash Flood!* videos has gradually been increasing and currently accounts for around 40 % of the total views, and 56.4 % of those are for narrated 360 video alone.

Figure 8 shows the monthly views for 2017. There was very little activity on either the website or YouTube channel in January and February but increased during March. The activity in March can be attributed to a feature on *Flash Flood!* in NERC's Planet Earth Magazine (Skinner, 2017), and the promotion of the Hull Science Festival on 2nd April 2017 where SGG ran a featured exhibit. March 2017 saw the most monthly views for the SGGs website in the record (405) and best performing month in the record for the YouTube channel was April 2017 (677). Many of these views were from a series of 360 videos from an undergraduate field trip, uploaded in March but used as part of the Hull Science Festival exhibit and thus accumulating a steady number of views. A series of 360 videos covering the European Geoscience Union's General Assembly was also released that month and attracted many views. The narrated *Flash Flood!* 360 video was released on the 11th April and was the most viewed video that month with 142.

The NERC UnEarthed Science Showcase took place on 17-19 November 2017 and attracted over 5250 visitors. In the week preceding the event the narrated 360 video was viewed 50 times, was viewed 6 times during the event, and 42 times in the week after. In November the Flash Flood! videos had a total of 215 views, 81.1 % of the total YouTube channel views. The UnEarthed exhibit also featured the *Humber in a Box* game – the demo video on the channel for this game received 32 views, so in all 93.2 % of all video views in November 2017 were related to the UnEarthed exhibit.

5. Discussion

The SeriousGeoGame *Flash Flood!* has been a success at meeting Objective 1 - to create a positive experience for the user with scientists and the research topic. Most interactions have been positive and when users have provided feedback this has also been overwhelmingly positive. When users have been asked what they thought of *Flash Flood!* most have opted to share how much they enjoyed it over providing feedback on what they learned or how they'd like to see it improved – for example, In Figure 6, of 42 comments on *Flash Flood!,* 35 were about enjoyment.

The success against Objective 2 - to increase interest for the user in the research topic - is more difficult to evaluate as this manifests after the interaction with *Flash Flood!*. The increase in interest relating to the exhibits has been gauged using the analytics available through the SGG website and YouTube channel to observe changes in traffic over time. It is not possible to determine the source of this traffic (i.e., is it from the public or other academics) or the motivation for the online interaction. Over the course of the SGG project there has been a steady growth in the number of overall views of the website and YouTube channel – in regards to the YouTube channel, the Flash Flood! related videos are increasingly driving this growth and the proportion of views relating to the three videos over the other 48, growing from 20 % at the start of 2017 to 39 % by the end of 2018.

The NERC UnEarthed event of November 2017 presented the best opportunity to evaluate the impact of an individual event in driving traffic towards these sources as there were no other events or activities that month. As 93 % of all YouTube views for that month were related to the exhibit, this suggests that it was successful in achieving Objective 2. For *Flash Flood!* itself, the videos received 215 views in November 2017, the most of any month on record and more than double the views of the months before and after. Views of the SGG website were also higher than the months before and after. Breaking this down there were more views of the narrated *Flash Flood!* 360 video in the 7 days prior to the event than there were during the event and 7 days after, meaning that much of the internet traffic is driven by promotion of the event (via sharing YouTube links on the Twitter account) rather than in response to visiting the exhibit – as the majority of SGG's Twitter audience are scientists, science communicators, or educators, it is possible that the increased traffic emerges from within the industry and not from the target public audience.

In terms of the SeriousGeoGames model, all the elements have proven useful. Science festivals have proven an effective way to engage large amounts of people in a short space of time, and when researchers of all levels are under time pressure from several demands this has proven and efficient way to conduct engagement activities. The public who attend the events clearly find them an overwhelmingly positive experience even when they were not of the traditional socio-economic groups associated with science festival attendance. For example, the NERC UnEarthed event was held in the Dynamic Earth centre in Edinburgh which normally requires an entry fee – the organisers arranged a waiver for this for the duration of the festival and many of comments received were from parents stating how much they appreciated this as they had not previously been able to visit the centre because of the entrance fee.

The video game element is the least developed of the three and consequently the one which receives the most specific feedback. In the main this is because of limitations in the application and the desire to have more freedom or an objective to achieve, and this can cause confusion in some who are expecting a more developed game-like experience. This should be viewed as a huge opportunity for further development – there is a strong desire for audiences of science festivals for game-like exhibits (not just video games), especially where there is a competitive element, and these are currently underrepresented. However, the game-like appearance and feel of *Flash Flood!* is viewed as a positive by almost all users, and even the sight of an Xbox control pad within the science festival hall sparks excitement in some members of the audience.

Since the inception of SGG, the use of VR has been a draw for the exhibits - as soon as one person is seated and wearing the HMD, looking off in different directions, a crowd soon gathers to see what is going on. The curiosity and novelty invoked by VR has proven successful in attracting people to interact with the exhibit and scientists. As VR has developed and become more mainstream over the years this has changed, but not diminished. *Flash Flood!* was often the only VR exhibit at events when first produced but now is often one of several, however as the hardware is relatively cheap compared to development costs, it often remains the only bespoke piece software as opposed to video demos or 360 photographs/videos. Comments have shifted from "I've never used VR before" to "my friend has one of these", but the enthusiasm to try it is still high.

The use of real research data adds value to *Flash Flood!* and users are interested to find out that 3D environment is built from data collected in a real river, and the flood based on a real event. This is usually followed by questions about where the river is and when it happened and provides a useful conversation starter to discuss the issues around flash flooding and forecasting these types of events. We have also received comments from the public saying how pleased they were we were exhibiting something based on real, ongoing research, and not demonstrating basic scientific principles and experiments.

However, the most important element of any *Flash Flood!* exhibit is the team of scientists which interact with the public, sharing their enthusiasm for science and their research expertise. It is especially successful when their research aligns with the exhibit, but this is not vital – many of the interactions take place beyond the application itself so it is possible for the scientists to share their own personal research interests without impacting negatively on the objectives. Users particularly enjoy interacting with either Chris or Jess who provided the voice overs for *Flash Flood! Vol.2* and are often surprised they are real people who are scientists in real life.

A criticism of the SeriousGeoGames model presented is that the objectives are possibly too narrow or unambitious. There is scope within *Flash Flood!* for it to be used to increase the understanding of the research topic, or even to change behaviours of the public, such as encouraging them to sign up for automatic flood warning alerts. Delivering and evaluating these objectives within a festival setting, without having a negative impact on the original objectives, is likely not feasible and more suited to a less busy and longer interaction in workshops or classrooms and this has been explored using the desktop and 360 version. *Flash Flood!* has also been used in workshops and has also been reported as being used in school lessons even though it was not conceived or designed for this use. The efficacy of the application in this context has not yet been explored and is beyond the scope of this study.

6. Conclusion

The *Flash Flood!* application is game-based, built around real research data, and has been used to engage thousands of people at science festivals and events. There have been numerous versions of the application across different platforms, including desktop, 360 YouTube videos, and utilising VR. *Flash Flood!* has demonstrated that the SeriousGeoGame model - utilising elements of science festivals, video games, and virtual reality, to produce game-like applications built around a core of real research models and/or data – has had success at achieving the first objective of producing a positive experience for the user. However, although there is evidence that it is successful against the second objective, to increase the user's interest in the research topic, this has proven more difficult to evaluate effectively. There remains great potential to develop *Flash Flood!* and other SeriousGeoGames, particularly using the video games elements and use outside of science festivals to achieve more ambitious objectives.

Data Availability

The data used in this study can be made available on request by emailing the corresponding author. Game files for *Flash Flood!* can be found at https://sourceforge.net/projects/flash-flood/

Ethics Statement

The study complied with all the Ethical Approval processes for the University of Hull. Specific considerations were paid to the use of virtual reality – disclaimers were given in game and verbally about potential dizziness, and to reduce risk participants were required to be seated at all times. In regards to safeguarding and child protection no SeriousGeoGames or Earth Arcade exhibit crew are ever responsible for the care of children who must be accompanied by an adult before participating. Crew are instructed to never find themselves alone with a child. Crew are prohibited from photographing the exhibit whilst the public are present (often exceeding the photography policy of the event). Whilst participating the public are handed the VR headset to have ownership of it during the activity and instructed how to adjust and wear it, and told to remove whenever they like – crew do not touch the headset whilst it is on someone else's head.

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Figures

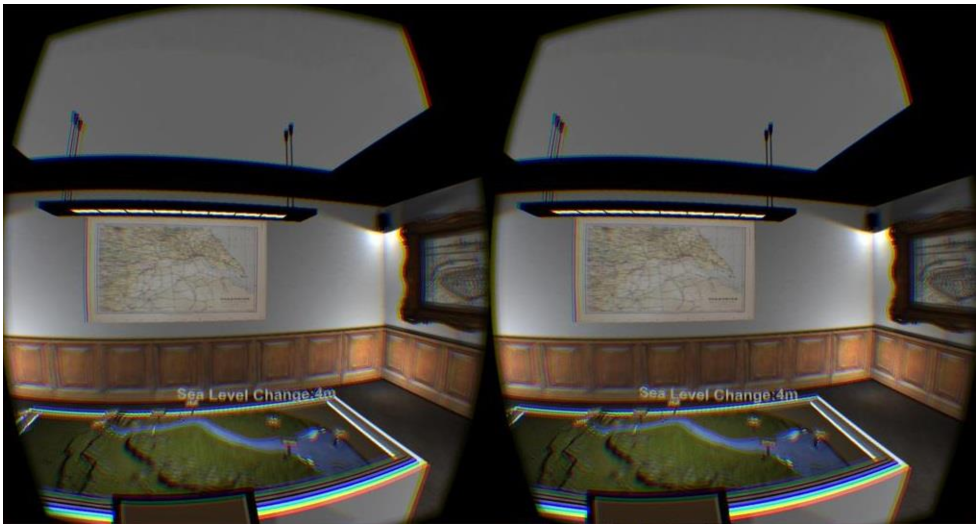

Figure 1 – The view inside *Humber in a Box*.

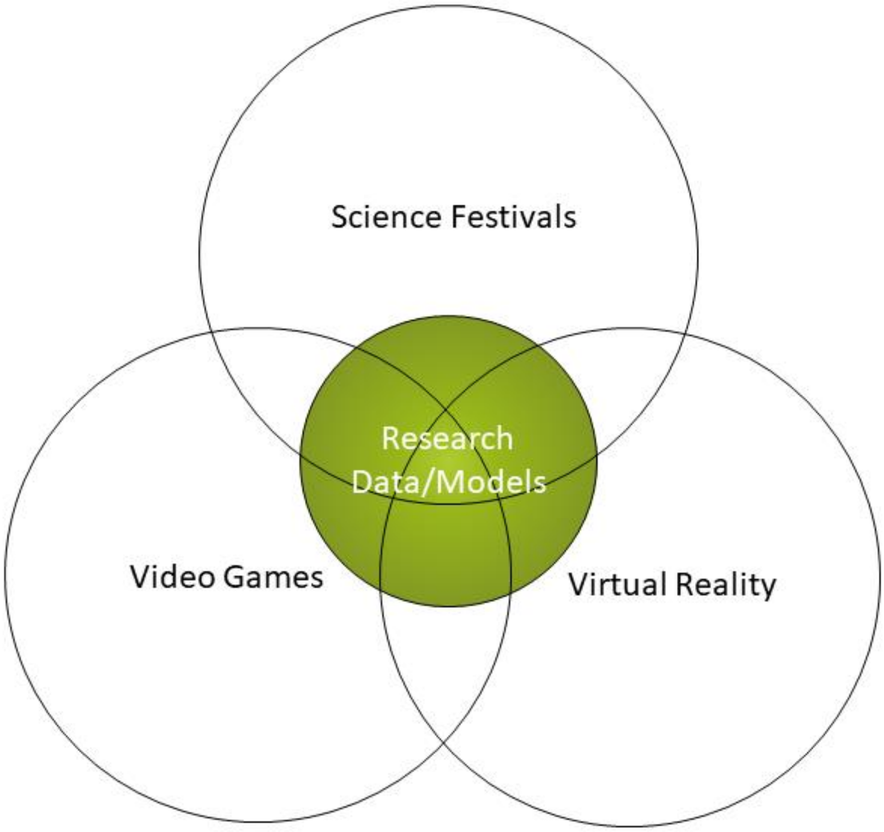

Figure 2 – Venn diagram showing the SeriousGeoGame model – a true SeriousGeoGame would be positioned in the middle of the diagram, built with research data and/or models, and using elements from science festivals, videos games, and virtual reality.

Geosci. Commun. Discuss., https://doi.org/10.5194/gc-2019-8
Manuscript under review for journal Geosci. Commun.
Discussion started: 17 May 2019

Figure 3 – Google Earth images showing the reach section surveyed and used for *Flash Flood!.* The right-hand image is from before the flood in 2006 (Google Earth, 2019a), and left-hand image from after the flood in 2007 (Google Earth, 2019b).

Figure 4 – Screen shot from the original *Flash Flood!.*

Geosci. Commun. Discuss., https://doi.org/10.5194/gc-2019-8
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Figure 5 – Screenshot from *Flash Flood! Vol.2*.

Geosci. Commun. Discuss., https://doi.org/10.5194/gc-2019-8
Manuscript under review for journal Geosci. Commun.
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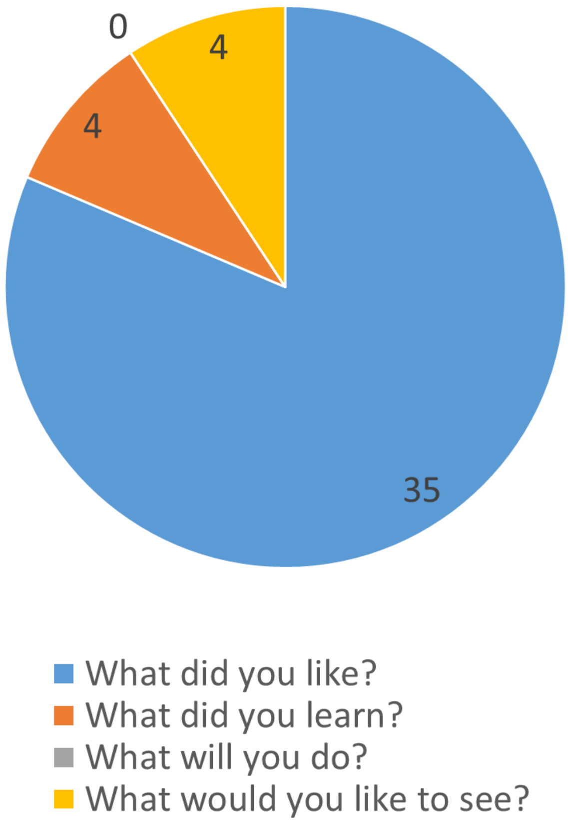

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765 **Figure 6 – Division of responses relating to Flash Flood! at Hull Science Festival 2018.**

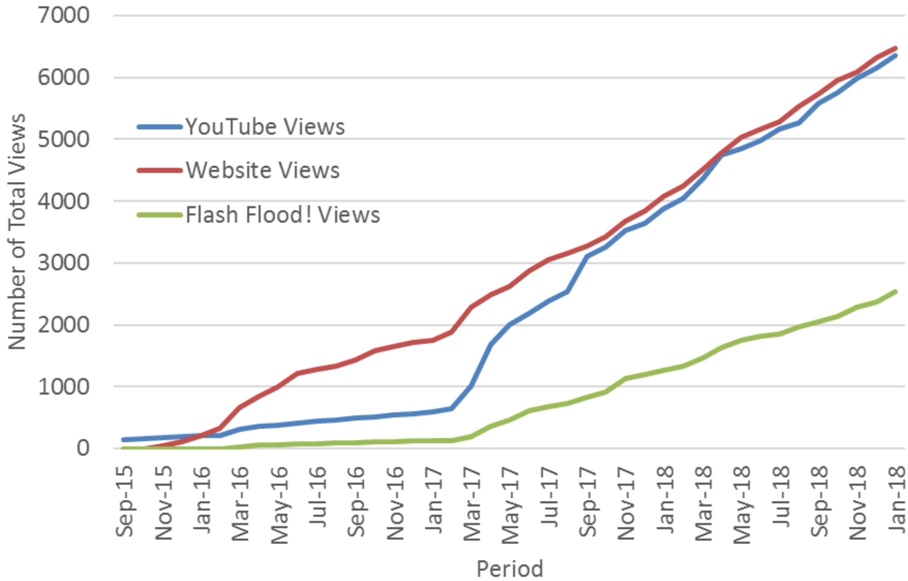

Figure 7 – Aggregated total YouTube and Website views for SeriousGeoGames since September 2015 to January 2019. Also shown are the total views for all *Flash Flood!* related YouTube content.

Geosci. Commun. Discuss., https://doi.org/10.5194/gc-2019-8
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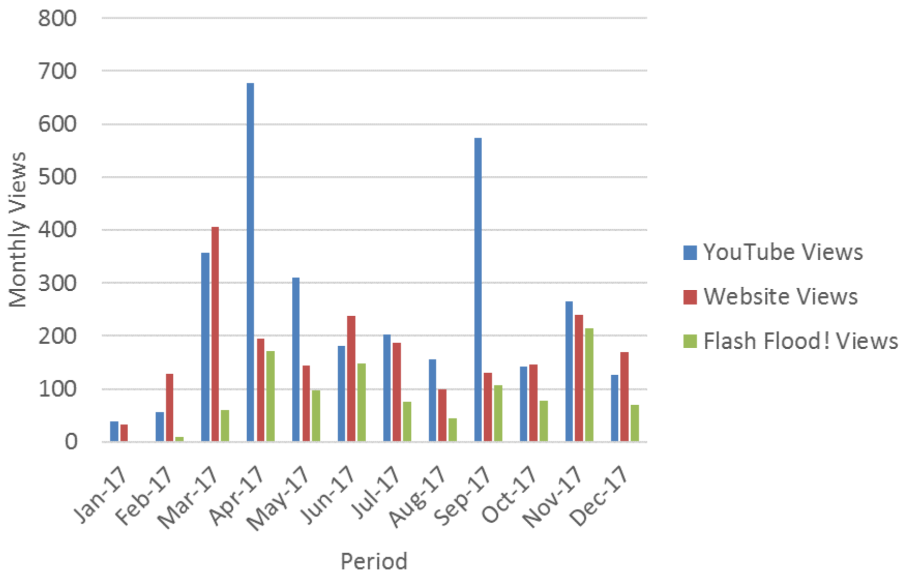

Figure 8 – Monthly views for the SeriousGeoGames website, YouTube channel, and the Flash Flood! videos for 2017.