1   *Flash Flood!* **– A SeriousGeoGame combining science festivals, video games, and virtual reality with**

2   **research data for communicating flood risk and geomorphology.**

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5   **Abstract**

6   The risk of flooding around the world is large and increasing yet in many areas there is still a difficulty

7   in engaging the public with their own flood risk. Geomorphology is a science that is linked to flooding

8   and can exacerbate risks but awareness of the science with the public is low, and declining within

9   academia. To increase awareness it is important to engage the public directly with the science and

10   those who are working to reduce flood risks – this starts by inspiring people to seek out further

11   information through positive experiences of the science and researchers. Here, a new design model is

12   presented to engage the public with specific research projects by using useful components offered by

13   the popular mediums of games, virtual reality, and science festivals, to allow the public to get 'hands

14   on' with research data and models – SeriousGeoGames. A SeriousGeoGame, *Flash Flood!,* was

15   developed around real geomorphology survey data to help engage the public with a flood risk related

16   research project by placing them in a river valley as it undergoes a geomorphically-active flooding from

17   intense rainfall event. *Flash Flood!* was exhibited at two science-focussed events and formal

18   evaluation was captured using a short questionnaire, finding that the majority of audience had a

19   positive interaction (95.1%, n=344) and wanted to know more about flooding (68.0%, n=344) and

20   geomorphology (60.1%, n=344). It is hoped these interactions will increase the likelihood that future

21   engagements with relevant agencies will be more fruitful, especially 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 estimates 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 that poses real risk, but this is the situation practitioners find themselves in.

Geomorphology is the science of how planetary surfaces form and change. Geomorphic processes 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 that can make flood waters more damaging. Clean up of deposited material, sometimes contaminated, increases the post-event cost. Geomorphic processes also contribute to the likelihood of flooding with erosion and deposition altering a river channel's capacity to hold water, or even changing 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). Geomorphology is a key part of many pressing environmental issues, such as flooding (Lane et al., 2007; Slater, 2016), soil erosion (García-Ruiz et al., 2015), sand mining (Bendixen et al., 2019), and the transport of plastic pollution (Hurley et al., 2018), all of which are of great interest to the public and media, however, the term itself as a distinct discipline is declining within academia, and virtually 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 impacts of flooding, it is unfortunate that practitioners already find themselves playing catch up in the communication of even

47 present day risks (Curtin, 2017). Clarke et al. (2017) asserts, the responsibility is with

48 geomorphologists, and by extension flood management practitioners, to effectively communicate

49 these risks.

50 This paper presents a case study of the *Flash Flood!* application, an interactive virtual reality (VR)

51 activity designed to highlight the geomorphic risk posed by flooding from intense rainfall, more

52 commonly known as flash flooding. VR generally uses two screens held within a headset (Head

53 Mounted Display or HMD) so that each eye can only see one screen, with each showing a three-

54 dimensional (3D) scene at a different angle to produce the illusion of depth and immersing the user in

55 a different and artificial environment. The rest of Section 1 highlights the proposed SeriousGeoGame

56 model of combing elements of VR and video gaming with elements from research projects, such as

57 field data or numerical modelling codes. In Section 2, the specific research context for *Flash Flood!* is

58 described, followed by a description of the development of the application in Section 3. Section 4

59 details the evaluation methods and the events where the application was tested. The results of the

60 evaluation is shown in Section 5, and discussed in Section 6, before conclusions are presented in

61 Section 7.

62   1.1 The SeriousGeoGames Model

63 The SeriousGeoGames Lab was established in 2014 to explore the use of games, and gaming

64 technology, in enhancing the research, teaching, and communication of geosciences. The first

65 SeriousGeoGame produced was *Humber in a Box* (Figure 1), a novel dynamic merging of a research-

66 grade hydraulic model - CAESAR-Lisflood (Coulthard et al., 2013) - with a software package used by

67 games developers to create games and virtual environments (known as a gaming engine) – UNITY-3D.

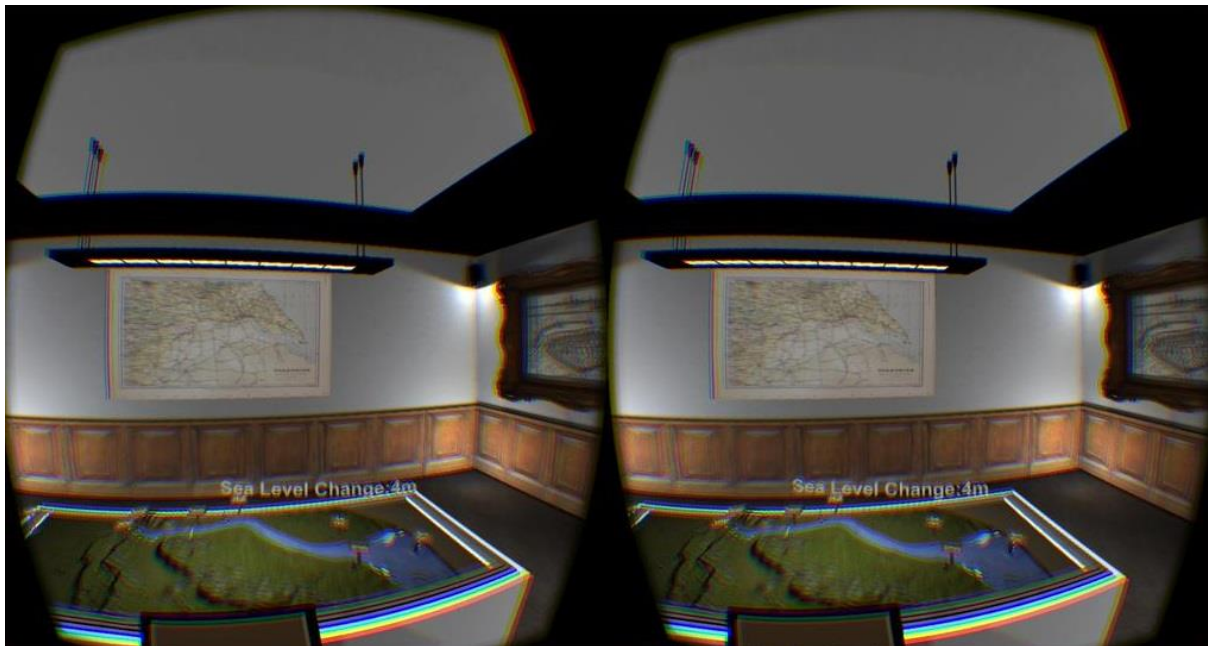
68 Participants viewed a 3D model of the Humber Estuary, UK, on top of box in a museum style space,

69 while tidal flows were calculated using the CAESAR-Lisflood code and animated within UNITY-3D.

70 Participants could then simulate past and future scenarios by altering the base sea level giving them

71   an idea of future flood risk with rising sea levels. The scene was viewed using immersive VR via an

72   Oculus Rift Developer Kit 2 model of HMD.

73

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

75   *Humber in a Box* proved a popular exhibit at events and festivals across the UK and the anecdotal

76   experiences of what worked well provide a framework for a simple model to design future

77   SeriousGeoGames from. The SeriousGeoGame model is one of design choices and considers that they

78   will be predominantly used within a science festival setting where interactions may be short, a few

79   minutes at most, and turn-over of users is high. They should look and feel like video games even if

80   they do not qualify as games themselves. They should exploit VR as a medium of interaction immersing

81   people into new environments. Crucially, they should provide people a first-hand interaction with

82   elements of the ongoing research, such as incorporating field data or numerical modelling codes.

83   A successful SeriousGeoGame will achieve two objectives –

84   1. To create a positive experience for the participant with scientists and the research topic

85   (create fun)

86   2. To increase interest for the participant in the research topic (create curiosity)

87 To use an analogy borrowed from religious evangelism, the purpose is to 'plant a seed' with the

88 participant that might 'germinate' with future interactions with science, scientists, or relevant

89 practitioners in the future. Whether the positive interaction does in fact plant this seed is a matter of

90 trust and something exhibitors will never be able to view come to light.

91 It is important to emphasise that the SeriousGeoGames model has been constructed through design

92 choices and anecdotal experiences of previous activities and events. It incorporates three key

93 elements – science festivals, video games, and virtual reality – that can help to achieve the two

94 objectives.

95   1.2 Science Festivals

96 The science festival is a common feature of the public engagement with research landscape. The

97 vibrant UK Science Festival Network boasts 50 festival members, who in 2018 ran 4,018 events,

98 featuring 10,941 scientists, and achieved 1,225,779 face-to-face interactions (Woolman, 2019). The

99 US scene is also growing, with the Science Festival Alliance growing from just four member festivals in

100 2009 to around two dozen in 2012 (Durant, 2013), and in 2017 47 member festivals shared science

101 and research with over 2 million members of the public (Science Festivals Alliance, 2018).

102 Traditionally, a science festival will be focussed on a central exhibition space, populated by stands and

103 exhibits, focussing on interactive demonstrations highlighting either basic science principles, or more

104 bespoke demonstrations for research projects. Science festivals also usually feature talks and panels

105 by scientists on contemporary issues, and workshops that take people into more detail. Many festivals

106 encourage more creative methods of engaging audiences, including café crawls, story-telling events,

107 improvised comedy, orchestral performances, and films (Durant, 2013).

108 The goal of a Science Festival is usually to celebrate science and research (often that performed or

109 funded by the organisers) and to engage non-specialists (Bultitude, 2014). As such, they have become

110 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 most successful engagements emerge from the conversations engendered (Jensen and Buckley, 2014; Wiehe, 2014).

Science Festivals could be described as niche in their nature, appealing to a small sub-set of the population. According to a 2011 MORI poll, only 3% of the UK population attended a Science Festival in the previous year (Jensen and Buckley, 2014) and this remained at 3% for the latest poll in 2014 (Castell et al., 2014). A criticism of Science Festivals is that they only attract those who are already 'science interested' and who tend to be well-educated, meaning that there is little socio-economic diversity across the attendees (Bultitude, 2014). However, evaluations of events that 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 (including 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 research as they provide a first-hand experience that 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 28% of UK households owning a gaming console (BARB, 2019), and 36% for US households (Entertainment

135   Software Association, 2018). These figures do not count PCs, smartphones, or tablets that are used

136   for gaming, which increases the figure to 64% in the US (Entertainment Software Association, 2018).

137   The flexibility and complexity that can be afforded by video games has made them an attractive tool

138   for engaging people with complex issues such as climate change (Porter and Córdoba, 2009; Reason,

139   2007; Warburton, 2003). This has led to the development of 'serious games', games where learning is

140   a core objective without losing sight of the entertainment element (Abt, 1987; Charsky, 2010; Crookall,

141   2010) and there are several studies showing that serious games have been effective in delivering the

142   intended learning outcomes (Amory et al., 1999; Bellotti et al., 2013; Betz, 1995; Chin et al., 2009;

143   Coleman et al., 1973; Connolly et al., 2012; Gosen and Washbush, 2004; Hobbs et al., 2018, 2019; Lane

144   and Yi, 2017; Mani et al., 2016; Mitchell and Savill-Smith, 2004; Vogel et al., 2006; Wilson et al., 2009).

145   Serious games can be used to create virtual analogues of real world places or physical phenomena for

146   public engagement, such as volcanism (Hobbs et al., 2018, 2019; Mani et al., 2016).

147   1.4 Virtual Reality

148   Virtual reality (VR) can be used to refer to any computer-based simulation featuring a virtual world

149   (e.g. Markowitz et al., 2018; Merchant et al., 2014; Mikropoulos and Natsis, 2011), however it is used

150   here to refer specifically to 'immersive' VR where a user will typically use a HMD to view the virtual

151   world. It is currently regarded as an emerging technology, but VR has been around since the 1960s

152   (Sutherland et al., 2003) and has seen various phases of development, particularly in education (e.g.,

153   Bricken and Byrne, 1993). It has only been recently, with the development of HMDs such as Oculus

154   Rift, HTC VIVE, and Playstation VR, that the technology has enabled mainstream use of VR.

155   VR simulations often share features with video games and thus share many of the same learning

156   advantages, such as being engaging and motivating (Abulrub et al., 2011; Psotka, 2013). However, the

157   immersion and presence (the feeling of physically being in the virtual world) produces experiences

158   that are highly engaging allowing the user to focus more on the learning outcomes (Bricken and Byrne,

159   1993; Markowitz et al., 2018; Salzman et al., 1999). Furthermore, users consider the virtual

160 environment as real (Blascovich and Bailenson, 2011) and can develop a strong attachment and

161 internalisation toward them (Clark, 1997; Weisberg and Newcombe, 2017). A particular advantage of

162 VR is that it can allow users to feel closer to otherwise abstract or distant ideas (Trope and Liberman,

163 2010), for example in Markowitz et al. (2018) users were shown 'first-hand' (via VR HMD) the impacts

164 of ocean acidification and reported increased knowledge gain and interest in the subject as a

165 consequence.

166 VR is not without its limitations. Cost remains a considerable barrier to its uptake and use, with popular

167 HMDs costing several hundred GBP (for example, Oculus Rift S ~£400, VIVE Pro ~£800) and requiring

168 a gaming specification PC to run. The use of VR can also induce a nausea or dizziness (sometimes called

169 cybersickness), similar to motion sickness, and can also cause headaches and eyestrain (Rebenitsch

170 and Owen, 2016). In one test, seated participants using the Oculus Rift HMD for less than 15 minutes

171 reported a 22% occurrence of cybersickness (Munafo et al., 2017).

172 **2. Flooding from Intense Rainfall**

173 2.1 The Research Context

174 *Flash Flood!* was conceived as an engagement activity to support the Flooding from Intense Rainfall

175 (FFIR) research programme, funded by the Natural Environment Research Council UK (NERC). The FFIR

176 programme described itself as "A five year NERC funded programme aiming to reduce the risk of

177 damage and loss of life caused by surface water and flash floods" (Flooding from Intense Rainfall,

178 2019). The UK based and focussed programme brought together experts from several Universities,

179 environmental consultancies, the Met Office, the Environment Agency, and the British Geological

180 Survey to better understand the role intense and localised rainfall events had on both rural and urban

181 flooding, with a strong focus on end-to-end forecasting on events (Dance et al., 2019; Flack et al.,

182 2019). Thunderstorms, driven by strong convection in summer months, form and dissipate rapidly and

183 can be highly localised covering just a 1-3 km wide area. Despite good understanding and being able

184   to forecast the conditions in which they form, it is presently not possible to provide accurate forecasts

185   of when and where the storms themselves will form.

186   The focus of the simulation would be on a sub-section of the programme concerning the modelling of

187   the geomorphic impacts of flash flooding. For most flood events in the UK changes to the river bed,

188   channel, and surrounding flood plain through processes of erosion, deposition, and transport (i.e.

189   geomorphic activity) are negligible to resulting flooding. This is reflected in the current flood

190   forecasting situation in the UK where geomorphic activity is considered as a source of uncertainty that

191   influences model results to a much lesser extent than other sources, such as the rainfall input (Flack

192   et al., 2019). Despite being rare there have been recent high-profile examples of these extreme events

193   including Boscastle (2004), Cockermouth (2009), Glenridding (2015), and Coverack (2017). Because of

194   the risk to life and property it is important there is an awareness of these extreme events and how

195   and when they occur.

196   The geomorphic activity induced by flash flooding can make the flooding even more devastating to

197   communities who can find their properties inundated with mud and debris as well as water.

198   Transported material in flood water increases its power and ability to erode, making it able to destroy

199   and wash away infrastructure, such as bridges. It can also have a profound effect on the river valleys

200   themselves, with some floods inducing so much geomorphic change that they fundamentally change

201   the behaviour of the river for several years, sometimes decades. These flood events have been

202   referred to previously as threshold events (Bull, 1979; Chappell, 1983; Fryirs, 2016; Milan, 2012;

203   Schumm, 1979).

204   Threshold events relate to a concept in geomorphology science called river sensitivity, a concept

205   described by Kristie Fryirs as 'lost', but of increasing significance for landscapes under a changing

206   climate, in her Gordon Warwick Award winner's address to the British Society for Geomorphology in

207   2015 and subsequent paper (Fryirs, 2016). The concept can be summarised by the equation below –

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

209   (adapted from Fryirs, 2016)

210   The equation assumes that every river has a stable behaviour, with it displaying consistent responses

211   to similar events. This stability is maintained by mature vegetation cover and a paucity of sediment

212   that can be moved by the river. However, there exists a threshold magnitude of flood event that will

213   disturb this stability by removing the vegetation cover, exposing sediment, and transporting it

214   elsewhere in the channel. After the event, the channel begins recovery (or relaxation) through a period

215   of enhanced dynamism in the geomorphology until new vegetation has matured and sediment

216   sources exhausted. The balance between how often these events occur and how long it takes a river

217   channel to recover is the river's sensitivity. During the threshold event and the river's recovery the

218   amount of sediment delivered downstream in the system is greatly increased and this in turn may

219   influence the flood risk in those areas (Lane et al., 2007; Slater, 2016). Predictions of climate change

220   for the UK suggest flood events will become more likely and more extreme (Dankers and Feyen, 2008;

221   Ekström et al., 2005; Feyen et al., 2012; Fowler and Ekström, 2009; Pall et al., 2011; Prudhomme et

222   al., 2003) disrupting the balance determining river sensitivity – the impacts of this on rivers and future

223   flood risk is not known but is likely to be negative.

224   2.2 The Research Data

225   The case study at the heart of *Flash Flood!* is the 2007 flood event in the upland valley of Thinhope

226   Burn, Northern England, as detailed by Milan (2012). The event was an FFIR event that could be

227   described as a threshold event for the system. During a six-hour period a highly localised yet intense

228   convective storm precipitated 82mm of rainfall on the upper catchment (Met Office, 2003) resulting

229   in a flash flood – those who witnessed the event described a wall of water and the sound of boulders

230   crashing along the river bed (Milan, 2012). The valley floor was fundamentally changed by the event

231   with large geomorphic changes, including the straightening and widening of the main channel,

232   stripping out of flood plain vegetation, the deposition of material in the channel and on the flood plain

233   (see Figure 2), and increased mobility of material subsequently (Milan, 2012).

234

Figure 2 – Google Earth images showing the reach section surveyed and used for *Flash Flood!*. The
235

right-hand image is from before the flood in 2006 (Google Earth, 2019a), and left-hand image from
236

after the flood in 2007 (Google Earth, 2019b). The flood has cut meanders resulting in a straighter
237

channel, stripped out vegetation, and deposited loose sediment on the flood plain (the lighter
238

colour in the right-hand image).
239

240 The usefulness of this case study for the development of *Flash Flood!* was the availability of ground

241 survey data of the stable river valley just three years prior to the flood, and repeat surveys afterwards,

242 which were used by Milan (2012) and provided for this work. To have detailed surveys shortly before

243 a geomorphically active event such as this is rare and cannot be planned for so provided an exciting

244 opportunity. This survey was captured in the summer of 2003 using a back-pack Global Positioning

245 Satellite (GPS) system across a 500 m reach section. Although similar surveys were available for after

246 the flood, it was decided to recapture the same 500m in more detail using a Terrestrial Laser Scanner

247 (TLS) in the summer of 2014. The recovery period after extreme events varies widely between

248 different areas, depending on factors like local vegetation, soil or climate, but can take decades -

249 although this survey was conducted 7 years after the flood the channel had still yet to recover and

250 largely reflected the immediate post-flood environment.

251 To give an indication of the height of the peak flood extent, simple modelling was performed within

252 the CAESAR-Lisflood software (Coulthard et al., 2013), using elevations derived from the 2003 GPS

253 survey and the estimated peak discharges from Bain et al. (2010) to drive the model hydraulics.

254 **3. Development**

255 The Flash Flood! application was designed by the SeriousGeoGames Lab and developed by indie-

256 games developers BetaJester Ltd using the UNITY-3D gaming engine. There have been two iterations

257 of the VR-based software with the second being optimised based on the experiences exhibiting the

258 original version.

259 3.1 The original *Flash Flood!*

260 The original *Flash Flood!* was developed in 2015. The 3D environment was built using the popular

261 gaming engine UNITY-3D. The before and after flood scenes were constructed from the DEM using

262 the data described in Section 2.2, each converted into a point cloud. A sample of each point cloud was

263 extracted, converted to a mesh, and imported into UNITY-3D. The scenes were populated using

264 textured renders and 3D objects (known as assets), with the scene being more heavily populated with

265 trees than in real life to help blur edges and create a more interesting 3D environment for participants

266 to explore.

267

268 **Figure 3 – Screen shot from the original *Flash Flood!*.**

269   The exhibit used an Alienware X51 R3 (Intel Core i5 6400 CPU @2.71 Ghz – 16Gb RAM – NVIDIA

270   GeForce GTX 970), which was labelled as "Oculus-ready", with the consumer model Oculus Rift HMD.

271   The application was optimised to a lower standard than the equipment specification afforded to allow

272   a desktop-only version of the software to be released. For example, the graphics were kept simple

273   (see Figure 3) and the representation of water kept to an animated plain that was angled down in the

274   direction of the river and would rise and fall giving the impression of rising and falling water levels as

275   it intersected the landscape. The public participants explored the scene using the two joysticks on an

276   XBOX controller and needed to use no other buttons or d-pads.

277   The participant began the simulation within the river valley viewing it from a first-person perspective.

278   They were free to explore the whole scene with movement restricted at the edges by hills or invisible

279   barriers. The flood animation timeline did not begin automatically and only started when a crew

280   member pressed the P button on the keyboard.

281   The simulation moved along a 6 hour timeline that took 30 seconds per hour timestep, for a total of 3

282   minutes. It began at 15:00 and on-screen prompts described the scene at each step –

283   15:00 – "Clouds begin to gather"

284   16:00 - "A storm is brewing"

285   17:00 – "The storm intensifies"

286   18:00 – "Intense rainfall falls on the uplands of the river"

287   19:00 – "Rain water from the uplands swells the river level. A flash flood is coming!"

288   20:00 – "The flood has reached its peak"

289   21:00 – "The flood has receded leaving a scene of devastation"

290   During 19:00 the eponymous flash flood wave passed through the scene – this was produced using

291   two shapes, a box and wedge (as the flood toe), textured in the same way as the water, to give an

292   impression of the "wall of water" described by witnesses (Milan, 2012). Throughout the timeline the

293   water turned increasingly brown to represent the debris within the water. As the simulation

294   transitioned between 20:00 and 21:00 the before the flood scene was switched for the after the flood

295   scene. Most of the changes were obscured under the height of the water as this was the peak of the

296   flood, but it still required a removal and repositioning of the participant within the scene (a process

297   known as respawning) resulting in some sudden, unrealistic changes.

298   The limitations of time and funding meant that there was no sound incorporated into the original

299   version and narration was provided via a one-to-one interaction with a crew member – usually a

300   scientist within a relevant research area, or a science communication generalist. This had the

301   advantage of being able to tailor the message based on the crew member's research field and the age

302   and responsiveness of the participant.

303   3.2 *Flash Flood! Vol.2*

304   In 2018, an opportunity arose to redevelop the original *Flash Flood!.* Where the original had been

305   limited in its graphics and representation of river flow due to the release of a desktop-only version,

306   there were no such limitations for *Vol.2*. Instead, the new development was optimised for a new set

307   of equipment using the Alienware 17R5 Oculus-Ready laptops (Intel i7-8750H @ 2.20GHz – 8GB RAM

308   – NVIDIA GeForce GTX 1070), with an aim of achieving a look and feel of a AAA-game (games produced

309   by large gaming companies intended for the global commercial market). This was partly in response

310   to an increasing number of anecdotal comments on the basic level of the original graphics and

311   participants becoming more accustomed to ever more sophisticated VR experiences. Photo-realistic

312   assets were used for textures and 3D objects, and the scene was made wooded like the original to

313   make a more interesting scene (see Figure 4). The transitions at the edges of the scene were

314   significantly improved by removing the hills and replacing these with an extended landscape (that

315   could not be explored) and hiding the edges using stone bridges. The basic horizontal plain of water

316   was replaced by the more sophisticated River Auto Material (R.A.M. by NATUREMANUFACTURE)

317 asset, with customisation from the developers for the representation of the flash flood showing a

318 rapidly rising water level with debris in the form of rocks and logs. *Vol.2* uses the same data and flood

319 timeline as the original version.

320

321 **Figure 4 – Screenshot from *Flash Flood! Vol.2*.**

322 From an exhibitor point of view the main limitation of the original version was the staffing resource

323 required due to the one-to-one narration provided by the operator – this interaction was exhausting,

324 and a single operator could manage around four or five demos before requiring a rest during busy

325 periods. This means each set up required a minimum of two operators rotating regularly, and an extra

326 operator for every two sets to allow for breaks and control of the crowd. This limited the number of

327 demonstrations that could be achieved and size of exhibits that could be supported. To overcome this

328 limitation *Vol.2* uses a soundtrack with narration. The user chooses between two narrators – Chris

329 (voiced by Dr Chris Skinner) and Jess (voiced by Dr Jess Moloney). As video gaming is often perceived

330 as a male space with women and girls feeling excluded or discriminated against (for example,

331 Delamere and Shaw, 2008), it was decided the choice of narrator would default to Jess so that

332 participants would encounter a female scientist first. The two narrations follow slightly different

333   scripts with Chris's being more general and Jess's drawing more on Dr Moloney's research into dating

334   past flood events (Moloney et al., 2018). The choice of a single male and female voice was a starting

335   point and allows for an increased representation of voices with future developments.

336   3.3 Ancillary developments

337   The two iterations of VR software are not the only developments relating to *Flash Flood!* nor should

338   the achievement of the two objectives be limited to the time and space within the science festival hall.

339   The activity was promoted and supported by the SeriousGeoGames social media accounts (Facebook

340   and Twitter) and website. At times this was enhanced by support from the University of Hull Marketing

341   and Communication team, plus other colleagues at the University of Hull, other Universities

342   (particularly Reading and Newcastle), and the NERC.

343   To make the application more accessible a desktop-only version was made available via SourceForge

344   that could be controlled using a mouse and keyboard. This was free to download and would operate

345   on any reasonably modern windows machine. However, several schools reported they wished to use

346   the software but were unable to due to networking restrictions on school machines and in response

347   two 360 video versions were produced and made available via YouTube – a narrated version (*Flash

348   Flood! 360*) and a non-narrated version (*Flash Flood! Classroom*). These videos allowed headtracking

349   but not the freedom to explore the scenes. To support both the desktop and video versions a manual

350   was produced and articles aimed at students and teachers published (Skinner, 2018; Skinner and

351   Milan, 2018).

352   To support the original version of *Flash Flood!* a handout was produced. The handout included brief

353   descriptions of the flood event, links to the SeriousGeoGames website and social media accounts, and

354   an activity that could be done alongside the simulation. The intention was to mimic the taking of field

355   notes performed by geomorphologists, before and after the flood, particularly for use with the

356   desktop and YouTube versions of *Flash Flood!* outside of events (it was also available as a PDF

357   download). At events the handout was given out along with a "I survived the Flash Flood!" badge and

358 was also free to take from the table. It was used to engage members of the public either waiting for a

359 turn or accompanying a participant by getting the participant to describe what they were seeing so it

360 could be written into the field notes section.

361 **4. Evaluation**

362 The different versions of *Flash Flood!* have been demonstrated at events since its debut at the Hull

363 SciFest in March 2016, several years before any evaluation activity beyond informal conversation with

364 participants and headcounts was conducted. The experience of exhibiting has provided a wealth of

365 anecdotal information valuable for designing new activities but is potentially biased (Jensen, 2015)

366 and not suitable for formal evaluation (Neresini and Bucchi, 2011). Previously, evaluation at events

367 has been eschewed as it was perceived to intrude on the experience of the participants and potentially

368 impede on the success of the objectives, especially when the activity is just one exhibit of many as

369 part of a larger science festival. Summative evaluation, conducted after participation with activities,

370 can reduce the intrusion on interactions – an example would be autonomous methods for participants

371 to leave feedback, such as graffiti walls and feedback cards (Grand and Sardo, 2017). Autonomous

372 methods have been tried alongside *Flash Flood!* previously, for example at the 2018 Hull SciFest.

373 The formal evaluation of *Flash Flood!* was conducted using *Flash Flood! Vol.2* during two events. The

374 first event was Scarborough Science and Engineering Week (SSEW) 2019 held 8-10 October 2019 at

375 Scarborough Spa, Scarborough, UK. SSEW was targeted at schools in the local area, with two days (8

376 and 9 October 2019) for secondary school and college pupils (ages 11-18) and a day for primary school

377 pupils (ages 5-11). The second event was the Open Day for the British Geological Survey (BGS) held at

378 their campus in Keyworth, UK, on 12 October 2019. This was a one-day, ticketed event, aimed at

379 families where all 1,800 free tickets were taken up.

380 The evaluation for both events used the same questionnaire (see Figure 5). Questionnaires are not

381 best suited for busy science festival settings but are an effective way of gathering quantitative

382 information (Grand and Sardo, 2017; Wiehe, 2014). In an attempt to reduce this impact the

383   questionnaire was designed and hosted via the Formstack app on iPads, displayed in stands –

384   participants filled and submitted the form on the iPad rather than using paper surveys. The

385   questionnaire was designed to assess *Flash Flood! Vol.2* versus the two Objectives in Section 1.1,

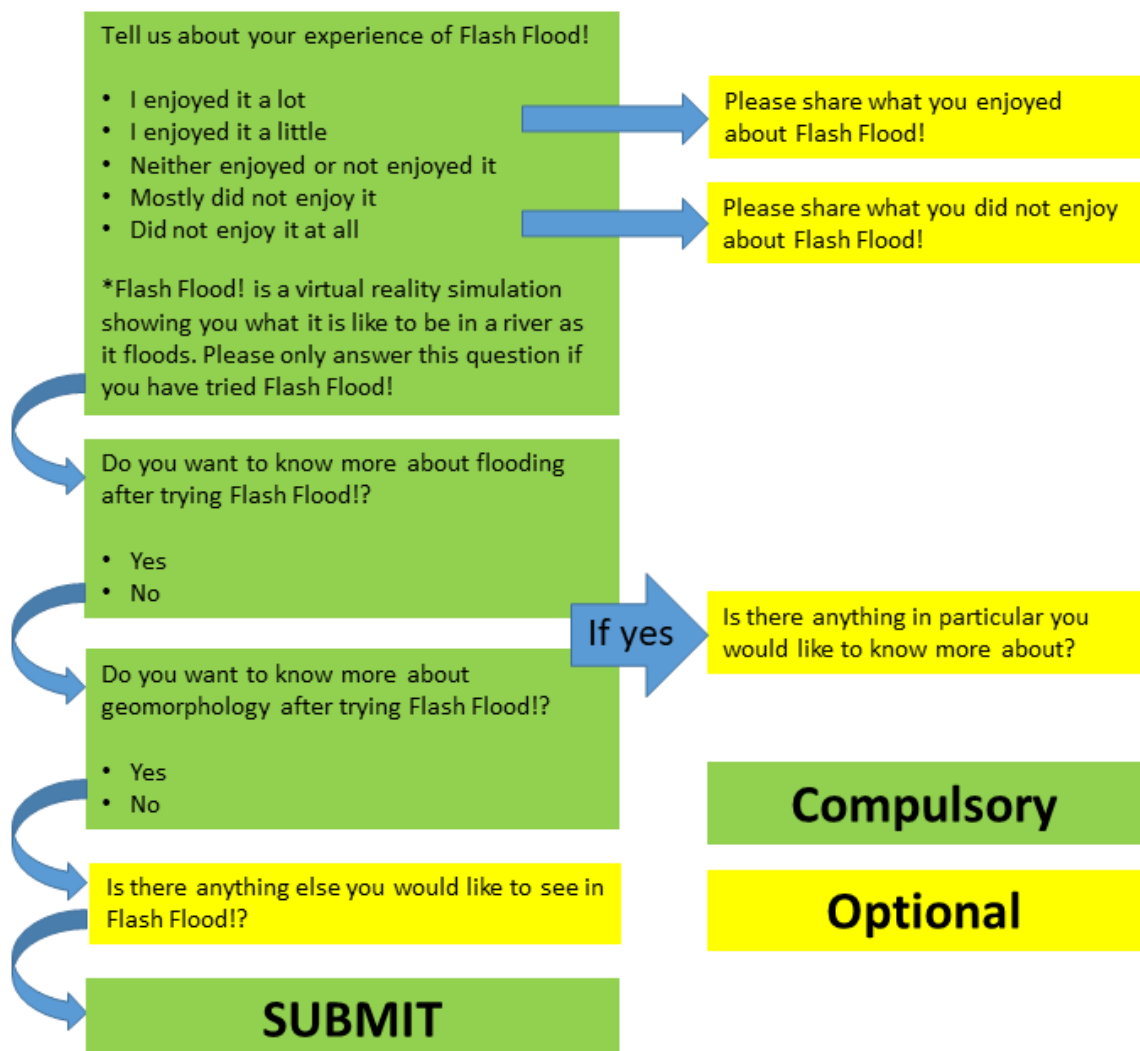
386   which can be summarised as creating fun and curiosity. Participants were orally referred to the

387   questionnaires by exhibit crew after finishing their turn on *Flash Flood! Vol.2*. Completion was

388   voluntary and participants were not observed whilst completing it. At SSEW, up to four VR stations

389   running *Flash Flood! Vol.2* were operating at once along with two iPad evaluation stations, and at BSG

390   Open Day there were up two VR stations and one iPad evaluation station.

391

392 **Figure 5 - Flow diagram showing the questionnaire design. All respondents are offered all questions**

393 **on the left-hand side, whilst questions on the right-hand side were only shown under indicated**

394 **conditions. All questions in green boxes had to be answered to allow the form to submit.**

395 At both events a large (3m wide - 2m high) canvas banner advertising *Flash Flood!* was on display

396 featuring the following text –

397 "Flash Flood!

398 Geomorphology: The science of how landscapes change

399 Try our Virtual Reality demo to see how floods can change river valleys

400 Climate change is predicted to increase flooding, erosion, and changes to our rivers

401 Flash Flood! has been built using data from a real river and is based on a real flood"

402 The space set up for both events is shown in Figure 6. Whilst the BSG Open Day was a traditional

403 tabletop activity and banner set up, SSEW featured some more design elements, like event fencing, a

404 static drone display, and an immersive forest soundscape within the fencing.

405

406 **Figure 6 – Exhibit set up for the Scarborough Science and Engineering Week (left) and the British**

407 **Geological Survey Open Day (right). The iPad and stand for the evaluation station at the British**

408 **Geological Survey Open Day is just off shot to the right of the image.**

409   The ancillary developments designed to support the exhibit include the SeriousGeoGames website

410   (hosted in Wordpress) and YouTube channel. Both Wordpress and YouTube provide detailed analytics

411   of views, audience, sources, and other useful information that can be broken down by date. This

412   analytic data was used to evaluate whether the online content, and the *Flash Flood!* handout that

413   signposted participants to it, was useful for achieving the two objectives during the NERC UnEarthed

414   event in 2017.

415   **5. Results**

416   This Section details the results of the evaluation of *Flash Flood!*, beginning with the informal, anecdotal

417   information garnered from years of exhibiting with different versions of the application (5.1). Sections

418   5.2 and 5.3 detail the formal evaluation of *Flash Flood! Vol.2* over two events, for the two objectives,

419   creating fun (5.2) and creating curiosity (5.3). In Section 5.4, an analysis of the ancillary developments

420   is provided.

421   5.1 Anecdotal Information

422   Even without a formal evaluation useful lessons had been learned such as it being obvious that

423   participants enjoyed the activity. Some words were often used in informal conversations to describe

424   their experiences, such "epic" and "sick" (meant positively), and particularly "weird" describing the

425   uncanny experience of immersion in a virtual world that is exciting yet out of the ordinary. Other

426   comments included variations of "it's like Minecraft" that have evolved into "it's like Fortnite". *Flash*

427   *Flood!* has been highlighted in the feedback obtained by events, usually via comment walls. At NERC

428   Into the blue event in 2016 comments under the "Things I loved about Into the blue" included "flash

429   flood", and under "Things I learned at Into the blue" was "Rivers are fantastic!". Into the blue also ran

430   a public vote for most popular stand, for which *Flash Flood!* was awarded joint-3rd out of 40 exhibits

431   and events.

432   Not all feedback has been positive and there have been a few negative comments received during

433   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?" was a common form of question at the start of demonstrations.

In conversation, it was often commonly asked of participants what they might like to see included in *Flash Flood!*. Common suggestions included 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, for example something to shoot, such as zombies (see Curtin, 2017). With *Vol.2,* where there were usually more VR stations available to do multiple simultaneous demos, several have commented that they would like to have them linked and be able to explore the scene together with their friends.

Flash Flood! Vol.2 was first used at the two day Hull SciFest 2018 as one of activity within a wider 'Earth Arcade' space of several activities (see https://seriousgeo.games/eartharcade/). The event consisted of shows, workshops, and a Discovery Zone of 45 exhibits, of which the Earth Arcade was one. 3,039 members of the public visited the Discovery Zone but there are no data on how many visited the Earth Arcade. An informal evaluation was conducted for the whole Earth Arcade using a post-it board, with four questions –

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, of which 42 related to *Flash Flood!* directly, featuring identifying terms like "virtual reality", or referred to the Earth Arcade space as a whole. 35 were posted under the question 1 and all were positive. 9 of the responses identified particular features of *Flash Flood!* that they enjoyed. Only one negative comment was posted, under question 4, stating "I liked it mostly apart from the graphics". The results of this evaluation are potentially biased due to the positive framing of the questions.

459   5.2 Objective 1 – Creating Fun

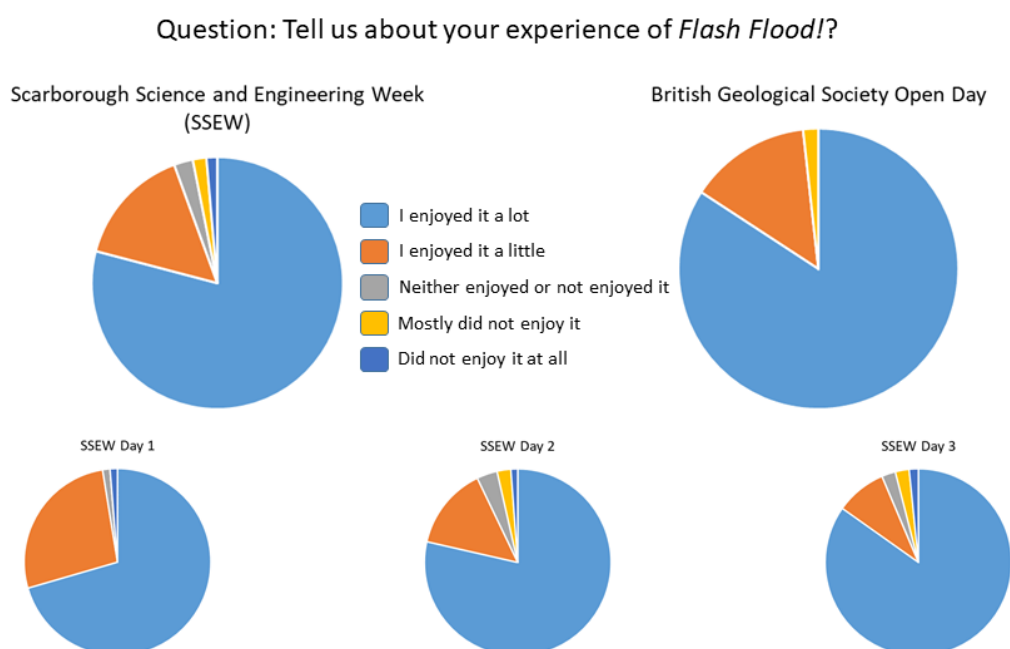
460   The ability of *Flash Flood! Vol.2* to create fun was evaluated using questionnaires at two events in

461   October 2019. The first question asked participants to "Tell us about your experience of *Flash Flood!*?"

462   and the results can be seen in Figure 7. 3 responses were collected over the two events with 79.9%

463   stating they enjoyed it a lot and a further 15.1% stating they enjoyed it a little, meaning 95.1% enjoyed

464   it in some form.

465

466   **Figure 7 - Charts showing the questionnaire responses to the question "Tell us about your**

467   **experience of *Flash Flood!*?" from Scarborough Science and Engineering Week (8-10 October 2019)**

468   **and the British Geological Survey Open Day (12 October 2019).**

469   This level of enjoyment only varied slightly, with the participants of the BGS Open Day reporting to

470   have enjoyed it the most of the four days (98.3%, n=57). The second day of SSEW saw the lowest levels

471   of enjoyment (92.9%, n=84). Over the three days of SSEW, the primary school pupils on Day 3 were

472   more likely to say they enjoyed it a lot (84.8%, n=125), than the secondary school pupils (74.5%,

473   n=162), whilst participants at the BGS Open Day reported similar levels to Day 3 (84.2%, n=57).

474 Those who reported they enjoyed the activity were prompted to volunteer a free-text answer to the

475 question "What did you enjoy about *Flash Flood!*?" which received 210 answers. Answers were

476 analysed and binned into categories – general (for example, "I enjoyed everything"), content (for

477 example "I enjoyed learning about the flood"), technology (for example, "I liked it looked real"), and

478 miscellaneous (answers not falling into the above or that did not make sense). Overall, the technology

479 proved most popular (38.1%, n=210) then general (33.8%, n=210), and then the content (25.2%,

480 n=210), however, for the BSG Open Day content proved most popular (45.2%, n=31), general next

481 (29.0%, n=31), and then technology (25.8%, n=31).

482 Eight responses were provided for the question "What did you not enjoy about *Flash Flood!*?" of which

483 more than half referred to the technology, such as "bad graphics", "Made me dizzy", or "It hurt my

484 eyes". One response was "Chris" which could either refer to Dr Chris Skinner's voice over or himself

485 as he was acting as crew for this event.

486 5.3 Objective 2 – Creating Curiosity

487 The evaluation of whether *Flash Flood! Vol.2* created curiosity was conducted through two questions

488 – "Do you want to know more about flooding than before trying *Flash Flood!*?" and "Do you want to

489 know more about geomorphology than before trying *Flash Flood!*?". 68.0% (n=344) of respondents

490 stated they did wish to learn more about flooding and 60.1% (n=344) wished to learn more about

491 geomorphology. A breakdown of the data for the events and days in shown in Figure 8. Between the

492 events, the level of curiosity regarding flooding was similar, with 67.9% (n=287) at SSEW and 68.4%

493 (n=57) at the BSG Open Day wanting to know more, yet regarding geomorphology more participants

494 at the BSG Open Day wanted to know more (64.9%, n=57) than at SSEW (59.2%, n=57). The primary

495 school pupils were more likely to want to know more about flooding (68.8%, n=125) than the

496 secondary school pupils (67.3%, n=162), and were more likely to want to know about geomorphology

497 (62.4% to 56.8%).

498

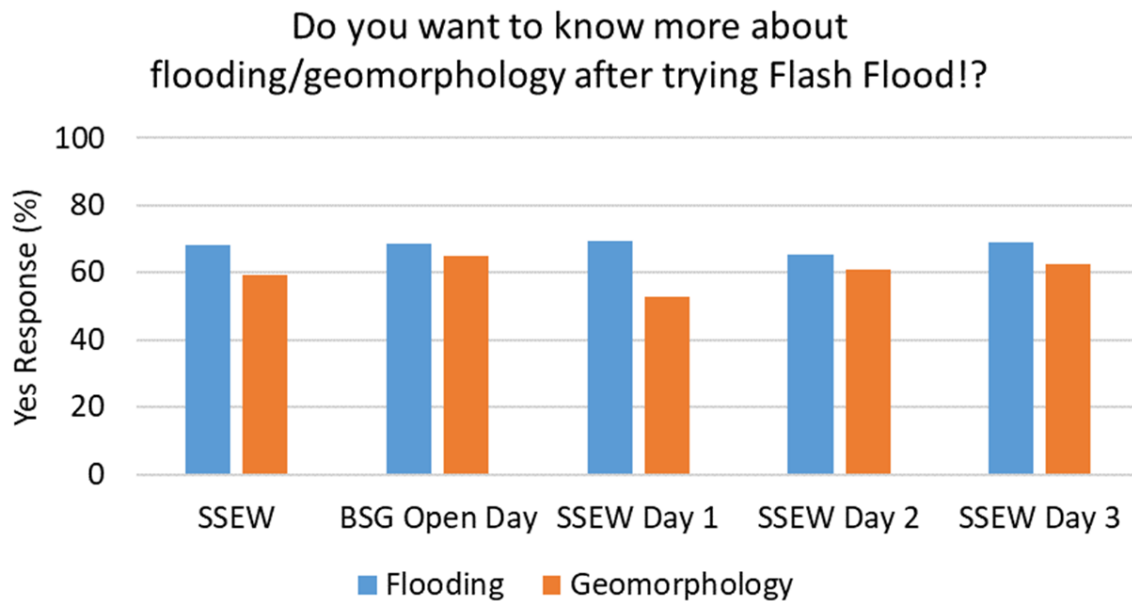



Figure 8 – Levels of respondents responding yes to questions asking if they would like to know more about the research topics in *Flash Flood!*. Data are split between Scarborough Science and Engineering Week 2019 (SSEW) and the British Geological Survey Open Day 2019 (BGS Open Day), and further into the three days of SSEW.

If participants answered yes to either of the questions they were then offered opportunity to volunteer a free-text response to "Is there anything in particular you would like to know more about?". The responses have been binned into the categories – general, content, technology, and miscellaneous as in Section 5.2 – with the majority of responses (55.9%, n=93) falling in miscellaneous with responses like "No" or "Not really". Overall, 28.0% (n=93) wanted to know more about elements of the content, and 11.8% (n=93) wanted to know more about the elements of the technology. At SSEW, 25.3% (n=83) wanted to know more about the content and 13.3% (n=83) the technology, whilst at the BSG Open Day 50% (n=10) wanted to know more about the content and no one wanted to know more about the technology.

All participants were offered the opportunity to enter a free-text response to the question "Is there anything else you would like to see in *Flash Flood!*?" which got 83 responses, 42.2% relating to the

514 technology and 14.5% to the content. A common theme was for extra features associated with video

515 games, such as challenges, a larger map, better graphics, or multiplayer modes. At the B[...]Open Day

516 more participants wanted to extra features relating to the content (41.7%, n=12) than the technology

517 (33.3%, n=12).

518 5.4 Ancillary developments

519 To support the activity at events, ancillary activities were produced, mainly online. These include the

520 SeriousGeoGames website and videos on the SeriousGeoGames YouTube channel. This section

521 analyses the potential of these for assisting in achieving the two objectives. Figure 9 shows the growth

522 in views for the website, YouTube channel, the individual 360 *Flash Flood!* videos, plus the aggregated

523 views of all *Flash Flood!* videos (three in total – two 360 videos and a demo for the original version).

524 The YouTube channel has more views than the website but only since February 2019 – before this

525 both the website and YouTube channel were on similar levels of views and growing at around 200

526 views a month.

527

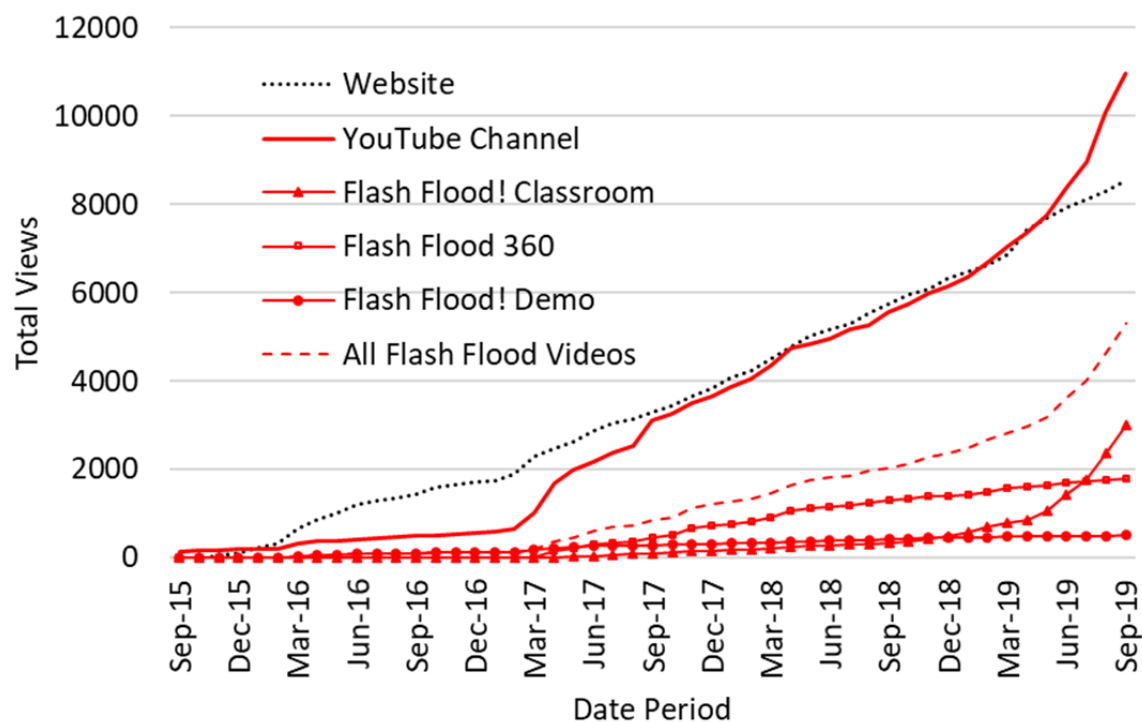



Figure 9 - Cumulative views for SeriousGeoGames online content, including the SeriousGeoGames website and YouTube channel, and cumulative views for the *Flash Flood!* related videos on the SeriousGeoGames YouTube channel.

The growth in the aggregated views for all these videos is also shown in Figure 9. As a share of overall views on the SeriousGeoGames channel, the *Flash Flood!* videos has gradually been increasing and currently accounts for around 48.3% of the total views. The *Flash Flood! Classroom* version has gained in popularity with over 3,000 views in 2019 and 3,515 in total (as of 24/10/2019). 2,940 (83.6%) have come from YouTube searches, with the top 5 search terms being "360 flood", "Flood VR", "VR Flood", "360 video flood", and "flood 360".

The analytics provided by YouTube Studio provide the opportunity to assess whether exhibiting acts to drive people towards the YouTube versions after the event. The NERC UnEarthed Science Showcase took place on 17-19 November 2017, attracted over 5,250 visitors, and one exhibit featured both *Flash Flood! VR* and *Humber in a Box*. The *Flash Flood!* handout was used to support the activity, referring people to the *Flash Flood! 360* video. For the 17-day period covering the event plus the week prior and the week following (10-26 November 2017), the video received 88 views (35 direct – straight to URL, YouTube search, or channel page), an increase from 41 (6 direct) during the 17-day period 23 October to 9 November 2017. This reduced down again to 69 views (36 direct) for the 17-day period 27 November to 13 December 2017.

6. Discussion

6.1 Objectives

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. During the two

events where formal evaluations were collected, 95.1% of respondents said that either enjoyed it a little or enjoyed it a lot, with 79.9% enjoying it a lot.

The success against Objective 2 - to increase interest for the user in the research topic – was also assessed via questionnaire at two events and *Flash Flood!* was shown to be able to meet this objective, with 68.0% of respondents wanting to know more about flooding and 60.1% wanting to know more about geomorphology. The level of curiosity generated for geomorphology is lower and likely reflects that it does not feature as prominently within the exhibit – there is a small description on the banner but little mention within the simulation itself (an extra optional response of "I don't know what geomorphology is" might have proven revealing for this question).

6.2 Comparison between school and family audiences

The formal evaluation was conducted at two different events. At SSEW the audience were groups from local schools accompanied by teachers, whilst at the BGS Open Day the audience was self-selecting having chosen to book a ticket and attend the event. The audience at the BGS Open Day was more likely to report having enjoyed the activity and were more likely to want to know more about both flooding and geomorphology. When asked what they enjoyed, the BGS Open Day audience were more likely to say something relating to the content over the technology, and likewise when asked what they would like to know more about and what they would like adding to the activity. In contrast, at SSEW the majority of responses wanted technology related features adding to the activity. The nature of the BGS Open Day means that those electing to attend are likely to already have an interest in science (Bultitude, 2014) so the content will more likely be in line with their pre-existing interests.

6.3 Comparison between primary and secondary school audiences

The SSEW event segregated its audience by having two days attended by secondary school pupils followed by a single day attended by primary school children. Over all factors, the primary school pupils were more positive, with slightly highly overall proportion enjoying the activity but a greater

575   proportion reporting they enjoyed it a lot. Both secondary and primary school pupils reported similar

576   levels of wanting to know more about flooding after trying *Flash Flood!*, although this was slightly

577   higher with primary school pupils. Primary school children were more likely to want to know about

578   geomorphology than secondary school children. Although primary school pupils do respond more

579   positively to the activity, secondary school pupils also respond positively in the majority, suggesting

580   the activity is effective for engaging both age ranges.

581   6.4 Ancillary developments

582   To support the *Flash Flood!* activities there is online information via the SeriousGeoGames website

583   and YouTube channel. During the NERC UnEarthed event of November 2017, a handout was used

584   referring participants to the *Flash Flood! 360* video on YouTube and this did result in an increase in

585   views from 41 for a period before the event to 88 for the period before, during, and following the

586   event. 35 of the 88 views were direct, meaning they came from typing in the URL, from YouTube

587   searches, or selecting the video from the SeriousGeoGames YouTube channel, whilst 47 views came

588   from using links, including on Twitter (15) and preventionweb.net (11). Even if it is (wrongly) assumed

589   that all 47 of the increased views came from participants at the event this would represent just 0.009%

590   of the 5,250 attendees suggesting that the exhibit and hand outs are not successful in driving traffic

591   to the online content.

592   The *Flash Flood! Classroom* version was produced in response to discussions with teachers at events

593   for use in schools and has been supported by articles targeting this use (Skinner, 2018; Skinner and

594   Milan, 2018). This video has seen increased growth in 2019, with over 3,000 views where 90.7% are

595   from YouTube searches. However, only 0.6% of these searches used the term "flash flood classroom

596   version", suggesting that the increase in views is a result of the video showing up in search results for

597   more generic searches rather than being used in schools. The majority of views come from the US

598   (38.5%) with the UK share of audience too small to be shown by YouTube's analytics, suggesting that

599   views are not likely to be a result of the UK-focussed articles.

600 The results from the ancillary developments are disappointing and do not suggest that they are

601 effective at supporting the exhibition activity of *Flash Flood!*. There is little evidence of it being used

602 within classrooms too. However, the increase in views for *Flash Flood! Classroom* via generic search

603 terms indicates that a new audience can be found through optimising use of search terms and presents

604 an attractive area of future development.

605 6.5 Reflections

606 A major development between the original *Flash Flood!* and the *Flash Flood! Vol.2* that was used for

607 the formal evaluation was the inclusion of a voice-over track. This helped to engage more participants

608 at one time as it no longer required a one-to-one interaction with a crew member. It also reduced the

609 resource needed to crew exhibits as it reduced the level of fatigue within the crew. However, it also

610 limited the conversations between participants and crews, which are where the most positive science

611 engagements occur (Jensen and Buckley, 2014; Wiehe, 2014). For events like SSEW, with large school

612 groups in attendance, where the volume of participants makes such interactions difficult, *Flash Flood!*

613 *Vol.2* seemed particularly suited. At family-orientated events like the BSG Open Day, interactions are

614 more relaxed and the activity could benefit from additional follow-on interactions providing additional

615 information on flooding, geomorphology, and how the 3D scene was constructed (akin to the debrief

616 of Crookall, 2010). In this, *Flash Flood! Vol.2* shows potential for use in facilitating more in depth

617 interactions between the public and scientists at appropriate events.

618 The next steps for developing SeriousGeoGames, including *Flash Flood!*, would be to broaden the

619 objectives to include learning objectives and/or to drive behavioural changes. For example, an

620 application could teach people about specific elements of flood risk and encourage them to make

621 flood plans or sign up to flood warning services, or an application about plastic pollution could teach

622 people about hidden sources of plastic and encourage them to use less of these. However, *Flash Flood!*

623 has been designed for short term interactions in busy event spaces and would likely need adapting

624 and expanded to meet such objectives. The video game elements in *Flash Flood!* are the least

625 developed and present the area of greatest opportunity going forward. At present it cannot be

626 classified as a game - it lacks objectives for participants to achieve or challenges to be completed - yet

627 it stills creates fun and curiosity. However, some comments were received stating disappointment

628 that there was little do other than exploring the limited game world and observing the flood. If the

629 narrow objectives of *Flash Flood!* were expanded to include defined learning objectives, possibly

630 within the a workshop or classroom environment, developing more gaming features would be the

631 obvious way to achieve this.

632 **7. Conclusion**

633 The SeriousGeoGames design model seeks to build activities for festival-like events that allow the

634 public to interact directly with elements of research, such as field observations and numerical models.

635 The activities should look and feel like a video game and experienced via virtual reality. The Objectives

636 are to create fun and curiosity for the subject matter for the participant. Through the *Flash Flood!*

637 activity, a virtual reality simulation showing a geomorphically active flooding from intense rainfall

638 event based on a real event, the SeriousGeoGames model was shown to be successful, with most

639 participants reporting to have enjoyed the activity and the majority reporting to wanting to know

640 more about the subject matter of flooding and geomorphology. This remains true for several audience

641 types, including groups across all school age ranges and also family audiences. Ancillary developments

642 online offered little support to the exhibition of the activity, with minimal traffic relating to events,

643 but could offer a new audience for the activities outside of events.

644 **Data Availability**

645 The evaluation data collected at the events and used in the study can be found online at

646 https://universityofhull.box.com/s/y0lifdeax70u6tk7n81k96xxie5bqbf4. Game files for *Flash Flood!*

647 can be found at https://sourceforge.net/projects/flash-flood/

648 **Ethics Statement**

649 The study complied with all the Ethical Approval processes for the University of Hull. Specific

650 considerations were paid to the use of virtual reality – disclaimers were given in game and verbally

651 about potential dizziness, and to reduce risk participants were required to be seated at all times. In

652 regards to safeguarding and child protection no SeriousGeoGames or Earth Arcade exhibit crew are

653 ever responsible for the care of children who must be accompanied by an adult before participating.

654 Crew are instructed to never find themselves alone with a child. Crew are prohibited from

655 photographing the exhibit whilst the public are present (often exceeding the photography policy of

656 the event). Whilst participating the public are handed the VR headset to have ownership of it during

657 the activity and instructed how to adjust and wear it, and told to remove whenever they like – crew

658 do not touch the headset whilst it is on someone else's head.

659 **Acknowledgements**

660 The author would like to thank Laura Hobbs and an anonymous reviewer for their valuable and

661 insightful comments. These have contributed to a much improved revised manuscript.

662 The original *Flash Flood!* was funded by a Knowledge Transfer grant from the NERC Flooding from

663 Intense Rainfall project (SINATRA NE/K00896X/1 and FRANC NE/K008900/1) . *Flash Flood! Vol.2* was

664 funded through the Higher Education Innovation Fund award for the Earth Arcade. The *Flash Flood!*

665 360 videos were funded using the NERC Into the blue prize fund. The *Flash Flood!* handout was funded

666 by an Outreach Grant from the British Society for Geomorphology. Game and VR development was

667 conducted by BetaJester Ltd.

668 The success of Flash Flood! would not have been possible without the following people who have

669 championed it, helped with design, and volunteered at exhibits – Hannah Cloke, Tom Coulthard, Dan

670 Parsons, Sarah Dance, Chloe Morris, Jess Moloney, Rob Thompson, Matt Perks, Dave Milan, Jazmin

671 Scarlett, Bas Bowedes, Serena Teasdale, Ryan Lay, Adam Boyne, Josh Porter, John van Rij, Hannah

672 Williams, Jackie McAndrew, Phil Bell-Young, Mark Lorch, Xuxu Wu, Leiping Ye, Jack Laird, Michelle

673 Kinnon, David Flack, Louise Arnal, Ye Chen, Josh Johnson, Robert Houseago, Flo Halstead, Greg Smith,

674 Jenny James, Catherine Mascord, Jo Dewey, Jo Arnett, Annie Ockelford, Freija Mendrick, Marijke De

675 Vet, Nilufar Xiaokaiti, Sergio Duran, Amy Skinner, Cat Fergusson-Baugh, Chloe Carter, Zoe Kennington,

676 Courtney Derrico, Joanna Saw, Sojiro Fukuda, Jack Buckingham, Anna Baar, Evdokia Tapoglou, Elena

677 Bastianon, Irene Satiropoulou, and Karen Rodgers.

678

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