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

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

3   Dr Chris Skinner – Energy and Environment Institute, University of Hull

4   Email – c.skinner@hull.ac.uk

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 which 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 framework is

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

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

14 'hands 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 science festivals and similar events in the UK by

18 scientists on the project, and supported with online content including videos. Through event feedback

19 it was shown to create positive experiences for participants and inspired curiosity as seen through

20 online analytics. This is hoped to inspire more fruitful engagements with relevant agencies in the

21 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 risk. Resilience to hazards is borne out of preparedness, and preparedness is built on

47   knowledge, so the first step in building societal and individual resilience to geomorphic-flooding

48   hazards is by making people aware and more curious the topic. As Clarke et al. (2017) asserts, the

49   responsibility is with geomorphologists, and by extension flood management practitioners, to inspire

50   this curiosity.

51   This paper presents a case study of the *Flash Flood!* application, a game-based virtual reality (VR)

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

53   commonly known as flash flooding. It highlights the SeriousGeoGame model of using science festivals,

54   video games, and VR to allow the public to interact 'hands-on' with scientific data to promote

55   enjoyment and curiosity in flooding and geomorphology. In Section 2, the specific research context

56   for *Flash Flood!* is described, followed by a description of the development of the application in Section

57   3. The evaluation of the application against its stated objectives is shown in Section 4, and discussed

58   in Section 5, before conclusions in Section 6.

59   ### 1.1 The SeriousGeoGames Model

60   The SeriousGeoGames Lab (SGG) was established in 2014 to explore the use of games, and gaming

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

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

63   grade hydraulic model - CAESAR-Lisflood - (Coulthard et al., 2013) with a gaming engine – UNITY-3D.

64   Users viewed a 3D model of the Humber Estuary on top of box in a museum style space, and tidal

65   flows were calculated using the CAESAR-Lisflood code and animated within UNITY-3D. Users could

66   then simulate past and future scenarios by altering the base sea level giving them an idea of future

67   flood risk with rising sea levels. The scene was viewed using immersive VR via an Oculus Rift Developer

68   Kit 2 Head Mounted Display (HMD).

69   *Humber in a Box* proved a popular exhibit at events and festivals across the UK before becoming

70   obsolete in 2018. The experiences of what worked well provide a framework for a simple model to

71   design future SeriousGeoGames from – A SeriousGeoGame should look and feel like a video game and

72   exploit VR as the medium of interaction with the application. It should be optimised for use in a science

73   festival setting where interactions may be short, a few minutes at most, and turn over of users is high.

74   Fundamentally, a SeriousGeoGame should afford the user a first-hand experience of interacting with

75   research and therefore should feature research models and/or data at its core (Figure 2).

76   A successful SeriousGeoGame will achieve two objectives –

77   1. To create a positive experience for the user with scientists and the research topic (fun)

78   2. To increase interest for the user in the research topic (curiosity)

79   It is tempting to include a third objective, to try and increase the understanding of the research topic,

80   but from experience this is difficult to achieve/evaluate within the busy science festival setting. To use

81   an analogy borrowed from religious evangelism, the purpose is to 'plant a seed' with the user which

82   might 'germinate' with future interactions with science, scientists, or relevant practitioners in the

83   future. Whether the positive interaction does in fact plant this seed is a matter of trust and something

84   exhibitors will never be able to view come to light. When knowledge transfer does occur it will likely

85   not be through interaction with the SeriousGeoGame but through the interaction with the scientists

86   exhibiting it (Jensen and Buckley, 2014), and in particularly through a debrief with the user afterwards

87   (Crookall, 2010). Through this model it is feasible to engage people with both objectives without them

88   trying the SeriousGeoGame itself, for example, a child might be engaging with the SeriousGeoGame

89   whilst their parents are interacting with the scientist. Interaction with the activity is not limited to the

90   time and space of the science festival hall but supported by ancillary activities, such as websites, social

91   media, and videos.

92   With the model established, below we investigate each of the three elements – science festivals, video

93   games, and virtual reality – to see what advantages they give for meeting the two objectives.

94   1.2 Science Festivals

95   The science festival is a common feature of the public engagement with science landscape and for

96   many researchers the local annual science festival is likely one of their few interactions with members

97   of the public. The vibrant UK scene, for example, boasts 11 large annual science festivals which can

98   attract between 6,000 and 50,000 visitors (Jensen and Buckley, 2014), and the UK Science Festival

99   Network has 45 member festivals (Science Festivals Network UK, 2019). The US scene is also growing,

100   with the Science Festival Alliance growing from just four member festivals in 2009 to around two

101   dozen in 2012 (Durant, 2013), and in 2017 47 member festivals shared science and research with over

102   2 million members of the public (Science Festivals Alliance, 2018).

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

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

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

106   by scientists on contemporary issues, and workshops which take people into more detail. Many

107   festivals encourage more creative methods of engaging audiences, including café crawls, story-telling

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

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

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

111   a core method used to engage the public with the latest research (Jensen and Buckley, 2014). The true

112   power of Science Festivals is their ability to bring the public and scientists together, and the successful

113   engagements emerge from the conversations engendered (Jensen and Buckley, 2014).

114   Science Festivals could be described as niche in their nature, appealing to a small sub-set of the

115   population. In a 2011 MORI poll showing that only 3% of the UK population attended a Science Festival

116   in the previous year (Jensen and Buckley, 2014). A criticism of Science Festivals is that they only attract

117   those who are already 'science interested' who tend to be well-educated, meaning that there is little

118   socio-economic diversity (Bultitude, 2014). However, evaluations of events which have targeted

119   under-represented groups have seen the same success by facilitating interactions between scientists

120   and the public (Jensen and Buckley, 2014).

121   1.3 Video Games

122   Video gaming is big business, with retail sales of video games accounting for 51.3 % of the UK's

123   entertainment retail market (includes music, video and games), and worth £3.84bn (Entertainment

124   Retailers Association, 2018). It is forecast that there are 2.3 billion people using video games

125   worldwide, with a global market of US$137.9bn (Wijman, 2018). The popularity of videogames has

126   not gone unnoticed by educators, with dedicated educational versions available of popular games

127   such as Minecraft, Roblox, Assassin's Creed, and SimCity, and the educational games market is

128   expected to reach US$17bn by 2023 (Adkins, 2018).

129   Video games are powerful tools for engaging people with science as they provide a first-hand

130   experience which can inspire an emotional response (Mendler De Suarez et al., 2012; Squire, 2003;

131   Wu and Lee, 2015). In addition, games are fundamentally fun (Wu and Lee, 2015), and as such they

132   are naturally engaging and motivating for the user (Ryan et al., 2006). Video games are popular, with

133   64 % of US households owning a gaming device and an average of two gamers per household

134   (Entertainment Software Association, 2018).

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

136   for engaging people with complex issues such as Climate Change (Porter and Córdoba, 2009; Reason,

137   2007; Warburton, 2003). This has led to the development of 'serious games', games where learning is

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

139   2010), and there are several studies showing that serious games have been effective in delivering the

140   intended learning outcomes (Bellotti et al., 2013; Chin et al., 2009; Coleman et al., 1973; Connolly et

141   al., 2012; Gosen and Washbush, 2004; Mani et al., 2016; Mitchell and Savill-Smith, 2004; Vogel et al.,

142   2006; Wilson et al., 2009).

143   1.4 Virtual Reality

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

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

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

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

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

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

150   Rift, HTC Vive, and Playstation VR, that the technology has enabled mainstream use of VR.

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

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

153   immersivity and presence (the feeling of physically being in the virtual world) produce experiences

154   which are highly engaging allowing the user to focus more on the learning outcomes (Bricken and

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

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

157   internalisation to them (Clark, 1997; Weisberg and Newcombe, 2017). A particular advantage of VR is

158   that it can allow users to feel closer to otherwise abstract or distant ideas (Trope and Liberman, 2010),

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

160   ocean acidification and reported increase knowledge gain and interest in the subject as a

161   consequence.

162   **2.   Flooding from Intense Rainfall**

163

164   2.1 The Research Context

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

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

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

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

169 2019). The UK based and focussed programme brought together experts from several Universities,

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

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

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

173 2019). Thunderstorms, driven by strong convection in summer months, form and dissipate rapidly and

174 can be highly localised covering just 1-3 km wide. Despite good understanding and being able to

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

176 of when and where the storms themselves will form.

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

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

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

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

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

182 which influences model results to a much lesser extent to other sources, such as the rainfall input

183 (Flack et al., 2019). However, there are rare and extreme examples where flood events induce

184 significant geomorphic activity, with recent high-profile examples including Boscastle (2004),

185 Cockermouth (2009), Glenridding (2015), and Coverack (2017).

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

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

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

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

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

191 the behaviour of the river for several years. These flood events have been referred to previously as

192 threshold events (BULL, 1979; Chappell, 1983; Fryirs, 2016; Milan, 2012; Schumm, 1979).

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

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

195 climate in her medal winner address to British Society for Geomorphology in 2015 (Fryirs, 2016). The

196 concept can be summarised by the equation below –

197
$$River\ Sensitivity = \frac{\text{Recurrence of Threshold Events}}{\text{Time Required to Recover}}$$

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

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

200 which can be moved by the river. However, there exists a threshold magnitude of flood event which

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

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

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

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

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

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

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

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

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

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

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

212   2.2 The Research Data

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

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

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

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

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

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

219 which saw large geomorphic changes during the event (see Figure 3) and increased mobility of

220 material subsequently (Milan, 2012).

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

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

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

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

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

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

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

228 (TLS) in the summer of 2014. Although this survey was conducted 7 years after the flood the channel

229 had still yet to recover and largely reflected the immediate post-flood environment.

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

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

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

233 **3. Development**

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

235 games developers BetaJester using the Unity-3D gaming engine. There have been two iterations of

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

237 original version.

238 3.1 The original *Flash Flood!*

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

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

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

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

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

244   trees than in real life to help blur edges and create a more interesting 3D environment for the user to

245   explore.

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

247   GeForce GTX 970), which was labelled as "Oculus-ready", and the consumer model Oculus Rift. The

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

249   desktop-only version of the software to be released. Graphics were kept simple (see Figure 4) and the

250   representation of water kept to an animated plain which was angled down in the direction of the river

251   and would rise and fall given the impression of rising and falling water levels as it intersected the

252   landscape. Users explored the scene using the two joysticks on an Xbox controller and needed to use

253   no other buttons or d-pads.

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

255   user was free to explore the whole scene with movement restricted at the edges by hills or invisible

256   barriers. The flood animation timeline did not begin automatically and only started when the operator

257   pressed the P button on the keyboard.

258   The simulation moved along a 6 hour timeline which took 30 seconds per hour timestep, for a total of

259   3 minutes. It began at 15:00 and on-screen prompts described the scene at each step –

260   15:00 – "Clouds begin to gather"

261   16:00 - "A storm is brewing"

262   17:00 – "The storm intensifies"

263   18:00 – "Intense rainfall falls on the uplands of the river"

264   19:00 – "Rain water from the uplands swells the river level. A flash flood in coming!"

265   20:00 – "The flood has reached its peak"

266   21:00 – "The flood has receded leaving a scene of devastation"

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

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

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

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

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

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

273   flood, but it still required a respawning of the user resulting in some sudden, unrealistic changes.

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

275   version and narration was provided via a one-to-one interaction with an operator – usually a scientist

276   within a relevant research area, or a science communication generalist. This had the advantage of

277   being able to tailor the message based on the operator's research field and the age and responsiveness

278   of the user.

279   3.2 *Flash Flood! Vol.2*

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

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

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

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

284   – NVIDIA GeForce GTX 1070), with an aim of achieving a look and feel of a AAA-game. This was partly

285   in response to an increasing number of comments on the basic level of the original graphics and users

286   becoming more accustomed to ever more sophisticated VR experiences. Photo-realistic assets were

287   used for textures and 3D objects, and the scene was made wooded like the original to make a more

288   interesting scene. The transitions at the edges of the scene were significantly improved by removing

289 the hills and replacing these with an unexplorable extended landscape and hiding the edges using

290 stone bridges (see Figure 5). The basic horizontal plain of water was replaced by the more

291 sophisticated River Auto Material (R.A.M. by NATUREMANUFACTURE) asset, with customisation from

292 the developers for the representation of the flash flood showing a rapidly rising water level with debris

293 in the form of rocks and logs. *Vol.2* uses the same data and flood timeline as the original version.

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

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

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

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

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

299 demonstrations which could be achieved and size of exhibits which could be supported. To overcome

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

301 (voiced by Dr Chris Skinner) and Jess (voiced by Dr Jess Moloney) – defaulting to Jess. The two

302 narrations follow slightly different scripts with Chris's being more general and Jess's drawing more on

303 Dr Moloney's research into dating past flood events (Moloney et al., 2018). The choice of a single male

304 and female voice was a starting point and allows for an increased representation of voices with future

305 developments.

306   3.3 Ancillary developments

307 The two iterations of VR software are not the only developments relating to Flash Flood! nor is the

308 achievement of the two objectives limited to the time and space within the science festival hall. The

309 activity was promoted and supported by the SGG social media accounts (Facebook and Twitter) and

310 the SGG website. At times this was enhanced by support from the University of Hull Marketing and

311 Communication team, plus other colleagues at the University of Hull, other Universities (particularly

312 Reading and Newcastle), and the Natural Environment Research Council.

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

314   descriptions of the event, links to the SGG website and social media accounts, and an activity which

315   could be done alongside the simulation. The intention was to mimic the taking of field notes

316   performed by geomorphologists, before and after the flood. At events the handout was given out

317   along with a "I survived the Flash Flood!" badge and was also free to take from the table. It was also

318   used for those waiting to have a turn on the simulation or watching others to occupy them and was

319   used with a clipboard and pencil to fit the fieldwork image.

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

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

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

323   the software but were unable to due to networking restrictions on school machines – in response a

324   360 video version was produced and made available via YouTube. This version allowed headtracking

325   but not free movement. It included sound and two versions were available, one with narration and

326   one without. To support both the desktop and 360 versions a manual was produced, and articles

327   aimed at students and teachers published (Skinner, 2018; Skinner and Milan, 2018).

328   **4.   Evaluation**

329   4.1 Objective 1 – Fun

330   Through demonstration of *Flash Flood!* at events it is obvious that most participants enjoy the activity.

331   Verbal feedback has included words describing the activity as "epic" or "sick", both meant as a

332   positive. The most common word received as feedback has been "weird" most often delivered with a

333   smile on their face – it is obvious that it is meant as a positive, that the uncanny experience of

334   immersion in a virtual world is exciting, yet out of the ordinary.

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

336   NERC Into the blue comments under the "Things I loved about Into the blue" included "the gogls"

337 (Goggles = VR headset) and "flash flood", and under "Things I learned at Into the blue" was "Rivers

338 are fantastic!". Into the blue also ran a public vote for most popular stand, for which *Flash Flood!* was

339 awarded joint-3rd out of 40 exhibits and events.

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

341 exhibits. Mostly these are to do with issues relating to VR, for example it makes them feel dizzy or

342 nauseous, or simply that they did not like it. Other comments have been around dissatisfaction with

343 the graphics of the game or wanting more game-like objectives. On this latter point, "What am I

344 supposed to do?" is a common question at the start of demonstrations.

345 In conversation, it is often commonly asked of participants what they might like to see included in

346 *Flash Flood!*. Common suggestions include better graphics, being able to explore a wider space, or

347 wildlife such as sheep, wolves, bears, or dinosaurs. Others would like more game like elements like

348 something to shoot, such as zombies (see Curtin, 2017). With *Vol.2* where more sets available to do

349 multiple simultaneous demos, several have commented that they would like to have them linked and

350 being able to explore the scene together with their friends.

351 At the 2018 Hull Science Festival, at the University of Hull, *Vol.2* was used as part of an Earth Arcade.

352 The Earth Arcade is a room of game-like activities all designed to communicate key global

353 environmental issues in a non-intrusive way. The games range in style and complexity so that a family

354 audience can engage with it effectively. Games included were –

355 • *Flash Flood! Vol. 2* – five sets

356 • *Plastic Fishing* – a game aimed at pre-school children using magnetic fish to highlight ocean

357 pollution and plastic waste (see seriousgeo.games/eartharcade/eartharcade_9)

358 • *Flood City: Hull* – A PowerPoint game showing the impacts of sea level rise on coastal flooding

359 in a city

360 • *River in a Box* – An EmRiver stream table (see seriousgeo.games/eartharcade/eartharcade_3)

361 • A table with relevant Top Trump cards and colouring pens and paper (

362

363   The Earth Arcade was situated in its own space, like a mini-festival within the festival, and this space

364   was used to provide evaluation boards for participants to leave comments with four questions offered

365   –

366   1. What did you enjoy?

367   2. What did you learn?

368   3. What will you do?

369   4. What would you like to see?

370   In total 69 responses were posted on the board, 42 of which related to *Flash Flood!,* either directly or

371   using an appropriately descriptive term (such as Virtual Reality) or as part of the whole Earth Arcade

372   exhibit. Figure 6 shows the division of these 42 responses.

373   The majority of the responses were describing what they liked, with all answers positive. 26 of the

374   responses were generic, for example "The flud computers" or "I enjoyed everything", whilst 9 were

375   more descriptive in what they enjoyed –

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

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

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

379   "It felt real"

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

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

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

383   "hid in the chrees"

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

385   The only negative comment received was under "What would you like to see?" and stated "I liked it

386   mostly apart from the graphics". Other comments in that section were –

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

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

389   "2 very excited boys on the flood VR. Suggestions: Allow bridge access? Gurgling voices if in the

390   riverbed when the flash flood arrives?"

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

392   "I lerned about floods"

393   "I learn a lot about flash floods"

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

395   "I learnt about what happens during flash floods"

396   4.1 Objective 2 - Curiosity

397   To fulfil the first objective, it is important to keep interactions between the public and scientists as

398   informal and as natural as possible, avoiding anything which might be intrusive to this. Therefore, in a

399   science festival setting methods of formally and quantitatively assessing the publics' response, for

400   example using questionnaires, is not appropriate nor helpful. This is especially true when considering

401   individual exhibits within a festival hall where each exhibit may wish to conduct their own evaluations

402   – this would become tiresome for the public who only wish to have fun, exciting, and interesting

403   engagements.

404   To assess the success of *Flash Flood!,* and other SeriousGeoGames, against Objective 2 users are

405   signposted to online media relating to SGG. Figure 7 shows the total views for the SGG website and

406   YouTube channel, with each accumulating a remarkably similar total since September 2015, and both

407   have been growing at a similar rate of around 200 views per month since the beginning of 2018.

408 There are three *Flash Flood!* related videos on the SGG YouTube channel (out of a total of 51 videos)

409 – a preview demo for the original version, and the two 360 versions. The growth of aggregated views

410 for all these videos is also shown in Figure 7. As a share of overall views on the SeriousGeoGames

411 channel, the *Flash Flood!* videos has gradually been increasing and currently accounts for around 40

412 % of the total views, and 56.4 % of those are for narrated 360 video alone.

413 Figure 8 shows the monthly views for 2017. There was very little activity on either the website or

414 YouTube channel in January and February but increased during March. The activity in March can be

415 attributed to a feature on *Flash Flood!* in NERC's Planet Earth Magazine (Skinner, 2017), and the

416 promotion of the Hull Science Festival on 2nd April 2017 where SGG ran a featured exhibit. March 2017

417 saw the most monthly views for the SGGs website in the record (405) and best performing month in

418 the record for the YouTube channel was April 2017 (677). Many of these views were from a series of

419 360 videos from an undergraduate field trip, uploaded in March but used as part of the Hull Science

420 Festival exhibit and thus accumulating a steady number of views. A series of 360 videos covering the

421 European Geoscience Union's General Assembly was also released that month and attracted many

422 views. The narrated *Flash Flood!* 360 video was released on the 11th April and was the most viewed

423 video that month with 142.

424 The NERC UnEarthed Science Showcase took place on 17-19 November 2017 and attracted over 5250

425 visitors. In the week preceding the event the narrated 360 video was viewed 50 times, was viewed 6

426 times during the event, and 42 times in the week after. In November the Flash Flood! videos had a

427 total of 215 views, 81.1 % of the total YouTube channel views. The UnEarthed exhibit also featured

428 the *Humber in a Box* game – the demo video on the channel for this game received 32 views, so in all

429 93.2 % of all video views in November 2017 were related to the UnEarthed exhibit.

5. Discussion

431 The SeriousGeoGame *Flash Flood!* has been a success at meeting Objective 1 - to create a positive

432 experience for the user with scientists and the research topic. Most interactions have been positive

433   and when users have provided feedback this has also been overwhelmingly positive. When users have

434   been asked what they thought of *Flash Flood!* most have opted to share how much they enjoyed it

435   over providing feedback on what they learned or how they'd like to see it improved – for example, In

436   Figure 6, of 42 comments on *Flash Flood!,* 35 were about enjoyment.

437   The success against Objective 2 - to increase interest for the user in the research topic - is more difficult

438   to evaluate as this manifests after the interaction with *Flash Flood!*. The increase in interest relating

439   to the exhibits has been gauged using the analytics available through the SGG website and YouTube

440   channel to observe changes in traffic over time. It is not possible to determine the source of this traffic

441   (i.e., is it from the public or other academics) or the motivation for the online interaction. Over the

442   course of the SGG project there has been a steady growth in the number of overall views of the

443   website and YouTube channel – in regards to the YouTube channel, the Flash Flood! related videos

444   are increasingly driving this growth and the proportion of views relating to the three videos over the

445   other 48, growing from 20 % at the start of 2017 to 39 % by the end of 2018.

446   The NERC UnEarthed event of November 2017 presented the best opportunity to evaluate the impact

447   of an individual event in driving traffic towards these sources as there were no other events or

448   activities that month. As 93 % of all YouTube views for that month were related to the exhibit, this

449   suggests that it was successful in achieving Objective 2. For *Flash Flood!* itself, the videos received 215

450   views in November 2017, the most of any month on record and more than double the views of the

451   months before and after. Views of the SGG website were also higher than the months before and

452   after. Breaking this down there were more views of the narrated *Flash Flood!* 360 video in the 7 days

453   prior to the event than there were during the event and 7 days after, meaning that much of the

454   internet traffic is driven by promotion of the event (via sharing YouTube links on the Twitter account)

455   rather than in response to visiting the exhibit – as the majority of SGG's Twitter audience are scientists,

456   science communicators, or educators, it is possible that the increased traffic emerges from within the

457   industry and not from the target public audience.

458   In terms of the SeriousGeoGames model, all the elements have proven useful. Science festivals have

459   proven an effective way to engage large amounts of people in a short space of time, and when

460   researchers of all levels are under time pressure from several demands this has proven and efficient

461   way to conduct engagement activities. The public who attend the events clearly find them an

462   overwhelmingly positive experience even when they were not of the traditional socio-economic

463   groups associated with science festival attendance. For example, the NERC UnEarthed event was held

464   in the Dynamic Earth centre in Edinburgh which normally requires an entry fee – the organisers

465   arranged a waiver for this for the duration of the festival and many of comments received were from

466   parents stating how much they appreciated this as they had not previously been able to visit the centre

467   because of the entrance fee.

468   The video game element is the least developed of the three and consequently the one which receives

469   the most specific feedback. In the main this is because of limitations in the application and the desire

470   to have more freedom or an objective to achieve, and this can cause confusion in some who are

471   expecting a more developed game-like experience. This should be viewed as a huge opportunity for

472   further development – there is a strong desire for audiences of science festivals for game-like exhibits

473   (not just video games), especially where there is a competitive element, and these are currently

474   underrepresented. However, the game-like appearance and feel of *Flash Flood!* is viewed as a positive

475   by almost all users, and even the sight of an Xbox control pad within the science festival hall sparks

476   excitement in some members of the audience.

477   Since the inception of SGG, the use of VR has been a draw for the exhibits - as soon as one person is

478   seated and wearing the HMD, looking off in different directions, a crowd soon gathers to see what is

479   going on. The curiosity and novelty invoked by VR has proven successful in attracting people to interact

480   with the exhibit and scientists. As VR has developed and become more mainstream over the years this

481   has changed, but not diminished. *Flash Flood!* was often the only VR exhibit at events when first

482   produced but now is often one of several, however as the hardware is relatively cheap compared to

483   development costs, it often remains the only bespoke piece software as opposed to video demos or

484   360 photographs/videos. Comments have shifted from "I've never used VR before" to "my friend has

485   one of these", but the enthusiasm to try it is still high.

486   The use of real research data adds value to *Flash Flood!* and users are interested to find out that 3D

487   environment is built from data collected in a real river, and the flood based on a real event. This is

488   usually followed by questions about where the river is and when it happened and provides a useful

489   conversation starter to discuss the issues around flash flooding and forecasting these types of events.

490   We have also received comments from the public saying how pleased they were we were exhibiting

491   something based on real, ongoing research, and not demonstrating basic scientific principles and

492   experiments.

493   However, the most important element of any *Flash Flood!* exhibit is the team of scientists which

494   interact with the public, sharing their enthusiasm for science and their research expertise. It is

495   especially successful when their research aligns with the exhibit, but this is not vital – many of the

496   interactions take place beyond the application itself so it is possible for the scientists to share their

497   own personal research interests without impacting negatively on the objectives. Users particularly

498   enjoy interacting with either Chris or Jess who provided the voice overs for *Flash Flood! Vol.2* and are

499   often surprised they are real people who are scientists in real life.

500   A criticism of the SeriousGeoGames model presented is that the objectives are possibly too narrow or

501   unambitious. There is scope within *Flash Flood!* for it to be used to increase the understanding of the

502   research topic, or even to change behaviours of the public, such as encouraging them to sign up for

503   automatic flood warning alerts. Delivering and evaluating these objectives within a festival setting,

504   without having a negative impact on the original objectives, is likely not feasible and more suited to a

505   less busy and longer interaction in workshops or classrooms and this has been explored using the

506   desktop and 360 version. *Flash Flood!* has also been used in workshops and has also been reported as

507   being used in school lessons even though it was not conceived or designed for this use. The efficacy

508   of the application in this context has not yet been explored and is beyond the scope of this study.

509   **6. Conclusion**

510   The *Flash Flood!* application is game-based, built around real research data, and has been used to

511   engage thousands of people at science festivals and events. There have been numerous versions of

512   the application across different platforms, including desktop, 360 YouTube videos, and utilising VR.

513   *Flash Flood!* has demonstrated that the SeriousGeoGame model - utilising elements of science

514   festivals, video games, and virtual reality, to produce game-like applications built around a core of real

515   research models and/or data – has had success at achieving the first objective of producing a positive

516   experience for the user. However, although there is evidence that it is successful against the second

517   objective, to increase the user's interest in the research topic, this has proven more difficult to

518   evaluate effectively. There remains great potential to develop *Flash Flood!* and other

519   SeriousGeoGames, particularly using the video games elements and use outside of science festivals to

520   achieve more ambitious objectives.

521   **Data Availability**

522   The data used in this study can be made available on request by emailing the corresponding author.

523   Game files for *Flash Flood!* can be found at https://sourceforge.net/projects/flash-flood/

524   **Ethics Statement**

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

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

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

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

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

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

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

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

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

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

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550

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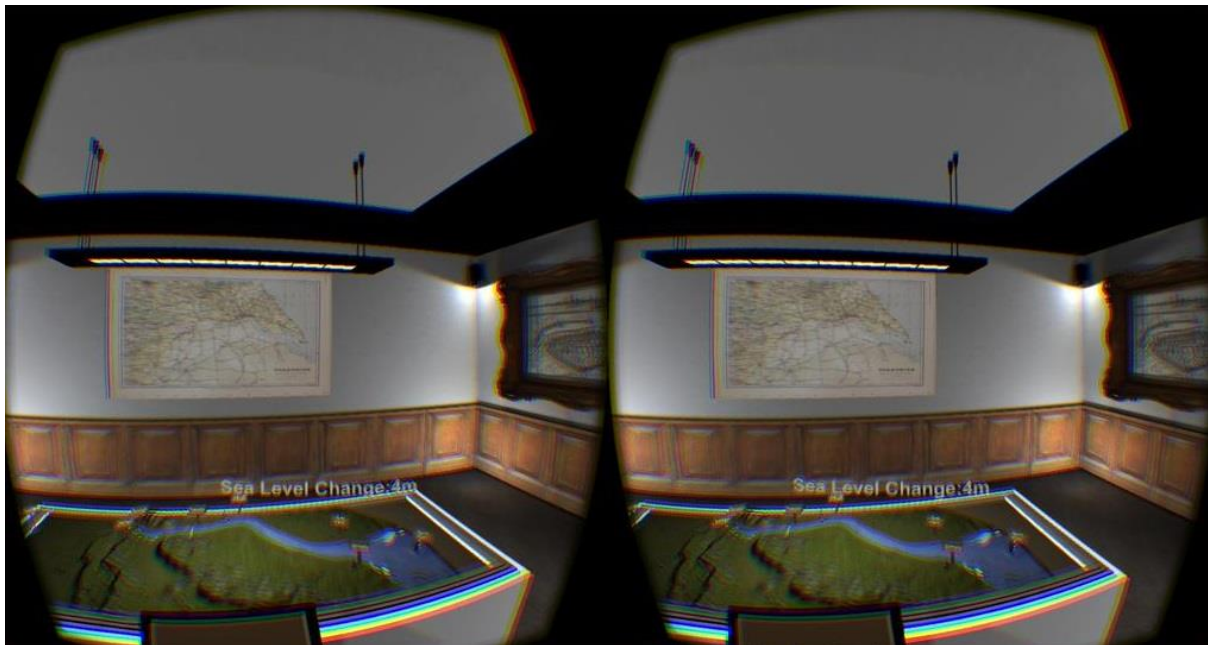
748   **Figures**

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

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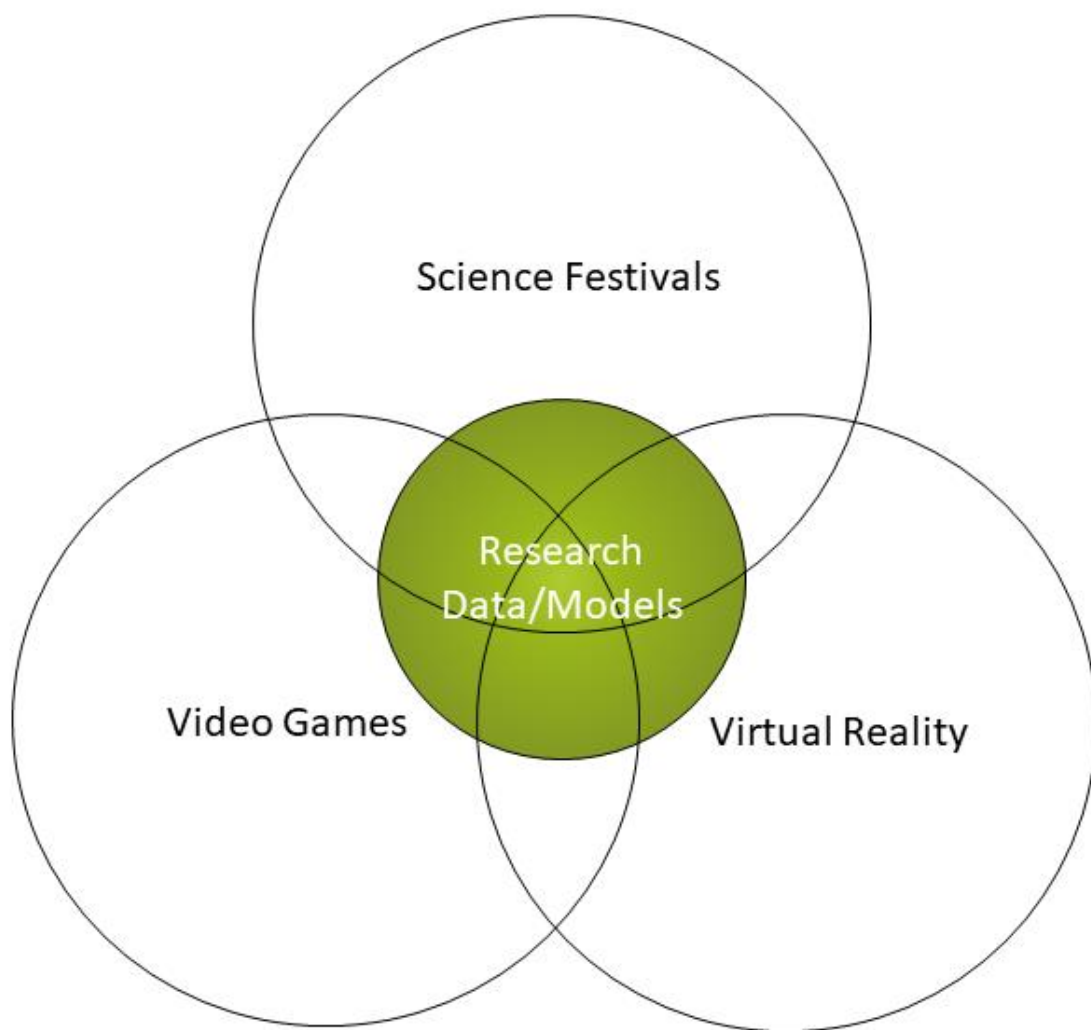

752 **Figure 2 – Venn diagram showing the SeriousGeoGame model – a true SeriousGeoGame would be**

753 **positioned in the middle of the diagram, built with research data and/or models, and using elements**

754 **from science festivals, videos games, and virtual reality.**

755

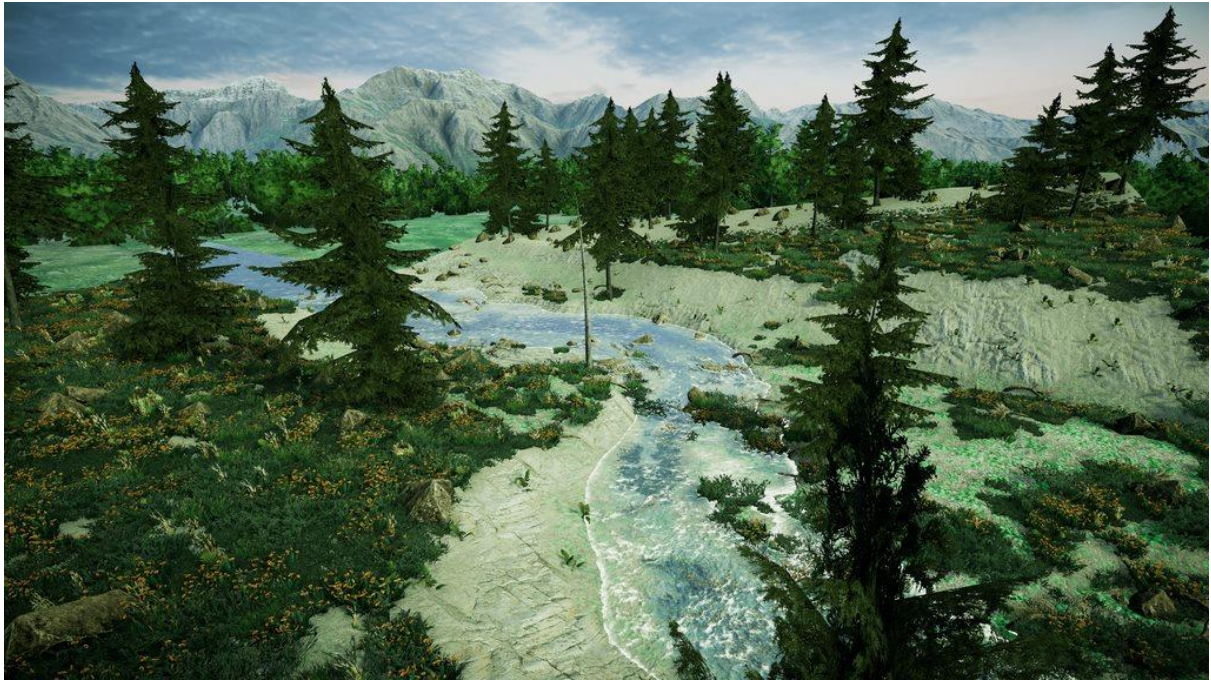
756

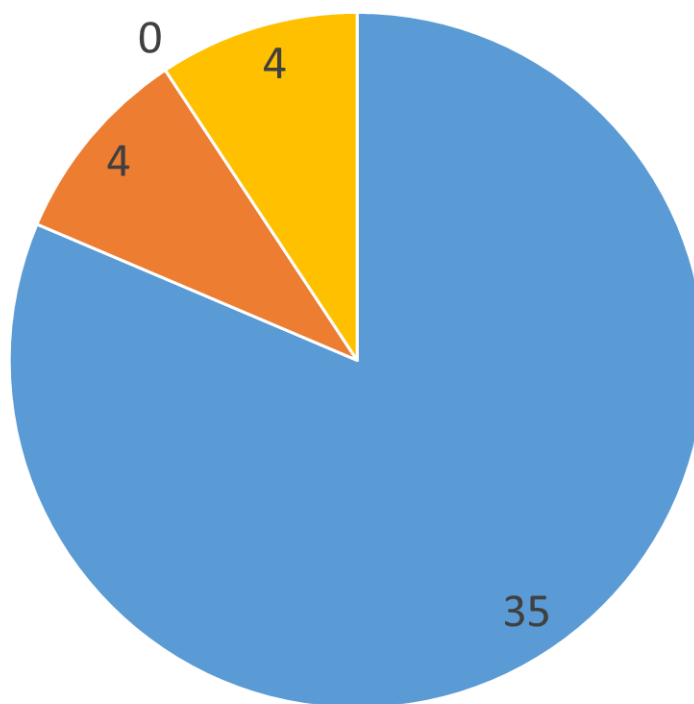
757   **Figure 3 – Google Earth images showing the reach section surveyed and used for *Flash Flood!*. The**

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

759   **after the flood in 2007 (Google Earth, 2019b).**

760

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

762

763   **Figure 5 – Screenshot from *Flash Flood! Vol.2*.**

What did you like?
What did you learn?
What will you do?
What would you like to see?

764

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

766

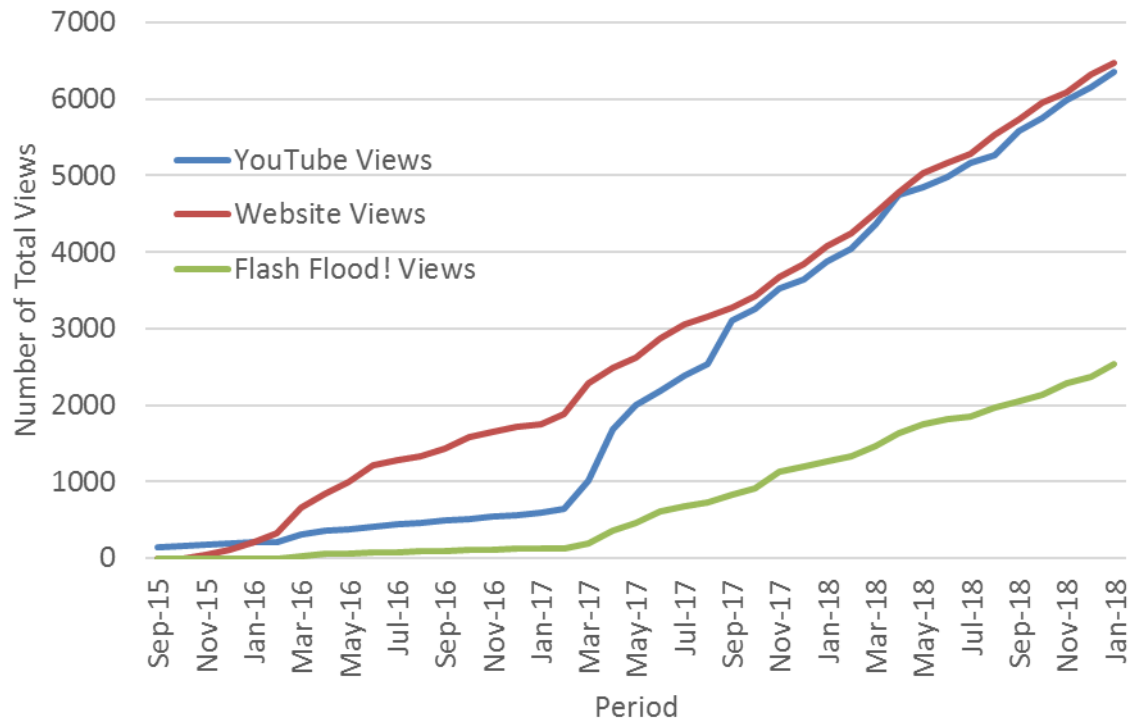



Figure 7 – Aggregated total YouTube and Website views for SeriousGeoGames since September

2015 to January 2019. Also shown are the total views for all *Flash Flood!* related YouTube content.

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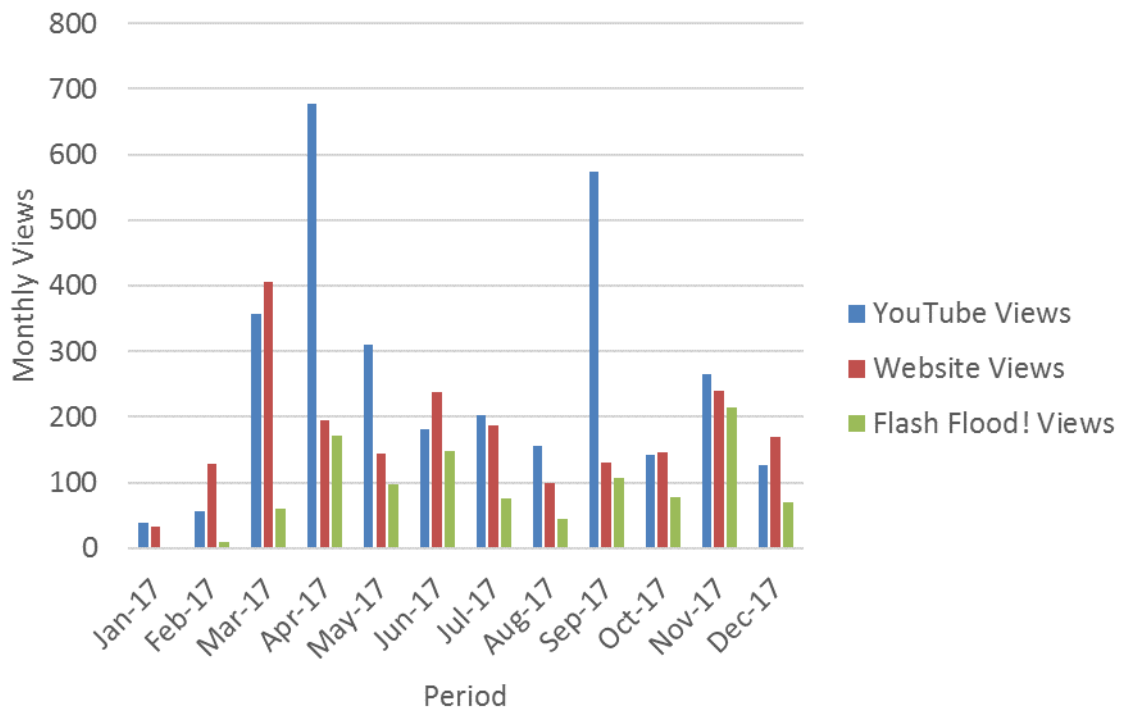
772   **Figure 8 – Monthly views for the SeriousGeoGames website, YouTube channel, and the Flash Flood!**

773   **videos for 2017.**

774