Response to Referees

General Response after Major Revisions

I would like to thank both Referees for helpful and insightful comments. These have helped to significantly improve the revised manuscript submitted for further review.

In response to both Referees' comments, I have completed a more detailed and formal evaluation of the activity at two events. This evaluation used a questionnaire via the Formstack app using iPads. I have clarified where information is anecdotal, and whilst some of this information is still included it has been made less prominent and not used to make the conclusions of the study. As a consequence the revised manuscript is substantially different to the original.

In terms of how I originally proposed to revise the manuscript, I have not included a detailed literature review of activity, exhibit, and event level evaluations – on reflection I consider that this would be best as a separate piece of work as the revised manuscript would not benefit from additional length. There is a short summary of evaluation methods and why the chosen method was selected.

I have added greater clarification of the SeriousGeoGames model, making it clear that choices made were design decisions based off anecdotal information.

I have increased explanation of gaming terminology used.

I have provided better explanation and increased evidence behind findings.

Individual responses and by line changes are detailed below –

Referee 1 – Laura Hobbs

General comments I really enjoyed reading this; it's an important contribution to a field that it can be difficult to get work published in due to the constraints of data collection, and it also makes some very important points about that. It is also important to consider that when discussing results and explain how conclusions have been drawn in the light of sometimes limited data. For example, more presentation and discussion of observational and quantified data from event feedback are needed to support statements made - this would be interesting to see. At the moment I'm wondering what the evidence is behind some of the findings, and about the finer details of how evaluation data were collected and analysed. This is research in its own right; some work is probably needed to pull that information together (or, perhaps, rephrase some of the text so that some elements are more suggestions than assertions). Some of the gaming terminology in particular needs to be made more accessible to those without the relevant background technical knowledge or interest, as it's entirely possible that readers may be interested in using games for communication, but not themselves be gamers.

However, the description of the game and it's development use are valuable in their own right and are rightly a strong focus of the paper. It's great to see work in this field and I'll look forward to reading (and citing, I'm sure) the final paper. Specific comments and technical corrections - please see attached pdf.

Thank you, Laura. I enjoyed reading your comments and I think the manuscript has benefitted from your experience in this field. I consider I have addressed your comments above in the revised manuscript. Responses to your in-line comments are made below -

Line 12 - What do you mean by best components? For what purpose, and in whose view?

This was a design choice. Have edited to "Here, a new design model is presented to engage the public with specific research projects by using useful components offered by the popular mediums of games,

virtual reality, and science festivals, to allow the public to get 'hands on' with research data and models – SeriousGeoGames."

Line 28 - This is really interesting, and a great way to make your point. There could be more exploration here here about why people are more engaged with risks from zombies than flooding.

I agree but is beyond the scope of this study. I am currently working on a project that is looking into this and the implications for public engagement.

Line 31 - Why? What takes precedence?

Have removed this comment.

Line 42 - This clause doesn't make sense - should it be WITH the science being well reported?

Have rephrased this section – "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)."

Line 47 - This feels like it could have a citation.

Have removed this section.

Line 52 - There needs to be a brief explanation of VR here (and that you're referring to immersive VR), and perhaps a note that it will be described in more detail later.

Have included – "VR generally uses two screens held within a headset (Head Mounted Display or HMD) so that each eye can only see one screen, with each showing a three-dimensional (3D) scene at a different angle to produce the illusion of depth and immersing the user in a different and artificial environment."

Line 64 - Not everyone will understand what this means; it merits an explanation, even if just briefly in parentheses.

Have edited to - "with a software package used by games developers to create games and virtual environments (known as a gaming engine) – UNITY-3D"

Line 68 - Not everyone will know what an Oculus Rift is.

Have edited to – "The scene was viewed using immersive VR via an Oculus Rift Developer Kit 2 model of HMD"

Line 69 - Why did it become obsolete?

Have removed this reference – basically we lost the original development files and cannot update it to new equipment and drivers.

Line 75 - Is this essential? If so, why? What is the evidence that you've drawn on to come to this conclusion? Were there other models with different features for comparison?

Have included – "The SeriousGeoGame model is one of design choices and considers that they will be predominantly used within a science festival setting where interactions may be short, a few minutes at most, and turn-over of users is high."

Line 78 - What do you mean here? Detailed datasets, or broader (but not basic) links to research? It's possible to engage people and spark interest in research using broader links, so if its the former, why, and how do you know?

Have included – "Crucially, they should provide people a first-hand interaction with elements of the ongoing research, such as incorporating field data or numerical modelling codes."

Line 86 - Absolutely. This paragraph makes a very important point that often gets lost when considering analysis of these projects, which can present difficulties in publishing. This recognition of the value of planting that seed is hugely valuable too.

Thank you – this is a key point for the manuscript and justifies the choice of the two objectives.

Line 142 - In the case of Minecraft at least, there are analogies to real world settings and processes too - not to try and engineer a link to our work, but there may be some useful references for background information in these: https://jcom.sissa.it/archive/18/02/JCOM_1802_2019_N01, https://www.bgci.org/files/Worldwide/Education/Roots_PDFs/Roots15.1(med).pdf (pp. 20-23), https://eos.org/wp-content/uploads/2018/10/Nov-18_magazine.pdf?x64125 (pp. 25-29).

Thank you, have added – "Serious games can be used to create virtual analogies of real world places or physical phenomena for public engagement, such as volcanism (Hobbs et al., 2018, 2019; Mani et al., 2016)."

Line 168 - Great description - it'd be useful to have mention here of the difficulties that some people have with VR experiences.

Have added – "VR is not without its limitations. Cost remains a considerable barrier to its uptake and use, with popular HMDs costing several hundred GBP (for example, Oculus Rift S ~£400, VIVE Pro ~£800) and requiring a gaming specification PC to run. The use of VR can also induce a nausea or dizziness (sometimes called cybersickness), similar to motion sickness, and can also cause headaches and eyestrain (Rebenitsch and Owen, 2016). In one test, seated participants using the Oculus Rift HMD for less than 15 minutes reported a 22% occurrence of cybersickness (Munafo et al., 2017)."

Line 231 (Figure 3) - This needs a brief outline of the changes visible, for those who aren't used to identifying them.

Have added in text and in Figure description – "The flood has cut meanders resulting in a straighter channel, stripped out vegetation, and deposited loose sediment on the flood plain (the lighter colour in the right-hand image)."

Line 262 - It'd be good to explain why here.

Have edited to – "The application was optimised to a lower standard than the equipment specification afforded to allow a desktop-only version of the software to be released. For example, the graphics were kept simple (see Figure 3) and the representation of water kept to an animated plain that was angled down in the direction of the river and would rise and fall giving the impression of rising and falling water levels as it intersected the landscape."

Line 277 – is

Edited

Line 297 - Not everyone is going to understand the AAA terminology - it either needs explaining or a different, more generic term (higher-end, maybe).

Have added – “AAA-game (games produced by large gaming companies intended for the global commercial market).”

Line 307 (Figure 5) - I can't see Figure 5

Have included the figure!

Line 315 - Why?

Have edited to – “As video gaming is often perceived as a male space with women and girls feeling excluded or discriminated against (for example, Delamere and Shaw, 2008), it was decided the choice of narrator would default to Jess so that participants would encounter a female scientist first.”

Line 331 - So it wasn't necessary to use the simulation in order to be able to use the handout?

Have edited to include – “The intention was to mimic the taking of field notes performed by geomorphologists, before and after the flood, particularly for use with the desktop and YouTube versions of Flash Flood! outside of events (it was also available as a PDF download).”

Line 344 - How? To be able to draw the conclusions made, there needs to be more information given about the observational data collected.

This is from informal conversations and now falls under the Anecdotal information sub-section within the Results section.

Line 352 - How many people voted, and how many votes did the stand get?

This information is not available.

Line 356 - Do you have any quantification of positive vs. negative comments?

No, this was from informal conversations. However, positive by far outweighed negative, but obviously my perception may be positively biased and/or participants may just be giving me a response they think I want.

Line 371 - So is this counted as an SGG too? If so, how does that fit with the criterion of using VR? (Or if that's not an essential criterion, that needs to be made clearer in the text).

This section has been removed.

Line 375 - Extra (

Line 386 - How many attendees were there?

This section has been heavily edited, but included – “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.”

Line 386 - Were these whole comments, or individual elements which may have occurred within one piece of feedback left by a single attendee?

Whole comments, although this section has been removed.

Line 389 - They're being asked to give a positive repsonse, so you would expect positive answers here. It'd be interesting to see some more quantified content analysis here, although the data may be too limited for this to be analysed in depth.

This is true so have moved this evaluation into the Anecdotal information sub-section and not included it as part of the formal evaluation.

Line 413 - Yes, absolutely - can't stress the content of this paragraph enough.

I totally agree but due to the manuscript revisions I have removed this paragraph…

Line 455 - There needs to be more elaboration on what was collected here and what it contained. What observational information was collected? How many events were these data collected at - were there more than those described here, which the text seems to imply? Is there any quantification to support that it was overwhelmingly positive?

This has been removed in revised manuscript.

Line 457 - How much privacy/anonymity did people have when giving this feedback - could this have affected the results?

This was considered with the new evaluations – "Participants were orally referred to the questionnaires by exhibit crew after finishing their turn on Flash Flood! Vol.2. Completion was voluntary and participants were not observed whilst completing it."

Line 458 - This should be drawn together above, in the evaluation section - and also discussed with the caveat that participants were asked questions that framed responses in a positive way - they weren't asked what they didn't like, or given a completely open choice on what to give feedback on.

This has been removed.

Line 481 - How many?

This has been removed.

Line 487 - Comments to the event organisers, or at the stands?

Have removed these reflections. These comments were made to the crew of our stand.

Line 491 - Is the video game element likely to be the most familiar of the three to attendees - and how does this intersect with how able they feel to make comments?

This is likely to be true and the additional evaluations did see many comments on the video gaming element. I think a more granular evaluation would be required to make this conclusion and beyond the scope of this study.

Line 497 - This is important - the efficacy of gaming in drawing people in (the same happens if they get a glimpse of Minecraft!).

This was an anecdotal reflection and has been removed.

Line 522 - Is this an actual existing criticism, or a potential one?

Have removed this section.

Line 527 - Definitely.

Line 530 - Absolutely - it's a paper in its own right (I'd like to read it though if you ever get the data). Hoping to one day do this.

This would be important work and something I hope to do also.

Line 533 - How many? Thousands is a bit too vague! It would also help to know for comparison of your sample size for feedback collection.

I don't have numbers. Have removed this comment.

Referee 2 – Anonymous

This paper presents an intriguing idea around creating a visualization of a flood using VR to represent an often overlooked aspect of flood risk, to engage with participants of a science festival through encouraging their curiosity and sense of fun. It is a well written paper that describes the process of designing the game and testing it in a science festival scenario, however despite the interesting concept there are a couple of flaws I would like to see addressed before publication.

Firstly I think there is scope to improve the literature section, both in terms of quantity and source. Additionally I would like to see more description of how this simulation operates as a game, as it appeared from the descriptions to be more of a visualization? It would be great to get more information here. The figures could do with a bit of refining (particularly the graphs) as although they presented interesting ideas I found them to be a bit confusing. In particular the presentation of the 'model' which I thought needs to be far clearer. With a little work, the visualization of a model would be really useful in this paper to help the reader understand the main premise.

My greatest concern, however, was with the evaluation. Although the author stated that science festivals are not conducive to evaluation, that is not actually the case if the appropriate evaluation method is chosen beforehand and designed carefully into the activity. For a really good example please see the works of Sardo and Grand (Science in Culture: Audiences Perspectives Engaging with Science at a Summer Festival, 2016 and What Works in the Field? Evaluating Informal Science Events, 2017). Even if you wold prefer not to evaluate in a science festival, it is still possible to evaluate this game in other environments specifically designed for evaluation, which would provide a much more empirical as opposed to anecdotal data-set.

Having said that, I do think the idea and the effort that have gone into the game design are worthy of publication, but I think some more robust evaluation of the game needs to be done before that can happen. When that happens I look forward to reading the results!

I'd like to thank the anonymous Referee for their comments and suggestions. They have raised several valid points which I have addressed in the General Comments above. In particular, they raised important points regarding evaluation that I would be keen to further explore in future work.

I have made further responses to the line by line comments below –

Line 46 - This needs a reference.

This refers to the opening statement regarding plans for zombie apocalypses and flooding.

Line 48 - I am not sure I am comfortable with using a blog post as a reference here.

This isn't a blog post, it's a commentary article published in the journal Earth Surface Processes and Landforms - doi:10.1002/esp.4129

Line 55 - What about section one?

Have edited to – “The rest of Section 1 highlights the proposed SeriousGeoGame model of combing elements of VR and video gaming with elements from research projects, such as field data or numerical modelling codes. In Section 2, the specific research context for *Flash Flood!* is described, followed by a description of the development of the application in Section 3. Section 4 details the evaluation methods and the events where the application was tested. The results of the evaluation is shown in Section 5, and discussed in Section 6, before conclusions are presented in Section 7.”

Line 58 - 'conclusions -are presented- in Section 6'

As above.

Line 70 - Why did it become obsolete?

Have removed this comment.

Line 70 - How were these data collected?

Have edited to make it clear this is anecdotal information – “Humber in a Box proved a popular exhibit at events and festivals across the UK and the anecdotal experiences of what worked well provide a framework for a simple model to design future SeriousGeoGames from.”

Line 70 - I don't know what model you are referring to here - clarification would help me understand this section.

Have added – “The SeriousGeoGame model is one of design choices and considers that they will be predominantly used within a science festival setting where interactions may be short, a few minutes at most, and turn-over of users is high.”

Line 72 - Why is this the case? Where is the data or literature to support this assumption?

As above – have clarified that these are design choices based from anecdotal information.

Line 75 - How does the game design interact with the learning objectives and the evaluation design?

Have added – “They should look and feel like video games even if they do not qualify as games themselves.” – to make it clear that the activities do not have to be games.

Line 75 (Figure 2) - This is a very confusing diagram. Firstly it is not how a Venn diagram works as the circle with the research data/models covers several of the intersections, which also have no additional detail in them. What is the cross over between video games and science festivals? What about video games and virtual reality? It feels like this would be a great place to put a reflection on the literature and theory of this study, what are the learning objectives, or methodology for example, but the image certainty needs work. Additionally what do you mean by research data/models? Those are very different things.

Have removed this diagram as it was not helpful.

Line 84 - This is a challenge, however in this sentence I would refer to studies which demonstrate the difficulties of doing longitudinal studies on attitudes and behaviour change. If you struggle to find examples from informal science communication and education environments there are plenty of examples from formal environments.

I have not included this here as it does not refer to attitudes or behaviour changes specifically, although I appreciate there is similarity.

Line 87 - I am still confused by the model.

Have added – “It is important to emphasise that the SeriousGeoGames model has been constructed through design choices and anecdotal experiences of previous activities and events. It incorporates three key elements – science festivals, video games, and virtual reality – that can help to achieve the two objectives.”

Line 89 - So are you measuring the objectives of the VR as a tool itself or as a facilitation for engagement with scientists? These are different things.

Have removed this reference and address this in the revised discussion – “A major development between the original Flash Flood! and the Flash Flood! Vol.2 that was used for the formal evaluation was the inclusion of a voice over track. This helps to engage more participants at one time as it no longer requires a one-to-one interaction with a crew member. It also reduced the resource needed to crew exhibits as it reduced the level of fatigue within the crew. However, it also limited the conversations between participants and crews that are where the most positive science engagements occur (Jensen and Buckley, 2014; Wiehe, 2014). For events like SSEW, with large school groups in attendance, where the volume of participants makes such interactions difficult, Flash Flood! Vol.2 seemed particularly suited. At family-orientated events like the BSG Open Day, interactions are more relaxed and the activity could benefit from additional follow-on interactions providing additional information on flooding, geomorphology, and how the 3D scene was constructed (akin to the debrief of Crookall, 2010). In this, Flash Flood! Vol.2 shows potential for use in facilitating more in depth interactions between the public and scientists at appropriate events.”

Line 97 - This needs clarification - I think what you mean is about formally supported face-to-face interactions with the public to discuss their research, as science communication happens in many environments often informally, and you are also missing the huge interactions researchers have through social media and other platforms.

Agreed, have removed this comment.

Line 98 - Are there any more up to date figures? A lot has changed in 5 years.

Have edited – “The vibrant UK Science Festival Network boasts 50 festival members, who in 2018 ran 4018 events, featuring 10,941 scientists, and achieved 1,225,779 face-to-face interactions (Woolman, 2019).”

Line 113 - 'that'

Changed

Line 116 - I would expect an Ipsos MORI ref here for their own data?

The original data is no longer available, have edited – “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).”

Line 123 - 'including'

Changed

Line 134 - Is there no UK data for this? Cultural differences can be significant.

Have edited to – “Video games are popular, with 28% of UK households owning a gaming console (BARB, 2019), and 36% for US households (Entertainment Software Association, 2018). These figures do not count PCs, smartphones, or tablets that are used for gaming, which increases the figure to 64% in the US (Entertainment Software Association, 2018).”

Line 146 - Explain this term?

This term is defined earlier in the manuscript, now on Lines 51-52.

Line 185 - I feel like the way this is written is down-selling the importance of your work, because despite the fact that these phenomena are rare, sharing understanding about the devastating consequences is actually even more important!

Agree! Have edited – "Despite being rare there have been recent high-profile examples of these extreme events including Boscastle (2004), Cockermouth (2009), Glenridding (2015), and Coverack (2017). Because of the risk to life and property it is important there is an awareness of these extreme events and how and when they occur."

Line 195 - Is there no literature for this other than a talk?

Have edited – "Threshold events relate to a concept in geomorphology science called river sensitivity, a concept described by Kristie Fryirs as 'lost', but of increasing significance for landscapes under a changing climate, in her Gordon Warwick Award winner's address to the British Society for Geomorphology in 2015 and subsequent paper (Fryirs, 2016)."

Line 197 - This needs a reference

Added.

Line 202 - This section needs better referencing

This is a fundamental concept available in text books. It is summarising the equation, now referenced as Fryirs (2016).

Line 229 - How fast does recovery normally take, is there a standard justification for this timeline?

Have added later – "The recovery period after extreme events varies widely between different areas, depending on factors like local vegetation, soil or climate, but can take decades - although this survey was conducted 7 years after the flood the channel had still yet to recover and largely reflected the immediate post-flood environment."

Line 257 - I'm confused by the definition of user vs operator, it would help for this to be clarified.

Have changed to crew and participants throughout to clarify.

Line 273 - This term should be explained for those unfamiliar with video game terminology

Have edited to – "Most of the changes were obscured under the height of the water as this was the peak of the flood, but it still required a removal and repositioning of the participant within the scene (a process known as respawning) resulting in some sudden, unrealistic changes."

Line 284 - Explain this term?

Have added – "AAA-game (games produced by large gaming companies intended for the global commercial market)."

Line 331 - This is only anecdotal - needs data

This is now in a sub-section titled Anecdotal information.

Line 335 - This is very tenuous for a large event, where that comment may have been referencing a different stand, even if there were no other VR practitioners there.

Have removed this.

Line 344 - This section solidifies a concern I am having that this is less of game than a visualisation or simulation. There don't appear to be any objectives that can be achieved or activities that the player can do. Perhaps reframing this activity as such may help with evaluation?

Have made it more explicit throughout the manuscript that *Flash Flood!* is not a game, although it is designed to look and feel like one.

Line 361 - Lonely parenthesis.

This section has been removed.

Line 365 - Is there any demographic data available here for context? Number of attendees, location, source of attendance etc?

This section is now under anecdotal information.

Line 371 - Can you share this data?

Have uploaded this data to a shared folder and added link at end of manuscript.

Line 379 - This section should be edited for clarity - there are too many examples. Some kind of analysis would help condense this?

This section has been removed.

Line 400 - I disagree, evaluation can be done in a science festival setting, when designed appropriately - please see suggested references in the review. If you would prefer not to do that however, it would be useful to do some more structured evaluation in a different environment either before hand or after?

The revised manuscript details a more formal evaluation.

Line 408 - However you won't be able to tell from the user data if they used a VR interface here, correct? So the interaction with the visualisation without the immersive experience of VR would change the way the player interacts with it.

This is true, the analytics do not show this but this isn't what was being tested – the manuscript using the analytics to assess whether the events are driving traffic to the supporting online content.

Line 413 - The monthly views for what specifically?

Have removed this figure.

Line 429 - I'm struggling to connect this to curiosity. There are some really great measures of science curiosity and it's importance in science learning/engagement (see Dan Kahan's work) but I'm not sure what measure you are demonstrating here and how you can quantify if it's actually curiosity you are looking at.

Have removed this section – the intention was to measure curiosity by how much additional traffic was seen on supporting online material that could be related to events, equating this to the public

seeking further information. More detailed analysis of the analytic data suggests that this isn't the case however.

Line 438 - Again I would disagree - there are tools and approaches that can help you do this.

Revised manuscript reflects this.

Line 449 - I would question how you can be certain of this, as with the data you have presented I wouldn't know for sure, perhaps you could add these additional analytics.

More detailed analysis of the data suggests this isn't the case and has been removed from the manuscript.

Line 454 - You can check this data using analytics and if you have already done so I think it would be valuable to share it.

This is included in the revised manuscript – "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."

Line 459 - How does this match with the single-user focus of a VR simulation?

The original *Flash Flood!* and *Vol.2* are both single-user focused, but *Vol.2* allows us to run more stations at one time, engaging more users.

Line 499 - So this suggests that the true value of the simulation is as a fcailitation tool? This is an interesting perspective and one that would be easy to evaluate.

It has value for this but is useful as an activity alone – "A major development between the original Flash Flood! and the Flash Flood! Vol.2 that was used for the formal evaluation was the inclusion of a voice over track. This helps to engage more participants at one time as it no longer requires a one-to-one interaction with a crew member. It also reduced the resource needed to crew exhibits as it reduced the level of fatigue within the crew. However, it also limited the conversations between participants and crews that are where the most positive science engagements occur (Jensen and Buckley, 2014; Wiehe, 2014). For events like SSEW, with large school groups in attendance, where the volume of participants makes such interactions difficult, Flash Flood! Vol.2 seemed particularly suited. At family-orientated events like the BSG Open Day, interactions are more relaxed and the activity could benefit from additional follow-on interactions providing additional information on flooding, geomorphology, and how the 3D scene was constructed (akin to the debrief of Crookall, 2010). In this, Flash Flood! Vol.2 shows potential for use in facilitating more in depth interactions between the public and scientists at appropriate events."

Line 503 - Is that in real life or in the game? That may add a more 'game-like' feel to it if it were more interactive?

This would be separate.

Line 507 - But that would be a very effective way to get some good evaluative data.

It would but would tell us about the science festival setting.

Line 765 (Figure 6) - I'm really not sure what this pie chart is trying to show, I wold actually assume this is more of an assessment of the questions themselves than of the activity. 'What will you do?' is quite a difficult question to answer, which might be why is got the least number, as opposed to 'what do you

like' which gets the most. I would hesitate to use this as demonstration of the effectiveness of the game.

Have removed this figure and moved discussion into Anecdotal information.

Line 766 (Figure 7) - I would suggest that both figure 7 and figure 8 show the same thing, and I'm not sure you need them both. Figure 7 in particular is very good at showing the increase in users over time. If you want the additional data you could aggregate the two using a timeline which identifies the festivals and promotional events which stimulated the increase in views.

See above.

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

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

Email – c.skinner@hull.ac.uk

Abstract

The risk of flooding around the world is large and increasing yet in many areas there is still a difficulty in engaging the public with their own flood risk. Geomorphology is a science thatwhich is linked to flooding and can exacerbate risks but awareness of the science with the public is low, and declining within academia. To increase awareness it is important to engage the public directly with the science and those who are working to reduce flood risks – this starts by inspiring people to seek out further information through positive experiences of the science and researchers. Here, a new framework design model is presented to engage the public with specific research projects by using useful the best components offered by the popular mediums of games, virtual reality, and science festivals, to allow the public to get 'hands on' with research data and models – SeriousGeoGames. A SeriousGeoGame, *Flash Flood!,* was developed around real geomorphology survey data to help engage the public with a flood risk related research project by placing them in a river valley as it undergoes a geomorphically-active flooding from intense rainfall event. *Flash Flood!* was exhibited at science festivals and similar events in the UK by scientists on the project, and supported with online content including videos. Through event feedback it was shown to create positive experiences for participants and inspired curiosity as seen through online analytics.*Flash Flood!* was exhibited at two science-focussed events and formal evaluation was captured using a short questionnaire, finding that the majority of audience had a positive interaction (95.1%, n=344) and wanted to know more about flooding (68.0%, n=344) and geomorphology (60.1%, n=344). This It is hoped these interactions willto inspire increase the likelihood that futuremore fruitful engagements with relevant agencies will be more fruitful, especially in the future when it matters most.

~~1.~~ 1. Introduction

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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 ~~which~~ that poses real~~them the greatest~~ risk, but this is the situation ~~environment~~ practitioners find themselves in.

Geomorphology is the science of how planetary surfaces form and change. ~~and~~ Geomorphic processes ~~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 that~~which~~ can make flood waters more damaging. Clean up of deposited material, sometimes contaminated, increases the post-event cost. Geomorphic processes~~ology~~ also contribute~~s~~ to the likelihood of flooding with erosion and deposition altering a river channel's capacity to hold water, or even changinge 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~~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 present day risks (Curtin, 2017). Resilience to hazards is borne out of preparedness, and preparedness is built on knowledge, so the first step in building societal and individual resilience to geomorphic flooding hazards is by making people aware and more curious the topic. As Clarke et al. (2017) asserts, the responsibility is with geomorphologists, and by extension flood management practitioners, to effectively communicate these risksinspire this curiosity.

This paper presents a case study of the *Flash Flood!* application, an interactive game based virtual reality (VR) activity designed to highlight the geomorphic risk posed by flooding from intense rainfall, more commonly known as flash flooding. VR generally uses two screens held within a headset (Head Mounted Display or HMD) so that each eye can only see one screen, with each showing a three-dimensional (3D) scene at a different angle to produce the illusion of depth and immersing the user in a different and artificial environment. The rest of Section 1It highlights the proposed SeriousGeoGame model of using science festivals, video games, and VR to allow the public to interact 'hands-on' with scientific data to promote enjoyment and curiosity in flooding and geomorphologycombing elements of VR and video gaming with elements from research projects, such as field data or numerical modelling codes. In Section 2, the specific research context for *Flash Flood!* is described, followed by a description of the development of the application in Section 3. Section 4 details the evaluation methods and the events where the application was tested. The results of the evaluation of the application against its stated objectives is shown in Section 54, and discussed in Section 65, before conclusions are presented in Section 76.

1.1 1.1 The SeriousGeoGames Model

The SeriousGeoGames Lab (SGG) was established in 2014 to explore the use of games, and gaming technology, in enhancing the research, teaching, and communication of geosciences. The first SeriousGeoGame produced was *Humber in a Box* (Figure 1), a novel dynamic merging of a research-

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grade hydraulic model - CAESAR-Lisflood~~–~~ (Coulthard et al., 2013) - with a software package used by games developers to create games and virtual environments (known as a gaming engine) – UNITY-3D. Participants~~Users~~ viewed a 3D model of the Humber Estuary, UK, on top of box in a museum style space, while~~and~~ tidal flows were calculated using the CAESAR-Lisflood code and animated within UNITY-3D. Participants~~Users~~ could then simulate past and future scenarios by altering the base sea level giving them an idea of future flood risk with rising sea levels. The scene was viewed using immersive VR via an Oculus Rift Developer Kit 2 ~~Head Mounted Display (HMD).~~model of HMD.

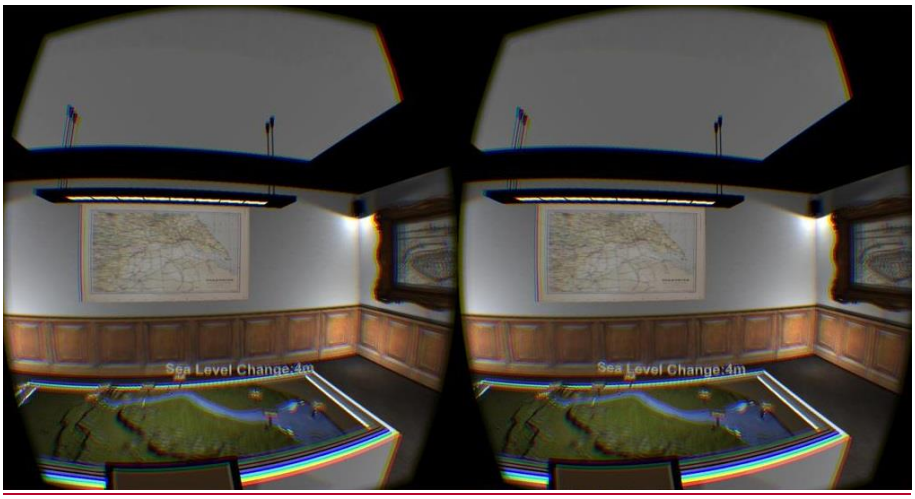

Figure 1 – The view inside *Humber in a Box*.

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

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~~2).~~ The SeriousGeoGame model is one of design choices and considers that they will be predominantly used within a science festival setting where interactions may be short, a few minutes at most, and turn-over of users is high. They should look and feel like video games even if they do not qualify as games themselves. They should exploit VR as a medium of interaction immersing people into new environments. Crucially, they should provide people a first-hand interaction with elements of the ongoing research, such as incorporating field data or numerical modelling codes.

A successful SeriousGeoGame will achieve two objectives –

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

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

~~1.2 With the model established, below we investigate each of the three elements – science festivals, video games, and virtual reality – to see what advantages they give for meeting the two~~

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~~objectives~~It is important to emphasise that the SeriousGeoGames model has been constructed through design choices and anecdotal experiences of previous activities and events. It incorporates three key elements – science festivals, video games, and virtual reality – that can help to achieve the two objectives.

~~1.3~~ 1.2 Science Festivals

The science festival is a common feature of the public engagement with research~~science~~ landscape ~~and for many researchers the local annual science festival is likely one of their few interactions with members of the public~~. The vibrant UK Science Festival Network boasts 50 festival members, who in 2018 ran 4,018 events, featuring 10,941 scientists, and achieved 1,225,779 face-to-face interactions (Woolman, 2019). ~~scene, for example, boasts 11 large annual science festivals which can attract between 6,000 and 50,000 visitors (Jensen and Buckley, 2014), and the UK Science Festival Network has 45 member festivals (Science Festivals Network UK, 2019).~~ The US scene is also growing, with the Science Festival Alliance growing from just four member festivals in 2009 to around two dozen in 2012 (Durant, 2013), and in 2017 47 member festivals shared science and research with over 2 million members of the public (Science Festivals Alliance, 2018).

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

The goal of a Science Festival is usually to celebrate science and research (often that performed or funded by the organisers) and to engage non-specialists (Bultitude, 2014). As such, they have become

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

Science Festivals could be described as niche in their nature, appealing to a small sub-set of the population. According to~~In~~ a 2011 MORI poll, ~~showing that~~ only 3% of the UK population attended a Science Festival in the previous year (Jensen and Buckley, 2014) 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~~which~~ have targeted under-represented groups have seen the same success by facilitating interactions between scientists and the public (Jensen and Buckley, 2014).

~~1.4~~ 1.3 Video Games

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Video gaming is big business, with retail sales of video games accounting for 51.3~~.~~% of the UK's entertainment retail market (including~~ed~~ 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~~science~~ as they provide a first-hand experience that~~which~~ can inspire an emotional response (Mendler De Suarez et al., 2012; Squire, 2003; Wu and Lee, 2015). In addition, games are fundamentally fun (Wu and Lee, 2015), and as such they are naturally engaging and motivating for the user (Ryan et al., 2006). Video games are popular, with 28% of UK households owning a gaming console (BARB, 2019), and 36% for US households

(Entertainment Software Association, 2018). These figures do not count PCs, smartphones, or tablets that are used for gaming, which increases the figure to 64% in the US (Entertainment Software Association, 2018) ~~64 % of US households owning a gaming device and an average of two gamers per household (Entertainment Software Association, 2018)~~.

The flexibility and complexity that~~which~~ can be afforded by video games has made them an attractive tool for engaging people with complex issues such as c~~C~~limate c~~C~~hange (Porter and Córdoba, 2009; Reason, 2007; Warburton, 2003). This has led to the development of 'serious games', games where learning is a core objective without losing sight of the entertainment element (Abt, 1987; Charsky, 2010; Crookall, 2010)~~,~~ and there are several studies showing that serious games have been effective in delivering the intended learning outcomes (Amory et al., 1999; Bellotti et al., 2013; Betz, 1995; Chin et al., 2009; Coleman et al., 1973; Connolly et al., 2012; Gosen and Washbush, 2004; Hobbs et al., 2018, 2019; Lane and Yi, 2017; Mani et al., 2016; Mitchell and Savill-Smith, 2004; Vogel et al., 2006; Wilson et al., 2009). Serious games can be used to create virtual analogues of real world places or physical phenomena for public engagement, such as volcanism (Hobbs et al., 2018, 2019; Mani et al., 2016).

~~1.5~~ 1.4 Virtual Reality

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

VR simulations often share features with video games and thus share many of the same learning advantages, such as being engaging and motivating (Abulrub et al., 2011; Psotka, 2013). However, the

immersionvity and presence (the feeling of physically being in the virtual world) produces experiences thatwhich are highly engaging allowing the user to focus more on the learning outcomes (Bricken and Byrne, 1993; Markowitz et al., 2018; Salzman et al., 1999). Furthermore, users consider the virtual environment as real (Blascovich and Bailenson, 2011) and can develop a strong attachment and internalisation toward them (Clark, 1997; Weisberg and Newcombe, 2017). A particular advantage of VR is that it can allow users to feel closer to otherwise abstract or distant ideas (Trope and Liberman, 2010), for example in Markowitz et al. (2018) users were shown 'first-hand' (via VR HMD) the impacts of ocean acidification and reported increased knowledge gain and interest in the subject as a consequence.

VR is not without its limitations. Cost remains a considerable barrier to its uptake and use, with popular HMDs costing several hundred GBP (for example, Oculus Rift S ~£400, VIVE Pro ~£800) and requiring a gaming specification PC to run. The use of VR can also induce a nausea or dizziness (sometimes called cybersickness), similar to motion sickness, and can also cause headaches and eyestrain (Rebenitsch and Owen, 2016). In one test, seated participants using the Oculus Rift HMD for less than 15 minutes reported a 22% occurrence of cybersickness (Munafo et al., 2017).

~~2.~~ 2. Flooding from Intense Rainfall

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2.1 The Research Context

Flash Flood! was conceived as an engagement activity to support the Flooding from Intense Rainfall (FFIR) research programme, funded by the Natural Environment Research Council UK (NERC). The FFIR programme described itself as "A five year NERC funded programme aiming to reduce the risk of damage and loss of life caused by surface water and flash floods" (Flooding from Intense Rainfall, 2019). The UK based and focussed programme brought together experts from several Universities, environmental consultancies, the Met Office, the Environment Agency, and the British Geological Survey to better understand the role intense and~~,~~ localised rainfall events had on both rural and urban flooding, with a strong focus on end-to-end forecasting on events (Dance et al., 2019; Flack et al.,

2019). Thunderstorms, driven by strong convection in summer months, form and dissipate rapidly and can be highly localised covering just a 1-3 km wide area. Despite good understanding and being able to forecast the conditions in which they form, it is presently not possible to provide accurate forecasts of when and where the storms themselves will form.

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

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

Threshold events relate to a concept in geomorphology science called river sensitivity, a concept described by Kristie Fryirs as ~~-~~'lost', but of increasing significance for landscapes under a changing

climate, in her Gordon Warwick Award~~medal~~ winner's address to the British Society for Geomorphology in 2015 and subsequent paper (Fryirs, 2016)~~(Fryirs, 2016)~~. The concept can be summarised by the equation below –

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

~~(~~

(adapted from Fryirs, 2016)

~~2.2~~ The equation assumes that every river has a stable behaviour, with it displaying consistent responses to similar events. This stability is maintained by mature vegetation cover and a paucity of sediment that~~which~~ can be moved by the river. However, there exists a threshold magnitude of flood event that~~which~~ will disturb this stability by removing the vegetation cover, exposing sediment, and transporting it elsewhere in the channel. After the event, the channel begins recovery (or relaxation) through a period of enhanced dynamism in the geomorphology until new vegetation has matured and sediment sources exhausted. The balance between how often these events occur and how long it takes a river channel to recover is the river's sensitivity. During the threshold event and the river's recovery the amount of sediment delivered downstream in the system is greatly increased~~,~~ and this in turn may influence the flood risk in those areas (Lane et al., 2007; Slater, 2016). Predictions of climate change for the UK suggest flood events will become more likely and more extreme (Dankers and Feyen, 2008; Ekström et al., 2005; Feyen et al., 2012; Fowler and Ekström, 2009; Pall et al., 2011; Prudhomme et al., 2003) disrupting the balance determining river sensitivity – the impacts of this on rivers and future flood risk is not known but is likely to be negative.

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~~2.3~~ 2.2 The Research Data

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The case study at the heart of *Flash Flood!* is the 2007 flood event in the upland valley of Thinhope Burn, Northern England, as detailed by Milan (2012). The event was an FFIR event thatwhich could be described as a threshold event for the system. During a six-hour period a highly localised yet intense convective storm precipitated 82 mm of rainfall on the upper catchment (Met Office, 2003) resulting in a flash flood event – those who witnessed the event described a wall of water and the sound of boulders crashing along the river bed (Milan, 2012). The valley floor was fundamentally changed by the event withwhich saw large geomorphic changes, during the event including the straightening and widening of the main channel, stripping out of flood plain vegetation, the deposition of material in the channel and on the flood plain (see Figure 23), and increased mobility of material subsequently (Milan, 2012).

Figure 2 – Google Earth images showing the reach section surveyed and used for *Flash Flood!*. The right-hand image is from before the flood in 2006 (Google Earth, 2019a), and left-hand image from after the flood in 2007 (Google Earth, 2019b). The flood has cut meanders resulting in a straighter channel, stripped out vegetation, and deposited loose sediment on the flood plain (the lighter colour in the right-hand image).

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The usefulness of this case study for the development of *Flash Flood!* was the availability of ground survey data of the stable river valley just three years prior to the flood, and repeat surveys afterwards, whichwhich were used by Milan (2012) and provided for this work. To have detailed surveys shortly before a geomorphically active event such as this is rare and cannot be planned for so provided an

exciting opportunity. This survey was captured in the summer of 2003 using a back-pack Global Positioning Satellite (GPS) system across a 500 m reach section. Although similar surveys were available for after the flood, it was decided to recapture the same 500m in more detail using a Terrestrial Laser Scanner (TLS) in the summer of 2014. The recovery period after extreme events varies widely between different areas, depending on factors like local vegetation, soil or climate, but can take decades - ~~A~~although this survey was conducted 7 years after the flood the channel had still yet to recover and largely reflected the immediate post-flood environment.

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

3. Development

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

3.1 The original *Flash Flood!*

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

Figure 34 – Screen shot from the original *Flash Flood!*.

The exhibit used anthe Alienware X51 R3 (Intel Core i5 6400 CPU @2.71 Ghz – 16Gb RAM – NVIDIA GeForce GTX 970), whichwhich was labelled as "Oculus-ready", withand the consumer model Oculus Rift HMD. The application was optimised to a lower standard than the equipment specification afforded to allow a desktop-only version of the software to be released. For example, the gGraphics were kept simple (see Figure 34) and the representation of water kept to an animated plain thatwhich was angled down in the direction of the river and would rise and fall givingen the impression of rising and falling water levels as it intersected the landscape. The public participants Users explored the scene using the two joysticks on an XBbOXox controller and needed to use no other buttons or d-pads.

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

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

15:00 – "Clouds begin to gather"

16:00 - "A storm is brewing"

17:00 – "The storm intensifies"

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

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

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

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

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

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

3.2 *Flash Flood! Vol.2*

In 2018, an opportunity arose to redevelop the original *Flash Flood!.* Where the original had been limited in its graphics and representation of river flow due to the release of a desktop-only version, there were no such limitations for *Vol.2*. Instead, the new development was optimised for a new set of equipment using the Alienware 17R5 Oculus-Ready laptops (Intel i7-8750H @ 2.20GHz – 8GB RAM – NVIDIA GeForce GTX 1070), with an aim of achieving a look and feel of a AAA-game (games produced by large gaming companies intended for the global commercial market). This was partly in response to an increasing number of anecdotal comments on the basic level of the original graphics and ~~users~~ participants becoming more accustomed to ever more sophisticated VR experiences. Photo-realistic assets were used for textures and 3D objects, and the scene was made wooded like the original to make a more interesting scene (see Figure 4). The transitions at the edges of the scene were significantly improved by removing the hills and replacing these with an ~~unexplorable~~ extended landscape (that could not be explored) and hiding the edges using stone bridges ~~(see Figure 5)~~. The basic horizontal plain of water was replaced by the more sophisticated River Auto Material (R.A.M. by NATUREMANUFACTURE) asset, with customisation from the developers for the representation of the flash flood showing a rapidly rising water level with debris in the form of rocks and logs. *Vol.2* uses the same data and flood timeline as the original version.

Figure 4~~5~~ – Screenshot from *Flash Flood! Vol.2.*

From an exhibitor point of view the main limitation of the original version was the staffing resource required due to the one-to-one narration provided by the operator – this interaction was exhausting, and a single operator could manage around four or five demos before requiring a rest during busy periods. This means each set up required a minimum of two operators rotating regularly, and an extra operator for every two sets to allow for breaks and control of the crowd. This limited the number of demonstrations that~~which~~ could be achieved and size of exhibits that~~which~~ could be supported. To overcome this limitation *Vol.2* uses a soundtrack with narration. The user chooses between two narrators – Chris (voiced by Dr Chris Skinner) and Jess (voiced by Dr Jess Moloney)~~ – defaulting to Jess~~. As video gaming is often perceived as a male space with women and girls feeling excluded or discriminated against (for example, ~~(~~Delamere and Shaw, 2008), it was decided the choice of narrator would default to Jess so that participants would encounter a female scientist first. ~~-~~The two narrations follow slightly different scripts with Chris's being more general and Jess's drawing more on Dr Moloney's research into dating past flood events (Moloney et al., 2018). The choice of a single male and female voice was a starting point and allows for an increased representation of voices with future developments.

3.3 Ancillary developments

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

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

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

To support the original version of *Flash Flood!* a handout was produced. The handout included brief descriptions of the flood event, links to the SeriousGeoGames website and social media accounts, and an activity that could be done alongside the simulation. The intention was to mimic the taking of field notes performed by geomorphologists, before and after the flood, particularly for use with the desktop and YouTube versions of *Flash Flood!* outside of events (it was also available as a PDF download). At events the handout was given out along with a "I survived the Flash Flood!" badge and was also free to take from the table. It was used to engage members of the public either waiting for a

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turn or accompanying a participant by getting the participant to describe what they were seeing so it could be written into the field notes section.

4. Evaluation

The different versions of *Flash Flood!* have been demonstrated at events since its debut at the Hull SciFest in March 2016, several years before any evaluation activity beyond informal conversation with participants and headcounts was conducted. The experience of exhibiting has provided a wealth of anecdotal information valuable for designing new activities but is potentially biased (Jensen, 2015) and not suitable for formal evaluation (Neresini and Bucchi, 2011). Previously, evaluation at events has been eschewed as it was perceived to intrude on the experience of the participants and potentially impede on the success of the objectives, especially when the activity is just one exhibit of many as part of a larger science festival. Summative evaluation, conducted after participation with activities, can reduce the intrusion on interactions – an example would be autonomous methods for participants to leave feedback, such as graffiti walls and feedback cards (Grand and Sardo, 2017). Autonomous methods have been tried alongside *Flash Flood!* previously, for example at the 2018 Hull SciFest.

The formal evaluation of *Flash Flood!* was conducted using *Flash Flood! Vol.2* during two events. The first event was Scarborough Science and Engineering Week (SSEW) 2019 held 8-10 October 2019 at Scarborough Spa, Scarborough, UK. SSEW was targeted at schools in the local area, with two days (8 and 9 October 2019) for secondary school and college pupils (ages 11-18) and a day for primary school pupils (ages 5-11). The second event was the Open Day for the British Geological Survey (BGS) held at their campus in Keyworth, UK, on 12 October 2019. This was a one-day, ticketed event, aimed at families where all 1,800 free tickets were taken up.

The evaluation for both events used the same questionnaire (see Figure 5). Questionnaires are not best suited for busy science festival settings but are an effective way of gathering quantitative information (Grand and Sardo, 2017; Wiehe, 2014). In an attempt to reduce this impact the questionnaire was designed and hosted via the Formstack app on iPads, displayed in stands –

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participants filled and submitted the form on the iPad rather than using paper surveys. The questionnaire was designed to assess *Flash Flood! Vol.2* versus the two Objectives in Section 1.1, which can be summarised as creating fun and curiosity. Participants were orally referred to the questionnaires by exhibit crew after finishing their turn on *Flash Flood! Vol.2*. Completion was voluntary and participants were not observed whilst completing it. At SSEW, up to four VR stations running *Flash Flood! Vol.2* were operating at once along with two iPad evaluation stations, and at BSG Open Day there were up two VR stations and one iPad evaluation station.

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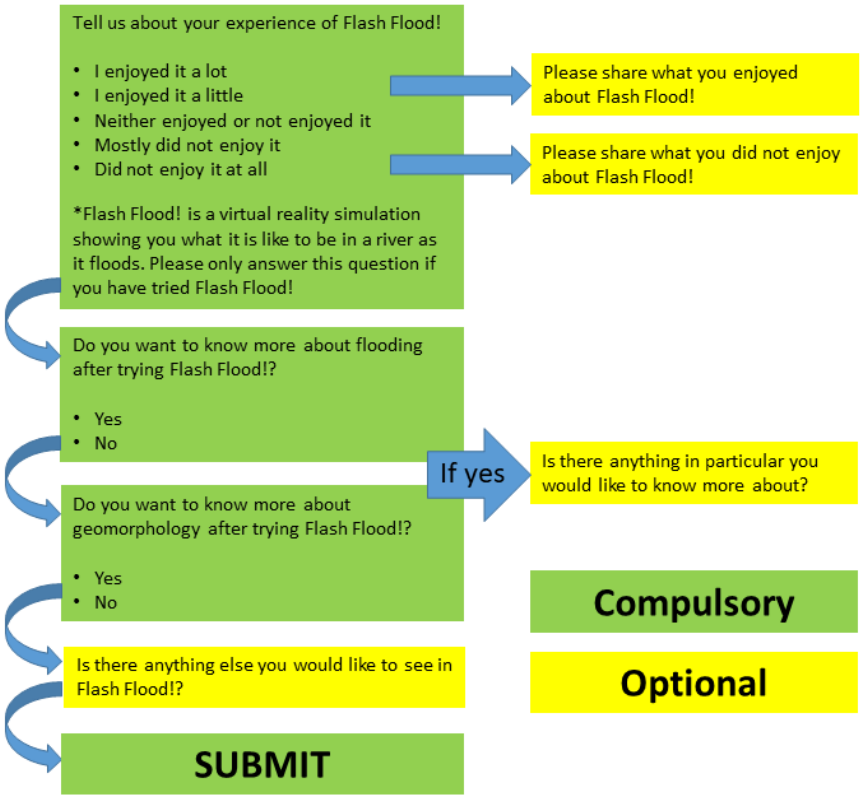

Figure 5 - Flow diagram showing the questionnaire design. All respondents are offered all questions on the left-hand side, whilst questions on the right-hand side were only shown under indicated conditions. All questions in green boxes had to be answered to allow the form to submit.

At both events a large (3m wide - 2m high) canvas banner advertising *Flash Flood!* was on display featuring the following text –

"Flash Flood!

Geomorphology: The science of how landscapes change

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

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

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

The space set up for both events is shown in Figure 6. Whilst the BSG Open Day was a traditional tabletop activity and banner set up, SSEW featured some more design elements, like event fencing, a static drone display, and an immersive forest soundscape within the fencing.

Figure 6 – Exhibit set up for the Scarborough Science and Engineering Week (left) and the British Geological Survey Open Day (right). The iPad and stand for the evaluation station at the British Geological Survey Open Day is just off shot to the right of the image.

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The ancillary developments designed to support the exhibit include the SeriousGeoGames website (hosted in Wordpress) and YouTube channel. Both Wordpress and YouTube provide detailed analytics of views, audience, sources, and other useful information that can be broken down by date. This analytic data was used to evaluate whether the online content, and the *Flash Flood!* handout that signposted participants to it, was useful for achieving the two objectives during the NERC UnEarthed event in 2017.

~~4.~~ 5. ~~Evaluation~~Results

This Section details the results of the evaluation of *Flash Flood!*, beginning with the informal, anecdotal information garnered from years of exhibiting with different versions of the application (5.1). Sections 5.2 and 5.3 detail the formal evaluation of *Flash Flood! Vol.2* over two events, for the two objectives, creating fun (5.2) and creating curiosity (5.3). In Section 5.4, an analysis of the ancillary developments is provided.

~~4.1 Objective 1 – Fun~~ 5.1 Anecdotal Information

Even without a formal evaluation useful lessons had been learned such as it being obvious that participants enjoyed the activity. Some words were often used in informal conversations to describe their experiences, such “epic” and “sick” (meant positively), and particularly “weird” describing the uncanny experience of immersion in a virtual world that is exciting yet out of the ordinary. Other comments included variations of “it’s like Minecraft” that have evolved into “it’s like Fortnite”.

~~Through demonstration of *Flash Flood!* at events it is obvious that most participants enjoy the activity. Verbal feedback has included words describing the activity as “epic” or “sick”, both meant as a positive. The most common word received as feedback has been “weird” most often delivered with a~~

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~~smile on their face – it is obvious that it is meant as a positive, that the uncanny experience of immersion in a virtual world is exciting, yet out of the ordinary.~~

Flash Flood! has been highlighted in the feedback obtained by events, usually via comment walls. At NERC Into the blue event in 2016 comments under the "Things I loved about Into the blue" included ~~"the gogls" (Goggles = VR headset) and~~ "flash flood", and under "Things I learned at Into the blue" was "Rivers are fantastic!". Into the blue also ran a public vote for most popular stand, for which *Flash Flood!* was awarded joint-3rd out of 40 exhibits and events.

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

In conversation, it was~~is~~ 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~~like~~ something to shoot, such as zombies (see Curtin, 2017). With *Vol.2*, where there were usually more VR stations~~sets~~ available to do multiple simultaneous demos, several have commented that they would like to have them linked and be~~ing~~ 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 –

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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.

5.2 Objective 1 – Creating Fun

The ability of *Flash Flood! Vol.2* to create fun was evaluated using questionnaires at two events in October 2019. The first question asked participants to "Tell us about your experience of *Flash Flood!*?" and the results can be seen in Figure 7. 344 responses were collected over the two events with 79.9% stating they enjoyed it a lot and a further 15.1% stating they enjoyed it a little, meaning 95.1% enjoyed it in some form.

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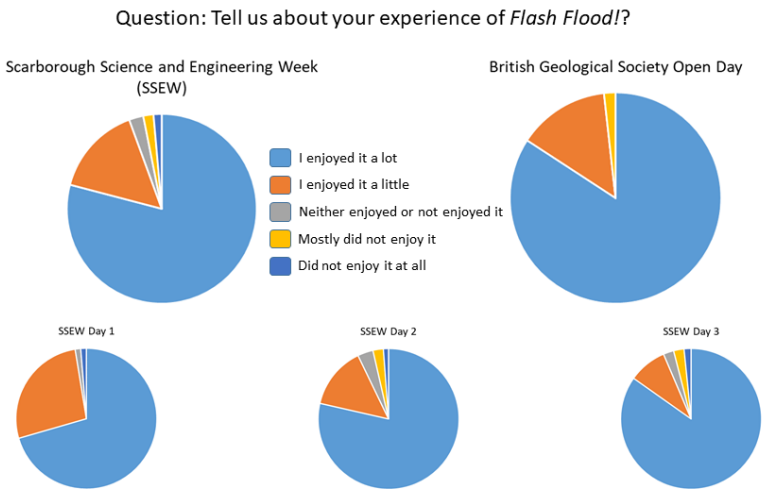

Figure 7 - Charts showing the questionnaire responses to the question "Tell us about your experience of *Flash Flood!*?" from Scarborough Science and Engineering Week (8-10 October 2019) and the British Geological Survey Open Day (12 October 2019).

This level of enjoyment only varied slightly, with the participants of the BGS Open Day reporting to have enjoyed it the most of the four days (98.3%, n=57). The second day of SSEW saw the lowest levels of enjoyment (92.9%, n=84). Over the three days of SSEW, the primary school pupils on Day 3 were more likely to say they enjoyed it a lot (84.8%, n=125), than the secondary school pupils (74.5%, n=162), whilst participants at the BGS Open Day reported similar levels to Day 3 (84.2%, n=57).

Those who reported they enjoyed the activity were prompted to volunteer a free-text answer to the question "What did you enjoy about *Flash Flood!*?" which received 210 answers. Answers were analysed and binned into categories – general (for example, "I enjoyed everything"), content (for example "I enjoyed learning about the flood"), technology (for example, "I liked it looked real"), and miscellaneous (answers not falling into the above or that did not make sense). Overall, the technology proved most popular (38.1%, n=210), then general (33.8%, n=210), and then the content (25.2%,

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n=210), however, for the BSG Open Day content proved most popular (45.2%, n=31), general next (29.0%, n=31), and then technology (25.8%, n=31).

Eight responses were provided for the question "What did you not enjoy about *Flash Flood!*?" of which more than half referred to the technology, such as "bad graphics", "Made me dizzy", or "It hurt my eyes". One response was "Chris" which could either refer to Dr Chris Skinner's voice over or himself as he was acting as crew for this event.

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

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

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

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

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

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

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

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

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

"It felt real"

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

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

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

"hid in the chrees"

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

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

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

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

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

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

~~"I lerned about floods"~~

~~"I learn a lot about flash floods"~~

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

~~"I learnt about what happens during flash floods"~~

~~4.1 Objective 2 - Curiosity~~5.3 Objective 2 – Creating Curiosity

The evaluation of whether *Flash Flood! Vol.2* created curiosity was conducted through two questions – "Do you want to know more about flooding than before trying *Flash Flood!*?" and "Do you want to know more about geomorphology than before trying *Flash Flood!*?". 68.0% (n=344) of respondents stated they did wish to learn more about flooding and 60.1% (n=344) wished to learn more about geomorphology. A breakdown of the data for the events and days in shown in Figure 8. Between the events, the level of curiosity regarding flooding was similar, with 67.9% (n=287) at SSEW and 68.4% (n=57) at the BSG Open Day wanting to know more, yet regarding geomorphology more participants at the BSG Open Day wanted to know more (64.9%, n=57) than at SSEW (59.2%, n=57). The primary school pupils were more likely to want to know more about flooding (68.8%, n=125) than the secondary school pupils (67.3%, n=162), and were more likely to want to know about geomorphology (62.4% to 56.8%).

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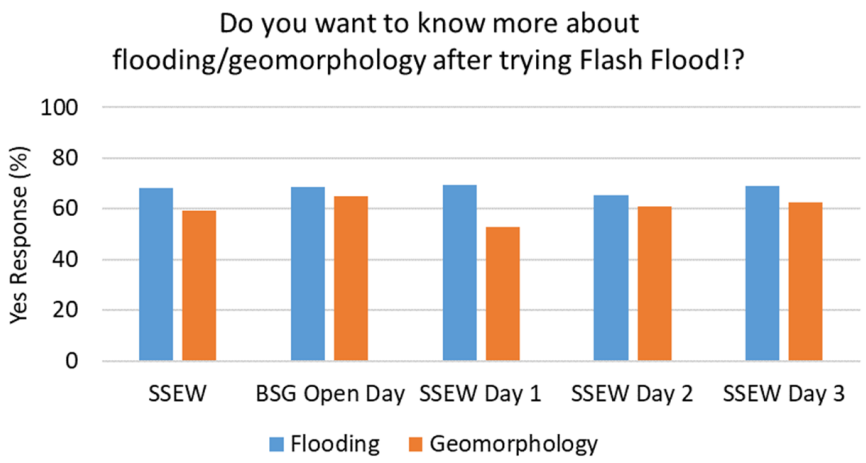

Figure 8 – Levels of respondents responding yes to questions asking if they would like to know more about the research topics in *Flash Flood!*. Data are split between Scarborough Science and Engineering Week 2019 (SSEW) and the British Geological Survey Open Day 2019 (BGS Open Day), and further into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

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technology and 14.5% to the content. A common theme was for extra features associated with video games, such as challenges, a larger map, better graphics, or multiplayer modes. At the BSG Open Day more participants wanted to extra features relating to the content (41.7%, n=12) than the technology (33.3%, n=12).

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

5.4 Ancillary developments

To support the activity at events, ancillary activities were produced, mainly online. These include the SeriousGeoGames website and videos on the SeriousGeoGames YouTube channel. This section analyses the potential of these for assisting in achieving the two objectives. Figure 9 shows the growth in views for the website, YouTube channel, the individual 360 *Flash Flood!* videos, plus the aggregated views of all *Flash Flood!* videos (three in total – two 360 videos and a demo for the original version). The YouTube channel has more views than the website but only since February 2019 – before this both the website and YouTube channel were on similar levels of views and growing at around 200 views a month.

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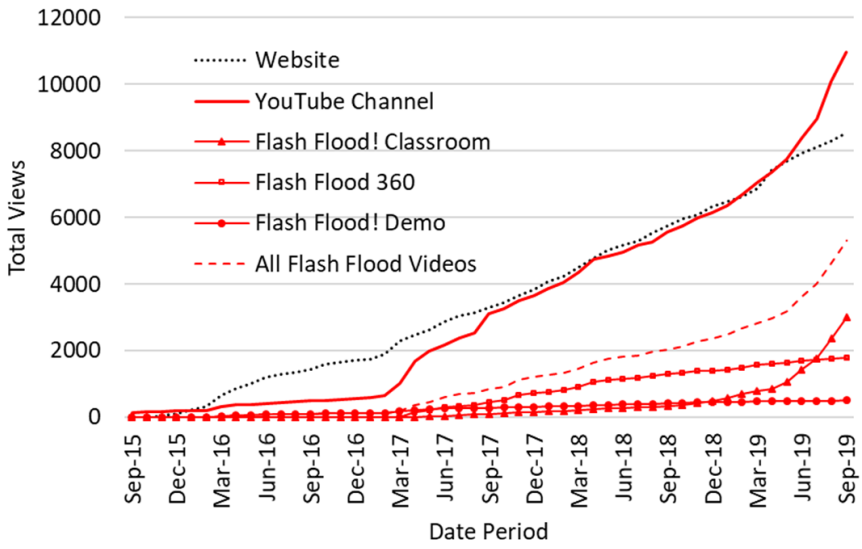

Figure 9 - Cumulative views for SeriousGeoGames online content, including the SeriousGeoGames website and YouTube channel, and cumulative views for the *Flash Flood!* related videos on the SeriousGeoGames YouTube channel. ~~To assess the success of *Flash Flood!*, and other SeriousGeoGames, against Objective 2 users are signposted to online media relating to SGG. Figure 7 shows the total views for the SGG website and YouTube channel, with each accumulating a remarkably similar total since September 2015, and both have been growing at a similar rate of around 200 views per month since the beginning of 2018.~~

~~There are three *Flash Flood!* related videos on the SGG YouTube channel (out of a total of 51 videos) – a preview demo for the original version, and the two 360 versions.~~ The growth in the~~of~~ aggregated views for all these videos is also shown in Figure 9~~7~~. As a share of overall views on the SeriousGeoGames channel, the *Flash Flood!* videos has~~s~~ gradually been increasing and currently accounts for around 48.3~~0~~ % of the total views~~, and 56.4 % of those are for narrated 360 video alone~~. The *Flash Flood! Classroom* version has gained in popularity with over 3,000 views in 2019 and 3,515

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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”.

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

The 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, ~~and~~ 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. ~~In the week preceding the event the narrated 360 video was viewed 50 times, was viewed 6 times during the event, and 42 times in the week after. In November the Flash Flood! videos had a total of 215 views, 81.1 % of the total YouTube channel views. The UnEarthed exhibit also featured the *Humber in a Box* game – the demo video on the channel for this~~

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~~game received 32 views, so in all 93.2 % of all video views in November 2017 were related to the UnEarthed exhibit.~~

~~5.~~ 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.~~When users have been asked what they thought of *Flash Flood!* most have opted to share how much they enjoyed it over providing feedback on what they learned or how they'd like to see it improved – for example, In Figure 6, of 42 comments on *Flash Flood!,* 35 were about enjoyment.~~

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

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~~this growth and the proportion of views relating to the three videos over the other 48, growing from 20 % at the start of 2017 to 39 % by the end of 2018.~~

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 proportion reporting they enjoyed it a lot. Both secondary and primary school pupils reported similar levels of wanting to know more about flooding after trying *Flash Flood!*, although this was slightly higher with primary school pupils. Primary school children were more likely to want to know about geomorphology than secondary school children. Although primary school pupils do respond more positively to the activity, secondary school pupils also respond positively in the majority, suggesting the activity is effective for engaging both age ranges.

6.4 Ancillary developments

To support the *Flash Flood!* activities there is online information via the SeriousGeoGames website and YouTube channel. During the NERC UnEarthed event of November 2017, a handout was used referring participants to the *Flash Flood! 360* video on YouTube and this did result in an increase in views from 41 for a period before the event to 88 for the period before, during, and following the event. 35 of the 88 views were direct, meaning they came from typing in the URL, from YouTube searches, or selecting the video from the SeriousGeoGames YouTube channel, whilst 47 views came from using links, including on Twitter (15) and preventionweb.net (11). Even if it is (wrongly) assumed that all 47 of the increased views came from participants at the event this would represent just 0.009% of the 5,250 attendees suggesting that the exhibit and hand outs are not successful in driving traffic to the online content.

The *Flash Flood! Classroom* version was produced in response to discussions with teachers at events for use in schools and has been supported by articles targeting this use (Skinner, 2018; Skinner and Milan, 2018). This video has seen increased growth in 2019, with over 3,000 views where 90.7% are from YouTube searches. However, only 0.6% of these searches used the term "flash flood classroom version", suggesting that the increase in views is a result of the video showing up in search results for more generic searches rather than being used in schools. The majority of views come from the US (38.5%) with the UK share of audience too small to be shown by YouTube's analytics, suggesting that views are not likely to be a result of the UK-focussed articles.

The results from the ancillary developments are disappointing and do not suggest that they are effective at supporting the exhibition activity of *Flash Flood!*. There is little evidence of it being used within classrooms too. However, the increase in views for *Flash Flood! Classroom* via generic search terms indicates that a new audience can be found through optimising use of search terms and presents an attractive area of future development.

6.5 Reflections

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A major development between the original *Flash Flood!* and the *Flash Flood! Vol.2* that was used for the formal evaluation was the inclusion of a voice-over track. This helped to engage more participants at one time as it no longer required a one-to-one interaction with a crew member. It also reduced the resource needed to crew exhibits as it reduced the level of fatigue within the crew. However, it also limited the conversations between participants and crews, which are where the most positive science engagements occur (Jensen and Buckley, 2014; Wiehe, 2014). For events like SSEW, with large school groups in attendance, where the volume of participants makes such interactions difficult, *Flash Flood! Vol.2* seemed particularly suited. At family-orientated events like the BSG Open Day, interactions are more relaxed and the activity could benefit from additional follow-on interactions providing additional information on flooding, geomorphology, and how the 3D scene was constructed (akin to the debrief of ~~(~~Crookall, 2010). In this, *Flash Flood! Vol.2* shows potential for use in facilitating more in depth interactions between the public and scientists at appropriate events.

The next steps for developing SeriousGeoGames, including *Flash Flood!*, would be to broaden the objectives to include learning objectives and/or to drive behavioural changes. For example, an application could teach people about specific elements of flood risk and encourage them to make flood plans or sign up to flood warning services, or an application about plastic pollution could teach people about hidden sources of plastic and encourage them to use less of these. However, *Flash Flood!* has been designed for short term interactions in busy event spaces and would likely need adapting and expanded to meet such objectives. The video game elements in *Flash Flood!* are the least developed and present the area of greatest opportunity going forward. At present it cannot be classified as a game - it lacks objectives for participants to achieve or challenges to be completed - yet it stills creates fun and curiosity. However, some comments were received stating disappointment that there was little do other than exploring the limited game world and observing the flood. If the narrow objectives of *Flash Flood!* were expanded to include defined learning objectives, possibly within the a workshop or classroom environment, developing more gaming features would be the obvious way to achieve this.~~The NERC UnEarthed event of November 2017 presented the best~~

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

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

~~The video game element is the least developed of the three and consequently the one which receives the most specific feedback. In the main this is because of limitations in the application and the desire to have more freedom or an objective to achieve, and this can cause confusion in some who are expecting a more developed game like experience. This should be viewed as a huge opportunity for~~

~~further development – there is a strong desire for audiences of science festivals for game-like exhibits (not just video games), especially where there is a competitive element, and these are currently underrepresented. However, the game-like appearance and feel of *Flash Flood!* is viewed as a positive by almost all users, and even the sight of an Xbox control pad within the science festival hall sparks excitement in some members of the audience.~~

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

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

~~However, the most important element of any *Flash Flood!* exhibit is the team of scientists which interact with the public, sharing their enthusiasm for science and their research expertise. It is especially successful when their research aligns with the exhibit, but this is not vital – many of the interactions take place beyond the application itself so it is possible for the scientists to share their~~

~~own personal research interests without impacting negatively on the objectives. Users particularly enjoy interacting with either Chris or Jess who provided the voice overs for *Flash Flood! Vol.2* and are often surprised they are real people who are scientists in real life.~~

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

~~6.~~ 7. Conclusion

The SeriousGeoGames design model seeks to build activities for festival-like events that allow the public to interact directly with elements of research, such as field observations and numerical models. The activities should look and feel like a video game and experienced via virtual reality. The Objectives are to create fun and curiosity for the subject matter for the participant. ~~The *Flash Flood!* application is game-based, built around real research data, and has been used to engage thousands of people at science festivals and events. There have been numerous versions of the application across different platforms, including desktop, 360 YouTube videos, and utilising VR. *Flash Flood!* has demonstrated that the SeriousGeoGame model – utilising elements of science festivals, video games, and virtual reality, to produce game-like applications built around a core of real research models and/or data – has had success at achieving the first objective of producing a positive experience for the user. However, although there is evidence that it is successful against the second objective, to increase the~~

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~~user's interest in the research topic, this has proven more difficult to evaluate effectively. There remains great potential to develop *Flash Flood!* and other SeriousGeoGames, particularly using the video games elements and use outside of science festivals to achieve more ambitious objectives.~~Through the *Flash Flood!* activity, a virtual reality simulation showing a geomorphically active flooding from intense rainfall event based on a real event, the SeriousGeoGames model was shown to be successful, with most participants reporting to have enjoyed the activity and the majority reporting to wanting to know more about the subject matter of flooding and geomorphology. This remains true for several audience types, including groups across all school age ranges and also family audiences. Ancillary developments online offered little support to the exhibition of the activity, with minimal traffic relating to events, but could offer a new audience for the activities outside of events.

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Data Availability

The ~~data used in this study can be made available on request by emailing the corresponding author~~evaluation data collected at the events and used in the study can be found online at https://universityofhull.box.com/s/y0lifdeax70u6tk7n81k96xxie5bqbf4. Game files for *Flash Flood!* can be found at https://sourceforge.net/projects/flash-flood/

Ethics Statement

The study complied with all the Ethical Approval processes for the University of Hull. Specific considerations were paid to the use of virtual reality – disclaimers were given in game and verbally about potential dizziness, and to reduce risk participants were required to be seated at all times. In regards to safeguarding and child protection no SeriousGeoGames or Earth Arcade exhibit crew are ever responsible for the care of children who must be accompanied by an adult before participating. Crew are instructed to never find themselves alone with a child. Crew are prohibited from photographing the exhibit whilst the public are present (often exceeding the photography policy of the event). Whilst participating the public are handed the VR headset to have ownership of it during

the activity and instructed how to adjust and wear it, and told to remove whenever they like – crew do not touch the headset whilst it is on someone else's head.

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899 **References**

900 Abt, C. C.: Serious games, University Press of America. [online] Available from:
901 https://books.google.co.uk/books/about/Serious_Games.html?id=axUs9HA-hF8C&redir_esc=y
902 (Accessed 18 March 2019), 1987.

903 Abulrub, A.-H. G., Attridge, A. N. and Williams, M. A.: Virtual reality in engineering education: The
904 future of creative learning, in 2011 IEEE Global Engineering Education Conference (EDUCON), pp.
905 751–757, IEEE., 2011.

906 Adkins, S. S.: The 2018-2023 Global Game-based Learning Market, Serious Play Conf., (July), 1–43,
907 2018.

908 Amory, A., Naicker, K., Vincent, J. and Adams, C.: The use of computer games as an educational tool:
909 Identification of appropriate game types and game elements, Br. J. Educ. Technol., 30(4), 311–321,
910 doi:10.1111/1467-8535.00121, 1999.

911 Bain, V., Gaume, E. and Bressy, A.: Hydrometeorological Data Resources And Technologies for
912 Effective Flash Flood Forecasting HYDRATE Deliverable Report 4.1 : POST FLOOD EVENT ANALYSIS.
913 [online] Available from: www.hydrate.tesaf.unipd.it (Accessed 18 March 2019), 2010.

914 BARB: Games console households, Broadcast. Audience Res. Board [online] Available from:
915 https://www.barb.co.uk/tv-landscape-reports/tracker-games-consoles/ (Accessed 22 October 2019),
916 2019.

917 Bellotti, F., Kapralos, B., Lee, K., Moreno-Ger, P. and Berta, R.: Assessment in and of Serious Games:
918 An Overview, Adv. Human-Computer Interact., 2013, 1–11, doi:10.1155/2013/136864, 2013.

919 Bendixen, M., Best, J., Hackney, C. and Iversen, L. L.: Time is running out for sand, Nature, 571(7763),
920 29–31, doi:10.1038/d41586-019-02042-4, 2019.

921 Betz, J. A.: Computer Games: Increase Learning in an Interactive Multidisciplinary Environment, J.

922 Educ. Technol. Syst., 24(2), 195–205, doi:10.2190/119m-brmu-j8hc-xm6f, 1995.

923 Blascovich, J. and Bailenson, J.: Infinite Reality: Avatars, Eternal Life, New Worlds, and the Dawn of
924 the Virtual Revolution, William Morrow & Co., 2011.

925 Bricken, M. and Byrne, C. M.: Summer Students in Virtual Reality, in Virtual Reality, pp. 199–217,
926 Elsevier., 1993.

927 Bull, W. B.: Threshold of critical power in streams, Geol. Soc. Am. Bull., 90(5), 453, doi:10.1130/0016-
928 7606(1979)90<453:TOCPIS>2.0.CO;2, 1979.

929 Bultitude, K.: Science festivals: Do they succeed in reaching beyond the “already engaged”?, J. Sci.
930 Commun., 13(4), 1–3, 2014.

931 Castell, S., Charlton, A., Clemence, M., Pettigrew, N., Pope, S., Quigley, A., Navin Shah, J. and Silman,
932 T.: Public Attitudes to Science 2014 - Main Report. [online] Available from: www.ipsos-mori.com
933 (Accessed 22 October 2019), 2014.

934 Chappell, J.: Thresholds and lags in geomorphologic changes, Aust. Geogr., 15(6), 357–366,
935 doi:10.1080/00049188308702839, 1983.

936 Charsky, D.: From Edutainment to Serious Games: A Change in the Use of Game Characteristics,
937 Games Cult., 5(2), 177–198, doi:10.1177/1555412009354727, 2010.

938 Chin, J., Dukes, R. and Gamson, W.: Assessment in Simulation and Gaming, Simul. Gaming, 40(4),
939 553–568, doi:10.1177/1046878109332955, 2009.

940 Clark, A.: Being There: Putting Brain, Body, and World Together Again, MIT Press, Cambridge., 1997.

941 Clarke, L., Schillereff, D. and Shuttleworth, E.: Communicating geomorphology: an empirical
942 evaluation of the discipline’s impact and visibility, Earth Surf. Process. Landforms, 42(7), 1148–1152,
943 doi:10.1002/esp.4129, 2017.

944 Coleman, J. S., Livingston, S. A., Fennessey, G. M., Edwards, K. J. and Kidder, S. J.: The Hopkins Games

945 Program: Conclusions from Seven Years of Research, Educ. Res., 2(8), 3–7,
946 doi:10.3102/0013189X002008003, 1973.

947 Connolly, T. M., Boyle, E. A., MacArthur, E., Hainey, T. and Boyle, J. M.: A systematic literature review
948 of empirical evidence on computer games and serious games, Comput. Educ., 59(2), 661–686,
949 doi:10.1016/J.COMPEDU.2012.03.004, 2012.

950 Coulthard, T., Neal, J., Bates, P., Ramirez, J., de Almeida, G. and Hancock, G.: Integrating the
951 LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape
952 evolution, Earth Surf. …, 38(15), 1897–1906, doi:10.1002/esp.3478, 2013.

953 Coulthard, T. J., Ramirez, J., Fowler, H. J. and Glenis, V.: Using the UKCP09 probabilistic scenarios to
954 model the amplified impact of climate change on drainage basin sediment yield, Hydrol. Earth Syst.
955 Sci., 16(11), 4401–4416, doi:10.5194/hess-16-4401-2012, 2012.

956 Crookall, D.: Serious Games, Debriefing, and Simulation/Gaming as a Discipline, Simul. Gaming,
957 41(6), 898–920, doi:10.1177/1046878110390784, 2010.

958 Curtin, J.: How frightened should we be of flooding? - Creating a better place, Environ. Agency Blog
959 [online] Available from: https://environmentagency.blog.gov.uk/2017/10/27/how-frightened-
960 should-we-be-of-flooding/ (Accessed 18 March 2019), 2017.

961 Dance, S., Ballard, S., Bannister, R., Clark, P., Cloke, H., Darlington, T., Flack, D., Gray, S., Hawkness-
962 Smith, L., Husnoo, N., Illingworth, A., Kelly, G., Lean, H., Li, D., Nichols, N., Nicol, J., Oxley, A., Plant,
963 R., Roberts, N., Roulstone, I., Simonin, D., Thompson, R. and Waller, J.: Improvements in Forecasting
964 Intense Rainfall: Results from the FRANC (Forecasting Rainfall Exploiting New Data Assimilation
965 Techniques and Novel Observations of Convection) Project, Atmosphere (Basel)., 10(3), 125,
966 doi:10.3390/atmos10030125, 2019.

967 Dankers, R. and Feyen, L.: Climate change impact on flood hazard in Europe: An assessment based
968 on high-resolution climate simulations, J. Geophys. Res., 113(D19), D19105,

969 doi:10.1029/2007JD009719, 2008.

970 Delamere, F. M. and Shaw, S. M.: “They see it as a guy’s game”: The politics of gender in digital
971 games, Leis. Loisir, 32(2), 279–302, doi:10.1080/14927713.2008.9651411, 2008.

972 Durant, J.: The role of science festivals, Proc. Natl. Acad. Sci., 110(8), 2681–2681,
973 doi:10.1073/pnas.1300182110, 2013.

974 Ekström, M., Fowler, H. J., Kilsby, C. G. and Jones, P. D.: New estimates of future changes in extreme
975 rainfall across the UK using regional climate model integrations. 2. Future estimates and use in
976 impact studies, J. Hydrol., 300(1), 234–251, doi:10.1016/j.jhydrol.2004.06.019, 2005.

977 Entertainment Retailers Association: Streaming drives entertainment sales 9.4% higher in 2018 to
978 sixth consecutive year of growth but physical remains crucial to deliver megahits - ERA, Entertain.
979 Retail. Assoc. [online] Available from: https://eraltd.org/news-events/press-
980 releases/2019/streaming-drives-entertainment-sales-94-higher-in-2018-to-sixth-consecutive-year-
981 of-growth/ (Accessed 18 March 2019), 2018.

982 Entertainment Software Association: 2018 Sales, Demographic, and Usage Data: Essential facts
983 about the computer and video game industry. [online] Available from: http://www.theesa.com/wp-
984 content/uploads/2018/05/EF2018_FINAL.pdf (Accessed 18 March 2019), 2018.

985 Feyen, L., Dankers, R., Bodis, K., Salamon, P. and Berredo, J. I.: Fluvial Flood Risk in Europe in Present
986 and Future Climates, [online] Available from:
987 http://publications.jrc.ec.europa.eu/repository/handle/JRC68817 (Accessed 15 September 2017),
988 2012.

989 Flack, D., Skinner, C., Hawkness-Smith, L., O’Donnell, G., Thompson, R., Waller, J., Chen, A., Moloney,
990 J., Largeron, C., Xia, X., Blenkinsop, S., Champion, A., Perks, M., Quinn, N. and Speight, L.:
991 Recommendations for Improving Integration in National End-to-End Flood Forecasting Systems: An
992 Overview of the FFIR (Flooding From Intense Rainfall) Programme, Water, 11(4), 725,

993 doi:10.3390/w11040725, 2019.

994 Flooding from Intense Rainfall: Flooding From Intense Rainfall | Project FRANC & Project
995 SINATRA, [online] Available from: https://blogs.reading.ac.uk/flooding/ (Accessed 18 March 2019),
996 2019.

997 Fowler, H. J. and Ekström, M.: Multi-model ensemble estimates of climate change impacts on UK
998 seasonal precipitation extremes, Int. J. Climatol., 29(3), 385–416, doi:10.1002/joc.1827, 2009.

999 Fryirs, K. A.: River sensitivity: a lost foundation concept in fluvial geomorphology, Earth Surf. Process.
1000 Landforms, 42(1), 55–70, doi:10.1002/esp.3940, 2016.

1001 García-Ruiz, J. M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J. C., Lana-Renault, N. and
1002 Sanjuán, Y.: A meta-analysis of soil erosion rates across the world, Geomorphology, 239, 160–173,
1003 doi:10.1016/j.geomorph.2015.03.008, 2015.

1004 Google Earth: Thinhope Burn, UK (April 27 2006) 54°52’45.14”N 2°31’23.41”W eye alt 727m,
1005 Infoterra Ltd Bluesky, 2019a.

1006 Google Earth: Thinhope Burn, UK (January 1 2007) 54°52’45.14”N 2°31’23.41”W eye alt 727m,
1007 Getmapping plc, 2019b.

1008 Gosen, J. and Washbush, J.: A Review of Scholarship on Assessing Experiential Learning
1009 Effectiveness, Simul. Gaming, 35(2), 270–293, doi:10.1177/1046878104263544, 2004.

1010 Grand, A. and Sardo, A. M.: What Works in the Field? Evaluating Informal Science Events, Front.
1011 Commun., 2, doi:10.3389/fcomm.2017.00022, 2017.

1012 Hobbs, L., Stevens, C. and Hartley, J.: Digging Deep into Geosciences with Minecraft, Eos
1013 (Washington. DC)., 99, doi:10.1029/2018eo108577, 2018.

1014 Hobbs, L., Stevens, C., Hartley, J. and Hartley, C.: Science Hunters: An inclusive approach to engaging
1015 with science through Minecraft, J. Sci. Commun., 18(2), doi:10.22323/2.18020801, 2019.

1016 Hurley, R., Woodward, J. and Rothwell, J. J.: Microplastic contamination of river beds significantly
1017 reduced by catchment-wide flooding, Nat. Geosci., 11(4), 251–257, doi:10.1038/s41561-018-0080-1,
1018 2018.

1019 Jensen, E.: Highlighting the value of impact evaluation: enhancing informal science learning and
1020 public engagement theory and practice, J. Sci. Commun., 14(3), 1–14, 2015.

1021 Jensen, E. and Buckley, N.: Why people attend science festivals: Interests, motivations and self-
1022 reported benefits of public engagement with research, Public Underst. Sci., 23(5), 557–573,
1023 doi:10.1177/0963662512458624, 2014.

1024 Lane, H. C. and Yi, S.: Playing With Virtual Blocks: Minecraft as a Learning Environment for Practice
1025 and Research, in Cognitive Development in Digital Contexts, pp. 145–166, Elsevier Inc., 2017.

1026 Lane, S. N., Tayefi, V., Reid, S. C., Yu, D. and Hardy, R. J.: Interactions between sediment delivery,
1027 channel change and flood risk in a temperate upland catchment, Earth Surf. Process. Landforms, 32,
1028 429–446, doi:10.1002/esp.1404, 2007.

1029 Mani, L., Cole, P. D. and Stewart, I.: Using video games for volcanic hazard education and
1030 communication: An assessment of the method and preliminary results, Nat. Hazards Earth Syst. Sci.,
1031 16(7), 1673–1689, doi:10.5194/nhess-16-1673-2016, 2016.

1032 Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D. and Bailenson, J. N.: Immersive Virtual Reality
1033 Field Trips Facilitate Learning About Climate Change, Front. Psychol., 9, 2364,
1034 doi:10.3389/fpsyg.2018.02364, 2018.

1035 Mendler De Suarez, J., Suarez, P., Bachofen, C., Fortugno, N., Goentzel, J., Gonçalves, P., Grist, N.,
1036 Macklin, C., Pfeifer, K., Schweizer, S., Van Aalst, M. and Virji, H.: Games for a New Climate:
1037 Experiencing the Complexity of Future Risks task Force report editors task Force Members and
1038 Contributing authors. [online] Available from: http://tinyurl.com/BUPardee-G4NC. (Accessed 18
1039 March 2019), 2012.

1040 Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W. and Davis, T. J.: Effectiveness of virtual
1041 reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-
1042 analysis, Comput. Educ., 70, 29–40, doi:10.1016/j.compedu.2013.07.033, 2014.

1043 Met Office: 5km UK Composite Rainfall Data from the Met Office NIMROD System, NCAS Br. Atmos.
1044 Data Centre, available at : http://catalogue.ceda.ac.uk/uuid/82adec1f896af6169112d09cc1174499
1045 (last access: 20 September 2016), 2003.

1046 Mikropoulos, T. A. and Natsis, A.: Educational virtual environments: A ten-year review of empirical
1047 research (1999-2009), Comput. Educ., 56(3), 769–780, doi:10.1016/j.compedu.2010.10.020, 2011.

1048 Milan, D. J.: Geomorphic impact and system recovery following an extreme flood in an upland
1049 stream: Thinhope Burn, northern England, UK, Geomorphology, 138(1), 319–328,
1050 doi:10.1016/j.geomorph.2011.09.017, 2012.

1051 Mitchell, A. and Savill-Smith, C.: The use of computer and video games for learning: A review of the
1052 literature. [online] Available from: www.LSDA.org.uk (Accessed 18 March 2019), 2004.

1053 Moloney, J., Coulthard, T. J., Rogerson, M. and Freer, J. E.: Reassessing Holocene Fluvial Records -
1054 Applying A New Quality Control Criterion To Radiocarbon Dated Geomorphological Data, Am.
1055 Geophys. Union, Fall Meet. 2018, Abstr. #EP11E-2110 [online] Available from:
1056 http://adsabs.harvard.edu/abs/2018AGUFMEP11E2110M (Accessed 14 May 2019), 2018.

1057 Munafo, J., Diedrick, M. and Stoffregen, T. A.: The virtual reality head-mounted display Oculus Rift
1058 induces motion sickness and is sexist in its effects, Exp. Brain Res., 235(3), 889–901,
1059 doi:10.1007/s00221-016-4846-7, 2017.

1060 Neresini, F. and Bucchi, M.: Which indicators for the new public engagement activities? An
1061 exploratory study of European research institutions, Public Underst. Sci., 20(1), 64–79,
1062 doi:10.1177/0963662510388363, 2011.

1063 Office for National Statistics: Families and Households - Office for National Statistics, Off. Natl. Stat.

[online] Available from:
https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2017 (Accessed 18 March 2019), 2017.

Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Hilberts, A. G. J., Lohmann, D. and Allen, M. R.: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000, Nature, 470(7334), 382–385, doi:10.1038/nature09762, 2011.

Porter, T. and Córdoba, J.: Three Views of Systems Theories and their Implications for Sustainability Education, J. Manag. Educ., 33(3), 323–347, doi:10.1177/1052562908323192, 2009.

Prudhomme, C., Jakob, D. and Svensson, C.: Uncertainty and climate change impact on the flood regime of small UK catchments, J. Hydrol., 277(1), 1–23, doi:10.1016/S0022-1694(03)00065-9, 2003.

Psotka, J.: Educational Games and Virtual Reality as Disruptive Technologies, J. Educ. Technol. Soc., 16, 69–80, doi:10.2307/jeductechsoci.16.2.69, 2013.

Reason, P.: Education for Ecology, Manag. Learn., 38(1), 27–44, doi:10.1177/1350507607073021, 2007.

Rebenitsch, L. and Owen, C.: Review on cybersickness in applications and visual displays, Virtual Real., 20(2), 101–125, doi:10.1007/s10055-016-0285-9, 2016.

Ryan, R. M., Rigby, C. S. and Przybylski, A.: The Motivational Pull of Video Games: A Self-Determination Theory Approach, Motiv. Emot., 30(4), 344–360, doi:10.1007/s11031-006-9051-8, 2006.

Salzman, M. C., Dede, C., Loftin, R. B. and Chen, J.: A Model for Understanding How Virtual Reality Aids Complex Conceptual Learning, Presence Teleoperators Virtual Environ., 8(3), 293–316, doi:10.1162/105474699566242, 1999.

Schumm, S. A.: Geomorphic thresholds: t he concept and i t s applicationsI. [online] Available from:

https://pdfs.semanticscholar.org/8509/62189c833c950e9b94a0713fb8200aeeb810.pdf (Accessed 18 March 2019), 1979.

Science Festivals Alliance: Science Festivals Alliance: 2017 Annual Report. [online] Available from: https://sciencefestivals.org/wp-content/uploads/2017-SFA-Annual-Report-Lo-Res.pdf (Accessed 18 March 2019), 2018.

Skinner, C.: Riding the (Flood) Wave - Flash Flood! Desktop, Teach. Geogr., In Press, 2018.

Skinner, C. and Milan, D.: Visualising the Geomorphic Impacts of Flood Risk, Geogr. Rev., In Press, 2018.

Slater, L. J.: To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales?, Earth Surf. Process. Landforms, doi:10.1002/esp.3927, 2016.

Smith, M.: One in ten Brits have a zombie plan | YouGov, YouGov [online] Available from: https://yougov.co.uk/topics/politics/articles-reports/2017/09/08/one-ten-brits-have-zombie-plan (Accessed 18 March 2019), 2017.

Squire, K.: Video Games in Education, Int. J. Intell. Simulations Gaming, 1, 49–62 [online] Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.543.5729&rep=rep1&type=pdf (Accessed 18 March 2019), 2003.

Sutherland, I. E., Blackwell, A. and Rodden, K.: Number 574 Sketchpad: A man-machine graphical communication system, [online] Available from: http://www.cl.cam.ac.uk/ (Accessed 18 March 2019), 2003.

Trope, Y. and Liberman, N.: Construal-level theory of psychological distance, Psychol. Rev., 117(2), 440–463, doi:10.1037/a0018963, 2010.

Vogel, J. J., Vogel, D. S., Cannon-Bowers, J., Bowers, C. A., Muse, K. and Wright, M.: Computer Gaming and Interactive Simulations for Learning: A Meta-Analysis, J. Educ. Comput. Res., 34(3), 229–

243, doi:10.2190/FLHV-K4WA-WPVQ-H0YM, 2006.

Warburton, K.: Deep learning and education for sustainability, Int. J. Sustain. High. Educ., 4(1), 44–56, doi:10.1108/14676370310455332, 2003.

Weisberg, S. M. and Newcombe, N. S.: Embodied cognition and STEM learning: overview of a topical collection in CR:PI, Cogn. Res. Princ. Implic., 2(1), 38, doi:10.1186/s41235-017-0071-6, 2017.

Wiehe, B.: When science makes us who we are: Known and speculative impacts of science festivals, J. Sci. Commun., 13(4), doi:10.22323/2.13040302, 2014.

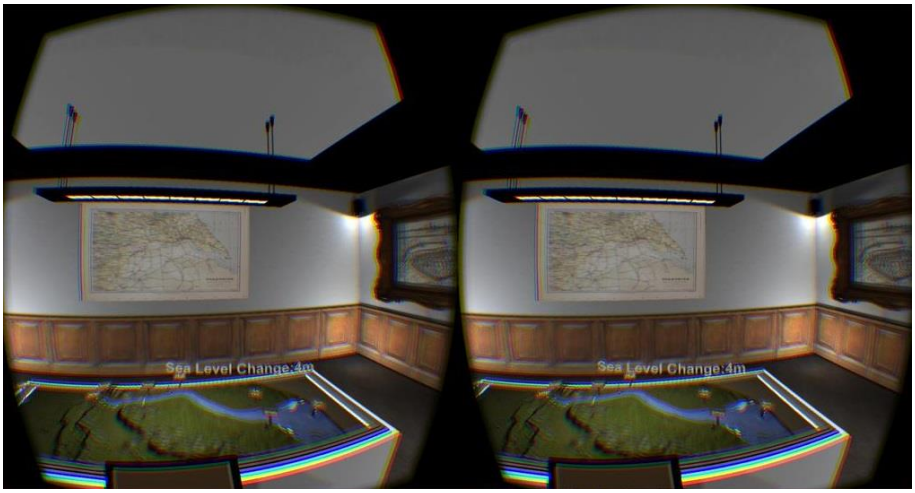
Wijman, T.: Global Games Market Revenues 2018 | Per Region & Segment | Newzoo, Newzoo [online] Available from: https://newzoo.com/insights/articles/global-games-market-reaches-137-9-billion-in-2018-mobile-games-take-half/ (Accessed 18 March 2019), 2018.

Wilson, K. A., Bedwell, W. L., Lazzara, E. H., Salas, E., Burke, C. S., Estock, J. L., Orvis, K. L. and Conkey, C.: Relationships Between Game Attributes and Learning Outcomes, Simul. Gaming, 40(2), 217–266, doi:10.1177/1046878108321866, 2009.

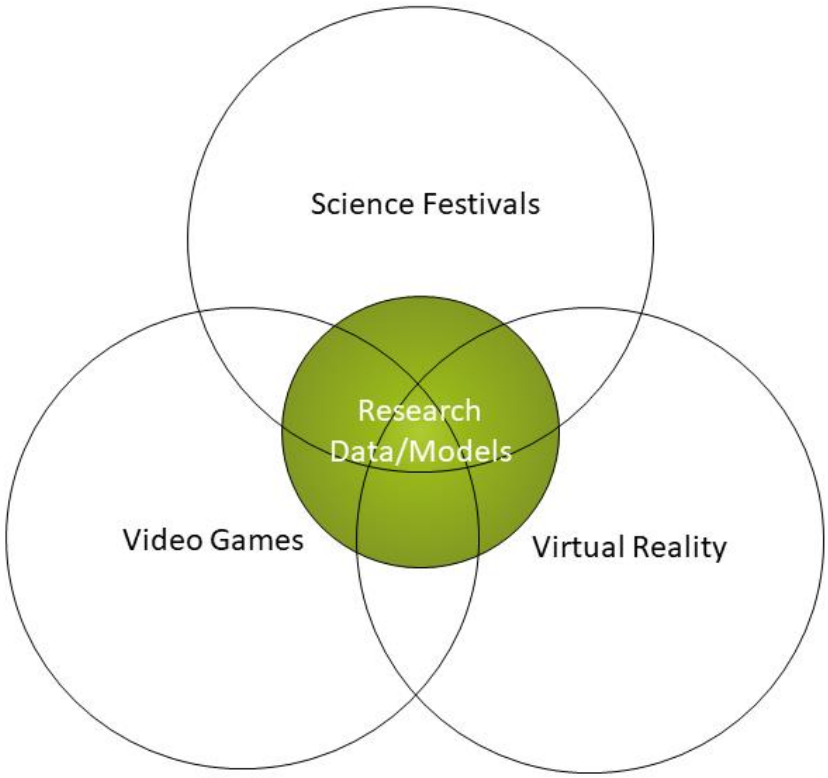
Woolman, A.: Rounding up the Network in 2018, UK Sci. Festiv. Netw. [online] Available from: http://sciencefestivals.uk/rounding-up-the-network-in-2018/ (Accessed 22 October 2019), 2019.

Wu, J. S. and Lee, J. J.: Climate change games as tools for education and engagement, Nat. Clim. Chang., 5(5), 413–418, doi:10.1038/nclimate2566, 2015.

~~Figures~~



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

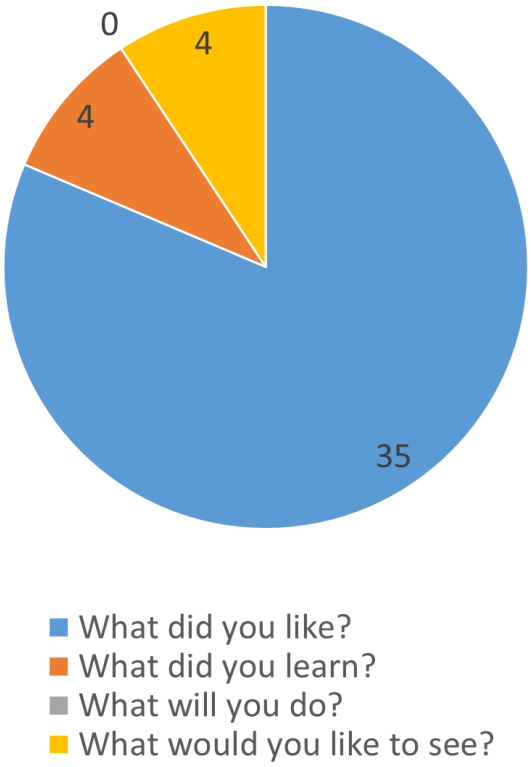


~~Figure 2 – Venn diagram showing the SeriousGeoGame model – a true SeriousGeoGame would be positioned in the middle of the diagram, built with research data and/or models, and using elements from science festivals, videos games, and virtual reality.~~

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

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

~~**Figure 5—Screenshot from *Flash Flood! Vol 2*.**~~



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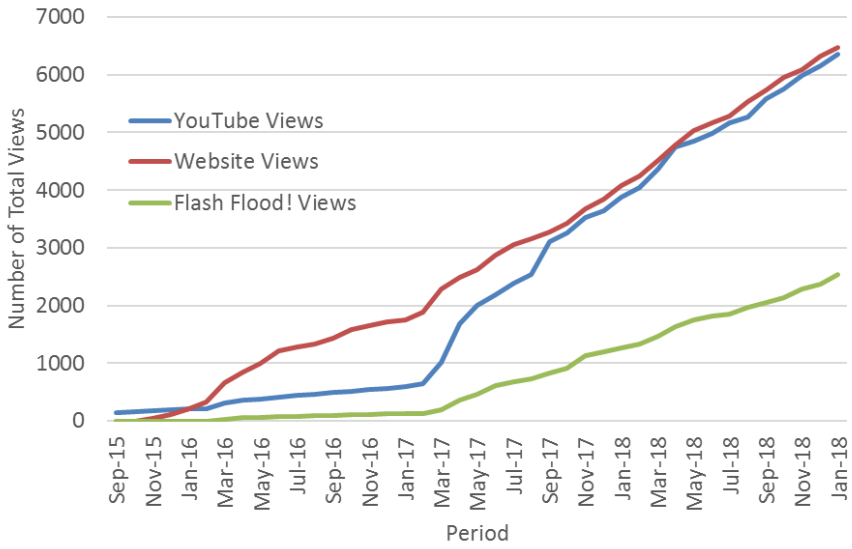
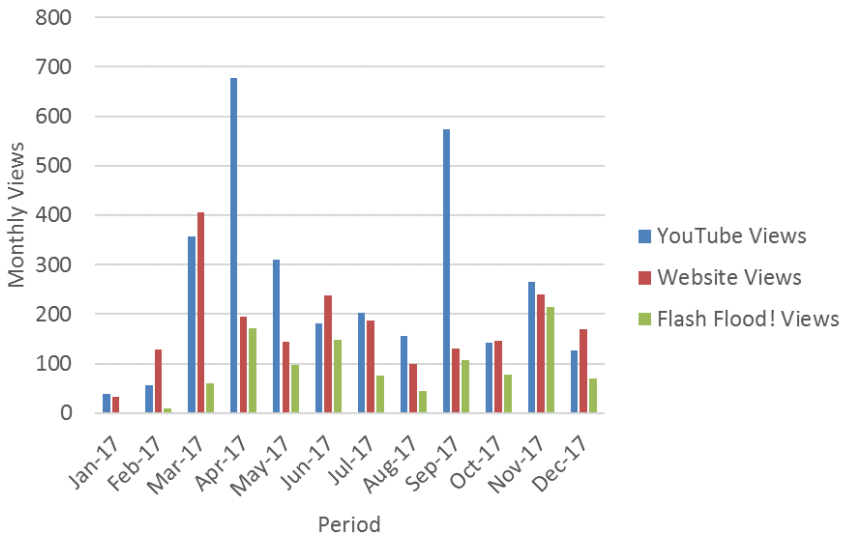
1146 ~~Figure 6 – Division of responses relating to Flash Flood! at Hull Science Festival 2018.~~



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



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