Authors response to Review comment by Olivier Dewitte (Referee) for "Formation, breaching and flood consequences of a landslide dam near Bujumbura, Burundi"

Léonidas Nibigira[1], Hans-Balder Havenith[1], Pierre Archambeau[2], and Benjamin Dewals[2]

[1]Geohazards and Environment, Department of Geology, University of Liege, 4000 Liege-Belgium

[2]Hydraulics in Environmental and Civil Engineering (HECE), Research unit Urban & Environmental Engineering, University of Liege, 4000 Liege-Belgium

Correspondence to: Léonidas Nibigira (leonidas.nibigira@doct.ulg.ac.be)

Throughout this document, each Reviewer comment is bordered in black and is directly followed by authors' response. Sometimes, in case two or more comments have a certain affinity, they are bordered together and answered once and for all. When a rewording is proposed, the text is in italics and in quotation marks.

1. **General comment:**

> Dear colleagues,
>
> The research proposed by Nibigira and co-authors focuses on landslide damming and possible subsequent flood occurrence in Bujumbura. More specifically, the authors focus on a large landslide that develops in a watershed flowing toward the city center. The first part deals with geophysics and landslide 3D and 2 D reconstruction. The second part is with the modelling of the landslide. The third part deals with the simulations of the floods and their associated hazard induced by dam breaching. The manuscript presents interesting results for such an understudied region; especially when one considers that in these African regions data scarcity is commonplace. I agree with the comments and suggestions by the first reviewer. I have therefore done my review accordingly (see supplement material). This includes minor to moderate comments and technical corrections. Two points I insist to are the weathering of the lithology and, for the introduction, the data-scare context and methodological challenges of the study area.
>
> Regards
>
> Olivier Dewitte

Thank you for your very interesting and enriching comments and suggestions to our manuscript.

Specific comments:

2. 1: (Line 20) The introduction can be improved as it suffers from a lack of state of the art referencing to the general literature on landslide dam and related flood modelling. As it stands now we miss the broader context of this study (scientific and societal needs to perform such a study, challenges to get relevant input data for modelling, context of data scarcity in the studied region, methodological challenges, etc.). Then, based on this context, comes the objectives that you aim at studying a specific landslide in a specific region.

A rewording of the introduction is proposed below (Fig. 3 is the former Fig. 14 moved as suggested later within the comment 2.28):

"*The city of Bujumbura, the capital of Burundi, faces serious problems related to natural hazards. Floods are the most important natural challenge in terms of induced losses. This is aggravated by heavy tropical rains. It also becomes clear that geohazards strongly contribute to the risk of flooding. In February 2014, floods resulting from a failure of a temporarily created landslide dam caused 64 casualties. Over 940 houses were destroyed and this resulted in over 12,500 homeless people (UNITAR/UNOSAT 2014, Reliefweb 2014). This indicates that a complete assessment of flood risk should consider landslides which may be considered as some of the most important natural hazards in the region. They interact with the hydrographic network by forming natural dams. The formation of landslide dams is caused by the combination of several factors. Many spectacular cases report the involvement of earthquakes as a major trigger (Adams, 1981; Cui et al., 2012). For example, the Wenchuan earthquake in 2008 caused up to 828 landslide dams (Fan et al., 2013). In addition to earthquakes, also long and heavy rain falls (Li et al., 2011) as well as other local parameters can lead to slope instability and to landslide dam formation. Losses related to natural dams can occur both during and after the formation of the dam. Losses that occurred during the formation are exemplified by the cases of the village of Hsiaolin that had been entirely buried in 2011 under a massive debris flow and landslide in southern Taiwan (Li et al., 2011) or by the sweeping of Attabad and Sarat villages in Northern Pakistan in 2010 (Butt et al., 2013). In many other cases, final losses are mainly related to the dam failure and associated downstream floods. Related studies (Cui et al., 2006; Wells et al., 2007; Downs et al., 2009; Wang et al, 2016; Costa and Schuster, 1988; Li et al., 2002, Dong et al., 2011; Chen et al.,2004) show that the effects of dam failure can be many times greater than those caused by sliding during the formation of the dam. Although different methods have been proposed and applied to understand their formation and/or breaching mechanisms (Korup,2004; Corominas and Moya, 2008; Crosta and Clague, 2009; Dong et al., 2009; Nandi and Shakoor, 2009; Shrestha, B. and Nakagawa, 2016), each case of natural dam has its own specificities related to the local context. Therefore, case studies are very important. Unfortunately, there is a lack of both case studies and data required by the analyses. Consequently, statistical studies based on past events are almost useless if the risk of dam formation or of the breach of an existing dam has to be assessed. This underlines the importance of scenario simulations supported by the use of modern modeling tools, even if those are often compromised by the lack of validated inputs. In Central Africa (including Burundi, where the city of Bujumbura is located), despite existing work in the field of environmental hazard analysis (Ilunga, 2006; Moeyersons et al., 2010;*

Nibigira et al., 2015; Michellier et al., 2016; Jacobs et al., 2017), studies providing quantified landslide multi-risk scenario analyses are still rare. This lack of multi-risk studies in equatorial Africa was highlighted recently by Jacobs et al. (2016). For the city of Bujumbura, there is a clear need to develop a multi-risk study, analyzing, on one hand, the hazard related to landslide activation and natural dam formation, and, on the other hand assessing the potential impacts on the hydrographic network resulting from the breach of those dams.

We applied such a study to the existing mass movement called 'Banana Tree Landslide' (called BTL below). This landslide was chosen for its size (it is the largest active landslide in the vicinity of Bujumbura with a volume of more than 4×10^6 m^3*) and due its position along the Kanyosha River, upstream from the city (Fig. 1) making it a potential danger for people and infrastructures in the area. As the gorge is relatively narrow at the level of the landslide, a displacement of the BTL of a few tens of meters would be enough to form a natural dam and a reservoir lake which could later break with all the risks that such an event represents for the part of the city located downstream. The lifespan of natural dams cannot be known accurately and can be relatively short: less than one hour for 34% of the known cases investigated by Peng and Zang (2012) and 27% of all cases according to Costa and Schuster (1988). Moreover, considering the tropical climate context of the target area, it can be assumed that the reservoir behind a new dam can be quickly filled after very intense rainfalls that occur on a regular basis during the wet season. All those parameters reduce considerably the time between the dam formation and the possible dam breaching, highlighting the necessity to know in advance the consequences corresponding to different scenarios, particularly for such areas where warning systems are not very effective or just missing. Our recent observations show that the western part of the landslide (in the foreground of Fig. 2a), with relatively soft slopes, is marked by very local slope instabilities (yellow and light blue dotted contours) that do not contribute to the general movement. However, the eastern part (black dot outlines in Fig. 2a) presents steep slopes near the river; this active zone is 250 m wide and could soon move to form a landslide dam. The presence of water ponds in this eastern part (Fig. 3c) is likely to contribute to future instability that could develop along the main sliding axis BC (shown in Fig. 2a). In order to understand the landslide mechanisms in terms of triggering factors, evolution and effects, numerical modelling has been carried out to analyse its stability, also under dynamic (seismic) conditions. The effects of the dam and its breaching on the flood potential along the river and the consequences especially downstream in the urban area were studied through an additional hydraulic model. Simulated flood scenarios are discussed with respect to parameters such as the water depth, the flow velocity and the floodplain delineation."*

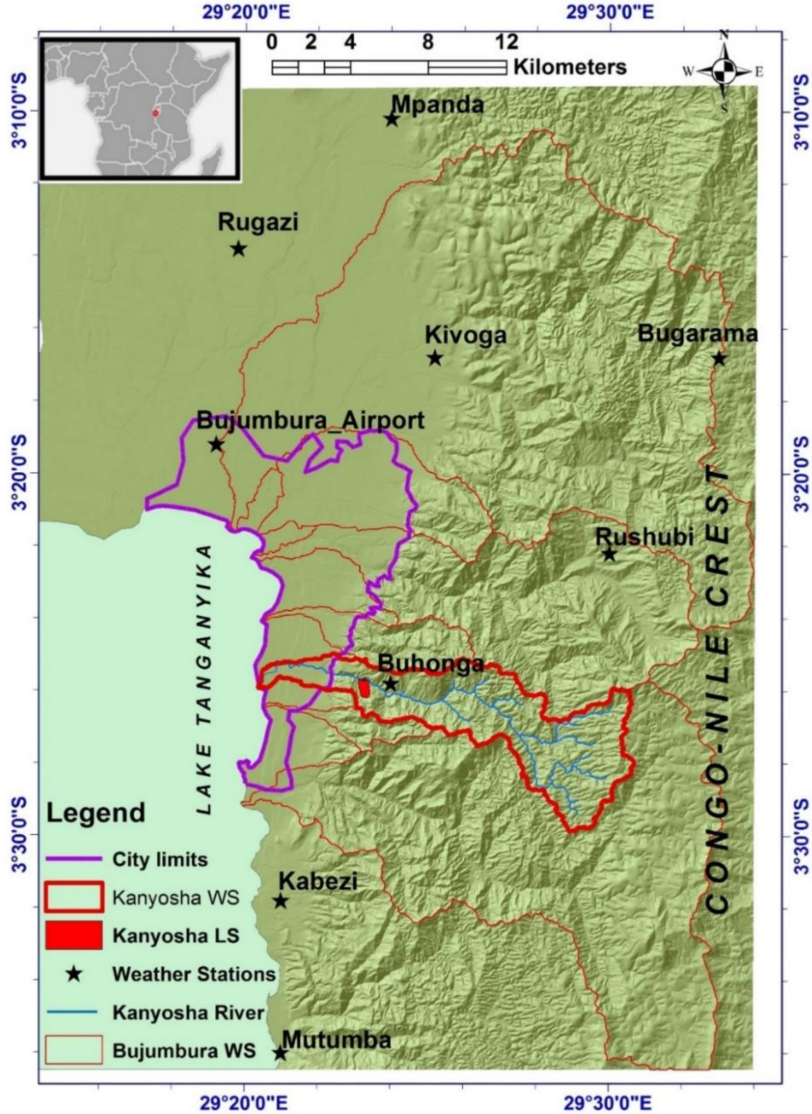

Figure 1. *Map of Bujumbura region with indication of watersheds for the main rivers, the limits of the city and the Lake Tanganyika. The watershed of the Kanyosha River is highlighted in the central part, with the river network inside. The weather stations in and around Bujumbura, the Kanyosha Landslide (in the text called 'Banana Tree Landslide', also referred to as BTL, in red contours) and the Congo-Nile crest are also shown. 'LS' and 'WS' stand for 'Landslide' and 'Watershed', respectively.*

Figure 2. *(a) View of BTL (black dotted contour) and of the main scarp (red dotted contour) from downstream (other orange and light blue dotted contours mark other instabilities). The landslide sliding direction and the river flow direction are indicated by red and black arrows, respectively. AB indicates the height (=26 m) of the landslide frontal part near the river; BC outlines the BTL length in the sliding direction (~750 m); CD shows the height of the main scarp (~ 75m) along profile BCE. The blue line indicates the river channel axis. (b) Waterfall over a destroyed old hydraulic structure. (c) View of the river bed during the dry season with presence of cobbles and fine boulders that are deposited after floods during the wet season.*

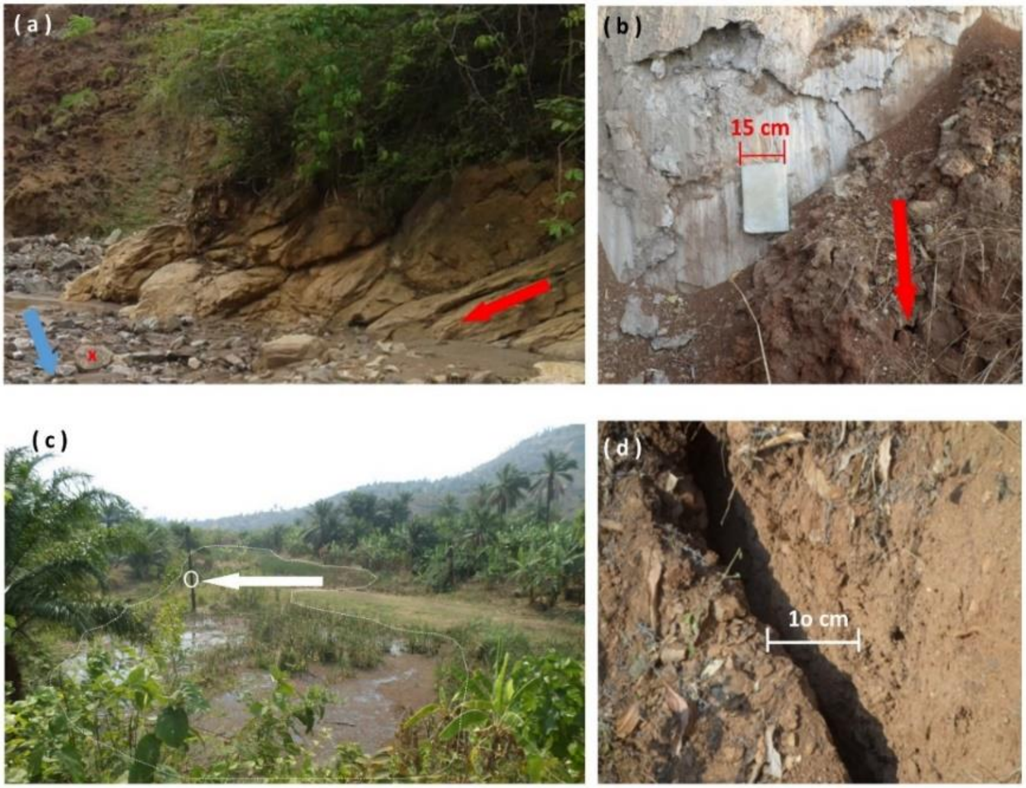

Figure 3. *Field observations highlighting the critical stability state of BTL. (a) View of the rock structures at the foot of the landslide (note the boulder marked by a red cross in the lower left part has a diameter of about 60 cm), generally dipping towards the north (left side), parallel to the sliding direction (red arrow). The blue arrow indicates the river flow direction. (b) View of a crack on the sliding interface in clay. The red arrow shows the direction of sliding of the right part along the clay layer. (c) Pond on the landslide with an oil palm designated by the white arrow. This shows that these ponds are recent (oil palm trees do not grow in water; its particular foliage compared to others shows that its growth was stopped recently). (d) A crack found on the landslide surface.*

2. 2: (Fig. 1) The relief is represented with shiny colors. I would have combined them with a hill shade view to improve readability.

To take into account your very relevant recommendations, the map has been modified (see Fig. 1 above).

2. 3: (Fig. 1) Delete the "_"

The "_" is deleted from the legend of Fig. 1.

2.4: (Fig. 1) Color issues: blue for watershed delineation and red for a river is weird. I suggest blue for the river and another color for the watershed.

Your suggestions are taken into account: blue is used for the river network while red is used for the watershed delineation (Fig. 1).

2.5: (Fig. 2) where is the waterfall located?

This waterfall formed on a former flood control structure is located at 270 m downstream the cross section 3 shown in Fig. 4 (shown below).

2.6: (Line 50) This means that the dotted contour line used in Figure 2 represents only part of the landslide; i.e. the landslide section that you consider in the modelling. That something that should be stressed better within the Figure caption. So far, this figure shows some landslide parts such as the one where the compass rose is positioned that are not delineated alone. Based on the figure and its caption alone, it looks strange.

Your opinion is very relevant, since other instabilities appear on the figure.

Indeed, the whole site of the BTL is strongly weakened, creating small secondary landslides juxtaposed with the main landslide. These are located at the foot of the slope along the Kanyosha River and do not follow the dynamics of the global movement. They are detached by small blocks that are then subject to erosion and are therefore not likely to produce significant effects on the risk of flooding. This is well expressed from line 48 to line 51 of the manuscript.

In our opinion, the confusion comes partly from the fact that the figure is not strongly announced, leading the reader to ask himself some questions before having a look at the following parts of the manuscript. For this reason, we believe that moving the paragraph from Line 48 to Line 51 of the manuscript ("Our recent observations ... move and form a landslide dam") and inserting it before Fig. 2 of the manuscript would help to improve the manuscript, as it will serve as introduction to the Fig. 2.

For this purpose, we propose, on the agreement of the Editor, the displacement of the aforementioned paragraph in the revised version of the manuscript.

This is, with a slight correction ("*yellow and blue dotted contour*" is added in parentheses after "local *slope instabilities*"), the paragraph that will be moved to serve as introduction to Fig. 2:

Our recent observations show that the western part of the landslide (in the foreground of Fig. 2a), with relatively soft slopes, is marked by very local slope instabilities (yellow and light blue dotted contours) that do not contribute to the general movement. However, the eastern part (black dot outlines in Fig. 2a) presents steep slopes near the river; this active zone is 250 m wide and could soon move to form a landslide dam.

Moreover, related information will be added within the Fig. 2 caption as follows for much more details:

Figure 2. *(a) View of BTL (black dotted contour) and of the main scarp (red dotted contour) from downstream (other orange and light blue dotted contours mark other instabilities). The landslide sliding direction and the river flow direction are indicated by red and black arrows, respectively. AB indicates the height (=26 m) of the landslide frontal part near the river; BC outlines the BTL length in the sliding direction (~750 m); CD shows the height of the main scarp (~ 75m) along profile BCE. The blue line indicates the river channel axis. (b) Waterfall*

over a destroyed old hydraulic structure. (c) View of the river bed during the dry season with presence of large boulders that are deposited after floods during the wet season.

2.7: (Line 51) The presence of water ponds is a sign of the landslide current activity. However, can you elaborate more on the role of those ponds on future instability? Do you have references to support this?

First, this idea is strongly supported later by our results. In fact, these ponds contribute to the saturation of the landslide body, whereas in sections 3.1 and 3.2, we have quantified the impact of groundwater on landslide, as it greatly reduces the factor of safety (FoS) and increases X-acceleration.

The weight of water ponds also contributes to the loading of the sliding. The impact of the slope overloading on the landslide dynamics is also strongly highlighted both by Terzaghi (1950), Varnes (1978), Popescu (1994) and Popescu (2002).

2.8: (Line 53) well, I wonder how one single landslide could have on impact in the country's economy. I suggest to rephrase this in a more balanced way: "... makes it a potential danger for people and infrastructures of that area".

Yes, a rewording of Line 53 of the manuscript will be made to include your suggestion. This was the result of an error in writing and the correction is already included at Line 74 of this document, within the proposed rewording of the introduction in our reply to comment 2.1 above. Our intention was to apply "imminent danger" only to "for life" and point out the possibility of slight economic issue, regardless of the degree of impact. Based on the disastrous consequences of the landslide along the Gasenyi River in February 2014, there is a real disruption at least for the short term. More than 940 homes destroyed and 12500 homeless people to manage, especially in a non-preparedness situation. Reconstruction and studies as well as corollary changes to operate to avoid new disasters in the area etc., can require a real effort in the context of a fragile economy.

Moreover, the BTL is more than 3 times larger than that of the Gasenyi River (under 10 m high for the Gasenyi landslide dam while the BTL can potentially be 15 m-20 m high).

To give an idea of what such disastrous event can coast to the economy, we would like to present a brief analysis of the flood of 2014.

First, it should be noted that for 2014, the Government of Burundi adopted an austerity budget policy (that was called '***GUTUBIKA UWAVUBI***' in Kirundi, the Burundian language), with an annual budget of 1403.3 billion Burundian Francs (909.8 million USD).

Following the catastrophic floods that occurred in February 2014 (Table 1), a joint mission of some agencies and programs of the United Nations, the European Union, the African Development Bank and the World Bank was deployed to evaluate the disaster.

Overall, according to estimates given by the technical teams, the losses related to public infrastructure, Crops and private houses exceeded 18.9 Million USD. That is about 2.1% (of which 0.49% for the public infrastructures and 1.6% for Crops and private houses) of the annual budget of the State.

However, the rehabilitation and management measures and especially the resulting disaster prevention measures are much cheaper than the initial damages. These fees were estimated at 105.7 million USD, the equivalent of 11.61% of the annual budget. This is, unfortunately, a real challenge, in the economic context mentioned above.

In terms of harvests, an estimate was made by FAO while for infrastructure, the evaluation was carried out by a team of UNDP and IOM, supported by both the Road Sector Project Implementation Units and the Public Works & Urban Management unit.

(FAO: Food and Agriculture Organization, UNDP: United Nations Development Program)

> 2.9: (Line 62: channel description) I know that they are some definitions related to the size. I am not sure a 40 cm diameter is appropriate for a pebble. Not even 10 cm to be checked with a classification system adapted for your study.

The extended Udden-Wentworth grain-size scale nomenclature will be applied, as proposed later in our reply for the comment 2.12. Grain-size in the text proposed to comment 2.12 is reworded accordingly.

> 2.10: (Line 63: channel description) size of those stones? Usually, above few tens of cm we call them boulders.

A rewording is proposed within the reply to 2.12.

> 2.11: (Line 65: channel description) Accumulation zones of what?

This section is improved by the use of a suitable grain-size classification. The accumulation consists of fine materials (clay and silt) trapped in small flats or generally upstream of the remains of old hydraulic structures. Often, within these areas develop small green islets like those shown in Fig. 2.b. The rewording proposed in the reply to the comment 2.12 includes all these details.

> 2.12: (Line 65: channel description) Do you make a distinction between pebbles and debris? If so, where does debris come from? More info needed.

Regarding the comments from 2.7 to 2.10 and their reply given above, a rewording of the channel description (Sec. 2.1) is proposed below:

"The Kanyosha River main channel has deposits with variable grain size. Based on the extended Udden-Wentworth grain-size scale nomenclature (Terry and Goff, 2013), the riverbed material can be classified into three main groups. The first consists of cobbles of around 10 cm in diameter or more (Fig. 2c). The coarse part of this category consists of fine boulders, with a diameter generally under 40 cm. The second group is made up of isolated medium boulders that are often prone to the action of humans, carving them into building materials (mainly paving plates).

This category is difficult to take into account due to its strong irregularity. The third group consists of silt and clay zones, generally near former hydraulic structures in the downstream part of the river. In this category, we can mention small herbaceous islets, often located near the river overbanks. As in the second group, this category is found only in small isolated and scattered areas, subject to strong seasonal variations. Globally, the first group remains hydraulically predominant. Here, the variability of the grain size was accounted for by means of sensitivity analysis (Sec. 3.3).

In 2006, hydraulic structures were constructed to regulate the river; but they were quickly damaged by floods during the following raining seasons. Nonetheless, isolated cobbles resulting from the destruction of these structures are observed. They join the second group described above. The accumulation of material upstream of the remains of the structures often form horizontal platforms, generating small waterfalls (Fig. 2b).''

Details for the Udden-Wentworth grain-size scale nomenclature are provided in Table 1 below:

PARTICLE LENGTH (dI) km	m	mm	Φ	GRADE	CLASS	FRACTION Unlithified	FRACTION Lithified
1075			-30	very coarse	Megalith	Megagravel	Mega-Conglomerate
538			-29	coarse			
269			-28	medium			
134			-27	fine			
67.2			-26	very fine			
33.6			-25	very coarse	Monolith		
16.8			-24	coarse			
8.4			-23	medium			
4.2			-22	fine			
2.1			-21	very fine			
1.0	1048.6		-20	very coarse	Slab		
0.5	524.3		-19	coarse			
0.26	262.1		-18	medium			
	131.1		-17	fine			
	65.5		-16	very coarse	Block		
	32.8		-15	coarse			
	16.4		-14	medium			
	8.2		-13	fine			
	4.1	4096	-12	very coarse	Boulder		
	2.0	2048	-11	coarse			
	1.0	1024	-10	medium			
	0.5	512	-9	fine			
	0.25	256	-8	coarse	Cobble	Gravel	Conglomerate
		128	-7	fine			
		64	-6	very coarse	Pebble		
		32	-5	coarse			
		16	-4	medium			
		8	-3	fine			
		4	-2		Granule		
		2	-1	very coarse	Sand	Sand	Sandstone
		1	0	coarse			
		0.50	1	medium			
		0.25	2	fine			
		0.125	3	very fine			
		0.063	4	coarse	Silt	Mud	Mudstone or Shale
		0.031	5	medium			
		0.015	6	fine			
		0.008	7	very fine			
		0.004	8		Clay		
		0.002	9				
		0.001	10				
		0.0005	11				
		0.0002	12				
		0.0001	13				

Table 1: Extended Udden-Wentworth grain-size scale for sedimentary particles, after Blair and McPherson (1999). (Source: Terry and Goff, 2013).

2.13: (Fig. 3) Colors are not used at their best. Suggestions for improvement: for elevation: avoid blue. As you are studying flood, it is pretty confusing. If you do not use blue for topography, you can use it for the river (which sounds more logical). Then the cross sections can be in black.

2.14: (Fig. 3_ caption) As it reads now, it is pretty confusing. It seems that you have used a hillshade product for the modelling. In addition, the figure shows a mix of DEM and hillshade.

2.15: (Fig. 3_caption) No need to repeat in the caption what you have in the legend.

Here bellow is the proposition for Fig.3 (according to the proposition, the number of that figure will be 4 instead of 3, due to the previous insertion of the former Fig.14) and its caption, based on comments 2.13, 2.14 and 2.15:

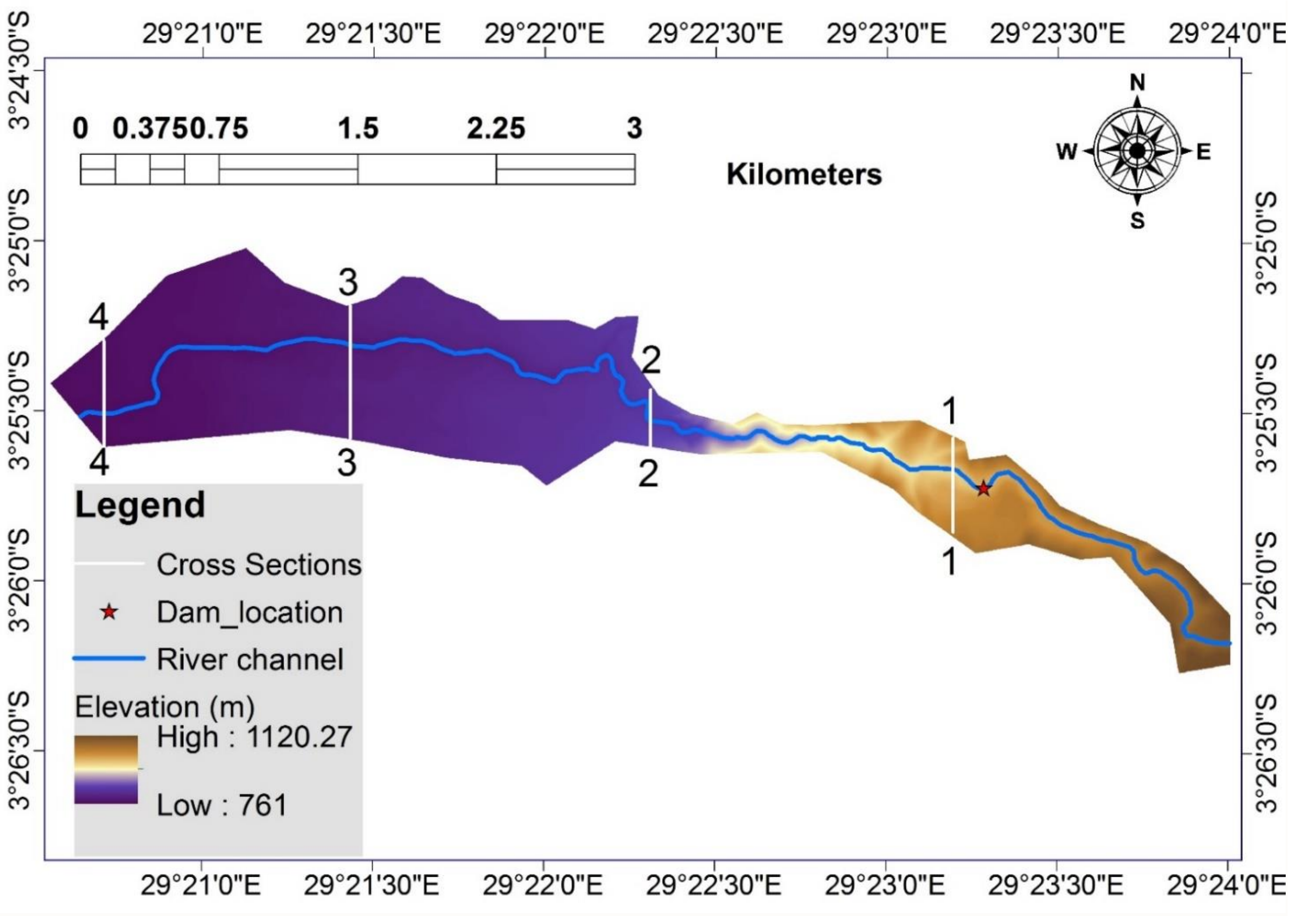

Figure 4. Digital elevation model (m) used for hydraulic modelling within the computation domain with cross sections where hydrographs were extracted and dam location. The river main channel is also highlighted.

2.16: (Line 94) Up to now, there is no reference in the landslide description that the material is made of rock. From figure 2, it looks as if most of the landslide material is highly weathered. I think it is important to mention this weathering issue as this is something very specific of this type of tropical climate.

The original material of BTL is a gneiss which, by the alteration, is partially transformed into a clay on the surface. The depth of the altered layer is about 20 m.

The study area experiences alternations between dry and rainy seasons. The long dry season (from June to September) is followed by the small rainy season (from October to December), then by the small dry season (during the months of January and February). The cycle ends with the strong rainy season from March to May, just before the return of the dry season. Since the photos in Fig. 2 were taken in October, the ground was relatively wet, but not quite enough compared to December and the strong rainy season.

Especially for the low parts of the landslide, the humidity is never very low due to the recharge of the water table by the ponds of water located on the landslide. On the other hand, the groundwater recharge follows the dynamics of the seasons. In the context mentioned above, the action of the rainy season in the body of the landslide is quickly sensible, due to the water that sneaks in the interstices.

2.17: (Line 96) GPS? Why not deriving the profile from the DEM?

The geophysical survey technique by electric tomography profiles requires elevation values at each of the electrodes positioned every 5m. Thus, additional elevation values were needed to complete the 10X10 m DEM.

2.18: (Line 110) Can you say something about the material and the weathering conditions?

Indeed, the details given in response to comment 2.16 above in terms of material and weathering conditions will be inserted in the manuscript, Line 110, just after the sentence "It corresponds to the average type of the material found within the landslide". The text should be the following:

"*The original material of BTL is a gneiss which, by the alteration, is partially transformed into a clay on the surface. The depth of the altered layer is about 20 m. The study area experiences alternations between dry and rainy seasons. The long dry season (from June to September) is followed by the small rainy season (from October to December), then by the small dry season (during the months of January and February). The cycle ends with the strong rainy season from March to May, just before the return of the dry season. Since the photos in Fig. 2 were taken in October, the ground was relatively wet, but not quite enough compared to December and the strong rainy season. Especially for the lower parts of the landslide, the humidity is never very low due to the recharge of the water table by the ponds of water located on the landslide. On the other hand, the groundwater recharge follows the dynamics of the seasons. In the context mentioned above, the action of the rainy season in the body of the landslide is quickly sensible, due to the water that sneaks in the interstices*.".

2.19: (Fig. 6) Not visible (The point 14)

2.20: (Fig. 6) X scale of Figure 5 starts with 0 close to the landslide main scarp and the river axis is at 900 m… I suggest the same scale is used here for the sake of clarity.

The modified version of Fig.6 (the number of that figure will be 7 instead of 6 for reasons mentioned above) is proposed below:

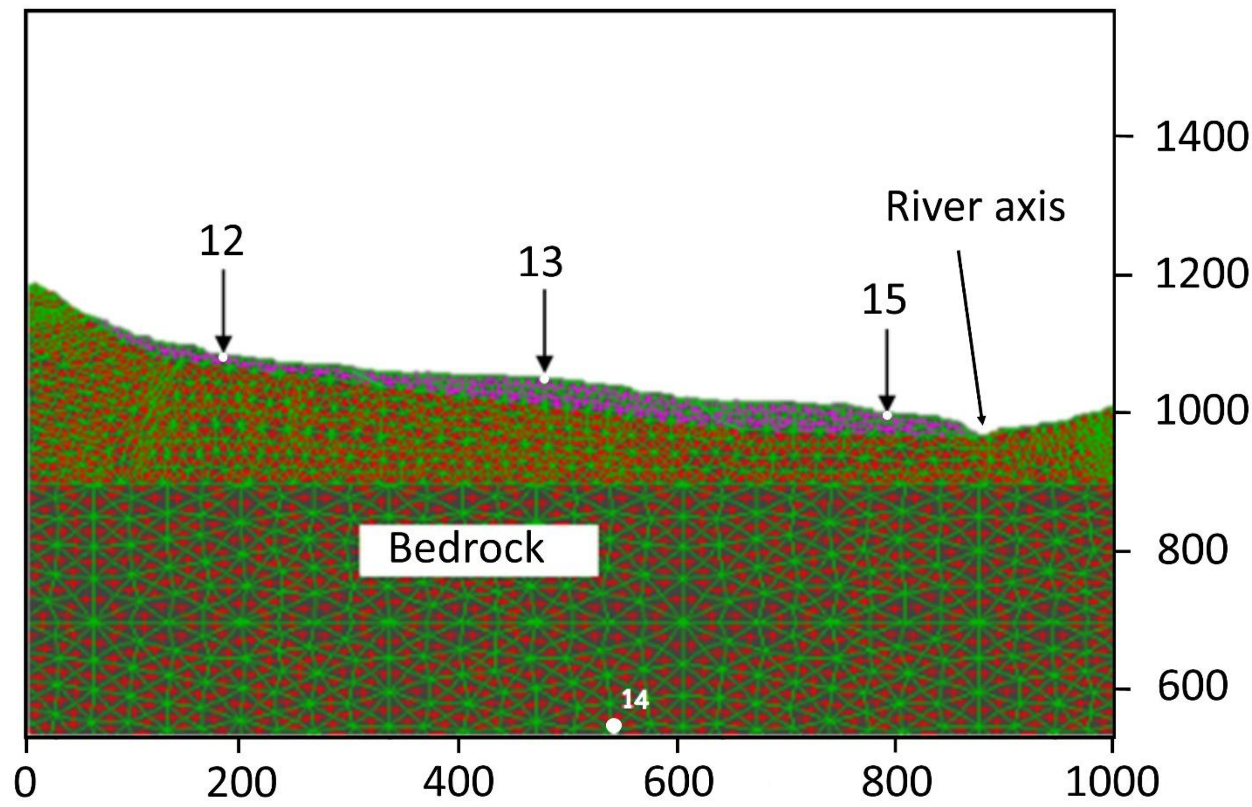

Figure 7. Materialization of blocks, joints and materials for the actual model. The history (measurement) points 12, 13 and 15 (white dots) located, respectively, on the upper, middle and lower block correspond to the surface area where parameters were monitored (e.g. the *x*-acceleration). The point 14 is located at the basis of the model, within the bedrock. The axis of the Kanyosha River is located to the right of the history point 15.

2.21: (Line 140) References that justify these options? Can you discuss this?

Even tough each case is different, data availability helps to refer to an existing data base and case studies within the study area. Unfortunately, considering the context of data scarcity in the region, it is not easy to find related references. This is why we did not assign a single value, but 4 different shaking duration values to well illustrate the behavior of the model corresponding to different scenarios. The seismic context is analyzed on the basis of earthquakes data from the Global Seismographic Network stations of the Incorporated Research Institutions for Seismology (IRIS) on the Lake Tanganyika Region. Therefore, based on that situation and local site effects, the 0.1g-wavelet used is chosen as reasonable value to predict the behavior of the landslide under very moderate seismic shaking.

2.22: (Line 264) Replace by "could".

This will be corrected in the revised version of the manuscript.

2.23: (Line 265) The origin of the water pounds present in the landslide can also be of runoff concentration origin.

Yes, we do agree with you and this was already mentioned in the discussion section within the first version of the manuscript (Line 399 of the manuscript).

2.24: (Line 265) You mean, in the landslide body?

We mean water ponds on the landslide (BTL), as shown in Fig. 3c above (Fig. 14c in the manuscript).

2.25: (Line 269) You mean BTL landslide is it?

Yes. To avoid any confusion, we shall change “Kanyosha Landslide” into “BTL”.

2.26: (Line 271) Have you observed/measured this, or are they hypothesis. For such a large landslide, the response of the displaced material can be more complex that just following the seasonality of the wet periods.

This statement is not limited to the BTL, but rather most landslides in Bujumbura, especially those located along the Mugere River (in the south of the City Bujumbura) and Muha River (north of the Kanyosha River). From 2012 to 2016, field investigations were carried out to assess the risk of landslides. Benchmarks had been installed at some specific scarps and cracks’ boundaries. Their relative position change and distances were measured over time to follow the movement of the ground. Therefore, this is based on field observations and measurements.

2.27: (Line 397) Nowhere earlier clay is mentioned as being a component of the landslide material. Some info needs to be provided earlier.

We think this is now corrected and it is compliant with the details added above in the material description. This is also corrected by moving the Fig. 6 (which also includes a clay description and its role in the landslide dynamics) as suggested within the comment 2.28 below.

2.28: (Fig. 14) This figure must appear much earlier in the text, when description of the landslide is made. This figure does not provide results s.s. and in addition is called just after Figure 2.

This figure will be moved and inserted in the introduction (section 1), as it is within the reworded text of the introduction proposed above.

2.29: (Fig. 14_Caption) Is this important to focus on the river bed material in this context?

It is not very important, as the main information here is the orientation of layers.

2.30: (Line 436) To add a comment to those of reviewer 1, discussion should also focus on the extension of the hazard zone with regard to the use of a 10 m resolution DEM. In addition, being familiar with the region, I know that river banks can sometimes be of several meters high, i.e. well above the water depth that you modelled. Can you comment on that as well?

The reply to the question on the extension of the hazard zone will be included in the reply to the Reviewer 1 Comments (2.6).

Regarding the compatibility of our results with the field reality in terms of water depth, we strongly agree with you that the river banks can sometimes be several meters deeper.

Our results are rather satisfactory and are in line with that statement for the following reasons:

i. Water depth as given in Figure 11a and 11b of the manuscript show that, for scenarios leading to the water overflow beyond the main channel (e.g. breach-induced flow), the water depth values at the cross section reach 3.5 m - 4 m in the upstream parts (cross section 1 and 2) and 1.8 m – 2 m downstream (cross section 3 and 4). This corresponds well to the field reality and is in line with the digital terrain model. In the urban area, the main channel depth is not very high and, at some locations, a water depth greater than 1.5 m can lead to a considerable floodplain width.

ii. Considering the entire modelled river reach, the water depth varies from 0 m to 15.95 m. That means that there are already modelled values greater than those presented at the cross sections. As this can be well visualized in the Fig. R1 below, cross sections do not correspond to the maximum modelled water depth.

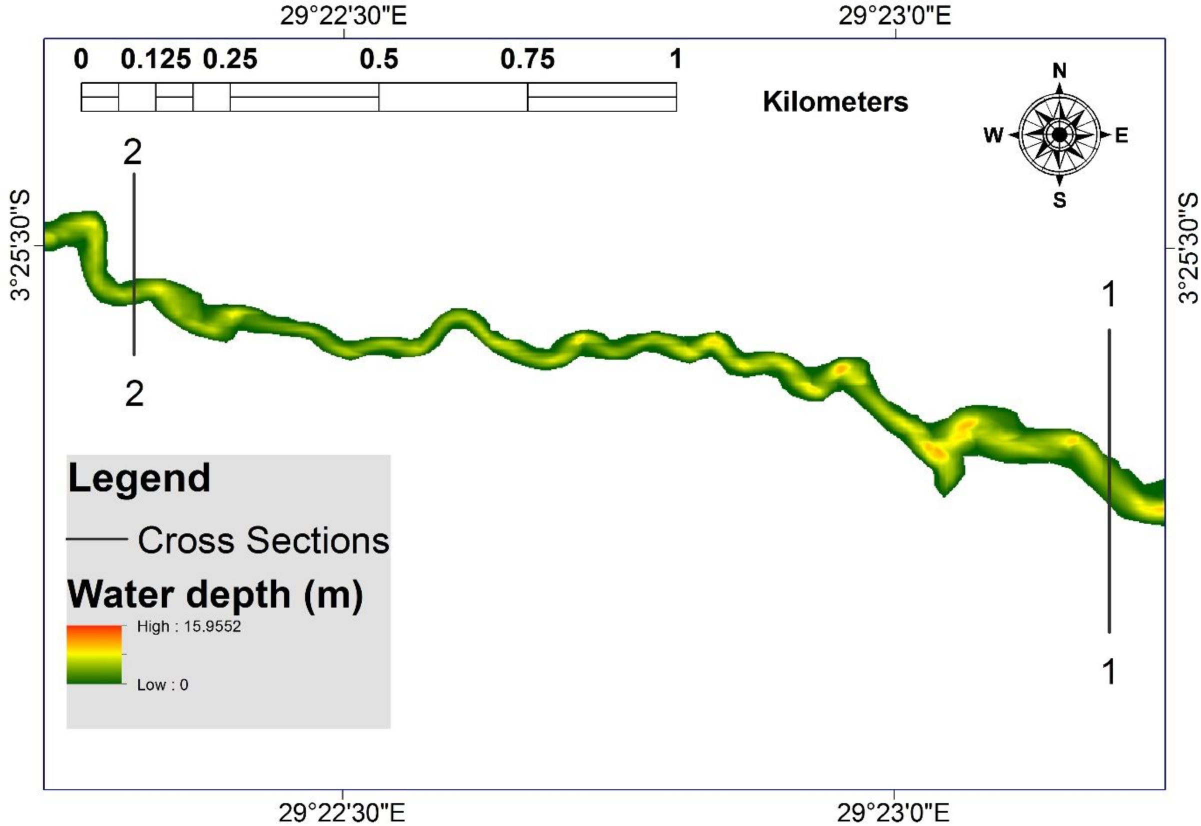

Figure R1. View of water depth map between cross sections 1 and 2, corresponding to the breaching-scenario, with a 50 year-flood.

This means that high values do exist, but they are not necessarily localized in cross-sections, as the cross sections' location was determined before the model run while water depth and other hydraulic characteristics are provided in the model output.

iii. Due to the asymmetry of some cross sections, the river overflows on the side corresponding to the lower overbank. Thus, the water depth may not always reach the level of the highest river banks.

References

Adams, J.E.: Earthquake-dammed lakes in New Zealand, Geology, 9, 215-219, 1981.

Butt, M., Umar, M. and Qamar, M.: Landslide dam and subsequent dam-break flood estimation using HEC-RAS model in Northern Pakistan, Natural Hazard, 65(1), 241-254, 2013.

Chen, C.C., Chen, T.C., Yu, F.C. and Hung, F.Y.: A Landslide Dam Breach induced Debris Flow—A Case Study on Downstream Hazard Areas Delineation, Environmental Geology, 47, 91–101, 2004.

Corominas, J. and Moya, J.: A review of assessing landslide frequency for hazard zoning purposes, Engineering Geology, 102 (3–4), 193–213, 2008.

Costa, J.E. and Schuster, R.L.: The formation and failure of natural dams, Geological Society of American Bulletin, 100, 1054–1068, 1988.

Crosta, G.B. and Clague, J.J.: Dating, triggering, modelling, and hazard assessment of large landslides, Geomorphology, 103 (1), 1–4, 2009.

Cui, Y., Parker, G., Braudrick, C., Dietrich, W.E. and Cluer, B.: Dam removal Express Assessment Models (DREAM). Part 1: Model development and validation, Journal of Hydraulic Research, 44(3), 291-307, 2006.

Cui, P., Dang, C., Zhuang, J.Q., You, Y., Chen, X.Q. and Scott, K.M.: Landslide-dammed lake at Tangjiashan, Sichuan province, China (Triggered by the Wenchuan Earthquake, May 12, 2008): risk assessment, mitigation strategy, and lessons learned, Environ Earth Sci, 65,1055–1065, 2012.

Dong, J.J., Tung, Y.H., Chen, C.C., Liao, J.J. and Pan, Y.W.: Discriminant analysis of the geomorphic characteristics and stability of landslide dams, Geomorphology, 110, 162–171, 2009.

Downs, P.W., Cui, Y., Wooster, J.K., Dusterhoff, S.R., Booth, D.K., Dietrich, W.E. and Sklar, L.S.: Managing reservoir sediment realease in dam removal projects: An approach informed by physical and numerical modelling of non-cohesive sediment, International Journal of River Basin Management, 7(4), 433-452, 2009.

Fan, X.M., Westen C.J., Xu, Q., Gorum, T. and Dai, F.C.: Analysis of landslide dams induced by the 2008 Wenchuan earthquake, J Asian Earth Sci, 57:25–37, 2012.

Ilunga, L. : Etude des sites majeurs d'érosion à Uvira (R.D. Congo), Geo-Eco-Trop, 30 (2), 1-12, 2006.

Jacobs, L., Maes, J., Mertens, K., Sekajugo, J., Thiery, W., Van Lipzig, N., Poesen, J., Kervyn, M. and Dewitte, O.: Reconstruction of a flash flood event through a multi-hazard approach: Focus on the Rwenzori Mountains, Uganda, Nat. Hazards, 84(2), 851–876, doi:10.1007/s11069-016-2458-y, 2016.

Korup, O.: Geomorphometric characteristics of New Zealand landslide dams, Engineering Geology, 73, 13–35, 2004.

Li, M.H., Hsu, M.H., Hsieh, L.S. and Teng, W.H.: Inundation potentials analysis for Tsao-Ling landslide lake formed by Chi-Chi earthquake in Taiwan, Natural Hazards, 25, 289–303, 2002.

Li,M.-H., Sung, R.-T., Dong, J.-J., Lee, C.-T. and Chen, C.-C.: The formation and breaching of a short-lived landslide dam at Hsiaolin Village, Taiwan— Part II: Simulation of debris flow with landslide dam breach, Engineering Geology, 123 (1-2), 60–71, 2011.

Michellier, C., Pigeon, P. and Kervyn, F.: Contextualizing vulnerability assessment: a support to geo-risk management in central Africa, Nat Hazards, 82, S27-S42, 2016.

Moeyersons, J., Trefois, P., Nahimana, L., Ilunga, L., Vandecasteele, I., Byizigiro, V. and Sadiki, S.: River and landslide dynamics on the western Tanganyika rift border, Uvira, D.R. Congo: Diachronic observations and a GIS inventory of traces of extreme geomorphologic activity, Natural Hazards, 53 (2), 291-311, 2010.

Nandi, A. and Shakoor, A.: A GIS-based landslide susceptibility evaluation using bivariate and multivariate statistical analyses, Engineering Geology, 110, 11–20, 2009.

Nibigira, L., Draidia, S. and Havenith, H.-B.: GIS-based landslide susceptibility mapping in the Great Lakes region of Africa, Case study of Bujumbura Burundi, Engineering Geology for Society and Territory, 2, 985-988, 2015.

Peng, M. and Zhang L.M.: Breaching parameters of landslide dams, Landslides, 9, 13–31, 2012.

Popescu, M.E.: Landslide causal factors and landslide remedial options, Proc. 3rd Int. Conf. Landslides Slope Stability and Safety of Infra-Structures, pp. 61-81, 2002.

Popescu, M.E. and Yamagami, T.: Back Analysis Of Slope Failures - A Possibility Or A Challenge?, Proc. 7th Intern. IAEG Congress, Lisbon, 4737-3744, 1994.

Reliefweb: Burundi: Floods and Landslides - Feb 2014, available at: http://reliefweb.int/disaster/fl-2014-000019-bdi (Accessed 21 November 2016), 2014.

Shresta, B. and Nakagawa, H.: Hazard assessment of the formation and failure of the Sunkoshi landslide dam in Nepal, Natural Hazards, 82(3), 2029-2049, 2016.

Terry, J.P. and Goff, J.: Mega clasts: proposed revised nomenclature at the coarse end of the Udden-Wentworth grain-size scale for sedimentary particles, Journal of Sedimentary Research, 84, 192–197, 2014.

Terzaghi, K.: Mechanisms Of Landslides, Geological Society of America, Berkley, 83-123, 1950.

UNITAR / UNOSAT: Storm damage, Kinama/Kamenge. Areas of Bujumbura, Burundi, available at: http://reliefweb.int/map/burundi/storm-damage-kinamakamenge-areas-bujumbura-burundi-17-february-2014 (Accessed 21 November 2016), 2014.

Varnes, D. J.: Slope movement types and processes, In Schuster, R.L., Krizek, R.J. (Eds) Landslides, Analysis and Control, Special report 176: Transportation Research Board, National Academy of Sciences, Washington, D. C., 11-33, 1978.

Wang, H.-W., Tullos D. and Kuo W.-H.: Simulating bed evolution following the Barlin Dam (Taiwan, China), failure with implications for sediment dynamics modeling of dam removal, International Journal of Sediment Research, 31(4), 299-310, 2016.

Wells, R.R., Langendoen, E. and Simon, A.: Modeling pre and post removal sediment dynamics: The Kalamazoo River, Michigan, Journal of the Americcan Water Ressources Association, 43(3), 773-785, 2007.