We would like to thank the editor and the two reviewers for their comments on our manuscript that helped us to improve its content. We provide our responses in red below each comment in black to the both reviewers and the editor. We also provide a summary of the main changes in a table, specifying in which pages and lines of the revised manuscript we made such changes and which comment(s) prompted them

Reply to Reviewer 1

General comments

This is an interesting paper on the use of citizen science to create flood maps (extent, depth) using the memory of leaders and people in the community in an area of Dakar, Senegal. The extent is compared with remote sensing and the idea is innovative but lacking in details in places.

Specific comments

Line 45 – what is meant by citizens from the community? Sometimes citizens are located around the world so I think this is too narrow a definition of citizen science

We agree with this comment. Consequently we have removed "from the community". The sentence now reads Line 43 "Citizen science is a form of collaborative research involving citizens into scientific projects (Wiggins and Crowston, 2011)"

Line 48 – "…social media, mobile, smartphones…" – what do you mean by mobile here? Do you mean mobile devices? Mobile phones? You mean phones that are not smartphones?

We mean mobile devices. To avoid redundancy, we have removed smartphones as they are a subset of mobile devices. (Line 47)

Line 49 – Open Street Map should be OpenStreetMap

Thanks. We have now corrected this (Line 47).

Line 49 – the references of Goodchild 2007 and Silvertown 2009 seem strange for OpenStreetMap, Google Earth and Geo-Wiki – there are much better references for these three applications. If you reference Goodchild (2007), then you should really mention Volunteered Geographic Information. You need better alignment between your references and your text.

This was an error in referencing. We now propose (Line 48):

Mooney, P and Minghini, M. 2017. A Review of OpenStreetMap Data. In: Foody, G, See, L, Fritz, S, Mooney, P, Olteanu-Raimond, A-M, Fonte, C C and Antoniou, V. (eds.) Mapping and the Citizen Sensor. Pp. 37–59. London: Ubiquity Press. DOI: https://doi.org/10.5334/bbf.c. License: CC-BY 4.0 for OSM

Fritz, S., McCallum, I., Schill, C., Perger, C., Grillmayer, R., Achard, F., Kraxner, F.,Obersteiner, M., 2009. Geo-Wiki.Org: the use of crowd-sourcing to improve global land cover. Remote Sensing 1 (3), 345e354. For Geo-Wiki

Le Yu & Peng Gong (2012) Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives, International Journal of Remote Sensing, 33:12, 3966-3986, DOI: 10.1080/01431161.2011.636081 for Google Earth

Line 50-54 – the literature review on flooding/hydrology and citizen science is a bit brief. There is quite a bit of work in this area and should be described in more detail.

We agree that there already exists significant literature on these topics and we have previously compiled a review of studies in the field of flood hazard assessment using citizen science published in Sy et al. (2019). Therefore, we did not want to repeat ourselves in this contribution. Nevertheless, we agree we could still say more and have replaced the passage "The use of … to interpret increases significantly" with the following (Line 50- 57):

The use of citizen science has also emerged in the field flood analysis in recent years. The existing works could be classified by looking at which phase of flood risk management they are dealing with and considering the timing, i.e. before, during and after the flood event. For example, Sy et al (2019) did a review on the use of citizen science in flood hazard assessment, discussing its potential to gather information needed to develop realistic scenarios and provide flood hazard parameters, such as extent and water depth, that could help understanding the hazard level at site. Assumpção et al, (2018) focused on the role citizen science could play in flood modelling and demonstrated its value to provide information for nourishing, calibrating and validating flood modelling in particular where data are scare. It is worth mentioning that most of the existing studies dealt with fluvial flooding, fewer studies concern pluvial or groundwater flooding (See, 2019).

Line 54 – this paper used memory and citizen science in the context of wildlife conservation so it is worth citing as one example: https://onlinelibrary.wiley.com/doi/full/10.1111/tgis.12300

Thank you for having brought this article to our attention. We have integrated it as follows (Line 57-59):

Moreover, none of those citizen science projects studied the reconstruction of past events using the citizen memory, in contrary to the field of wildlife conservation, where Zhang et al, (2017) demonstrated the value of citizen data for mapping past phenomena that were not otherwise recorded.

Section 2 – I am missing details about the type of flooding that occurs in this area, i.e. pluvial, fluvial, surface, etc.?

Thank you for raising this question. We now provide more details on the type of flooding occurring in our area of study (Line 76-78):

Flooding in this area is mainly due to runoff and rainwater, which are not absorbed by impermeable surfaces, made worse by rapid urbanization and the ineffective drainage network, combined with the rise of groundwater at some locations. Therefore, our area is characterized by multiple types of floods.

Line 78 – I do not see how Figure 2 shows 'novel methods in citizen science' – why are these novel in the context of citizen science? Based on what evidence? Perhaps it is better to say that you are combining different participatory approaches together. Otherwise I think the figure is good for showing the approach taken.

The reviewer is correct that Figure 2 does not show where the novelty is. We have modified the sentence as follows (Line 86-87): "We developed a framework combining different participatory approaches together (Fig. 2).

Line 96 – what does "In some cases it was possible to register the narrative" mean? Record it digitally?

Yes, the narrative was digitally recorded with a smartphone. We have modified the sentence to read (Line 106-107) "In some cases, it was possible to digitally record the narrative using a smartphone.

Line 102 – what does "fixing pins" mean – putting pins on the map? What does "handled GPS" mean?

Yes, fixing pins mean pins that can be put on the map. Handled GPS should have been written as (Line 112) "handheld GPS" as it was a pocket navigation device

Line 106 – "…were put into a mental condition" does not make sense in English – you probably mean put into a relaxed state or something else?

It is Line 117 in our version. We have replaced "mental condition" with "a relaxed state"

Line 119 – what does "using scale mapping" mean?

The map that was used was drawn at the scale of the neighbourhood, so we have modified this part to read "using maps at the scale of the neighbourhood" (Line 129)

Line 127 – (and in other places with similar use of confronting) – "confronting the story"- this need to be rewritten to something clearer in English as we would not express it this way.

We have changed this phrase accordingly, depending on the meaning of the concerned sentence. We have now written "cross-checking the story …." (Line 137)

Line 129 – 130 – this appears to be an assumption. Do you have a reference or evidence to back this up?

We have added the reference of Rubin, 2005 at the end of the sentence (Line 140).

Rubin, D. C., 2005, A Basic-Systems Approach to Autobiographical Memory, Current Directions in Psychological Science, https://doi.org/10.1111/j.0963-7214.2005.00339.x

Line 154 – you do not need to mention Bland and Altman the second time or the third time on line 156.

Thanks. We have corrected the sentence as follows (Line 171-172):

We used the Bland-Altman method (1986) which allows determining the level of agreement between data acquired with two different techniques, even if there is no information about the "true" values (Bland and Altman, 1986).

Section 3.1.3 – there are few details on the remote sensing, e.g. where did you obtain the training data? Where did you obtain the validation data? What was the accuracy? Perhaps add this to your supplementary material.

This was an error in the writing. In fact, we used unsupervised classification instead of a supervised one, see Line 193.

Line 184 – use the word "aggravating"-replace this with another, more appropriate English word such as worsen, exacerbate, etc. or you can remove it, e.g. "regarding the processes that worsen the flood…"

Thanks. We have replaced the phrase by "The neighbourhood chiefs identified different processes that worsen the flood" (Line 212-213)

Figure 5 – Can you provide R-square values or correlation with each image?

We have performed an analysis on the level of agreement between the two approaches to obtain the same information and not a correlation analysis. We could provide the R-square values or correlation statistics, but it would be meaningless on two datasets providing the same information. A correlation analysis could be done if we were to determine the correlation between the height of the person and the level of the water provided, for example.

Line 229 – What is a "graphic semiology"?

It refers to a standardized set of rules and practices in map representation. In order to improve the clarity of the sentence, we propose to now rewrite it as (Line 260-261): "Moreover, maps are usually constructed applying standard rules of graphic semiology (Thomas, 2001) that does not necessary take into account the cultural background or the knowledge of the citizen (Fuchs et al., 2009)

We also add the following reference (Line 260) : Isabelle Thomas, « Cartographie d'aujourd'hui et de demain : rappels et perspectives. », *Cybergeo : European Journal of Geography* [En ligne], Cartographie, Imagerie, SIG, document 189, mis en ligne le 27 mars 2001, consulté le 31 juillet 2019. URL: http://journals.openedition.org/cybergeo/3812; DOI: 10.4000/cybergeo.3812 (Line x to line y)

Line 250 – in deep should be in-depth

Thanks. We have now replaced "in deep" with "in-depth" (Line 282)

Line 269 – What does "to ensure people implication in our project…." Mean?

We wanted to express the fact that by creating a Facebook page dedicated to this project, people would feel like they belong to a group sharing the same interest and therefore willing to share information and feeling more involved, but at this stage, it was more motivation than implication. We have modified the sentence to (Line 305-306) "As Facebook is one of the most used social media in Yeumbeul North (Sy, 2019 doctoral thesis), we created a page to interact with the local citizens and motivate them to be part of the project".

Figure 6 – You need to label a), b) and c) in your figure caption

Indeed, the labels were missing in the figure caption. The caption has now been corrected to (Line 535-538) "Figure 7. Bland-Altman plots for different flooding events (a) 2005, (b) 2009 and (c) 2012. These graphs show differences between water depth provided by neighbourhood chiefs (NC) and local representatives (LR) in meters against averaged values of NC and LR. Blue line is the mean difference value and the red dotted lines show the +/- 1.96 standard deviation (SD) water depth differences for all observations". Line x to line y

Technical correction

There are numerous English errors in the text as well as awkward phrasing and incorrect use of verb tenses. I suggest that you ask a native English speaker to edit your paper or you use a professional editing service. This will also help to improve the readability of the paper. Here is an example of awkward phrasing:

We asked a native English speaker to edit the paper after having implemented all corrections.

Line 97 – the narrative allowed identifying which neighbourhoods were flooded" would be rewritten as ".the narrative allowed the neighbourhoods that were flooded to be identified" OR ".the narrative allowed for identification of which neighbourhoods were flooded.

Thank you. We have rephrased this as (Line 107-108) “the information obtained from the narrative allowed the neighbourhoods that were flooded to be identified”

Line 180 – “identify rainfall” should be “identified rainfall”
Thanks. This has been corrected (Line 208)

Line 171 – “results from both images treatment were compare”-not entirely sure what you mean
This one is part of the remote sensing section which has been completely rewritten as the editor suggests.

Line 183 – “removal of the wall painting” - I think you mean removal of the wall paint or removal of the paint on the walls
Indeed. We have rewritten this as “removal of the paint from walls” (Line 211)

Line 275 (and other places): – Do not use contractions in scientific writing, e.g., don’t
Contractions in Line 311 and other places have been changed

Reply to Reviewer 2

General comments

The paper presents a project of citizen science aiming at documenting past flood events in Dakar, Sénégal, for which no information about the extent, water levels of past events were available. The paper presents a methodology that is of interest for other countries, in particular developing countries for which this kind of information is rarely available. The method allows gathering information that is relevant for flood prevention and preparedness. However, the method requires knowledge of the local culture and social conventions to be put in practice and is relatively time consuming as it is based on participatory approaches and mapping. A comparison with flooding extend estimated using remote sensing data is also provided. The paper is well presented and written and clearly illustrates the added value of the approach, in particular in providing information about water level that cannot be obtained using remote sensing data. Additionally, the participatory approach allows the local communities to be better informed about flood prevention. The paper is of interest for the readers of Hydrology and Earth System Sciences, in particular in the context of socio-hydrology.

2/ p.5, stage 2: using their methodology, the authors obtain two information about water levels: the first one from the mapping after the training, the second one after the field survey. How did they resolve possible conflicting results? Which source of information did they consider as the most reliable?

The water level obtained after the chiefs’ narration in the house was qualitative. The pins were used in order to provide an idea first idea of the spatial distribution and the water depth. While the measurement obtained in the field by graduated ruler were qualitative. The idea was rather to check if the same site indicated as being very high with red pin in the house correspond to the one quantified higher in order to consolidate the geographic location and the measurement.

3/ p.5 line 145. Would it be possible that local representative could be reluctant to contradict the neighbourhood chiefs by giving information that could differ from the one provided by the neighbourhood chiefs? Or did the authors only informed local representatives of the location where they had to provide a water level value?

We only indicated the site location to the local representatives. They did not know in advance the value given by the chief for the same site see: (Line 161-162)

4/ p.6; the section about remote sensing is quite vague about the methods really put in practice. It could be useful to provide more detailed information on the methods.

This section about remote sensing has been completely rewritten as suggested by the editor

5/ p.8 line 232. How did the authors verify that the way to use and produce maps had been properly understood?

To check how to use and produce the maps was well understood we carried out the following:

-training (familiarise the contributor with the map so that they can distinguish between different symbols, for example)

-Localisation test (ask contributor to locate themselves on the map)

Reply to Editor

The topic is extremely interesting and timely in order to help obtaining information on flood risk for many poorly gaged parts of the world

The weakest point of the work is the comparison with the remote sensing estimates, that is, instead, crucial in order to understand how much we may rely on the reconstructions made by people, even if the remote sensing estimates are also affected by very large uncertainties (and such uncertainty is an issue that you should try to address better and more quantitatively than you do at ll. 255-260 and in particular you should refer to the limits of the specific images and methods you use for each flood event: acquisition times, resolution, etc

We tried to explain better the source of uncertainties for the remote sensing (Line 287-296). But the quantification is challenging as we lack of reference data on these flood events from independent and reliable sources, as no records were taken during those events (e.g. country database). We can only discuss the different sources in a relative way, with the overlapping areas.

The section on remote sensing (3.1.3) is to be completely rewritten, as both Referees require, providing much more information on the input data and a clear layout of the steps used to process the images and retrieving the estimation of the flooded areas. Some of the phrases you suggest in the reply to Ref2 are not clear ("Various image improvement and correction techniques have been applied" and "Since both methods are equal, the second method is used."???). In addition you do not explain why you use different remote sensing data for the different floods (2005 with Spot and 2009 and 2012 with Google Earth). And you should not change the remote sensing source, for a fair comparison you should use the same method for all the events. Actually, it would be better to use always the Google Earth images, since they are available in many other parts of the world and the method to estimate the flooded areas from such images, if well explained, may be reproduced elsewhere.

We agree that using satellite images from the same provider would have been the best strategy. However, the world coverage is not homogeneous and it is even sparser in some areas when looking back in the past. Therefore, we were not able to find free images from the same remote sensing source for the 3 flood events. That is the reason why we used heterogeneous data. As required by both referees, the section 3.1.3 has been rewritten by providing more information on the input data, and a clear layout of the steps used to process the images and to retrieve the flooded areas. You can find this improvement from line 176 to 204 and the new image (figure 3)

Other comments

Caption of Fig. 2 specify that the flowchart refers to citizen-based methods only. And add a flowchart with the steps for remote sensing method (see comment above)

We modified the caption of the Fig. 2 accordingly and we added a flowchart with the steps for remote sensing method as Fig. 3

Section 3.1: please describe better how “local representative” are identified by the agencies. It is not clear which kind of people they are (representative of what?) and why we expect differences in respect to the chiefs (different education?age?)

We clarified the term of local representatives and how they were selected by the local associations (Line 152-155). In addition, we give more information on why we expect difference in respect with the chief (Line 93-95)

On Ref2 Comment

“2/p.5, stage 2: using their methodology, the authors obtain two information about water levels: the first one from the mapping after the training, the second one after the field survey. How did they resolve possible conflicting results? Which source of information did they consider as the most reliable?” Please explain also in the revised text how conflicting results are managed.

With regard to this comment from referee 2, we would like to clarify the fact that the water levels obtained when discussing with the chiefs were qualitative (very high, medium, low), and those measured on the field survey were quantitative (measured in meters). The field mapping objective was to obtain quantitative measurements. The potential conflict was more related to the correspondence between the qualitative and the quantitative value, e.g. if a high level corresponded to a high value for the flood. The results of these checks showed 2 conflict of interests. In these 2 cases we trusted field measurements, as our assumption is that when looking at the scene, memory retrieval is facilitated.

Figure 4 and Table 3 add also the amount of overlapping between the estimates of flooded areas obtained through citizens and through remote sensing.

We added the amount of overlapping between the estimates of flooded areas obtained through remote sensing on old Figure 4, now Figure 5 and the table 3

Summary of the main changes

	Comments	Main Changes	New Location
Modification of the literature review on flooding/hydrology and citizen science	The literature review on flooding/hydrology and citizen science is a bit brief. There is quite a bit of work in this area and should be described in more detail.	The use of citizen science has also emerged in the field flood analysis in recent years. The existing works could be classified by looking at which phase of flood risk management they are dealing with and considering the timing, i.e. before, during and after the flood event. For example, Sy et al (2019) did a review on the use of citizen science in flood hazard assessment, discussing its potential to gather information needed to develop realistic scenarios and provide flood hazard parameters, such as extent and water depth, that could help understanding the hazard level at site. Assumpção et al, (2018) focused on the role citizen science could play in flood modelling and demonstrated its value to provide information for nourishing, calibrating and validating flood modelling in particular where data are scare. It is worth mentioning that most of the existing studies dealt with fluvial flooding, fewer studies concern pluvial or groundwater flooding (See, 2019)	Page 2, line 50-57
Details on the types of floods in the study area	Section 2 – I am missing details about the type of flooding that occurs in this area, i.e. pluvial, fluvial, surface, etc.?	Flooding in this area is mainly due to runoff and rainwater, which are not absorbed by impermeable surfaces, made worse by rapid urbanization and the ineffective drainage network, combined with the rise of groundwater at some locations. Therefore, our area is characterized by multiple types of floods.	Page 3, line 76-78
Modification of the section on remote sensing	The section on remote sensing (3.1.3) is to be completely rewritten, as both Referees require, providing much more information on the input data and a clear layout of the steps used to process the images and retrieving the estimation of the flooded areas. Some of the phrases you suggest in the reply to Ref2 are not clear (“Various image improvement and correction techniques have been applied” and “Since both methods are equal, the second method is used.”???). In addition you do not explain why you use different remote sensing data for the different floods (2005	We used data from remote sensing analysis to assess the reliability of the extents of flooded areas provided by the two citizens groups. Our requirements were: 1) availability of images for the years considered, 2) free access of data, 3) sufficient resolution for the size of our study area (9km^2), and 4) minimum cloud cover. Radar images such as TerraSAR-X, Radarsat-2 or COSMO-SkyMed, can provide information with high resolution (Schubert et al., 2012) and can capture flooded areas in cloudy conditions at day and at night (Mason et al., 2014; Schuman, 2017), but they are not free of charge and, most importantly for our case, no images were available for the periods of interest. Consequently, we only used available optical satellite images from different sensors. The main characteristics of these products are given in table 2. Flooded areal extents were obtained following the process chain describes on Fig. 3. For 2005 event, we used two SPOT images (23/10) and (07/09) provided by the applied Remote Sensing Laboratory (LTA) of the Institute of Earth Sciences (IST) of the University Cheikh Anta Diop (UCAD) (table 2). It should be noted that we did not find an image from before the flooding and hence we used an image obtained during a dry period. These two multispectral SPOT 5 images of 10 m resolution were merged with a SPOT 5 panchromatic image of a spatial resolution of 2.5 m to increase their spatial accuracy. We then applied the normalized difference water index (NDWI; Khajuria et al., 2017) to - the	Page 6-7, line 176-204 And figure 3

	with Spot and 2009 and 2012 with Google Earth). And you should not change the remote sensing source, for a fair comparison you should use the same method for all the events. Actually, it would be better to use always the Google Earth images, since they are available in many other parts of the world and the method to estimate the flooded areas from such images, if well explained, may be reproduced elsewhere.	water signature from other land-use types. The NDWI is calculated following the method of McFetters (1996), using the green and the near-infrared bands: $NDWI = \frac{Green-NIR}{Green+NIR}$ An unsupervised classification was then performed to cluster pixels having similar NDWI values, using the ISODATA (Iterative Self-Organizing Data Analysis Technique) clustering algorithm provided through the software Erdas Imagine 2014©. The classes are then coded to highlight only the water areas. These areas were then digitized on both images. Finally, both layers are compared and only areas corresponding to flooded areas are kept. An area is considered as flooded if water can be detected only on the image after the flood. For the 2009 and 2012 events, we used images available from Google Earth. Google launched Google Earth in 2005 (Cha and Pak, 2007), and it provides free online aerial and satellite images covering many parts of the world, with various resolutions and sensors. The highest resolution, about 0.5 m, is provided by Worldwide and QuickBird satellite imagery operated by Digital Globe. For each flood event, we examined the historical true colour composite imagery from Google Earth using the time slider bar of Google to find one image as close as possible to the flood event and another one in a dry period after the event. These images were then photo-interpreted to identify areas of water. These areas were digitized and then compared to extract only areas considered as flooded.	
	The weakest point of the work is the comparison with the remote sensing estimates, that is, instead, crucial in order to understand how much we may rely on the reconstructions made by people, even if the remote sensing estimates are also affected by very large uncertainties (and such uncertainty is an issue that you should try to address better and more quantitatively than you do at ll. 255-260 and in particular you should refer to the limits of the specific images and methods you use for each flood event: acquisition times, resolution, etc	A good spatial agreement exists between flood extents determined from remote sensing and citizen science, with better agreement from the data provided by the neighbourhood chiefs. However, areas provided by remote sensing are smaller. This discrepancy can be explained by various factors. One could be the different spatial resolution of the selected images, which varyed from 0.5 m to 2.5 m, the larger probably not being probably small enough to capture all flooded areas (Grimaldi et al., 2016) at the scale we worked. A second factor concerns the different time lapses between images. Post-event images from Google Earth were captured at intervals from 1 to 15 days and therefore may not have captured the maximum extent. Furthermore, for the 2005 event, one image was obtained during the flooding, with the second image taken one year after with the assumption it was captured during a dry period. A third factor is related to technical limitations of the capability of optical satellites to detect flooded areas, which is reduced when clouds are present (Malinowski et al., 2017; Mallinis et al., 2013). Finally, the efficiency of the NDWI index used to detect water areas could be altered by noise (Xu, 2005).	Page 10, line 287-296

Clarification of the terms "local representative" and "chief"	Please describe better how "local representative" are identified by the agencies. It is not clear which kind of people they are (representative of what?)	The selection was based on the previously mentioned criteria. As these associations operate locally, they personally know residents and the choice of the inhabitants to be the representatives of the neighbourhood was based on a consensus among the associations. From here on, we use the term "local representatives" to refer to these selected people A chief is the qualification given to an official delegate (Tall, 1986) representing the municipal administration (GDS, 1986) and is therefore the focal point for the inhabitants, also in case of disasters	Page 5, lines 152-155 Page 3-4 lines 93-95
Modification of figure 2		Based on the questions we had from all the reviewers on the methods, the figure 2 has been modified to be clearer	Page 3, line 86-87 Figure 2, page 17
Addition of a new figure	add a flowchart with the steps for remote sensing method		Figure 3, page 18
Modification of Table 3 and figure 4 (old numbering)	add also the amount of overlapping between the estimates of flooded areas obtained through citizens and through remote sensing		table 3, page 26 Figure 5, page 20

Reconstituting past flood events: the contribution of citizen science

Bocar Sy[1,*], Corine Frischknecht[1], Hy Dao[2, 3], David Consuegra[1, 4], Gregory Giuliani[3]

[1] Department of Earth Sciences, Faculty of Science, University of Geneva, 13 rue des Maraîchers, Geneva, 1205, Switzerland
[2] Department of Geography and Environment, Geneva School of Social Sciences, University of Geneva, 66 boulevard Carl Vogt, Geneva, 1205, Switzerland
[3] Institute for Environmental Sciences, University of Geneva, 66 Boulevard Carl Vogt, Geneva, 1205, Switzerland
[4] Institute of Territorial Engineering, School of Management and Engineering Vaud, 1 route de Cheseaux, Yverdon-les-Bains, 1401, Switzerland

Correspondence to: Bocar Sy (Bocar.Sy@unige.ch)

Abstract. Information gathered on past flood events is essential for understanding and assessing flood hazard. In this study, we present how citizen science can help retrieving this information, in particular in areas with scarce or no instrumental measurements on past events. The case study is located in Yeumbeul North (YN), Senegal, where flood impacts represent a growing concern for the local community. This area lacks instrumental records on flood extent and water depth as well as information on the chain of causative factors. We developed a framework using two techniques to retrieve information on past flood events by involving two groups of citizens who were present during the floods. The first technique targeted the part of the citizens' memory, which records information on events, recalled through narratives, whereas the second technique focused on scaling past flood event intensities using different parts of the witnesses' body. These techniques were used for 3 events, which occurred in 2005, 2009 and 2012. They proved complementary by providing quantitative information on flood extents and water depths, and by revealing factors that may have contributed in aggravating floods for 3 events which occurred in 2005, 2009 and 2012.

1 Introduction

Together with Asia, Africa is the continent most affected by floods (UNISDR-CRED, 2015). Between 2000 and 2018, there were 698 flood disasters in Africa, killing more than 14,250, affecting 45 million people, and causing 6.8 million USD of economic losses (EM-DAT, 2018). West African countries, such as Burkina Faso or Senegal, appear to experience an increase in flood disasters due to the population growth and to the urbanization of flood-prone areas (Di Baldassarre et al., 2010). Between 1990 and 2014, floods were responsible for 86% of the economic losses from natural disasters in Senegal only (Preventionweb, 2018). During that period, years 2005, 2009, and 2012 were marked by severe urban floods, particularly affecting the capital of Senegal, Dakar, causing human casualties and impairing socio-economic conditions (GFDRR, 2014). The country is facing enormous challenges in flood risk management, exacerbated by climate change (Douglas et al., 2008; Urama and Ozor, 2010), rapid and uncontrolled urbanization, lack of drainage infrastructure, and rapid changes in land-use that worsen drainage patterns (Chen et al., 2015; Ahiablame and Shakya, 2016).

The government and local authorities of Senegal have tried several strategies to mitigate urban floods, such as developing emergency plan, relocating inhabitants, and building water retention basins. However, two key aspects have not yet considered that are needed for these measures to work. On the one hand, it is necessary to understand the causes and characteristics of floods and, on the other hand, the population must be involved in the process of risk management. Information on magnitude and intensity of flood events, as well as on processes controlling the flood, is at the core of flood hazard assessment and zoning (EXCIMAP, 2007). This fundamental information is scarcely available in the region (GFDRR, 2014; Sy et al., 2016). The absence of an organized data acquisition system during floods leads to the absence of a comprehensive catalogue on past flood events and consequently on flood hazard maps.

Without records of past events and without the possibility of capturing the time dimension in terms of frequency of occurrence, accurate flood hazard assessment is impossible to achieve. Moreover, floods are not only triggered by natural factors, but are frequently influenced by man-made processes (WMO, 2012; DAEC, 2016), which are not easily recorded by ground-based instruments (Townsend and Walsh, 1998) or remote sensing (Sanyal and Lu, 2004).

Consequently, new alternatives must be explored. Citizen science is a form of collaborative research involving citizens ~~from community~~ in scientific projects (Wiggins and Crowston, 2011). Citizen science has attracted much attention from scientists in many fields such as ecology (Dickinson et al., 2010; Silvertown, 2009), astronomy (Raddick et al., 2007), and more recently hydrology (Buytaert et al., 2014; Paul et al., 2018). Rapid advancement in various modern technologies - internet, web 2.0, virtual globe, location-based services, social media, mobile devices, ~~smartphones,~~ interactive geo-visualization interfaces such as ~~Open Street Map~~ OpenStreetMap; Google Earth, Geo Wiki (~~; Silvertown, 2009~~ Fritz et al 2009; Yu and Gong 2012; Mooney and Minghini 2017) - as well as the rise of participatory research characterized by greater user interactivity and collaboration, increase the number and the subjects investigated by citizen science projects. ~~The use of citizen science has also emerged in flood analysis for multiple purposes (Sy et al., 2019) including near real time mapping of flooding, crisis mapping, and other modelling projects (in which the volume of data to interpret increases significantly. However, none of those citizen science projects explicitly studied the reconstruction of past events, and the use of citizen memory.~~ The use of citizen science has also emerged in flood analysis in recent years. The existing works can be classified according to which phase of flood risk management they are dealing with i.e. before, during or after the flood event. For example, Sy et al., (2019) reviewed the use of citizen science in flood hazard assessment, discussing its potential to gather information needed to develop realistic scenarios and provide flood hazard parameters, such as extent and water depth, that could help understanding the hazard level at site. Assumpção et al, (2018) focused on the role citizen science could play in flood modelling and demonstrated its value to provide data for informing, calibrating and validating flood models, particularly where data are scare. It is notable that most of the existing studies dealt with fluvial flooding; fewer studies consider pluvial or groundwater flooding (See, 2019). Moreover, none of those citizen science projects studied the reconstruction of past events using the citizen memory, unlike the field of wildlife conservation where Zhang et al, (2017) demonstrated the value of citizen data for mapping past phenomena that were not otherwise recorded.

The objective of this work is twofold: 1. retrieve flood extents and water depths for different past events and, 2. determine whether citizen can clarify the causal chain of flood events. We also assessed the reliability of these data with cross comparisons and against independent methods, such as remote sensing.

2 Characteristics of the study area

Our citizen science approach was applied to the suburbs of Yeumbeul North (YN), one of the municipal districts of Pikine in Dakar city, Senegal, West of Africa (Fig. 1). YN covers an area about 9 km^2. It is one of the most populated districts of Senegal, with 168’379 inhabitants (ANDS, 2015), and a population density of approximately 18,700 inhabitants/km^2. YN is characterized by lowlands with elevation less than 20 m above sea level and is highly urbanized with more than 80% of its territory covered with buildings, critical facilities and roads (Sy et al 2016). It is one of the suburbs most affected by flooding. Figure 1 displays the state of the permanent water bodies (Lakes Warouwaye and Wouye), which existed before the retention basins were implemented as mitigation measures after the 2012 floods (GFDRR, 2014; Sy et al 2016).

Administratively, YN is divided into 82 major neighbourhoods. In each of them, a delegate, chosen among the inhabitants of the neighbourhoods, represents the municipal administration (decree N 86-761 Republic of Senegal) (GDS, 1986). The delegate should be from the site and at least 35 years old. One of the delegate’s tasks is to sensitize the neighbourhood inhabitants on how to face disasters. In this paper, the delegate will be designated under the qualification of neighbourhood chief (Tall, 1986), appellation employed by the local population.

Flooding in this area is mainly due to runoff and rainwater, which are not absorbed by impermeable surfaces, made worse by rapid urbanization and the ineffective drainage network, combined with the rise of groundwater at some locations. Therefore, our area is characterized by multiple types of floods. Flooding occurs during the rainy season, which usually starts in July and ends in October. The 3 events under investigation occurred in 2005, 2009 and 2012. Their timeframe and the peak rainfall intensity are provided in table 1. The timeframe was retrieved from the Emergency Events Database (EM-DAT) database (EM.DAT, 2018), whereas the rainfall intensity values were registered at the station of Dakar-Yoff located 20 km away from the study area.

3 Methods

3.1 Investigation on past flood events

Since there is currently no catalogue on past flood events available for the Dakar region, we decided to investigate the potentiality of citizen science in the retrieval of this information. We developed a framework ~~applying novel~~ combining different participatory approaches together in the field of citizen science (Fig. 2).

The field campaign was carried out from July to August 2017. Our approach involved two different groups of citizens. Participants were selected based on three criteria: 1) to have witnessed the 3 flood events; 2) to have a good spatial knowledge of the study area and the flooded areas; 3) their social credibility. Therefore, the first group consisted of the chiefs of the 82 neighbourhoods of the municipal district of Yeumbeul North. A chief is the qualification given to an official delegate (Tall, 1986) representing the municipal administration (GDS, 1986) and is therefore the focal point for the inhabitants, also in case of disasters. The majority of this group were male (98%) and the age varied from 40 to 90 years, with an average of 66 years. The second group was composed of 182 ~~local representatives~~people, 2 or 3 per neighbourhood. 72% were men, with ages varying between 35 and 60. The average was 38 years old. The under-representation of women in the study is not our choice, but instead due to the socio-cultural context of the country (Creevey, 1996).

3.1.1 Neighbourhood chiefs: from episodic memory into flood information

This group of citizens was involved in a two-stage approach set up to optimize the validity, reliability and utility of the collected data, and to transform memory of past floods into temporal and spatial information. The first stage is based on the use of episodic memory through in-person interviews in the chief's house. Episodic memory designates the process by which the human being remembers events with their context: date, place and emotional state (Tulving, 1972, 1993, 2002), and is part of the long-term memory (Zack et al 2000). The second stage relies on participatory mapping (IFAD, 2009) and on-site visits.

Face-to-face interviews were conducted with each chief of the 82 neighbourhoods. These persons are nominated by the local population because of their reputation, as they are considered senior and among the first inhabitants of the neighbourhood. The in-person interview was forecast to last between 45 to 60 minutes but it depended on the history told and no time limit was imposed. At the end, interviews lasted from 30 to 60 minutes. In some cases it was possible to register the narrative digitally using a smartphone. The information obtained from the narrative allowed the neighbourhoods that were flooded to be identified~~identifying which neighbourhoods were flooded~~. Then the chiefs of flooded neighbourhoods were involved in a participatory mapping in the house and in the field, together with hand/GIS mapping for the latter case. The purpose of this second step was to formalize and express the chiefs' memories of the floods (as witnesses or victims) in explicit form in order to obtain past information useable for flood hazard assessment, such as flood extent and water depth. Tools such as land-use paper maps of the area with footprint of houses and different land-use categories (see figure 1), ~~fixing pins~~putting pins on the map, ~~handled~~ handheld GPS and mobile GIS were used.

Stage 1: Investigation on past flood information in neighbourhood chief's house

The methodology of this stage was derived from techniques used in police investigation (Fisher, 2010, Perfect et al 2008). Compared to other forms of interviews, it allows the witness (here the neighbourhood chief) to play a more active role, by expressing freely his history without being interrupted or influenced by questions, which could distort the memory (Loftus and Palmer, 1974). First, neighbourhood chiefs were put into a ~~mental condition~~ relaxed state allowing them to focus their thoughts, cognitive and emotional state by closing their eyes (Perfect, 2008) and avoiding physical and psychological distraction (e.g. telephone calls) during this phase, as it requires intense concentration (Fisher, 2010). Some neighbourhood chiefs felt uncomfortable when closing their eyes. In such cases, they were told to focus on a blank surface, like a table or the floor. Once ready, they expressed their memories of the event in the form of descriptive stories, as they came to their mind, using their own words and language, Wolof in that case, in order to avoid misunderstanding. They were instructed to describe in detail anything that may be related to the event, such as a) processes that accompanied the flood (e.g. the rupture of a water drainage pipe, manmade obstacles); b) important political or public events as time indicators (e.g. proximity to a presidential election, football game); c) peculiar flood-related measures taken by the authorities enabling the event to be dated; d) spatial indicators such as place names, street names allowing to reconstruct the flooded areas, and, e) the event itself, with information making it possible to deduce the height of water reached (e.g. “water reached our knees”).

Following the narrative, only chiefs who indicated having been confronted with floods went through participatory mapping using ~~scale mapping~~ maps at the scale of the neighbourhood (62 chiefs out of 82, see supplementary material 2). This phase required a training on how to read and use a map. Therefore, the concerned neighbourhood chiefs were first familiarized with a land-use map of their neighbourhood locating their house and details about their area including main and secondary roads as well as houses. After this introductory explanation, the neighbourhood chiefs used the map to describe their spatial perception of the different flood events, using a distinctive colour pencil to draw the flood contours of each year. Coloured pins were used for indicating the water depth at different locations on the map; red for high level of water, green for medium and yellow for low. This method allows obtaining a qualitative indication of the water depth as well as its spatial distribution.

Stage 2: Investigation on past flood information with neighbourhood chiefs in the field

The objective of stage 2 was to consolidate the response by confronting cross-checking the story leading to the first map to the on-site mapping. To do this, neighbourhood chiefs brought us to the places they previously described. This is important because memory retrieval is facilitated when the context of the event is recreated, and neighbourhood chiefs can also use their other senses (sight, hearing, smell) to better remember the event (Rubin, 2005). We drew the polygon of the spatial extension using a mobile GIS, with GPS receiver automatically recording the site location. Furthermore, we measured 64 sites for the water level indicated by 49 neighbourhood chiefs with a graduated ruler (supplementary material 3, 4 and 5) and took the GPS coordinates. Post-processing treatments include merging the contours of flooded areas obtained on paper map with the ones obtained in the field as well as checking the correspondence between qualitative water levels obtained with the coloured pins to the water level measurements. The objective of the latter was to verify if the sites indicated as having had very high-water levels on the paper map from stage 1 (red pin) corresponded to a high-water level measured in the field. Since we assume that memory retrieval is facilitated when one is present at the site, we consider the field value to be more reliable.

3.1.2 Local representatives: participatory mapping on flood extent and water level of past flood events

The second group involved in investigating past flood events was composed of 182 local representatives selected by associations well implemented locally (e.g. “Réseau d’Information d’Education de Communication”, “Association des Relais Communautaires de Yeumbeul”) dealing with development of the neighbourhood and awareness on health issues. The selection was based on the previously mentioned criteria. As these associations operate locally, they personally know residents and the choice of the inhabitants to be the representatives of the neighbourhood was based on a consensus among the associations. From here on, we use the term “local representatives” to refer to these selected people. The aim for involving local representatives is to confront their information with the one provided by the neighbourhood chiefs in order to check the consistency between the two sources. 2 or 3 local representatives were selected per flooded neighbourhood, accounting for 130 out of 182 representatives, in order for them to confront their memories and reach a common agreement (Swanson et al., 2016) before providing information on flood extent and water depths for the different flood events. Data on flood extent were retrieved by participatory mapping using hands-on techniques. For this, representatives were trained the same way as the chiefs. These maps were then digitized. Regarding water level, information was retrieved on the same 64 sites as indicated by the neighbourhood chiefs, but without any prior knowledge on the depths given by the chiefs, and depths information was given using the different parts of the human body, e.g., ankle, knee or shoulder. This strategy was proposed to provide local representatives with a visual resource to describe the water level more easily. Then, the pre-defined tags were converted into quantitative data by using average body segment lengths expressed as a fraction of body height defined in the field of physical anthropometry (Winter, 2009; Drillis and Contini, 1966). The bottom-up dimensionless coefficients applied for each anthropometric segment (supplementary material 6) are (Winter, 2009;Contini, 1972): ankle (0.039), knee (0. 285), wrist (0.485), elbow (0.63), chest (0.72), shoulder (0.818), chin (0.870). Finally, the water depth was obtained by multiplying the value of the appropriate coefficient by the contributor’s (local representative) height, measured on site using tape measure (supplementary material 3, 4, 5 and 6).

As we used two different approaches to obtain the same information, we needed to assess the level of agreement instead of the correlation between the two datasets. We used the Bland-Altman method (1986) ~~(Bland and Altman, 1986)~~, which ~~allows~~ determines ~~determining~~ the level of agreement between data acquired with two different techniques, even if there is no information about the “true” values (Bland and Altman, 1986). In our case, we assessed depth values that could not be measured instrumentally during the flood events under study. The Bland-Altman method calculates the differences between the results obtained with two different approaches and plot them against the average of the two approaches.

3.1.3 Remote sensing analysis

~~In order to assess the reliability of flooded areas provided by the two citizens groups, we used remote sensing analysis. Our constrains were: 1) the availability of images for the years considered, 2) the availability of free access, 3) a resolution sufficient for the size of our study area (9km^2), and 4) a minimum cloud cover. Radar images such as TerraSAR-X, Radarsat-2 or COSMO-SkyMed, can provide information with high resolution (Schubert et al., 2012) and can capture flooded areas in cloudy conditions at day and at night (Mason et al., 2014; Schuman, 2017) but their costs were prohibitive and no images were available for the periods of interest. Consequently, we only used optical satellite images, available at the Applied Remote Sensing Laboratory (LTA) of the Institute of Earth Science (IST) of the University Cheikh Anta Diop (UCAD) and satellite images from Google Earth historical imagery as listed in table 2.~~

The flooded areas for the 2005 event were determined using available Spot 5 images i.e. one acquired during the 2005 flood event and one acquired in 2006 in the absence of flooding.

The multispectral Spot images of 10 m resolution were merged with a Spot panchromatic image with a spatial resolution of 2.5 m to increase their spatial accuracy. In order to detect water-covered areas, we applied the normalized difference water index (NDWI) (Khajuria et al., 2017) and supervised classification methods on both sharpened images. Finally, results from both images treatment were compared to extract the flooded areas.

For the events of 2009 and 2012, flooded areas have been obtained by comparing and photo-interpreting high-resolution true colour composite images from Google Earth historical imagery, about 0.5 m resolution, before and up to 3 weeks after the flood events.

We used data from remote sensing analysis to assess the reliability of the extents of flooded areas provided by the two citizens groups. Our requirements were: 1) availability of images for the years considered, 2) free access of data, 3) sufficient resolution for the size of our study area ($9km^2$), and 4) minimum cloud cover. Radar images such as TerraSAR-X, Radarsat-2 or COSMO-SkyMed, can provide information with high resolution (Schubert et al., 2012) and can capture flooded areas in cloudy conditions at day and at night (Mason et al., 2014; Schuman, 2017), but they are not free of charge and, most importantly for our case, no images were available for the periods of interest. Consequently, we only used available optical satellite images from different sensors. The main characteristics of these products are given in table 2. Flooded areal extents were obtained following the process chain describes on Fig. 3.

For 2005 event, we used two SPOT images (23/10) and (07/09) provided by the applied Remote Sensing Laboratory (LTA) of the Institute of Earth Sciences (IST) of the University Cheikh Anta Diop (UCAD) (table 2). It should be noted that we did not find an image from before the flooding and hence we used an image obtained during a dry period. These two multispectral SPOTS 5 images of 10 m resolution were merged with a SPOT 5 panchromatic image of a spatial resolution of 2.5 m to increase their spatial accuracy. We then applied the normalized difference water index (NDWI; Khajuria et al., 2017) to - the water signature from other land-use types. The NDWI is calculated following the method of McFetters (1996), using the green and the near-infrared bands:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

An unsupervised classification was then performed to cluster pixels having similar NDWI values, using the ISODATA (Iterative Self-Organizing Data Analysis Technique) clustering algorithm provided through the software Erdas Imagine 2014©. The classes are then coded to highlight only the water areas. These areas were then digitized on both images. Finally, both layers are compared and only areas corresponding to flooded areas are kept. An area is considered as flooded if water can be detected only on the image after the flood.

For the 2009 and 2012 events, we used images available from Google Earth. Google launched Google Earth in 2005 (Cha and Pak 2007), and it provides free online aerial and satellite images covering many parts of the world, with various resolutions and sensors. The highest resolution, about 0.5 m, is provided by Worldwide and QuickBird satellite imagery operated by

Digital Globe. For each flood event, we examined the historical true colour composite imagery from Google Earth using the time slider bar of Google to find one image as close as possible to the flood event and another one in a dry period after the event. These images were then photo-interpreted to identify areas of water. These areas were digitized and then compared to extract only areas considered as flooded.

4 Results

4.1 Identifying chain of events

The chain of events, which triggered floods in YN, was retrieved from the narrative obtained from 82 neighbourhood. For the 2005, 2009 and 2012 events, all the 82 chiefs of neighbourhoods ~~identify~~ identified rainfall as the primary factor. 29 chiefs (neighbourhood number 1, 2, 3, 7, 9, 17, 19, 20, 28, 29, 31, 32, 33, 34, 35, 36, 39, 40, 41, 44, 49, 50, 56, 57, 62, 67, 70, 72, 76; see Fig.1) also indicated the rise of the water table, substantiated by wet ground, greening of walls due to the water infiltration, and removal of ~~the wall painting~~paint from walls.

~~Regarding the aggravating processes, which~~The neighbourhood chiefs identified different processes that worsened the flood, by either increasing the quantity of water or obstructing the flow, they varied depending on the year of the event and the location. For example, for the 2005 event, 4 neighbourhood chiefs (13, 36, 46, and 67) mentioned the failure of the pipeline of the road of Malika, used for water drainage, as a cause of increasing the intensity of the flood event. 8 neighbourhood chiefs (7, 17, 18, 20, 21, 28; 45, 77) mentioned the overflow of the Warouwaye Lake. 15 neighbourhood chiefs (7, 13, 17, 18, 19, 20, 21, 28, 36, 45, 46, 67, 72, 76, 77) mentioned actions achieved by local population, such as emptying of septic tanks located in their house, which contributed in aggravating this event and had also direct consequences on health (e.g. cholera epidemics) (Wade et al., 2009). Pipeline failure and emptying of septic tanks occurred during the 2009 event, but at different locations, e.g. near the municipal hospital of Yeumbeul North for the pipeline failure. For the 2012 event, the 82 chiefs ~~didn't~~did not recall any aggravating processes.

4.2 Flood extent mapping

Flood extents for the 2005, 2009, and 2012 events were obtained from the two citizen groups using the methodologies described in Figure 2 and then compared to the results derived from remote sensing analysis (Fig. 3).

As a first result, the citizen science revealed that the 2005 event was the most widespread whereas the 2012 event was the smallest (table 3). Flooded areas provided by local representatives are slightly smaller than those indicated by neighbourhood chiefs (table 3), showing variations from 1.8% in to 2005 to 0.6% in 2012 (table 3). In terms of mapping, slight differences appear on the extents identified between the two citizen groups (Fig. 3), but areas overlap reasonably well (Fig. 4).

Remote sensing analysis confirms the main flooded areas in the centre part of the study area (Fig. 3), but some discrepancies occur on the edges. The total surface area is smaller than the one provided by citizen science for all years (table 3~~).~~), but shows the same tendency of decreasing surfaces from 2005 to 2012. We also find that flood extents provided by neighbourhood chiefs agreed better with the remote sensing than those provided by local representatives for all events.

4.3 Water depth information

Water depth is one of the key parameters considered in describing flood intensity and mapping hazard (Van Alphen et al., 2007), but difficult to record during flood events. Therefore, retrieving flood depths from past events is of prime interest. Figure 5 displays scatter diagrams of depth values obtained with the two different groups of citizens using the techniques described in the methods (see Fig. 2) on 64 sites, sampled over 49 neighbourhoods. Each site has paired observations. The maximum flood depth retrieved is 2.5 m for the 2005 event, 1.5 m for the 2009 event, and 1.2 m for the 2012 event.

Figure 6 shows the plots obtained applying the Bland-Altman method for the 2005, 2009 and 2012 events for the 64 sites of measurements. The value of the mean differences, expressed in meters and indicated by the blue line is 0.16 for the 2005 event, 0.23 for 2009 and 0.26 for 2012. The limits of agreement, also displayed, are set at 95% of confidence interval. The differences being normally distributed, these limits are defined by the mean difference +/- 1.96 the standard deviation σ of the differences. For the 2005 event, the range for the differences is from 0.68m to -0.37m, with two values out of these limits. For 2009 and 2012, three values are out of range, the interval being 0.78m to -0.32m for 2009 and 0.62m to -0.11m for 2012.

5 Discussion and conclusion

In this study, we used citizen science to retrieve information on three past flood events having impacted the region of Dakar during the past 10 years. Our approach provides quantitative information on water depth, helps retrieving the flood extents and provides insights on aggravating factors of the intensity of floods.

Our methodology consisted of a set of techniques to gather the most complete spectrum of information. Those techniques are unusual in the field of flood hazard assessment and we had to resolve some challenges related to the time elapsed and the understanding of maps. One of the techniques is based on people's episodic memory. We used face-to-face interviews with neighbourhood chiefs, applying specific tools in order to limit external influence and distortion of memory. Moreover, the procedure was completed with a scene visit with each neighbourhood chief involved in order to consolidate the information provided verbally. The scene visit is very important because the time elapsed between the oldest event and the date of the study is about 12 years. As time goes by, memories can become vague (Lacy and Stark, 2013). However, people having faced traumatic and stressful events, like floods in our case, tend to keep a more accurate, detailed, and time persistent memory of the event (Sotgiu and Galati, 2007).

Another technique involved participatory hands-on mapping. Mapping can represent a challenging task for laypersons (Handmer, 1985; Żyszkowska, 2015, 2017) as they may have difficulties to understand and to locate themselves on a map. Moreover, maps are usually ~~composed~~ constructed ~~of a graphic semiology~~ applying by standard rules of graphic semiology (Thomas, 2011) ~~and recommendations~~ that does not necessary ~~rarely~~ take into account the culture or knowledge of the citizen

(Fuchs et al., 2009). Therefore, if a citizen has no experience in reading or producing maps, information can be incorrectly reported. To overcome this problem, we trained people to ensure they understood the map; we explained what they should be doing and how to do it.

Quality and reliability of citizen science data is a growing research field (Flanagin and Metzger, 2008; Crall et al., 2011; Silvertown et al., 2015). In our study, we developed different strategies in order to improve these two aspects. We decided to work with two different target groups according to the context and the purpose of the study. The objective was to check the consistency of information between the two groups. If the same flooded area is mentioned by the two groups, there is a good chance that the area was effectively flooded. Due to the social organisation of the Dakar region, one way to limit issues about source credibility (Flanagin and Metzger, 2008) was to involve neighbourhood chiefs. Indeed, these chiefs are appointed by local citizens, based on the trust placed on them and on their long-lasting presence in the area. Usually, they have a good memory and good verbal abilities. Moreover, as a witness or sometimes as a victim, they were at the forefront of the flood scene, therefore representing a valuable source of information to describe the chain of events. The second group was composed of local representatives. The selection was made with the support of local and well-implemented associations.

Identifying the chain of processes generating flooding is very important for flood hazard assessment (DAEC, 2016) as it enables considering more realistic flood scenarios. Citizens living in flood affected areas are not often included in post-event or flood hazard assessments, although they could provide accurate insights as they have a good understanding of their surroundings (Tran et al., 2009), and an in-depth knowledge on the specific realities. Our study demonstrates this as neighbourhood chiefs allowed identifying additional natural and man-made factors that contributed to flooding, such as the rise of ground water, the Warouwaye lake overflow, and the emptying of septic tanks.

In terms of flooded areas, the results obtained per event with the two groups of citizens are similar. Some spatial differences can be observed regarding the extent. Reasons for the differences could be related to a) a more ~~in-deep~~ in-depth knowledge of the neighbourhood and their surroundings by the chiefs, as they have the confidence (Tall, 1998) of the inhabitants, therefore having access to more detailed information; b) the techniques used in mapping the areas: with neighbourhood chiefs, we used a two-stage procedure to retrieve the flood extent, involving hands-on mapping and GIS mapping in the field, whilst the local representatives only produced hands-on maps that were then digitized.

~~When compared to remote sensing analysis, spatial differences can also be noticed which can be explained by a) the resolution of the selected images varies from 0.5 to 2.5 m, probably not accurate enough to capture all flooded areas (Grimaldi et al., 2016); b) the acquisition time as the post-event images were taken up to one year after the flood; c) the technical limitation as satellites cannot capture floods inside a structure that are solid like buildings or under vegetation canopies (Wilson et al., 2007; Mallinis et al 2013);d) the efficiency of the algorithm used for the remote sensing analysis (Bates et al., 1997; Schumann et al., 2009).~~

A good spatial agreement exists between flood extents determined from remote sensing and citizen science, with better agreement from the data provided by the neighbourhood chiefs. However, areas provided by remote sensing are smaller. This discrepancy can be explained by various factors. One could be the different spatial resolution of the selected images, which varyed from 0.5 m to 2.5 m, the larger probably not being probably small enough to capture all flooded areas (Grimaldi et al., 2016) at the scale we worked. A second factor concerns the different time lapses between images. Post-event images from Google Earth were captured at intervals from 1 to 15 days and therefore may not have captured the maximum extent. Furthermore, for the 2005 event, one image was obtained during the flooding, with the second image taken one year after with the assumption it was captured during a dry period. A third factor is related to technical limitations of the capability of optical satellites to detect flooded areas, which is reduced when clouds are present (Mallinis et al 2013; Malinowski et al., 2017). Finally, the efficiency of the NDWI index used to detect water areas could be altered by noise (Xu, 2005).

Concerning water depth retrieval, one of the techniques was inspired from studies expressing flood hazard levels on maps using body scale (e.g. EXCIMAP, 2007; Luke et al., 2018). Therefore, quantitative data on water depth were retrieved using a proportion of the size of the human body borrowed from physiology field (Winter, 2009). These values represent an average (Drillis and Contini, 1966), since the length of human body segments depend on body structure (Contini, 1972), gender and racial origin, and therefore could be a source of uncertainties. However, when comparing the two approaches used for water depth investigation, we find a fairly good agreement, with an average differences below 0.3m, which is in the range of other comparisons done for example between observed and simulated methods (Kutija et al., 2014).

Both implication and motivation from citizens are necessary for the success of citizen science projects (Rotman et al., 2012). ~~To ensure people implication in our project, we first created a Facebook page (http://www.facebook.com/xeexmeude.com) in order to interact with the local citizens~~As Facebook was one of the most used social media in Yeumbeul North at the time of the study (Sy, 2019), we first created a page to interact with local citizens and motivate them to be part of the project. Second, we designed and presented the project in a way to convince contributors that their contribution will be beneficial for them and their neighbours. Third, we worked with community leaders (Bénit-Gbaffou and Katsaura, 2014) and local associations to ensure a better acceptance of the project.

Citizen science requires involvement and time, compared to remote sensing analysis, which could now also take advantage of the free availability of radar images such as sentinel (Malenovský et al., 2012). However, at the scale we worked, these images do~~n't~~not offer the required spatial resolution (Twele et al., 2016), and they don't provide information on depth of flood, which is one of the critical information for flood hazard assessment that we were able to obtain with citizen science.

In conclusion, our study shows the potential of citizen science in retrieving quantitative and reliable information on past flood events, especially in areas where no or few records of past events are available. Our investigation strategy, by involving two different groups of citizens, increases the reliability on the data obtained. Provided the functioning of the society subject to floods is well understood, such approach can be replicated in other parts of the world. Moreover, considering the fact that citizens have been involved in the various steps of this project, they have developed skills in flood data acquisition and understanding of flood processes. They can thus better integrate a decision-making process around flood risk.

Author contributions

BS conceived the study and carried out citizen science project in the field. BS analysed the results and compiled the figures with input from CF. The outline of the manuscript was drafted by BS, HD, DC, GG, CF. BS and CF prepared the manuscript with contributions from all co-authors. All the authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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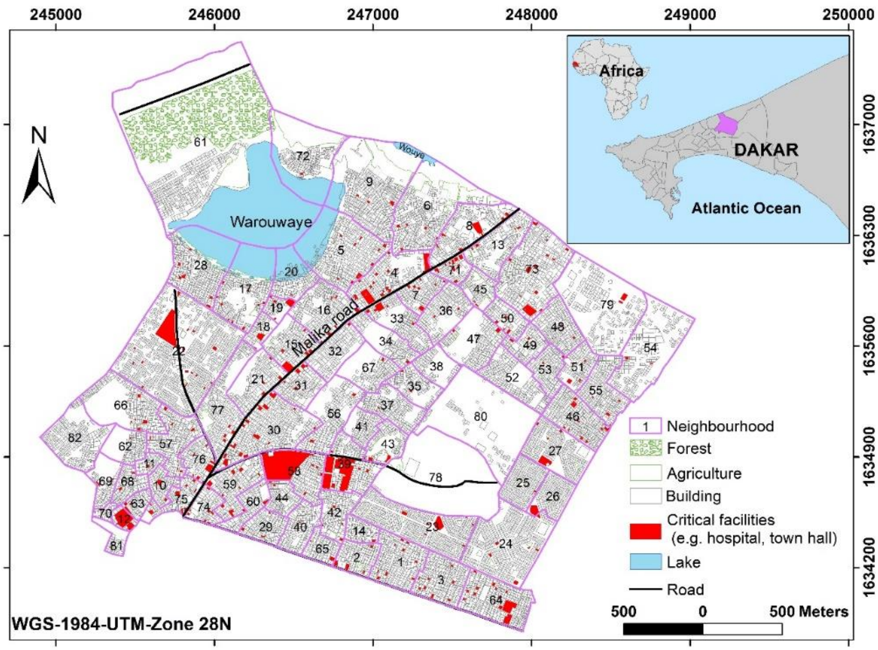
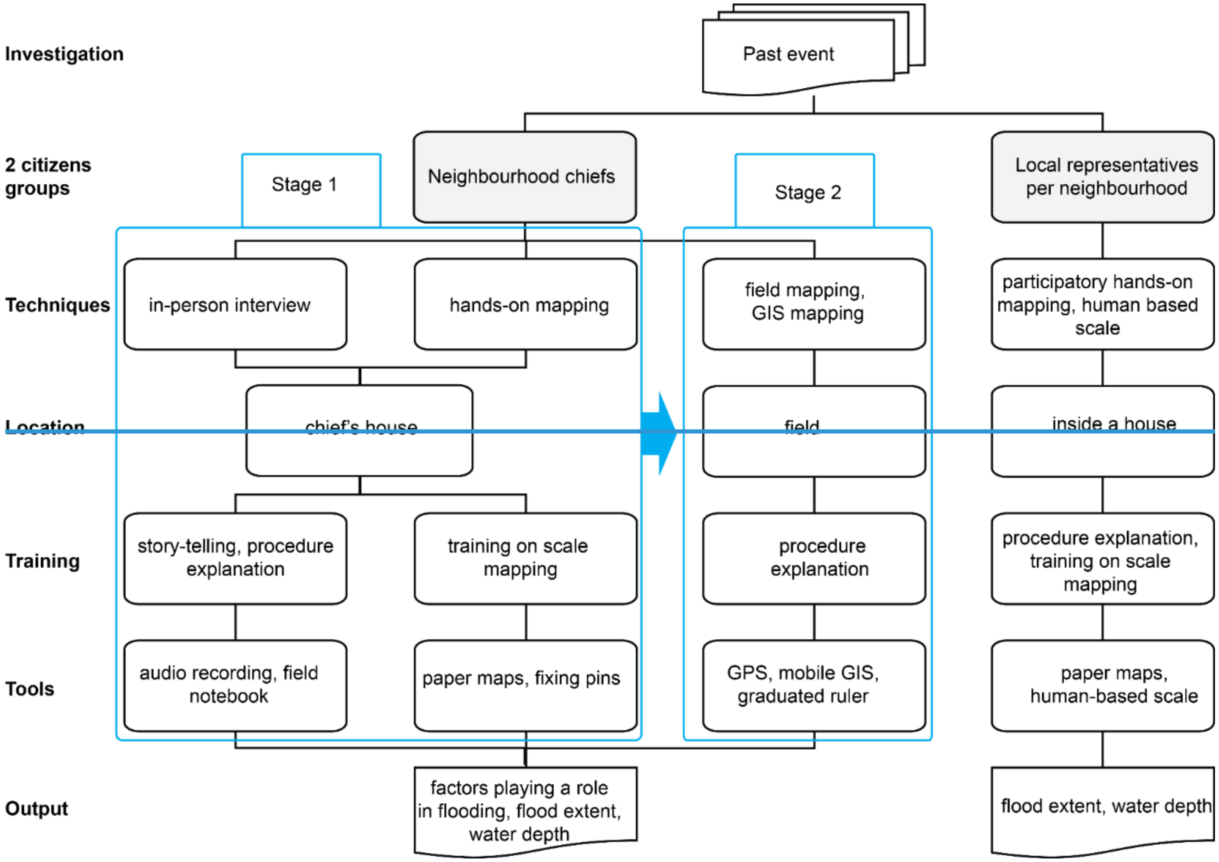


Figure 1: Location of the study area. The insert on the right corner locates our study area in the city of Dakar in Senegal. The central map represents our study area Yeumbeul North, without the retention basins that were constructed after the 2012 flood. The 82 neighbourhoods are designated by a number from 1 to 82. The corresponding names are provided in the supplementary material 1 (SM1).


Investigation
Past event
2 citizens groups
Stage 1
Neighbourhood chiefs
Stage 2
Local representatives per neighbourhood
Techniques
in-person interview
hands-on mapping
field mapping, GIS mapping
participatory hands-on mapping, human based scale
Location
chief's house
field
inside a house
Training
story-telling, procedure explanation
training on scale mapping
procedure explanation
procedure explanation, training on scale mapping
Tools
audio recording, field notebook
paper maps, fixing pins
GPS, mobile GIS, graduated ruler
paper maps, human-based scale
Output
factors playing a role in flooding, flood extent, water depth
flood extent, water depth

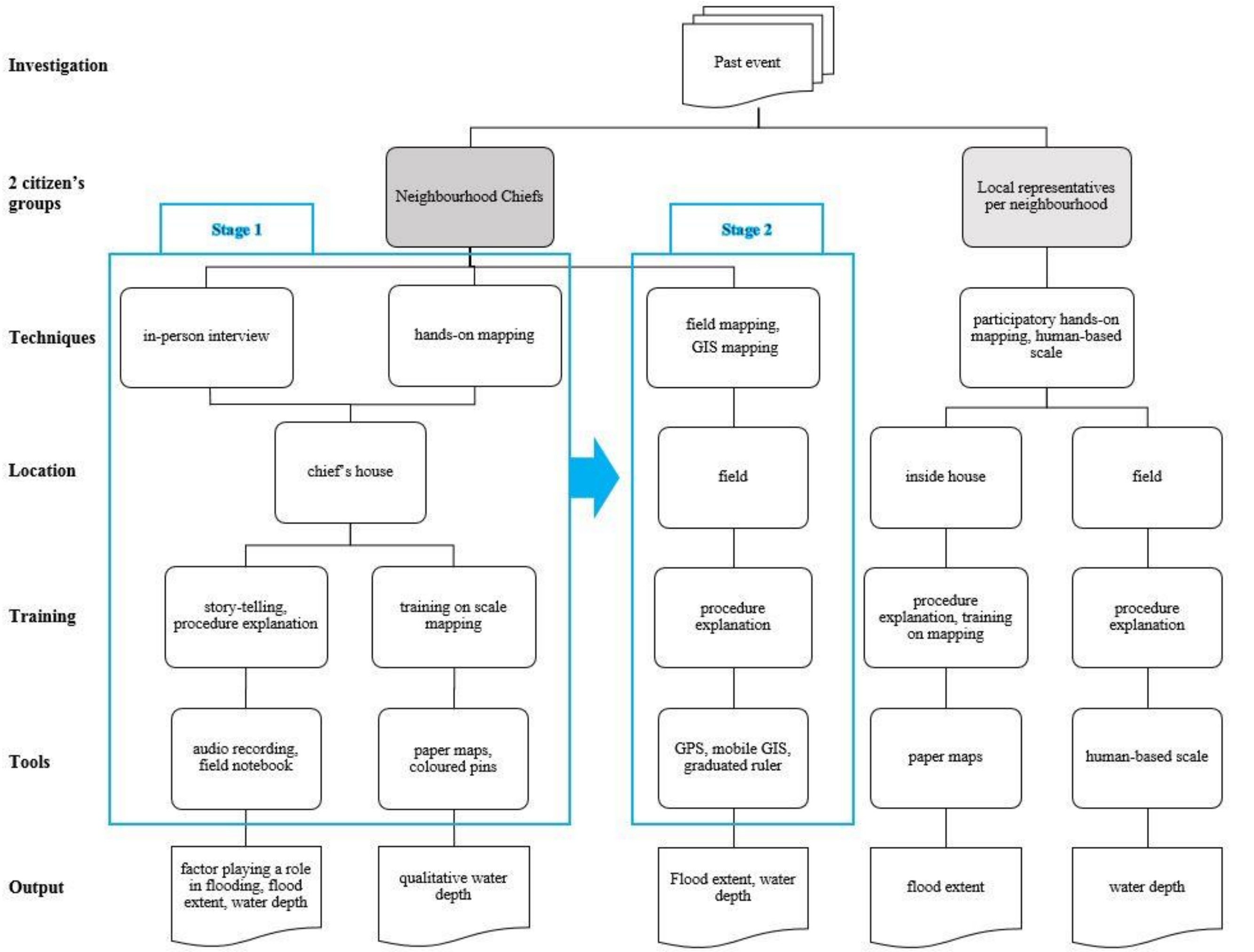


Figure 2. Framework for retrieving past flood information by citizen-based methodology

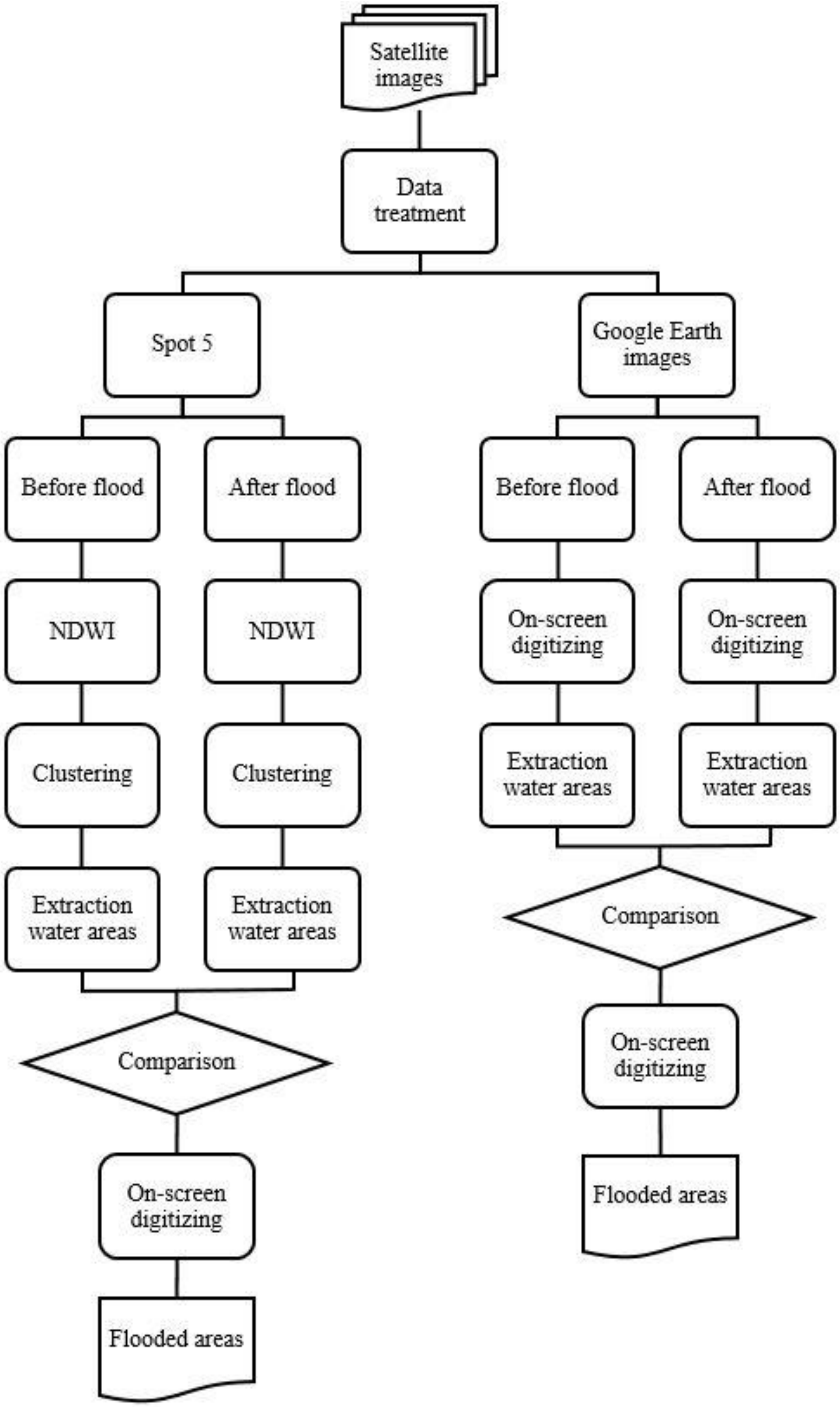


Figure 3. Framework for retrieving flooded areas by remote sensing analysis

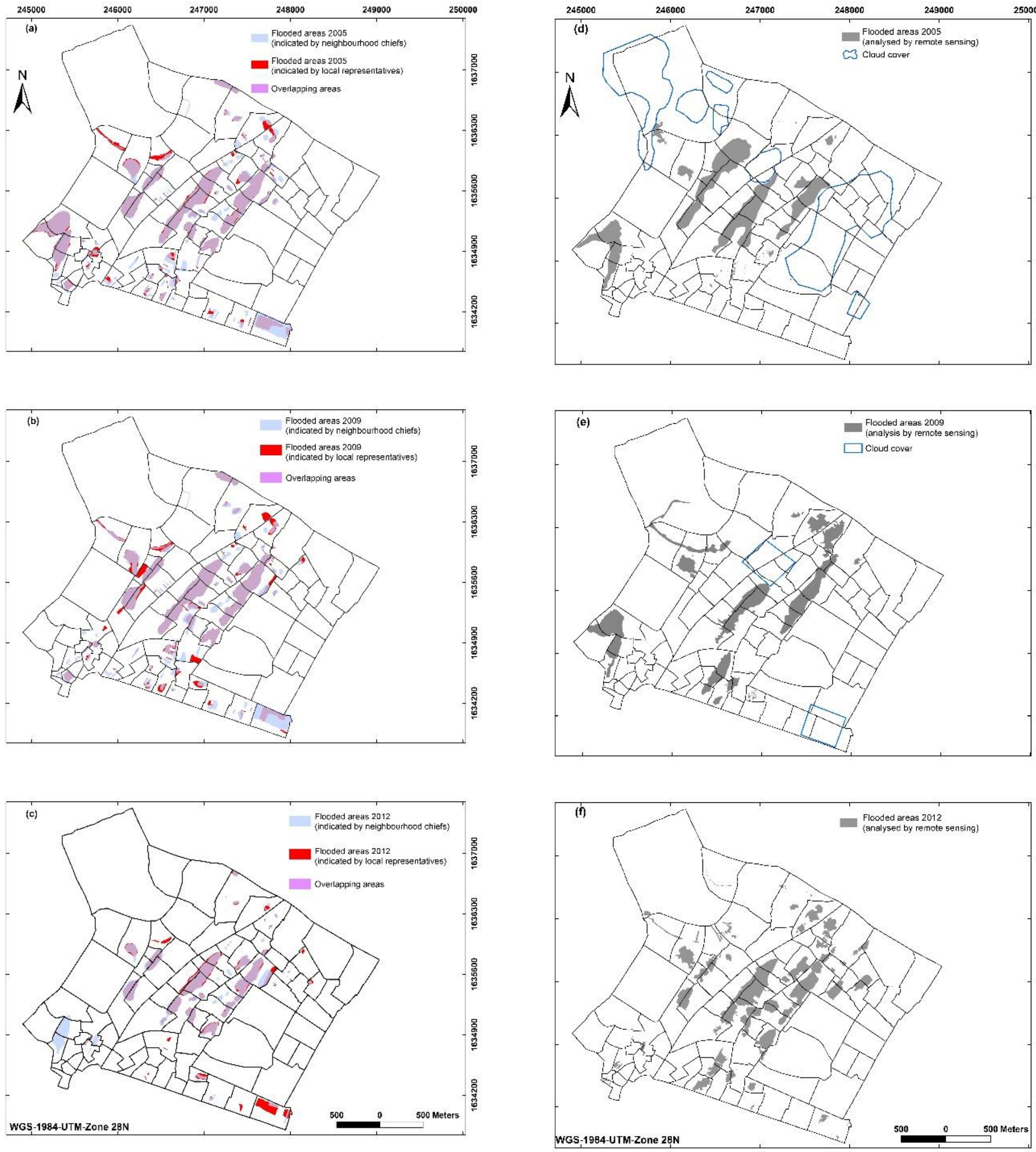
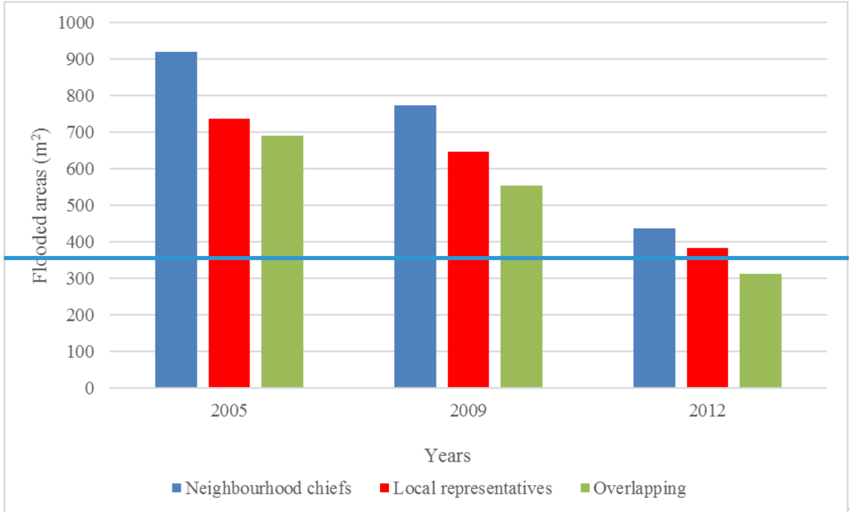
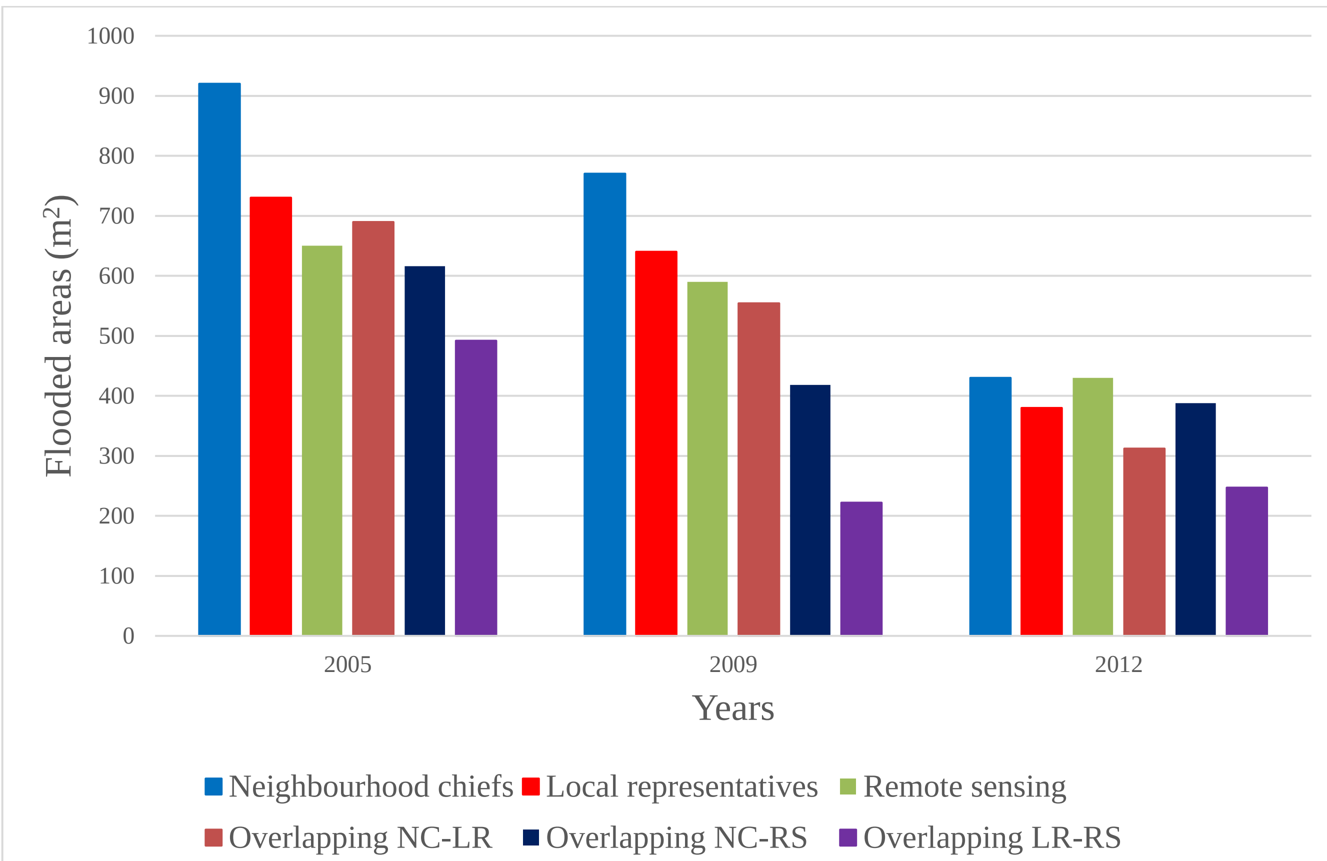


Figure ~~3~~4: Left side: Spatial distribution of flooded areas based on citizen science techniques, (a) 2005, (b) 2009, and (c) 2012. Right side: flooded areas based on remote sensing data (d) 2005, (e) 2009, and (f) 2012.





~~**Figure 4: Flooded areas obtained by the two citizen groups and the surface of overlapping areas between the two results**~~

Figure 5. Flooded areas obtained by the two citizen groups and remote sensing with the surface of overlapping areas between the two results citizen groups (1), neighbourhood chiefs and remote sensing (2), and local representatives and remote sensing (3)

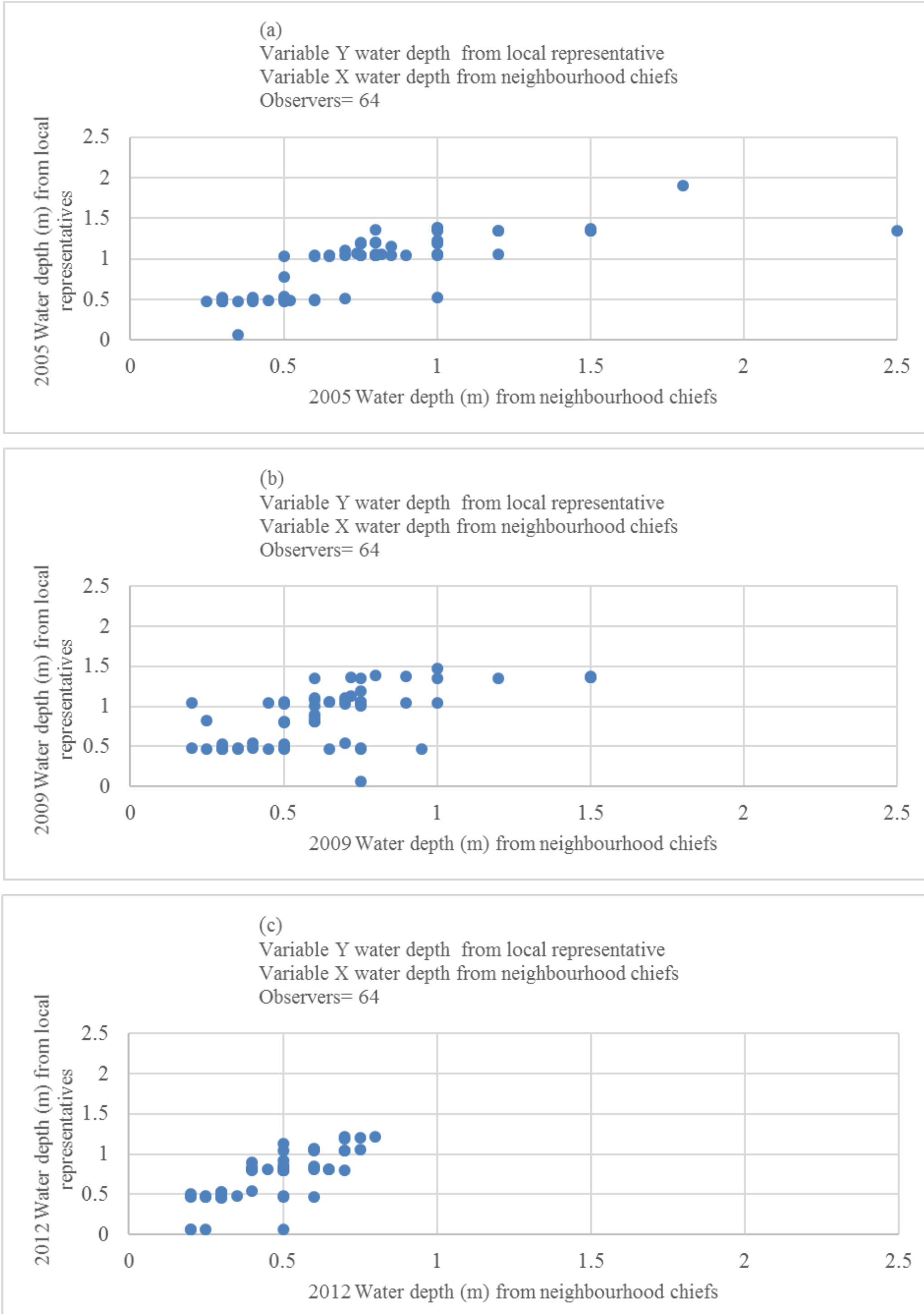
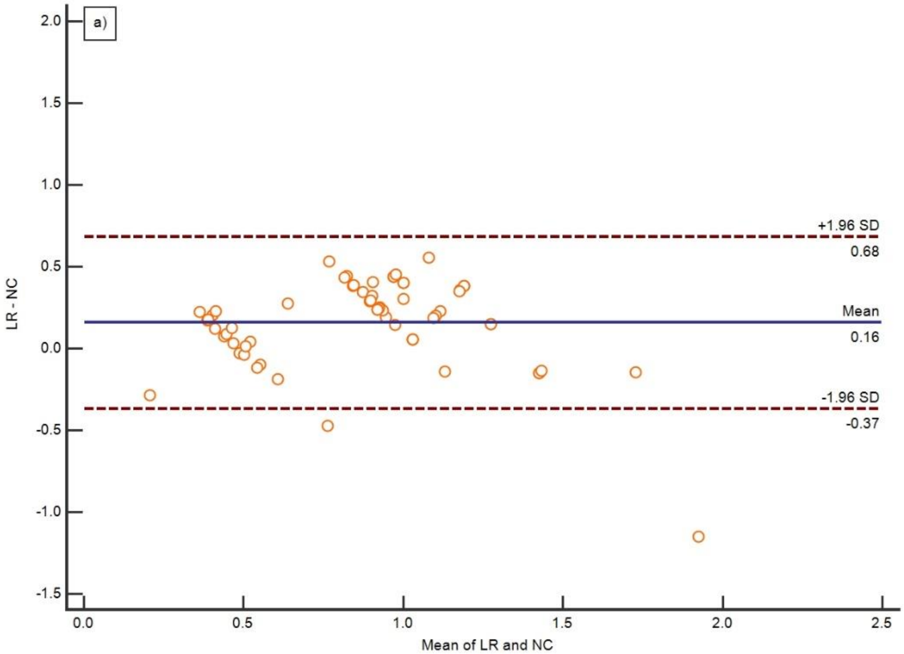
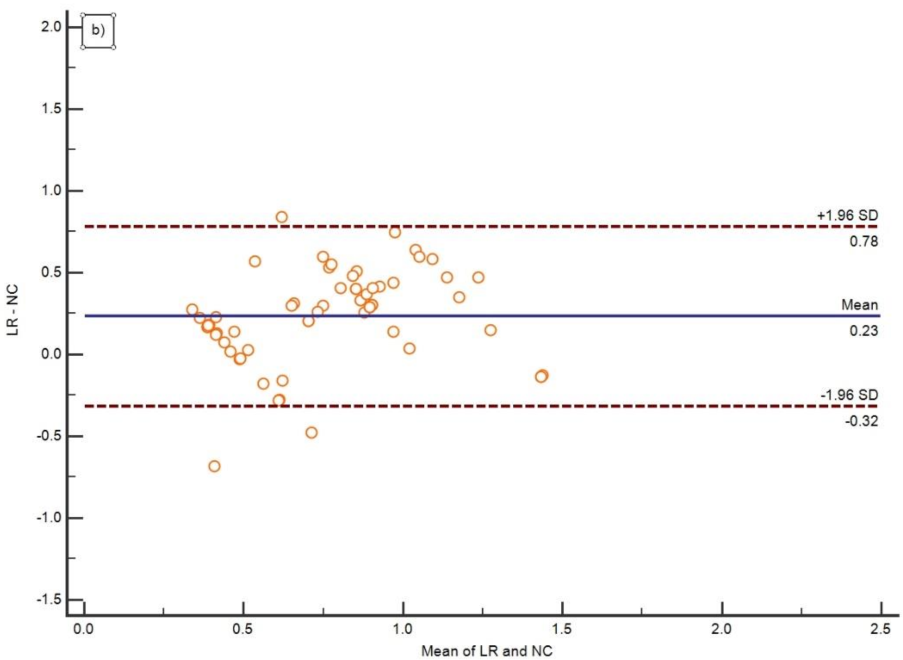


Figure ~~5~~6: Scatter diagram of water depth information provided by neighbourhood chiefs and local representatives techniques for 3 different flooding events (a) 2005, (b) 2009, and (c) 2012


a)
+1.96 SD
0.68
Mean
0.16
-1.96 SD
-0.37
LR - NC
Mean of LR and NC


b)
+1.96 SD
0.78
Mean
0.23
-1.96 SD
-0.32
LR - NC
Mean of LR and NC

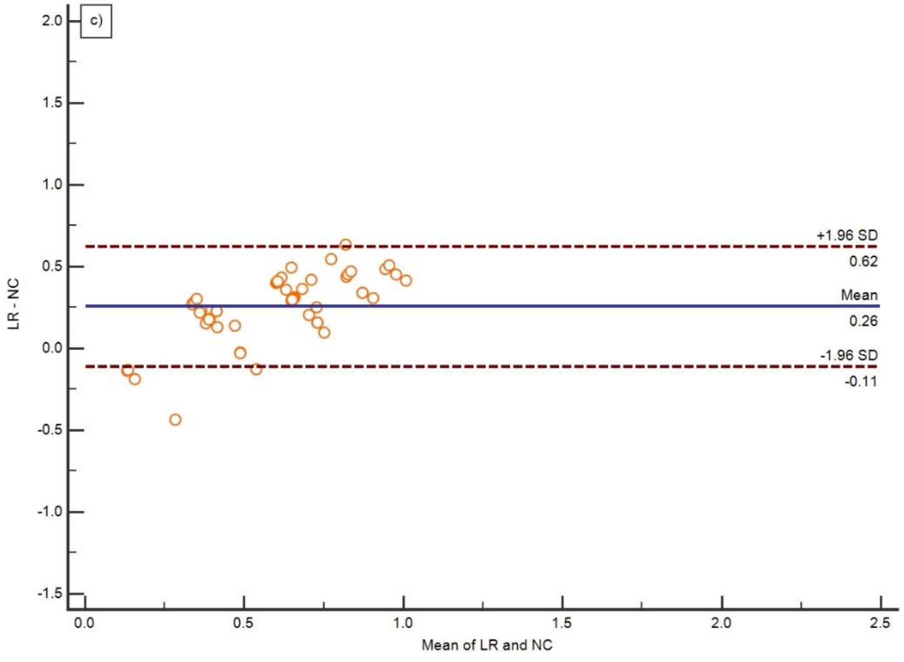


Figure 7. Bland-Altman plots for different flooding events (a) 2005, (b) 2009 and (c) 2012. These graphs show differences between water depth provided by neighbourhood chiefs (NC) and local representatives (LR) in meters against averaged values of NC and LR. Blue line is the mean difference value and the red dotted lines show the +/- 1.96 standard deviation (SD) water depth differences for all observations

~~Figure 6. Bland-Altman plots of differences between water depth provided by neighbourhood chiefs (NC) and local representatives (LR) in meters against averaged values of NC and LR. Blue line is the mean difference value and the red dotted lines show the +/- 1.96 standard deviation (SD) water depth differences for all observations.~~

Table 1 The beginning and the end of the 3 flood events according to the Emergency Events Database (EM-DAT), as well as rainfall intensity peak of each event in Dakar-Yoff station coming from the National Agency for Civil Aviation and Meteorology (ANACIM) database in Senegal

Flood events	**2005**	**2009**	**2012**
start	20.08	09.08	15.08
end	10.09	20.09	31.08
Peak rainfall intensity	50 mm/h (04.09)	40 mm/h (24.08)	145.5 mm/h (26.08)

Table 2 Remote sensing data

Data/images	Date	Satellite / sensor	Resolution	Source
Mutispectral color	07/09/2005	Spot-5/HRV	10 m	UCAD
Mutispectral color	23/10/2006	Spot-5/HRV	10 m	UCAD
Panchromatic	23/10/2006	Spot-5/HRV	2.5 m	UCAD
Digital Globe©	11/03/2009	Worldview / QuickBird	0.5 m	Google Earth©
Digital Globe©	14/10/2009	Worldview / QuickBird	0.5 m	Google Earth©
Digital Globe©	08/03/2012	Worldview / QuickBird	0.5 m	Google Earth©
Digital Globe©	31/08/2012	Worldview / QuickBird	0.5 m	Google Earth©

Table 3 Comparison of flooding areas coming from citizen science techniques deployed in Yeumbeul Nord (neighbourhood chiefs and local representatives) and remote sensing analyses

	~~Citizen science~~				~~Remote sensing~~	
	~~Neighbourhood chiefs~~		~~Local representatives~~			
~~Years~~	~~Flooded areas (km²)~~	~~% of the study area~~	~~Flooded areas (km²)~~	~~% of study area~~	~~Flooded areas (km²)~~	~~% of study area~~
~~2005~~	~~0.92~~	~~10~~	~~0.73~~	~~8.2~~	~~0.65~~	~~7.3~~
~~2009~~	~~0.77~~	~~8.6~~	~~0.64~~	~~7.2~~	~~0.59~~	~~6.6~~
~~2012~~	~~0.43~~	~~4.8~~	~~0.38~~	~~4.3~~	~~0.43~~	~~4.8~~

	Citizen science				Remote sensing		Overlapping		
	Neighbourhood chiefs (NC)		Local representatives (LR)				NC / LR	NC / remote sensing	LR / remote sensing
Years	Flooded areas (km^2)	% of the study area	Flooded areas (km^2)	% of study area	Flooded areas (km^2)	% of study area	area (km^2)	area (km^2)	area (km^2)
2005	0.92	10	0.73	8.2	0.65	7.3	0.69	0.62 (95%)	0.49 (75%)
2009	0.77	8.6	0.64	7.2	0.59	6.6	0.55	0.42 (71%)	0.22 (37%)
2012	0.43	4.8	0.38	4.3	0.43	4.8	0.31	0.39 (91%)	0.25 (58%)