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. At the bottom of the editor's answer, you will find also the revised manuscript with changes marked

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. 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 (ll 153-156). In addition, we give more information on why we expect difference in respect with the chief (ll 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 measurements in the field. 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 consider 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

Reconstituting past flood events: the contribution of citizen science

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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, particularly 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 all 3 flood events.

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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 loss (EM-DAT, 2018). West African countries, such as Burkina Faso or Senegal, appear to be experiencing an increase in flood disasters due to population growth and the urbanization of flood-prone areas (Di Baldassarre et al., 2010). Between 1990 and 2014, floods were responsible for 86% of the economic loss from natural disasters in Senegal alone (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).

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The government and local authorities of Senegal have tried several strategies to mitigate urban floods, such as developing emergency plans, relocating inhabitants, and building water retention basins. However, two key aspects, required for these measures to work, have not yet been considered. Firstly, it is necessary to understand the causes and characteristics of floods and, secondly, the local population must be involved in the process of risk management. Information on the 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 temporal 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 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 advancements in various modern technologies - internet, web 2.0, virtual globe, location-based services, social media, mobile devices, interactive geo-visualization interfaces such as OpenStreetMap; Google Earth, Geo Wiki (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 of studies and the subjects investigated by citizen science projects. 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 citizens can clarify the causal chain of flood events. We also assessed the reliability of these data with by comparing against independent methods, such as remote sensing.

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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 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 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 these, 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 neighbourhood and at least 35 years old. One of the delegate's tasks is to inform the neighbourhood inhabitants about how to face disasters. In this paper, we will referred to with delegate as a 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 considered here 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 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) have witnessed the 3 flood events; 2) have a good spatial knowledge of both the study and flooded areas; 3) their social standing. Therefore, the first group consisted of the chiefs of the 82 neighbourhoods in 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 their ages varied from 40 to 90 years, with an average of 66

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years. The second group was composed of 182 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 was not by 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

For this group of citizens, we used a two-stage approach to optimize the validity, reliability and utility of the collected data, and to transform memories of past floods into temporal and spatial information. The first stage is based on the use of episodic memory through in-person interviews conducted in the chief's house. Episodic memory is the process by which humans remember events in 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 involves 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 oldest inhabitants of the neighbourhood. Each interview was expected to last between 45 and 60 minutes, but it varied according to the history told and no time limit was imposed. Ultimately, interviews lasted from 30 to 60 minutes. In some cases it was possible to record the narrative digitally using a smartphone. The information obtained from the narrative allowed the neighbourhoods that were flooded to be identified. 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), putting pins on the map, 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 investigations (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 relaxed state, allowing them to focus their thoughts and cognitive and emotional states 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 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 that could act as time indicators (e.g. proximity to a presidential election, football game); c) notable flood-related measures taken by the authorities enabling the event to be dated; d) spatial indicators such as place

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and street names allowing reconstruction of the flooded areas, and e) the event itself, including information allowing deduction of the water depth (e.g. “the water reached our knees”).

Following the narrative, only chiefs who indicated having been confronted with floods went through participatory mapping using maps at the scale of the neighbourhood (62 out of 82 chiefs, see supplementary material 2). This phase required 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 other features in 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 a 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 corroborate the chiefs’ responses from stage 1 by cross-checking the information leading to the map from stage 1 with 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 the water level as indicated by 49 neighbourhood chiefs with a graduated ruler (supplementary material 3, 4 and 5) at 64 sites and took the GPS coordinates. Post-processing treatments include merging the contours of flooded areas obtained on the 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 quantitative 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 people, selected by local associations (e.g. “Réseau d’Information d’Education de Communication”, “Association des Relais Communautaires de Yeumbeul”) that deal 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 of involving local representatives is to integrate their information with that provided from 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

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recall 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, local representatives went to the same 64 sites as indicated by the chiefs, but without having any prior knowledge on the depths given by the chiefs, and depth 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, as 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) and chin (0.870). Finally, the water depth was obtained by multiplying the value of the appropriate coefficient by the contributor's (local representative) height, as measured on site with a 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), which determines 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 plots them against the average of the two approaches.

3.1.3 Remote sensing analysis

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 water

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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 identified rainfall as the primary factor. 29 chiefs (neighbourhood numbers 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 pointed out the rise of the water table, substantiated by wet ground, greening of walls due to the water infiltration, and removal of paint from walls.

The neighbourhood chiefs identified different processes that worsened the flood, by either increasing the quantity of water or obstructing the typical flow, for both different locations and events. For example, for the 2005 event, 4 neighbourhood chiefs (13, 36, 46, and 67) mentioned the failure of the pipeline in the road of Malika, used for water drainage, as 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 performed by the local population, such as emptying of household septic tanks, which aggravated this event and also had direct consequences on health (e.g. cholera epidemics) (Wade et al., 2009). Pipeline failure and emptying of septic tanks also 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 did not recall any aggravating processes.

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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. 4).

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 between the extents identified by the two citizen groups (Fig. 4), but the areas overlap reasonably well (Fig. 5).

Remote sensing analysis confirms that the main flooded areas were in the central part of the study area (Fig. 4), but some discrepancies occur at the edges. The total surface area is smaller than that 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 6 displays scatter diagrams of depth values obtained from the two different groups of citizens using the techniques described in the methods (see Fig. 2) at 64 sites, sampled over 49 neighbourhoods. We have two measurement from each site. The maximum retrieved flood depth is 2.5 m for the 2005 event, 1.5 m for the 2009 event, and 1.2 m for the 2012 event. Figure 7 shows the data obtained by applying the Bland-Altman method for the 2005, 2009 and 2012 events for the 64 sites of measurements. The value of the mean differences in water depth, indicated by the blue line, is 0.16 m for the 2005 event, 0.23 m for 2009 and 0.26 m for 2012. The limits of agreement, also displayed, are set at 95% confidence intervals. Assuming the differences to be normally distributed, these limits are defined by the mean difference +/- 1.96 multiplied by the standard deviation σ of the differences. For the 2005 event, this range is from 0.68m to -0.37m, with two values out of these limits. For 2009 and 2012, three values are outside the 95% confidence interval which is from 0.78m to -0.32m for 2009 and 0.62m to -0.11m for 2012.

5 Discussion and conclusion

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

Our methodology consisted of a set of techniques designed to gather the most complete spectrum of information. These techniques are unusual in the field of flood hazard assessment and we had to resolve some challenges associated with the time elapsed since the events and participant's understanding of maps. One technique is based on people's episodic memory; we

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used face-to-face interviews with neighbourhood chiefs, applying specific tools in order to limit external influence and memory distortion. The procedure was then completed by a scene visit with each neighbourhood chief involved in order to consolidate the verbally provided information. The scene visit is very important because the time elapsed between the oldest event and the date of this study is about 12 years. And, as time goes by, memories can become vague (Lacy and Stark, 2013). However, people who have experienced traumatic and stressful events, like floods, tend to retain 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 understanding and locating themselves on a map. Moreover, maps are usually constructed applying by standard rules of graphic semiology (Thomas, 2011) that does not necessary take into account the cultural background 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 on how to read a map and locate themselves to ensure they understood the map and we explained what they should be doing and how to do it.

Developing the 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 obtained from the two groups. If the same area is described as flooded by both groups, there is a good chance that the area was indeed flooded. Due to the social organisation of the Dakar region, we limited issues regarding source credibility (Flanagin and Metzger, 2008) by involving neighbourhood chiefs. Indeed, these chiefs are appointed by local citizens, according to the trust placed in 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 on the chain of events. The second group was composed of local representatives, selected 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 analysis of more realistic flood scenarios. Citizens living in flood affected areas are not frequently included in post-event or flood hazard assessments, even though they could provide useful insights as they have a good understanding of their surroundings (Tran et al., 2009) and an in-depth local knowledge. Our study demonstrates this as neighbourhood chief's identified both 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 from the two groups of citizens are similar for each event, although some spatial differences can be observed regarding the extent. Reasons for the differences could be related to a) a more in-depth knowledge of the neighbourhood and their surroundings by the chiefs, as they have the confidence (Tall, 1998) of the inhabitants and therefore have access to more detailed information; b) the techniques used in mapping the areas. With neighbourhood chiefs,

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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.

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).

One of the techniques used to retrieve water depths was inspired from studies expressing flood hazard levels on maps using a 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 less than 0.3 m, which is within the range of other comparisons between observed and simulated methods (Kutija et al., 2014).

Both involvement and motivation from citizens are necessary for the success of citizen science projects (Rotman et al., 2012). 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. Secondly, we designed and presented the project in a way to convince contributors that their contribution will be beneficial for them and their neighbours. Thirdly, 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 can 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 not offer the required spatial resolution (Twele et al., 2016) nor information on the depth of the flood, which is a critical datum for flood hazard assessment that we was 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, involving two different groups of citizens, increases the reliability of the obtained data. Provided that the functioning of the society subject to floods is well understood, such an approach can be replicated in other parts of the world. Moreover, the citizens that have been involved in the various steps of this project have developed skills in flood data acquisition and an understanding of flood processes. They can thus better integrate into a decision-making process regarding flood risk.

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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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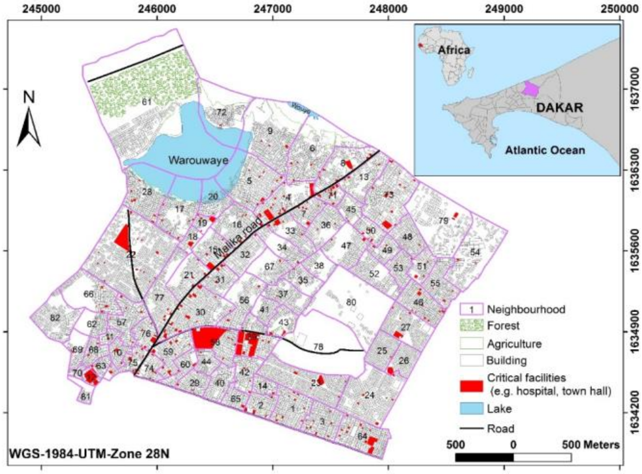


Figure 1. Location of the study area. The insert on the right corner locates our study area in the city of Dakar in Senegal. The central map represents our study area Yeumbeul North, without the retention basins that were constructed after the 2012 flood. The 82 neighbourhoods are designated by a number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

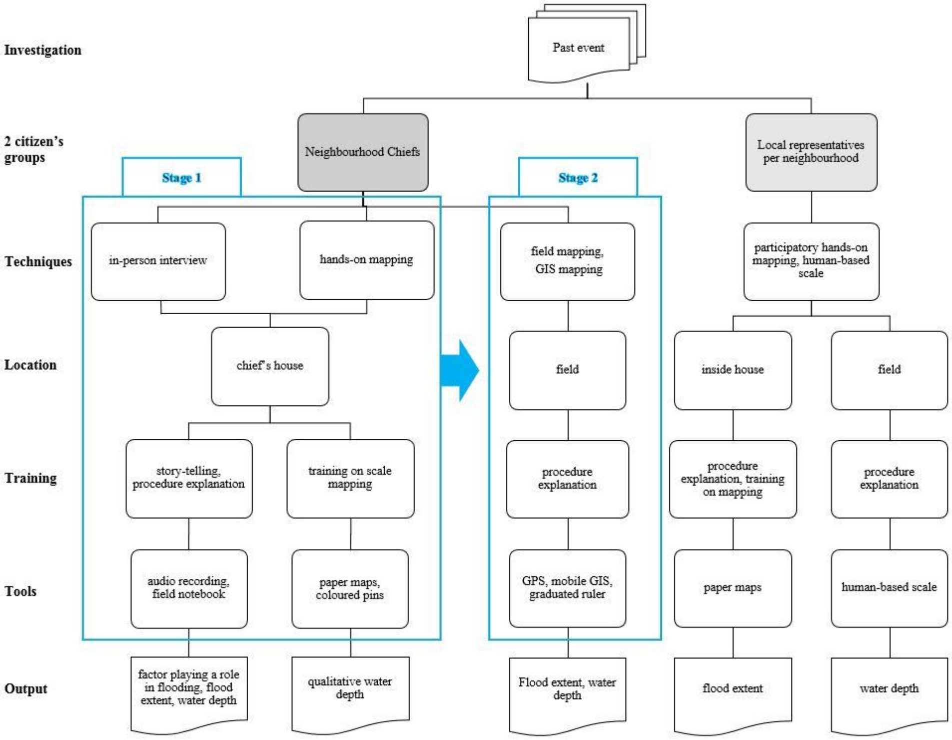


Figure 2. Framework for retrieving past flood information by citizen-based methodology

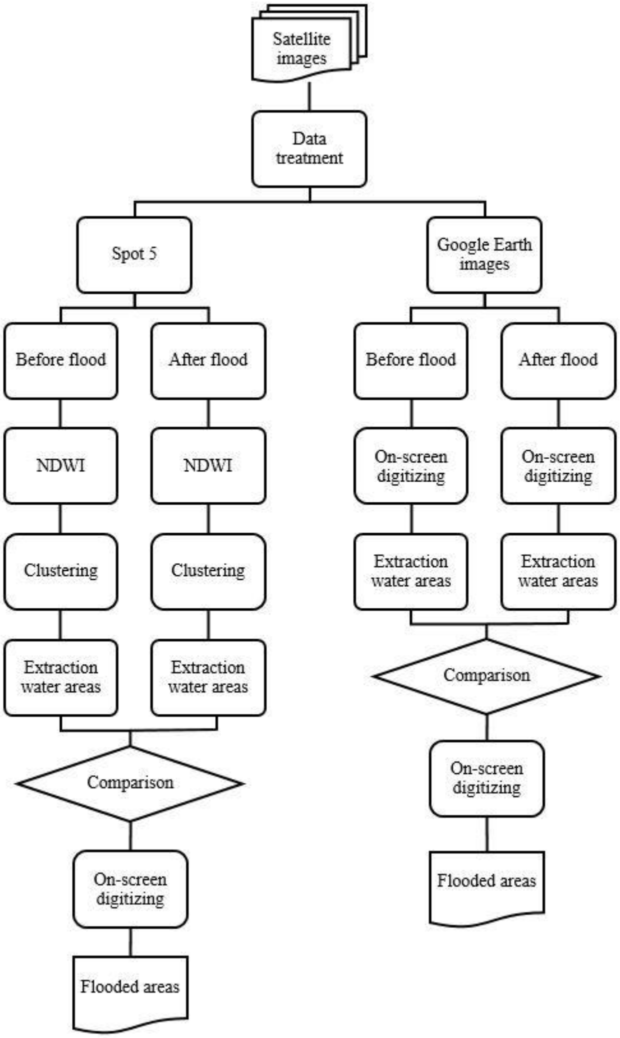


Figure 3. Framework for retrieving flooded areas by remote sensing analysis

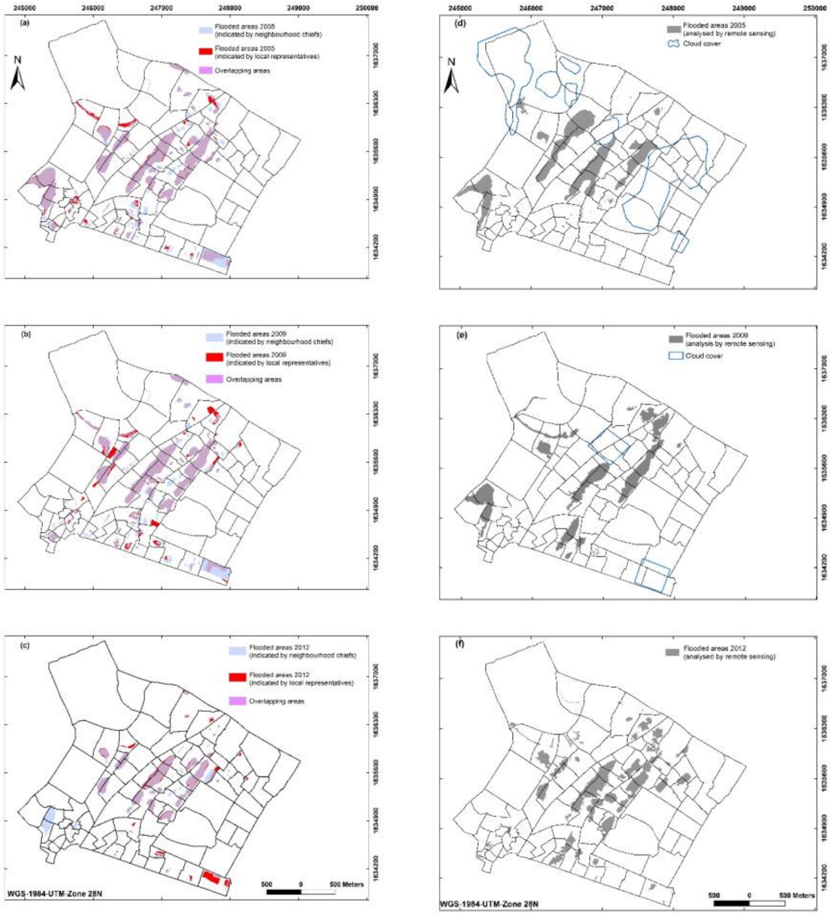


Figure 4. Left side: Spatial distribution of flooded areas based on citizen science techniques, (a) 2005, (b) 2009, and (c) 2012. Right side: flooded areas based on remote sensing data (d) 2005, (e) 2009, and (f) 2012.

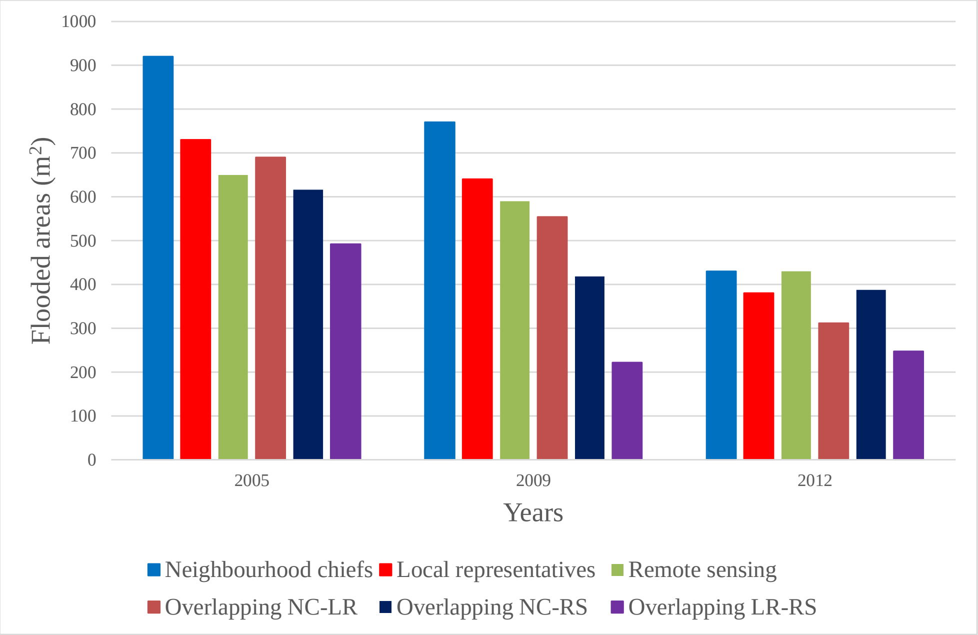


Figure 5. Flooded areas obtained by the two citizen groups and remote sensing with the surface of overlapping areas between the two results citizen groups (1), neighbourhood chiefs and remote sensing (2), and local representatives and remote sensing (3)

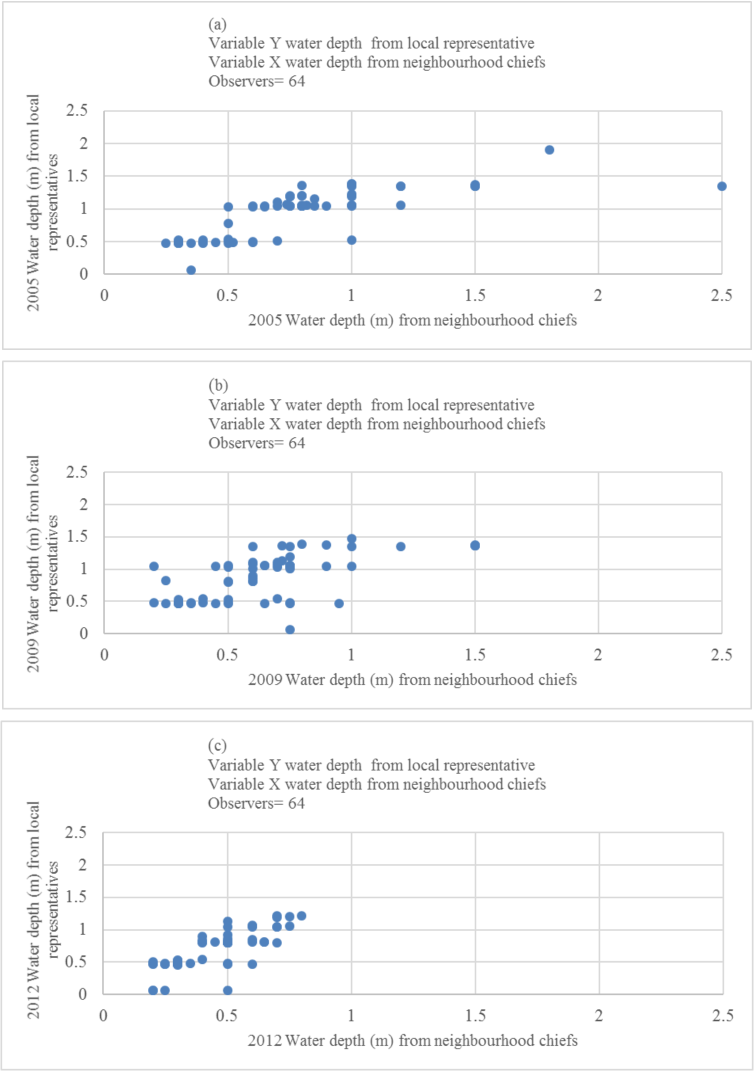
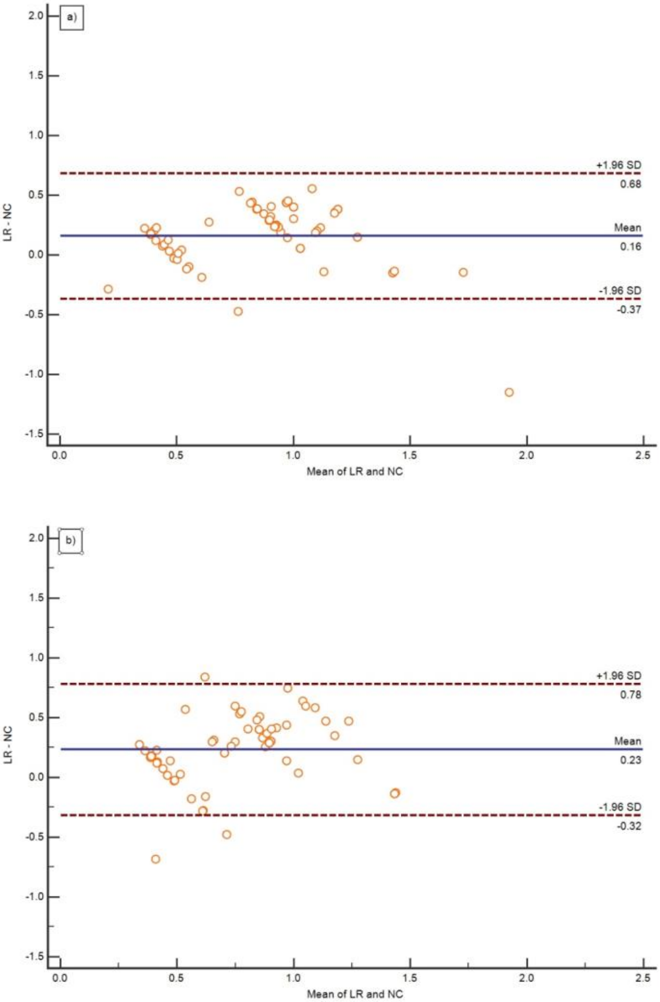


Figure 6. Scatter diagram of water depth information provided by neighbourhood chiefs and local representative's techniques for 3 different flooding events (a) 2005, (b) 2009, and (c) 2012

a)
+1.96 SD
0.68
Mean
0.16
-1.96 SD
-0.37
LR - NC
Mean of LR and NC
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
0.5
1.0
1.5
2.0
2.5
b)
+1.96 SD
0.78
Mean
0.23
-1.96 SD
-0.32
LR - NC
Mean of LR and NC

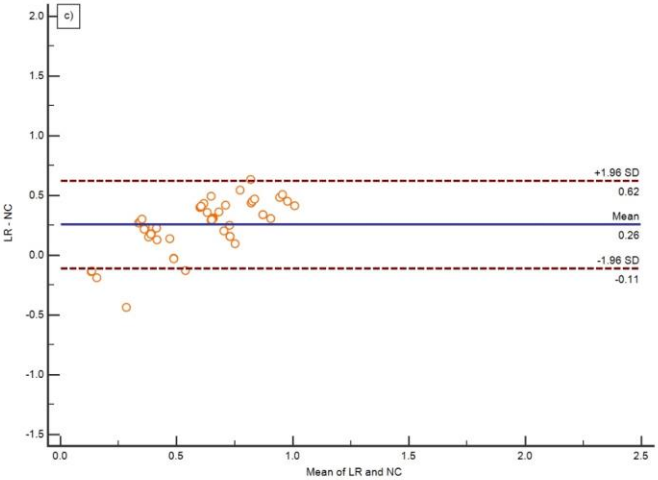


Figure 7. Bland-Altman plots for different flooding events (a) 2005, (b) 2009 and (c) 2012. These graphs show differences between water depth provided by neighbourhood chiefs (NC) and local representatives (LR) in meters against averaged values of NC and LR. Blue line is the mean difference value and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

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		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%)