

# Socio-physical Vulnerability to Flooding in Senegal

An Exploratory Analysis with New Data  
& Google Earth Engine



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## Abstract

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Each year thousands of people and millions of dollars in assets are affected by flooding in Senegal; over the next decade, the frequency of such extreme events is expected to increase. However, no publicly available digital flood maps, except for a few aerial photos or post-disaster assessments from UNOSAT, could be found for the country. This report tested an experimental method for assessing the socio-physical vulnerability of Senegal using high capacity remote sensing, machine learning, new social science, and community engagement. This scientific approach to flood analysis developed in this report is much faster and much more responsive than traditional flood mapping, at only a fraction of the cost. First Cloud to Street's customized water detection algorithms were run for several publicly available satellites (MODIS, Landsat) to map major floods from the last 30 years and second machine learning approach to hydrology in Google Earth Engine was trained on the maps of past floods. Third, a Principal Component Analysis, which ran on custom-designed Census Senegal variables, revealed five underlying dimensions of social vulnerability to flooding. Overall, the research predicts a floodplain in Senegal of 5,596 km<sup>2</sup>, 30% of which is high-risk zone where over 97,000 people live. Approximately 5 million people live in the 30 *arrondissements* that have very high social vulnerability profiles compared to other *arrondissements*. In a future version, this risk platform could be set to stream satellite imagery public and other sensors, so that the vulnerability analysis for Senegal can be updated with the mere refresh of a browser page – no downloading is required.

# 1. Introduction – New threats, New Innovations, and Bringing New Vulnerability Analysis to Senegal

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The risk and impact of natural hazards is increasing faster than at any other time in human history due climatic change and major population migration. Floods account for almost half of all weather-related disasters over the last two decades, affecting 2.3 billion people. Each year, millions of people and billions of dollars' worth of assets around the world are affected by floods, which cause more economic, social, and humanitarian losses worldwide than any other type of hazard (UNISDR, 2015). By 2030, the number of people and GDP exposed to flooding will double as a result of climate change and population migration (World Resources Institute, 2015). This is simply not a level of risk that the world is able to absorb. Today, disaster management is overwhelmingly a reactionary practice, with 87% of disaster funding spent on immediate response (Keating et al., 2014). In developing countries, 80% of people exposed to floods, including countries such as Senegal, do not have flood insurance (Keating et al., 2014). The authors estimate that many people living in the floodplain today would likely not appear on an official flood map and therefore cannot fully prepare or be protected by government.

Traditional vulnerability models, used to assess river geomorphology and hydrology, are physically based, time-intensive, costly, do not incorporate social dimensions of the vulnerability to disasters, and are not responsive to or inclusive of communities. First and foremost, the process of building new hydrologic and hydraulic models to reflect geomorphic changes can costs millions of dollars and take years to calibrate and validate. These barriers can prohibit development of hydrologic models in a timely manner, especially considering that new assessments are required each time a new major event comes through the area.

Second, traditional flood risk analysis requires a significant amount of expert data that is rarely publically available or easy to create. Initiatives like CLUVA (Climate Change and Urban Vulnerability in Africa) have invested in building GIS systems in Saint-Louis, Senegal's second largest city, but program managers note that data gaps remain regarding stakeholder knowledge about flood vulnerability between communities, regional, and state governments. While it is recognized by Senegalese academics that that "appropriate information presented in appropriate ways can have a catalytic role in risk prevention" (Diagne, 2007), the authors could find no publicly available digital flood maps, save for a few aerial photos or post-disaster assessments from UNOSAT (UN Satellite Service).

In addition, most hydrologic models do not consider the social dimensions of vulnerability, an equally important element for disaster response and preparedness. Finally, with a few key exceptions such as Building Resilience and Adaptation to Climate Extremes and Disasters (BRACED) and a select set of other projects, there are few good models of inclusive and genuine community engagement around resilience and vulnerability assessment in Senegal. Further, there are arguably no approaches that integrate community input and treat local knowledge and expertise with the same value afforded to external scientific assessments of vulnerability in the area.

Despite a relative lack of risk data and vulnerability modeling for Senegal, it is critical to understand what makes the area socially and physically vulnerable to flooding, especially as climatic changes are likely to exacerbate this hazard. Flood risk is constantly changing in Senegal due to changing climate and urban settlement. As in much of the Sahel, Senegal has experienced a history of highly uncertain climatic conditions, varying between cycles of drought to eras of frequent and severe flooding. After several very dry decades between 1968–1997, regional Senegalese climate has shown a 35% increase in average rainfall between 2000 and 2005 (Nicholson 2005). In addition to changing climate, Senegal has undergone significant land use change triggered by extreme drought in the 1970s, 80s, and 90s which forced rural populations into urban areas (Goldsmith, Gunjal, & Ndarishikanye, 2004). The peak urbanization rate of Senegal’s capital, Dakar, was estimated around 7-8%, and 44% of Senegalese currently live in urban areas (Mbow, Diop, Diaw, & Niang, 2008).

As the frequency of intense flood events increases, the results of rapidly changing human and natural dynamics in Senegal have increased vulnerability to floods. In 2005, continuous heavy rains from August into early September caused flooding in Dakar, leading to 46 deaths, a cholera epidemic, and the evacuation of 60,000 people (Tschakert, Sagoe, Ofori-Darko, & Codjoe, 2010). Again in 2009, Dakar floodwaters destroyed 30,000 homes, which affected over a half a million people and resulted in \$44.5 billion (USD) in damage and loss. In 2012, another catastrophic flood devastated already fragile public infrastructure and contaminated over 7,700 drinking water sources. The United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) found that between 100,000 and 300,000 Senegalese are affected by floods, including in rural areas and cities such as Saint-Louis and Kaolack (UNOCHA, 2013). These floods were major disasters for the region, not just because of the physical threat, but also because of the social, economic, and political conditions of the people and communities that were affected. The social dimensions of Senegal are rapidly changing with urbanization and climate change, which highlights the need for dynamic flood vulnerability assessments.

Borrowing from the Global Resilience Partnership and Zurich Flood Resilience Program, this report defines flood resilience as enabling sustained development of human, financial, natural, social, and physical capital over time. Flood resilience is not an endpoint, but represents an evolving effort to adapt as flood vulnerability shifts with climate, land use, economic, and demographic changes. A flood resilient society must be able to learn from the consequences of its own adaptation efforts as well as changes in vulnerability due to internal (land use, levee construction) and external (storm frequency) forces. This process of “learning” will only build resilience if knowledge about the changing system translates into more transparent and democratic interventions (Pahl-Wostl, Becker, Knieper, & Sendzimir, 2013). Different types of knowledge about vulnerability can come from both analysis by researchers and experiences of people in flood-affected communities. New technology can combine these disparate but complementary sources.

Lack of information means that practitioners lack clear guidance on how to prioritize spending and other resources, and how and where to design programs to increase preparedness and reduce the degree of impact. Accessibility of this information is seen as vital to enhancing people’s capacity to deal with the impacts of climate change (Hellmuth, Mason, Vaughan, Van Aalst, & Choularton, 2011; T. Mitchell et al., 2010). Likewise, the production of climate information for decision-making is increasingly being seen as an entry point for joining up work

on climate change adaptation, disaster risk reduction, and development in climate-sensitive places (Ahmed, Kodijat, Luneta, & Krishnamurthy, 2015; Foresight, 2012). Heavy investments in drainage and infrastructure systems have been funded by the World Bank (\$90 million USD) through the Storm Water Management and Climate Change Adaptation Project. However, gaps remain in coordination and communication between key stakeholders, residents, and government officials, and between different government agencies (Diagne, 2007; Vedeld, Coly, Ndour, & Hellevik, 2015).

This report focuses on the preparedness stage of the disaster cycle and seeks to address critical information gaps for answering the question of where and how to prepare Senegal for extreme flooding today and in years to come.

Climate information generated through monitoring and analysis activities is becoming an integral part of risk management and resilience programming. Fortunately, the abundance of cheap physical and digital sensors, data-collective satellites, and higher capacity computing power has created a wealth of data at finer resolution, faster speed, and lower cost than previously imaginable. An open, big data revolution enables scientists to understand more than ever about disasters and create insights at the speed and scale needed to make practical decisions for more adequate disaster management. This new resource, however, requires new scientific methods.

This report combines new big data analysis tools with the best available rapid assessment tools in social and physical science to explore the potential for understanding and addressing information gaps about flood risk in Senegal. Streaming satellite imagery available in Google Earth Engine (GEE) is one alternative, which can generate flood vulnerability maps quickly and cheaply for immediate planning and decision-making after a flood event, while more precise hydrologic models are developed. GEE is a geographic data repository coupled with a cloud-computing platform that provides access to the historical library of public satellite imagery and other scientific map products and analytical tools for the development of scientific algorithms. The GEE platform offers unique benefits for vulnerability assessments in flood-prone developing countries for three primary reasons: 1) the amount of data it stores and provides access to, 2) its high-volume data processing capability, and 3) the use of a web browser interface. GEE's data catalog is a multi-petabyte archive of georeferenced datasets essential for disaster assessment and prediction, including images from earth observing satellites (e.g. Landsat, MODIS) and airborne sensors, weather and climate datasets, digital elevation models, and others. GEE can process these high-volume datasets extremely quickly by parallelizing the processing among thousands of central processing units (CPUs). Finally, this analytical power is accessible from any computer with a good internet connection, allowing regional to global analyses to be run even on low-configuration desktop computers, evading the need for expensive software, processing, or data management systems. Lastly, the use of a web browser interface allows users to share data and analyses immediately by sending out a simple browser link. The license to use GEE is currently free for scientific, governmental, and even commercial use.

We leveraged the modeling capabilities of GEE and R to assess the current geomorphology and hydrology of the region based on satellite remote sensing data. Furthermore, the authors used state-of-the-art tools and methods to assess social vulnerability of the region based on multi-source socio-economic data. A critical piece of predicting future change of floods and preparing for this threat is understanding where floods have occurred in the past and what kind of



mitigation investments have been successful. Flood inundation data are also a necessary input for the new, data-driven hydrology methods developed by Cloud to Street and adapted to Senegal for this report. Therefore the authors first built a historic flood inventory for Senegal based on two multi-decade satellite data repositories: MODIS and Landsat. This is described in Chapter 2a. Next, the authors use these past floods as training data for a machine learning model in five priority watersheds in order to estimate the probable floodplain in those places. This is described in Chapter 2b. Chapter 3 details the social vulnerability of Senegal that the authors created with a sample of raw Senegalese Census data provided exclusively to this research team and its partners.

The results estimate the number and nature of major floods that have occurred in Senegal in the recent past and predict which parts of the country and population are at risk from future extreme flood. It also describes the main social conditions expected to lead to more loss and which areas/*communes* have the most vulnerable populations.

This risk information can help to more quickly answer questions regarding which areas will be affected hardest and why, and where government should spend its limited resources for disaster mitigation and resilience. In addition to the technical strengths, the tool affords impressive communication capabilities for decision-makers. Not only are the resulting maps highly engaging, easy to understand, and interactive, but the results are presented with the generally recognizable Google Maps base layer.

Just as new algorithms and scientific methods are required to harness big data, new approaches to management – how the authors govern and engage communities in resilience – are required for applying these insights in order to take full advantage of the insights produced by the tools. Providing responsive flood vulnerability maps can play an important role in shifting disaster mitigation efforts to where they are most needed, and engaging local decision makers in future generations of the work to tailor their own tool-building, as outlined by the final section, will have the potential to transform disaster management. Thereby, the authors argue that this combination of big data and community input has the power to turn big data on its head, equipping non-experts with data and capacities rather than just extracting and crunching data from people. The localized science and analysis can help individuals understand the climate crisis and take control when preparing and responding to hazards. The platform streams the most recent satellite data collected, and so analysis can be updated with the mere refresh of a browser page – no downloading is required. In regions undergoing rapid land-use change like Senegal, GEE's constantly up-to-date data catalog can provide critically responsive analysis. This responsive analysis, combined with biophysical and social vulnerability assessments, provides actionable information of where to focus investments in disaster resilience. The alternative – waiting for hydrologic model updates from scientific experts – may lead to slow results and an information gap at times when timely information is sorely needed.

In following chapters, this report aims to: 1) holistically assess the current threat from floods and 2) outline the opportunities and limitations of these new approaches by understanding vulnerability in Senegal.

1. Biophysical risk: building a historical flood database in Senegal (Chapter 2a)
2. Biophysical risk: the hydrology of the landscape (Chapter 2b)

3. Social vulnerability to disaster (Chapter 3)
4. Combined socio-physical vulnerability (Chapter 4)
5. Participatory engagement for flood resilience (Chapter 5)

This report builds the foundations of a tool to assess biophysical and social dimensions of risk that is flexible enough to include adjustments by local experts with knowledge and context of important variables of flood risk in their region. When fully built, this tool can also be used to analyze how vulnerability changes over time by running the model over specific years and months, when land use, geomorphology, and human settlement patterns may have shifted. It could dynamically identify population and infrastructure at risk for flooding by drawing on open global satellite data, the national census, mobile phone call detail records, and the crowd. The tool, designed for governments, residents, communities, aid agencies, and researchers alike, is deeply rooted in three key strategies for transformation: human-centered scientific modeling, community-based learning, and government-level development impact. Our model relocates resilience into the hands of communities and reshapes traditional scientific modeling to be inclusive of those traditionally not engaged in the knowledge creation process. The co-produced vulnerability tool will be rooted in community needs, but our framework is designed to complement and integrate with existing resilience efforts at the national level.

## 2a. Biophysical Risk: Building a Historical Flood Database in Senegal

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With the goal of understanding historic flood risk and generating predictive capacity of future flood events the authors use machine learning algorithms, a novel approach in hydrology. A major requirement of machine learning algorithms is having known, representative pixels of where flood events have occurred previously to give predictive ability to these methods. In machine learning parlance, this is commonly known as training data. To either recreate historical flood events or infer the extent of future floods from changing conditions, a database of historical flood events that are representative of the hydrological and biophysical parameters of a region are needed. Presented below are the steps towards building an operational machine learning algorithm for flood extent in Senegal, including the development of a historical database of flood observations, collection of conditioning variables (e.g. precipitation, land use), and application of machine learning algorithms to these datasets for prediction of historical flood extents.

A critical piece of predicting floods and flood vulnerability of an area and preparing for these potential threats is understanding where floods have occurred in the past and what kind of mitigation investments have been successful. However, there is currently no existing spatial data for flood events in Senegal offered by the DFO database. The authors therefore created a small database of historic flood events and on which to apply their customized water detection algorithms to map major floods in the country from the past 30 years using Google Earth Engine. Google Earth Engine (GEE) is the best-suited platform for this analysis because it provides a consistent historical library of multiple satellite sensors along with a parallelized computing engine allowing facile analysis of imagery.

We found that the most extensive flooding occurs in *departments* consisting of predominantly rural areas. According to our results, the most extensive flood in terms of area was from rain events in August–September 2007 (DFO 3180) that covered 1,213 to 2,320 km<sup>2</sup>, depending on the flood detection method used. Limitations of our flood detection in this initial baseline assessment restrict the utility of our resulting flood maps, especially where potentially extreme flood events were not detected. Primarily, our flood event inventory likely does not include all flood events that have occurred in Senegal’s history.

### I. Historical Flood Events

There is no consistent data source for flooding for the globe. Flood data is usually collected on an event-by-event or country-by-country basis and the only collection of geospatial flood events that is global and historic in nature is the Dartmouth Flood Observatory (DFO), which maintains an inventory of major historical flood events<sup>1</sup>. While this database offers useful data for each flood event from 1985 to present, such as estimates of flood size, number of people affected, and approximately 200 mapped floods (1999-2011) for various countries, these data sources do not culminate in a dataset robust enough to detect regional trends and drivers of changes in flood behavior. There is currently no existing spatial data for flood events in Senegal in the DFO

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<sup>1</sup> The Dartmouth Flood Observatory conducts global remote sensing-based fresh water measurement and mapping in “near real time” and records such information into a permanent archive.

<http://floodobservatory.colorado.edu/>

database. The lack of spatial flood data prevents the hydrology community from being able to scale inundation prediction maps, including application of machine learning techniques that could inform mitigation and adaptation programs.

We created a list of flood events in Senegal that could be gathered from publicly available information sources. These sources include: existing databases, academic articles, institutional reports, and news articles. The principal data source used to identify the occurrence of historical flood events in Senegal was the DFO database where 7 floods were identified (Table 1). Several additional sources of information corroborated the information found within the DFO database, including UNITAR's Operational Satellite Applications Programme (UNOSAT)<sup>2</sup> and Copernicus Emergency Management Service (EMS)<sup>3</sup>. Additional sources that yielded evidence of additional flood occurrence included news briefs from Building Resilience and Adaptation to Climate Extremes and Disasters (BRACED) of heavy rain events in 2015 that caused flooding in Dakar and Saint-Louis (Building Resilience and Adaptation to Climate Extremes and Disasters, 2015).

The results of this preliminary analysis that relied upon publicly available information are summarized in Table 1. Our analysis does not represent an exhaustive list of floods within Senegal and in future collaboration with local partners the authors would seek to add further detail.

**Table 1: List of historical flood events occurring within Senegal.**

Register #	Detailed Locations <sup>4</sup>	Date Began	Date Ended	Affected (km <sup>2</sup> )	Source
C2S0001	Dakar, Ngor, Saint-Louis	8/6/2015	11/1/2015	N.D.	BRACED
DFO3971	Dakar, major cities in interior	8/24/2012	8/29/2012	79 242.7	DFO, UNOSAT
DFO3531	Dakar	8/24/2009	8/26/2009	8 510.69	DFO, UNOSAT
DFO3180	Senegal River Valley; Mauritania - Gorgol region - Maghama, Mbout, Kaedi Assaba - Barkeol, Kankossa; Senegal - Thiès, Louga, Matam, Kaolack, Tamba and Dakar	8/31/2007	9/20/2007	167 997.63	DFO
DFO2729	Dakar area.	8/20/2005	9/10/2005	333.207	DFO

<sup>2</sup> The UNOSAT Flood Portal provides free access to satellite-derived flood data in GIS vector format. The portal includes data for flood events occurring since 2007 for which UNOSAT did satellite image analysis. <http://floods.unosat.org/geoportal/catalog/main/home.page>

<sup>3</sup> The Copernicus Emergency Management Service platform allows "users" to provision satellites within hours or days for disaster response. The results of these "activations" are published on Copernicus EMS.

<sup>4</sup> Note that most descriptions in the 'Detailed Locations' column are taken verbatim from the DFO database, and generally reflect the district names around the time of the flood. For example, Matam is listed as a department (in the Saint-Louis region) for flood DFO1866 and as a region for flood DFO2315, because of official boundary changes that occurred between these two floods (in February 2002). To ensure consistency in the rest of the report, administrative areas are referred to by their name at the time of the 2013 census. Additionally, the Geba River, affected by flood DFO2315, is more commonly known as Kayanga in Senegal (Geba being the name used in Gambia and Guinea-Bissau).

DFO2315	Senegal - Northern Kanel region, Central Nioro region, Matam region. Kaolack, Kaffrine. Assaba, Gorgol, Brakna and Adrar; Southeastern Mauritania - Affole area, Timbedra Gambia - Upper River Division; Guinea-Bissau - eastern area. Bafata and Gabu provinces. Geba river valley	8/9/2003	11/5/2003	78 728.11	DFO
DFO1866	Saint-Louis Region - Districts: Podor, Dagana and Matam. Louga Region - Districts: Kacbacmer, Linguature and Louga	1/9/2002	1/12/2002	62 705.79	DFO
DFO1008	Southwest Region: Nouakchott	9/24/1995	10/8/1995	47 808.22	DFO

## II. Mapping Historical Flood Events

The identification of historical flood events and dates of their occurrence allows for the utilization of a large library of earth-observing satellite sensors for flood detection. There are a number of satellite missions available for earth observation including: the Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat missions 1-8, and most recently Sentinel-1 (operation late-2014). Each sensor has unique advantages and challenges but in general image collection frequency, spatial resolution, and spectral resolution define the utility of each sensor (Table 2). The two MODIS satellites, Terra and Aqua, have been used extensively to develop a number of flood algorithms (Boschetti, Nutini, Manfron, Brivio, & Nelson, 2014; Feng et al., 2012; Islam, Bala, & Haque, 2009; Xiao et al., 2006) given that the mission produces global coverage every one to two days, making it ideal for rapid response to flood events. However, these sensors have notoriously low spatial resolution (250 meters per pixel, and the flood must cover the entire pixel to be detected). On the other hand, Landsat satellites are higher-resolution (30 meters per pixel) but have a return period of 16 days, making the coincidence of flood events and imagery rare. Still, a number of water detection algorithms have been developed for Landsat sensors with a few applications to flood extent (Chignell, Anderson, Evangelista, Laituri, & Merritt, 2015; Donchyts, Schellekens, Winsemius, Eisemann, & van de Giesen, 2016; Feyisa, Meilby, Fensholt, & Proud, 2014; Yang et al., 2014). Lastly, Sentinel-1, a synthetic aperture radar (SAR) sensor, is able to address the common challenge of clouds that obfuscate areas of analysis and limit the utility of both MODIS and Landsat. The Sentinel-1 technology is relatively new, having been launched in late-2014, which limits the historical reach of this data source; however, development of flood detection algorithms has been generated for SAR technologies in general based on private satellites (Martinis, Twele, Strobl, Kersten, & Stein, 2013; Martinis, Twele, & Voigt, 2009; Mason, Giustarini, Garcia-Pintado, & Cloke, 2014).

For the purposes of flood detection, there is a suite of satellites to choose from that, together, can overcome the respective limitations of each. GEE is an ideal computing platform to build a database of historical floods that requires the fusion of multiple satellite imagery data sources. GEE brings together the full libraries of MODIS, Landsat, and Sentinel-1, and provides the computational power to integrate these products over the historical stack of imagery. The following is a description of the methods used to detect floods across each type of satellite sensor and the benefits and shortcomings of each.

Agency	Sector Name	Operational	Spectral Resolution	Spatial Resolution	Image Extent	Return Period
National Aeronautics and Space Administration (NASA)	Terra Moderate Resolution Imaging Spectroradiometer (Terra – MODIS)	2000 – Present	36 spectral bands	250m (bands 1-2) 500m (bands 3-7) 1000m (bands 8-36)	Global	Daily
National Aeronautics and Space Administration (NASA)	Aqua Moderate Resolution Imaging Spectroradiometer (Aqua – MODIS)	2002 – Present	36 spectral bands	250m (bands 1-2) 500m (bands 3-7) 1000m (bands 8-36)	Global	Daily
National Aeronautics and Space Administration (NASA)	Landsat 8 Operational Land Imager (OLI)	2013 – Present	11 spectral bands	30m (bands 1-7 & 9) 15m (panchromatic band) 100m (TIRS bands 10-11)	170km x 185km	16-days
National Aeronautics and Space Administration (NASA)	Landsat 7 Enhanced Thematic Mapper (ETM+)	1999 – Present	8 spectral bands	30m (bands 1-7) 15m (panchromatic band)	170km x 185km	16-days
National Aeronautics and Space Administration (NASA)	Landsat 5 Thematic Mapper (TM)	1984 – 2013	7 spectral bands	30m (bands 1-5 & 7) 120m (thermal band)	172km x 185km	16-days
National Aeronautics and Space Administration (NASA)	Landsat 4 Thematic Mapper (TM)	1982 – 1993	7 spectral bands	30m (bands 1-5 & 7) 120m (thermal band)	170km x 185km	16-days
European Space Agency (ESA)	Sentinel-1A/B	Sentinel-1A: 2014 – Present Sentinel-1B: 2016 – Present	1 synthetic aperture radar (SAR) band	5m (wave & strip mode) 20m x 40m (wide mode)	20km x 20km to 400km x 400km (depending on mode)	3 to 6-days (from two satellite constellation)
European Space Agency (ESA)	Sentinel-2A/B Multispectral Imager (MSI)	Sentinel-1A: 2014 – Present Sentinel-1B: 2016 – Present	13 spectral bands	10m (visible & near-infrared) 10m (shortwave infrared) 60m (atmospheric correction)	290km x 300km	2 to 5-days (from two satellite constellation)

**Table 2: Summary of available satellite sensors for the observation of flood events.**

### III. Flood Detection Methods

There is a large variety of water detection algorithms that can be applied to the imagery from the flood detection sensors listed above (see Coltin et al. (2016) for a review for the MODIS sensor alone). For flood detection in Senegal, the authors chose four sensors, MODIS and Landsat 5-8, principally due to their availability over the time frame of historical flood events. MODIS also has the advantage of daily scenes that increases the likelihood of getting a cloud-free look at flood events. In this analysis, different water detection techniques were used for MODIS and Landsat images. For MODIS, the authors utilized the method developed by the Dartmouth Flood Observatory and NASA's Near Real Time Flood Mapping<sup>5</sup> platform. In addition, an automatic threshold detection technique known as Otsu thresholding was used to optimize the selection of water versus land pixels. For Landsat, a recently developed Automated Water Extraction Index (AWEI), an improvement over other water indices, was applied to available Landsat scenes. The following section describes the methods in full.

#### 1. MODIS Imagery

Daily MODIS satellite images that coincided with the dates of the identified floods in Senegal were collected using GEE's satellite sensor data catalog. Only 7 of the 8 flood events identified above coincided with the availability of MODIS imagery (2000 – present). Across these 7 events 839 images were collected and analyzed. Of the water detection techniques available, the method utilized by the Dartmouth Flood Observatory and NASA's Near Real Time Flood Mapping<sup>6</sup> platform was chosen for use in Senegal (Brackenridge, Anderson, & Caquard, 2009). This method allows for the detection of discrete flood events from daily MODIS imagery. In particular, the DFO algorithm is able to avoid a common misclassification of cloud shadows and hill shade areas as water due to their similar spectral signatures. The DFO algorithm overcomes this issue by applying either 2 or 3-day composites of images that maintain stationary elements (water) and eliminate mobile elements (cloud shadows) between daily images. The 2-day composites are able to capture highly transient flood events though more “noise” may be present due to the coincidence of cloud shadows, leading to more false positives. On the other hand, 3-day composites reduce the coincidence of cloud shadows across scenes but miss rapid or flash flood events that are highly transient, creating more false negatives. The choice of 2- or 3-day composites comes with this inherent trade-off. Overall, however, this method provides a relatively accurate approach for observing flood events. In a quantitative comparison among several flood detection techniques, the DFO algorithm was found to have a relatively high measure of precision and recall when compared to other water detection algorithms (Coltin et al., 2016).

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<sup>5</sup> The Land, Atmosphere Near real-time Capability for EOS (LANCE) supports application users interested in monitoring a wide variety of natural and man-made phenomena. Near Real-Time (NRT) data and imagery from the AIRS, AMSR2, MISR, MLS, MODIS, OMI and VIIRS instruments are available much quicker than routine processing allows. Most data products are available within 3 hours from satellite observation. NRT imagery are generally available 3-5 hours after observation. <https://earthdata.nasa.gov/earth-observation-data/near-real-time>

<sup>6</sup> The Land, Atmosphere Near real-time Capability for EOS (LANCE) supports application users interested in monitoring a wide variety of natural and man-made phenomena. Near Real-Time (NRT) data and imagery from the AIRS, AMSR2, MISR, MLS, MODIS, OMI and VIIRS instruments are available much quicker than routine processing allows. Most data products are available within 3 hours from satellite observation. NRT imagery is generally available 3-5 hours after observation. <https://earthdata.nasa.gov/earth-observation-data/near-real-time>

## 2. Landsat Imagery

Water detection techniques for Landsat often use band thresholding, primarily Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) (Gao, 1996; Xu, 2006). Feyisa et al. (2014) presented a new water index, the Automated Water Extraction Index (AWEI), which addresses several shortcomings of other water indices such as NDWI or MNDWI. In particular, it has been recognized that water indices face two major problems: 1) results obtained using different indices are inconsistent; 2) threshold values applied to distinguish water from non-water are unstable, varying with scene and locations (Ji, Zhang, & Wylie, 2009). These problems are pronounced in classifications with significant areas of low-albedo surfaces and the presence of shadows. To address these issues, Feyisa et al. (2014) formulated two equations based on Landsat 5 “blue” and “green” bands termed non-shadow (*nsh*) and shadow (*sh*).  $AWEI_{nsh}$  is primarily formulated to eliminate non-water pixels including build-up urban areas and  $AWEI_{sh}$  is designed to further improve accuracy by removing cloud shadows. As a result, these equations can be used in isolation or combination depending on the specific challenges of a scene or location to minimize misclassifications.

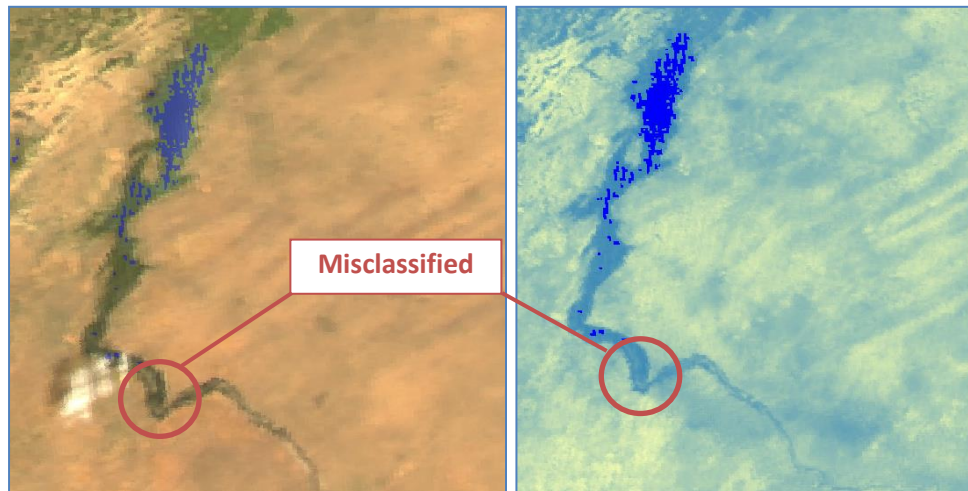
The AWEI algorithms developed by Feyisa et al. (2014) were implemented over Senegal where Landsat images were available. Across the 8 flood events, 5 flood events had available Landsat imagery that totaled 266 images and were analyzed using the methods of Feyisa described above. The  $AWEI_{sh}$  and  $AWEI_{nsh}$  equations were generalized to all Landsat sensors including 4, 5, 7, and 8 allowing for potentially more “looks” during each flood event. To restrict the AWEI thresholds to appropriate pixels a cloud mask was applied to each available Landsat image (Zhu & Woodcock, 2012).

## 3. Automatic Thresholding

A common problem with the threshold technique for water detection is determining the appropriate threshold for each satellite image used. The spectral reflectance of land and water (see Figure 1 land-water histograms for example) are known to vary from region to region and even among images of the same locations due to changing environmental variables such as depth, water turbidity, chemical composition and surface appearance. As case in point, it was found for Landsat 8 images over the Murray-Darling Basin in Australia that optimal thresholds for MNDWI across the region ranged from -0.20 to 0.40 (Donchyts, Schellekens et al., 2016).

The DFO flood detection method described above utilizes three thresholds to identify water pixels within an image including: a ratio of NIR and RED bands (NIR/Red Ratio), a threshold of the Red band, and a threshold of the SWIR band with standard values of 0.70, 2027, and 675, respectively. Using these standard thresholds for this analysis, several misclassifications occurred over the extent of Senegal, highlighting the need for adjustments to these thresholds (Figure 1).





**Figure 1: Areas of water detection where the standard threshold values of the DFO algorithm misclassified water bodies as land. (left: Lac de Guiers in visible spectrum; right: Lac de Guiers in Shortwave Infrared - SWIR).**

To determine optimal thresholds for distinguishing land from water a technique known as Otsu thresholding was used (Otsu, 1975). In short, the Otsu threshold determines the interclass variance within a land/water histogram to find the threshold of the greatest interclass variance. The maximum interclass variance indicates the optimal threshold for detection of water versus land. To determine the highest interclass variance and thus the optimal threshold, different thresholds were tested in a stepwise fashion (~100 thresholds) to identify where the interclass variance peaks. Otsu thresholding is known to work best when the water class represents a significant portion of pixels within the histogram and are not obfuscated by clouds. This technique has been successfully employed in several studies including detection of watercourses in the Murray-Darling Basin in Australia using Landsat-8 (Donchyts, Schellekens, et al., 2016), river delineation of the Brahmaputra River in India using Landsat-5 (Yang et al., 2014), and surface water detection in the Yangtze River Basin in China (Li et al., 2013).

For this assessment of Senegal, the internal MODIS Quality Assurance (QA) bands were used to identify the least cloudy image and remove cloudy pixels, and a range of threshold values were tested. A buffer region around a permanent water mask, provided by a dataset mapping forest cover in the 21st century by Hansen et al. (2013), was used to ensure a high proportion of water pixels in the sample area. The resulting histograms were used to determine the optimal threshold using methods presented by Otsu (1975).

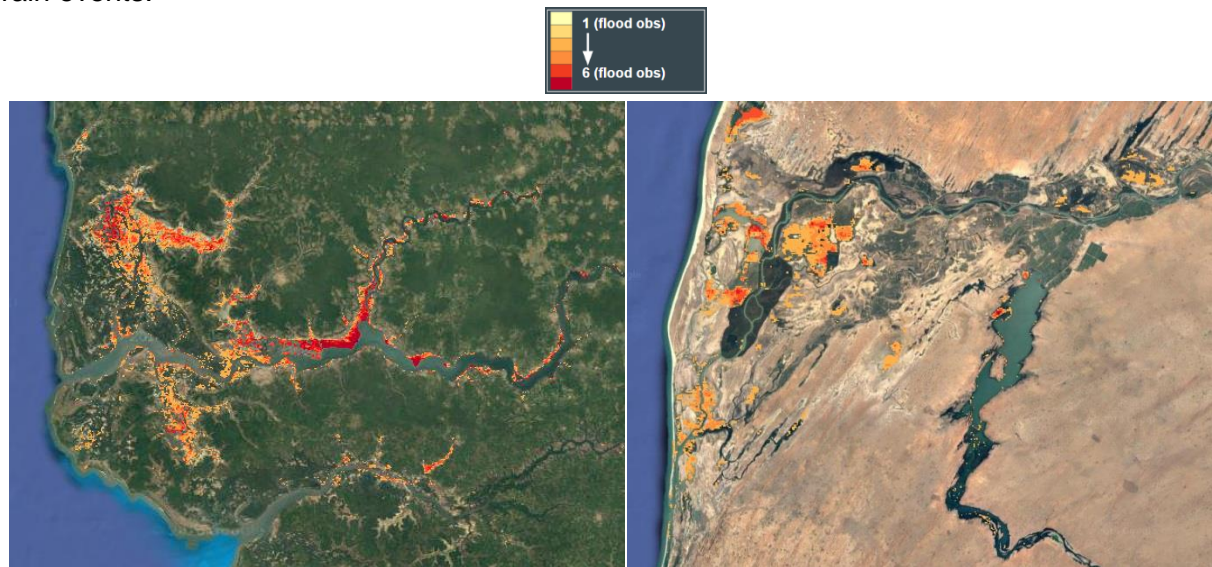
#### 4. UNOSAT Data

UNOSAT Spatial flood extent data was used as comparison with other datasets to better understand flooding in Senegal and to shed light on the advantages of SAR data. The UNOSAT Flood Portal listed several flood events for Senegal and, in one case, also hosted spatial data of inundation extent. Specifically, an image was captured by the Canadian Space Agency Radarsat-2 sensor on September 5th, 2012, and was analyzed for flood extent surrounding in the Saloum Delta surrounding Kaolack city and the Kaolack and Fatick provinces. The methodology behind this flood detection was not publicly available and cannot be compared to other methodologies. This dataset does, however, provide insight into the benefits of SAR data in seasons of high cloud coverage and targeted specifically to areas experiencing severe flooding.

## IV. Flood Detection Results

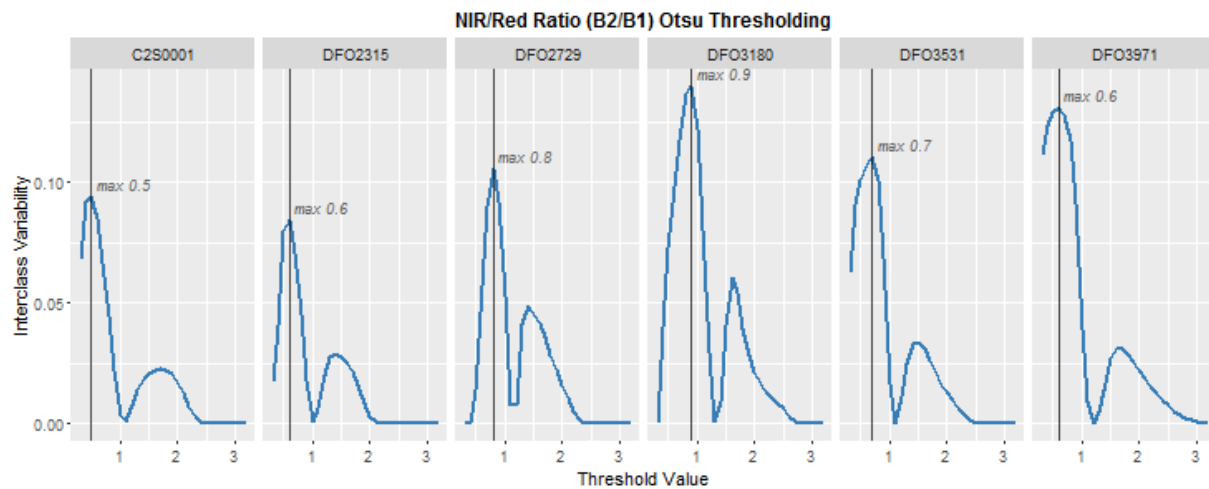
### 1. DFO Algorithm Implementation

In general, the DFO algorithm identified flooding in deltaic wetlands and low-lying areas surrounding rivers. Within major cities such as Dakar, Saint-Louis or Kaolack, the DFO algorithm was unable to detect significant flooding that had otherwise been reported. The lack of detection in urban areas can be explained by “mixed” pixels where the spectral response is a mix of multiple land use land covers such as impervious surface, vegetation, and water within one 250-m<sup>2</sup> pixel. Conversely, in rural areas and wetlands, where flooded areas occupy larger natural features rather than smaller, urban features, this effect is less pronounced. Figure 2 below shows the results of the DFO algorithm flood detection in urban (Saint-Louis) and rural (Ziguinchor) areas by illustrating the number of times an area or pixel was observed as flooded across the recorded flood events. This map highlights areas that regularly flood during heavy rain events.

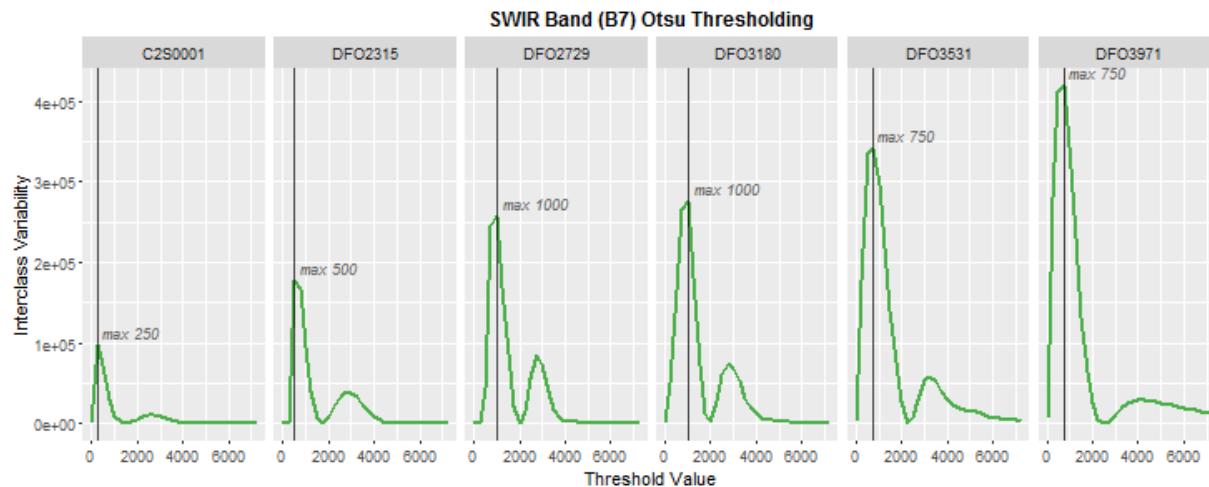


**Figure 2: Number of times an area (pixel) flooded from 2003–2015 in Senegal using the DFO algorithm (left: Ziguinchor, Senegal; right: Saint-Louis, Senegal and Senegal River).**

Methods for improving the DFO algorithm were also explored due to observable error in classification of water and land when using standard thresholds. Specifically, the authors applied an Otsu thresholding technique that automatically selects an optimal threshold based on the interclass variance between the reflectance of land and water. The results obtained confirm the necessity for implementation of Otsu thresholds as the range for the NIR/Red Ratio and SWIR threshold were 0.49 – 0.85 and 290 – 885, respectively. Although the range of values of the NIR/Red Ratio and the SWIR threshold clustered around the standard DFO default values of 0.70 and 675, respectively, these ranges indicate that improvements in flood detection can be obtained by updating the thresholding per event. This can be explained by variations in image artifacts such as haze, changing phenology of vegetation, or turbidity of water within individual scenes. Figures 3 and 4 show the results of the Otsu thresholding across the flood events tested and for the NIR/ Red Ratio and SWIR bands.



**Figure 3: Otsu thresholding results for the NIR/ Red Ratio**

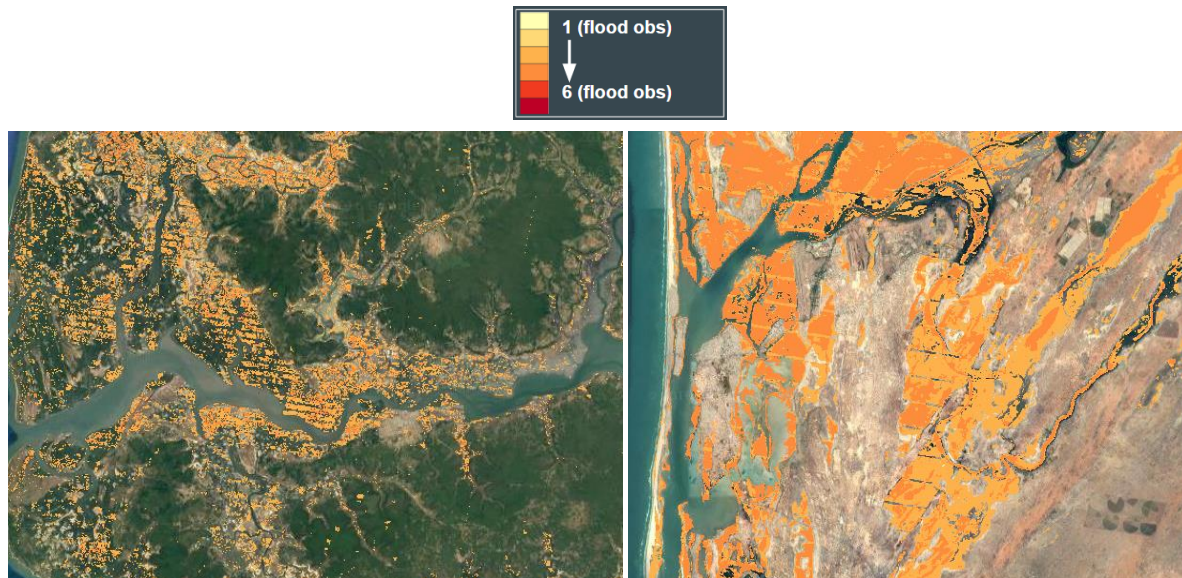


**Figure 4: Otsu thresholding results for the SWIR band**

## 2. Feyisa Algorithm Implementation

A flood detection algorithm for Landsat was also prepared with the aim of improving the detection of flooding in urban areas. An Automated Water Extraction Index (AWEI) presented by Feyisa et al (2014) was implemented across available Landsat 4 – 8 imagery that coincided with flood events. The results of this approach can be seen in Figure 5, which compared to the DFO algorithm has improved detection capabilities in Saint-Louis, Senegal. From these images, flooding was observed in the southeastern portions of Saint-Louis (Figure 5 – right) as well as in surrounding deltaic wetlands located in rural areas (Figure 5 – left).

**Figure 5: Number of times an area (pixel) flooded from 2003–2015 in Senegal using the Feyisa algorithm (left: Ziguinchor, Senegal; right: Saint-Louis and Senegal River).**



It is important to note that, unlike the DFO algorithm, smaller portions of Senegal are observable during flood events. Compared to the DFO algorithm, only 3 of the 6 catalogued flood events had available images to apply the Feyisa flood detection method, minimizing the temporal utility of this method. Additionally, Landsat 7, which covers a significant time period from 1999 to present, is of marginal utility because a sensor error in 2003 created “striping” within images (see Figure 5). As a result, the coverage of Landsat is compromised but, in return, higher detail in urban areas is possible.

## V. Flood History in Senegal

The area of each flood event was calculated over each *department* in Senegal to demonstrate which areas have the most persistent flooding (Table 3). On an area basis, the results demonstrate that the most extensive flooding occurs in *departments* consisting of predominantly rural areas. This is consistent with our observations above where rural areas had significant flooding in deltaic wetlands. According to our results, the most extensive flood in terms of area was from rain events in August – September 2007 (DFO 3180) that covered 1,213 to 2,320 km<sup>2</sup>, depending on the flood detection method used. These results are consistent with the DFO catalogue in identifying the most extensive flood events, though the magnitude differs as the DFO catalogue reported 167,997 km<sup>2</sup> for the August – September 2007 floods. The DFO estimate is nearly the total area of Senegal and likely is calculated beyond the boundaries of Senegal, using impacted boundaries (*departments*, watersheds) as a basis for calculation, or both. Alternatively, our results provide a more realistic estimate of actual area inundated within *departments* in Senegal providing a more detailed understanding of affected areas.

Depending on the flood detection method used, different estimates of affected area are found, highlighting the need to use multiple sensors and observation when possible. In general, the Feyisa method consistently predicts greater flooded areas than the DFO flood detection method, even in rural areas where the DFO algorithm is considered to perform best. The greater resolution of Landsat provides greater sensitivity to flooded pixels, though the number of

observations through time is limited by the fact that only 3 of the 6 catalogued floods had available Landsat imagery.

**Table 3: Summary of inundated area (km<sup>2</sup>) detected by the DFO and Feyisa methods within each department.**

Department	DFO2315 9-Aug-03		DFO2729 20-Aug-05		DFO3180 31-Aug-07		DFO3531 24-Aug-09		DFO3971 24-Aug-12		C2S0001 6-Aug-15		Total -	
	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa
Bignona	235.5	354.0	300.6	N/A	333.5	213.4	67.8	N/A	2.2	0.0	90.4	N/A	939.7	567.4
Fatick	100.3	131.3	98.1	N/A	200.1	127.2	45.0	N/A	9.3	0.0	17.1	N/A	452.7	258.6
Matam	266.7	748.3	35.0	N/A	146.2	513.3	0.0	N/A	0.3	0.2	0.6	N/A	448.3	1261.8
Dagana	90.9	415.7	25.3	N/A	141.6	334.9	1.7	N/A	1.7	0.0	3.0	N/A	261.1	750.8
Sedhiou	39.9	26.1	49.2	N/A	71.8	0.1	16.3	N/A	2.2	0.0	15.8	N/A	179.5	26.2
Podor	122.3	825.8	1.9	N/A	56.3	633.1	0.0	N/A	0.9	0.0	2.2	N/A	181.3	1458.9
Oussouye	29.3	36.1	45.1	N/A	56.4	51.9	0.0	N/A	0.0	0.0	5.0	N/A	130.9	88.0
Foundiougne	18.7	360.6	13.7	N/A	67.0	258.1	9.5	N/A	1.7	0.0	0.8	N/A	110.6	618.8
Ziguinchor	23.8	42.5	34.3	N/A	43.7	42.4	1.6	N/A	0.0	0.0	4.5	N/A	103.3	84.9
Kaolack	20.1	33.3	17.3	N/A	46.6	14.1	5.1	N/A	3.2	2.5	8.0	N/A	92.2	49.8
Nioro-Du-Rip	7.4	3.9	6.7	N/A	2.4	0.8	1.2	N/A	4.9	0.6	6.7	N/A	22.7	5.3
Velingara	10.0	25.1	1.9	N/A	10.6	0.0	0.2	N/A	0.3	0.0	3.4	N/A	23.0	25.1
Mbour	1.0	22.9	7.8	N/A	8.7	16.2	2.7	N/A	0.1	0.0	0.1	N/A	20.2	39.1
Bakel	5.0	48.2	0.0	N/A	9.5	33.7	0.0	N/A	0.0	0.0	0.0	N/A	14.5	81.9
Kolda	1.0	4.3	0.0	N/A	7.6	0.0	0.1	N/A	0.5	0.0	3.0	N/A	9.1	4.4
Tambacounda	9.2	36.9	0.0	N/A	1.4	54.3	0.0	N/A	0.0	0.1	0.2	N/A	10.6	91.3
Louga	1.7	26.7	0.8	N/A	4.8	2.7	0.0	N/A	0.0	0.0	0.0	N/A	7.3	29.4
Dakar	1.0	0.4	1.1	N/A	1.7	3.3	0.4	N/A	0.1	0.0	0.0	N/A	4.2	3.7
Gossas	1.1	4.3	0.2	N/A	1.6	4.9	0.3	N/A	0.5	2.4	0.0	N/A	3.5	11.6
Tivaouane	0.1	1.2	0.0	N/A	1.7	3.4	0.0	N/A	0.0	0.0	0.4	N/A	1.8	4.6
Rufisque-Bargny	0.1	0.7	0.0	N/A	0.2	5.7	0.0	N/A	0.0	0.0	0.0	N/A	0.2	6.4
Thies	0.0	0.3	0.0	N/A	0.1	0.4	0.0	N/A	0.0	0.0	0.0	N/A	0.1	0.7
Pikine	0.0	0.3	0.0	N/A	0.1	3.8	0.0	N/A	0.0	0.0	0.0	N/A	0.1	4.1
Bambey	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.0
Diourbel	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.1
Kebemer	0.0	0.1	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	0.1
Kedougou	0.0	1.1	0.0	N/A	0.0	0.1	0.0	N/A	0.0	0.0	0.0	N/A	0.0	1.2
Kaffrine	0.0	1.0	0.0	N/A	0.0	0.2	0.0	N/A	0.0	2.5	0.0	N/A	0.0	3.7
Linguere	0.0	2.4	0.0	N/A	0.0	2.3	0.0	N/A	0.0	0.9	0.0	N/A	0.0	5.5
Mbacke	0.0	0.0	0.0	N/A	0.0	0.0	0.0	N/A	0.0	1.1	0.0	N/A	0.0	1.1
<b>Total</b>	<b>985</b>	<b>3,153</b>	<b>639</b>	<b>N/A</b>	<b>1,213</b>	<b>2,320</b>	<b>152</b>	<b>N/A</b>	<b>28</b>	<b>10</b>	<b>161</b>	<b>N/A</b>	<b>3,017</b>	<b>5,484</b>

Inundated area is one measure of flood severity, though more important is an understanding of the human impact of flood events. With new advances in estimating population and poverty using machine learning techniques and remote sensing data (Jean et al., 2016; Stevens, Gaughan, Linard, & Tatem, 2015), it is possible to quantify affected areas in terms of population. This was done using an available dataset for Senegal provided by World Pop on population density. Table 4 summarizes the results.

The estimates of population in inundated zones in Table 4 differ substantially by flood detection method, more so than the estimates of area of flooded zones. The Feyisa method, for 2 out of the 3 flood detections available, greatly overpredicts the population affected as compared to the DFO algorithm. In the case of the 2003 and 2007 floods, the Feyisa method estimates are an order of magnitude greater. These differences can be explained, again, by the fact that the Feyisa method is able to detect flood occurring in urban areas, where population is much greater, while the DFO method performs best in rural or deltaic wetland areas with low populations. Since the population is uneven across Senegal and rural/urban contexts, the Feyisa

method greatly over predicts compared to the DFO method, emphasizing its utility when it comes to flood impacting urban areas. Of course, where no Landsat imagery is available, the DFO method still provides estimates and relative areas that are impacted, though likely largely underestimated.

Department	DFO2315 9-Aug-03		DFO2729 20-Aug-05		DFO3180 31-Aug-07		DFO3531 24-Aug-09		DFO3971 24-Aug-12		C2S0001 6-Aug-15	
	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa	DFO	Feyisa
Dagana	97	56928	9601	N/A	872	45187	24491	N/A	123	0	33	N/A
Matam	18	53296	14969	N/A	1421	33449	8470	N/A	0	0	16	N/A
Podor	210	46329	6141	N/A	106	34367	2541	N/A	0	0	63	N/A
Foundiougne	25	22263	845	N/A	716	15829	3032	N/A	423	0	81	N/A
Pikine	0	595	0	N/A	0	29705	52	N/A	0	0	0	N/A
Bignona	3409	13755	8010	N/A	10801	7853	11785	N/A	2446	0	99	N/A
Dakar	0	1093	0	N/A	0	16060	0	N/A	0	0	2496	N/A
Ziguinchor	529	11001	2956	N/A	3614	5454	3930	N/A	375	0	0	N/A
Rufisque-Bargny	0	458	0	N/A	0	15938	12	N/A	0	0	0	N/A
Mbour	0	8719	68	N/A	1458	6022	1323	N/A	267	0	0	N/A
Fatick	320	7332	2676	N/A	3214	6862	6500	N/A	1462	0	259	N/A
Kaolack	534	5809	1867	N/A	6814	5099	10320	N/A	322	850	832	N/A
Bakel	0	4558	450	N/A	0	1361	1166	N/A	0	0	0	N/A
Mbacke	0	2	0	N/A	0	3	0	N/A	0	3298	0	N/A
Sedhiou	835	2683	2465	N/A	3034	1	4751	N/A	984	0	104	N/A
Oussouye	273	915	0	N/A	2121	1661	2437	N/A	0	0	0	N/A
Gossas	0	876	462	N/A	76	1333	475	N/A	53	251	167	N/A
Tambacounda	1	754	166	N/A	0	1265	4	N/A	0	13	0	N/A
Velingara	185	1007	455	N/A	96	0	528	N/A	9	0	19	N/A
Nioro-Du-Rip	395	458	443	N/A	384	98	122	N/A	60	58	299	N/A
Louga	0	288	23	N/A	7	21	47	N/A	0	0	0	N/A
Thies	0	124	0	N/A	0	169	18	N/A	0	0	0	N/A
Tivaouane	16	88	2	N/A	0	180	69	N/A	0	0	0	N/A
Kolda	112	232	61	N/A	0	0	283	N/A	2	0	10	N/A
Kaffrine	0	49	0	N/A	0	11	0	N/A	0	146	0	N/A
Linguere	0	47	0	N/A	0	24	0	N/A	0	10	0	N/A
Diourbel	0	11	0	N/A	0	29	0	N/A	0	0	0	N/A
Kedougou	0	7	0	N/A	0	1	0	N/A	0	0	0	N/A
Bambey	0	2	0	N/A	0	1	0	N/A	0	0	0	N/A
Kebemer	0	1	0	N/A	0	0	0	N/A	0	1	0	N/A
<b>Total</b>	<b>6958</b>	<b>239679</b>	<b>51662</b>	<b>N/A</b>	<b>34733</b>	<b>227982</b>	<b>82357</b>	<b>N/A</b>	<b>6526</b>	<b>4627</b>	<b>4475</b>	<b>N/A</b>

**Table 4: Summary of population in inundated areas determined two different flood detection methods (DFO and Feyisa) and World Pop data.**

## VI. Limitations

Several limitations of the data analysis provided above should be noted to highlight the bounds of its utility. First and foremost, our estimates of flood extent and thus affected populations do not provide the potential full coverage of flood events in Senegal. Our exercise in cataloguing flood events was based on publically available information; additional flood events beyond those highlighted are therefore likely. Additionally, our observations of floods are limited by available and usable (*i.e.*, cloudless) imagery, which is rare during major rain events. Lastly, the estimates of flooded areas are not certain and are lacking validation data, which is consistently a challenge for ephemeral flood events. Together, these limitations restrict the utility of our flood maps where potentially high severity flood events were not observed that would deserve equal attention. The use of these flood maps is best applied to further modeling where validation and uncertainty in flood plains can be communicated.

## 2a. Biophysical Risk: Data-Driven Hydrology with Machine Learning

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New data-driven methods hold the promise of overcoming limitations in traditional flood modeling and allowing us to predict floods faster and more dynamically for new places in which data are currently lacking. This chapter details the exploratory methods used to develop a machine learning flood prediction model for Senegal and provides a preliminary estimation of areas most vulnerable to flooding in the watersheds mostly likely to be at risk from these extreme events. Building on the flood database described in the previous chapter, the research described here has two corresponding goals: 1) understanding the methods, the benefits and the current limitations of applying new data tools to Senegal, and 2) developing the science to optimize machine learning algorithm parameters across climatological and ecological gradients.

These results show that machine learning (*ml*) algorithms have the potential to be able to reproduce benchmark historic floods as detected by remote sensing, especially using Random Forest on the flood detected with MODIS satellites (accuracy of 97%). The Saint-Louis region was the primary testing ground for customizing the algorithm, where the authors designed and assessed four machine learning approaches on 10 flood conditioning factors. Scaling the tool to an additional five watershed regions, which were selected in consultation with at Agence Française de Développement and which cover 34% of the country, the authors predicted a floodplain of 5,596 km<sup>2</sup> and 30% of that floodplain (1,641 km<sup>2</sup>) is considered high risk, meaning the model predicted flooding in 100% of the trials. Over 97,000 people could be at high risk of exposure to flooding according to analysis conducted using the WorldPop gridded population dataset.

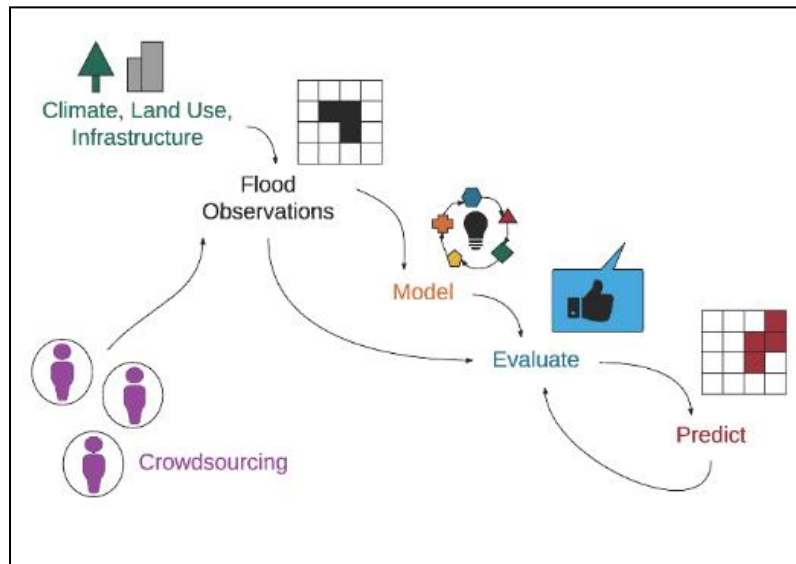
To describe this research and its promise for physical vulnerability assessment in Senegal, this chapter first provides contextual background on traditional and new strategies for flood modeling (Section 2b.1). The authors describe the methods used to develop a Senegal machine learning model and its outputs (Sections 2b.2 and 2b.3). In the final two sections, the authors discuss the limitations and further research, and provide guidance on using the science developed for the report as a tool for future analysis of vulnerability in Senegal.

### I. Introduction

Machine learning (*ml*), defined as advanced programming strategies that provide computers with the ability to learn without being explicitly programmed, is a cutting-edge new tool increasingly used to analyze flooding. Applying these tools to International River Basins (IRBs) allows hydrologists and programmers to overcome the current limits of understanding the river dynamics and to better predict floods and vulnerability. However, because the data-driven flooding approach developed for this report is so new, its results are not yet fully tested.

Traditionally, large-scale flood modeling of IRBs relied on physically-based flood models that are rooted in equations describing the physical movement of water. These models are usually expensive to build, require significant expertise to calibrate, and can take days of computation time to generate a single set of results. Model outputs also only represent a snapshot of flood risk because the parameters used in the model are time-specific (rainfall, land use, population). Being static as such can quickly render the outputs from traditional models irrelevant, especially in areas of rapid development.

As a response, many experts are arguing for simpler, satellite-based approaches, even at the cost of significant decreases in accuracy, in order to address the urgent need for hydrologic data in IRBs (Hossain, Katiyar, Hong, & Wolf, 2007). Machine learning algorithms and remote sensing are increasingly used in lieu of process-based methods to advance the field of hazard forecasting by producing flood maps at higher speed and lower cost (Naghbi & Pourghasemi, 2015; Rasouli, Hsieh, & Cannon, 2012; Solomatine & Xue, 2004). Initial applications of machine learning in the field of hydrology included the use of neural networks and support vector machines to predicting flood extent (Han, L, & N, 2007; Liong & Sivapragasam, 2002) and rainfall-runoff flow rates (Campolo, Andreussi, & Soldati, 1999; Lin, Cheng, & Chau, 2006). These and other studies (Hong, 2008; Pradhan, 2010; Tehrany, Pradhan, & Jebur, 2013; D. Wang et al., 2013) showed the algorithms could prove useful in modeling extreme events. This study, which applies machine learning to generate flood predictions in Senegal, tests this ground-breaking methodology and has high potential to transform the way global inundation modeling is done.



**Figure 6: Conceptual model workflow for machine learning based flood plain prediction.**

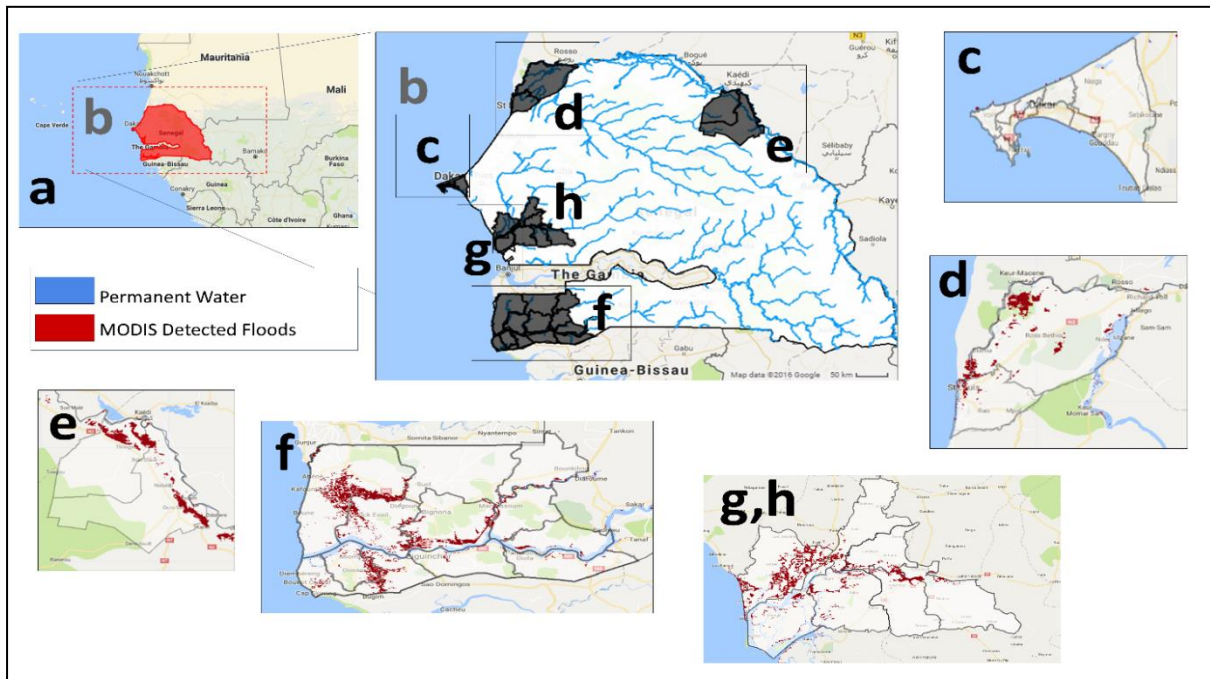
## II. Methods

### 1. Study Areas

Three river valleys (Senegal River, Saloum River, Casamance River) and the Dakar area were identified as candidates for modeling because of the availability of training data and based on feedback from personnel at Agence Française de Développement. In-depth model training and validation was conducted in along the Senegal River Valley (SRV) in the Saint-Louis region, in northwestern Senegal. The region was selected as the primary prototype because of its high population, its history of flooding, and the robust library of training data. Flooding is considered the greatest hazard on the risk continuum in this area (Pelling & Wisner, 2012). In addition to this in-depth study, less in-depth modeling was done for another part of the SRV; for the Saloum and Casamance river valleys; and for the Dakar area.

These study areas span 32 different *arrondissements* in the following administrative regions: Saint-Louis, Matam, Fatick, Kaolack, Dakar, Sédhiou, and Ziguinchor, as shown in Figure 7. The full list of *arrondissements* is given in Table A2.





**Figure 7: Maps of Senegal (a), showing the study areas (b) chosen for the machine learning model: floods were predicted in the area around Dakar (c); in the Senegal River Valley for selected *arrondissements* of the Saint-Louis (d) and Matam (e) regions; in the Casamance River for selected *arrondissements* of the Ziguinchor and Sedhiou regions (f); and in the Saloum River Valley for selected *arrondissements* of the Kaolack (g) and Fatick (h) regions. Red pixels indicate areas of MODIS-detected floods that are used as training data for the machine learning model.**

## 2. Flood Conditioning Factors

Flood conditioning factors describe the environmental conditions contributing to physical flood risk in a given watershed. While local scale data may be scarce, cutting-edge new efforts to generate global layers for many of these variables can be of use. For this study, flood conditioning factors (Table A1) were selected based on a literature review of both traditional and statistical flood models (Tehrany et al., 2013; Z. Wang et al., 2015). The significance of any given conditioning factor is expected to vary across landscape types. Factors were constrained to open source datasets in order to ensure the model could be replicated easily by anyone with access to the Internet.

Ten total flood conditioning factors were chosen including: slope, digital elevation model (DEM), curvature, stream power index (SPI), topographic wetness index (TWI), impervious surface, normalized difference vegetation index (NDVI), event precipitation, height above nearest drainage (HAND), and Euclidean distance from river. All variables were subsampled at a 30 m resolution and metadata details for each dataset can be found in Table A1.

## 3. Model Development

The machine learning algorithms rely on training or reference data to determine landscape patterns of flooding. See Chapter 1 for a detailed explanation of how training data was created. Training data from the two different sources described in Chapter 2a, including the Dartmouth

Flood Observatory algorithm (MODIS, 250 m resolution) and the Feyisa algorithm (Landsat, 30 m resolution), were tested for this analysis. This process, allowed us to explore how imagery resolution and detection approach impacted model predictions. Training data from both approaches in the form of a gridded binary raster (0 = flood, 1 = no flood) was stratified into the two classes and then randomly subsampled at 30 m resolution.

Using this training data, four different types of supervised machine learning algorithms were tested: (1) Random Forest (RF), (2) Support Vector Machine (SVM), (3) Fast Naive Bayes (NB) and (4) Classification & Regression Trees (CART). These four algorithms range from very simple (NB) to very complex ensemble classifiers (RF). While each algorithm relies on different statistical decision rules, they all use a similar framework, where flood conditioning factors and training data are inputs that generate a floodplain as an output (Figure 8).

#### 4. Performance Metrics

In a process called k-fold validation, model training and testing is repeated 10 times, withholding a separate 10% of training pixels each time. At the conclusion of the modeling exercise, each algorithm has a training and validation score indicating how well it identifies flooded pixels on familiar pixels (training data) or unfamiliar data (validation data) relative to the benchmark data. The average score is used to assess overall performance (Mannel, Price, & Hua, 2011) and is recorded in a table called a confusion matrix. Model results are then evaluated on a suite of metrics (Table 5) based on how many pixels in each class (flooded or not flooded) were correctly labeled in the modeled floodplain ( $A_m$ ) when compared to the benchmark or training data ( $A_b$ ). These metrics, derived from the confusion matrix, have been used to evaluate other flood models (Alfieri et al., 2013; Bates, 2004; Werner, Hunter, & Bates, 2005) and measure accuracy with and without penalties for overprediction and underprediction.

**Table 5: Metrics for evaluating model performance, error and bias.**

Metric	Explanation	Equation
Hit Rate (H)	Pixels labeled as flooded in the training data ( $A_b$ ) intersected with ( $\cap$ ) those predicted to be flooded by the model ( $A_m$ ) (Sampson et al., 2015a)	$H = \frac{A_m \cap A_b}{A_b}$
False Alarm Rate (F)	Measure overestimating of the floodplain (between 0-1, 1 means all pixels are “false alarms” falsely labeled as flooded) (Wu et al., 2012)	$F = \frac{A_m \setminus A_b}{A_m \cap A_b + A_m \setminus A_b}$
Critical Success Rate (C)	Penalties for under and other prediction ratio of the total intersection of predicted and benchmark flood pixels divided by the total number or union ( $\cup$ ) of flooded pixels in both sets. Ranges from 0 -1 (1= perfect match) (Sampson et al., 2015b)	$C = \frac{A_m \cap A_b}{A_m \cup A_b}$
Mean Error ( $E_a$ )	Mean absolute error ( $E_a$ ) where $B$ is benchmark flooded fraction, $M$ is modeled flooded fraction and $N$ is number of grid cells formed by aggregating test case raster results to ~1 km scale. (Sampson et al., 2015a)	$E_a = \frac{\sum_{i=1}^N  M-B }{N}$
Error Bias (B)	Score of 1 and greater indications a tendency to overpredict and scores between 0-1 indicate underprediction. (Sampson et al., 2015a)	$B = \frac{A_m/A_b}{A_b/A_m}$

### III. Results

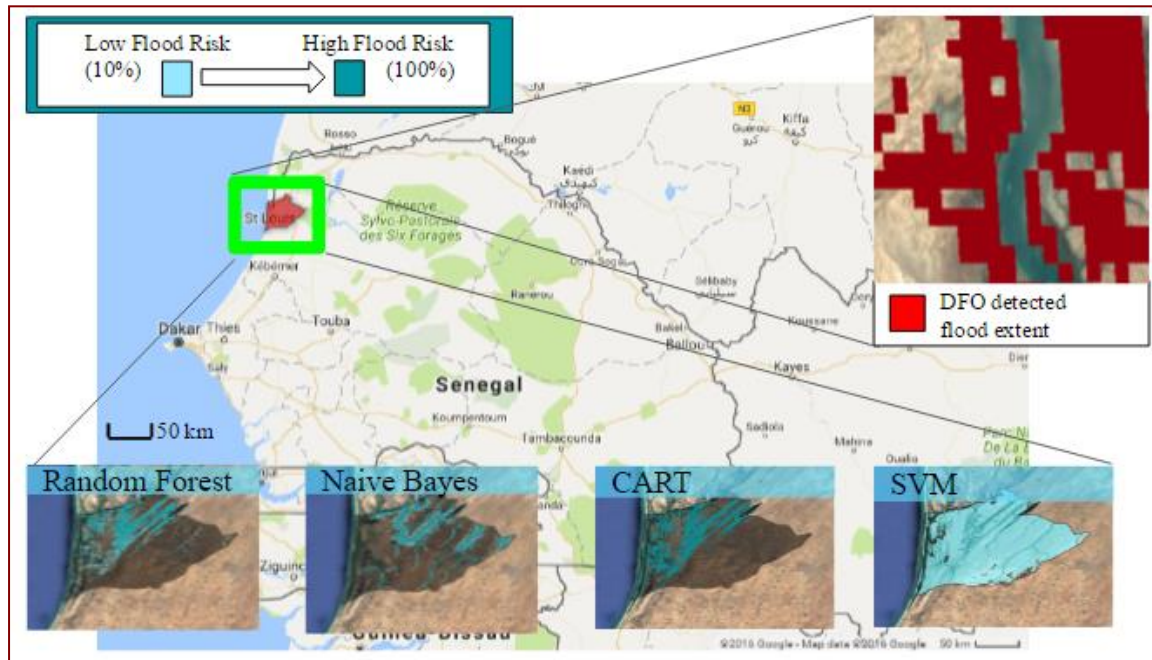
This model generates a 1 arc-second (30 meters) flood prediction extent across the six specified study regions (Figure 8) and can be applied anywhere in the country for any storm occurring within the Landsat and MODIS histories. The parallelized GEE computing framework divides the study region into tiles for simultaneous processing which allows the model to be run for any watershed in Senegal on a laptop from the Internet within a matter of minutes.

#### 1. Saint-Louis Prototype

Four machine learning classifiers using two different types of training data were tested for the Saint-Louis region (Figure 8) with a range of model parameters. Accuracies for both types of training data are reported in Table A3. Overall model accuracies ranged from 47–92% with Hit Rates between 52-98%, comparable to accuracies reported in other applications of these algorithms to classification problems in GEE (Dong et al., 2016; Goldblatt, You, Hanson, & Khandelwal, 2016; Johansen, Phinn, & Taylor, 2015). Algorithms trained using the DFO flood detection algorithm outperformed those trained using the Feyisa method by 11% (overall accuracy) and 12% (Hit Rate). Model calibration improved RF Hit Rates by 5%.

These results suggest that models trained with MODIS, rather than Landsat, training imagery will have higher accuracy. Among the four algorithms tested, the Random Forest algorithm has the greatest potential for accurately predicting floodplain extent based on training data, with an average Hit Rate of 97% and the lowest False Alarm rate (14%) relative to the other algorithms. Based on these results, RF should be prioritized when using machine learning for hydrologic

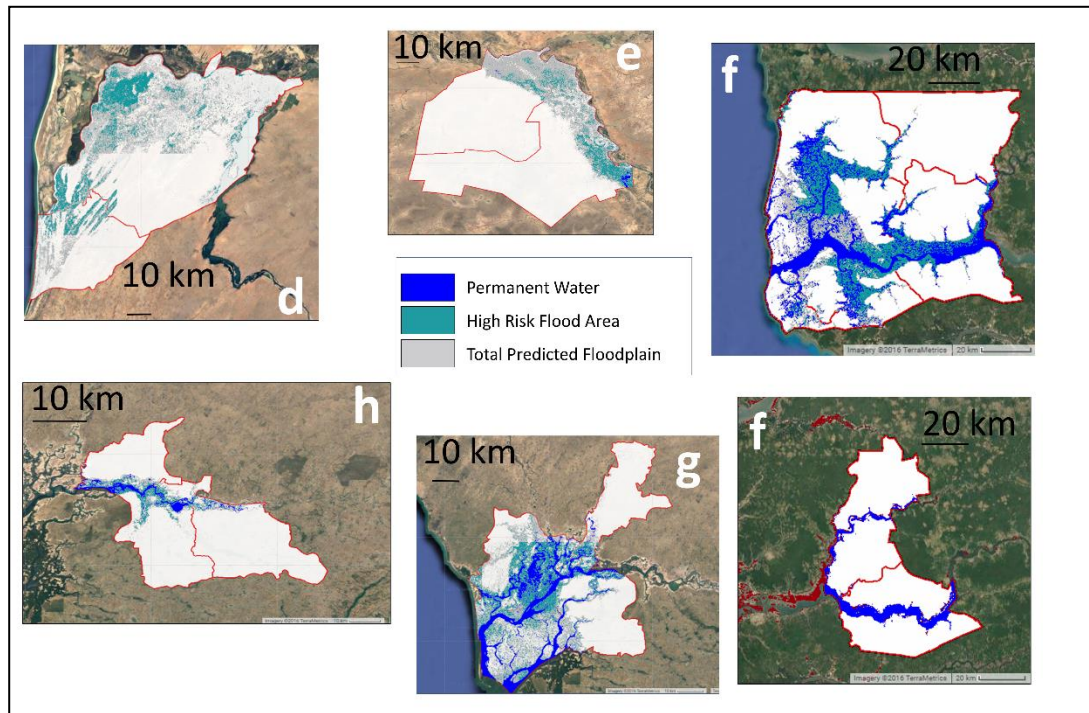
assessment in Senegal. However, performance metrics for other algorithms are still in the range of that reported in flood literature, suggesting that these approaches should not be discarded entirely.



**Figure 8: Example flood predictions based on the DFO historic flood #3180 detected from the Global Flood Database detection algorithm (upper right corner) in the Saint-Louis region along the Senegal River. The color gradient (lower images) indicates the number of times (1-10) a pixel was marked as flooded across the ten k-fold validation trials.**

## 2. Predictions for Flood-Prone Regions across Senegal

The Saint-Louis prototype was used to inform a Random Forest flood prediction model for five other regions in Senegal (Figure 9) covering an area of 24,992 km<sup>2</sup>, or 34% of the total area of the country. The model estimates a total predicted floodplain of 5,596 km<sup>2</sup> and 30% of that floodplain (1,641 km<sup>2</sup>) is considered high risk, meaning the model predicted flooding in 100% of the trials. Over 14,000 people in each study region on average are at high risk of exposure to flooding according to analysis conducted using the WorldPop gridded population dataset. For all the regions analyzed in this study, over 97,000 people are estimated to be at very high risk of flood exposure.

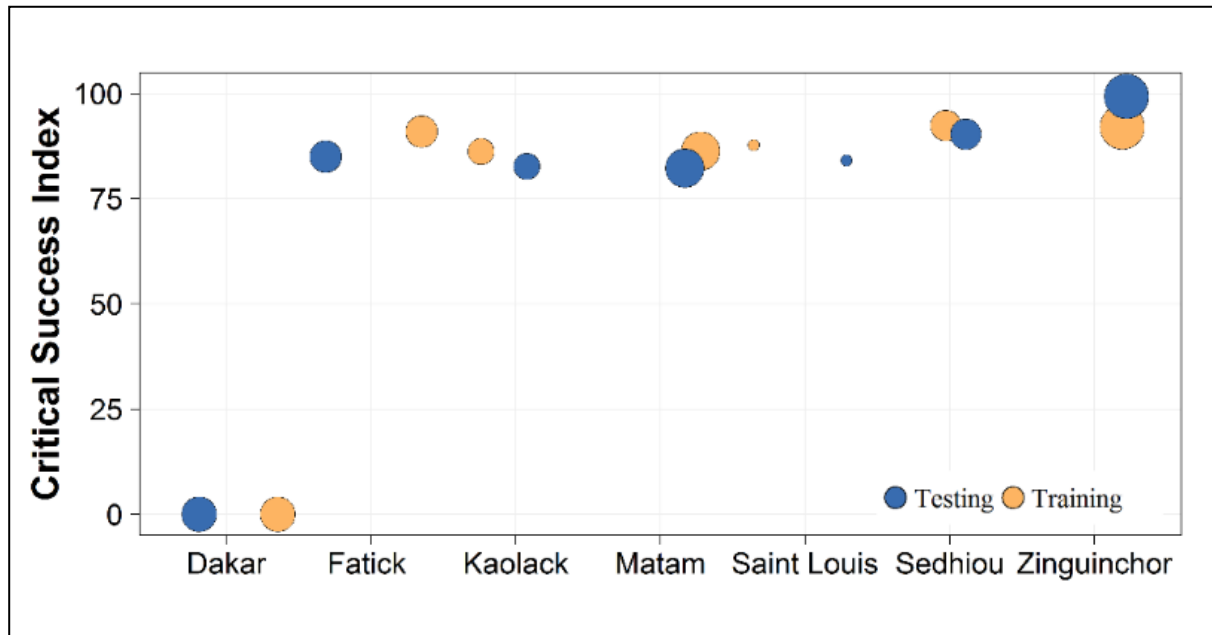


**Figure 9: Floodplain extents for each of the five focus regions. Flood extents within the focus regions (white outlined in red) are separated into the total predicted floodplain (any area marked as flooded during validation, marked as grey) and the high-risk floodplain (any area marked as flooded during 10 out of the 10 validation trials, marked as dark turquoise). The Casamance River Valley was divided into two separate models for flood-prone *arrondissements* in the Ziguinchor and Sédhiou regions because of memory restrictions in GEE.**

	Area Analyzed (km <sup>2</sup> )	Total Risk Area (km <sup>2</sup> )	% in Predicted Zone	High Risk Area (km <sup>2</sup> )	People at Risk
<b>Matam</b>	5,135	1,051	20%	114	38,400
<b>Fatick</b>	3,162	1,085	34%	528	17,038
<b>Kaolack</b>	1,906	204	11%	89	2,109
<b>Saint-Louis</b>	3,990	1,399	35%	523	8,208
<b>Dakar</b>	559	0	0%	0	0
<b>Ziguinchor</b>	7383	1,616	22%	349	31754
<b>Sédhiou</b>	2,855.81	241	8%	39	4,426

**Table 5: Results showing the region area, the total risk area (any pixels classified as flooded in any trial, the high-risk area and the total population in the high-risk floodplain for each region. These results were generated using the Random Forest machine learning classifier trained with the MODIS September 2007 historic detected flood raster.**

## IV. Error, Model Limitations, and Further Research



**Figure 10: Critical Success Indices for training and validation (testing) rounds across the six River regions tested and Dakar. Bubble size is the relative areas of training data for each region.**

Model bias shows the Random Forest algorithm has a bias to overprediction. RF has an average Error Bias of 1.16; an Error Bias between 0-1 show underprediction and  $> 1$  shows overprediction. This overprediction is reflected in the false alarm rate, which ranges from 5-15%. Therefore total floodplain extent estimates are expected to be ~90% of the predicted total as a result of this model bias. Despite this bias toward overprediction, mean error still falls between 0.04-0.13, an exciting finding that shows the Random Forest model can be used to make reasonably accurate predictions with only a modest amount of parameterization. However, currently the model can only be run on areas smaller than 10,000 km<sup>2</sup> because of memory constraints in GEE. Therefore the authors recommend the development of country-wide model based on a nested mosaic of smaller models tailored to the specific conditions of local regions instead of using a generic national approach. Also, the model currently is most successful in areas with robust training data, achieving high Critical Success rates in areas with training data. Figure 10 shows the impact of the lack of training data on the Critical Success Index of Dakar, whereas regions with training data are able to achieve high Critical Success Rates. As the results from Figure 10 and Table 6 show, in areas where the flood detection algorithm cannot identify floods to be used for training, the model is completely unable to generate predicted floodplains. The inclusion of higher resolution training data with broader spatial coverage could significantly improve model capabilities.

## V. Conclusion

Accurate flood mapping is crucial for protecting vulnerable populations and mitigating the catastrophic economic losses that can result from flood events. This dynamic socio-political and environmental context requires rapid, on-demand analysis executable within the constraints of

sparse field data. Results from this research demonstrate the potential of using machine learning to revolutionize flood modeling for this region.

	Hit Rate	False Alarm Rate	Mean Error	Error Bias
<b>Dakar</b>	0%	0%	0.01	0.00
<b>Fatick</b>	90%	15%	0.13	1.09
<b>Kaolack</b>	89%	5%	0.06	1.23
<b>Matam</b>	90%	11%	0.11	1.29
<b>Saint-Louis</b>	87%	11%	0.11	1.07
<b>Sédhiou</b>	95%	5%	0.04	1.18
<b>Ziguinchor</b>	98%	11%	0.05	1.11

**Table 6: Accuracy rates across several metrics indicate how the machine learning model succeeded in each of the test watershed in Senegal.**

This project tested four machine learning algorithms trained with two different resolutions of training data for the September 2012 floods in the Saint-Louis region.

These results show that machine learning algorithms have potential to be able to reproduce benchmark historic floods as detected by remote sensing with Hit Rates between 51-98%. DFO-trained models had higher performance metrics than the Landsat-trained models by 5-19%. Model calibration improved Hit Rates by up to 11%. The RF model, trained with DFO-MODIS data, had the highest success rate with an overall accuracy of 91.5% and an average hit rate of 97%. A third of the focus regions lie within the modeled floodplain in the Senegal, Souma, and Casamance River Valleys and over 100,000 people are at very high risk of flood exposure.

## 3. Social Vulnerability to Disaster in Senegal

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Social conditions that make one community more likely to experience loss from a disaster – loss of life, loss of livelihood, lack of recovery – is critical to understanding the threat of and resilience to flooding in Senegal. The field of social vulnerability investigates the ways the non-physical systems of an area contribute to the population’s capacity to absorb and recover from a disaster. Although social vulnerability and resilience sciences have advanced immensely in the last two decades, the social science – particularly for developing countries – lags considerably behind the geophysical study of disasters. Yet, it is possibly even more important to understand what makes developing communities vulnerable where the climatic changes are likely to hit hardest and where existing inequality is often the greatest. This chapter examines two questions: 1) what social characteristics drive vulnerability in Senegal?; and 2) which *arrondissements* are more likely to experience loss during extreme flooding and other fast onset disasters?

To answer these questions, the authors conducted a literature review and a factor analysis to assess social vulnerability for Senegal. This analysis was built on a sample of anonymized individual level census data from 2013, provided by Agence Nationale de la Statistique et de la Démographie du Sénégal (ANSD). Using the IPCC definition of vulnerability, the Cutter conceptualization of disaster, and our literature review of vulnerability for the region, the authors selected 19 variables that are expected to contribute to social vulnerability to flooding in Senegal and which were not correlated with each other as shown in Table 7.

Important socioeconomic characteristics for Senegal in general include i) a population of 3.031 million (21.7% of the population) internet users by 2015 estimates (Central Intelligence Agency, 2016), ranking 14<sup>th</sup> in Africa; ii) a low median age in highly rural *arrondissements* (13 years in the Naming *arrondissement*, in the southern part of the country); iii) a large youth population, even in the *arrondissements* with the highest median age (26 years in Grand Dakar and Dakar Plateau). According to a 2012 estimate by the UN Economic Commission for Africa, this places Senegal’s median age below that of Africa as a whole.

We found five underlying dimensions to drive vulnerability in Senegal: 1) a lack of basic informational resources, 2) age (elderly populations), 3) disabilities, 4) dense hubs, and 5) population increase from internal migration. The resulting social risk index reveals 30 *arrondissements* to be the most socially vulnerable. In total, approximately 5 million people live in *arrondissements* that have very high social vulnerability profiles compared to other *arrondissements*.

There are many ways to improve this work and further develop this science in order to refine our resultant profile of who is vulnerable in Senegal and make statistical predictions of which groups are going to be more vulnerable. To mention a few: i) incorporating big data options like cell phone data to provide information that the census cannot, and ii) eliciting stakeholder input. In terms of adding cellphone data, these resulting population estimates may add temporal scales so the authors can tell how vulnerability changes seasonally or even hourly. Cell phone data may also add finer spatial resolution and additional dimensions like social cohesion. Third and most importantly, the next phase of the social vulnerability analysis would have a strong focus on getting feedback from leaders in government, NGOs, and communities in vulnerable areas. This feedback would be used for obtaining and selecting social vulnerability variables. Chapter 5 discusses options and recommendations for conducting this local engagement.



## I. Introduction

Disasters including floods are not just physical phenomena. They are deeply influenced by the social, demographic, economic, and political conditions of the human populations they affect. As a result, two communities hit by the same hazard will likely experience different amounts of loss in the short and long term. In the Chicago heat wave of 1995, black communities that had the same rates of violence, poverty, and were located in the same area experienced significantly different death rates (33 vs. 3 deaths for every 100,000 residents in one example); depending on how frequently their community members interacted with each other. Knowing one another – from church, talking on the street, or meeting in local stores – proved to be lifesaving (Klinenberg, 2003). When Katrina hit land, New Orleans had a relatively low elderly population. Sixteen percent of the city’s residents were over 60 according to the 2005 US Census. Yet 75% of deaths from the hurricane were people in this age bracket (Brunkard, Namulanda, & Ratard, 2008). In Senegal’s July 2016 floods, around 12,000 people were affected; out of which more than 75% were poor farmers whose crops were destroyed, putting their livelihoods at stake (ACAPS, 2016). This chapter explores several of these trends in Senegal.

The field of social vulnerability investigates the ways in which the non-physical systems of an area contribute to its population’s capacity to absorb and recover from a disaster. Quantitative social vulnerability distills the social dimensions of that put people at risk into measurable numeric proxies and holistic indexes of overall risk. These social dimensions can range from economic or social conditions of a household – such as poverty status, dependency ratio, and other factors – to physical characteristics – such as disabilities, age, and gender of an individual. Given influence factors in determining the outcome of a disaster, integrating these dimensions is critical in order to understand the threats posed to a region holistically.

The Intergovernmental Panel on Climate Change’s defines vulnerability as:

“the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt” (IPCC, 2014)

Social vulnerability is defined as the potential of a community or individual to experience loss from a hazard due to risk dimensions that are social in nature, rather than physical or ecological (Cutter, Boruff, & Shirley, 2003). After decades of research, there is some consensus in the social science research community around the demographic, behavioral, and psychological characteristics that make people and communities vulnerable at least in a general sense (Cutter et al., 2003). These dimensions of vulnerability fall along a spectrum of universality or generalizability; some dimensions are fairly well documented and consistent across geographies (Cutter et al., 2003), while others vary significantly across time, place, and context.

People who have more financial resources, who are not especially young or old, and have strong community support are less vulnerable. The elderly are vulnerable because of their health, disability, lack of transport, and lack of access to information and other resources (Ngo, 2001). Communities with a majority of their population above age 65 are likely to be more vulnerable than with a majority population between ages 30 and 45. Conversely, children, particularly infants and young children, are vulnerable because of their dependence on adults and their psychological impressionability (Peek, 2008). Crime can indicate reduced community cohesion, and prevent evacuation in rapid onset events like fires and floods. Governance may be weak in violent areas, leading to corruption of disaster aid, and preventing help from getting

to those most in need (Tellman, Alaniz, Rivera, & Contreras, 2014). In many scenarios women are more vulnerable than men because of their lack of resources – both material and informational (A. Fothergill, 1996a; Neumayer & Plümper, 2007a). Psychological factors are increasingly recognized as significant at every stage of disaster response (Werg, Grothmann, & Schmidt, 2013a). Furthermore, culture has a strong influence on risk perception and requires a very local and nuanced analysis to understand, which often demands qualitative study (Adger, Barnett, Brown, Marshall, & O'Brien, 2013).

While the dimensions of social vulnerability have mostly been explored through qualitative methods, there has been an academic effort over the last two decades to quantify these dimensions in order to estimate or even predict social vulnerability. These assessments have primarily come in the form of geospatial indices (de Sherbinin, 2014). Over the last two decades, social vulnerability researchers have begun to distill the dimensions of social vulnerability into empirically based indicators. When combined in summary indices, typically using demographic information, these tools describe who is most vulnerable and where the most vulnerable are located before, during, and after a crisis (Tate, 2012). If measured using benchmarks and monitored over time, these indicators may serve as diagnostic tools.

Our methodology is based on the Social Vulnerability Index (SoVI) developed by Dr. Susan Cutter at the University of South Carolina. SoVI uses Principal Components Analysis (PCA) based factor analysis on a large set of county- or tract-level US Census variables in order to determine a set of underlying dimensions of vulnerability e.g. Hispanic ethnicity, special needs individuals, Native American ethnicity, and service industry employment (Cutter et al., 2003). An updated model in 2010 added new dimensions such as family structure, language barriers, vehicle availability, medical disabilities, and healthcare access in the preparation for and response to disasters. Other approaches to social vulnerability or similar themes that use other methods and datasets exist, but those are not as widely relied upon within the scientific or practitioner community. The factor analysis-based approach and other methods have been used in a small set of countries and regions around the world.

Although social vulnerability and resilience sciences have advanced immensely in the last two decades, the social science – particularly for developing countries – lags considerably behind the geophysical study of disasters. Yet, it is possibly even more important to understand what makes developing communities vulnerable where the climatic changes are likely to hit hardest and where existing inequality is often the greatest.

Qualitative and statistically descriptive assessments of Senegal consistently describe several attributes that make certain groups more vulnerable in general.

Poverty and marginalized communities, which in Senegal are chiefly concentrated in rural communities, are consistently estimated to be at higher risk and subject to a variety of other threats like violence that compound existing vulnerability. Poverty and concentration of marginalized groups is a determinant of higher social vulnerability as these groups are considered more sensitive than others and have less adaptive capacity (Alice Fothergill & Peek, 2004; Holmes, Sadana, & Rath, 2010; O'Hare, 2001).

Generally, communities with more women are more sensitive to hazards due to gendered risks and vulnerabilities (A. Fothergill, 1996a; Holmes et al., 2010; Ray-Bennett, 2009). Also, in Senegal, the level of literacy amongst women is low due to major drop-outs from school (UNESCO, 2012). Possible reasons are early marriage, teenage pregnancy, and socio-cultural

norms regarding the role of women in the society. Educational progress does play a crucial role in increasing human adaptive capacity (Reid & Vogel, 2006; Tschakert, 2007). However, a high female population with low literacy can be related to high social vulnerability as an outcome.

The primary sector, viz. agriculture, which is concentrated in rural areas (with more than half the Senegalese population), contributes 20% of Senegal's GDP. On the other hand, the secondary and tertiary sectors, viz. industries and services located in the cities, contribute 80% of Senegal's GDP. This huge disparity in income to secondary and tertiary sectors and their concentration in urban centers act as a major driver of rural to urban migration (Urban Habitat, 2014).

As noted earlier in this chapter, rural communities are at much higher risk of loss from disasters; however, in Senegal, places with the most vulnerable populations tend to be peri-urban areas, as they consist primarily of informal settlements (World Bank, 2012). People from rural areas migrate to these areas and develop neighborhoods without drainage canals and sewage systems. In Dakar, within one decade (from 1998 to 2008), around 40% of new inhabitants moved into zones of high flood potential (Geoville Group, 2009; World Bank, 2010). Besides urban/rural setting, several other characteristics make some communities or groups more vulnerable than others, specifically in Senegal. Table 7 outlines the indicators used in the report's analysis, with references to literature that supports their use in identifying vulnerable people. This report explores a quantitative vulnerability assessment of some of the generalizable dimensions of vulnerability through an exploratory model. Overall, some papers argue that inequities build into governance structures and the cultural history of the country creates a cycle of vulnerability driven by underlying systemic conditions. Vulnerability therefore goes beyond the directly measurable characteristics of communities (Sané, Gaye, Diakhaté, & Aziadekey, 2015).

Social vulnerability is critical to understanding the threat of and resilience to flooding in Senegal. Some research on vulnerability in the country argues that social dimensions of vulnerability were more critical to the overall stability of Senegal than pressures from environmental and climatic changes. "Compared to this pervasive manifestation of social vulnerability, climate extremes appear to be a minor hazard, although the recent heavy rainfalls did significantly disrupt rural livelihoods" (Tschakert, 2007).

To examine the social nature of flooding risk in the country in this report, the authors ask:

1. What social characteristics drive vulnerability in Senegal?
2. Which *arrondissements* are more likely to experience loss during extreme flooding and other fast onset disasters?

## II. Methods

Social vulnerability cannot be measured directly, at least in full, so scientists use variable proxies that can be directly measured and monitored in order to model underlying relationships, both positive and negative (Cutter et al., 2003). This report uses a common factor analysis-based approach to assess social vulnerability for Senegal. The goal of this model is to reduce the measurable (and available) characteristics of Senegal to the latent dimensions that may determine social vulnerability to disaster.

## 1. Data for Social Indicators

Through a partnership with Data-Pop Alliance and the Agence Nationale de la Statistique et de la Démographie du Sénégal (ANSD), the authors were given access to Senegal's official census, the Recensement Général de la Population et de l'Habitat, de l'Agriculture et de l'Élevage (RGPHAE) (Agence Nationale de la Statistique et de la Démographie du Sénégal, 2013). The ANSD supplied documentation about the census collection process, including the original questionnaires and census workers' handbook, and provided support on accessing and understanding the data.

The 2013 edition of the RGPHAE was conducted over the 21-day period from November 19 to December 14 of that year, and collected information at the household level (on a variety of topics including family structure, asset ownership, agricultural practices, and living situation) as well as detailed information about each individual living in the household (such as demographic information and education/work history). The ANSD provided access to a 10% sample of all responses, resulting in a dataset of 145,952 household records comprising 1,245,551 individual inhabitants (roughly 1/10th of Senegal's population of 14 million people).

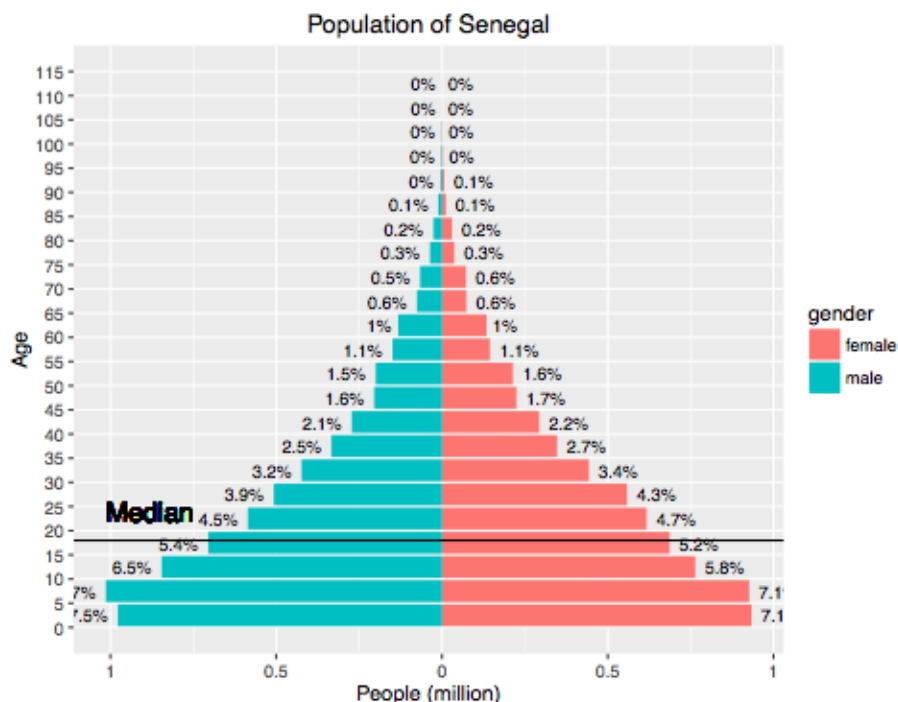
At the third administrative level (generally referred to as "CAV"), Senegal is mainly divided into *arrondissements*, but also into areas called *communes* and *villes* (generally large towns and cities, respectively), which are administered separately from *arrondissements*. However, each commune and ville generally shares boundaries with an *arrondissement* that it has historically been associated with, and it is not uncommon to refer to all areas of 3rd administrative level simply as "*arrondissements*". For the purposes of this paper, the authors take "*arrondissement*" to mean a 3rd administrative level area that includes an official *arrondissement* and its contiguous towns and cities, to ensure that every census record can be geolocated to a single *arrondissement*. Using a combination of spatial merges in GIS, shapefiles from the GADM database of Global Administrative Areas (GADM, 2015), and Senegal's laws on changes in the administrative division of the country (République du Sénégal, 1996, 2013), the authors were able to associate each census response with one of the 122 *arrondissements* that existed at the time the census was undertaken.

The household and individual results from the census were used to build 25 indicators relevant to social vulnerability. Using the IPCC definition of vulnerability introduced in Section 3.1, the Cutter conceptualization of disaster and the authors' literature review of vulnerability for the region, the authors selected available variables from the Senegalese census that are expected to contribute to social vulnerability to flooding in Senegal. Each variable has been known to contribute to vulnerability in the region or more generally (see Table 7) based on an extensive literature review by the authors. Certain indicators were drawn directly from responses to a specific question in the census (e.g.: Are you male or female?); others were built from combinations of responses to multiple questions (e.g.: Are you male or female? + Are you the head of the household?). All indicators (with the exception of population density) were built at the individual/household level; and later aggregated at the *arrondissement* level by taking the arithmetic mean (for numeric indicators) or the percentage of "true" values (for binary indicators). Population density was calculated by dividing the surface area in the GADM shapefiles by the number of individual census responses. Table 7 summarizes the selected indicators, their origin, and supporting literature.

## 2. Demographic Profile of Senegal

Senegal has a population of 13.1 million people, of which about 54% live in rural areas. The country is characterized by growing youth population (Janneh, 2012), with a median age of 18 country-wide as shown in Figure 11.

Figure 11: Population attributes of Senegal



Median age is especially low in highly rural *arrondissements* (13 years in the Niaming *arrondissement*, in the southern part of the country), but even the *arrondissements* with the highest median age (26 years in Grand Dakar and Dakar Plateau) have a large youth population.

There are a half dozen major language groups, the largest of which are Wolof (38.7%), Pular (26.5%), and Serer (15%). Roughly one third of the population can read and write at least one language, but rates range a lot from one *arrondissement* to another: for instance, in Almadies (a wealthy part of Dakar inhabited by diplomats and expats) roughly 60% of inhabitants can read and write, whereas the rate is as low as 7% in Koulor (in the Tambacounda region). Higher literacy rates are observed in urban areas and their peripheries, especially in the west of the country near the cities of Dakar, Thiès, and Ziguinchor, and to a lesser degree around the eastern city of Tambacounda. Unemployment also ranges widely, from 35% in Fafacourou (a highly rural *department* in the southern region of Kolda) to 8% in Cabrousse (a coastal village in the south west of Senegal), with a national average of 16%.

Generally speaking, unemployment is concentrated in the northeastern part Senegal and, to a lesser degree, in the central southern portion of the county (Central Intelligence Agency, 2016).

The country has 3.031 million (21.7% of the population) by 2015 estimates ranking 14<sup>th</sup> in Africa for number of internet users (Central Intelligence Agency, 2016). The percentage of people who

have internet and a computer in their household is below 10% in all but 5 *arrondissements*; of those 5 *arrondissements*, all are located in the Dakar region. However, mobile phone ownership is widespread, with 81% of households reporting that they own a mobile phone. At the *arrondissement* level, household mobile phone ownership ranges from 45% in Dar Salam (in the Kédougou region in southeastern Senegal) to 92% in Almadies (a wealthy part of Dakar).

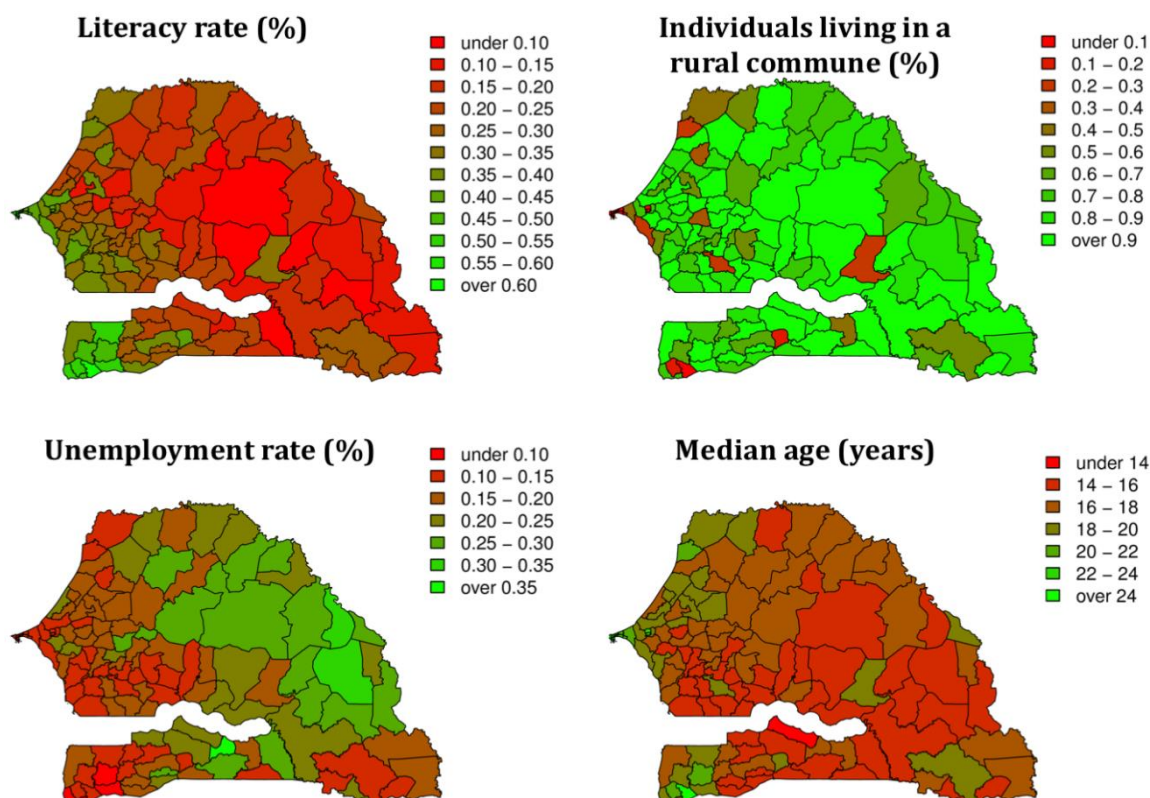
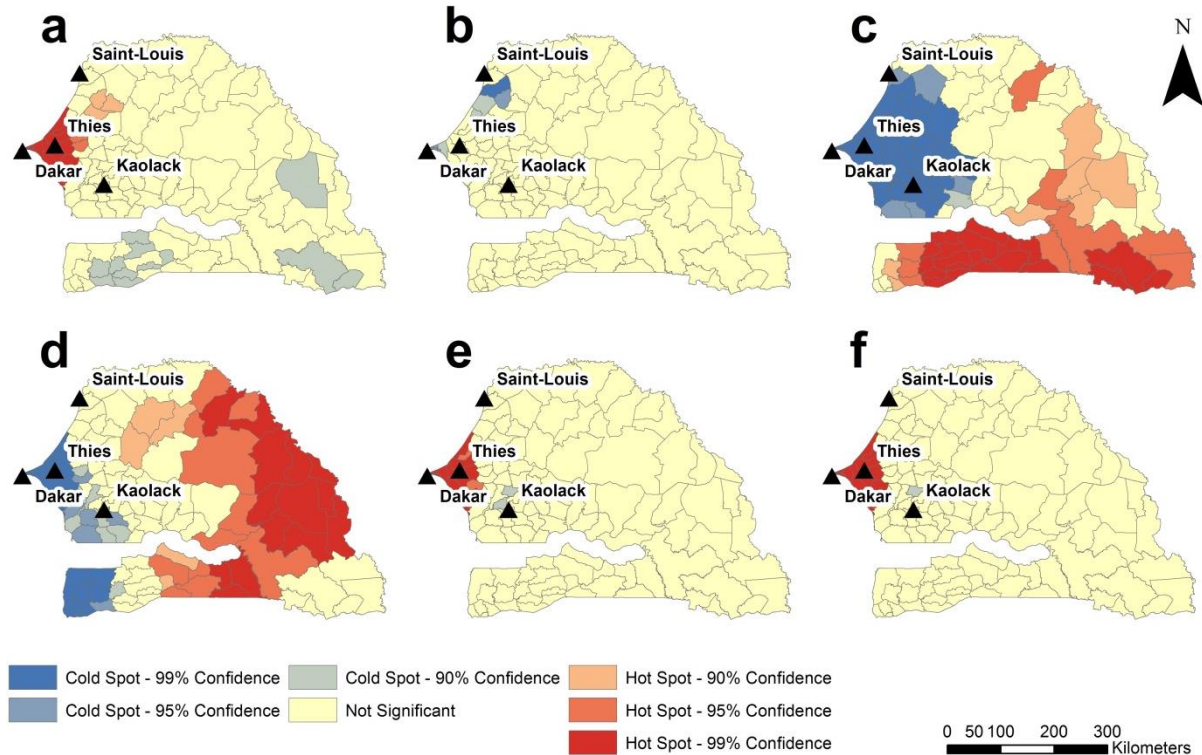


Figure 12: Spatial demographic profile of Senegal (by *arrondissement*): (a) Literacy rate; (b) Urban/Rural distribution (c) Unemployment rate, (d) Median age.

### 3. Spatial hotspots of Key Dimensions that Affect Social Vulnerability

In order to understand spatial vulnerability outcome profile, it is important to gain an understanding of how key social and economic dimensions vary across the geographic space. Here, the authors carried out a spatial hotspot analysis using the ESRI ArcMap Gettis-ord  $G_i^*$  statistic on the following variables: *pop\_size*, *pop\_density*, *pct\_female*, *pct\_skipped\_meal\_7days*, *pct\_unemployment*, *pct\_information\_internet*. Descriptions of the variables referred to in this section can be found in Table 7. The authors find that population size and density (given by the *pop\_size* and *pop\_density* variables, respectively) and access to resources (proxied through the *pct\_information\_internet* variable) are concentrated in the western part of the country where major cities such as Dakar and Thiès are located (Figure 13). In addition, the western region has higher food security, as the *pct\_skipped\_meal\_7days* variable indicates a cold spot in the region. Similarly, the western region shows high employment (based on the *pct\_unemployment* variable). On the contrary, the eastern region has low employment levels and the entire region is identified as a hotspot of unemployment. Interestingly, the *pct\_female* variable does not show a major hotspot in the country, suggesting that women are not concentrated in any one region but rather the levels are randomly distributed

across geographic space. In summary, these hotspots suggest that there are regions in the country where a particular social or economic dimension has significant spatial relationship. However, this does not suggest that the social vulnerability outcome profile will display emergent spatial patterns, but rather that emergent patterns are likely.



**Figure 13: Spatial hotspots of key variables that affect vulnerability, measured at the *arrondissement* level: a) Population size; b) Percentage of females; c) Percentage of households where a member missed a meal in the last 7 days due to lack of resources; d) Percentage of unemployed individuals; e) Percent of households with access to internet and a computer; f) Population density**

#### 4. Variable Selection

Using the criteria described in Section 3.2 of this chapter, the authors initially selected 25 variables from the aggregated ground census data to assess social vulnerability in Senegal (as shown in Table 7). In order to reduce redundancies in the data, the authors performed pair-wise comparison of variables to identify multicollinearity in the data and dropped some variables on the basis these pair-wise correlations. The authors removed the variables iteratively until the selected variables were sufficiently non-redundant. Specifically, this was achieved with two iterations. In the first iteration, the authors identified variables that were correlated with at least three other variables with a correlation coefficient greater than  $|0.7|$ . Here, the authors dropped the *pct\_child*, *pct\_female\_hoh*, and *pct\_top\_quantile\_children* variables. During the next iteration, the authors used the criteria to identify variable pairs with correlation coefficient greater than  $|0.8|$ . On this basis, the *pct\_literacy* and *pct\_difficulty\_bathing* variables were also dropped. After our iterative pair-wise comparison, the authors selected 19 variables with to carry out Principal Component Analysis (PCA)-based factor analysis.

Table 7: Input variable matrix and literature review

Dimension	Name of Variable in model	Description	Data Source	Literature Reference
Crowded	avg_num_residents	High number of people per household	Senegal Census	(Brenkert & Malone, 2005; Maheu, 2012; Mbow et al., 2008)
Population density	pop_size OR pop_density*	People per <i>arrondissement</i> People per km <sup>2</sup>	Senegal Census & GADM	(Brenkert & Malone, 2005; Gencer, 2013; Mbow, Diop, Diaw, & Niang, 2008; Rufat, Tate, Burton, & Maroof, 2015)
Female	pct_female*	High proportion of females	Senegal Census	(Chatterjee & Sheoran, 2007; A. Fothergill, 1996b; Holmes et al., 2010; Neumayer & Plümper, 2007b; Reid & Vogel, 2006; UNESCO, 2012)
Age (youth)	pct_youth	% of children below 4	Senegal Census	Sané, 2015*; Newport and Godfrey, 2003** ; Chatterjee and Sheoran, 2007**
Age (elderly)	pct_elderly*	% of people over 45	Senegal Census	(Maharaj, 2012; Mbaye, Ridde, & Kâ, 2012; Ngo, 2001; Parmar et al., 2014)
Female-headed households	pct_female_hoh		Senegal Census	(UNESCO, 2012)
Youth-headed households	pct_child_hoh	Households headed by people 14 or younger	Senegal Census	(International Monetary Fund, 2010; Vanderbeck & Worth, 2015)
Mother with many dependents	avg_n_infants* OR pct_top_quantile_children	Woman with infants OR a high % of people with an extreme number of children based on the country average	Senegal Census	
Disability (vision)	pct_difficulty_vision*	High difficulty seeing	Senegal Census	(Chatterjee & Sheoran, 2007; Drame & Kamphoff, 2014; Jonkman & Kelman, 2005)
Disability (hearing)	pct_difficulty_hearing*	High difficulty hearing	Senegal Census	(Chatterjee & Sheoran, 2007; Drame & Kamphoff, 2014; Jonkman & Kelman, 2005)
Disability (mobility)	pct_difficulty_walking*	High difficulty walking or going up stairs	Senegal Census	(Chatterjee & Sheoran, 2007; Drame & Kamphoff, 2014; Jonkman & Kelman, 2005)
Disability (memory)	pct_difficulty_memory*	High difficulty with memory or concentration	Senegal Census	(Chatterjee & Sheoran, 2007; Jonkman & Kelman, 2005)

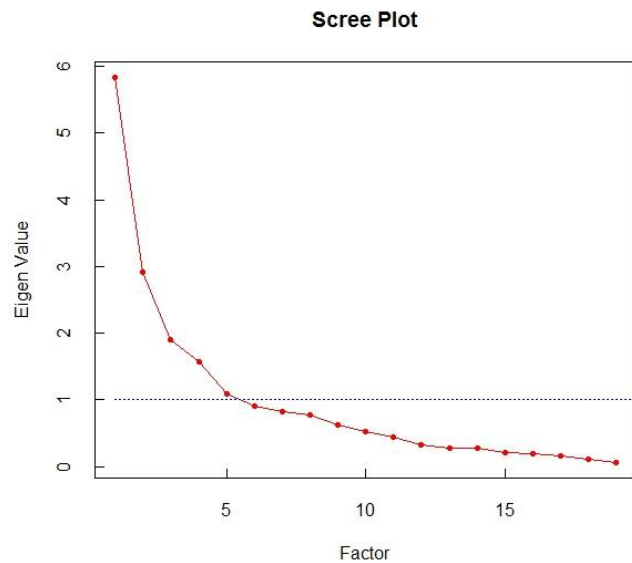


Dimension	Name of Variable in model	Description	Data Source	Literature Reference
Disability (personal care)	pct_difficulty_bathing	High difficulty when caring for oneself, e.g., bathing	Senegal Census	(Chatterjee & Sheoran, 2007; Jonkman & Kelman, 2005)
Education	pct_undereducation*	People 15 or older with less than a 5th grade level education	Senegal Census	(Brenkert & Malone, 2005; Drame & Kamphoff, 2014; Tschakert, 2007)
Social cohesion/ community stability	pct_migration_internal*	Communities in which many members moved in the past year	Senegal Census	(Kahn et al, 2003; Kane et al., 1993; Newport & Jawahar, 2003; Werg, Grothmann, & Schmidt, 2013b)
	pct_migration_external*	Communities in which many members moved out the past year		
Literacy	pct_literacy	% of people who can read and write	Senegal Census	(Brenkert & Malone, 2005; Rufat et al., 2015)
Unemployment	pct_unemployment*	% who want to work but do not have a job	Senegal Census	
Access to Information (stationary source)	pct_information_stationary*	% of Households with a radio, landline or Television	Senegal Census	(Ngo, 2001; Tschakert, 2007)
Access to Information (mobile phone)	pct_information_mobile*	% of Households with a Mobile Phone	Senegal Census	
Access to Information (internet)	pct_information_internet*	% of Households with a computer/laptop and Internet/Wi-Fi	Senegal Census	(Jonkman & Kelman, 2005)
Wealth income/resources	pct_skipped_meal_7days* OR pct_skipped_care_12months*	% of Households where a member had to skip a meal in the last 7 days OR failed to receive care in the last 12 months due to lack of resources	Senegal Census	(Brenkert & Malone, 2005; Alice Fothergill & Peek, 2004; Sané et al., 2015)
Rural (population)	pct_rural*	% of community that is rural	Senegal Census	(Brenkert & Malone, 2005; Tschakert, 2007)
<b>Note: Variables that are marked with “*” are finally included in Factor Analysis.</b>				

## 5. PCA-Based Factor Analysis

Principal Component Analysis (PCA) is a statistical dimension reduction algorithm which uses an orthogonal transformation technique to convert a set of correlated variables into a new reduced set of uncorrelated variables. These new sets of uncorrelated principal components can be used to summarize the original data based on relatedness between different variables (Cutter et al., 2003). Each variable, both in the original data with pre-selected variables and the newly-derived uncorrelated set of factors, should in some way affect the social vulnerability outcome. While variables in the original data can be labeled in how they affect social vulnerability based on existing literature and ground knowledge, the factors obtained from PCA-based factor analysis needs to be reinterpreted in order to determine their relationship with social vulnerability. Once these relationships are identified, the factors are rescaled by applying a directional (multiplying by a value of -1 or +1 depending upon how the given factor is related to social vulnerability) and a summation of factors will then reflect the final social vulnerability scores.

In this study, the authors performed PCA-based factor analysis using varimax rotation with the selected 19 variables, after reducing multilinearity in the data, in the R programming platform (Revelle, 2016). Of the several principal components obtained, the authors selected components or factors that explained maximum variability in the data. Here the authors used a scree plot, which shows the relation between Eigen values and the number of factors considered. The authors found that for five factors Eigen values remained greater than one. Factors with Eigen values less than one are unstable and have much less variability, owing to the fact that in PCA the first few components account for a significant majority of the variation in the original data. Thus, the authors selected these five factors considering the cut-off value of 1 (Figure 14). These five factors explain ~69 % of the variation in the original dataset.



**Figure 14: Scree plot showing Eigen values and factors obtained from PCA. Blue dotted line shows the threshold considered for factors selection.**

**Table 8: Key dimensions of Social Vulnerability in Senegal**

Factor	Interpreted name	% Variation explained	Governing Variables	Correlation coefficients	Expected relation with Social Vulnerability (Directional)
1	Lack of basic and informational resources	17%	pct_skipped_meal_7days pct_information_stationary pct_skipped_care_12months pct_information_mobile	(-)-0.91 0.79 (-)-0.76 0.71	-
2	Elderly population	15.5%	pct_elderly	(-)-0.85	-
3	Disabilities	15%	pct_difficulty_walking pct_difficulty_hearing pct_difficulty_vision pct_difficulty_memory	0.9 0.89 0.84 0.71	+
4	Dense hubs	15%	pct_information_internet pop_density pct_rural	0.78 0.77 (-)-0.71	+
5	Population increase from internal migration	6%	pct_migration_internal	0.82	+

A significant variation among the 19 input variables, which the authors identified to be closely related to the social vulnerability outcome, is captured by five factors. These factors will differentiate administrative units considered in this study based on their relative social vulnerabilities as determined from the underlying dimensions of the data. Table 8 lists all five factors with the percentage of variation in the original data they, their governing variables, and their significant correlates in the original data. After examining the nature and direction of correlation of each factor with individual variables in the original data, the authors determined their expected relationship with the final social vulnerability.

### **Lack of basic and informational resources**

The first factor, which describes most of the variation among the variables, captures social vulnerability due to food insecurity, access to resources in terms of healthcare, and information from stationary sources like television and radio. This factor is strongly correlated with the pct\_skipped\_meal\_7days variable (percentage of households where someone had to skip a meal in the previous week due to lack of resources). The greater the percentage of people skipping meals due to resource unavailability, the more vulnerable a region may be to environmental hazards like flooding, which will likely further exacerbate and disrupt the ability to grow or purchase food. Two other dominant variables explaining this factor are pct\_skipped\_care\_12months (percentage of households where a member failed to receive health care in the previous year due to lack of resources) and pct\_information\_stationary (percentage of households with access to a radio, television, or landline phone).

Access to regular health care (Sané et al., 2015) reflects higher resilience of the population towards natural hazards. In the absence of accessibility to food and healthcare, the population is

more socially vulnerable, especially since disaster may further disrupt access to medicine, which may be in even higher demand during flood periods due to new diseases that can occur. Our first factor variable is negatively correlated with the `pct_skipped_meal_7days` and `pct_skipped_care_12months`, meaning that a higher value of factor variable is associated with fewer skipped meal and healthcare needs; and therefore this factor is negatively associated with the social vulnerability outcome, meaning that a higher value of factor variable is associated with lower social vulnerability. In addition to the aforementioned two variables, the factor variable is also positively loaded with access to information (Tschakert, 2007), which reflects higher resilience of the population towards environmental hazards including flood events, for example if they lack access to flood warning. This suggests that, in general, the population that is otherwise deprived of access to food and healthcare services still has access to sources of gaining information. The same populations that lack access to information, which can be important in early warning, may also be unable to store resources to draw upon in a disaster if they have trouble meeting basic food and health needs. Overall, this factor variable explains 17% of the variation in the data.

### **Elderly Population**

Our second factor explains 15.5% of the variation in the data. Note that this factor is negatively correlated ( $\rho = -0.85$ ) with the `pct_elderly` variable (percentage of people age 45 or older). Overall, the elderly are more sensitive to environmental risks and have less overall adaptive capacity, which makes them more vulnerable to environmental disasters (Filiberto et al., 2009). In Africa specifically, aging is closely related to increased vulnerability (Parmar et al., 2014) due to high illiteracy rate, informal employment, and early retirement, particularly in rural areas. Informal employment, which is predominant in the case of women, usually does not provide any pension arrangements. According to the International Monetary Fund (2010), only 17% of elderly people in Sub Saharan Africa receive a pension. Therefore, the authors expect that a higher value of this factor is associated with lower social vulnerability.

In general there is more demand for medical facilities from older populations (Maharaj, 2012) and low availability of such facilities in poor countries like Senegal (Leye et al., 2013) increases risk to this group. In Senegal, the “Plan Sésame” was introduced in 2006 to reduce social vulnerability (Mbaye et al., 2012) and provides free access to public healthcare services to elderly people of 60 years and over (Maharaj, 2012; Parmar et al., 2014). These trends are further indicative of the high social vulnerability of elderly populations during flood periods.

### **Disabilities**

One in every ten children in Africa has some type of disability (Drame & Kamphoff, 2014). Disabilities make people vulnerable as they may pose barriers to their participation in mainstream education and employment. Furthermore, disabilities increase the risk of loss during floods in poor countries where government do not have enough capacity and resources to take special steps to evacuate and prepare this population. Nonetheless, several steps have been taken in Senegal to close the gap in education between disabled populations and others. For example, the Senegalese parliament passed a law of “Social Orientation” in 2010, giving children and youth with disabilities a right to free education in their nearest neighborhood school with mainstream school settings (ACPF, 2011; Plessis & Reenen, 2011); however, considering the poverty level in Senegal, this “Education for all” vision will likely take time to enact and implement.

Our factor variable takes into account disabilities related to hearing, walking and vision, explaining 15% of the variation in the data. The `pct_difficulty_walking` and `pct_difficulty_hearing` variables (percentage of people who experience high levels of difficulty with walking/stairs and hearing, respectively) are the dominant variables loaded in the factor variable, followed by `pct_difficulty_vision` and `pct_difficulty_memory` (percentage of people who experience high levels of difficulty with vision and memory/concentration, respectively). All four variables are positively correlated with the factor variable, suggesting that a higher value of the factor variable is associated with a higher percentage of population with the aforementioned disabilities. Keeping in consideration the present socio-economic and political conditions in the country, people with disabilities are generally more sensitive to environmental hazards, because it can be difficult to receive evacuation instructions, rebuild livelihoods quickly, or take advantage of relief programs and compete with others for resources. For these reasons, disabled populations may to a certain extent have less adaptive capacity, eventually leading this group to be more socially vulnerable than others (Drame & Kamphoff, 2014). This also suggests that a higher value of the factor variable represents higher social vulnerability.

### Dense Hubs

This factor describes “Dense Hubs”, viz. highly connected areas, and explains 15% of the variation in the input data. The dominant variables explaining this dimension of vulnerability are `pct_information_internet` (percentage of households with access to a computer and/or the Internet), `pct_rural` (percentage of individuals living in a *commune* classified as rural) and `pop_density` (population density). The `pct_information_internet` and `pop_density` variables are positively loaded, indicating that the factor represents high population density areas with good internet connectivity. The `pct_rural` variable is negatively loaded, which reinforces the fact that this factor captures information on dense urban regions. With regions of high population density, exposure to flood risks would be higher. Urban areas with lack of urban planning increases the likelihood of a disaster event associated with floods (Gencer, 2013; Mbow et al., 2008; Sané et al., 2015). This is due to the fact that these areas are also poorly managed and governed when it comes to policies for integrating rural and urban areas (Urban Habitat, 2014). For example, in Dakar, an increased rate of urbanization has resulted in an increase in informal settlements, which covers almost 30% of urban areas. Furthermore, unplanned urban areas, with lower rents or housing costs, remain attractive to low-income households or poor rural migrants to settle in hazard-prone flood zones (Maheu, 2012; Simon, 2010). Lastly, low quality building material, poor transportation networks, and lack of healthcare facilities make these areas more vulnerable. For example, housing can easily collapse, evacuation can become difficult, and often post-flood epidemics are not dealt with adequately. Therefore, this factor is positively associated to social vulnerability.

Besides the explanation given above, there is also an overlap between vulnerability and urban poverty, as asserted in the urban vulnerability science literature (Gencer, 2013). Nevertheless, not all poor people are vulnerable to disasters and oftentimes people who are relatively rich are vulnerable as well. Social demographics do not completely determine vulnerability outcomes, as human choice can drive community development and interact with general sociodemographic variables.

### Population Increase from Internal Migration

This fifth and last factor describes the social vulnerability of a community as affected by migration of a significant number of people in a year. These migrants may be returning family members, distant relative visiting, or in general a new family migrating into the community. This

factor explains 6% of the variation in the data with a correlation coefficient of 0.82. With a community experiences an increase in incoming migrants, it may become less stable and more exposed to various threats like occupational hazards from specific jobs and communicable diseases, which migrants often bring with themselves (Kahn et al, 2003). A study carried by Kane et al. (1993) found that 27% of male Senegalese migrants were HIV-positive compared to 1% of non-migrants Senegalese males in the same area. Thus, this factor positively affects social vulnerability. On the other hand, migration can represent increase in off-farm income, and this cash flow and increased adaptive capacity help diversify income, and can enable investments to reduce risk.

### III. Social Vulnerability Profile of Senegal

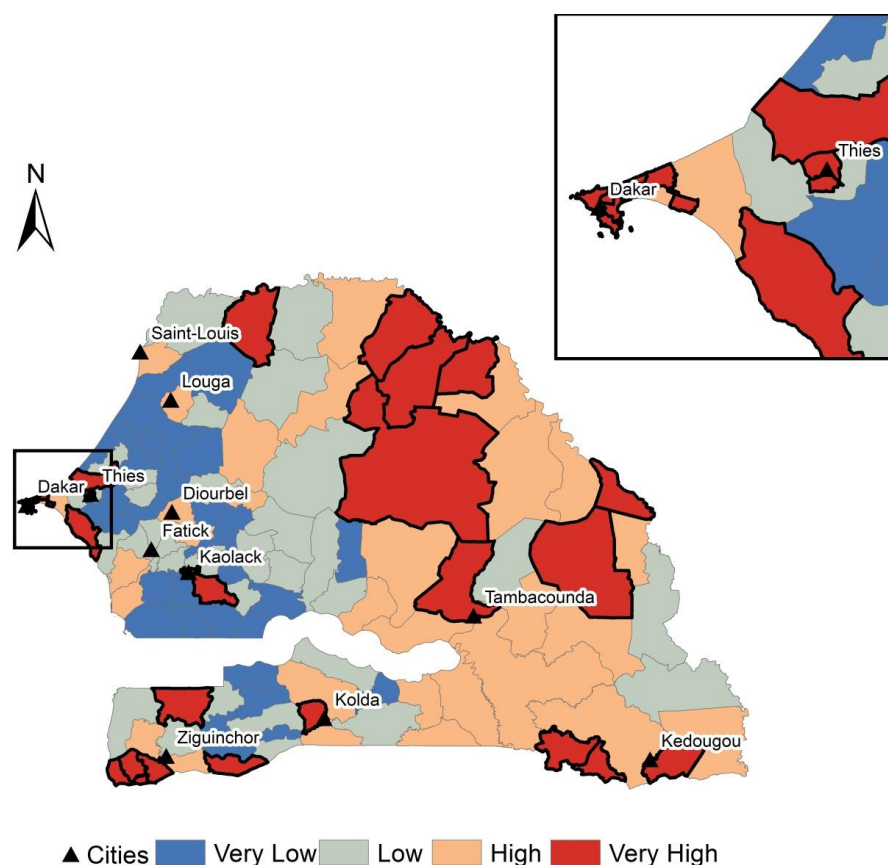
Social Vulnerability index is generated for Senegal using principal component analysis based factor analysis with nineteen indicators. It is classified into four categories: very low, low, high, and very high. Figure 15 shows the spatial patterns of social vulnerability for Senegal that the authors identified. Out of 122 *arrondissements* in Senegal, the resulting social risk index reveals thirty *arrondissements* to be the most socially vulnerable, i.e., with very high social vulnerability profile (Table 9). In total, the authors found that roughly 5 million people live in *arrondissements* that have a very high social vulnerability profile.

Our analysis showed that very high social vulnerability profiles in Senegal were mostly concentrated in *arrondissements* with major cities such as Dakar, Thiès, Kaolack, Ziguinchor, and others, as well as *arrondissements* located near these cities. In Senegal, urban population living in peri-urban areas has often been identified as the most vulnerable group to natural disasters. Due to uneven income distribution and the fact that major industries are located chiefly in cities, rural to urban migration is quite common in Senegal. Rapid and large-scale rural-to-urban population migration leading to unplanned urban expansion has been identified as a major driver for changes in regional hydrology leading to flooding in Senegalese cities such as Saint-Louis, Kaolack, Tambacounda, and Dakar (World Bank, 2012). In fact, the rural-to-urban migrants living in outlying areas of major cities are deprived of urban infrastructure and amenities and are often counted under rural population; Dakar is a good example with more than 30% of rural population. Furthermore, in these rapidly urbanizing regions, often the changes in policies lag behind the rate of rural-urban migration. This lagging political response to high rates of migration forces the migrant population from rural areas to end up residing in the outskirts of the cities, which are mostly low-lying flood-prone areas and prohibited construction zones. Gradually, migrant populations develop urban neighborhoods that are deprived of proper drainage and sewage systems. These complex migration and urban expansion dynamics have led to increased social vulnerability of the Senegalese population. This is best exemplified by the heavy rains of 2012 that resulted in a major flood disaster due to the combined effect of climate change and this unplanned development. Essentially, unplanned and unorganized construction in the outlying areas of the city changed the regional hydrology, resulting in the obstruction of water flow towards the ocean.

Besides the high social vulnerability of regions in or near major cities or towns, the authors identified a few *arrondissements* in central, northern, and south-eastern Senegal that have very high social vulnerability. Our in-depth analysis of the data suggests that the northern *arrondissements* are hotspots of population with different kinds of physical disabilities. Our analysis, however, does not identify the reason for which these *arrondissements* have a relatively higher proportion of people with physical disabilities compared to other *arrondissements*. Nonetheless, in addition to a relatively greater proportion of population with

disabilities, the authors identified several *arrondissements* in the central, northern, and south-eastern Senegal with lack of access to food, healthcare, and information, leading to very high social vulnerability profiles. The central and northern *arrondissements*, however, especially, have higher elderly population, which is generally more vulnerable to natural disasters. A key unifying feature of the central, northern, eastern *arrondissements* that the authors have identified to have very high social vulnerability is that these have predominantly rural characteristics. In several of these *arrondissements* farming is the principal occupation. As previous literature suggests, flooding in Senegal has severely affected agriculture and thus the livelihood of the population (ACAPS, 2016).

**Figure 15: Social vulnerability profile for Senegal generated using factor analysis of select social vulnerability indicators. Locations of a few cities have been shown on the map for reference.**



**Table 9: The 30 most social vulnerable *arrondissements*.**

S.No.	Region	<i>Arrondissement</i>	Estimated Population (2015)
1	Dakar	Almadies	290100
2	Dakar	Dakar Plateau	358000
3	Dakar	Grand Dakar	342400
4	Dakar	Parcelles Assainies	447600

5	Dakar	Guediawaye	496900
6	Dakar	Niayes	238900
7	Dakar	Pikine Dagoudane	421800
8	Dakar	Rufisque	217600
9	Kédougou	Fongolimbi	17600
10	Kédougou	Dakately	7900
11	Kédougou	Dar Salam	14600
12	Kaolack	Koumbal	337200
13	Kolda	Sare Bidji	88700
14	Matam	Agnam Civol	79300
15	Matam	Vélingara	68900
16	Sédhiou	Djibanar	107600
17	Saint-Louis	Mbane	88500
18	Saint-Louis	Cas-Cas	128200
19	Saint-Louis	Salde	93100
20	Tambacounda	Moudéry	98600
21	Tambacounda	Boynguel Bamba	45000
22	Tambacounda	Koussanar	48800
23	Thiès	Sindia	412800
24	Thiès	Thiès Nord	135800
25	Thiès	Thiès Sud	149900
26	Thiès	Pambal	126200
27	Ziguinchor	Sindian	58100
28	Ziguinchor	Cabrousse	18000
29	Ziguinchor	Loudia Ouolof	24000
30	Ziguinchor	Nyassia	16900

#### IV. Data Limitations

Though the dimension reduction conducted in this report was very successful, the conclusions that the authors can make from the results are limited for several reasons. Variable selection is arguably the most important part of a PCA-based approach. The data used in a social vulnerability index needs to be current, robust, and qualitatively verified by experts. Likewise, the outputs must be interpreted and used with intimate knowledge of the region and with the statistical limitations of the data in mind.

There could be important dimensions of vulnerability that were not represented as variables in the available data. The authors suspect these omitted variables could be important to social vulnerability in Senegal and other contexts. There are most likely more aspects that the authors are not aware of but that are critical for social vulnerability in the region. However, with the comprehensive nature of the available data, all the major aspects and dimensions of social vulnerability have been incorporated.



Beyond these data considerations, it is critical to note that PCA is not a predictive statistical model. The results presented here describe the natural groupings of the variables input into the model and not validated externally with disaster outcome data in a statistical sense. However, this essential point reinforces the importance of variable selection for this approach to social vulnerability. Again, the model is only as good as the variables that go into it and only describes the information it is given.

## V. Recommendations for Application and Further Research

Of the several ways to improve the scientific understanding of social vulnerability, the most important is incorporating more, locally contextualized input data. As the authors explain in the introduction of this section, many of the factors that make communities vulnerable differ widely across different cultural, political and other contexts, and at different stages of the disaster cycle. Many of those differences and the variables therefore necessary to include in a social vulnerability assessment can only be detected through local knowledge. For instance, what qualifies as relatively low-income varies between communities and across time. Also, culture has a strong influence on risk perception and requires a very local and nuanced analysis to understand, which often demands qualitative study (Adger et al., 2013).

The variables for a social vulnerability index must be constructed and reviewed in collaboration or consultation with local scientists, practitioners, and/or community members. The authors recommend a deep literature review on the region, or Senegal in general, conducted in collaboration with organizations or groups like local development staff, governments, and NGOs.

To cover the full set of indicators, the authors would almost certainly have to include ground information from conventional national surveys and incorporate big data options like cell phone data to provide information that the census cannot. This may add temporal scales so the authors can tell how vulnerability changes seasonally or even hourly. It may also add finer spatial resolution and additional dimensions like social cohesion.

We further recommend the exploration of other assessment models. Primarily, other statistical techniques, such as other data reduction methods and predictive models, could be useful. Regression-based modeling is the next frontier in social vulnerability analysis (Fekete, 2009) because it ensures that the models are describing an external reality of disasters, rather than just interpreting characteristics of input data. The authors built such a model for the U.S. for 2008-2012. This model was not created for the sake of this report for two reasons: 1) the approach has not been widely developed and verified for social vulnerability in the academic literature and 2) the geospatial damage data necessary to build such a model were not available to the authors at the time of this analysis.

Finally, two other critical potentials for moving forward with vulnerability analysis are: 1) determining the appropriate scale of analysis, and 2) exploring the responsive or even real time applications of vulnerability analysis. Though conducting quantitative social vulnerability analysis at higher spatial resolution offers new insight into the social conditions that lead to vulnerability, the geographic scale at which those new results are most meaningful remains a largely unexplored research area. The authors recommend using variograms or another scale sensitivity-analysis technique to determine the areas in which the data is most different.

Despite its conceptual and scientific limitations, integrating the social dimensions of hazards into the disaster cycle is necessary for fully successful emergency planning and response (National

Academy of Sciences, 2012). Indices can help reduce people's social risk before a disaster hits if appropriately integrated into planning and response. When fully developed, they can identify areas most in need of assistance when a disaster strikes. The appropriate index can also suggest areas most in need of recovery assistance post-disaster by knowing which communities had a low coping capacity prior to the disaster, and where they were located. A validated and fully functioning version of the model presented here may serve these purposes.

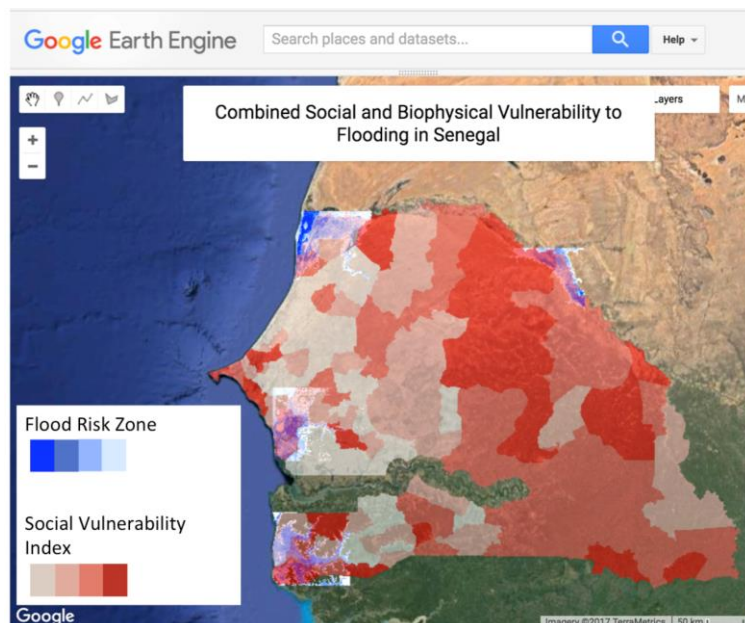
Lastly, there are a few ways to customize the social vulnerability assessment through the model based on the user's needs and interests. Some important decisions concern the variables to include, accurate interpretation of the identified factors, and assigning appropriate weights to the factors to derive final social vulnerability scores. These decisions could be made through expert consultation and incorporating decision making methodologies (Saaty, 2008).

## 4. Combined Socio-physical Vulnerability of Senegal

As previously explained, the authors tested our machine learning based approach to elucidate the spatial profiles of the biophysical risk in pre-selected river valleys. In fact, 33 *arrondissements* overlap with the Senegal, Saloum, and Casamance river valleys where the authors assessed the biophysical risk profiles. Our results showed that several of these river valleys have high biophysical risk. Specifically, there is higher population exposed to flood risk in Matam, Ziguinchor, Fatick, and Saint-Louis regions. Our social vulnerability assessment results suggest that specific *arrondissements* of these regions have very high social vulnerability (Table 10). For example, Sindian, Cabrousse, Loudia Ouolof, and Nyassia *arrondissements* of the Ziguinchor region have very high social vulnerability. Similarly, Agnam Civol in the Matam region has very high social vulnerability. There are also *arrondissements* that have high biophysical risk but have high social vulnerability (as opposed to very high social vulnerability). For example, Ogo, Rao, and Tendouck (and Niaguis) *arrondissements* in the Matam, Saint-Louis, and Ziguinchor regions, respectively, have high social vulnerability.

While these preliminary results are encouraging in identifying regions that have high biophysical risk and high social vulnerability, a complete nation-wide assessment of the biophysical risk profiles of the entire country is necessary to yield insights into the combined social vulnerability and biophysical flood risk profiles of the country. Therefore, a key next step is to strengthen the machine learning-based approach to delineate biophysical risk to flooding for the entire country. This will allow for a combined a combined national-scale assessment of food risk and social vulnerability. The most social vulnerable *arrondissements* within the flood risk zones of the Senegal watersheds analyzed in this report are shown in Table 10. The map of Senegal in Figure 16 shows the combined socio-physical vulnerability to flooding in Senegal for the watersheds modeled.

**Figure 16: Combined socio-physical vulnerability map for the five test watersheds of Senegal.**



**Table 10: Social vulnerability profiles of the select *arrondissements* where machine learning-based approach to estimate flood risk profiles was implemented.**

Region	Department	Arrondissement	Social Vulnerability
Sédhiou	Sédhiou	Djibabouya	Very Low
Sédhiou	Sédhiou	Djiredji	Very Low
Fatick	Fatick	Ndiob	Low
Kaolack	Kaolack	Ngothie	Low
Saint-Louis	Dagana	Ndiaye Mberess	Low
Sédhiou	Boukiling	Bona	Low
Ziguinchor	Bignona	Tenghory	Low
Matam	Matam	Ogo	High
Saint-Louis	Saint-Louis	Rao	High
Ziguinchor	Bignona	Tendouck	High
Ziguinchor	Ziguinchor	Niaguis	High
Kaolack	Kaolack	Koumbal	Very High
Matam	Matam	Agnam Civol	Very High
Sédhiou	Goudomp	Djibanar	Very High
Ziguinchor	Bignona	Sindian	Very High
Ziguinchor	Oussouye	Cabrousse	Very High
Ziguinchor	Oussouye	Loudia Ouolof	Very High
Ziguinchor	Ziguinchor	Nyassia	Very High

## 5. Participatory Engagement for Flood Resilience: A Blueprint for Engaging Local Senegalese in this Assessment

This chapter lays out a comprehensive methodology for engaging with stakeholders to further develop the flood vulnerability assessment described in the preceding chapters of this report. The flood vulnerability assessment was conducted remotely and derived from global or national remotely collected data sets. However, past international development and disaster risk reduction programs have found that involving local people in vulnerability and scientific assessments can be essential for improving the accuracy of the assessment as well as create significant resilience co-benefits for the communities engaged. Involving local people in risk assessment can lead to more durable response intervention programs that meet the needs of the community in question.

When implemented, stakeholder engagement enhances the accuracy, perception, and robustness of the scientific inputs of a vulnerability assessment. Stakeholders at the local level can provide researchers with detailed understanding of local flood extent and which

communities are most at risk from flooding. Through this process researchers can also uncover additional information useful in estimating and predicting the flood vulnerability of the country. Secondly, beyond enhancing the quality of scientific data, stakeholder engagement can increase the preparedness of the communities involved by raising awareness of risk factors and building the durability of disaster policies and infrastructure investments.

The engagement proposed here is designed to involve community-level stakeholders in participatory ways throughout the vulnerability assessment process in order to verify the location of historic flooding, “ground-truth” the social vulnerability assessment, and add fidelity to the machine learning based physical flooding analysis. In doing so, the interactions proposed here will build the resilience of communities involved and lay the ground work for more inclusive decision-making processes between relevant national and international stakeholder groups, such as development banks, governments, and other vulnerable communities.

## I. Introduction

We define stakeholders as those individuals or groups who can affect or be affected by the operations of an organization or project (R. K. Mitchell, Agle, & Wood, 1997). For this flood vulnerability research in Senegal, stakeholders include those parties who will contribute to, or be beneficiaries of, the flood mapping described in the previous chapters.

There are many case examples of how the quality and results of environmental planning, disaster risk reduction, and international development/aid projects are improved by including stakeholders in decision-making (Beierle, 2002; CARRI, 2013; Chambers, 1994; IIED, 2016; Pandey & Okazaki, n.d.; Pretty, Guijt, Thompson, & Scoones, 1995). The methodology outlined in this chapter builds on the success and challenges in the sector in order to provide background and a blueprint for a future participatory science strategy within the vulnerability assessment described in this report.

Stakeholder theory has its roots in many disciplines, including urban planning, international development, communications, and the business world (R. K. Mitchell et al., 1997). Thus, stakeholder engagement has many definitions. The World Bank defines stakeholder engagement as the process of “building and maintaining an open and constructive relationship with stakeholders [to] thereby facilitate and enhance a company’s or a project’s management of its operations, including its environmental and social effects and risks” (World Bank, n.d.). Regardless of the definition used, the term stakeholder engagement has become an all-encompassing reference to many processes that include (but are not limited to) stakeholder identification and analysis, outreach, communications, consultation, and partnership development (International Finance Corporation, 2007).

Engaging with stakeholders necessitates first understanding who those stakeholders are and how best to involve them in the project process. Through stakeholder identification and analysis, a business leader or project manager seeks to understand which individuals or groups have a stake, or vested interest, in the project at hand, and what motivates those stakeholders or entities towards action. Understanding this landscape can help a project team proactively engage with a stakeholder group and provide information or reach out to better understand the project context and risks of failure.

In international development and disaster risk reduction, stakeholder analysis is often a helpful first step in the project proposal process, and it can be a critical part of any subsequent project

interactions at the local level (ODI, n.d.). The engagement methodology outlined in this chapter primarily pulls from international development examples, though there are valuable lessons and principles to learn from other disciplines.

In international development, stakeholder engagement processes are often referred to as participatory engagement. Participatory stakeholder engagement processes seek to expand beyond external stakeholder analysis that determines potential risks to the project to involve the community in the project itself. Such practices champion local knowledge and imply a two-way street of information flow: rather than simply delivering information to a known audience about a project, the development or implementing agency is listening as well (GTZ, 2007, p. 9). Such engagement helps the project keep its goals relevant to the beneficiaries and assists with capacity building or training; both elements can be critical to long-term project adoption and success. Furthermore, involving people in a project process is a way of increasing ownership and democratizing the outcomes (Tschakert, 2007).

Processes that encourage stakeholder participation have long been a core of international development. However, the quality of decisions made through stakeholder participation is strongly dependent on the nature of the process or method leading to them (Reed, 2008). In international development, approaches to stakeholder participation have evolved over time: from largely awareness raising about a given project in the community in the late 1960s, to incorporating local perspectives in data collection and planning in the 1970s, to encouraging local stakeholders to participate in the project process from start to finish (Reed, 2008, p. 2418). An important development in the evolution of participatory engagement are “rapid rural appraisal” (RRA) and “participatory rural appraisal” (PRA). These approaches aim to incorporate the knowledge and opinions of rural people in the planning and management of development projects and programs. The Institute of International Environment and Development (IIED) and the Institute of Development Studies (IDS) were early collaborating authors on guiding frameworks and methodologies for RRA and PRA methods in the 1980s and 90s (Chambers, 1994; IIED, 2016; Pretty et al., 1995). These methodologies built on the traditions of activism and anthropology and evolved into participatory learning and action (PLA) systems that have increasingly been mainstreamed in the development world and has adapted over time to take on specific thematic challenges such as community-level adaptation to climate change (IIED, 2016).

Many development agencies have developed toolkits that set forth best practice methodologies and activities for participatory stakeholder engagement. These toolkits provide facilitation tips and activities that strive to keep development activities inclusive and “human-centered,” or focused on the needs of the beneficiary communities rather than an external agenda (GTZ, 2007; ideo.org, 2015; Pretty et al., 1995; Tekman, Hassapi, Chrysostomou, Konnaris, & Neophytou, 2012). Participatory stakeholder engagement activities include participatory planning (to include community mapping and participatory budgeting), survey and interview techniques, and educational games (ideo.org, 2015; Pretty et al., 1995).

For example, the ideo.org toolkit provides specific methodologies for gathering information in collaborative, inclusive ways within the context of a community in the developing world. They outline ways to invite and include people from across a community, as well as specific interview techniques for group settings (ideo.org, 2015). As technology changes and mobile technologies are increasingly available in rural areas, methods of participation are changing rapidly to incorporate digital survey tools and GPS devices as well as make use of cellular networks (Gordon, Schirra, & Hollander, 2011). For example, the World Food Programme’s mobile vulnerability mapping project utilizes SMS and call centers to gather data on food security in

remote areas via the existing phone network. Using this method WFP was able to gather 100,000 questionnaires in 2015 (Bauer, Attia, & Clough, 2016).

In the scientific community, one method of participatory stakeholder engagement is citizen science. Citizen science, also referred to as civic, participatory, or community science, is the act of involving citizens in science as researchers (Conrad & Hilchey, 2010). This inclusion of people who are not necessarily traditionally trained as scientists in data collection and research can democratize scientific processes, hold governments and companies accountable, and also increase the reach of a research team, or their ability to gather data (Conrad & Hilchey, 2010). Citizen science can either be citizen contributions to scientific studies that are ongoing, or science that is developed by and completed by citizens (Kruger & Shannon, 2000).

In both social science and physical science communities, crowdsourcing, or the act of gathering data from a large group of non-experts via survey, online, or other means, is often an umbrella term that includes citizen science practices (Lauriault & Mooney, 2014). Because of its capacity to scale data collection and/or feedback, crowdsourcing can be a useful technique for quickly gathering large amounts of data. For example, the US Geological Survey's Tweet Earthquake Dispatch utilizes crowdsourced data in the form of Twitter updates to track aftershocks following major earthquakes in real time ("Federal Crowdsourcing and Citizen Science Toolkit," n.d.; USGS, n.d.).

Disaster risk reduction is "the concept and practice of reducing disaster risks through systematic efforts to analyze and reduce the causal factors of disasters" (UNISDR, n.d.). This report focuses on the disaster risk reduction process of vulnerability analyses for the purposes of preparing communities and economies for disaster. Public stakeholder participation in disaster risk reduction planning specifically is critical for long term preparation and planning for crisis.

Integrating stakeholders into disaster risk reduction processes either via crowdsourcing or in-person workshops has several benefits. First, this gives a voice to the communities at risk from disasters (Tschakert, 2007, p. 382). Secondly, in vulnerability analyses, engaging local people early and often can help include local knowledge, contextualizing the analysis and giving fidelity to the contributing variables. In addition, such involvement also can educate members of a community and increase their resilience by making them more aware of risks. Finally, involving stakeholders can contribute to the lasting success of any ensuing interventions as it offers opportunities for capacity building and training of stakeholders during the project to ensure that follow-up can be accomplished locally (CARRI, 2013, p. 3; GTZ, 2007, p. 5).

Beyond involving local stakeholders, it is important to think about which stakeholders are involved. "Putting the vulnerable first" and including those demographic groups such as minorities, women, youth, or others who may not be a part of conventional city or disaster risk planning process can help grow the adaptive capacity of a community and increase resilience over time (Paavola & Adger, 2006). Indeed, some believe that the primary goal of any participatory stakeholder engagement intervention should be to be inclusive of as many different stakeholders/stakeholder groups as possible in order to reach and hear from those communities that often don't have a voice in existing decision-making or governance processes (Reed, 2008). This inclusion can help ensure that these populations are accounted for in the actions that are planned to reduce disaster risk (such as evacuation plans, infrastructure improvements, etc.). In addition, such inclusion and resulting capacity building can give vulnerable people and communities the skills to respond to disasters themselves, reducing death toll when events do happen (Pandey & Okazaki, n.d.).

However, being inclusive in participatory stakeholder engagement is difficult, especially when projects are conducted by outside parties. These challenges are shown in the case of Mercy Corps' work in Nepal, where routinely men were the only ones showing up to community disaster planning meetings. This meant the "least needy," the men, were the most aware of what to do in the event of a disaster, while dependents such as women and children were not well educated on evacuation or disaster response protocols and their needs were not voiced during the drafting of disaster plans. The organization had to become more creative in its outreach, turning to using street drama performances to make sure that the women and children in the community were included in risk awareness activities (Nepali Red Cross, 2009). As this case demonstrates, in order to realistically operationalize inclusive participatory stakeholder engagement with vulnerable communities, one must consider ethical lines, cultural and gender norms, and the capacity of the implementing organizations.

## II. Participatory Engagement for Flood Resilience in the Senegalese Context

As outlined in earlier sections of this report, flooding events in Senegal are frequent and destructive. Yet, in Senegal and across the Sahel region, drought is a much more pressing concern for many local leaders than flooding. This situation has led to information and policy response gaps around flooding (Tschakert et al., 2010). Additionally, many communities are not able to respond in order to keep themselves safe when flooding events happen. The remainder of this chapter describes a participatory stakeholder engagement process designed specifically for the flood vulnerability assessment for Senegal.

Following extreme 2009 floods, the Government of Senegal created its first recovery plan after a post-disaster needs assessment, which was conducted with the support of the international community and funded by the World Bank (The World Bank, 2014). Priority actions outlined in the report include: creating infrastructure to respond to urban flooding in Dakar and preparing a master plan for storm water management and preventing and mitigating disasters by a) developing an urban development plan that includes the mapping of flood risks, b) strengthening the management of flood risks, and c) educating affected communities. This plan for education and outreach was part of Senegal's effort to create a culture of "proactive preparedness" (World Bank, 2012). It shows interest in reaching out to the community about flooding, but not explicitly in learning what the community's needs are regarding flooding events.

In 2012, further flooding inspired additional flood risk management approaches and the government launched a revised ten-year flood management program. This new program aimed to involve local officials in the flood planning process, but does not explicitly speak to local citizen involvement (World Bank, 2014). In the Fall of 2016, extreme floods have again devastated Senegal. Outside of major urban centers, in the central part of the country, floods have highlighted a lack of communication and warning systems available as well as inadequate local awareness or capacity to react to the flooding (Trust.org, 2016). Clearly, and despite planning efforts, there remains today a missing link between local capacity to respond and government-level policy action.

Key NGOs operating in the area are helping to bridge this gap, build local capacity, and involve citizens in flood management and response. Building Resilience and Adaptation to Climate Extremes and Disasters (BRACED) has a program titled "Live With Water" that helps urban Senegalese to adapt to flood conditions safely and even use water to expand their livelihoods by launching small agricultural enterprises (BRACED, 2016). The participatory engagement the



authors propose to support our flood vulnerability assessment would also strive to close this policy gap by working to connect people with data to help them lend their voice to the decisions being made around flood resilience.

In order to ensure Cloud to Street is using the best physical and social risk data, it is necessary to engage with stakeholders across the area being mapped in Senegal. Determining the physical extent and frequency of flooding events in Senegal is not the only critical input for decision-making by government, NGOs, and other planning entities; it is also critical for these decision-makers to understand the ways that people react to floods and are vulnerable because of their social standing. In addition, as described in Chapter 3, flooding in Senegal does not affect every community in the same way. To fully understand flood risk, it is critical to analyze both the social and biophysical risk in areas affected by flooding and be able to quantify and qualify social vulnerability indicators appropriately.

### III. Methodology for Participatory Stakeholder Engagement

The participatory component of our vulnerability assessment would engage flood vulnerable populations in Senegal and include two kinds of interactions. The goal of these interactions is first to help verify or “ground truth” the spatial extent of the country’s past floods through digital and in-person engagement. The ultimate ambition of this goal is an online crowdsourcing tool that enables local communities to effectively refine the training inputs for machine learning based flood vulnerability assessments in their community, and improves the underlying algorithm overall. Secondly, multi-stakeholder engagement events will be aimed at building capacity in the digital platform, garnering feedback on social drivers of risk, and giving local partner organizations the ownership to carry flooding risk lessons into the future. These two components to the engagement strategy – digital tool and in-person workshop – work together to both improve the accuracy and precision of flooding vulnerability maps themselves, spread awareness of risk amidst affected populations, and facilitate increased adaptive capacity at the local level.

Through these two kinds of interactions, the authors aim to garner ground-level feedback and make adjustments to their data validation interface and flooding maps. In addition, these interactions would allow local partners to learn the flood vulnerability science and risk specific to their community. As a stand-alone tool, the power of a technical vulnerability assessment is small compared to the potential of empowering local decision-makers with access to big data and computing power in order to tailor their own tool-building in ways that the authors believe have the potential to transform disaster management. Once trained through the interventions described in this chapter, local citizens/stakeholders can continue to contribute to the assessment after the official project is complete.

Recommendations and options for the twin components listed above are described below. The first steps in stakeholder engagement are site selection and an outreach plan to engage the right people. After these are complete, multi-stakeholder in-person workshops will be conducted in each site and a digital feedback method/user interface for flood extent updates will be launched and monitored over time. In addition, Cloud to Street will develop a user interface for digital data collection to integrate the new data collected into the existing assessment and deploy this via the stakeholder workshop and other external methods. For more detail on this digital tool, see Section 5.3.1.

## 1. On-line Participatory Digital Flood Map Verification Tool

The flood vulnerability assessment for Senegal, described in Chapters 2b, 3 and 4, relies on the fidelity of large data sets spanning remote sensing and census information. In addition to utilizing available data from the cloud, Cloud to Street intends to draw on crowd-sourced flood observations from mobile devices and/or computers to automatically update the assessment over time. In addition to the in-person workshops, a digital interface tool will be utilized to gather widespread data on the areas that flood in Senegal. This tool would allow citizens to answer the question: “does/did this area flood or not?” in order to validate the mapped predictions and keep training the data to be more accurate, thus leading to more accurate understanding of past floods and prediction of the floodplain. As mentioned above, this tool would be utilized in the workshop setting as much as possible. The platform will also be designed with an eye towards scalability so that the authors can replicate the pilots proposed in this chapter as easily as possible.

To support this data collection tool, the authors will be working with digital visualization and user experience design firms (such as Development Seed) to explore user interfaces that are appropriate for such data validation in the context of Senegal. The data validation tool could fall at one or multiple points along a spectrum of complexity – from a simple text yes/no to a more complex mobile application to a website. The aim will be to keep the technology used as well as the application itself as simple as possible to accommodate high and low tech users. It will be critical to test this tool in the field during its development (before rollout) as well as garner feedback during its use and make adjustments as necessary.

The goal will be for utilization of this tool across all areas of Senegal prone to flooding. The data from the tool will be most valuable if the tool is understood by the users, utilized in a timely and accurate manner during and after flooding events, and if the users are located throughout the flood-prone areas of the country. The workshops’ training-of-trainers approach can help facilitate these processes, but the workshops themselves will not be able to recruit users from all flood vulnerable areas. Cloud to Street could work with AFD and other partners to utilize existing networks as well as Facebook and other digital outreach tools to spread the use of the tool. However, no matter how a user is introduced to the tool it is important for users to understand the importance of both reporting the information and reporting it correctly. Therefore, there would need to be easily understandable guides that explain the tool’s use as well as a training-of-trainers with other potential recruiters.

As they are collected both at the workshops and over time, these data would be combined into a final web map showing both physical and social vulnerability to flooding. The user interface would enable automatic updates to not only the physical map of flooding extent (i.e. are the flood contours correct?), but also eventually to the social vulnerability layers (i.e. are the demographics of this area represented correctly in the analysis?) through addition of separate questions in the future.

## 2. Workshop Site Selection

A sample of communities (towns within specific *arrondissements*), representing the spectrum of flood risk in Senegal and/or the demographics and socio-economic profile of its population, will be selected for workshop and digital engagement. Using the socio-physical flood vulnerability risk index from this report and the demographic data provided to us by the Agence Nationale de

la Statistique et de la Démographie du Sénégal, the sites can be selected to represent one or more of the categories listed below:

Most vulnerable *arrondissements*: Where are the areas that are most at risk from flooding (physical, social, and both) – both historic and current/future?

Highest vulnerability and lowest vulnerability locations: choosing a mix of high- and low-vulnerability locations based on past flooding events will allow for some comparison of responses.

Representative of Senegal's demographic and physical makeup: choosing a variety of terrain, location, poverty level, urban/rural makeup, etc. to represent Senegal as well as possible across all participatory data collection sites.

We propose piloting the effort in six communities in order to test the method before scaling up. The initial pilot is described in the section below. Further consultation with local partners in Senegal and with AFD will be necessary to determine which sites will be included in the eventual participatory engagement effort.

Success in implementation will depend on many factors such as rate of participation. To recruit the right participants and ensure the interventions are culturally relevant and appropriate, the implementers should plan each interaction in collaboration with local organizations that are familiar with the communities and have existing projects and trust relationships with community members (e.g. BRACED, Red Cross, the UN's World Food Programme).

### 3. In-Person Workshops

#### 1. Audience and Stakeholder Analysis

To determine the audience for the workshops and craft a participant invitation list, a comprehensive stakeholder analysis should be completed for the community. Cloud to Street would work with AFD and local partners to complete this analysis, asking for key local community groups, community leaders, local and national NGO representatives, and community members representative of a broad demographic. It is critical when analyzing stakeholders participation that local norms and power dynamics are taken into account so that all members of a community are actually represented. For example, it may be the case that one gender or social group has a more dominant place in the community, and reaching other social groups may take some creativity. This was the case in reaching women in the Nepal example cited above in Section 5.1 (Nepali Red Cross, 2009).

The result of this stakeholder analysis will be a stakeholder list or tracking document. This could include information for each stakeholder, such as the individual or group's name, the contact person and contact information, how the stakeholder could contribute to a workshop, whether there are any key considerations to keep in mind, how influential the stakeholder is over other potential participants, and the strategy for inviting the stakeholder to participate in the workshop(s). Such a tracking document is sometimes called a stakeholder map because it can show connections between the various stakeholders and stakeholder groups. Keeping this tracking list as simple as possible and utilizing a list format that is prevalent in many office scenarios (such as Microsoft Excel or Word) will make it easier to collaborate with local community groups in gathering this information and to maintain this information in the future.

After initial stakeholder audience research is complete, an invitation to participate in the workshop can be sent far in advance, through local community organizations and leaders. This can include the proposed agenda and outcome of the workshop itself, demonstrating the value-added to the participants.

## 2. Goals and Activities

One Participatory, multi-stakeholder, workshop will be conducted at each site during the course of the project process. Each workshop will be a first engagement and will lay the ground work for future digital or in-person interventions conducted by Cloud to Street or their partners. As such, the workshop will set up the data validation process and serve as an opportunity for training and strengthening of local partnerships. The format of a workshop can be adjusted to the context as needed based on stakeholder availability, anticipated attendance numbers, and participants' level of prior experience with mapping and/or participatory planning. These adjustments should be made in consultations with local community leaders.

The workshops would draw upon elements of focus group interviews and participatory mapping. Some questions that are general to the region or country can be asked of all participants to gain insight into demographic trends and risk to floods. In addition, activities that utilize maps and other visual tools in a hands-on manner can allow participants from across different education and language capacities to contribute meaningful information on the flood risk in their communities. And, finally, there can be activities that train the participants on how to use the interface of the digital tool that will collect information on the physical extent of flooding. Specific activities and the best communications tools to be utilized during the workshops can be determined in cooperation with AFD and in-country partners.

The goals for the in-person participatory stakeholder engagement workshops and a few design options for practically achieving that goal are detailed below:

**Primary Goal - Data collection:** collect data on social and physical flood vulnerability in the community. This information could be gathered through one or more of the following: map validation, participatory GIS, or focus group interview activities during an engagement workshop:

**Charrette-style map validation:** Present a printed copy of the machine learning flooding information map from Cloud to Street to local partners and community members. Encourage community members to mark the map with areas that are correctly shown vs. areas that lack flooding vulnerability data. Record feedback via note-taking and saving and georeferencing the map copies.

**Potential participation:** 10-40 community members and local partner organization representatives.

**Data Output:** Confirmed pixel location of historical flooding areas, identification of floods or non-flooded areas that Cloud to Street was previously unaware of.

**Additional Output:** Increased community ownership over spatial information, relationship-building between community members and partners and with Cloud to Street, and increased risk awareness for community participants.

**Example:** In Indonesia, participatory mapping and map validation has been used to help communities communicate spatial information to the government, including the boundaries of conservation areas. The process of participatory community mapping has helped resolve land ownership disputes and bring community members together (IFAD, 2009).

**Participatory GIS:** This builds on the previous activity. Participatory GIS can take place through in-person map drawing by community members in a workshop/group scenario and/or through a tour of the community with several local residents and partners with a printed map, digital map or GPS unit to mark areas that were flooded. If the latter option is chosen, a small group is preferable.

**Potential participation:** 2-10 community members and local partner organization representatives.

**Data Output:** Confirmed pixel location of historical flooding areas, identification of floods that Cloud to Street was previously unaware of.

**Example:** In 2011 in Gorakhpur, India, a facilitation team working with the Asian Cities Climate Change Resilience Network helped community members map areas in town prone to flood risk by using GPS handheld devices and satellite imagery printouts of the area. The points were then aggregated by the team and input into an overall hazard map for the city (Singh, 2014).

**Focus group-level participatory risk assessment and/or interviews:** This exercise is intended to include not only physical flooding risk, but also capture information on social vulnerability. Focus groups of 10+ people can participate in interviews where facilitators ask specific questions, or they could be group participatory risk identification exercises where people identify and rank their risks from flooding. Questions could be tailored to flooding in particular and could help identify and validate social vulnerability indicators.

**Potential participation:** 10-40 community members and partners.

**Data Output:** Identification and validation of social vulnerability indicators, understanding of the thresholds for measurement for these indicators.

**Additional Output:** Increased relationship-building and risk awareness/sharing within community participants.

**Example:** The Climate Change Collective Learning and Observatory Network in Ghana completed participatory risk assessment where participants, grouped by age and gender, were asked to elicit the various problems they face at the community level (free listing), write or draw them on index cards, then rank them, by order of importance, and score their severity or harm to wellbeing and livelihoods (CCLONG, 2009).

**Flooding map validation interface training:** As detailed in Section 5.3.3 below, Cloud to Street will work with other partner organizations to develop a simple user interface that can be used on a mobile device to validate the extent of physical flooding. This tool can be incorporated into the implementation of activities 1 and 3 above and the workshops can be used as a training-of-trainers for those community members who are willing/able to use such an interface to validate flooding in real time in the future.

**Potential participation:** Unlimited community members and partners.

**Data Output:** Confirmed pixel location of historical flooding areas, potential real-time updates during flood events.

**Example (of the interface):** In the US, the National Oceanic and Atmospheric Administration (NOAA) administers the iPhone and Android app “mPing,” that allows citizens to submit local precipitation reports in real-time storm events. This validates and supplements NOAA’s weather report data (“NSSL Projects,” n.d.).

**Secondary Goal:** Develop ongoing relationship with workshop participants and local partners. The success of community engagement work and participatory data collection depends on the strength of Cloud to Street’s relationships with local partners. A primary goal for the workshops, especially at the outset of this project, will be to establish and maintain relationships with organizations and individuals identified as key stakeholders – not just for Cloud to Street, but for local government entities as well.

In addition to these primary and secondary goals, Cloud to Street aims to further the following when planning in-person community engagement and participatory activities, as possible:

**Raise community risk awareness and build resilience.** This can be accomplished through scenario-planning activities or games (CARE, 2011; Tompkins, Few, & Brown, 2008) that engage workshop attendees and potentially the wider community in flood-risk awareness and safety training.

**Facilitate local solutions and community preparedness, utilizing methods of community-based disaster risk reduction.** Community-based disaster risk reduction activities focus on capacity building, elevating community awareness of risk, and being inclusive of vulnerable people (Pandey & Okazaki, n.d.). In this context, activities can include alerting local partner organizations of small grant application opportunities, helping train local partner organizations to carry out similar workshops, and working with larger NGO and government partners to facilitate complementary events on disaster risk management during/around the time of these workshops.

**Support community empowerment and inclusion in the regional and national disaster risk management planning process.** Utilizing stakeholder relationships fostered through this participatory process, Cloud to Street and their partners can connect local communities with national-level decision-makers planning for disaster risk reduction so that their specific vulnerabilities are known. In addition, training local and national partners on big data technology and the design and use of the data validation tool will help further this goal.

## IV. Next Steps and Follow Up

### 1. Tracking Success

Effective stakeholder engagement and participatory science efforts rests on a sound foundation of research, communication, and partnership. The success of the workshops and the data validation tool hinge on the strength of local partnerships, the ability to understand community dynamics and encourage key stakeholders to participate, and the clear communication of the goals of Cloud to Street and AFD’s work. In short, the success of the workshops and the utility of the tool will depend on the level of stakeholder buy-in and participation.

If conducted, the authors would assess the components of this project based on the data collection/validation goals set forth in Section 5.3. The participatory workshops will be successful if Cloud to Street is able to comprehensively validate and collect physical flood extent data and discuss necessary adjustments to social vulnerability indicators for the six workshop sites. During the events themselves, success can be measured by not only the number of people that participate, but also the quality of interaction. Particularly for the workshops, Cloud to Street can be adaptive on the ground and consistently solicit and capture feedback about what went well and what could be changed from local partners and participants. Cloud to Street plans to be adaptive and change the workshop invitees and format between workshop sessions (and during, as necessary) based on this feedback. For example, if there were too few participants at one workshop, additional outreach may be necessary preceding the next event.

With the data validation tool, success can be measured by rate of adoption as well as the quality and relevance of the data collected, and if it increases accuracy of the machine learning model. This success will depend on whether the goal of the tool is understood by the users and utilized in a timely and accurate manner during and after flooding events. Understanding the margins of error for this action will be helpful for determining the success of the data validation tool.

## **2. Overcoming Barriers to Success**

The success of the in-person workshops and online tool depend on the stakeholder engagement effort's ability to reach the appropriate audiences and build trust. Language barriers are a potential hurdle and translation assistance will be necessary for both workshops and the data validation tool. In addition, potential demographic differences between sites could hinder success and should be considered at all stages of planning and implementation for both the workshop and the data validation tool. For example, in urban areas of Senegal, large portions of the population live in unplanned informal settlements (Diagne, 2007, p. 553). If urban sites are chosen for workshops, different outreach strategies or workshop activities may be necessary to understand the social vulnerability landscape via workshop feedback. In addition to demographic and geographic differences, Cloud to Street and partners will need to maintain awareness about cultural definitions of vulnerability and risk that may vary for each community.

For the data validation tool, understanding the online/offline divide will be critical to success. How many people have access to what technology? Providing clear training on the tool's use as well as testing to make sure it is designed with the capacities of the user(s) in mind will help avoid potential challenges.

Working with local partners and key stakeholders will help clarify these and other potential challenges and keep such considerations at the forefront of project planning. The project team will need to be adaptable over the course of the project to be able to document and respond to these differences and adjust products and outcome indicators accordingly.

## Conclusions: Next Steps

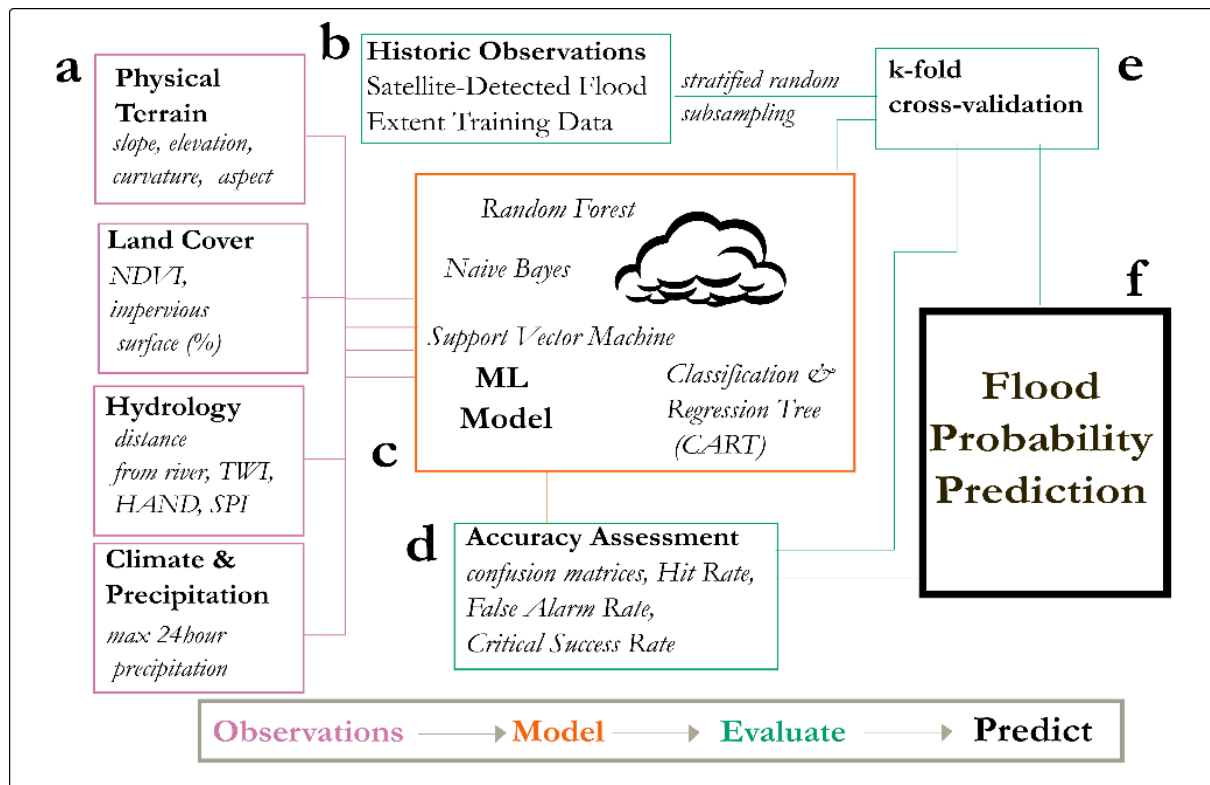
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Cloud to Street is committed to coupling innovations in participatory stakeholder engagement on the ground with innovations in digital mapping in the cloud and finding ways to scale the two together in a way that leaves no one behind. In addition to improving vulnerability information this project seeks to increase the overall resilience and adaptive capacity of vulnerable communities identified here, as well as enable improved equity and ownership in disaster risk management in Senegal moving forward. While this project is centered around flooding risk, many other disaster events and risks to human health and safety can be considered when providing basic risk assessment or emergency response training during a workshop, or have the opportunity to be included in the future as variables measured using the data validation tool interface. Cloud to Street seeks to actively think about the potential co-benefits of its activities in stakeholder engagement and participatory flood risk mapping, and work with communities to help them be able to continue this kind of monitoring in the future, after Cloud to Street's project work has come to a close.

Cloud to Street is at the forefront of real-time vulnerability mapping, harnessing the significant amount of spatial data now available for risk management on the ground. One of the great advantages of big data like satellite imagery is that it is easier than ever to scale such analyses for anywhere in the world. However, looking at the earth from above shows only half of the picture. Connecting satellite data to the people that are most vulnerable is a challenging step, but a necessary one in order to ensure equitable risk representation and paint the true picture of what is happening on the ground.



# Appendix



**Figure A1: Model structure and overview showing the key steps involved in creating floodplain maps.**

**Table A1: Flood Conditioning Factors Matrix:**

The following matrix describes major variables used in our predictive flood model. The authors chose well-established variables as inputs in order to be able to compare our performance with process-based models. Each dataset described below is natively available in the Earth Engine platform or calculated from datasets available in Earth Engine, with the exception of (3) Senegal Water Lines (NGA, 2015) and (13) Global HAND (Donchyts, Winsemius, Schellekens, Erickson, Gao, Savenije, & van de Giesen, 2016).

Factor	Global Dataset	Method & References
Precipitation (mm)	NOAA PERSIANN-CDR 0.25 degrees (Ashouri et al., 2015)	Precipitation summed for the duration of the flood
Impervious Surface (%)	2009 ESA GlobCover 300 m (Bontemps et al., 2011)	
Distance from River (m)	Senegal Water Lines (NGA, 2015)	$d_{x,y} = \sqrt{\sum_{j=1}^J (x_j - y_j)^2}$ <p>where x and y are vectors of coordinates and d is Euclidean distance between two points.</p>
Topographic Wetness Index (TWI)	WWF Hydrosheds 15 arc-second Flow Accumulation (Lehner, Verdin, & Jarvis, 2006)	TWI= $\ln(a/\tan\beta)$ where $\beta$ is local slope in radians, a is the upslope catchment area (Beven & Kirkby, 1979).
Stream power index (SPI)		Erosive power of stream, energy dissipation $SPI = As \tan \beta$ As is the catchment area (m <sup>2</sup> ) $\beta$ is the local slope gradient (degrees) (Florinsky, 2012)
Local Slope (degree)	SRTM (30 m) (Farr et al., 2007)	Local slope informs overland and lateral flow velocities (Moore et al. 1991)
Elevation (m)		Local elevation informs climate patterns, vegetation communities (Moore et al. 1991)
Curvature		The second derivative of the slope (Farr et al., 2007)
Height Above Nearest Drainage (HAND)	Global 30 m Height Above Nearest Drainage (Donchyts, Winsemius, Schellekens, Erickson, Gao, Savenije, & Giesen, 2016)	Digital elevation model normalized to nearest streamline.
Normalized Difference Vegetation Index (NDVI)	Landsat 7 ETM+ 30 m	(Near Infrared (NIR) - Red) / (Near Infrared (NIR) + Red) bands from Level L1T orthorectified scenes radiometrically corrected to TOA reflectance (Chander, Markham, & Helder, 2009)

**Table A2: Arrondissements, Departements, Regions and River Valleys modeled using machine learning.**

River	Region	Departement	Arrondissements
Senegal River	Matam	Matam	Agnam Civol
			Ogo
	Saint-Louis	Saint-Louis	Ndiaye Mberess
			Rao
Saloum River	Fatick	Fatick	Fimela
			Ndiob
		Foundiougne	Diofor
			Djilor
	Kaolack	Kaolack	Koumbal
			Ndiédieng
Ngothie			
Casamance River	Sédhiou	Boukiling	Bona
		Goudomp	Djibanar
		Sédhiou	Djibabouya
			Djiredji
	Ziguinchor	Bignona	Kataba 1
			Sindian
			Tendouck
			Tenghory
		Oussouye	Cabrousse
			Loudia Ouolof
		Ziguinchor	Niaguis
			Nyassia
Dakar	Dakar	Almadies	
		Dakar Plateau	
		Grand Dakar	
		Parcelles Assainies	
	Guediawaye	Guediawaye	
	Pikine	Niayes	
		Pikine Dagoudane	
		Thiaroye	
	Rufisque	Bambylor	
		Rufisque	

**Table A3: Performance metrics for each of the four algorithms for the September 2012 flood in the Saint-Louis region comparing the MODIS versus Landsat-based training imagery.**

Total modeled floodplains (risk areas) were calculated by summing pixel area of all pixels identified as flooded in any of the ten trials. High risk floodplains were identified by selecting all regions marked as flooded across all ten folds of cross-validation.

	Hit Rate*		Specificity**		False Alarm Rate		Critical Success Index		Overall Accuracy	
	MODIS	Landsat	MODIS	Landsat	MODIS	Landsat	MODIS	Landsat	MODIS	Landsat
<b>CART</b>	0.98	0.98	0.76	0.65	0.24	0.35	88.48	84.43	0.87	0.82
<b>NB</b>	0.52	0.15	0.81	0.82	0.20	0.19	60.35	22.72	0.67	0.48
<b>RF</b>	0.97	0.89	0.86	0.77	0.14	0.24	92.14	83.59	0.92	0.83
<b>SVM</b>	0.60	0.60	0.68	0.41	0.33	0.59	62.14	54.72	0.63	0.51

**Table A4: Comparing modeled floodplains between the September 2007 (DFO #3180) and the August 2003 (DFO #2315) seasonal floods.**

While model accuracies (not included) do not vary drastically between events, the high risk flood areas and total exposed population predictions are clearly sensitive to interannual variability.

	Area Analyzed (km <sup>2</sup> )	Total Risk Area (km <sup>2</sup> )	Percent in Predicted Zone (%)	High Risk Area (km <sup>2</sup> )	People at Risk
<b>Matam 3180</b>	5,135	1,051	20%	114	38,400
<b>Matam 2315</b>	5,135	802	16%	101	41,330
<b>Fatick 3180</b>	3,162	1,085	34%	528	17,038
<b>Fatick 2315</b>	3,162	781	25%	307	7,801
<b>Kaolack 3180</b>	1,906	204	11%	89	2,109
<b>Kaolack 2315</b>	1,906	221	12%	45	774
<b>Saint-Louis 3180</b>	3,990	1,399	35%	523	8,208
<b>Saint-Louis 2315</b>	3,990	1,267	32%	285	10,616
<b>Dakar 3180</b>	559	0	0%	0	0
<b>Dakar 2315</b>	559	0	0%	0	0
<b>Ziguinchor 3180</b>	7383	1,616	22%	349	31,754
<b>Ziguinchor 2315</b>	7383	1,494	20%	282	30,224
<b>Sédhiou 3180</b>	2,855.81	241	8%	39	4,426
<b>Sédhiou 2315</b>	2,855.81	122	4%	5	1,630

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<b>Technical Reports n°16</b>	Supporting Access to and Retention in Employment for Women by Enhancing Child Care Services in Turkey
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**Notes techniques n°23**

Évaluation de la politique d'aménagement du territoire en Tunisie de 1995 à 2010

**Technical Reports n°24**

Cocoa farmers' agricultural practices and livelihoods in Côte d'Ivoire

## What is AFD?

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Agence Française de Développement (AFD), a public financial institution that implements the policy defined by the French Government, works to combat poverty and promote sustainable development.

AFD operates on four continents via a network of 75 offices and finances and supports projects that improve living conditions for populations, boost economic growth and protect the planet.

In 2015, AFD earmarked EUR 8.3bn to finance projects in developing countries and for overseas France.

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