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Mapping Flood Risk Using Sentinel-1 Data: A Case Study of Niamey, Niger

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Abstract

Flood events are recognized to be one of the most among the most catastrophic disaster in the world, with a consequential loss of lives, goods, and services. Factors such as rapid urbanization, lack of proper infrastructure development, insufficient consideration of the environment, and the effect of climate change have made floods even more destructive, particularly for developing countries that lack the means to respond appropriately during such events. The impacts of flood disasters on people and the local economy are more severe in urban areas than in rural areas. Niamey has experienced frequent devastating flooding events in recent times, particularly in 2020. For this reason, producing a flood map for Niamey is crucial to see which places will be affected. This study aims to map potential flood areas after the 2020 flash flood using unsupervised classified sentinel 1 SAR images from the European Space Agency. For the research purpose, we used the Digital Earth Africa Sandbox platform to get and analyze the result. The inundated area map demonstrates that the flood affected approximately 149.541 km^2, the Built-up area highly prone to flooding: 18.325 km^2, the cropland area highly prone to flooding: 26.252 km^2, the Built-up area medium prone to flooding: 79.318 km^2, Cropland area medium prone to flooding: 13.26 km^2.

Keywords: flood map, sentinel-1, remote sensing, Digital Earth Africa, Niamey

INTRODUCTION

The world is facing increasingly extreme weather events such as heat waves, cyclones, droughts, and floods due to climate change. A recent IPCC Special Report 2021 (Pörtner et al., 2022) shows that human activities have caused global warming of approximately 1.0°C above the pre-industrial level. These phenomena negatively affect the environment and people's livelihood, particularly marginalized groups in the poorest regions, even though they are the least responsible for these changes [1–4].

Extreme flooding was becoming an essential issue for developing Sahelian countries. During the last 20 years, many authors said there are increasing floods and flood-related impacts in West Africa [5–9]. In a study conducted the authors examined flood trends across 11 catchments and discovered a notable rise in flood magnitude and frequency in the Sahelian region. Similarly, identified positive trends in flood magnitude and its correlation with the number of people affected in the Sahelian area of the Niger

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River Basin [2]. In a separate study a significant increase in flood events and associated damages in Niger, especially in the Tillabery, Niamey, and Dosso regions [10]. More recently, also investigated the flood trends in the same region [11].

The analysis of official data collected by the government on damages from 1998 to 2017 demonstrated increased flooding nationwide in Niger [12–19]. Approved that, regarding the regional and sub-regional impacts of flood, the southwestern areas of Niger were found to be most exposed to flood risks [20–25]. In the last two decades, the scientific community has predominantly directed its attention toward the alterations in the flood magnitude of the Niger River. The primary aim of these studies is to comprehend the current changes in the hydrological attributes of the river and to investigate the principal factors responsible for the escalated flooding incidents in the region. However, the Niger River is only one of the causes of flood risk in Niger, and most events are unrelated to river dynamics [26–30].

In late September 2019 that 16,375 houses had been destroyed, and 211,000 people were involved, in particular in the three regions of Zinder (80,534 people affected), Maradi (28,847), and Niamey (31,222). (OCHA 2019). In 2020, according to estimates by the Ministry of Humanitarian Action and Disaster Management, as of 07th September 2020, 432,613 people (52,404 households) have been affected by these floods. The most affected regions are respectively Maradi (135,450 victims), Agadez (96,240 victims), and Niamey (48,507 victims). Sixty-five people have died in this lousy weather (Niamey, 2020) [30]. The balance sheet also reports 36,155 houses collapsed, thousands of hectares of crops buried, and heads of cattle destroyed. The damage recorded was notably heavier in the regions of Agadez and Niamey, which previously were not among the most affected areas. In Niamey, the capital, the raging waters invaded the neighborhoods bordering the Niger River (Lamordé, Karadjé, Zarmagandey) as soon as the protective dike separated the river from these neighborhoods gave way following the torrential rains of Saturday, 05th September 2020.

Mainly two types of flooding are distinguished: First, flash floods occur every rainy season in some neighborhoods. Due to violent downpours, these floods often cause significant damage. The most exposed communities are those of Commune 5, particularly the informal sectors of Zarmagandey, Karadjé-Ganda, and Nialga. Kirkissoye. In Niamey 4, the most affected localities are Saga. Gamkalley and Tondigamey.

Then slow floods are due to the river's overflow from its minor bed. This type of flooding often occurs during the dry season. This river flooding is linked to water coming from Guinea and Mali. It can also be devastating through its effects on houses, especially rice fields. This flood, unlike the previous one, concerns residents of the river and those located in its backwaters. These are mainly the Kombo and Saga neighborhoods on the left bank and the informal sectors of Zarmagandey, Lamordé, Karadjé-Ganda, Nialga, and informal Banga-Bana on the right bank. During January and February, there is an annual rise in water levels spread over several months and can generate violent floods.

Niamey, a city situated on the banks of the Niger River, is susceptible to flooding due to the two flood peaks—the red flood and the black flood—in the middle basin of the river. In 2020, Niamey experienced the highest water levels ever recorded in the Niger River after a season of heavy rainfall. However, the city has faced widespread flooding over the past decade, indicating a shift in hydroclimatic patterns that were first observed after the significant droughts of the 1970s and 1980s—this phenomenon is referred to as the Sahelian Paradox. The overflow of the Niger River affects Niamey, which is reaching increasingly high levels, causing recurrent flooding of built-up and cultivated areas, thus affecting thousands of people. But river floods are not the only hydrological risk in Niamey, as flash floods are also recurrent, mainly due to weak drainage systems and lack of maintenance.

To overcome the flood disaster, researchers and scientists attempted flood mapping, opening the way with a flood vulnerability map that estimated the population and the major equipment exposed to flooding. At least three river flood event maps followed, which identified the flooded area and the flood depth (ABN/CRA 2007). Tiepolo and Braccio (2016) used historical data and scenarios for flood risk preliminary mapping in Niamey and didn't consider the Digital Elevation model DEM at 30 m [25].

Published information about flood mapping using sentinel-1 data in Niger is very scarce. To contribute to flooding risk attenuation, this paper seeks to identify the extent of the flood disaster in the area.

STUDY AREA DESCRIPTION

Niger has an area of 1,267,000 square kilometers (490,000 square miles) and seven countries border. Niger is a landlocked country situated in the heart of the Sahel region, which is a transitional zone between the tropical coast of West Africa and the Sahara Desert. It is between 11°65' and 23°55' N and 0°200 E and 16°00' E. Three zones compose the country: (i) Niger can be divided into two major zones—the northern region, encompassing over half of the country, which is primarily located in the Sahara Desert and receives rainfall of less than 200 mm; (ii) the central part, known as central Niger, which is a semi-arid area within the Sahel region with annual rainfall between 250 and 600 mm. This region is predominantly used for pastoral activities. (iii) the southern part of the country, which is where communities practice rainfed agriculture with a mean annual rainfall that rarely exceeds 800 mm (Comité Interministériel de Pilotage de la Stratégie de Développement Rural Secrétariat Exécutif, 2004; Fiorillo et al., 2018). In the central and southern regions of Niger, the growing season typically lasts for 3 to 5 months, followed by an extended dry period of 7 to 9 months. Rainfed agriculture is a widely adopted farming technique, with millet being the primary cereal crop, followed by sorghum. The Niger River is the major river of the country, flowing through the southwestern region. Its seasonal floods provide the opportunity for recessional and irrigated farming along its banks. The economy of Niger is predominantly based on subsistence rain-fed agriculture and animal husbandry.

The city of Niamey is located between 13°28 and 13°35 north latitude and 2°03 and 2°10 east longitude (Figure 1). It has five communal districts with an estimated population in 2020 of 1,324,670 inhabitants (INS, 2020), with an average density of 5,446 inhabitants/km^2 with a rate of annual growth of 3.6%. More than 20% of Niger's population lives in urban areas, of which nearly 40% are in the city of Niamey alone. The surface of Niamey is 255 km^2 or 0.02% of the total area of Niger.

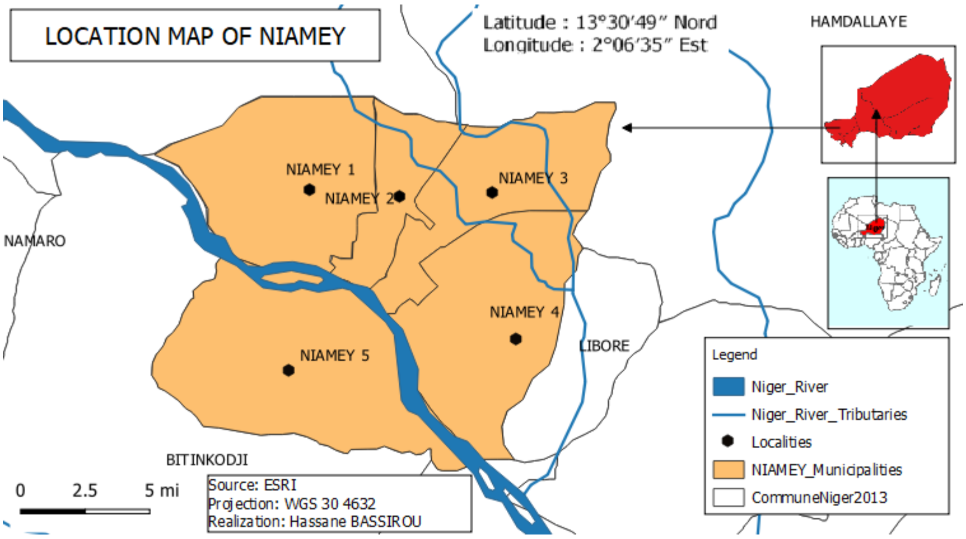

Figure 1. Location map of Niger.

The essential socio-economic activities in Niamey are administrative, agriculture, livestock, fishing, trade, crafts, and tourism. Irrigated agriculture involves rice, fruit, and market gardening grown along the river and in the Hydro-Agricultural Developments (AHA) of Saga and Kirkissey. Agricultural activities interest the men and women of the area and constitute income-generating activities, especially for the processing and marketing of products. However, the silting up of the river, the lack of pumping resources, and the lack of technical supervision are the main constraints to agricultural production.

The city is located on a plateau, providing a scenic view of the left bank of the Niger River. The right bank, on the other hand, is situated on an alluvial plain, with an elevation ranging between 180 and 250 meters above sea level. Although the river serves as the primary source of drinking water in the city, it is undergoing constant degradation due to desertification and pollution of its banks, leading to several sanitation issues.

LAND COVER LAND USE CLASSIFICATION OF NIAMEY

The land use and land cover are operated using the European Space Agency (ESA) world cover to see the unit occupation and the extent of water change (Figure 2). To have the land use and land cover through Digital Earth Africa sandbox, the (ESA) WorldCover provided a global land cover map at 10 m resolution based on Sentinel-1 data. The WorldCover project provides an 11-class land cover classification system, based on the United Nations Food and Agriculture Organization's Land Cover Classification System (LCCS). This system has been developed under the ESA WorldCover project. The United Nations Land Cover Classification System (UN-LCCS) allows for a hierarchical classification system that can be adjusted based on the available information, providing flexibility in the level of detail in the legend. It shows land unit occupation in Niamey with a significant build-up near the river flood-prone area. The vegetation comprises dry savannah and sparse bush scattered by rainfed cereals. The southern region experiences greater agricultural pressure, while the deforestation of brushland increases significantly in areas closer to settlements and urban centers.

HYDROLOGY

Two prominent flood peaks characterize the hydrological regime of the Niger River at Niamey (Figure 3). The first one is during the rainy season, July to September, where the black flow characterizes the inflow from tributaries. The second one is the flow from the upper Niger basin, whose peak arrives at Niamey during the dry season from December to January, called red flow or discharge. Thus, the flood associated with the inflows of the tributaries of Burkina is called the local

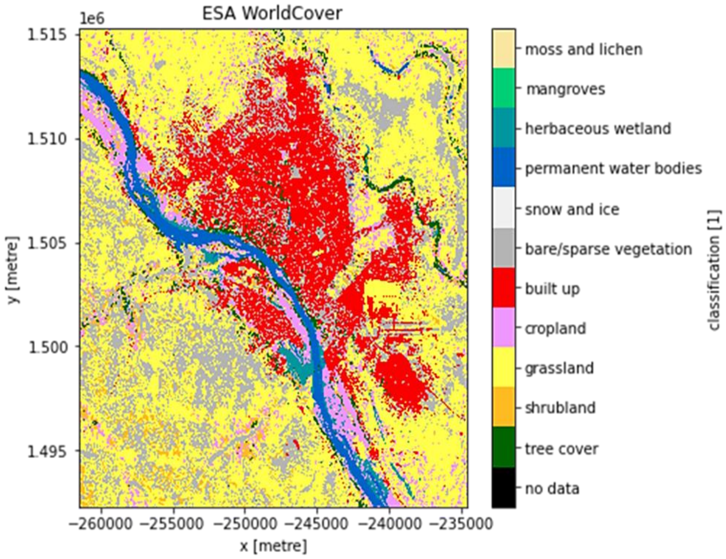

Figure 2. Land use and land cover of Niamey.

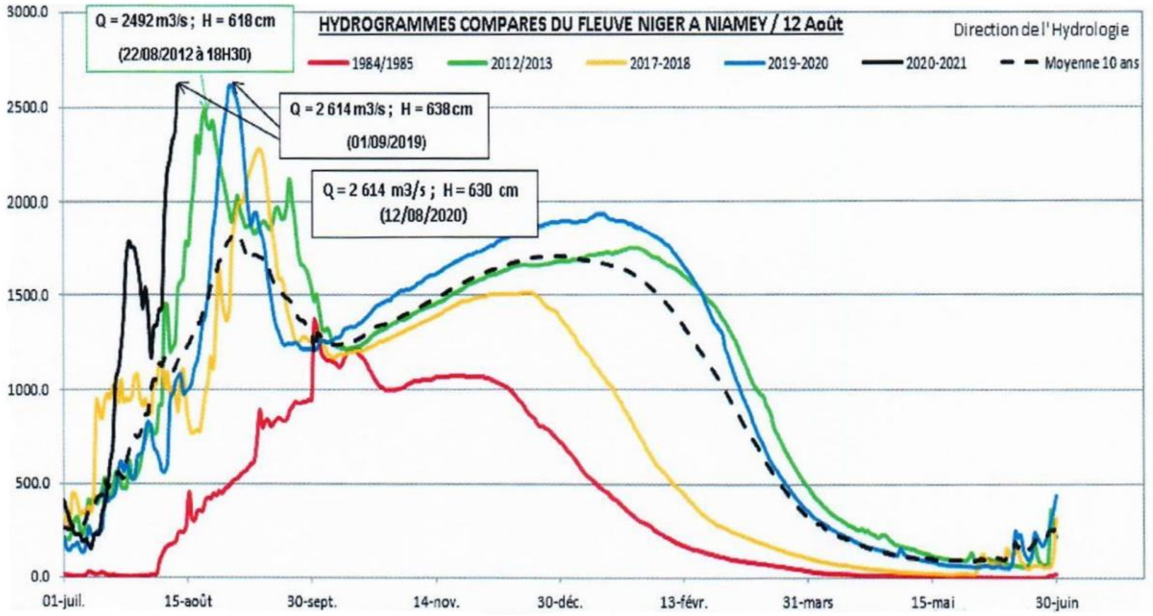

Figure 3. Hydrograph comparison of river Niger at Niamey.

flood (or black flood) because of its localized character in time and space, in contrast to the second flood called the Malian flood, which is generated by foreign inflows from the upper Niger basin: Guinea, Ivory Coast, and Mali.

The analysis of mean hydrographs in Niamey confirms the altered hydrological patterns previously noted by several researchers in the early 2000s. Additionally, the study highlights the anomalous behavior observed between 1964 and 2020 (as shown in Figure 3). Despite having similar peak magnitudes, these two flood events differed significantly in terms of flood length and duration in the red alert stage (where $Q > 2045\ m^3/s$), which led to levee breaches and collapses in the city.

The average hydrographs show that the hydrological year begins on July 1st and ends on June 31st of the following year. In Figure 3, four hydrological periods (1984–1985, 2012–2013, 2019–2020, 2020–2021) and the disastrous floods of 2012 and 2020 were analyzed. The alert thresholds for the city of Niamey with the relative flows are described in Table 1. Following the new calibration scale and the effects of flooding observed in the 2020 flood, it was possible to calculate the levels and flows the city's protective dykes can contain.

Table 1. Hydraulic hazard scenarios for the city of Niamey.

Script	**Magnitude**	**Height (cm)**	**Flow (m^3/s)**
Grey	Low water alert	0–140	0–25
Green	Normal condition	140–530	25–1443
Yellow	Frequent flooding	530–580	1443–1766
Orange	Severe flooding	580–620	1766–2045
Red	Flood catastrophic	620–750	2045–3084
Top dikes	Large floods in the city	660	2344

Source. *(Massazza, Tarchiani, et al., 2021)*

MATERIAL AND METHODS

Digital Earth Africa and Sentinel 1 Data

The methodology of this study involved utilizing Digital Earth Africa (DEA) and Sentinel 1 data. The DEA is a platform that offers a collection of Earth Observation data and analytical tools to facilitate the viewing and analysis of this data. The platform aims to translate Earth observations into useful insights that support sustainable development goals, thereby improving the lives of people across the African continent.

The platform deals with African and international stakeholders to ensure that Earth observation data is analyzed, interpreted, ready, rapidly available, and readily accessible to meet the needs of the communities. It comprises DE Africa Map, Sandbox, Notebook repository, Sentinel-1, DE Africa Metadata Explorer, and Open Geospatial Consortium (OGC) Web Services. please rewrite this part and make it plagiarism free Satellite-based flood monitoring is a powerful tool to map inundated areas and distinguish water, vegetation, and urban settlements. In this study, Digital Earth Africa sandbox used Synthetic Aperture Radar (SAR) images from the Sentinel-1 satellite, as images are available around the clock. Also, as a passive microwave sensing radar, cloud cover does not affect the images obtained. The satellites Sentinel-1A and 1B combined have a 6-day revisit frequency, which can create a near-real-time flood inundation map. The study area is the areal extent of the Niamey municipality in the Niger River basin in Niamey, Niger. This area was very badly affected during the floods of 2020. We used Digital Earth Africa (DEA) Sandbox to process the Sentinel-1 images.

The steps of data processing are shown in Figure 4. The pre-processed images have been classified using well-known classification methods, and the classification results have been evaluated to detect the flooded areas. The overall methodological workflow of the study is depicted in Figure 4, and details for each part are given in the subsequent sub-sections.

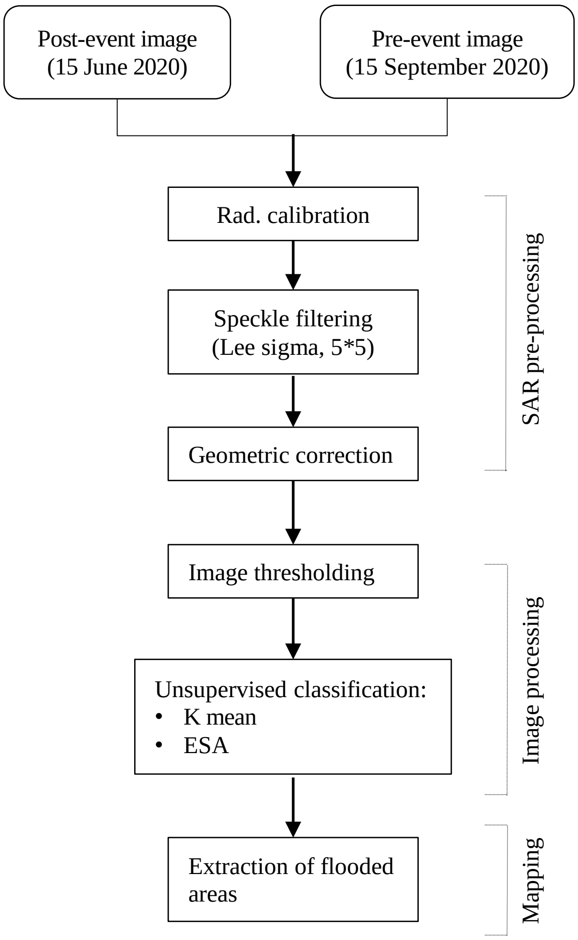

Figure 4. Flowchart of the methodology adopted from (Tavus et al., 2019) [23].

SAR Pre-processing

A step-wise procedure with radiometric calibration, speckle filtering, and geometric correction has been applied to the SAR datasets to generate calibrated SAR images. V.V. polarised images have been preferred for flood detection because they are considered more adequate than V.H. in several previous studies.

A geometric correction is needed; at this step, we applied the Range Doppler Terrain Correction algorithm to generate terrain-corrected and orthorectified SAR images. SRTM-3 and bilinear interpolation have been used as the base digital elevation model (DEM) for the correction.

Image Processing

Image Classification

The k-mean classification was used in DEA, an unsupervised classification algorithm called clusterization that groups objects into k groups based on their characteristics. The type has been applied by using three classes: water bodies, flooded areas, and others. All three classification methods were validated with the k-means clustering classification. The accuracy of the k-means clustering classification method for identifying urban areas in the study region was evaluated by comparing the results to the built area (urban area) map derived from the 2020 global land use/land cover data provided by the Food and Agriculture Organization (FAO) and the European Space Agency (ESA) World Cover dataset at a resolution of 10 meters.

Convert the Digital Number (D.N.) to Decibel values (dB). The Sentinel-1 backscatter data is provided in digital numbers (D.N.), which can be converted to decibel units (dB) by using the formula: 10∗log10 (D.N.)

When it comes to flood detection, SAR polarisation plays a crucial role. For this study, the images available during the flood had both V.V. and V.H. polarisations. However, V.V. polarisation was chosen as the preferred option due to the medium incident angle of the data, which makes the image more suitable for flood monitoring. Moreover, the same polarization (V.V.) was chosen to achieve the same co-polarisation (VV-VV) comparison that gives better results than the cross-polarisation (VH-VV).

Backscatter Distribution

Figure 5 depicts Backscatter, which is the measurement of the strength and direction of the radar signal that reflects toward the radar antenna. Backscatter can be defined as the amount of radiation that is scattered by a target and returned to the receiver in the direction of the transmitter. The process by which Backscatter is produced is called backscattering.

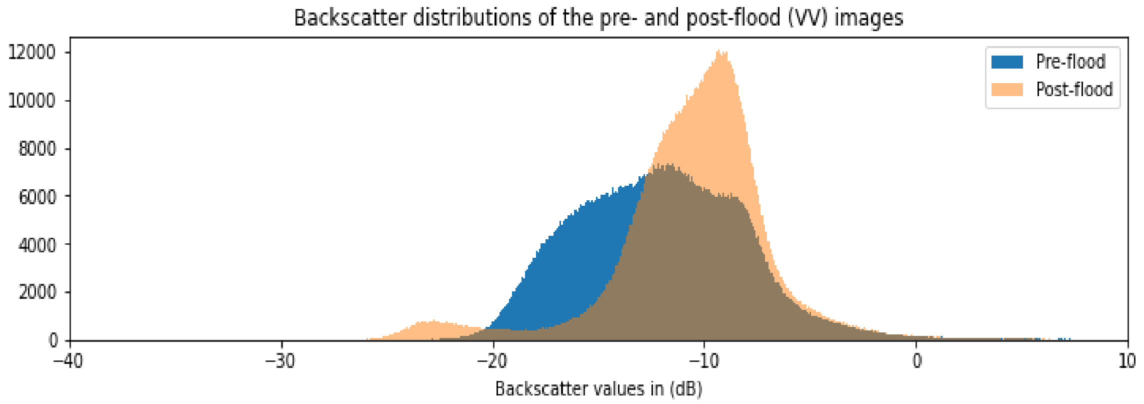

Figure 5. Backscatter distribution-21.863487 dB.

One simple and standard method for flood mapping is thresholding. Below the threshold level, the Backscatter is considered flooded land; above the threshold level, the Backscatter is regarded as dry land Image histograms are used to derive thresholds for creating a binary mask, where 0 represents land and 1 represents water. The amount of microwave radiation reflected from the ground surface is measured using a radar backscatter center that is sensitive to surface roughness, moisture content, and viewing geometry. DEA gives Sentinel-1 Backscatter like a Radiometric Terrain Correction (RTC) gamma-0 (${}_{\gamma}0$), and variation due to changing observation geometries have been mitigated.

Extraction of Flood Map

A manual selection of threshold backscattering coefficient values was used to determine open water and submerged urban areas with water. The extent of flooding was analyzed by plotting the time series of the number of flooded pixels in the images of the area during the major flood events of 2020. Flood maps were generated for pre- and post-flood events.

To generate the map, we utilized the k-means clustering technique to categorize the land into urban and non-urban areas. We then compared these results with the 2020 ESA WorldCover global land cover product for Niamey. This step-by-step procedure aims to generate a flood extent map for mapping affected areas. The method used to generate the flood extent involves analyzing changes detected in Sentinel-1 Synthetic Aperture Radar (SAR) data.

RESULTS AND DISCUSSION

The results presented aim to understand the flood extent based on the flash flood even of 2020 using Digital Earth Africa Sandbox tools. Thus, to determine and compute the flood extent the Digital Elevation Model at 30 m resolution (Figure 6) has been used. The area covered by the flood is calculated by adding up the pixels and converting the result into hectares. Figure 7 displays the resulting flood map for the study area. The criteria used are: The altitude of DEM inferior to 200 m is considered a high flood-prone area, and the one between 200 m and 2040 is regarded as a medium flood-prone area, which is used to determine the flood level.

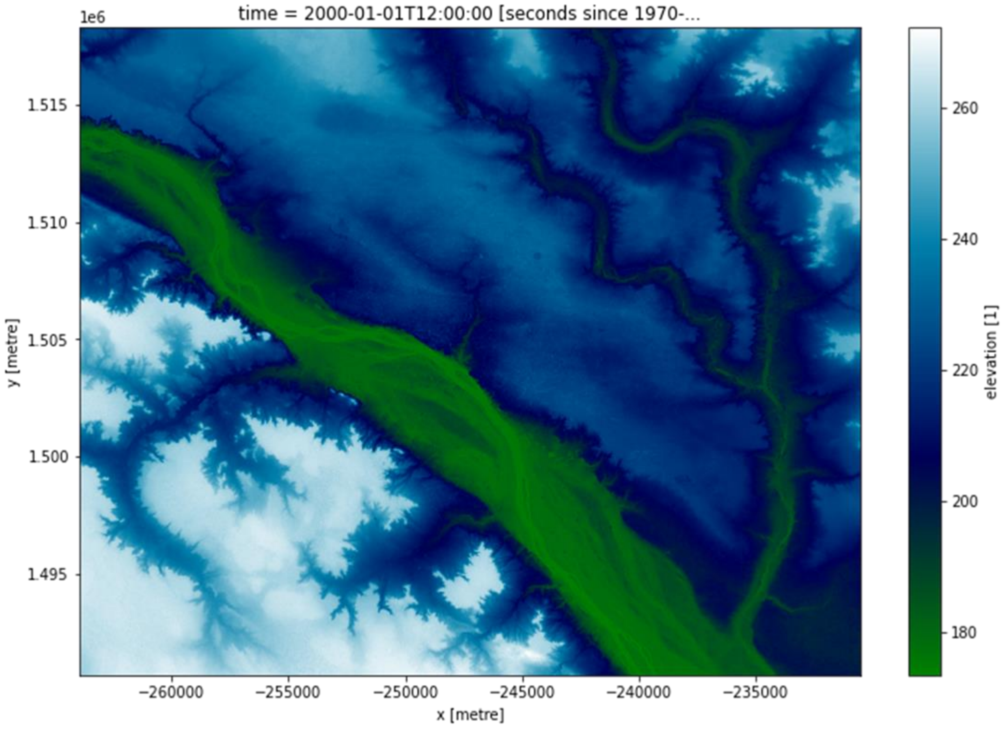

Figure 6. Digital elevation model of Niamey.

The geomorphological and geological characteristics of the Niger River Basin and the intense meandering river pattern led to flash flood phenomena in the broader area. The flood control drainage infrastructure is inadequate and certainly needs further improvements. In addition, the fact that main anthropogenic activities (agriculture and industry), extensive roads and constructions, critical facilities, and the more significant part of the city population lies in the area lead to the actuality that the flood disaster risk of the area is exceptionally high.

Several districts of Niamey are significantly affected because they are built in flood-prone areas. The right bank is located on alluvial deposits, making it more vulnerable to floods; the city's high urbanization rate has enhanced it. The Niamey 5 district, on that side, is partially in the eddies of the bed of the river Niger. Flood zones on the right bank concern the Lamordé district, Abdou Moumouni University, and the Zarmagandey-Karadjé-Saguia continuum on the left bank, the upstream section of Goudel and the downstream zone of Saga, located on alluvial deposits, are also particularly exposed to flooding.

Niger river bed silting is the fundamental cause of Niamey's increased flooding frequency. The Niger River level has been growing recently, which causes the recurrent flood of build-up and crop areas to affect many Niamey communities. The poor drainage systems and the lack of maintenance aggravate flash floods because riverine floods are not the only hydrological hazard. The high demographic rate of 3.9% and the rapid urbanization process of Niamey are likely to increase the flood exposure of communities and their settlements. The flood-prone areas are vulnerable due to high poverty levels, aggravating flood risk, and associated adverse impacts. The urbanization of the rural population following the droughts of the 1970s et 1980s created many housing difficulties. The government authorities permitted individuals to establish settlements in areas prone to flooding, either without knowledge of the risks or due to coercion. The overlapping of the recorded inundated area on the classified land cover map demonstrates that the flood affected approximately 149.541 Km^2, the Built-up area highly prone to flooding: 18.325 km^2, the Cropland area highly prone to flooding: 26.252 km^2, the Built-up area medium prone to flooding: 79.318 km^2, Cropland area medium prone to flooding: 13.26 km^2,

Built-up area unaffected to flooding: 8.724 km^2, Cropland area unaffected to flooding: 3.662 km^2 (Figure 7). By using mapping techniques, it is possible to gain a better understanding of the flood risk faced by individuals and communities. Armed with this knowledge, people can make more informed decisions about how best to reduce or manage the risk of flooding.

The MODIS Land Cover Type product has been chosen to estimate the amount of affected cropland (Figure 8). The Land Cover Type 1 band contains 17 distinct categories, including two categories related to cropland. The first cropland category, known as class 12, refers to areas where at least 60% of the land is used for cultivation. The second cropland category, class 14, describes areas where small-scale cultivation accounts for 40–60% of the land, and natural vegetation such as trees, shrubs, or herbs coexist with the cultivated land.

To analyze the relationship between cropland and flooding, the data from the Land Cover Type 1 band was compared to a flood extent layer. The flood extent layer was resampled to match the scale and projection of the MODIS layer to ensure accurate analysis. Both the cropland categories were extracted from the dataset and overlapped with the flood extent layer to identify areas where flooding has impacted cropland. The total cropland affected is 43.174 km^{2,} and the entire urban area is 106.367 km^2.

To calculate the potentially affected urban areas (as shown in Figure 9), the MODIS Land Cover Type dataset was used, following the same methodology as the previous two steps. Specifically, the 'Urban Class 13' from the 'Land Cover Type 1' band was extracted to evaluate the areas that may be affected by the disaster event. However, it should be noted that this process may underestimate the extent of affected urban areas due to challenges in detecting water within built-up regions.

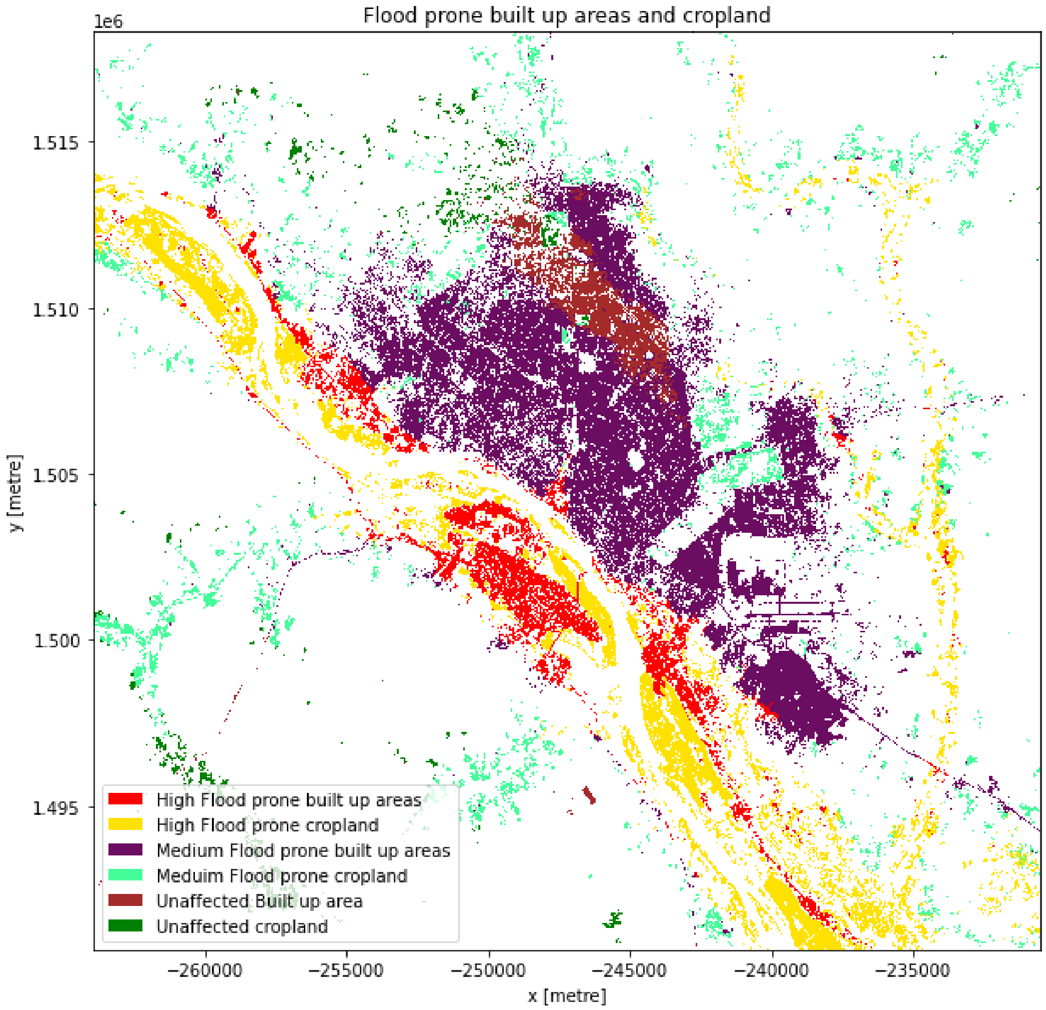

Figure 7. Flood-prone area.

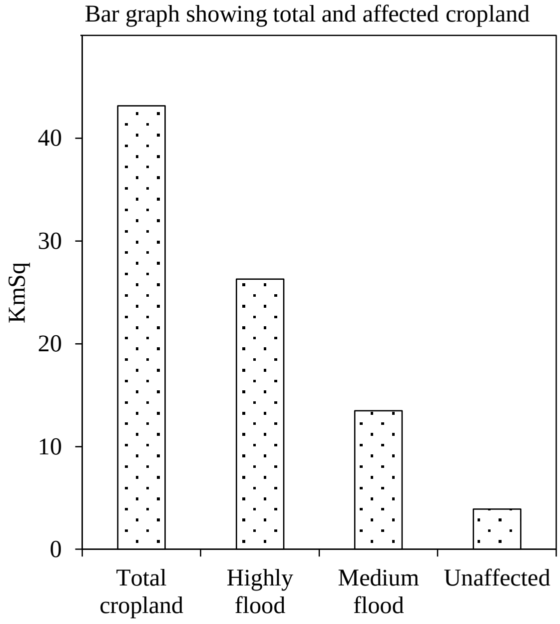

Figure 8. Total affected cropland.

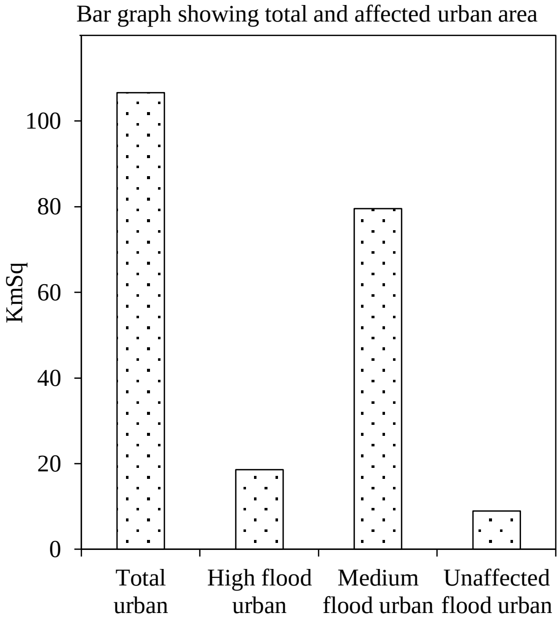

Figure 9. Total and affected urban area.

CONCLUSION

This study investigates the possibility of determining the flooded areas by classifying Sentinel-1 SAR data acquired over the City of Niamey, Niger, after the 2020 flood. For this purpose, pre- and post-disaster Sentinel-1 SAR data have been pre-processed, and images have been generated using The DEA Sandbox platform. These images have been classified using unsupervised classification methods.

Niamey is highly exposed to flood risks, as demonstrated in Figure 7 and shown by recorded damages during the last decade and the urban expansion rate in floodplains. With the increasing precipitation amounts and frequency of extreme events, the study indicates that the capital city of Niamey is now converging in a new hydro-climatic area. The use of Sentinel-1 SAR data products is beneficial to this application due to the sensitivity of the backscatter signal to open water. This signal provides valuable information for the analysis of water bodies and their dynamics.

As a tool to manage the emergency response after a flood inundation event, flood mapping helps to assess the extent of the affected areas on a large scale. It is the base for coordinating recovery activities and preventing mitigation measures in case of upcoming events. Floods are tools for sustainable management plans for sustainable development.

As a result of these findings, the study suggests that an updated and comprehensive flood-risk assessment should be established. Such an assessment should take into account the following factors:

- The characteristics of the morphology of the river basin that affect the hydrometric rating curve;
- The previous research about the recorded damages and losses
- The consideration and implication of all stakeholders and the hydroclimatic changes
- Analyze and interpret the river and likely flooded area expansion, both natural and artificial
- Improve flood early warning system

Author Contributions

All authors were involved in the production and writing of the manuscript. Conceptualization Hassane Bassirou; Data curation, Hassane Bassirou; Formal analysis, Hassane Bassirou, and Cheo; Investigation, Hassane Bassirou; Methodology, Hassane Bassirou, and Cheo; Project administration, Hassane Bassirou; Software, Hassane Bassirou; Supervision, Masamaéya D.-T. Gnazou, Ibrah Seidou Sanda and Ambe Emmanuel Cheo; Validation, Hassane Bassirou, Masamaéya D.-T. Gnazou, Ibrah Seidou Sanda and Ambe Emmanuel Cheo; Visualization, Ibrah Seidou Sanda and Ambe Emmanuel Cheo; Writing – original draft, Hassane Bassirou; Writing – review & editing, Hassane Bassirou, Masamaéya D.-T. Gnazou, Ibrah Seidou Sanda and Ambe Emmanuel Cheo.

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Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request and on the Digital Earth Africa platform.

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