Geospatial Capacity Building for Flood Resilience in the Sahel: the SLAPIS project case study

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Abstract

This study focuses on the development of a people-centred early warning system (EWS) against floods in the Sirba River basin between Niger and Burkina Faso. This densely populated area has witnessed an increase in extreme flooding events in recent years. Several flood forecasting systems in the Sahel exist, although there is no EWS that integrates the four components of people-centred EWSs, namely risk knowledge, monitoring and warning service, dissemination and communication, and response capacity. The proposed EWS, named SLAPIS, includes a risk knowledge component that involves defining four levels of vigilance. Its monitoring and alert component involves a user-friendly web application containing real-time data collected through automatic stations. The EWS communicate seamlessly with the national alert system. The response capacity is strengthened through the creation of a flood zone atlas. In this framework, the EWS integrates significant geoinformatics in preparation of local risk reduction plans and the awareness of local communities. In the SLAPIS case study, multi-temporal classifications were conducted using Sentinel-2 data and high-resolution images (approximately 10 cm) generated through Structure from Motion (SfM) techniques. Digital Terrain Model (DTM) creation for hydraulic model calibration employed a multiscale approach, incorporating GNSS survey data processed via Precise Point Positioning (PPP), HydroSHEDS (approximately 100m resolution), and commercial 10m resolution data. All information was calibrated, harmonised, and integrated into the EWS model, which is accessible via a web platform. Capacity building encompassed direct training and field implementation to streamline the primary EWS generation steps.

1. Introduction

The Sahelian zone, along with the Amazon, Indonesia, and central-southern Asia, is one of the hotspots most affected by global climate change. The climate and hydrology of the Sahel have undergone significant changes in recent decades (Turco et al., 2015). From the 1990s, there was a recovery in precipitation and an increase in streamflow in Sahelian rivers. Major streamflows have been observed despite lower precipitation in recent years, referred to as the first Sahel paradox (Descroix et al., 2013), along with a significant increase in extreme events, particularly floods, throughout the region. The streamflow increase is linked to the rise in extreme precipitation or changes in land use (Bigi et al., 2018). The second paradox of the Sahel is that despite greening, there has been an increase in the runoff coefficient.

Combined with population growth, these events have caused substantial damage that the population had never experienced before (Fiorillo *et al.*, 2018).

Niger country is no exception; the frequency of flood damage in Niger has increased significantly over the last decade. The growing frequency and intensity of extreme events has prompted governments to seek support from the international community to implement early warning systems to assist vulnerable riverside communities.

Early warning systems (EWS) are decisive in flood Risk Reduction. Local EWS are especially helpful in anticipating severe events (Cristofori et al., 2016).

Several flood forecasting systems in the Sahel (Niger-HYPE, World-Wide HYPE, GloFAS, SATH-ABN) exist. There is no EWS that integrates the four components of people-centred EWSs (UNISDR, 2006), namely risk knowledge, monitoring and warning service, dissemination and communication, and response capacity.

In this context, geoinformatics provides essential spatial analysis capabilities for identifying areas and main assets at risk. Establishing an effective forecasting, monitoring, and warning system for flood-prone communities requires integrating real time hydrological observations, models and geospatial data. Indeed, geoinformatics plays a crucial role in creating flood early warning systems. In the context of people-centred EWS, geoinformatics data contribute to the risk knowledge component. EWS's final output includes predictions of flooded areas based on meteorological and terrain morphological variables, which need to be harmonised through a precise and accurate coordinate reference system. Digital Elevation Models (DEMs) are required to calculate flood behaviour based on flow rate, and accurate maps of elements exposed to risk are needed for different flood scenarios. This information can be retrieved from the interpretation and analysis of remote sensing data. Finally, the EWS must be managed and presented in a user-friendly format, with users being informed and trained (De Filippis et al., 2022).

Between 2017 and 2021, the ANADIA 2 (Adaptation au changement climatique, prévention des catastrophes et développement agricole pour la sécurité alimentaire) project implemented a flood people-centred EWS on 120 km of the Sirba River before its confluence with the Niger River (Niger country).

The EWS is accompanied by the preparation of local risk reduction plans and the awareness of local communities. In 2023, the SLAPIS project (Système Locale d'Alerte Précoce pour les Inondations au Sahel) extended the EWS to the upstream stretch of the Sirba River, which is entirely in Burkina Faso. The 2023 SLAPIS project has seen the definition of an early warning system based on the SLAPIS prototype developed in ANADIA 2 for the Nigerien branch of Sirba River but extended in Burkina Faso, with the final goal of establishing a Transboundary Early Warning System for floods using a cascade training system.

The system is based on the integration of local observations with weather and hydrological forecasts through a risk information platform, an integrated information and communication mechanism, flood zone mapping, local flood risk reduction plans, and awareness and training actions. The system was designed based on existing needs, capacities, and technologies appropriate to the local context.

The Sirba basin areas, however, suffer from a general scarcity of geoinformatics data, and the available data between Burkina Faso and Niger are not generally harmonised. Further complicating the implementation and calibration of an EWS is the limited availability of known coordinate points for creating topographic networks and the lack of a dense geodetic network (Belcore et al., 2022).

In this complex context, the manuscript outlines the geoinformatics-related stages of EWS model generation for the project, data harmonisation, and the training and capacity-building activities related to the EWS.

2. Materials and Methods

The Sirba River is a major tributary of the Niger River in its middle basin. Its basin, spanning approximately 39,000 km², encompasses regions in Burkina Faso, which represents 93% of the basin, and Niger within the central Sahel. The basin's landscape features gentle slopes and various morpho-pedological units, primarily sandy glacis interspersed with granite domes emerging from the crystalline basement. These areas support sparse vegetation, with dense vegetation concentrated along the water courses and depressed areas. The agricultural landscape consists of a mosaic of rainfed cultivated fields.

The climate is semi-arid, characterised by a brief rainy season from June to September, with annual rainfall averaging between 400 and 700 mm (Tarchiani and Tiepolo, 2016). The Sahelian climate exhibits high rainfall variability and frequent dry spells. Human pressure and the hydrological extremes impact on the sub-Saharan landscape, initiating well-established changes in the land cover and in use. (Descroix et al., 2013). However, the combination of climatic and hydrological effects in the area, has become more frequent and impactful, with floods affecting local both urban and rural populations.

The chosen study segment of the ANADIA 2 project was a river branch spanning approximately 100 km (Figure 1). The Sirba River Basin is home to a population of 88,863 residing in 171 villages, with most settlements located along the river in areas prone to flooding (Tiepolo et al., 2021).

The study area includes the following basins, Figure 1:

1. Sirba Basin (Sirba, Faga, and Yali) in Burkina Faso;
2. Niger River: the Nigerien section upstream of Niamey, from the Malian border to the city of Niamey;
3. Transboundary basins (Burkina Faso and Niger) on the right bank of the Niger River upstream of Niamey (Gouroul and Dargol)

The geospatial products and geomatics technologies for the EWS include GNSS surveying for constructing a Digital Terrain Model (DTM) of the riverbed and collecting ground control points within the main villages, generating maps of flood-prone buildings and infrastructure through satellite and proximal sensing, creating a GIS platform for managing the model and its accessibility.

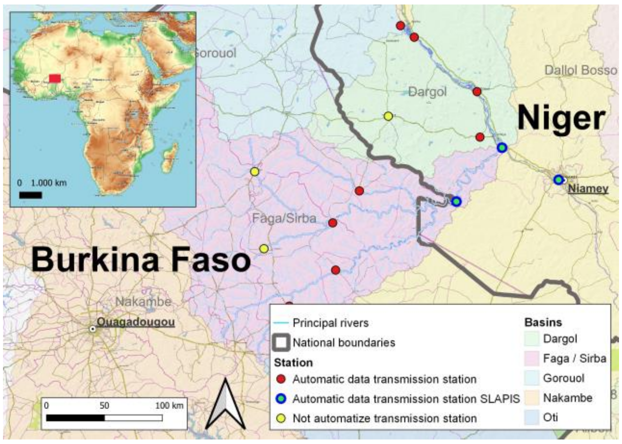

Figure 1. SLAPIS project study area.

The main limitation concerning the working area between Burkina Faso and Niger relates to the availability of data for generating DTMs with a sufficient resolution for accurate calibration of the hydraulic model. A multiscale approach was employed for DTM generation and land cover mapping. Specifically, as described in Figure 2, a commercial model was used, corrected, and calibrated with field measurements conducted using GNSS along the Nigerien branch of the Sirba River to delineate the riverbed morphology. High-resolution DTMs for three pilot villages were created through photogrammetric flights conducted with Unmcrewed Aerial Systems (UAS). Multispectral orthomosaics were also generated from these surveys using Structure from Motion (SfM) techniques. In three other pilot villages, which cannot be flown over for safety reasons, high-resolution images (0.5m) are used to extract elements exposed to risk through remote sensing. The DTM was used to calibrate the hydraulic model (not covered in this work), which was the basis for generating the boundaries of flood zones. The following paragraphs describe each step, including the knowledge transfer components.

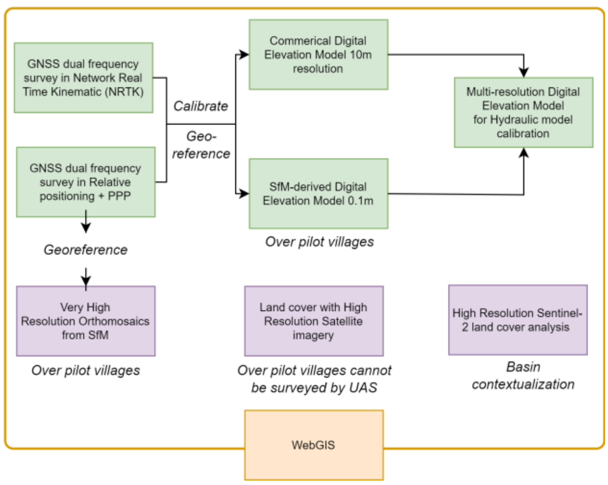

Figure 2. Geoinformatics data generation structure.

2.1. Training and capacity building in people-centred EWS

Communities are actively involved in defining flood risk reduction plans through participatory analysis, defining adaptive and mitigation measures to be implemented for each risk scenario (Tiepolo et al., 2019). SLAPIS considers two types of geospatial-related training, along with the hydraulic training and risk-knowledge activities: the North-South Training and the South-South Training.

The North-South Training, which consists of the transfer of skills to teams from Burkina Faso and Niger through on-site and Italy-based training, includes:

1. Execution of topographic and GNSS surveys in and data processing;
2. Geographic Information System (GIS) for data storage and management
3. the basis for remote sensing;

The South-South Training have transferred skills from experts in Niger to colleagues in Burkina Faso and vice versa.
The capacity building includes training and adapting the program structure to facilitate knowledge transfer at multiple levels through ongoing exchange and a cascading mechanism. This approach allows for the gradual training of trainers, thereby expanding the beneficiary base. The involved stakeholders operate at various levels: National Technical Services (NTS) of both countries, local administrations, riparian communities, and citizens.
The NTS receive specific technical training in Burkina Faso and Italy, which is followed by providing support in carrying out specific activities in Niger and Burkina Faso.

2.2. Satellite

The contextualisation of the Sirba basin, as well as the definition of the Sirba River boundaries, was accomplished using Sentinel-2 data. A pixel-based approach with supervised classification was applied, utilising tiles from 16 observations between 2017 and 2019, level 1C. The data were filtered for atmospheric coverage, less than 10% of cloud coverage, and only images from the dry period were selected to reduce the influence of the phenological component of the cover. The noise introduced by the Earth’s atmosphere on the images was reduced through a calibration based on the Dark Object Subtraction approach (Chavez, 1988). Nine classes were identified: Urban areas, Plateaux, Water, Riparian vegetation, Sandy bare soils, Vegetation of the plateaux, Red bare soils, Non-irrigated agricultural lands, pastures and Irrigated agricultural lands. Three hundred observations for each class were obtained through visual interpretation for the training test dataset, totalling 2,500 points. The classification was developed in Google Earth Engine environment (Belcore and Piras, 2023).

2.3. Topographic network and control points

A commercial digital terrain model with a 10-meter resolution was acquired to calibrate the hydraulic model. Since the model was generated by radar, it lacks information on the morphology of the Sirba Riverbed (Paragraph 2.5). Therefore, two topographic surveys were necessary to define the bed morphology and measure validation points for the commercial model. Given the scarcity of points of known coordinates and elevation in rural areas of the Sirba basin and the need to measure many points, a GNSS survey was chosen. In the Sirba River basin, there are no GNSS ground stations to perform relative positioning or Network Real Time Kinematic (NRTK) (Belcore et al., 2022). Although Continuously Operating Reference Stations (CORS) now cover most countries globally, some regions still remain excluded from this network (Figure 3).

Figure 3. Green dots indicate GNSS permanent stations on the IGS network (June 2024). The Sirba Basin is located in the red rectangle.

Therefore, to delineate the morphology of the riverbed, during the dry season, a topographic survey was conducted in which cross-sections of the Sirba River were measured using a master and a rover GNSS receivers communicating via radio-modem in an RTK mode. The base stations were reprocessed using the Precise Point Positioning (PPP) technique to compensate for the distance from CORS, as explained in (Belcore et al., 2022). The survey was conducted with local technicians in a hands-on training mode and covered more than 100 km of the Nigerien branch of the study area.

PPP technique consists of processing the pseudo-range and carrier phase measurements from GNSS multi-frequency receivers using data on satellite orbits and the ionosphere (Bisnath and Gao, 2009). This information is measured by CORS, which, unlike relative positioning, can be till hundreds kilometres far from the surveyor’s receiver (Kouba and Héroux, 2001). PPP can achieve centimetre-level precision in static mode (Pan *et al.*, 2015) when phase ambiguities are fixed as integer values in a correct way (Collins and Bisnath, 2011).

Eighteen master stations along the Nigerien Sirba were positioned, each acquiring data for an average of 3 hours. More than 3,000 points were measured in cross sections approximately 1 km apart from each other. The RINEX data from the stations were processed using PPP, and the measurements of the sections were reprocessed according to the PPP-processed coordinates of the master stations.

The PPP post-processing was realised online, with the free tool by the Canadian government, the Canadian Spatial Reference System (CSRS-PPP), which was selected upon precision tests (Belcore et al., 2022). The Up components were traslated to heights above the geoid with the EGM08 global model (Pavlis *et al.*, 2012).

Using the same approach, 20 control points in each pilot village.

The field survey was conducted with local technicians as a form of in-the-field training. The PPP processing was the subject of two days of training. The choice of an online system was due to its ease of use and simple GUI; moreover, it does not require software licenses or high-performance PCs. All these

characteristics were considered positive for the capacity building of the local technicians.
During the PPP survey were measured calibration points for the hydraulic model of the Sirba River and mapped the buildings close to the river.
A second GNSS survey was conducted to define the hydraulic levels in correspondence with main villages, gauging stations, confluence, and hydraulic structures.

2.4. Proximal sensing and Very High-Resolution Land Cover classification

Land cover (LC) adds crucial information to Early Warning Systems (EWS) plans, especially for estimating potential damages. However, it is rarely considered or is extracted from low spatial resolution data. Given the small size and the exposed elements to flood risk in the basin, for the pilot villages in Niger, it was decided to carry out photogrammetric flights using RGB and multispectral optical sensors.
Specifically, a mass-market RGB sensor, the Sony ILCE-5100 with 24 MP, and a prototypal optical sensor based on a Raspberry Pi NoIR and RGB cameras and a Raspberry board were used. The camera construction, setting and calibration is detailed in (Belcore *et al.*, 2019).
The images were processed in the Structure from Motion (SfM) proprietary software Agisoft Metashape. From the resulting point cloud were generated a Digital Surface Model (DSM) and two multiband orthophotos in Red, Green, Blue, and Red, Green, Near Infrared respectively.
The points measured from the GNSS survey were used as control points. In this case, the classification and mapping were not subjects of on-field training.

Using high-resolution optical data, an object-based classification with Random Forest (Breiman, 2001) was employed to semi-automatically map the elements at risk. Ten classes were identified: Water, Wetland, Agricultural, Trees, Metal Roofs Houses, Clustered Dark Areas, Sandy Soil, Grassland, Gullies, and Bricks Roofs House.
The training-test dataset comprised 200 elements per class, divided 50-50 for training and testing (Belcore, Piras and Pezzoli, 2022).

2.5. Digital Elevation Models

Due to the vastness of the basin, remote sensing was used for mapping and generating a medium-resolution DTM for calibrating a hydraulic model in the study area. A large scale, low resolution digital elevation model, HydroSHEDS (*Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales*), was used to characterise the mail topographical features (*HydroSHEDS*, 2024). HydroSHEDS is a hydrologically conditioned elevation model with a resolution of approximately 100m for the analysed latitude and has been generated from the Shuttle Radar Topography Mission (SRTM) in 2006 by the US Geological Survey (USGS).

Although HydroSHEDS DTM has been crucial for large scale definition of the land morphology of Sirba basin, its resolution was not sufficient for correctly calibrating the hydraulic model being equal to the average width of the Sirba (100m). Therefore, the commercial DTM with 10-meter resolution (Intermap Technologies, 2024) was acquired for the 2000 km² of the Nigerien part of the Sirba basin. The commercial DTM has a resolution of 10 meters and it is a model created through merge and interpolations of four different radar satellite missions between 2005 and 23011: SRTM 90, SRTM 30, ASTER, and GTOPO30 (Massazza *et al.*, 2019).
The elevation points resulting from the topographic survey were interpolated using kriging model, and the resulting DTM was included in the Intermap World 10 DTM. Any mismatch measured on adjacent pixels was adjusted by translating the 10-meter DTM to match the elevation of the points measured with GNSS considered as reference. The same workflow will be applied in the Burkina Faso study area.

2.6. Web application

In this context, the accessibility to information related to the EWS is crucial. SLAPIS rely on a web infrastructure for the management, storage and distribution of the hydraulic models the topographic data and the real-time updated weather and hydraulic data. This web infrastructure constitute the technological backbone of the early warning system, allowing the continuous monitoring of the risk and its dissemination in real time. the open access information is specifically designed to meet the local population and local technician needs.

3. Results and discussion

3.1. Training and capacity building in people-centred EWS

The NTS has been supported in training and raising awareness among local technical services, who in turn will be assisted in their training and outreach activities benefiting local administrations and communities. A conducive environment for integrating local knowledge and scientific insights through a continuous innovation mechanism has been created through the training.
Overall, the EWS model requires many different skills and a strong training component. From a technical perspective, the limited availability of data and the complex survey conditions necessitate a strong foundational preparation, which has been well assimilated by the trainees through fieldwork and classroom training sessions. The activities are still ongoing. The multiscale approach has proven positive, although further tests are needed to verify the harmonisation of the different digital models. The use of higher-resolution data is not excluded if it falls within the limits of the available resources.

The entire EWS model is now being constructed for areas in Burkina Faso, replicating the one developed in ANADIA.

The risk knowledge component of the EWS is based on the identification of four levels of vigilance: green (no flood), yellow (frequent flooding), orange (severe flooding) and red (catastrophic flooding) and the definition of flood scenarios connected to the levels of vigilance. Vigilance levels were identified using a combination of the non-stationary extreme value theory approach and the identification of impacts on human life, with the aim of quantifying the effects of climate change and being consistent with Niger's National Warning Code (Massazza *et al.*, 2019). The numerical hydraulic model was used to define the flood zones for each scenario and the propagation time of the flood wave. The hydraulic model used the geometry of the DTM calibrated by GNSS and surveys.
The monitoring and alert service is guaranteed by real-time flow measurements and forecasts derived from two automatic hydrometric stations along the Sirba River, as well as flow forecasts derived from hydrological models.
The dissemination and communication system has been integrated into the national warning system in accordance with

the specific skills of the various institutions. As soon as the flow exceeds the vigilance threshold level, the platform creates a bulletin, which is then sent to the relevant national and local authorities using the agreed communication channel (e-mail, telephone, radio, SMS or WhatsApp).

The implementation of response capacity took place after the hazard definition phase, materialised in a flood zone atlas, and the identification of issues, with field measurements and high-resolution aerial remote sensing performed by UAS and satellite. Local flood risk reduction plans have been prepared using an innovative approach (Tiepolo *et al.*, 2021) involving participation at every stage of the planning process (Tiepolo *et al.*, 2019).

3.2. Satellite

As illustrated in (Belcore and Piras, 2023), the sentinel-based land cover classification resulted in high-accuracy results, with most of the analysed classes correctly identified. The overall accuracy reached 90%. Within the classified land covers the most inaccurate class is the *Plateaux*, although its F1 score reaches 95%.

4-pixels erosion and 3-pixel dilation operations were applied to the classification to reduce some the salt-and-pepper effect seldom present in the scene. This paestetic post-processing operation was applied only on the Atlas printable version.

The high values of accuracy indicate a possibility of overfitting in the Random Forest model or a test dataset that is too small. However, even compared to LC Africa, the results are promising despite the homogeneity of surface spectral responses (Belcore and Piras, 2023).

The model was developed entirely using Google Earth Engine. The code is public and will be part of the training in September 2024, where NPLs will learn to use the Google Earth Engine platform for classification. They will be able to apply the model in specific periods or even in the future. Using Google Earth Engine allows cloud processing through a browser, overcoming issues related to the difficulty of obtaining data processing tools.

3.3. Topographic network, control points and DEMs

The GNSS surveys (Belcore *et al.*, 2022) carried out in rover-based mode with PPP post-processing resulted in 103 cross-sections with an average precision of 2 cm on the East component, 8 cm on the North component, and 4 cm on the Up component.

The results are acceptable and align with the precision requirements for the EWS model. The field activities involved the NTS, who demonstrated responsiveness and quick learning during the practical fieldwork. The data were used to calibrate the 10-meter DTM model. On average, a 60 cm difference was measured between the 10-meter DTM and the DTM interpolated from the GNSS points. Although significant, this error was attributed to the georeferencing methods of the Harris model and is consistent with the declared accuracies and precisions. Additionally, using a global geoid undulation model may have introduced further inaccuracies.

3.4. Proximal sensing and Very High-Resolution LC classification

The photogrammetric process resulted in the extraction of an R-G-B and an R-G-NIR orthomosaic for each surveyed village. The results related to ground control points (GCPs) and check points (CPs) are reported in Table 1.

RMSE (cm)		Easting	Northing	Altitude	Total error
GCP	**RGB**	3.52	3.77	3.79	6.40
	RGN	5.40	5.05	2.93	7.95
CP	**RGB**	3.75	3.81	7.90	5.67
	RGN	5.41	6.54	3.03	9.02

Table 1. Error on Ground Control Points (GCP) and Check points (CP) from the structure from motion (SfM) processing. Readapted from (Belcore, Piras and Pezzoli, 2022)

The UAS object-oriented classification achieved an accuracy of 0.94 and an F1 score ranging from 0.90 to 0.94 (Belcore, Piras and Pezzoli, 2022).

This high-detailed information can add an additional layer of insight by detecting items particularly endangered by floods. For example, houses built with non-water-resistant materials, such as those in southwest Niger, where traditional houses are made of earth and wood poles, can be identified.

The main challenges were encountered in defining areas that are not homogeneous within inhabited regions, generally characterised by everyday use elements adjacent to the houses. The data used, obviously, do not provide information about the usage of the identified elements, and the available information is generally limited. In these cases, the work of citizens and NPL was crucial. They participated in a training program organised to map these elements using very high-resolution images-derived maps as a base.

Given the limited safety conditions affecting some of the study villages, high-resolution mapping will be carried out using high-resolution satellite data (SkySat constellation) with 50cm spatial resolution.

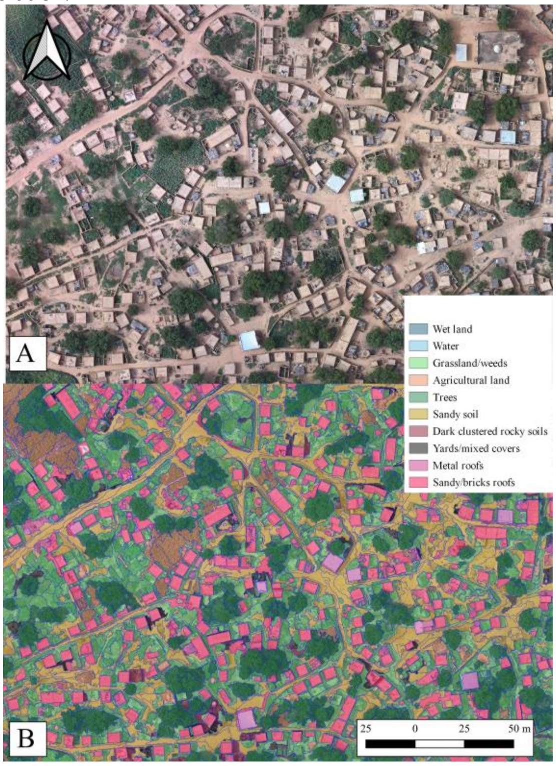

Figure 4. A) Example of the RGB orthomosaic generated with Structure from Motion; B) Same scene classified with the Random Forest model

3.5. Web application

The SLAPIS web application has been developed according to the latest interoperability and sharing standards and with the integration of different software for interface (GUI), process and database management (PostgreSQL/PostGIS) and open source data download (CKAN).
The web application interface is user-friendly and intuitive. The functionalities have been developed based on users' requirements to support flood monitoring along the river and provide real-time data—the content updates automatically and in real-time. In addition to the web application, a printed atlas has been developed and distributed to villages along the river (De Filippis *et al.*, 2022). It is accessible at https://www.slapis-niger.org.

4. Conclusion

The manuscript reports the general structure of training, response capacity, and dissemination activities of the EWS projects ANADIA and SLAPIS, focusing on the components related to geoinformatics and geomatic data. This work is intended as a summary of the activities conducted so far and a presentation of future ones, analysing the limitations and challenges that this entails in expanding the model. Although in a prototype form, it has led to positive results by designing and making the EWS system usable and strengthening the capacities of various national, regional, and local actors to adapt to climate change and reduce vulnerability to disasters in territorial planning and management.

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References

Belcore, E. *et al.* (2019) 'RASPBERRY PI 3 MULTISPECTRAL LOW-COST SENSOR FOR UAV BASED REMOTE SENSING. CASE STUDY IN SOUTH-WEST NIGER', in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W13*. International Society of Photogrammetry and Remote Sensing (ISPRS), pp. 207–214. Available at: https://doi.org/10.5194/isprs-archives-XLII-2-W13-207-2019.

Belcore, E. *et al.* (2022) 'Comparison of Free and Open PPP Services for Master-base Positioning in Geodetic Disadvantaged Areas: Case Study along the Sirba River in Sub-Saharan Africa':, in *Proceedings of the 8th International Conference on Geographical Information Systems Theory, Applications and Management. 8th International Conference on Geographical Information Systems Theory, Applications and Management*, Online Streaming, --- Select a Country ---: SCITEPRESS - Science and Technology Publications, pp. 37–47. Available at: https://doi.org/10.5220/0011039600003185.

Belcore, E. and Piras, M. (2023) 'Sentinel 2 High-Resolution Land Cover Mapping in Sub-Saharan Africa with Google Earth Engine':, in *Proceedings of the 9th International Conference on Geographical Information Systems Theory, Applications and Management. 9th International Conference on Geographical Information Systems Theory, Applications and Management*, Prague, Czech Republic: SCITEPRESS - Science and Technology Publications, pp. 27–36. Available at: https://doi.org/10.5220/0011746500003473.

Belcore, E., Piras, M. and Pezzoli, A. (2022) 'Land Cover Classification from Very High-Resolution UAS Data for Flood Risk Mapping', *Sensors*, 22(15), p. 5622. Available at: https://doi.org/10.3390/s22155622.

Bigi, V., Pezzoli, A. and Rosso, M. (2018) 'Past and Future Precipitation Trend Analysis for the City of Niamey (Niger): An Overview', *Climate*, 6(3), p. 73. Available at: https://doi.org/10.3390/cli6030073.

Bisnath, S. and Gao, Y. (2009) 'Current State of Precise Point Positioning and Future Prospects and Limitations', in M.G. Sideris (ed.) *Observing our Changing Earth*. Berlin, Heidelberg: Springer (International Association of Geodesy Symposia), pp. 615–623. Available at: https://doi.org/10.1007/978-3-540-85426-5_71.

Breiman, L. (2001) 'Random Forests', *Machine Learning*, 45(1), pp. 5–32. Available at: https://doi.org/10.1023/A:1010933404324.

Chavez, P.S. (1988) 'An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data', *Remote Sensing of Environment*, 24(3), pp. 459–479. Available at: https://doi.org/10.1016/0034-4257(88)90019-3.

Collins, P. and Bisnath, S. (2011) 'Issues in Ambiguity Resolution for Precise Point Positioning', in, pp. 679–687. Available at: http://www.ion.org/publications/abstract.cfm?jp=p&articleID=9628 (Accessed: 2 February 2021).

Cristofori, E., Albanese, A. and Boccardo, P. (2016) '8. Early Warning Systems & Geomatics: Value-added Information in the Absence of High Resolution Data', in Tiepolo, M., *Planning to cope with tropical and subtropical climate change*. De Gruyter Open, pp. 141–153. Available at: https://doi.org/10.1515/9783110480795-009.

De Filippis, T. *et al.* (2022) 'Hydrological Web Services for Operational Flood Risk Monitoring and Forecasting at Local Scale in Niger', *ISPRS International Journal of Geo-Information*, 11(4), p. 236. Available at: https://doi.org/10.3390/ijgi11040236.

Descroix, L. *et al.* (2013) 'Impact of Drought and Land – Use Changes on Surface – Water Quality and Quantity: The Sahelian Paradox', *Current Perspectives in Contaminant Hydrology and Water Resources Sustainability* [Preprint]. Available at: https://doi.org/10.5772/54536.

Fiorillo, E. *et al.* (2018) 'Recent Changes of Floods and Related Impacts in Niger Based on the ANADIA Niger Flood Database', *Climate*, 6(3), p. 59. Available at: https://doi.org/10.3390/cli6030059.

HydroSHEDS (2024). Available at: https://www.hydrosheds.org/ (Accessed: 19 June 2024).

Intermap Technologies (2024) *NEXTMap Elevation Data | Intermap*. Available at: https://www.intermap.com/nextmap (Accessed: 19 June 2024).

Kouba, J. and Héroux, P. (2001) ‘Precise Point Positioning Using IGS Orbit and Clock Products’, *GPS Solutions*, 5(2), pp. 12–28. Available at: https://doi.org/10.1007/PL00012883.

Massazza, G. *et al.* (2019) ‘Flood Hazard Scenarios of the Sirba River (Niger): Evaluation of the Hazard Thresholds and Flooding Areas’, *Water*, 11(5), p. 1018. Available at: https://doi.org/10.3390/w11051018.

Pan, S. *et al.* (2015) ‘Real-Time PPP Based on the Coupling Estimation of Clock Bias and Orbit Error with Broadcast Ephemeris’, *Sensors*, 15(7), pp. 17808–17826. Available at: https://doi.org/10.3390/s150717808.

Pavlis, N.K. *et al.* (2012) ‘The development and evaluation of the Earth Gravitational Model 2008 (EGM2008)’, *Journal of Geophysical Research: Solid Earth*, 117(B4). Available at: https://doi.org/10.1029/2011JB008916.

Tarchiani, V. and Tiepolo, M. (2016) ‘Risque et adaptation climatique dans la région Tillabéri, Niger : pour renforcer les capacités d’analyse et d’évaluation’, pp. 1–275.

Tiepolo, M. *et al.* (2019) ‘Flood Assessment for Risk-informed Planning Along the Sirba River, Niger’, *SUSTAINABILITY*, 11, pp. 1–21.

Tiepolo, M. *et al.* (2021) ‘Method for fluvial and pluvial flood risk assessment in rural settlements’, *MethodsX*, 8, p. 101463. Available at: https://doi.org/10.1016/j.mex.2021.101463.

Turco, M. *et al.* (2015) ‘Observed climate change hotspots’, *Geophysical Research Letters*, 42(9), pp. 3521–3528. Available at: https://doi.org/10.1002/2015GL063891.