Changes in surface water extent and volume in the Inner Niger Delta over 2000-2022 using multispectral imagery and radar altimetry

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In prep for Geocarto International, Mapping Flood Risk

Introduction

- **Surface water reservoir** (lakes, rivers, floodplains and wetlands): significant role as one of the primary water resources for ecosystems and populations
- **Floodplains:** regulating river flows, air temperature modulation, methane emissions and carbon trapping and release
- **Spatio-temporal dynamics of floodplains are still poorly understood** (lack of in situ data mainly)
- **Satellite remote sensing :** offers the possibility to quantify surface water stocks (SAR interferometry, multispectral imagery...)
- **Until now: no time series of surface water storage to properly monitor hydrological cycle of floodplains with spatial and temporal resolutions adapted**

Aims of the study:

(1) to quantify surface water extent and volume to create long time series (2000-2022)

(2) to compare and validate our method with other datasets

Inner Niger Delta (IND)

- **Central Mali** : longitudes 3-5°W, latitudes 13-17°N
- Composed of a network of rivers, tributaries, lakes and floodplains
- **Second largest wetland in Africa**
- Flat and sandy basin

- **Hydrological characteristics:**
  - Niger River (Ke-Macina) and its main tributary the Bani (Sofara)
  - Sources : high plateau of Guinea
  - Total drainage area ~73,000km²

- **Seasonal rainfall : West African Monsoon**
  - Wet season from August to December
  - Dry season from March to May: flow is reduced, 80 times less important than during rainy season

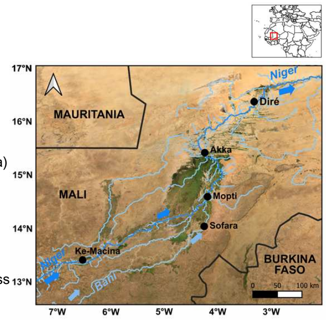


fig.1. Location of the IND and its two main rivers

Materials & methods

Surface water volume = surface water extent (multispectral imagery) x water levels (radar altimetry)

Surface water extent map

- **Multispectral imagery: MODIS sensor**
  - MOD09A1 product (https://appeears.earthdatacloud.nasa.gov/)
  - Level 3, 500 m, 8 days (composite), 7 spectral bands
  - 2000-2022 : 1,028 composites used
- **Surface water extent map method: Sakamoto *et al.*, (2007) method, adapted by Normandin *et al.*, (2018a)**
  - Spectral indexes (EVI, LSWI) and thresholds
  - 3 classes: non-flooded, mixed and flooded pixel

Water levels

- Network of virtual stations : time series of water levels (Normandin *et al.*, 2018b)
- AlTiS and MAPS softwares (Frappart *et al.*, 2015, Normandin *et al.*, 2018b, Frappart *et al.*, 2021)
- ERS-2 (35 days), ENVISAT (35 days), Saral (35 days), Sentinel-3A/3B (27 days)

Surface water volume

$$\Delta V = \sum_{j \in S} [h(\lambda_j, \varphi_j) - h_{min}(\lambda_j, \varphi_j)] \cdot \delta_j \cdot \Delta S$$

- ΔV : anomaly of surface water volume (km3)
- S : is the surface of the Inner Niger Delta (km²)
- $h(\lambda_j, \varphi_j)$: the water level, $h_{min}(\lambda_j, \varphi_j)$: the minimal water level for the pixel of coordinates (λ_j, φ_j)
- δ_j : equals 1 if the jth pixel is associated with inundated and 0 if not
- ΔS : pixel surface (0.25 km2)

Validation dataset

Surface water extent

- Global Surface Water (GSW, Pekel *et al.*, 2016): 1984-2021
  - 30 m, Landsat data, use of NDVI and HSV
- Global Surface Water Dynamics (GSWD, Pickens *et al.*, 2020): 1999-2021
  - 30 m, Landsat data, use of NDWI and MNDWI
- Flooding model (Zwarts *et al.*, 2018)
  - 30 m, Landsat and *in situ* data measured at Akka

Water levels

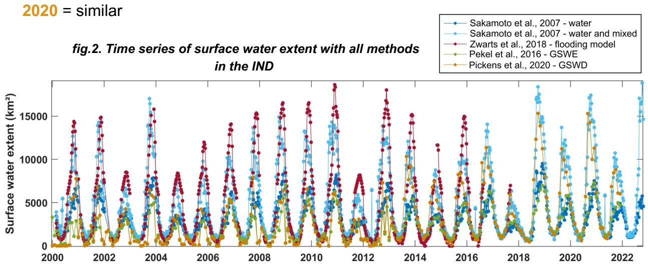
- ICESat-2, launched in 2018
- 91-day repeat cycle
- Advanced Topographic Laser Altimeter System (ATLAS)
- ATLAS/ICESat-2 L3A ATL13 product, which contains along-track surface water products for inland water bodies (Janinski *et al.*, 2021)

Results and discussion

Surface water extent - temporal (fig.2)

- Wet/dry periods, with maximum flood peak in 2011 (except for **Sakamoto et al., 2007 with mixed pixels**) and minimum flood peak in 2010
- **Sakamoto et al., 2007 with mixed pixels** and **Zwarts et al., 2006/2018** : 19% of differences
- **Sakamoto et al., 2007 without mixed pixels**, **Pekel et al., 2016** and **Pickens et al., 2020** = similar

fig.2. Time series of surface water extent with all methods in the IND



Water level maps - validation (fig.4)

- **Sakamoto et al. (2007, our method)** and **ICESat-2** : 64 comparisons
  - 29 with $R^2 > 0.6$, 18 between 0.2 and 0.6
  - 45 comparisons with a bias [-0.5 0.5 m]
  - 38 comparisons with RMSE between 0.25 and 0.75 m
- **Zwarts et al. (2006, 2018)** and **ICESat-2** : 10 comparisons
  - lack of *in situ* data after 2018
  - $R^2 < 0.1$ for all comparisons
- **Sakamoto et al. (2007, our method)** and **Zwarts et al. (2006, 2018)** : 226 comparisons
  - 55% of the comparisons with $R^2 < 0.1$, 10% with R^2 between 0.1 and 0.2, 33% with R^2 between 0.2 and 0.4, and 2% with $R^2 > 0.4$
  - high number of samples for each comparison

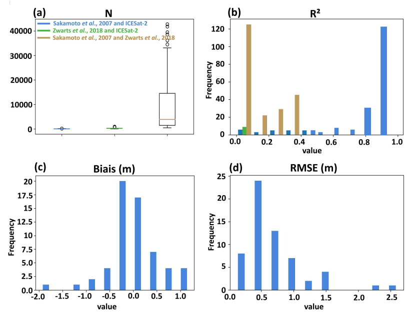


fig.4. Statistical parameters of water level maps comparisons between different methods

Mean annual flood duration- spatial (fig.3)

- **different patterns obtained with the different methods**
- **Sakamoto et al., 2007 with mixed pixels** and **Sakamoto et al., 2007 without mixed pixels** : problems in the upstream part with a lower flood duration in the main and secondary rivers
- spatial resolution of 500 m of MODIS : secondary network not well determined compared to others products
- **Pekel et al. (2016)** : lower flood durations (spectral indexes used to map water)
- **Zwart et al. (2006, 2018)** : overestimation of flood duration , all the IND is covered by water, lack of DEM in the digital flooding model
- **Pickens et al. (2020)** : network of river well identified, but flood extent seems too important

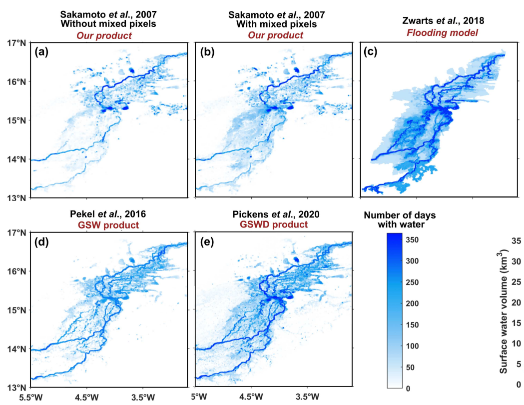


fig.3. Mean annual flood duration with the different methods

Surface water volume (fig.5)

- Zwarts et al. (2006, 2018) volumes are +21% superior to surface water volume of our method (Sakamoto et al. (2007))
- lack of in situ data for Zwarts et al. (20006, 2018) since 2018
- Extreme events are identified

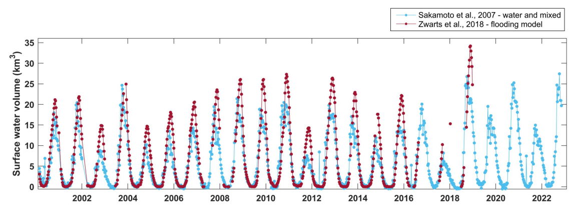


fig.5. Time series of surface water volume

Conclusion

- Surface water extent obtained using our method (Sakamoto et al., 2007, Normandin et al., 2018a) : similar annual cycle with other methods
- Different spatial patterns for the mean annual flood duration
- **Validation of water level maps for the first time, with best results for our method**

- **Next months: applying our method combining multispectral imagery and radar altimetry for different huge basins and lakes (Mackenzie, La Plata, Mississippi, Ob, Yangtze,Nil, Eyre, Chad) in different climates to study the impacts of the climate change and human activities**

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