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Groundwater recharge in semi-arid Sahel: spatial and temporal patterns

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1 Surface water and groundwater recharge

Localized infiltration of surface water below short-lived, seasonal ponds (*mares*) is an important source of groundwater recharge in semi-arid Sahel region (Desconnet, 1994; Massuel, 2005; Favreau et al., 2009) likely outnumbering the contribution of diffuse recharge. Using remote sensing, this study appraises the spatial extent and the average duration of ponding to delineate areas of high recharge potential as a basis for forthcoming recharge quantification. This study in the transboundary region of Benin, Niger, and Nigeria (Fig 1) is part of a technical cooperation project between the BGR and the Niger Basin Authority (NBA).

2 Water body detection

Water detection by optical remote sensing employs the specific spectral signature of water characterized by a strong absorption of the infrared light compared to soil or vegetation, which reflect most of the infrared spectra and in turn show strong absorptions in the visible spectra (Fig 2).

The **Modified Normalized Difference Water Index (MNDWI,** Xu, 2006, McFetters 1996) is a normalized spectral index that compares the information of two Landsat bands (Green and short wave infrared, SWIR1) to differentiate between water and terrain. Normalization by the sum reduces the bias produced by the irradiance/brightness variations allowing comparison within and beyond a single scene.

$$\mathrm{MNDWI} = \frac{\mathrm{Green} - \mathrm{SWIR1}}{\mathrm{Green} + \mathrm{SWIR1}}$$

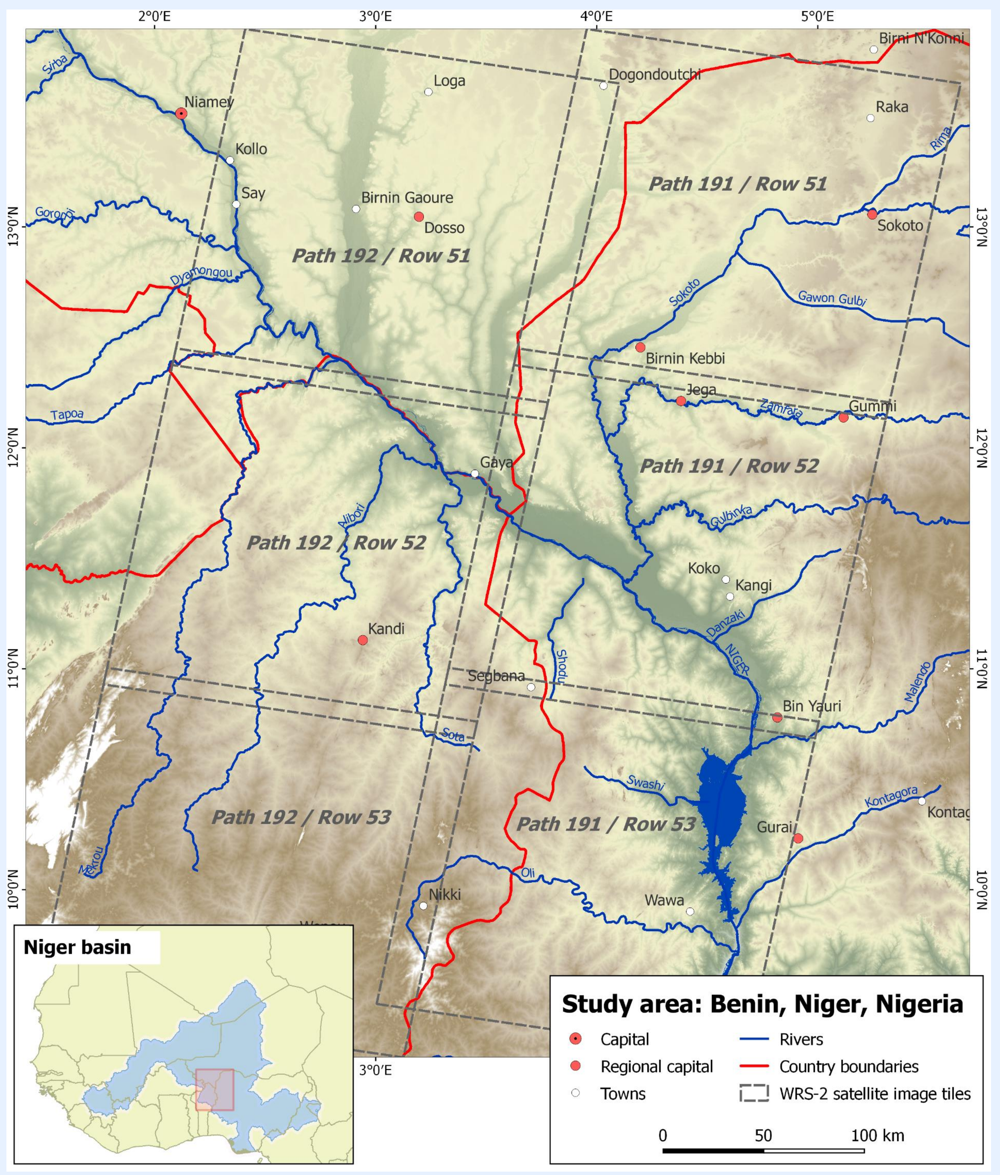

Fig. 1: Study area and coverage of six WRS-2 Landsat tiles

3 Workflow

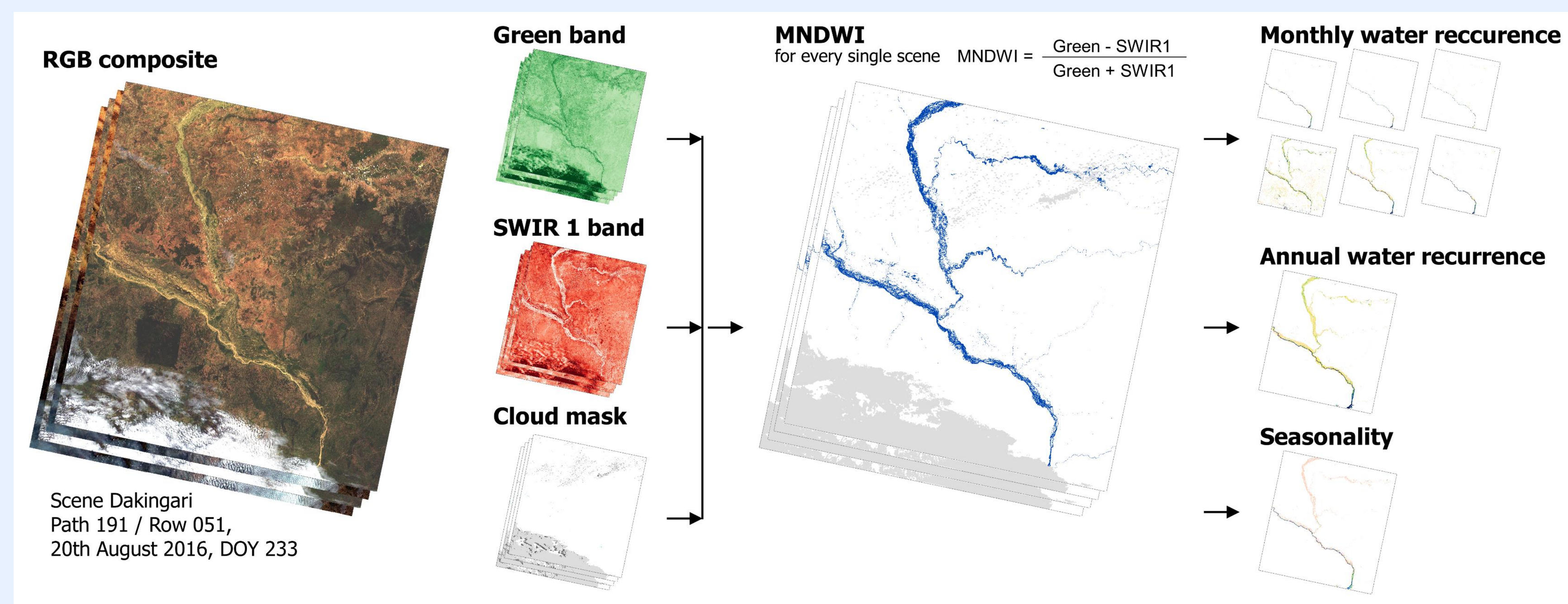

Fig. 2: MNDWI images were calculated for each single scene (between 261 and 326 scenes per tile) using the green and SWIR 1 bands. Cloud cover was masked using the USGS cfmask. Based on 1756 scenes in six WRS-2 satellite tiles, annual and monthly surface water distributions and seasonality were calculated.

4 Landsat time series

Landsat 4, 5, 7, and 8 scenes (1984 – 2016) from the Surface Reflectance Data set (Climate Data Records) were accessed via the USGS EROS Center. Scenes are Level 1 precision- and terrain-corrected and adjusted to account for atmospheric variation (Fig 3).

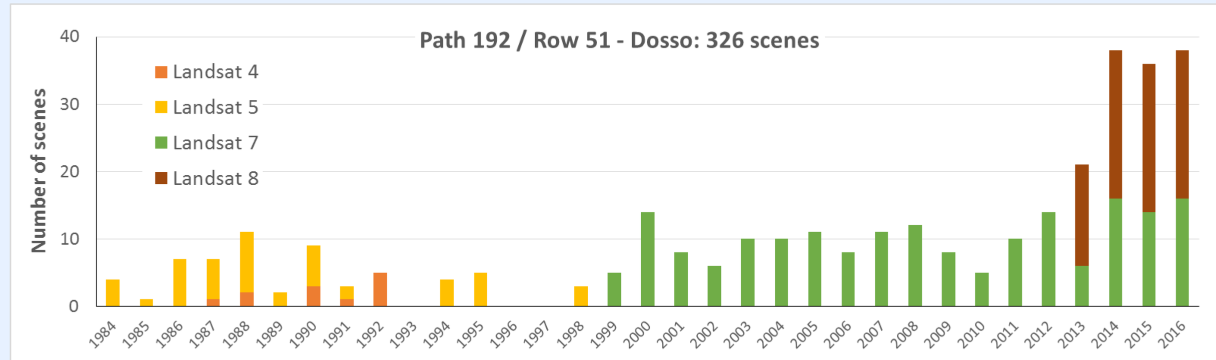

Fig. 3: Temporal availability of Landsat scenes and sensors for tile 192/51

5 Observations

The total number of valid observations per cell are restricted by:

1. the spatial and temporal availability of Landsat scenes due to the Landsat acquiring mission schedule with
2. high cloud cover during the rainy season (July - September).

The limited number of Landsat scenes for West Africa and high cloud cover during the pronounced rainy season (Fig 4) strongly restrict the number of observations (Fig 5) and bias the recorded occurrences of surface water.

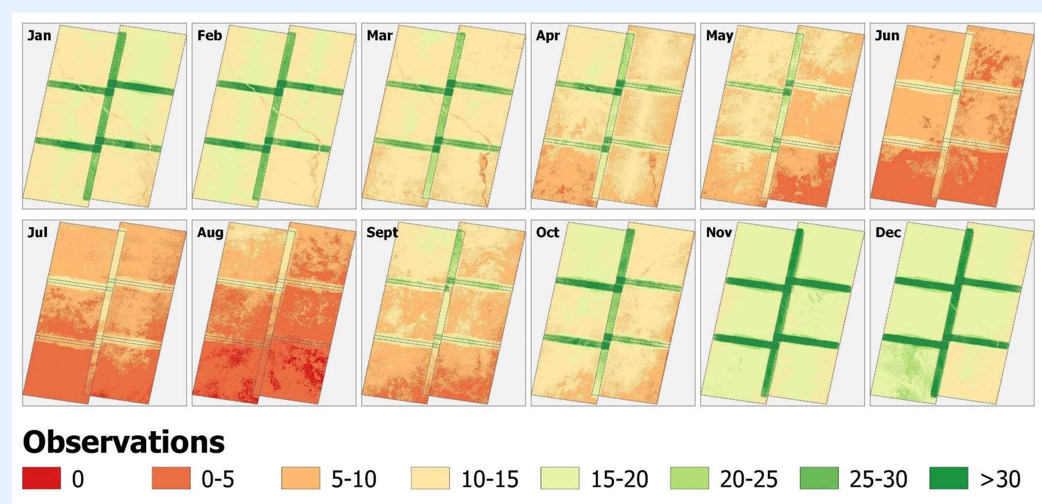

Fig. 5: Monthly distribution of valid observations within the study area. The unbalanced distribution highlights low numbers of observation in the cloudy rainy season, when observations on flooding is most important.

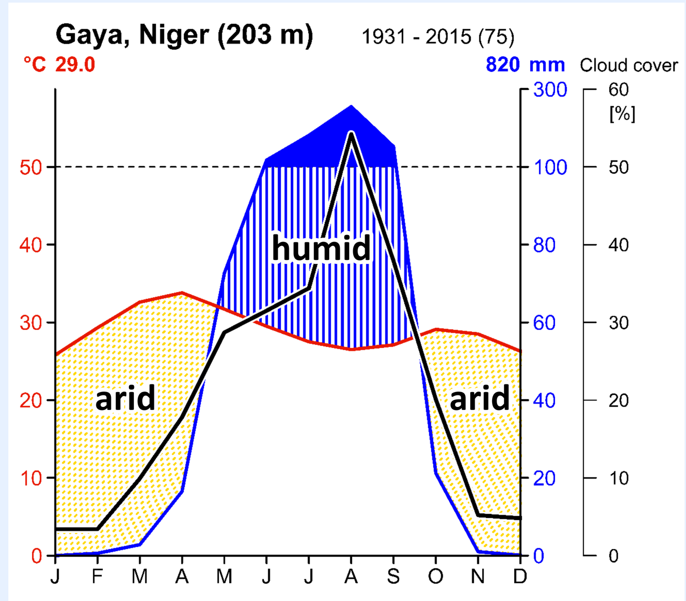

Fig. 4. Climate graph of Gaya, Niger, showing a semiarid climate, an unimodal rainfall pattern (7 arid and 5 humid months), and the average cloud cover calculated from satellite images.
Data source: GHCN v2 (Precip.), GHCN v3 (Temp.).

Results

6 Monthly water recurrence

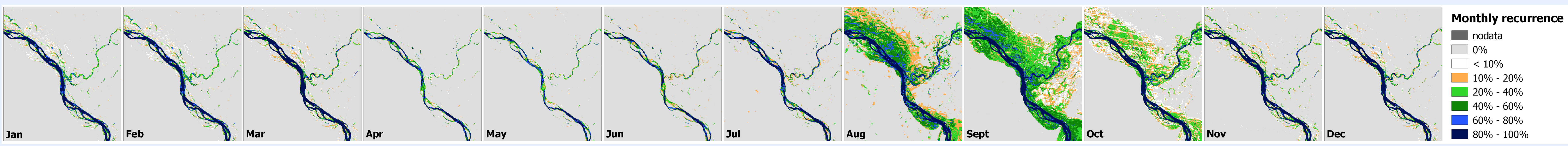

Fig. 6: Monthly water recurrence of the Sokoto – Niger confluence, Nigeria, reflecting the first flood following the local rains (August – September, "white flood") and prolonged high water levels of the Niger River (August – March , "black flood") due to the delayed arrival of the waters from the rainy season in the headwaters of the Niger River in Guinea, Côte d'Ivoire, and Mali.

7 Annual water recurrence

Water recurrence describes the inter-annual surface water variability for the years 1984 – 2016. It is measured as the frequency of water occurrence per cell and is expressed as the percentage of years between 1984 and 2016 an area was flooded. Water recurrence is calculated on a monthly (Fig 6) and annual basis (Fig 7).

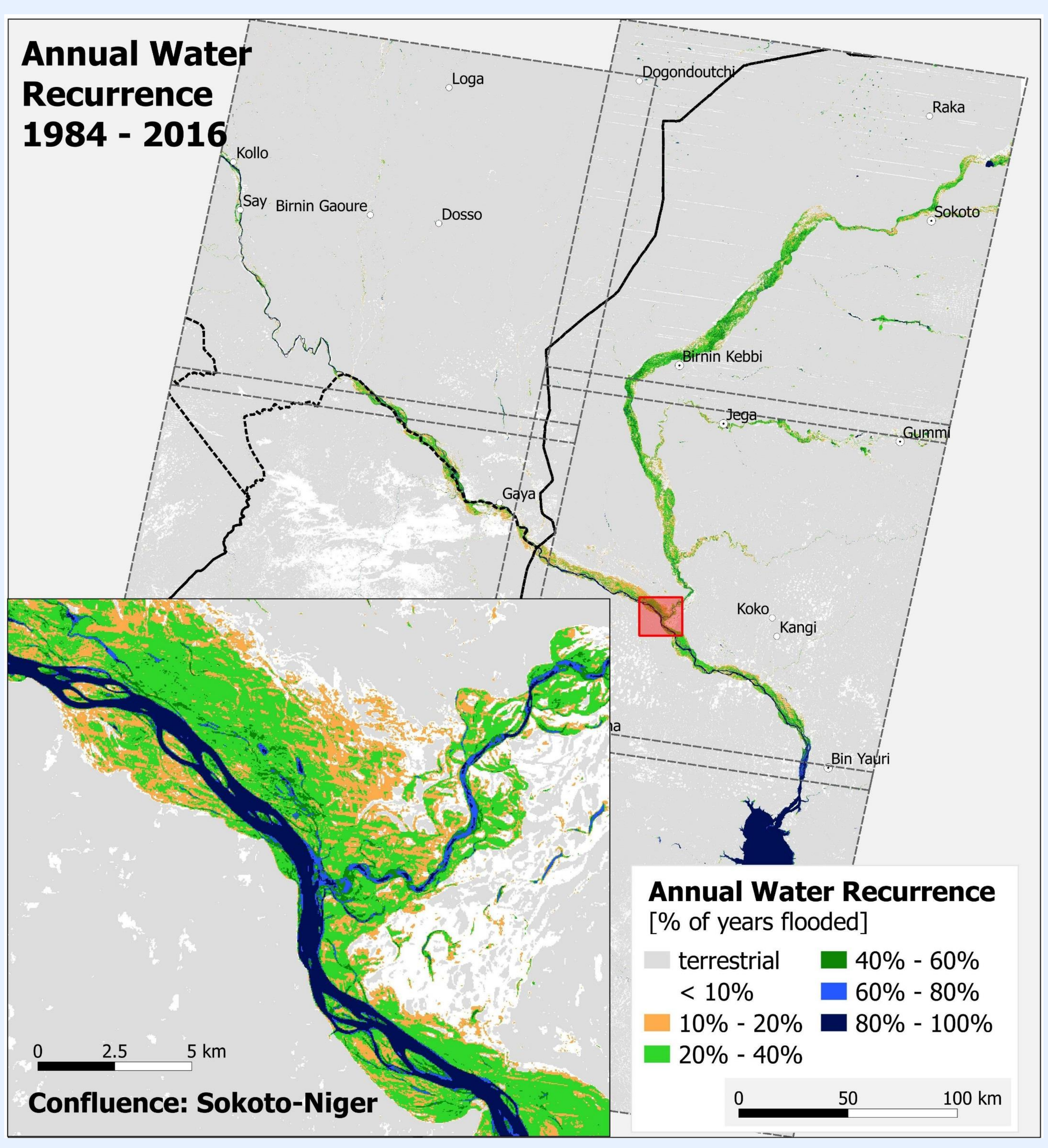

Fig. 7: Annual water recurrence delineating flood-prone areas and potential localized recharge zones.

8 Seasonality

Seasonality describes the intra-annual variability of surface water extent between 1984 – 2016. It is measured as the average number of months an area is flooded per year and allows to discriminate between permanent and seasonal water bodies. Seasonality <1 month or water recurrence less than 10% are strongly biased by low numbers of observations and reflect artefacts such as erroneous cloud masks.

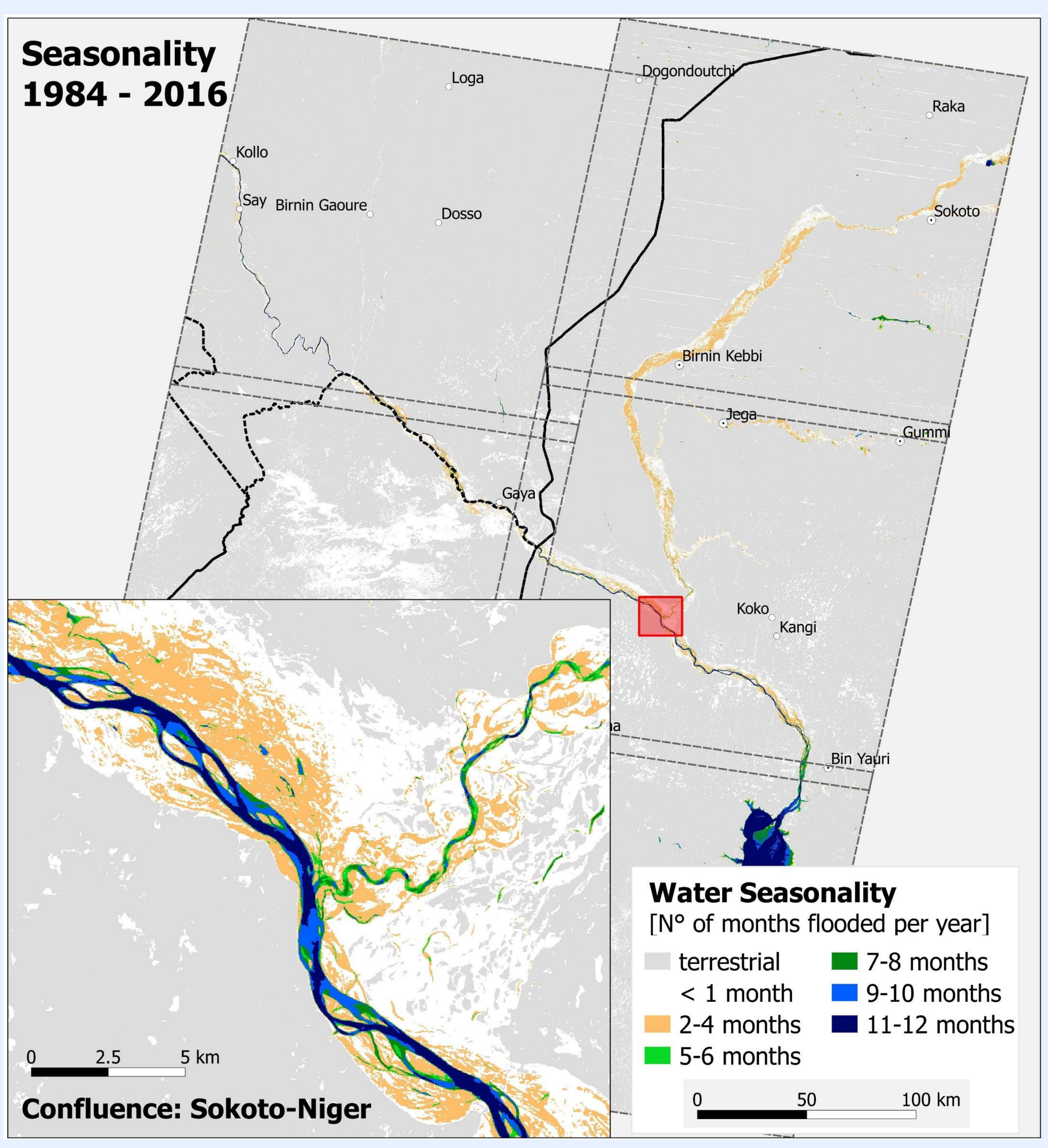

Fig. 8: Seasonality highlighting duration of flooding and activity periods of potential recharge zones.

9 Conclusions

MNDWI water body extraction using **Landsat time series** analysis offers

- a high spatial resolution (30m) for spatially detailed analysis
- a temporal depth (>30 years) for a robust analysis to delineate

➔ the average spatial and temporal distribution of a **minimum surface water extent**.

Shortcomings for water body extraction based on Landsat images are:

- low temporal resolution/long satellite revisit times (>2 weeks) prevent the detection of short rainfall events
- spatial resolution limits the extraction of small water bodies
- high plant water content interferes with the discrimination between surface water and vegetation in humid areas

Seasonality and **Recurrence** are **important tools** for:

➔ risk management and disaster prevention
➔ infrastructure planning
➔ recharge calculation

Recharge Calculation

Classification of **recharge zones** and **estimation of recharge quantity** can be based on

- frequency of flooding (recurrence 1984-2016)
- temporal relevance of flooding (seasonality)

Acknowledgements

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References

Desconnets, J (1994): *Typologie et caractérisation hydrologique des systèmes endoréiques en milieu sahélien* (Niger - degré carré de Niamey), Doctoral thesis, Université de Montpellier II
Favreau, G, Cappelaere, B, Massuel, S, Leblanc, M, Boucher, M, Boulain, N & Leduc, C (2009): Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review, *Water Resources Research*, vol. 45
Massuel, S (2005): *Evolution récente de la ressource en eau consécutive aux changements climatiques et environnementaux du sud-ouest Niger*., Doctoral thesis, Université de Paris
McFeeters, S (1996): The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features, *International Journal of Remote Sensing*, vol. 17, no. 7, pp. 1425–1432.
Xu, H (2006): Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery, *International Journal of Remote Sensing*, vol. 27, no. 14, pp. 3025–3033.