Orbital river gauge from optical and passive microwave radiometry. A comparison of capabilities

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Abstract

Climate change is impacting our everyday life and is altering the magnitude and frequency of weather-related extreme events such as precipitation, floods, and drought. For this reason, there is a great demand to study these phenomena in a changing environment on a large global spatial extent.
In the past, we developed a protocol for river gauge measurements using satellite passive microwave radiometer (PMR) data and applied over multiple river watersheds [2,1].
Exploiting the high sensitivity of microwave emission to water presence we use low frequency L-band (1–2 GHz) passive microwave radiometry (PMR) to monitor rivers and reservoirs and to compare over different microwave frequencies and polarization configurations. We successfully applied the methodology to ESA Soil Moisture and Sea Salinity (SMOS) sensor data reaching high correlation to in-situ discharge measurements over various river basins in different climate.
In this paper, we compare the capabilities of PMR and optical EO to observe river flow over the Amazon and Niger-Volta watershed. We tested the Moderate Resolution Imaging Spectroradiometer (MODIS), a low resolution (250 m – 5 km) NASA satellite data to derive hydrological time series. To understand the performance of optical orbital river gauge from MODIS comparable to the PMR gauge measurements we analyzed 8-day composite of Terra MOD09A1 in Google Earth Engine environment. The product is surface spectral reflectance of Bands 1 through 7 corrected for atmospheric conditions and averaged over an 8-day.
Results over tropical regions showed a significant obstacle of cloud cover for optical data (r2: 0.52, std: 0.33), where PMR has the potential to measure river streamflow (r2: 0.82, std: 0.12). Yet over regions with less clouds both optical and PMR can be good alternative to in-situ streamflow ground measurements.

1. Introduction

Satellite remote sensing is playing a key role in monitoring terrestrial run off as in-field measurements are costly to install and maintain on a global scale. In addition, hydrological observations are operated on a national basis where rivers crossing into several countries may have difficulties to obtain upstream flow data enabling proper water management and flood forecasting. There are good examples of international cooperations and initiatives of multinational data sharing like the Mekong Commission or the Danube Commission, yet it does not fully cover and enable the monitoring of global river flow. The importance of worldwide observations is becoming high priority as the advancement of global climate change necessitates a transcontinental understanding of weather driven phenomena such as the global water cycle and top-ranking natural disasters of flooding.
For this reason, since the early ages of satellite technology observing rivers was a fundamental application of orbital images. Ever since major efforts have been dedicated to use remote sensing in hydrology to expand and fill the gap in ground measurements. Schuman (2024) [3] reviews the evolution of satellite technology in flood mapping. The first satellites used for flood mapping were mid-resolution Landsat (30m) with a revisit capability of 16 days and MODIS with a daily frequency on low-resolution (1km). Yet the major limitation of optical data in river mapping is the cloud cover which blocks the visibility of the surface despite high revisit frequency. For this reason, since the availability of synthetic aperture radar (SAR) in the 1980' the all-weather satellites were used in river monitoring with a major limitation related to revisit frequency [22]. The launch of SWOT sensor has provided a state of-the-art in river monitoring by using innovative interferometric SAR technology, yet the repetition frequency of the sensors remains a major limiting factor.
The daily global monitoring of global runoff is however possible from passive microwave radiometry (PMR) which has been used extensively by Brakenridge and Kugler [2,1] and has been proved to provide river flow information since the launch of the first sensors in the 1970s. Despite low resolution the methodology can overcome major temporal limitations as it provides all-weather data on a daily basis.
This paper aims at studying the capabilities and limitations of PMR compared with optical remote sensing on the example of SMOS (2010-2024) and MODIS (2001 – 2024) data for river flow measurement. Aim is to discuss and provide guidelines on: 1) How limiting is cloud cover on optical data for river monitoring on different climate? 2) Is low resolution of PMR limiting factor? 3) Is river narrow channel a limiting factor for both observations? 4) What are the advantages related to the two different measurement technology? The study aims at finding answers related to these scientific questions related to remote sensing in hydrology.

2. Data and Methodology

2.1 Passive microwave SMOS data

Recent techniques using passive microwave remote sensing for river gauging can overcome the challenges of many optical satellite methods. Satellite systems based on PMR operate effectively independent of cloud cover. Systems operating in passive microwave bands feature a scanning swath approximately an order of magnitude wider than optical systems, allowing for the monitoring of larger areas with higher temporal resolution.
Fundamentally founded on the first principle of Maxwell equations, wide-swath satellite passive microwave radiometers can monitor river streamflow daily over decades with a

breakthrough robust method that circumvents the high-resolution requirement. Due to the high sensitivity of L-band microwave emission to water presence on the Earth's surface (up to 80 times higher permittivity than for land), even the coarse resolution, large footprint (20 – 30 km) of PMR (passive microwave radiometry) sensors enable the measuring of surface water extent on a subpixel scale when compared to nearby dry land [1,2]. This explains the essential potential of microwave remote sensing of water bodies compared to optical data and opens vast new potentials for hydrological observations. The PRM method utilizes the low resolution to fully cover water areal changes from low flow to peak flow (including all flood stages). In contrast, the high sensitivity of PMR signatures to river stage and discharge (rather than resolution) enables the hydrological measurements.
The methodology uses passive microwave emission in descending and ascending orbits, with H and V polarization at 1.4 GHz frequency, which is highly sensitive to water surface changes. Brightness temperature (T_b) measured by a passive microwave radiometer is related to the physical temperature (T) and the emissivity (ε) of the surface given by:

$$T_b = \varepsilon\, T \qquad (1)$$

Generally, a lower $T_b(m)$ occurs over a footprint containing water bodies compared to a higher $T_b(c)$ over a footprint on land without surface water. Under a constant physical temperature T, $T_b(m)$ decreases over locations along river channels where rising water levels cause a corresponding increase in water flow area extent (Figure 3).
Information related to surface water change is primarily conveyed in the emissivity controlled by the effective permittivity over the targeted area. At the same time, other factors such as roughness, soil moisture, vegetation cover, and atmospheric conditions may affect the brightness temperature as measured by an orbiting satellite radiometer above the atmosphere. According to equation (1), the physical temperature T must be cancelled to reach emissivity ε. This is achieved approximately by taking the measurement $T_b(m)$ value received over a river channel (measurement pixel) as the denominator, with the numerator being a calibration observation $T_b(c)$ not influenced by water area change (calibration pixel), which is chosen in the vicinity of the measurement pixel so that the physical temperature T is similar thanks to the correlation length of regional temperature variability. In this method, the signal ratio is defined by the relationship:

$$C/M = T_b(c)/T_b(m) \sim T\, \varepsilon(c)/\,[T\, \varepsilon(m)] = \varepsilon(c)/\varepsilon(m) \qquad (2)$$

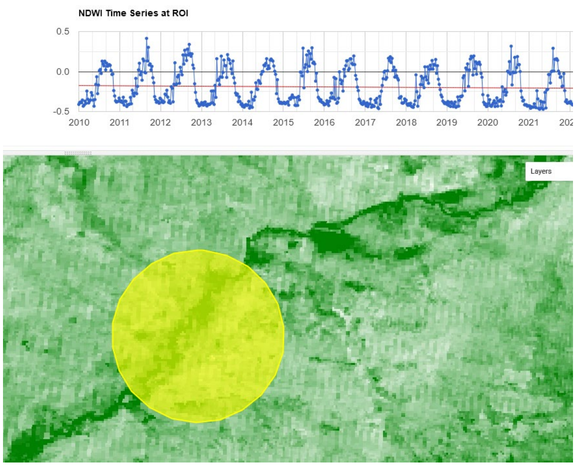
Where C/M refers to the commonly used C/M-ratio, $T_b(c)$ and $T_b(m)$ are the brightness temperature of the calibration and measurement pixel, respectively. The time series of the extracted C/M ratios result in satellite-based stream levels for selected stream reaches with a daily or near-daily temporal resolution. With this satellite method, the detection of flow condition changes, in principle, becomes feasible from space on a frequent temporal sampling basis in the tropics and higher latitudes. Our results include ESA Soil Moisture Ocean Salinity (SMOS) satellite data measuring hydrological time series over the Amazon and the Niger-Volta watersheds. The orbital level measurements include time series from 2010 to the present.

2.2 Optical MODIS data

To understand capabilities of optical remote sensing for river monitoring we analysed MOD09A1.061 dataset in the Google Earth Engine Data Catalogue (GEE). The MOD09A1.061 Terra Surface Reflectance 8-Day Global 500m dataset is a product of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite. This dataset provides an estimate of the surface spectral reflectance for MODIS bands 1 through 7 at a 500-meter resolution, corrected for atmospheric conditions such as gases, aerosols, and Rayleigh scattering. As of the writing of this paper the temporal coverage spans from February 18, 2000, to January 1, 2025, with data updated every eight days.
Each pixel in the dataset represents the best possible observation during the 8-day composite period. The selection criteria prioritize high observation coverage, low view angle, absence of clouds or cloud shadow, and minimal aerosol loading. The dataset includes seven reflectance bands, a quality assurance layer, and four observation bands. [17].
These bands are essential for various remote sensing applications, including vegetation monitoring, land cover classification, and change detection. The quality assurance layer provides information on the reliability of the reflectance data, indicating factors such as cloud cover, aerosol quantity, and other atmospheric conditions that may affect data quality. This allows users to assess the suitability of the data for specific applications.
The MOD09A1.061 dataset is widely used in environmental and climate studies due to its comprehensive temporal and spatial coverage. Its corrected surface reflectance values enable accurate analysis of terrestrial ecosystems and support various applications in Earth system science.
To calculate water surface extent on the floodplain we used the common calculation of the Normalized Difference Water Index (NDWI), which is used to monitor changes in water bodies and vegetation moisture content. NDWI is computed using the near-infrared (NIR) and shortwave infrared (SWIR) bands, specifically MODIS Band 2 (841–876 nm) and Band 5 (1230–1250 nm). The formula for NDWI is:

$$NDWI = \frac{\mathrm{Band}_2 - \mathrm{Band}_5}{\mathrm{Band}_2 + \mathrm{Band}_5}$$

Higher NDWI values indicate water presence, while lower values suggest dry conditions or land cover such as soil or vegetation [18]. This index is widely used for hydrological studies, flood monitoring, and drought assessment, making the MOD09A1 dataset an essential tool in Earth system science.
We used a 30 km buffer around each river reach location in line with the PMR approach. On figure 1 the GEE interface and the spatial extent of the buffer together with the extracted time series is visible.



1. Figure Time series of NDWI from MOD09A1 aggregated over 30km footprint (yellow)in Google Earth Engine

2.3 In-situ stage data

Accurate hydrological data is essential for water resource management, flood forecasting, and climate change studies. In South America, national hydrological agencies provide extensive datasets that support research and decision-making. Two key sources are the Sistema Nacional de Información de Recursos Hídricos (SNIRH) in Peru and the Sistema Nacional de Informações sobre Recursos Hídricos (SNIRH) in Brazil.
Peru’s SNIRH [19] is managed by the Autoridad Nacional del Agua (ANA). This platform provides real-time and historical hydrological data archive, including river discharge, precipitation, and groundwater levels. It integrates data from multiple monitoring stations across the country, supporting water resource planning, disaster risk management, and hydrological modeling. Given Peru’s vulnerability to extreme hydrometeorological events, such as El Niño-driven floods and droughts, SNIRH plays a critical role in early warning systems and climate adaptation strategies.
Similarly, Brazil’s SNIRH [20] is managed by the Agência Nacional de Águas e Saneamento Básico (ANA). The HidroWeb database within SNIRH provides access to historical and real-time hydrological time series, including river stage, discharge, and rainfall data from an extensive monitoring network. As Brazil has the largest river system in the world, including the Amazon Basin, SNIRH is vital for managing water resources, predicting extreme hydrological events, and supporting transboundary water cooperation.
These datasets provided by Peru’s SNIRH [19] and Brazil’s SNIRH [20] serve as valuable sources of river discharge, precipitation, and water level data for scientific research. These datasets can be processed using Python, allowing for automated data analysis, visualization, and integration with other hydrological and climatic datasets.
Data preprocessing can be efficiently conducted using Pandas, while numerical computations can be facilitated through NumPy. Visualization of trends and patterns can be achieved using Matplotlib and Seaborn.
By employing Python-based processing methods, these national hydrological datasets can be effectively utilized to improve large-scale water resource monitoring, supporting data-driven decision-making in hydrology and climate research.

3. Results

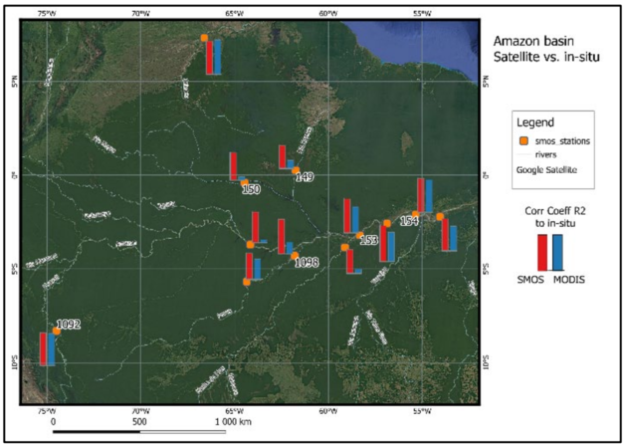
The capabilities of PMR and optical remote sensing for river flow monitoring has been explored in two selected study area; the Amazon watershed in South America and Niger-Volta watershed in West Africa. Comparison with in-situ data has been carried out over the Amazon main channel and its selected tributaries. Outputs and results are summarised in the following sections.

3.1 Tropical forest Amazon watershed

Comparison of PMR and MODIS time series has been carried out with combination of in-situ ground station data from Brazil and Peru. Satellite data was related to river stage measurements from the national water authorities and correlation was calculated in form of correlation coefficient (r2) for each river reach.

Table 1. River flow from SMOS and MODIS compared to in-situ data in the Amazon basin. Correlation coefficient is calculated with ground data.

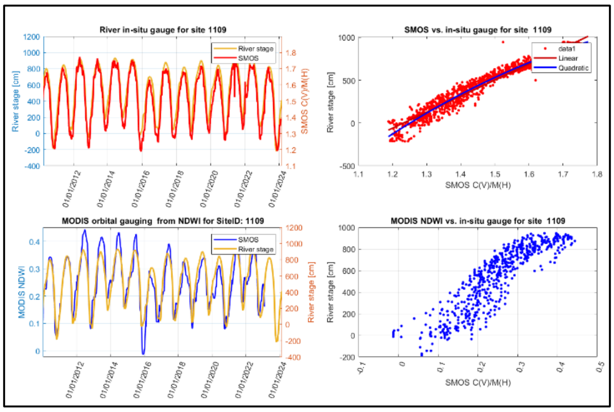
SiteID	Lat (deg)	Lon (deg)	Gauge Name	R-to smos	R-to modis
155	2.22	54.05	Santarém	0.864	0.665
154	2.09	55.34	Óbidos	0.914	0.876
153	3.20	58.32	Itacoatiara	0.912	0.698
1109	2.57	56.87	Parintins	0.960	0.790
1105	3.86	59.12	Nova Olinda Do Norte	0.645	0.122
1098	4.30	61.80	Beruri	0.927	0.313
152	3.70	64.16	Tefé - Missões	0.820	0.085
1099	5.68	64.35	Bacaba	0.700	0.545
144	7.31	66.61	Orinoco	0.885	0.927
150	0.40	64.48	Serrinha	0.737	0.095
149	0.25	61.75	Caracaraí	0.617	0.217
1092	8.38	74.53	Pucallpa-Lpo	0.877	0.860



2. Figure Correlation of orbital river gauge from MODIS and SMOS compared with ground stage observations in the Amazon watershed. Generally, higher correlation values were found for SMOS than for MODIS.

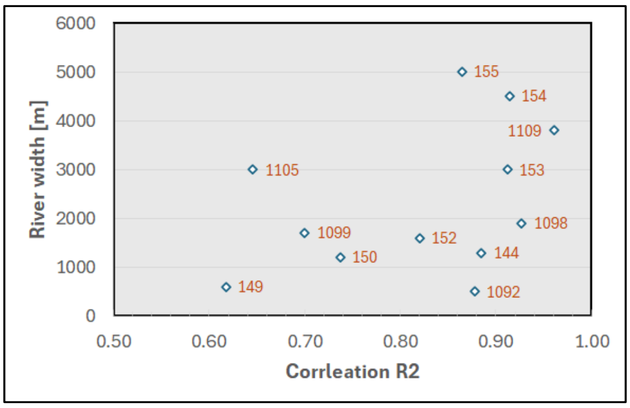
Highest agreement between ground and orbital observations for both optical and microwave sensors was found over the Amazon River around Obidos (Site ID 154) where both sensors showed a high accuracy in retrieving river stage from space (SMOS r2=0.91; MODIS r2=0.87). The river channel of the Amazon is about 4000 m wide at the reach surrounded by large lakes along the floodplain. The latter increases the open surface water ratio in the satellite footprint and enables the better detecting of flow area variation. Yet higher agreement to ground stage was found over PMR observation.
About 200 km upstream the Amazon River at the Parintins station (SiteID 1109) the highest consistency between PMR and in-situ stage (SMOS r2=0.96) was calculated compared to the lower correlation with MODIS observation (MODIS r2=0.79). Here the channel is again wide with an average width of 3500 m surrounded by floodplain lakes.

The lower correlation of optical data in the watershed may be due to the impact of both vegetation and cloud cover. In the Amazon River floodplain inundation is often covered by dense vegetation which can hinder the detection of open surface water below the forest canopy from optical data. PMR can overcome this key limitation as low frequency passive microwave signal can better penetrate vegetation and receive signal from the ground despite dense forest. For this reason, the detection of dense vegetated open surface water is possible from SMOS. And the received orbital river signal is in a higher agreement to ground stage compared to optical MODIS data. Besides, optical MODIS can be temporally limited by cloud cover which is not the case for all-weather microwave emission.



3. Figure Left: SMOS (red) orbital river gauge compared to in-situ (yellow) and MODIS (blue) aggregated NDWI compared to in-situ stage (yellow)over the Amazon River at Parintins (SiteID 1109) in Brazil. Right: Scatterplot reveals high correlation to SMOS (red) with lower correlation to MODIS (blue)

Both effects can contribute to the generally lower correlation of optical data (ave. MODIS R2=0.51; ave SMOS R2=0.82) to ground measurements not only along the main Amazon River channel (Site ID 153-155 and 1109) but also along its tributaries.

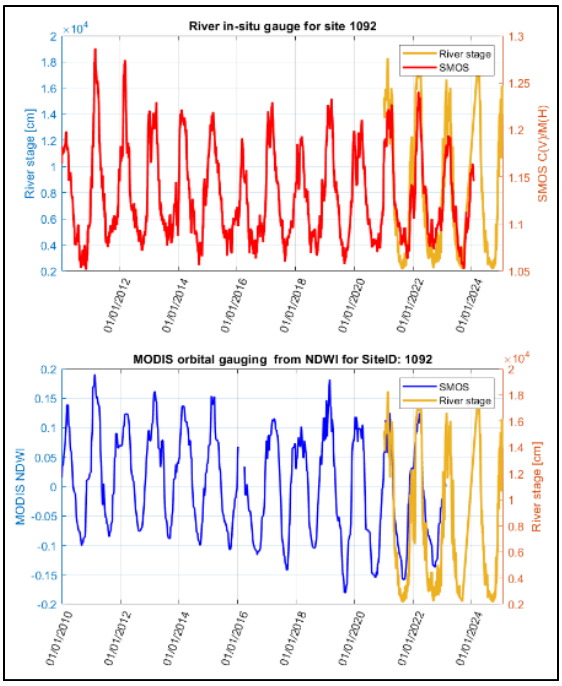


4. Figure No relation is detectable between SMOS orbital river gauge accuracy and river channel width. Not only large but also medium width river reaches can be monitored with PMR data despite low (25km) resolution.

In this study, we used the 25km daily gridded SMOS time series from 2010 to 2024 and observed river flow on river reaches of various width. We compared average river channel width with PMR performance as correlation to in-situ station data. As demonstrated on figure 4 there is no relation between the performance of the SMOS observations and the river width thus both large and narrow river reaches can be monitored from PMR. Despite large 25 km footprint SMOS is capable to capture river flow variations over reaches of 500 to 5000m width with high correlation to ground measurements. Thus, the low resolution of PMR data does not limit the use of the sensor type for river flow monitoring. PMR enables the monitoring of both small and large rivers because it is not dependent on the river channel size but on the sensitivity to change in the total area of river surface extent during stage variation.

In previous works [1], we provided evidence that the PMR river gauge approach can monitor narrow rivers with 50-100 m width over the Mekong tributary given the basic assumption that the floodplain is facing significant river flow area expansion during stage rise. Thus, the river width is not limiting the observation of river flow area changes from passive microwave observations despite low resolution of 36 km footprint of SMAP. The reason for this is the sensitivity of the microwave signal to water. As there is an almost 80x difference between land permittivity and water permittivity the microwave signal is fundamentally impacted by the increase of water surface area within the PMR footprint thus can effectively detect water presence on a sub-pixel basis.

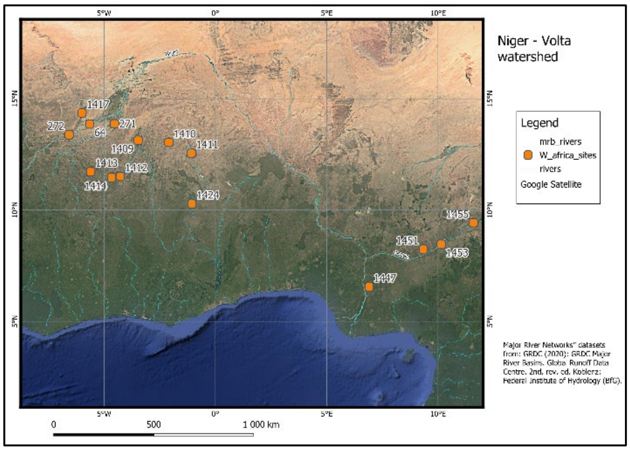
PMR and optical observations have been tested on the River Ucayali in Peru too (figure 5). Both satellite approaches provided high (>0.8) correlation to in-situ discharge. Yet the low stage conditions are not well captured by MODIS as a notable bias emerges from 2010 to present. Thus, the minimum stage has a higher uncertainty than for PMR. On the other hand, in-situ data is only available for a short period (2020-2025). Decadal satellite data could be used to work as a time machine; calibrate data based on the temporal overlap and retrieve calibrated orbital data in the past. The same methodology could be applied to NASA's SWOT Interferometer (KaRIn) instrument data measuring stage globally with low temporal 21-day repeat orbit. PMR could serve to fill the gap between observations and SWOT could be used to calibrate PMR data worldwide.



5. Figure SMOS (red) orbital river gauge compared to in-situ (yellow) and MODIS (blue) aggregated NDWI compared to in-situ stage (yellow)over the Ucayali River at Pucallpa-Lpo (SiteID 1092) in Peru.

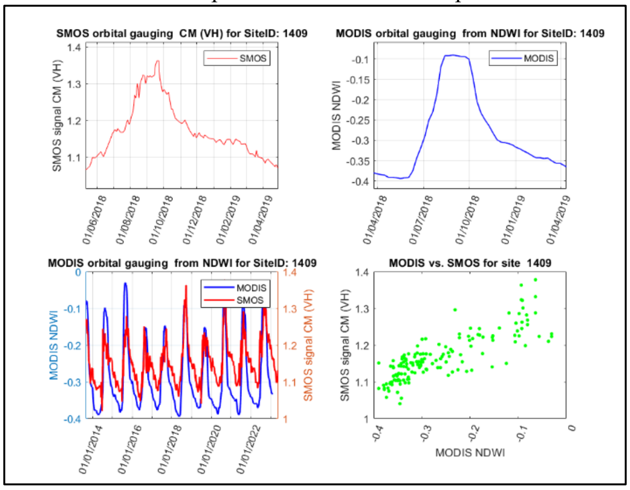
3.2 Semi-arid Niger watershed

Study was continued in the Niger River basin which is the largest in western Africa and the Niger is Africa’s third longest river (4,200 km). The drainage basin is 2,117,700 km2 in area (ten times as large as the Rhine basin), is spread over nine countries (Benin, Burkina Faso, Cameroon, Chad, Côte d’Ivoire, Guinea, Mali, Niger und Nigeria) and is home to more than 160 million people. High population growth combined with the impact of climate change and changes in land use are putting increasing pressure on the water resources, which are already unevenly distributed. [26]
The Niger Basin Authority (NBA) is an intergovernmental organization aiming to foster co-operation in managing and developing the resources of the basin of the Niger River. Optical and passive microwave river observations in West Africa were not validated as the NBA authority does not maintain public hydrological data portal.
We selected 15 river reaches over the Niger-Volta River basin to study capabilities of both PMR and optical imagery (figure 6, appendix 1). The North of the watershed is a semi-arid region with non-regulated river channel thus water expands over the floodplain during rising stage enabling the monitoring of river flow from area. Both optical and PMR are capable to detect flow area changes over the basin as cloud cover is not significantly hindering the observation of the region.



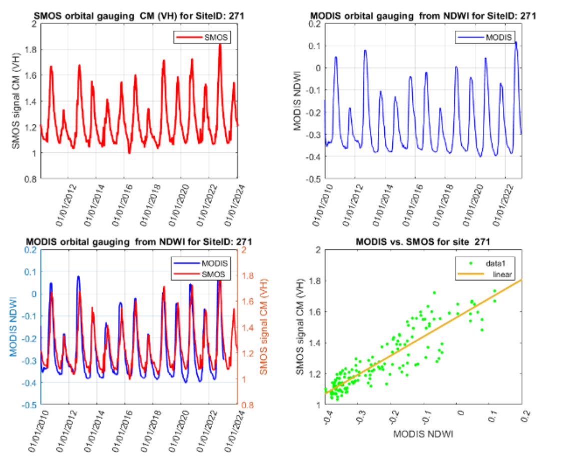
6. Figure Map with location of 15 observed river reaches studied from SMOS PMR and MODIS optical imagery in the Niger-Volta watershed

The frequency of the observations for MODIS are evenly distributed in time with 8-days frequency. Out of the 8-days the least cloudy images are selected and assigned to the given time frame. For this reason, each river location had 603 observations from 2010 to 2024. In contrast, SMOS has an average revisit frequency near the Equator (lowest temporal revisit) every 3-5 days in average. In general, 2-3 times more frequent data was available from low resolution SMOS for river monitoring as compared to MODIS. Rivers can face significant changes in stage within days yet alone flash floods that dramatically rise and fall in 24 to 48 h. Therefore, the higher the temporal resolution of the sensor the better chances there are to capture major hydrological events not only over large gradually changing rivers but over rapidly changing medium to narrow river reaches too.
During the wet season, which spans from May to October, rainfall causes high flow regimes while during the dry season flow remains low. The strong seasonal variation is captured on both optical and PMR dataset.
As no ground data was available in the region only extreme stages could be verified from the data. In early August 2018, communities in Northern and Upper East regions of Ghana were affected by heavy and continuous seasonal rainfall, which was exacerbated by the annual opening of the Bagre dam. [24]
Over the Black Volta (SiteID 1409) (figure 7) in Burkina Faso watershed the river width is around 250m with a major expansion to almost 4000m width in the peak flow period. The flood event in 2018 has been captured by SMOS and MODIS peaking early September 2018. Major flood in 2021 was also confirmed both on Relief Web bulletins [25] and SMOS satellite data. However major peak value on MODIS times series in 2015 could not be verified and seems to provide false alert from optical data.



7. Figure SMOS (red) and MODIS (blue) orbital gauge observations over the Black Volta in Burkina Faso (SiteID 1409)

In up-stream region of the Niger River in Mali watershed over both MODIS and SMOS seems to well capture the seasonal variation of river flow (figure 8). The correlation between the two time-series is over 0.8. The river reach is characterised with low vegetation cover and dry semi-arid climate where cloud cover does not have a major effect on optical observations. Even the major peak flow years seems to have a good agreement in the year 2018, 2021 and 2023 confirmed by ReliefWeb reports. [25]



8. Figure SMOS (red) and MODIS (blue) orbital gauge observations over the Niger River in Mali (SiteID 271)

Discussion and Conclusions

We provided evidence that not only large but also medium and narrow river reaches can be monitored by the low resolution (25km) PMR river gauge approach from SMOS due the high sensitivity of microwave emission to water presence on the

surface. In addition, microwave signal can penetrate through clouds thus its all-weather capability enables the high temporal frequency required for river monitoring (1-3days depending on latitude). This exceptional capability provides a huge advantage over optical datasets commonly used in river monitoring practice. Optical RS is significantly limited by cloud cover especially in tropical climate zones or during monsoonal precipitation that can last for weeks allowing no optical observation.
The major limitation related to PMR river monitoring can be steep river channel topography. The methodology highly depends on the surrounding surface terrain elevation as observations are based on river flow area variations. If river channel is narrow (mountainous terrain) or regulated with vertical walls (like in built-up environment) where no water flow area expansion happen the methodology is not able to observe river stage variation. Yet where river channel can expand on the floodplain even minor flow area changes can be detected and the evolution of river flow monitored with high accuracy to in-situ ground station data as demonstrated in this study.
The importance of temporal frequency for hydrological observation is fundamental in capturing not only gradually but rapidly changing events such as floods. In general, the higher revisit frequency the higher chances that no major event is missed over the monitored river section. Since PMR is not affected by cloud cover the low resolution is of advantage as it allows frequent acquisition. Another major advantage is related to the long-term data records with global data coverage since the late 1970s that can be calibrated to stage using in-situ or model data even if only available for some limited overlapping period in the past.

In sum, PMR has many advantages over optical river monitoring not only in temporal resolution but also in sensitivity to water presence on the surface. For this reason, SMOS river gauging can provide an effective and robust technique in frequent orbital and global monitoring of in-land water and is not limited or hindered by low spatial resolution. Limitations of the methodology are related to the requirement of river flow area variation. If no floodplain inundation happens the approach cannot be applied.
In the future there is a strong need to compare PMR results to SWOT the latest innovation in SAR interferometric river measurements.

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Appendix

Appendix 1
Locations of satellite observations over the Niger – Volta watershed

SiteID	**Lat (deg)**	**Long (deg)**	**River**	**country**
64	13.86082	5.64284	Niger	Mali
271	13.87498	4.52464	Bani	Mali
272	13.38177	-6.5677	Niger	Mali
1409	13.13348	3.46138	Black Volta	Burkina Faso
1410	13.04007	2.09144	White Volta	Burkina Faso
1411	12.55341	1.07596	White Volta	Burkina Faso
1412	11.50919	4.26802	Black Volta	Burkina Faso
1413	11.71995	5.59772	Lotio	Mali
1414	11.45171	4.65888	Black Volta	Burkina Faso
1417	14.36116	-5.98859	Canal du S ahel	Mali
1424	10.28774	1.05105	White Volta	Ghana
1447	6.556325	6.904188	Anambra	Nigeria
1451	8.238095	9.343256	Ankwe	Nigeria
1453	8.464183	10.14415	Benue	Nigeria
1455	9.426016	11.59648	Benue	Nigeria