DOI:10.28974/idojaras.2023.4.4

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 127, No. 4, October – December, 2023, pp. 473–484

A comparison of river streamflow measurement from optical and passive microwave radiometry

Zsófia Kugler * and **Viktor Győző Horváth**

Department of Photogrammetry and Geoinformatics
Budapest University of Technology and Economics
Műegyetem rkp. 3, H-1111 Budapest, Hungary

**Corresponding author E-mail kugler.zsofia@emk.bme.hu*

(Manuscript received in final form September 15, 2023)

Abstract— Climate change has a crucial impact on the global energy and water cycle. The hydrological cycle can be studied both from ground and satellite measurements on a global scale. Yet a comprehensive overview is challenging to establish given the spatial and temporal limitations related to various Earth Observation satellite sensors or maintenance of in-situ gauges. Optical remote sensing of visible light can not overcome the substantial obstacle from cloud cover that vastly limits its capability in daily global monitoring. Active satellite sensors like SAR or altimetry are not capable to provide global coverage on a daily basis, therefore, they can be geographically limited. Passive microwave radiometry (PMR) can acquire both daily and global scales that enables the temporally frequent and spatially extensive observations of continental river gauge. Previous studies demonstrated the use of PMR measurements for global daily river gauge benefiting from its high sensitivity of microwave radiation to water presence. This study aims at comparing the methodology of PMR to optical river gauge measurements based on the assumption that at selected locations along the river channel, increase in streamflow is related to increase in the floodplain water surface inundation. Comparison showed a significant obstacle of cloud cover over tropical regions, where PMR has the potential to measure river streamflow. Yet over regions with less clouds both optical and PMR can be good alternative to in-situ streamflow ground measurements.

Key-words: passive microwave radiometry, optical remote sensing, space hydrology, climate change impact, river gauge

1. Introduction

Climate change is impacting our everyday life and alters the magnitude and frequency of extreme weather related events such as precipitation, floods, and drought.

The Moderate Resolution Imaging Spectroradiometer (MODIS), a low resolution (250 m – 5 km) NASA satellite is playing a key contribution in applications that require frequent, large-scale observations such as streamflow monitoring. The two platforms, carrying MODIS sensor on-board, Aqua (launched in 2002) and Terra (launched in 1999) are monitoring the Earth every day with an almost full coverage of its complete surface for more than two decades. The unique collection of MODIS data for this reason enables long term monitoring of environmental phenomena and variations or trends in their behavior. It has the significant potential to capture river flow variations and assess global trends with the use of extended time series stretching over decades. Data can be obtained on no charge basis from different services like the https://modis.gsfc.nasa.gov/data/ that collects and provides data on different productions levels and applications like land, cryosphere, and oceans. MODIS is also provided on a near-real time basis at https://worldview.earthdata.nasa.gov/ just within 3–5 hours of being observed enabling rapid response to different types of natural or man-made disasters.

For all the above advantages, MODIS is playing a unique contribution to map physical processes of the Earth, especially to monitor the evolution of river streamflow on an almost daily frequency. Therefore, numerous applications have flourished in the past using MODIS images to observe rivers (*Brakenridge* 2005*, Zhan et al*, 2002; *Thenkabail*, 2005; *Sakamoto*, 2007; *Tarpanelli*, 2020). Still to overcome significant limitations related to cloud cover, the use of microwave emission of the Earth's surface measured by passive microwave satellite radiometers (PMR) has a notable contribution to continental streamflow measurement as demonstrated in several previous publications (*Brakenridge,* 2007, 2023; *Kugler et al.,* 2019)

In the past, we used both satellite Ka- (36.5 GHz) and L-band (1-2 GHz) passive microwave radiometry (PMR) data to acquire river discharge around the globe on a near-daily basis. Methodology is even capable of monitoring arctic river ice break-up during spring and freeze-up in the autumn allowing to understand climate change related internal variations of ice phenology at high latitudes (*Podkowa*, 2023).

2. Methodology

2.1. Passive microwave radiometers

The aim of using PMR in streamflow observations is the long-term, systematic monitoring of rivers across the world. The method was initially developed for Ka-band AMSR-E passive microwave senor data. The observations of the descending orbit, H polarization, and 36 GHz frequency, were found to be sensitive to water surface changes. In further studies we extended our investigations to low frequency PMR like ESA SMOS and NASA SMAP (2 GHz) sensors due to its better performance on tropical humid climate (*Kugler*, 2019). Brightness temperature (*Tb*) measured by a passive microwave radiometer is related to the physical temperature (*T*) and the emissivity (ε) of the surface given by:

$$Tb = \varepsilon\, T. \tag{1}$$

In general, a lower $Tb(m)$ occurs over a footprint containing water bodies compared to a higher $Tb(c)$ over a footprint on land without surface water. Under a constant physical temperature T, $Tb(m)$ decreases over locations along river channel, where rising water level (river stage) causes a corresponding increase in the water surface extent. However, microwave radiation is also influenced by many factors including physical temperature (T), permittivity (P), surface roughness (R), and soil moisture (θ):

$$Tb = \mathrm{f}\,(T, P, R, \theta)\ . \tag{2}$$

Information related to surface water change is primarily conveyed in the emissivity controlled by the effective permittivity over the targeted area, while 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 Eq.(1), the physical temperature T must be cancelled out in order to get at the emissivity ε. This is achieved approximately by taking the measurement $Tb(m)$ value received over a river channel (measurement pixel) as the denominator with the numerator being a calibration observation $Tb(c)$ not influenced by water change (calibration pixel), which is chosen in the vicinity of the measurement pixel so that the physical temperature T is similar thanks to the long correlation length of regional temperature variability. In this method, the signal ratio is defined by the relationship:

$$C/M\ Ratio = Tb(c)/Tb(m) \sim T\,\varepsilon(c)/\ [T\,\varepsilon(m)] = \varepsilon(c)/\varepsilon(m)\ , \tag{3}$$

where $Tb(c)$ and $Tb(m)$ are the brightness temperature of the calibration and measurement pixel, respectively.

The time series of the extracted *C/M* Ratio results in systematic satellite based hydrograph measurements for selected river reaches with a daily or near-daily temporal resolution. With this satellite method, the detection of flow condition changes over ungauged and inaccessible remote river channels is, in principle, feasible from space on a frequent temporal sampling. To compare PMR technics to optical low resolution data, we selected 22 satellite river gauges (SGR) over various river basins around the world from a PMR database of 2000 monitored SGRs (*Fig. 1*), over which PMR was proved to be in good agreement with ground measurements (*Kugler*, 2019). Data was compared for a time series from 2010 to present.

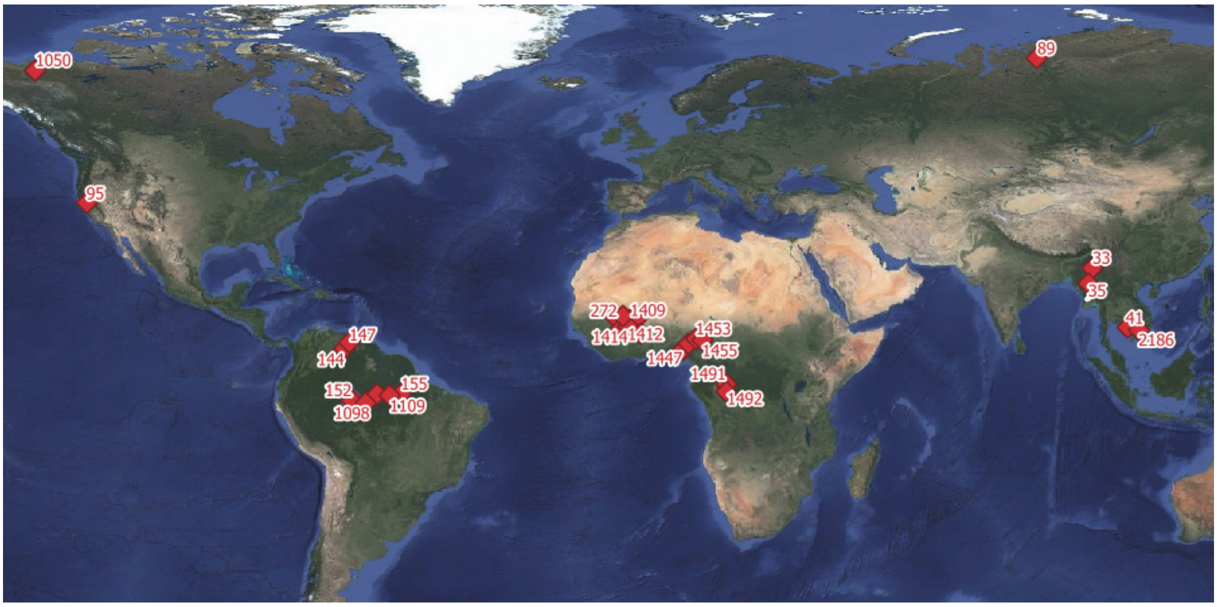

Fig. 1. Map of river gauging sites around the globe obtained from both PMR and optical data.

2.2. Optical MODIS data from Google Earth Engine

To compare PMR streamflow observations to MODIS river gauge, we use Google Earth Engine (GEE) to analyze considerable amount of optical satellite time series. Calculations were carried out on the Google Earth Engine Code Editor, a web-based integrated development platform (IDE) for the GEE JavaScript Application Programming Interface (API) (*Fig. 2*). GEE is an online cloud computing platform for processing multispectral and SAR satellite imagery. GEE was launched in 2010, and its datasets have been continuously expanded ever since. GEE is a free of charge web-based tool for academic purposes, where commercial use has recently been limited. GEE provides both Python and JavaScript APIs to the petabyte size Earth Observation (EO) satellite dataset of several decades. GEE Code Editor offers a Google Maps-based data visualizer capable to store and analyze satellite data. Numerous data sources can be instantly accessed and processed using GEE, which is very convenient for global or time related remote sensing studies (*Gorelick* 2017).

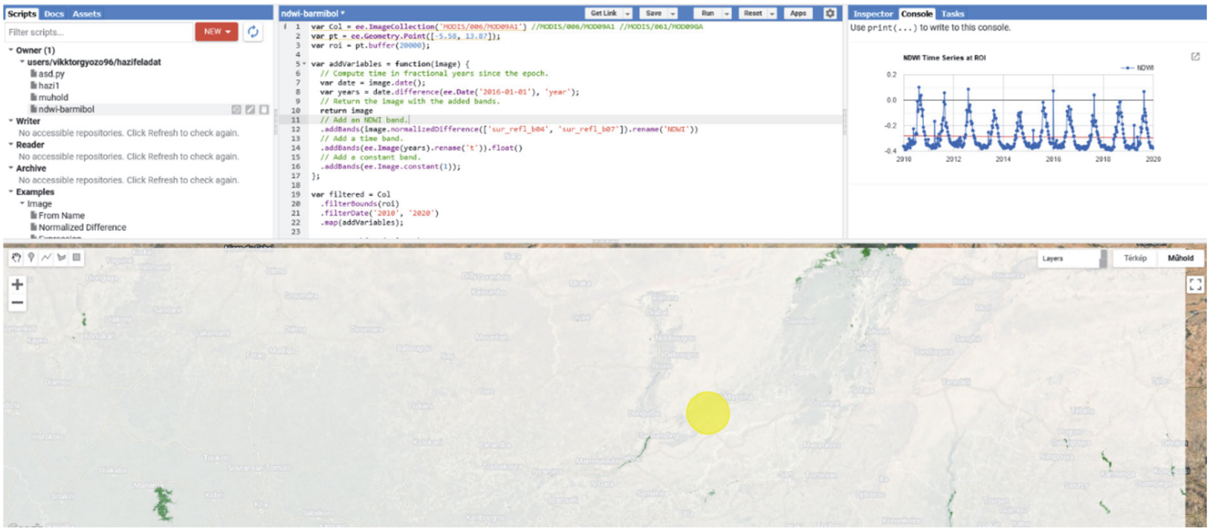

Fig. 2. Google Earth Engine Code Editor IDE capable to analyze several decades of Earth Observation satellite data. Yellow circle marks the extent of the 20 km buffer around SGR to select MODIS observations for streamflow analysis.

For comparison with PMR streamflow observations, we analyzed the MOD09A1.061 Terra Surface Reflectance 8-Day Global 500m dataset. This is a pre-processed dataset from data recorded by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the Terra satellite, which was launched in 1999. At the time of writing data can be accessed in the February 18, 2000 – July 4, 2023 time interval from this dataset. Terra-MODIS instruments scan the entire Earth's surface every 1 to 2 days. Terra MOD09A1 Version 6.1 product used in this study provides an estimate of the surface spectral reflectance of Terra MODIS Bands 1 through 7 corrected for atmospheric conditions such as gases, aerosols, and Rayleigh scattering. For each pixel, a value is selected from all the acquisitions within the 8-day composite period. The criteria for the pixel choice include cloud and solar zenith. When several acquisitions meet the criteria, the pixel with the minimum channel 3 (blue) value is used. (https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD09A1)

The dataset used in the analysis has a spatial resolution of 500 meters with the following bands and spectral resolutions:

sur_refl_b01	620–670 nm
sur_refl_b02	841–876 nm
sur_refl_b03	459–479 nm
sur_refl_b04	545–565 nm
sur_refl_b05	1230–1250 nm
sur_refl_b06	1628–1652 nm
sur_refl_b07	2105–2155 nm

To resemble the methodology of PMR observing water surface changes within the footprint of the microwave observations, we calculated NDWI for each MODIS pixel. For the NDWI calculations, the 4th band (545–565nm) and the 7th band (2105-2155nm) were used, with the standard formula of:

$$NDWI = \frac{(sur\_refl\_b04\ - sur\_refl\_b07\,)}{(sur\_refl\_b04\ + sur\_refl\_b07\,)}\,. \tag{4}$$

Because of the low spatial resolution of MODIS, data was aggregating neighboring pixels around the predefined locations of the selected 22 PMR SGR. Around each selected SGR location, a circular buffer of 20 km was applied, and NDWI values for each calculated pixel within the area are aggregated (*Fig. 3*). Calculations and display for one point took around 470 secs in GEE for the time series 2010–2022, but from this around 400 is displaying the calculated mosaics. Generating time series plots of any SGR took 10 seconds for 10 years of data. There was no filtering based on quality metrics provided for individual MODIS scenes (e.g., cloudy weather).

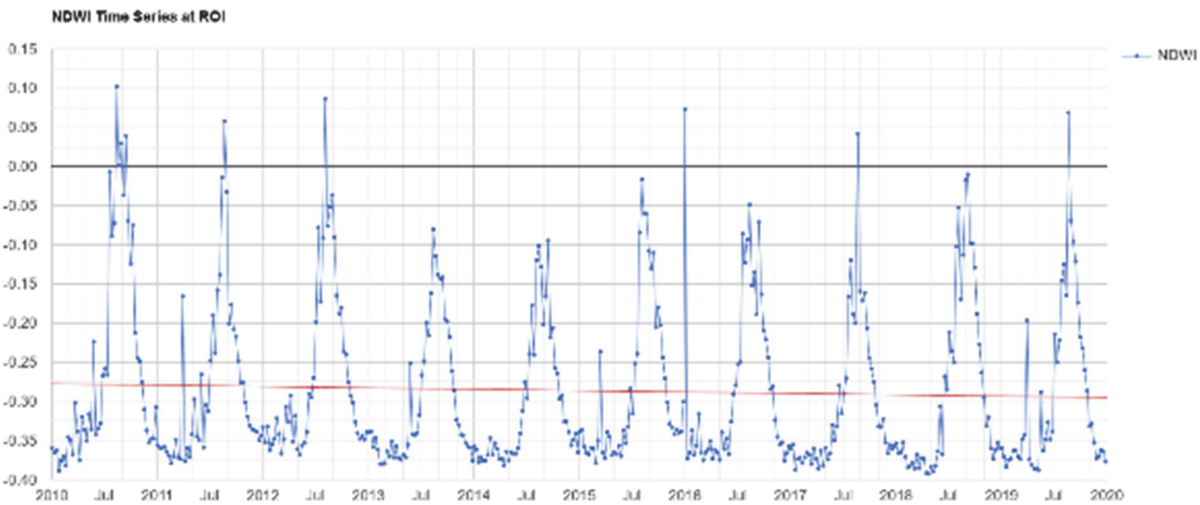

Fig. 3. A dataset derived in the 2010-2020 range for the SGR 64 over the Niger River, in Nigeria.

The time series were then automatically converted to a CSV format so they could be compared with previous PMR data analyzed in MATLAB environment. The script has been run for 22 SGR sites, and then compared to PMR streamflow observations from SMOS time series (2010–2022).

3. *Results*

The satellite river gauge observation from optical MODIS and PMR SMOS data show similar pattern in time (*Fig. 4*). As on the example of the Irrawaddy River in Myanmar SGR 35 (22.13°N, 96.03°E), both SMOS and MODIS follow the annual periodicity of the streamflow with high-flow state during summer and low-flow state during winter. Both time series follow the annual variation of humid tropical climate dominated by monsoon precipitation between May and October. In-situ data collected at Mandaly gauging station in Myanmar reflects high correlation between satellite and ground streamflow measurement regardless of the optical or PMR dataset (*Fig. 4*). Both dataset are in a high correlation as shown on the scatterplot. Results underline the robustness of the methodology observing water surface area change as an indicator for streamflow variation from both optical and microwave radiometers.

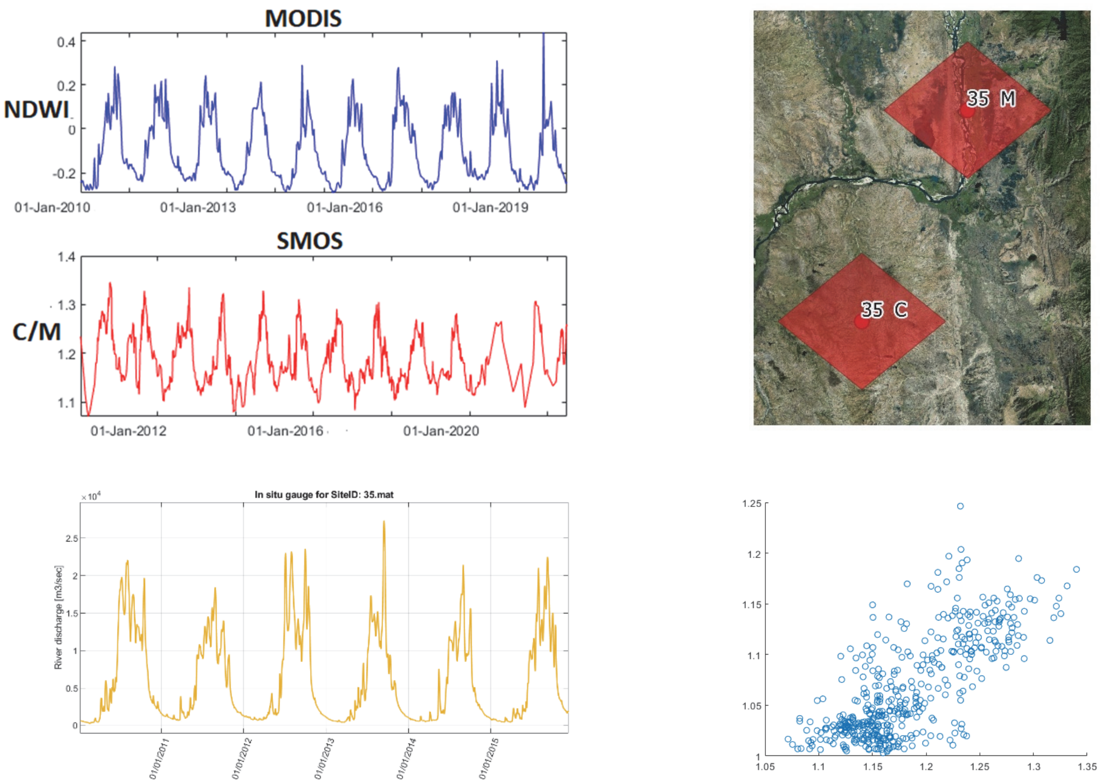

Fig. 4. Satellite river gauge derived from MODIS optical imagery (upper left) and SMOS PMR data (upper right) for SGR 35 (22.13°N, 96.03°E) over the Irrawaddy River in Myanmar. Map shows the location of PMR SGR for both M and C observation (upper right). Lower left figure shows in-situ streamflow [in m/s^2 units] data for the same period (lower left). Lower right figure is a scatterplot of SMOS and MODIS orbital gauge data.

In Ghana, over the White Volta basin, which is the largest rivers sub-basin of the Volta River in West Africa, SGR 1424 shows similar time series pattern for both SMOS and MODIS observations (*Fig. 5*). Tropical humid climate with wet summer (May–October) with southwest winds originating over the Atlantic Ocean and dry winter with strong dry warm winds from the desert in north cause an annual high-flow in summer and low-flow during winter. Most precipitation occurs in August, whereas the streamflow usually peaks in September.

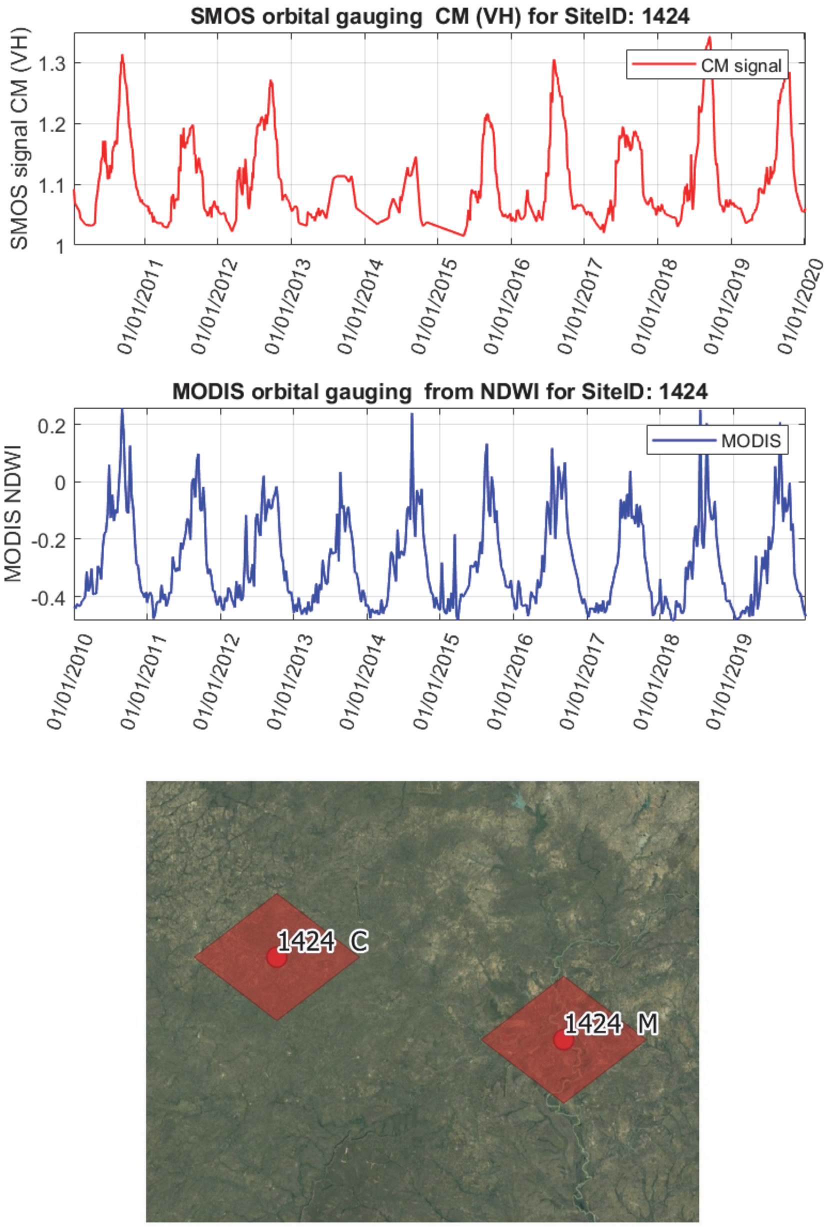

Fig. 5. Satellite river gauge derived from MODIS optical imagery and SMOS PMR data (upper two plots) for SGR 1424 (10.28°N, 1.05°W) over the White Volta River in Ghana. Lower map shows the location of PMR SGR for both M and C observation.

For SGR 1424 SMOS observation exhibits less noise than the MODIS observation. The number of observations is more than twice as many as for the optical data, but it is not the reason for higher noise. On the other hand, the channel width at the satellite gauging location is about 80 m, which is a relatively narrow river channel to measure discharge from space. That concludes that despite low resolution of SMOS, the sensitivity of water surface presence in the footprint enables the observation of inundation increase even for relatively low proportion of water within the observation (narrow river channel). It emphasises the strong capability of microwave emission to measure streamflow from space using all weather satellite systems on a near-daily basis with PMR data. Regarding optical data, given its strong limitation to cloud cover, it can only obtain information over regions, where cloud free scenes can be acquired within frequent time intervals.

The latter requirement is difficult to meet in wet tropical regions with strong cloud cover hindering the acquisition of optical data. As an example over the Purus River, a large tributary of the Amazon River in Brazil (*Fig. 6*), MODIS exhibits a high noise when compared to SMOS with clear seasonal variability of streamflow well correlating with ground gauge (*Kugler,* 2019). Comparing the two different measurements in a scatterplot confirm the low agreement of the MODIS and SMOS, as it can be seen on the scatterplot in the lower left figure. The reason for that might be cloudcover or the very complex environment that does not allow to accurately map inundation from optical data. The reason for more noise in the optical data needs further investigation. Yet the measurement of wet tropical climate seems to support the assumption that cloud cover may be a major limitation factor in near-daily observations.

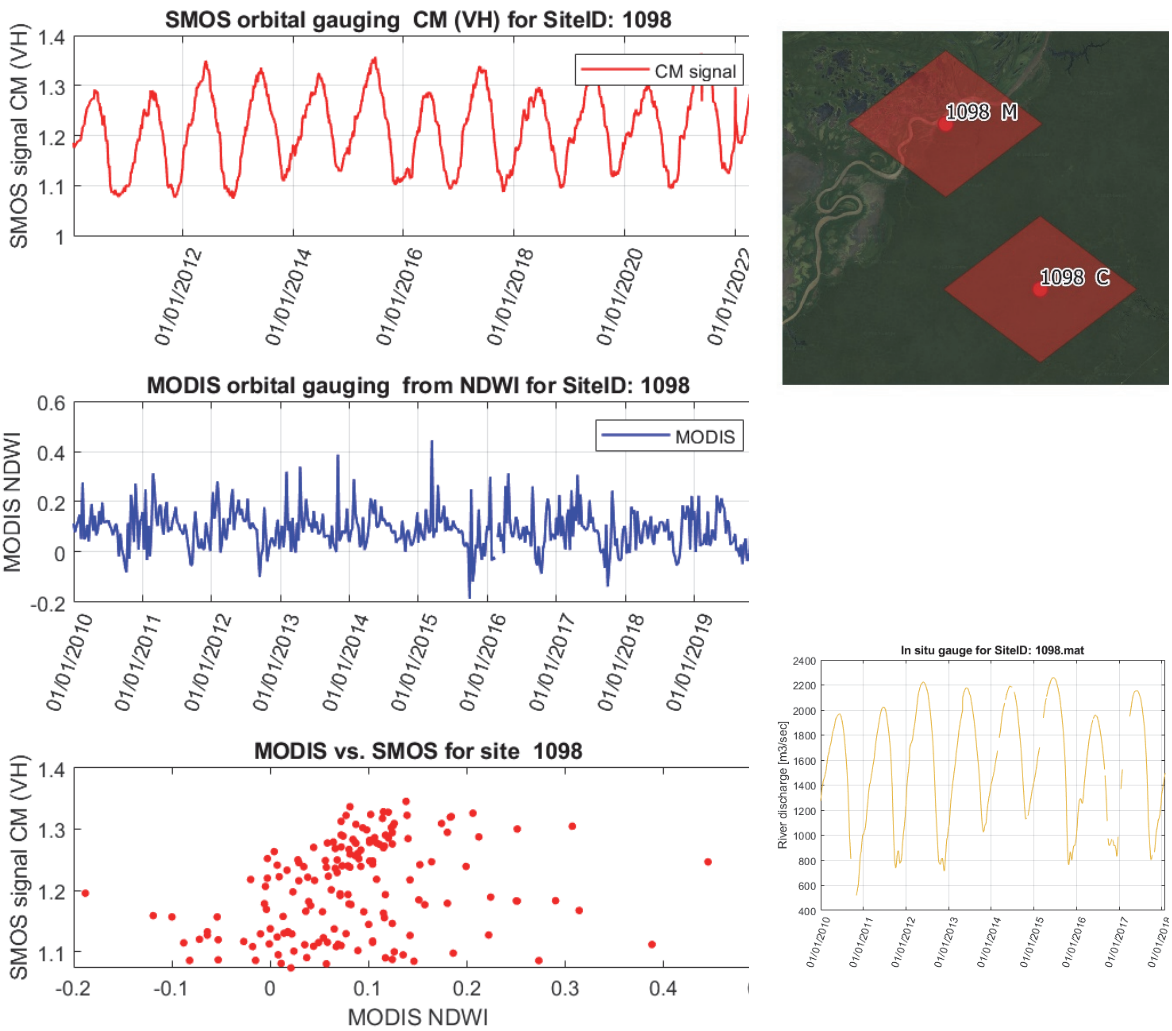

Fig. 6. Satellite river gauge derived from MODIS optical imagery and SMOS PMR data for SGR 1098 (4.65°S, 61.59°W) over the Purus River in Brazil (upper two figures). Upper right map shows the location of PMR SGR for both M and C observation. Lower right figure plots in-situ streamflow data [in m^3/s units]. Lower left graph is a scatterplot of SMOS and MODIS orbital gauge data.

4. Conclusions

This paper demonstrated the use of optical and PMR satellite technologies for continental river streamflow measurement. Satellite data were measuring river gauge from space using the strong correlation between water surface inundation and discharge over selected river reaches. Both optical and microwave satellite data were proved to be suitable for streamflow measurement.

Selected examples of orbital gauges suggest that cloud cover is a significant limitation for optical data. Yet some tropical climate showed good agreement between validated SMOS streamflow data and MODIS gauge time series despite high probability of clouds (like the example over the Irrawaddy or the Volta River). Dense tropical forest is also decreasing the accuracy of optical data reducing its capability to measure water extent over dense vegetation, as it is demonstrated on the example of the Amazon River basin.

Knowing that global climate change is expected to increase the magnitude and frequency of natural hazards like floods; it is crucial to understand changes in the terrestrial water cycle to face future challenges of climate change. Results could be used over ungauged river sections to check validity and double confirm results of PMR river gauge by independent measurements like optical data. It would be important over watersheds, where no validation data can be acquired, or hydrologic data is not collected or shared among major stakeholders. Thus, the comparison of results from both optical and PMR methods would be important to obtain reliable gauging time series from space without the need of collecting ground truth for validity.

Acknowledgement: Part of the work presented was supported by the National Research and Innovation Office.

References

Brakenridge, G.R., Anderson, E., 2005: MODIS-based flood detection, mapping, and measurement: the potential for operational hydrological applications. In: J., Marselek, G., Stacnalie, G., Bálint (eds.): Transboundary Floods, reducing risks through flood management NATO Science Series, *IV Earth and Environmental Scineces Vol. 72,* Springes, The Netherlands, 1-12.

Brakenridge, G.R., Nghiem, S.V., Anderson, E., Mic, R., 2007: Orbital microwave measurement of river discharge and ice status, *Water Resour. Res. 43*, W04405. https://doi.org/10.1029/2006WR005238

Brakenridge, G.R., Nghiem, S.V., and *Kugler, Z.*, 2023: Passive microwave radiometry at different frequency bands for river discharge retrievals. *Earth Space Sci. 10*, e2023EA002859. https://doi.org/10.1029/2023EA002859

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017*:* Google Earth Engine: Planetary-scale geospatial analysis for everyone, *Remote Sensing of Environment* Volume 202, 1 December 2017, Pages 18-27 doi:10.1016/j.rse.2017.06.031

Kugler, Z., Nghiem, S.V., and Brakenridge, G.R., 2019: L-Band Passive Microwave Data from SMOS for River Gauging Observations in Tropical Climates *Remote Sens. 11*, 835. https://doi.org/10.3390/rs11070835

MOD09A1.061 Terra Surface Reflectance 8-Day Global 500m dataset
https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD09A1#bands

Podkowa, A., Kugler, Z., Nghiem, S.V., and *Brakenridge, G.R.,* 2023: Ice freeze-up and break-up in Arctic Rivers Observed with satellite L-band passive microwave data from 2010 to 2020. *Water Resour. Res.* 59, e2022WR031939. https://doi.org/10.1029/2022WR031939

Sakamoto, T., Nguyen, N. V., Kotera, A., Ohno, H., Ishitsuka, N., and Yokozawa, M., 2007: Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. *Remote Sensing of Environment, 109(3),* 295-313.

Tarpanelli, A., Iodice, F., Brocca, L., Restano, M., and *Benveniste, J.,* 2020*:* River Flow Monitoring by Sentinel-3 OLCI and MODIS: Comparison and Combination. *Remote Sens. 12*, 3867. https://doi.org/10.3390/rs12233867

Thenkabail, P.S., Schull, M., and *Turral, H.,* 2005: Ganges and Indus river basin land use/land cover (LULC) and irrigated area mapping using continuous streams of MODIS data. *Remote Sens. Environ. 95,* 317–341. https://doi.org/10.1016/j.rse.2004.12.018

Zhan, X., Sohlberg, R.A., Townshend, J.R.G., DiMiceli, C., Carroll, M.L., and *Eastman, J.C.*, 2002: Detection of land cover change using MODIS 250 m data. *Remote Sens. Environ. 83*, 336–350. https://doi.org/10.1016/S0034-4257(02)00081-0