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The use of satellite remote sensing for exploring river meander migration

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ABSTRACT

Meandering rivers are complex systems that support high rates of biodiversity and the livelihoods of millions of inhabitants through their ecological services. Meandering rivers are often located in remote locations and cover long distances. As a result, observational satellites are crucial for investigating and monitoring meandering river dynamics. Satellite remote sensing technology is responsible for many advances in our knowledge about the variables that affect these rivers and their interaction with their surrounding floodplains. Furthermore, new sensors and the advent of cloud computing are allowing researchers to revisit theories that have hitherto lacked observational evidence to support them. In this paper, we review articles that have applied remote sensing techniques to analyse river meander migration processes. Our findings show that the majority of articles analysed the meandering rivers of the Ganges/Brahmaputra (29.0% of all articles) and the Amazon Basin (26.1%). We propose that these two locations are popular for different reasons: to improve management in highly populated floodplains of Ganges/Brahmaputra, and to investigate the meandering mechanisms without major anthropogenic interference in the Amazon Basin. Furthermore, most of the articles used Landsat for river monitoring (80.7%) and tracked the river changes throughout time using satellite time series (82.0%). However, the incorporation of Synthetic Aperture Radar satellites in papers was minimal, and only a small fraction (13%) of studies utilized cloud computing platforms for processing satellite images. Finally, we discuss new possibilities in terms of sensors and processing that might in the future advance our knowledge of river geomorphology.

1. Introduction

The constant and complex interactions between river channels and their surrounding floodplains, especially during periods of high flow, promotes the formation of sinuous and hydraulically complex rivers (Gualtieri et al., 2020; Zinger et al., 2013). The heterogeneous environments associated with sinuous rivers, comprising features such as oxbow lakes, scroll bars, and inundated forests (Luize et al., 2018; Sabo et al., 2005) means that meandering rivers and their floodplains are hotspots of biodiversity that support a large and growing number of people with food, water, nutrients, and transportation (de Moel et al., 2011; Hamilton et al., 2007; Heckenberger et al., 2007; Junk et al., 2012; Leauthaud et al., 2013; Pastor et al., 2022). However, the lateral migration of meandering rivers means that, although they bring many societal benefits, where they intersect human populations erosion may pose hazards to local riverine settlements and undermine infrastructure, such as bridges, levees and navigational routes (Basnayaka et al., 2022; Nagel et al., 2022). As a result, research on floodplains and meandering rivers is crucial to better understand how to optimise biodiversity, while protecting local communities and the infrastructure they rely on.

On sinuous rivers, the natural processes of outer-bank erosion and inner-bank sedimentation combine to drive lateral migration of the river across its floodplain. The higher flow velocity along the outer bank induces a helical flow pattern, amplifying shear stress there and consequently escalating the erosion rate of the bank. Conversely, the inner bank undergoes relatively lower velocity and reduced shear stress, promoting sediment deposition (Dietrich et al., 1979b). The sediment attached to the inner bank grows vertically and horizontally forming deposits called point bars (Braudrick et al., 2009; Dietrich et al., 1979b; Hickin and Nanson, 1975; Schumm and Khan, 1971; Schwendel et al., 2015). Over time these features, combined with the constantly evolving river curvature, produce intricate landscapes (Campos-Silva and Peres, 2016; Ielpi and Lapôtre, 2020; Zhou et al., 2000). Previous studies have identified different variables that affect rates of meander migration, such as the overall rate of sediment transport, the resistance of the river bank materials to erosion (which is affected also by the presence or

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absence of vegetation along the outer bank), and the local channel curvature (Camporeale et al., 2008; Constantine et al., 2014; Ielpi and Lapôtre, 2020; Schumm and Khan, 1971; Smith, 1976; Sylvester et al., 2019). The channel curvature, for instance, combined with the river sediment content, affects the point of maximum migration, which is usually located downstream of the point of maximum curvature (Güneralp and Rhoads, 2009; Hickin and Nanson, 1975; Ikeda et al., 1981; Nanson and Hickin, 1983, 1986; Sylvester et al., 2019). This difference in the location of the maximum channel curvature and maximum lateral migration, termed the phase-lag, amplifies channel curvature over time until the river cuts itself off, forming an oxbow lake (Camporeale et al., 2008). These interactions are complex and determine whether a river will migrate at a higher or lower rate. However, due to the difficulty of directly measuring river metrics in remote regions, wider rivers, and across large extents of the river network, our understanding of these processes and their associated morphometrics are usually based in theories with little to no supporting field evidence.

Remote sensing has long been used to quantify long-term river dynamics. In this review, we specifically focus on satellite remote-sensing systems which are capable of offering near-global coverage, thus excluding papers that use aerial photography, Unmanned Aerial Vehicle (UAV) or other non-satellite sensors. The use of satellite remote sensing allows large and inaccessible rivers of the world to be analysed (Shahrood et al., 2020; Sylvester et al., 2019). Since water bodies absorb more electromagnetic energy than land targets, especially within the infrared portion of the electromagnetic spectrum (Zhou et al., 2015), satellite images can be analysed to identify and track rivers above a certain width (considering the image spatial resolution) and their morphometric changes over space and time. Furthermore, longer time series of images, such as the series provided by the Landsat program, which has been running since 1984, allows researchers to investigate the behaviour of meandering rivers over time (Constantine et al., 2014; Valenza et al., 2020). However, until quite recently, such approaches have tended to be very time-consuming. The recent advent of cloud computing platforms such as Google Earth Engine (GEE) means that it is now possible to employ large numbers of satellite images to estimate river meander migration processes easily and at a global scale (Boothroyd, 2021; Nagel et al., 2022). These large-scale, and even global, analyses of meandering rivers using remote sensing have the potential to improve our understanding of processes that are still not well established, helping to manage and protect these biodiverse and (often) populous regions. This paper aims to present recent developments in the methods used to extract river morphometrics from satellite-based remote sensing and to review how these methods have been employed to deliver new insights into the rates and processes of river meander migration. Furthermore, we also identify some possible avenues for new research that could take advantage not only of new sensors that are being launched, but also novel processing techniques.

2. Satellite sensors and techniques for analysis of river morphology

2.1. Satellite sensors

The use of satellites to detect surface water resources is possible thanks to the distinct spectral signature of water as compared to adjacent land targets. Water, when exposed to solar radiation, highly absorbs infrared wavelengths (between 0.75 and 3.0 µm), while absorbing much less in the visible range (0.38 to 0.75 µm) (Fig. 1.A). As a result, optical satellites (which depend on the detection of reflected solar radiation to make inferences about surface properties) need at least one band in the infrared spectrum to detect water features. However, a complicating factor is that inland waters are rarely clear as they transport chlorophyll-a, organic and inorganic soil particles, and colored dissolved organic matter, which all also affect the water's spectral signature (Gholizadeh et al., 2016). These issues are a key concern in studies of water quality,

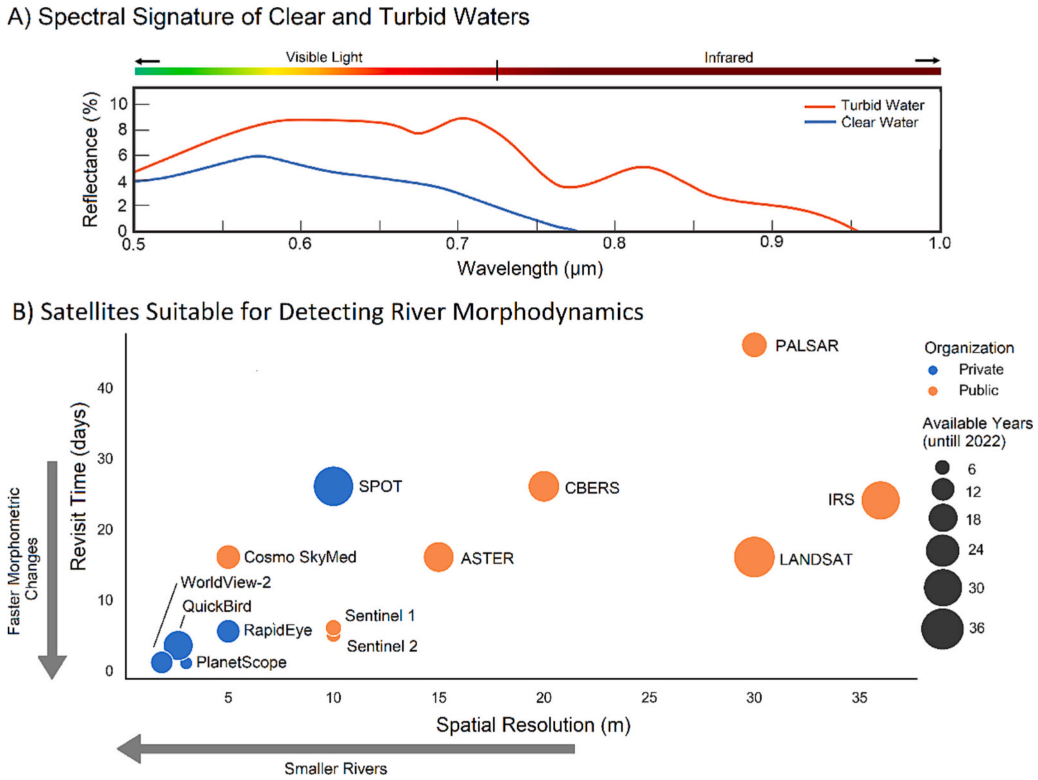

Fig. 1. A) Spectral signature for clear and turbid waters. Source: Malinowski et al. (2015). B) Characteristics of selected satellites suitable for analysing river morphodynamics. When a program has more than one sensor the revisit time was calculated using the combination of satellites (This was not undertaken for Landsat, since it has deployed a single sensor for most if its duration even if the Landsat revisit time currently is 8 days as both Landsat 8 and 9 are in operation).

but applications in river geomorphology typically seek to avoid this issue by using bands that are less affected by these components. For turbid waters, for example, the suspended sediment particles backscatter red and infrared radiation, so infrared bands with longer wavelengths might be necessary to effectively detect water features (Fig. 1.A) (Moore, 1980). Nonetheless, other satellites' characteristics are also important to detect rivers, such as the satellite revisit time and the database of historical data, which are crucial to be able to identify temporal changes in river morphology. Therefore, satellites developed by agencies such as the United States program LANDSAT (Land Remote-Sensing Satellite System), the Indian IRS (Indian Remote Sensing Satellite), and the Brazilian CBERS (China–Brazil Earth Resources Satellite) (Fig. 1.B), in addition to having no costs at the point of use, have a long historical database, making them very attractive to potential users.

The Landsat program stands out as the most widely used satellite platform used to study water resources. The program started with the launch of Landsat 4 in 1972, followed by Landsat 5 in 1984, Landsat 7 (1999), Landsat 8 (2013) and the recently launched Landsat 9 (2021). Its relatively high spatial resolution (60 m for Landsat 4 and 30 m for Landsat 5, 7, 8 and 9) and high sensor quality have allowed the expansion of remote sensing, once mainly restricted to land surface changes, to numerous applications focused on inland water resources, such as for water quality (Carpenter and Carpenter, 1983; Zuccari Fernandes Braga et al., 1993) and for flooding (Brown et al., 1987; Moore and North, 1974). Furthermore, since 1984 the Landsat program offers satellites with three different bands in the infrared spectrum (Near Infrared - NIR: 0.85–0.88 μm, shortwave infrared - SWIR 1: 1.57–1.65 μm, and SWIR 2: 2.11–2.29 μm), allowing for a variety of water detection algorithms and indexes to be developed and improved, such as the Normalized Difference Water Index (NDWI) (Gao, 1996), and the Modified Normalized Difference Water Index (mNDWI) (Xu, 2006). However, other similar optical satellite programs have also been developed, such as: (i) the IRS program, which was launched in 1989 (IRS-1A having a sensor that acquires data at 36.2 m of spatial resolution and had one infrared band in the range 0.77–0.86 μm), and; (ii) the CBERS programs, launched in 1999 (having a sensor at 20 m spatial resolution and one near infrared band). More recent satellites (while not having such a long historical archive of image acquisitions) have sensors that acquire data at much higher spatial and temporal resolutions. The European Sentinel 2, for example, launched in 2015, operates at a 10 m spatial resolution and with a revisit time of 5 days (due to the combination of two satellites), allowing the monitoring of smaller rivers and more rapid morphological changes.

In addition to passive optical sensors, Synthetic Aperture Radar (SAR) is an example of an active sensor that is also useful in water resources studies. The SAR, instead of detecting reflected solar radiation, emits and then receives microwave radiation backscattered by the earth's surface (Bamler, 2000). The great advantage of SAR is that it is able to capture images of the earth's surface regardless of the presence of cloud cover or other adverse weather and lighting conditions that have the potential to limit the use of optical sensors. The SAR microwaves in contact with water are usually scattered in other non-sensor directions, returning low signals to the radar. This low signal contrasts markedly with the higher bounce backscattered by rougher surrounding terrain, providing an ideal situation for water delimitation (Hess et al., 2003; Touzi et al., 2007; Zhou et al., 2000). These factors, combined with a higher spatial and temporal resolution, such as those provided by Sentinel-1 (10 m spatial resolution and 8 days revisit time – Fig. 1.B), and the Italian COSMO-SkyMed (with 5 m of spatial resolution and 16 days of revisit time) are ideal for river morphodynamic studies, especially in the cloudy conditions of the wet seasons that are critical for driving active river behaviour. However, although the technology is not new in fluvial geomorphological applications (Stølum, 1998), so far few studies have applied SAR to study the movement of rivers (Yan et al., 2021).

Although satellites developed by public space agencies are by far the most popular sensors used for water-related studies, the private sector is leading the development of new sensors with even higher spatial and temporal resolutions. These satellite programs launch a great number of sensors, called “constellations”, to decrease the revisit time while maintaining a high spatial resolution. The company Planet, for example, has since 2013 launched >130 satellites, creating a constellation that offers daily world coverage at 3 m spatial resolution. Similarly, WorldView-2 is a constellation operated by Maxar since 2009 that comprises 6 satellites with very high spatial (1.8 m) and temporal resolution (1.1 days). The SPOT satellite, on the other hand, today operated by Airbus Defence and Space, although it has a lower spatial and temporal resolution (10 m and 26 days), has been in operation for a longer historical duration (36 years in 2023). Nevertheless, despite the advantages of commercial satellites, which could open up the possibility of studying ever-smaller rivers at even higher monitoring frequencies, the use of private satellites is limited by the costs of acquiring the images. As a result, when these satellites have been applied to analyse river morphodynamics, researchers tend to use one single image, thus wasting their high revisit time capability (Constantine and Dunne, 2008; Fisher et al., 2013a; Santos et al., 2019).

2.2. *Extracting river geomorphology from satellite images*

There are different ways in which river morphodynamic metrics can be extracted from remote sensing imagery. Water indexes are an especially effective way to detect river features. These water indexes take advantage of the fact that the near-infrared and mid-infrared spectral ranges (higher than 0.74 μm) are highly absorbed by water (Zhou et al., 2015), while visible wavelengths (0.38 to 0.7 μm) are less absorbed (although still generally higher than for land targets), a signal difference that is exploited to detect areas of water. Spectral Indexes such as NDWI, which is a normalization between the green and infrared bands, mNDWI (green and mid-infrared bands), NDVI (Normalized Difference Vegetation Index – red and infrared bands) (Fig. 2.B), or simply the use of one single infrared band (Mondejar and Tongco, 2019), when combined with a threshold to separate water from land, can be used to create binary water maps (Fig. 2.D). These water index methods require less processing capacity and can be applied using simple Geographic Information System (GIS) software or programming techniques. More information about different water indexes is found in Acharya et al. (2018) and Li et al. (2016).

Another popular method is the use of Image Classification to create land use land cover (LULC) maps (Fig. 2.C), using machine learning algorithms such as Random Forest, and Support Vector Machine (SVM). However, these techniques require a much higher processing capacity and more knowledge of the analyst about the algorithm methodology to deliver good results. On the other hand, Freehand digitizing river contour (Al-Husban, 2018) is a method that requires almost no processing capacity (just loading the image). However, this method requires high resolution images (to avoid human analysis confusion) and is not suitable for large rivers and time series due to the exhausting nature of the task of manually digitizing the images. This method was not included in Fig. 2.

Whatever the method used to create them, once produced water binary maps can be used to extract river centerlines and bank lines (Fig. 2.F). Nonetheless, some methods directly apply the spectral indexes to estimate areas of erosion and sedimentation (Fig. 2.E) and other river metrics. With the river centerline (Fig. 2.F) different morphology metrics can be estimated, including river sinuosity, curvature, regions of inflexion (curvature minimum), meander wavelength, regions of no migration, and the meander migration rate (Fig. 2.G). The river sinuosity is a good measure of the overall degree of meandering, and although there are other methodologies, in general, sinuosity is estimated by dividing the distance between an upstream and downstream point on a river (considering a straight line or following the valley centerline) by the path length of the river centerline (Fig. 2.G). The time-

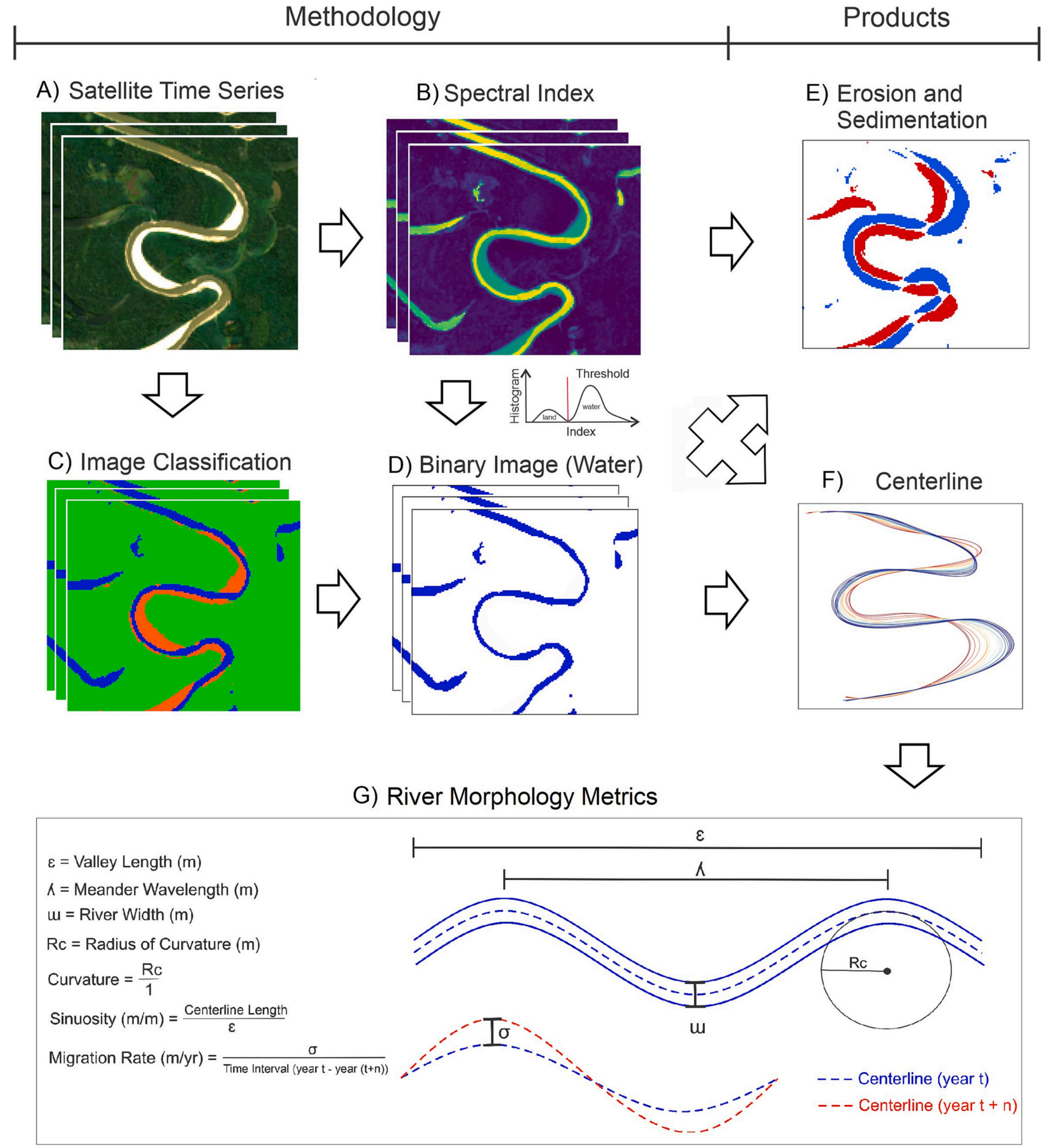

Fig. 2. Methods to extract river geomorphology metrics from remote sensing images.

averaged migration rate is estimated by dividing the distance between centerlines from two different times (considering a transect) by the time interval (Fig. 2.G). With the bank lines, it is possible to estimate other parameters such as the channel width and the location and curvature of the outer and inner banks. The radius of curvature is inversely proportional to the sinuosity and can be measured by defining the radius of a circle that fits the bend and bisects the inflexion points. These measurements are crucial to understanding the spatial and temporal planform dynamics of meandering rivers.

Some papers have developed and applied automated algorithms to detect river morphodynamics from Landsat imagery. These include algorithms such as RivWidth (Pavelsky and Smith, 2008), ChanGeom (Fisher et al., 2013b), SCREAM (Rowland et al., 2016), RivaMap (Isikdogan et al., 2017), RivMAP (Schwenk et al., 2017), PyRIS (Monegaglia et al., 2018), RiMARS (Shahrood et al., 2020), RivWidthCloud (Yang et al., 2020), and WSCDA (Nagel et al., 2022) (Table 1). The algorithm RivMAP (developed for use in a MATLAB environment), for example, requires the input of binary water images (estimated using the Support

Table 1
Properties of software packages employed to measure planform morphodynamics.

	Language	Centerline	Width	Erosion/Sedimentation	Curvature	Sinuosity	Migration Analysis
RivWidth	IDL	X	X				
ChanGeom	Matlab	X	X				
SCREAM	IDL	X	X	X	X	X	
RivaMap	Python	X	X				
RivMAP	Matlab	X	X	X	X	X	X
PyRIS	Python	X	X	X	X		X
RiMARS	Matlab	X					X
RivWidthCloud	GEE	X	X				
WSCDA	GEE			X			

Vector Machine algorithm) to measure the river centerline and perform extractions of bank lines, widths, lengths, angles, and curvatures (Schwenk et al., 2017). To measure areas of erosion, sedimentation, and cutoff identification, RivMAP compares temporally distinctive water binary images (Schwenk et al., 2017). The algorithm RiMARS (also developed for use in MATLAB) operates similarly, with the extraction of binary watery images (using mNDWI and an automatic threshold), followed by the estimation of the river centerline and different river metrics (Shahrood et al., 2020) (Table 1). To measure the movement of rivers, RiMARS considers the shift of the centroid of each meander (considered as a polygon) over time (Shahrood et al., 2020).

However, although popular, the use of binary water maps creates uncertainty (multiple classifications), requiring visual interpretation and thus limiting the development of the automation required when processing large-scale (continental or global) river geomorphology datasets (Isikdogan et al., 2017). As a result, to create more reliable, fully-automated, methods, non-binary water maps are now being applied by some river morphology algorithms. The algorithm WSCDA (Nagel et al., 2022; developed for the Google Earth Engine - GEE), for example, identifies areas of erosion and sedimentation by analysing only the mNDWI trend over time for each pixel (positive trends are classified as erosion and negative trends as sedimentation) using cloud computing (Table 1) (Nagel et al., 2022). The RivaMap uses a Multiscale Singularity Index applied to mNDWI to identify river curve-like singularities using orthogonal second-order derivatives along evenly spaced directions to extract information such as the river centerline and width (Table 1) (Isikdogan et al., 2017). To expand the use of RivaMap, Jarriel et al. (2020) analysed the temporal variability of the RivaMap Multiscale Singularity Index from different mNDWI Landsat images (variance of each pixel through time) to identify areas of erosion and sedimentation. With these areas mapped, the authors were able to identify that tidal and fluvial forces, channel connectivity, and anthropogenic activity were major influences in the rates of geomorphology activity in the Ganges Delta (Jarriel et al., 2020).

2.3. *Cloud computing*

While the availability of satellite data with growing lengths of historical archives is improving our understanding of river geomorphology, data processing is becoming a computational challenge. In this context, cloud computing platforms, such as the Google Earth Engine (GEE), which incorporates access to temporally long and global remote sensing datasets with powerful processing capability using thousands of computers working in parallel, are now enabling the analysis of river meander migration across much larger spatial scales than was possible previously (Boothroyd et al., 2021; Gorelick et al., 2017). Furthermore, since the platform operates on the cloud, it eliminates the necessity to own and maintain expensive physical hardware, and removes the inefficient requirement to download and store large datasets before any further processing (Sudmanns et al., 2020). These advantages are democratizing and expanding the application of remote sensing in all fields of Earth Observation (Boothroyd et al., 2021). However, so far, few studies have used the platform to directly extract river geomorphology data, with most instead using GEE to download satellite data for offline analysis (Table 1).

Isikdogan et al. (2017) and Schwenk and Foufoula-Georgiou (2016) using RivaMap and RivMap, respectively, for example, have used GEE to download remote sensing images before analysing the data in local server algorithms. Since GEE offers processing tools to extract information from hundreds or thousands of satellite images, the use of the platform to download a few images under-exploits its capability. Furthermore, GEE offers a wide range of databases that can be used to support river morphology studies. Langhorst and Pavelsky (2023), for example, used yearly water binary maps from 1999 to 2018, produced by Pickens et al. (2020), to identify rates of river migration globally. This was achieved using a similar approach to the SCREAM method (Rowland et al., 2016), which is based on identifying areas of erosion and sedimentation using raster information, a faster approach when compared to the vector centerline methods. Similarly, although not developed specifically for river morphology analysis, the Deltares Aqua Monitor is a tool built within GEE that detects land and water changes using Landsat time series on a global scale (Donchyts et al., 2016). Yang et al. (2020) and Wang et al. (2022) have developed RivWidthCloud and GrabRiver respectively on GEE, which uses a combination of Landsat or Sentinel 2 spectral indexes to extract the binary water mask needed to calculate river centerlines and widths. With this approach, Yang et al. (2020) were able to extract 1514 widths in USA and Canada from Landsat images between 1984 and 2018 with a high degree of accuracy (mean absolute error: 43 m; mean bias: −21 m).

In addition to large-scale studies, the democratization of cloud computing is promising to improve local water management. The WSCDA, for example, is based entirely on cloud computing and on non-binary water maps to generate erosion and sedimentation information (Nagel et al., 2022). With this approach the WSCDA algorithm was able to process 637 Landsat images along 3000 km of the Amazonian Juruá River in less than one minute (Nagel et al., 2022), creating a much larger dataset when compared to the 4 Landsat images analysed by RiMARS (Schwenk et al., 2017). Furthermore, Boothroyd et al. (2021) applied GEE to analyse the planform morphology and vegetation cover of an anthropogenically modified reach of the Po River (Italy). The authors used the mNDWI for water and NDVI for vegetation and identified that the first flooding period of the year, associated with snowmelt in late spring, coincides with higher vegetation coverage, which improves bank stability and decreases the rate of river migration. Tobón-Marín and Cañón Barriga (2020) applied GEE and Landsat to study eight different Colombian rivers. The authors identified that the rivers Magdalena and Cauca are influenced by La Niña events, which increase the rainfall in the Colombian territory and thus intensify the river sinuosity and connectivity of these two rivers. As a result, the democratization afforded by GEE might be used to advance local water management, with tangible benefits for communities previously unable to access geospatial and related space technologies.

3. River meander migration studies

We selected 800 peer-reviewed papers addressing meandering river planform dynamics using remote sensing. The search was performed in Web of Science using terms related to the river, such as “meandering rivers”, “river meander migration”, “meandering channels”, “planform river dynamics,”, “sinuous river”, “river cutoff “; and terms related to the methodology of analysis, such as “remote sensing”, and “satellite”. To identify the base literature that supports the area of meandering rivers using remote sensing a co-citation analysis was performed (Fig. 3). Co-citation is the frequency in which two items of earlier literature are cited together by the later literature, in our case, the 800 satellite river meander migration articles (Small, 1973). Therefore, Fig. 3 shows the most cited articles, which are represented by bigger size points and labels; the intensity between links, with thicker lines representing greater connection; and how close they are to each other in the graph (creating different colour groups), which exemplifies how relatable the articles are. From 32,287 cited papers, 921 entries were considered in the co-citation analysis due to their garnering of at least 5 citations.

The co-citation algorithm autonomously generated a total of four distinct groups within the co-citation network. Notably, the articles represented by the yellow nodes are intimately linked to the realm of remote sensing, predominantly encompassing the development of techniques to effectively extract river features from satellite images. In this context, the paper with the highest citation count both within the yellow group and the entire article dataset is a study conducted by Xu (2006). In this paper, Xu (2006) introduced the mNDWI, a widely acclaimed water index renowned for its efficacy in delineating water features through satellite imagery (a comprehensive elucidation of this index is provided in Section 2.2). Similarly, Feyisa et al. (2014) made significant contributions by presenting an alternative water index termed AWEI (Automated Water Extraction Index), and Isikdogan et al. (2017) devised a sophisticated tool capable of extracting a range of river morphometric parameters. Collectively, the articles comprising the yellow group can be characterized as foundational contributors to the realm of river extraction methodologies using remote sensing. Their innovative methodologies laid the groundwork, facilitating the subsequent proliferation of articles adopting these techniques in the domain of meandering rivers.

The articles in red, blue and green are related to geological, geomorphology and sedimentology journals. The closer the distance to the yellow group, the more related are the articles to modern remote sensing techniques. For instance, Yang et al. (1999), a standout work within the red group, occupies a relatively close position to the remote sensing cluster. This article is an early illustration of how GIS and remote sensing can be used to systematically monitor channel migration, which influenced the scientific community to adopt these technologies. Another highly cited article in the red group was produced by Schumm (1963), which is far away from the yellow group. This article underscores the foundational techniques employed in extracting river morphodynamics, harnessing aerial photogrammetry and comprehensive fieldwork. The author found a relationship between sinuosity and the shape of channels (width-depth ratio) and the percentage of silt and clay in rivers of the USA, paving the way to understanding how and where sinuous rivers are formed. However, a more recent shift has been observed in the community of researchers in the meandering rivers domain, where a change toward remote sensing techniques has led to groundbreaking insights in the field of river geomorphology. An illustrative example is the widely cited work by Constantine et al. (2014) which leveraged satellite imagery to identify sediment supply as a key driver of meander migration. As a result, the co-citation analysis illustrated how the base literature evolved and was fundamental to the field of river meander migration using satellites.

From the 800 articles extracted from the Web of Science, we filtered out articles that used aerial photogrammetry, laser scanner or other non-satellite remote sensing techniques, and articles that developed computational models and used remote sensing only for validation of the results. Therefore, we ended up with 138 articles that used satellite remote sensing to extract river meander migration movement. A total of 12.4% of papers had more than one study location (all locations were added in the analysis). The great majority of them have their study location in the Ganges/Brahmaputra Basin (28.99% of all articles – the basin is located around India and Bangladesh) and in the Amazon Basin (26.09% - around Brazil), followed by the Indian's South-East Watersheds (6.52%), and the Indian West South Coast Rivers Basin (5.80%) and the Río Colorado Watershed, in Bolivia (5.80%) (Fig. 4). The significant attention directed toward the Ganges/Brahmaputra Basin area can be attributed to the effort to comprehend the morphodynamics of these rivers. This emphasis might come from the notable concentration of human settlements residing in regions susceptible to flood and erosion impacts within this watershed. Specifically, India accommodates an astounding 389.8 million individuals, (accounting for 27% of its population), and Bangladesh hosts 94.4 million inhabitants (representing

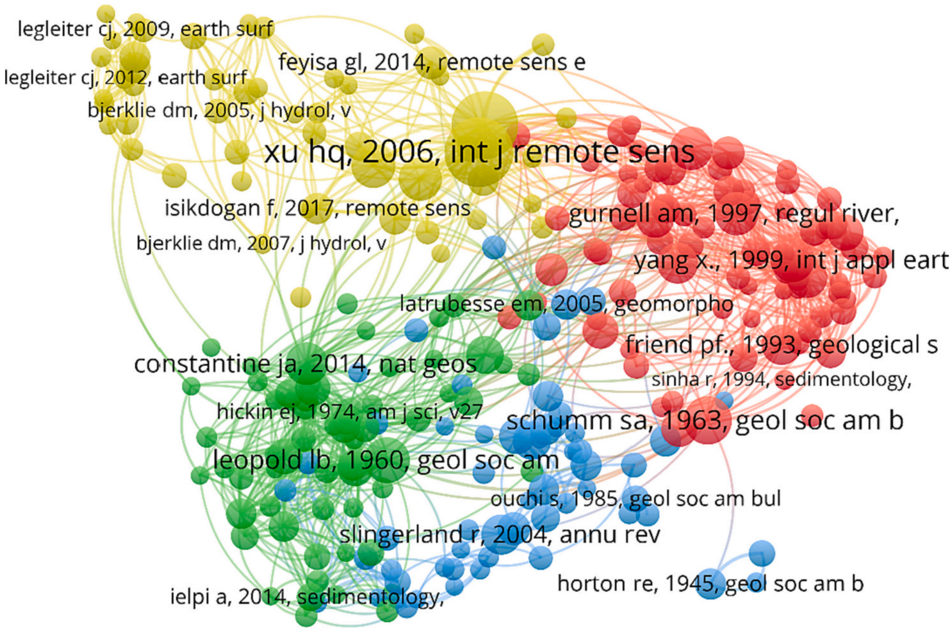

Fig. 3. Co-citation network of papers from 800 journals selected from the Web of Science collection in the field of river meander migration using remote sensing.

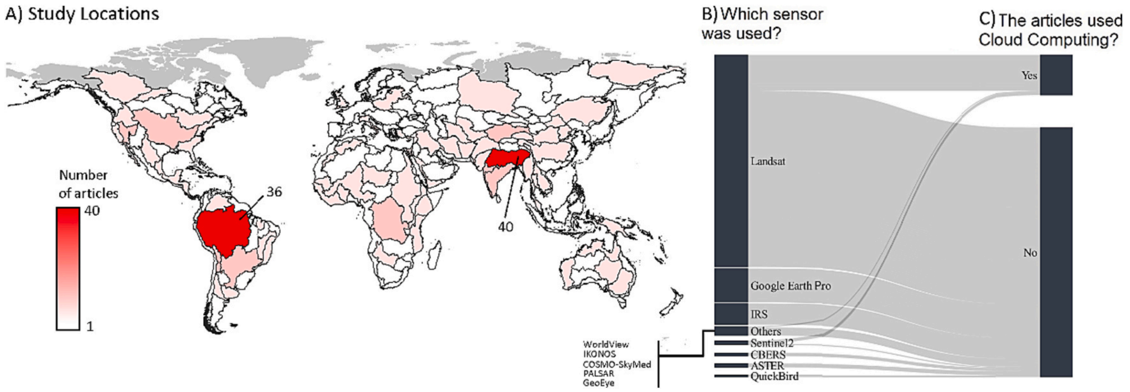

Fig. 4. Location of case studies using satellite remote sensing for river meander migration and Sankey diagram for river morphology using remote sensing literature. If a study covers more than one study location and linkage, it is represented multiple times on the map and the diagram.

57.5% of its population), residing in areas prone to flood and erosion risks (Rentschler et al., 2022). However, in the Amazon Basin, the rationale behind the substantial volume of articles possibly diverges. The comparatively sparse population density and the prevailing absence of significant infrastructure (Grill et al., 2019) render this region an optimal locale for investigating natural meandering systems without substantial anthropogenic interventions (Constantine et al., 2014; Nagel et al., 2022).

The great majority of the analysed articles (80.7%) used Landsat satellites to detect river morphodynamics (Fig. 4.B). Papers using images provided by the platform Google Earth Pro follow with 11.9%. The Google Earth Pro is a platform that provides time series of high-resolution satellite and aerial images for visualization using only true colour information (other infrared bands are not available). It is worth noting that Google Earth Pro's design restricts user-driven image processing, setting it apart from the classification of a cloud computing platform, such as the Google Earth Engine (GEE). Satellites from the Indian Remote Sensing Programme (IRS) follow with 11.1%, QuickBird with 3.0%, Sentinel 2 and ASTER with 2.2% each, and CBERS with 1.5%. The other satellites follow with 1%. Despite SAR's substantial benefits (Section 2.1), only one paper incorporated SAR images. However, due to lacking sensor specifics, this paper was excluded from the analysis. Furthermore, a small minority of all the identified studies used cloud computing (13%) for processing, even when considering papers published after 2010 (the year that GEE was launched) (Fig. 4.C). All the papers employing cloud computing in their analysis utilized the GEE platform in conjunction with satellites like Landsat or Sentinel 2. This choice arises from the fact that these satellite datasets are readily accessible within the GEE platform. Furthermore, 82% of papers used Time Series of satellites (with at least two dates) to analyse river meander migration, showing the importance of tracking the river morphodynamics throughout time.

4. River meander migration processes

River meander migration involves two different processes, erosion on the outer bank and sedimentation on the inner bank (Dietrich et al., 1979a). This spatial separation of process occurs due to the different velocity structure that exists within curved channels, which results in an increased flow velocity and thus shear stresses being exerted by the flow on the outer bank, thus promoting erosion, and lower shear stresses being exerted on the inner bank, thus promoting sedimentation (Bathurst et al., 1977; Dietrich et al., 1979a). The intriguing morphology of meandering rivers and their complex and important interactions with their surrounding floodplains have led to different studies investigating terrestrial sediment fluxes (Odgaard, 1987), floodplain development (Lauer and Parker, 2008), and ecosystem processes (Ward et al., 2002). The meandering river literature is mainly and was primarily based on analytical methods (Callander, 2003; Ikeda et al., 1981), field observations (Hooke and Yorke, 2011; Seminara, 2006) and numerical modeling (Asahi et al., 2013); which together developed a knowledge foundation of meandering theories. However, with the advent of satellites, remote sensing technology was able to be applied and test the existing theories on larger scales and in remote areas. Furthermore, the recent advances in computer processing allowed the application of satellites techniques to extract river metric information on global scales, such as the discovery that the median global migration rate is 1.52 m/yr, characterized by a log-normal distribution (Langhorst and Pavelsky, 2023). However, because of the often-limited spatial resolution of satellite images (such as 30 m for Landsat images), the research that incorporates satellites tends to center around larger river systems with a width of at least 30 m. This focus introduces a potential bias in the outcomes. This section discusses papers that used remote sensing to analyse river meander migration to test existing theories.

A process that once puzzled the scientific community was the relationship between rates of meander migration and the curvature. The stablished theory developed by Hickin and Nanson (1975), Nanson and Hickin (1983), and Nanson and Hickin (1986), was that the rate of meander migration reaches a maximum when the radius of curvature reaches 2–3 times the river width. Nonetheless, Sylvester et al. (2019), by considering the effects of upstream curvature on local migration rates (Furbish, 1988; Güneralp and Rhoads, 2009; Ikeda et al., 1981), tested the stablished theory using remote sensing and found divergent findings. The authors, using the RivaMap algorithm, and a Landsat database to study different Amazonian rivers from 1987 to 2017, found that the higher the normalized curvature (radius of curvature divided by the river width), the higher the river meander migration rate, in a quasi-linear relationship. Because of this effect, the authors identified that the locus of the maximum meander migration is just downstream of the peak bend curvature (what they describe as a phase-lag), leading to a downstream-rotational mode of meander migration. However, downstream-rotational meanders are not a rule and the position of the peak bend curvature might also be linked to the processes of sediment transportation and deposition (explained in the next section) (Ahmed et al., 2019).

Furthermore, another effect that puzzled the scientific community was the formation of point bars in concave-bank areas (in outer bank regions), forming counter point bars in some river segments, where erosion would be expected. In their examination of the Murrumbidgee River in Canada, Page and Nanson (1982) utilized in-situ data surveys and sediment collection to scrutinize these counter point bars. Their research unveiled that these counter point bars primarily consist of finer-grained sediments and tend to occur when the entire river bend shifts downstream. This shift, as described by Page and Nanson (1982), is likely influenced by a substrate with higher erosion resistance (Smith et al., 2009), potentially associated with the confinement of the valley wall. However, subsequent findings related to downstream-rotational meanders highlighted their causation to the phase-lag, as elucidated in the preceding section (Sylvester et al., 2019). Consequently, it was recognized that phase-lag is also responsible for the formation of counter point bars (Sylvester et al., 2021). In their analysis of the Amazonian Mamoré River in Bolivia, employing Remote Sensing Time Series, Sylvester et al. (2021) observed that these counter point bars tend to be more prevalent in highly curved bends. These bends typically form shortly after a cutoff event occurs (as explained in section 4.3).

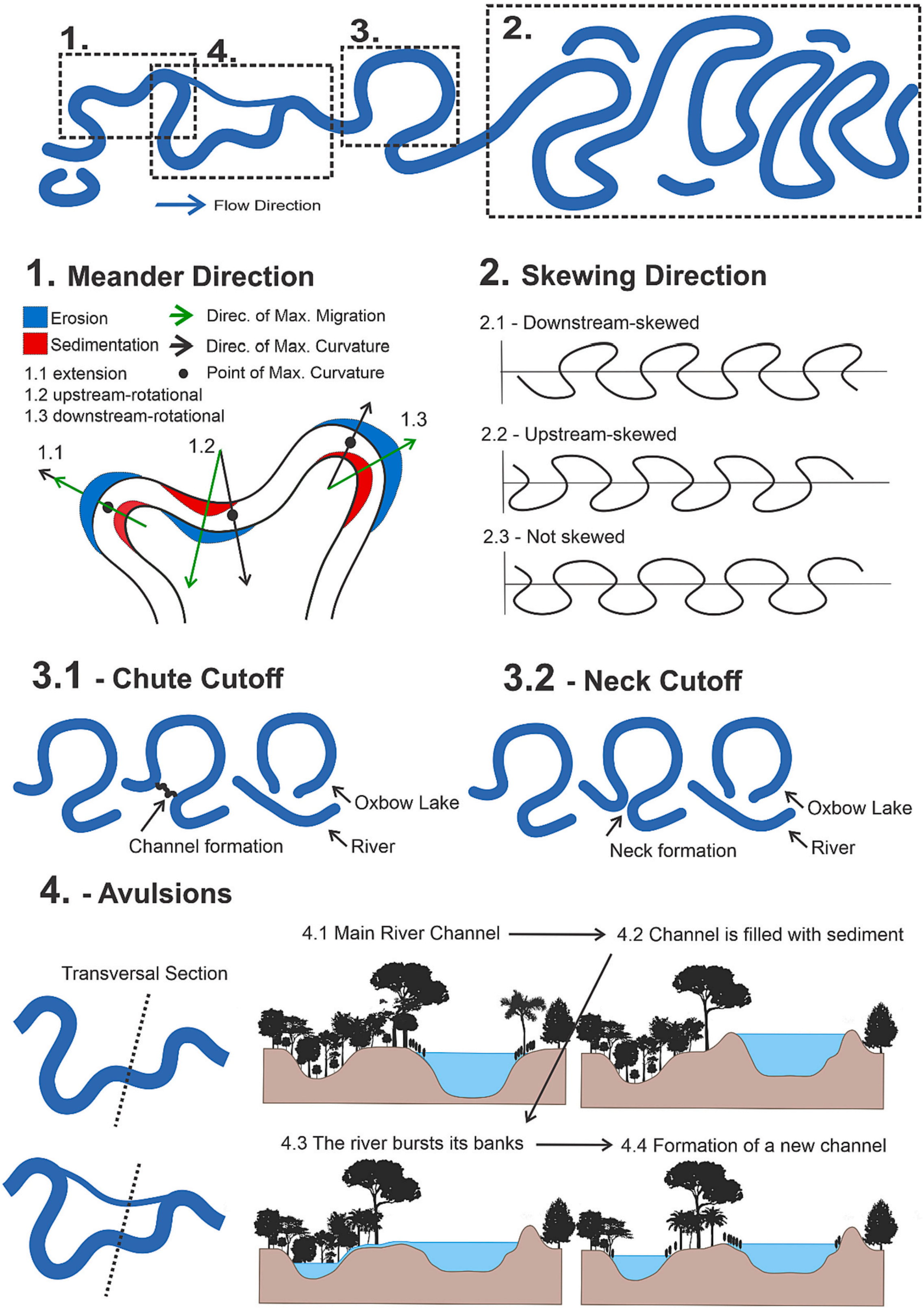

Fig. 5. River meander migration processes that can be investigated using remote sensing.

4.1. Sediment flux and river migration direction

High curvature bends might not produce high river meander migration unless the river transports high loads of sediments. There is a range of theories acknowledging the importance of sediment supply to the river meander migration process (Braudrick et al., 2009; Dietrich et al., 1979b; Hickin and Nanson, 1975; Schumm and Khan, 1971; Schwendel et al., 2015). However, understanding the behaviour of particles within river systems is intricate, involving various mechanisms. The sediment that the river carries for example, might have an external source, resulting from land erosion in the watershed, or an internal source, derived from the meander migration process itself (involving the erosion of outer bank areas) or from the bed floor of the river (Hooke, 2003). Nonetheless, the amount of external or internal sediment source that form the sediment banks (known as point bars) depends on the granulometry of the sediment (coarser sediments tend to be from more local sources) and the capacity the river have to transport the sediments (Hooke, 2003). However, due to the intricate nature of sediment behaviour and the fact that satellites can only capture the river's surface, papers employing satellite imagery typically concentrate on examining the relationship between the lateral movement of rivers and the overall river sediment load.

Satellite imagery allowed the expansion of study locations, supporting the claim that sediments are essential for a river to meander. Landsat imagery has corroborated that rivers with high sediment loads (sediment loads can themselves can be detected from calibrated Landsat images (Dethier et al., 2020; Flores et al., 2020)) are capable of producing large point bars on the inner bank (accumulation of sediments), increasing the river curvature, the rate of meander migration, and thus the river sinuosity (Ahmed et al., 2019; Constantine et al., 2014). Furthermore, the river's sediment load also impacts the direction of migration. In one analysis Ahmed et al. (2019), studying Amazonian rivers using Landsat data from 1984 to 2014, identified that rivers with high sediment loads tend to have faster downstream-rotational meanders (whereby migration occurs downstream of the point of maximum curvature - Fig. 4.2.3), while the few upstream-rotating (whereby migration occurs upstream of the point of maximum curvature - Fig. 4.2.2) meanders observed by the authors were located on rivers with lower sediment loads. The authors argued that the upstream-rotating meanders might be related to composite bends or the accumulation of sediments at the head of the point bar (Ahmed et al., 2019). The authors also identified that extensional meanders (where migration occurs on the same point of maximum curvature - Fig. 5.2.1) are rare and reflect an early stage of meander development (Ahmed et al., 2019).

As a result, while Sylvester et al. (2019) argued that the location of the maximum bend migration is closely related to river sinuosity, Ahmed et al. (2019) found that the sediment flux has a high impact on the location of the maximum migration rate. However, the findings of Sylvester et al. (2019) and Ahmed et al. (2019) are not necessarily in opposition, but rather they complement each other. The sinuosity and sediments interact with each other in a positive feedback cycle, leading to higher meander migration rates. Rivers with high sediment fluxes such as the Juruá River, build up point bars that force the river to curve (Hickin and Nanson, 1975). As the river meanders, the ongoing erosion of land amplifies the river's sediment load, due to the influx of local source sediments (Hooke, 2003), which encourages the formation of point bars. This, in turn, fosters a higher rate of meander migration. Furthermore, the sum of the upstream river curvatures increases the rates of migration (Furbish, 1988) and leads to higher rates of downstream-rotational meanders. The more the river rotates, the more sinuous the river becomes, leading to even more downstream-rotational meanders and sediment accumulation (Ahmed et al., 2019). However, there has been debate about whether lateral river migration is driven initially by outer bank erosion that induces local widening and thence inner bank deposition of the transported sediment (termed as *bank pull*), or whether first, the river sediment load deposited at the inner bank forces flow diversion and subsequent outer bank erosion (termed *bar push*). Previous studies exploring these mechanisms have been based on only a relatively few locations (Eke et al., 2014; Mason and Mohrig, 2019; Van De Lageweg et al., 2014), revealing a gap that satellite remote sensing has the potential to address.

While extension increases meander length, rotation increases the meander's asymmetry (Hooke, 1984). The combination of upstream extension/downstream meanders creates a combination of forms along the river, such as single loops, characterized by a single maximum migration peak, and compound loops, characterized by long loops with multiple local maximum migration peaks (Frothingham and Rhoads, 2003; Güneralp and Marston, 2012). A single loop transforms into a compound loop when a second arc along its perimeter evolves into an additional loop (Brice, 1974). Guo et al. (2021), using Landsat to investigate two rivers in China, found that compound bends for the Black River, which had slower bend migration, accounted for more than one-third of the total number of observed bends. In addition to the direction of meander migration, sinuous rivers also have different skewing directions. Among different theories, Guo et al. (2019), analysing Landsat data for 277 bends along 15 rivers, suggested that rivers tend to start with a downstream-skewed direction (more common in low sinuosity bends) (Fig. 5.2.1), evolving to an upstream-skewed status (Fig. 5.2.2) as the bend sinuosity increases until cutoff occurs. The authors found that 84% of the 411 identified cutoffs were upstream skewed. Although not explored by the authors, since high sediment flux rivers tend to have higher sinuosity, the upstream-skewing might be more predominant in these streams than in rivers with lower sediment loads. These and other interactions between different variables are complex but crucial for us to understand meandering rivers. These hypotheses could be tested by employing remote sensing to gather extensive data from various meanders, covering broader sediment loads and parameters than previous field and lab studies.

4.2. Migration rate and vegetation

Vegetation is an important variable that regulates the rate of river meander migration. The presence of vegetation roots stabilizes the river banks and thus increases the resistance to erosion, decreasing the rate of meander migration (Schumm, 1968; Smith, 1976). For a long time, scientists have theorized that vegetation is a crucial prerequisite for rivers to meander (Davies and Gibling, 2010; Fuller, 1985; Schumm, 1968). This theory was supported by research using alluvial successions, which identified that during the Ordovician period (>444 Myr ago, a period which is characterized by the colonisation of primitive vegetation on terrestrial portions of the Earth) the landscape would have been dominated by braided streams and that after vegetation rooting systems first evolved during the early Devonian, the prevalence of meandering rivers increased (Davies and Gibling, 2010). However, other authors have challenged this view by identifying or modelled meandering rivers on non-vegetated environments (Lapôtre et al., 2019; Santos et al., 2019; Santos et al., 2016). Ielpi and Lapôtre (2020), for instance, by analysing rivers across all climate zones (except polar) using Landsat remote sensing from 1970 to 2018, identified that contemporary unvegetated meanders do exist and that they migrate approximately 10 times more rapidly than vegetated rivers of the same size, refuting the concept that vegetation is a fundamental prerequisite for meander formation. However, although not crucial, the presence of vegetation might nevertheless contribute to meandering river dynamics due to the retention of sediments, sediment baffling, and bank stabilization processes (Ielpi et al., 2022).

Furthermore, in the same way that vegetation affects rivers, meandering rivers also impact vegetation dynamics. In vegetated regions, outer bank erosion destroys vegetation as a result of uprooting, whereas along the inner bank sedimentation creates new land for pioneering species to colonise. Peixoto et al. (2009), using Landsat images from 1984 to 2005 to study a relatively small area of 153,032 ha across different Amazonian rivers, have estimated that erosion released 22,734–64,623 Mg year^{-1} of carbon, while land accretion captured 3185 and 46,086 Mg year^{-1} due to vegetation regrowth during the study period. As a result, although the rates of erosion and sedimentation were similar, the destruction of plants in areas of erosion released more carbon than was sequestered by new vegetation growth on accreting lands. Expanding this methodology to entire basins using remote sensing and cloud computing might improve our understanding of carbon dynamics associated with river-driven physical disturbance in environmentally important regions such as the Amazon. Moreover, among other factors, the constant disruption that the river causes to the vegetation and the landscape also is known to drive diversification of species in floodplain regions (Nagayama and Nakamura, 2018; Ward et al., 1999).

4.3. Morphological disruptions

Morphological disruptions are abrupt events that change the river in a short period. Although they might be influenced by anthropogenic activity, they are essentially natural and are crucial to floodplain functioning. Cutoffs and avulsions, for example, regulate meander formation and provide floodplain landscapes with a rich variety of oxbow lakes. A cutoff happens when the river favours a shorter path, which in turn generates an oxbow lake as a sub-product and diminishes the overall river sinuosity (Camporeale et al., 2008; Handy, 1972; Lewis and Lewin, 1983; Weisscher et al., 2019). There are two different types of cutoff; neck cutoffs, which are formed by the intersection of the upstream and downstream meander limbs (Fig. 5.3.2), and chute cutoffs, which occur when a channel is formed and connects the upper and lower limbs of the river, which over time grows and becomes the main channel (Fig. 5.3.1) (Constantine et al., 2010). However, although cutoffs regulate river sinuosity, the abrupt river path change also disturbs the river dynamics. Soon after cutoff formation, the river often experiences an increase in its width and rate of migration in reaches located close to the cutoff (Schwenk and Foufoula-Georgiou, 2016). Stølum (1998) and Constantine and Dunne (2008), studying Amazonian rivers using optical and SAR remote sensing, found that the cumulative size-frequency distribution of oxbow lakes has a power-scaling or a lognormal shape, which means that there are far fewer large oxbow lakes than smaller ones.

However, cutoffs are more common in rivers with high rates of meander migration. Constantine et al. (2014) using Landsat imagery spanning 1985–2013, found that Amazonian rivers with higher sediment loads, due to their higher rates of river meander migration, also experience more cutoff events (Fig. 5.3). Furthermore, on average, although sediment loads drive migration and thus positively influence the rates of curvature formation (Ahmed et al., 2019), the high-sediment load rivers of the Amazon do not have substantially higher sinuosity. This is because those high-migration rivers also have a higher frequency of cutoffs, which, as mentioned, regulates river sinuosity. The cutoff causes a local disruption that suddenly decreases the local sinuosity and, on a large scale, limits the average sinuosity of the river. As a result, high sediment-load rivers are more dynamic, with higher rates of migration (increasing sinuosity) and cutoff (sinuosity regulator), than low sediment ones (lower variability).

Another abrupt change in the process of river meander migration occurs in circumstances when the river completely changes its channel across the floodplain, a process called avulsion (Fig. 5.4) (Chapman et al., 2005). These events occur when the channel is filled with sediments, which over time elevates the channel above the surrounding floodplain (Fig. 5.4.2). In this condition, erosion on the river levees might burst the bank (Fig. 5.4.3) and divert the water into a new channel that is carved at a lower elevation (Fig. 5.4.4) (Chapman et al., 2005; Slingerland and Smith, 1998). Valenza et al. (2020), investigating 63 avulsions from Andean, Himalayan, and New Guinean basins using Landsat time series extracted from GEE, have found that meandering rivers produce more severe avulsions (creation of large new channels) when compared to braided rivers. The combination of the different rates of meander migration, avulsion, and cutoff events creates intricate floodplains and heterogeneous environments. This is corroborated by Finotello et al. (2020) who, using satellite images and different river morphological parameters over 10,000 worldwide meanders, have identified that floodplain rivers are morphologically more complex than tidal channels. This observation aligns with earlier research findings (Marani et al., 2002).

4.4. Anthropogenic impacts

Human populations have always been attracted by floodplain regions. Along fertile floodplain areas, ancient civilizations such as Assyria, Babylon, and Sumer grew and developed with good access to water, navigation, and agriculture (Akhter et al., 2021). Today, around 255 million people live in floodplain areas that are prone to inundation (Tellman et al., 2021). The human presence highly affects river dynamics, for example through the construction of embankments to stabilize the riverbanks, straightening the river to locally reduce inundation, construction of dams, dredging, and indirectly, the alteration of hydrological, thermal and sediment regimes (Best and Darby, 2020; Grill et al., 2019; Nilsson and Berggren, 2000). These impacts reduce the river connectivity longitudinally (along the river), laterally (between the river and its floodplain), and temporally (hydrological seasons), reducing the exchange of water, organisms, sediments, organic matter, nutrients and energy throughout the environment (Ward, 1989; Ward and Stanford, 1995). Grill et al. (2019) have estimated that only 37% of all rivers longer than 1000 km are now free flowing, many of them in remote areas of the Amazon and Congo Basins.

The reduced connectivity of anthropogenically impacted rivers might also affect the formation of meanders in sinuous rivers. The impact of dams on meandering rivers, for example, is complex and still not clear. However, research has shown that meander formation might increase after dam construction, due to the sediment starvation of the channel, which increases the river's potential to erode (Legleiter, 2015; Shahrood et al., 2020). Legleiter (2015), for example, based on the literature, has identified studies that investigate the impact of damming on large rivers (>100 m width), showing that for these rivers there are positive impacts (i.e., higher rates of migration), while in small rivers (<100 m) the effect is the opposite, a theory that requires further investigation to determine how broadly applicable these trends are. This is because current investigations are based on individual study cases, not allowing for the isolation of the dam's impact on the other variables that also affect the river, such as the flooding regime, as Legleiter (2015) recognized. Satellite remote sensing has the potential to extend such analyses to identify the impact of dams on different rivers of the Earth, spanning a global range of sediment regimes and river widths.

In the Amazon basin, although it is regarded as being one of the last regions with no major anthropogenic influences (Grill et al., 2019), and so is preferred for river morphology studies, the scarce human population that lives along the river also influences the river dynamics. The riverine communities have long inhabited these regions due to the availability of oxbow lakes for fishing, fertile lands for agriculture, and the abundance of river paths for navigation (Campos-Silva and Peres, 2016; Schwartzman et al., 2013). The human populations that live along the river banks affect, and are affected by, river meander migration. For example, a drastic cutoff occurred in the Peruvian Ucayali River due to a channel opened by riverine communities to reduce river canoe travel (Fig. 6) (Schwenk and Foufoula-Georgiou, 2016). The event impacted negatively 20 communities that were living in the abandoned river reach, and one community downstream was destroyed due to the intensification of the erosion process (Coomes et al., 2009). However, access to the region improved due to the shorter river path, reducing transportation costs and even food prices (Coomes et al., 2009). Nagel et al. (2022), using the WSCDI algorithm and Landsat data from 1984 to 2020, identified that 152 communities (41.2% of all settlements) are affected by erosion and sedimentation along 3000 km of the Amazonian

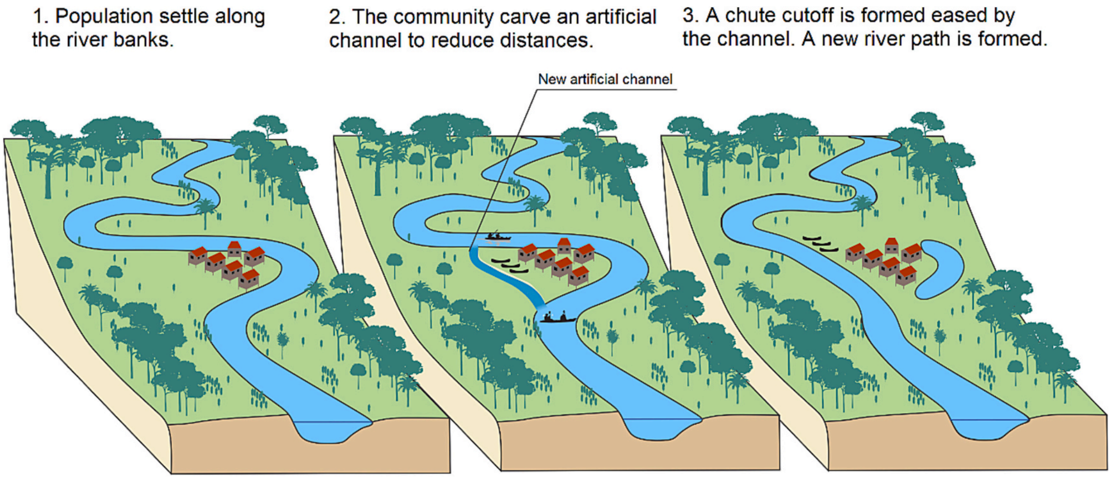

Fig. 6. Chute cutoff formation caused by a new artificial channel created by local communities.

Juruá River. The authors found that the majority of communities were living in stable regions (58.8%), which suggests a high local ecological knowledge about river geomorphology. The authors also suggest that communities living in unstable regions have a higher potential to move to other river banks or nearby cities, especially the ones suffering erosion along their shores (Nagel et al., 2022).

5. New possibilities

Satellite images combined with advanced processing techniques allowed the verification and reformulation of existing river meander migration theories. The spatial resolution limitation, when compared to other aerial images, makes the satellite remote sensing techniques more useful when applied over large regions (Fuller et al., 2013). Nonetheless, there are still many different theories that could be benefited or refuted by the use of satellite remote sensing, such as whether rivers are mainly driven by erosion (bank pull theory) or sedimentation (bar push theory) (Mason and Mohrig, 2019; Van De Lageweg et al., 2014). The capacity to extent the analysis to different rivers with different characteristics and environments might be used to identify processes and impacts that are difficult to isolate from the surrounding environment, such as the impact of dams on meandering rivers, which so far was done in individual study cases (Legleiter, 2015; Shahrood et al., 2020). Additionally, recognizing that sediment transport tends to be more pronounced at the riverbed, investigating the transformation of surface-suspended sediment data obtained through satellite imagery into a comprehensive measure of total sediment transport within the river will significantly enhance our understanding of the influence of sediment dynamics on the river meander migration phenomenon. Nonetheless, remote sensing constitutes just a single facet within the broader spectrum of river meander migration studies. Various other methodologies and approaches are employed within this field. When these diverse methods are harmoniously integrated, they collectively contribute to a more comprehensive understanding of the river meander migration process.

The availability of a reliable and long historical database of images makes Landsat imagery very popular in studies of river meander migration. The launch of Landsat 9 in 2021 will update images and extend even further the already long historical database (Masek et al., 2020), which will probably help to retain Landsat's popularity for river morphodynamic studies. However, Landsat satellites do have some limitations (such as their 30 m spatial resolution) that restrict their use: the study of small rivers and rivers with slow rates of migration (which precludes easy detection of erosion and sedimentation areas). Furthermore, the 16 days revisit time (which is now 8 days when including Landsat 8 and 9) might not be enough to capture highly dynamic processes or might leave a region with no images for even longer periods due to long periods of cloud cover. In the Amazon, where many river geomorphology studies are using Landsat (Constantine et al., 2014; Nagel et al., 2022; Peixoto et al., 2009; Sylvester et al., 2019), the analysis of river meander migration using remote sensing during the high flow period is strongly affected by the high degree of cloud cover throughout the wet season (Martins et al., 2018). Nonetheless, new sensors are being developed and launched which might overcome these limitations and thus are promising to study the movement of rivers.

Constellations of micro and nanosatellites are being launched and planned that have sensors with much higher spatial and temporal resolutions. Their high temporal resolution is possible only since these constellations are made up of dozens, hundreds, or thousands (planned for the company SatRevolution) of satellites (Nagel et al., 2020). The private sector is leading the development of satellite constellations, such as the Planet company, which launched a constellation of approximately 130 optical PlanetScope satellites, each with a rough spatial resolution of 3 m and a combined daily revisit time (Roy et al., 2021). Furthermore, although PlanetScope's radiometric limitations might affect areas that require precise colour information, such as in water quality monitoring (Maciel et al., 2020; Mansaray et al., 2021), the simple extraction of water features can easily be performed with the data from these satellites (Cooley et al., 2017; Mateo-Garcia et al., 2021) and thus might be used for river morphodynamic analysis. Strick et al. (2019), for example, have used PlanetScope to study bar dynamics in a braided river in Canada. However, the imagery from these satellites is not free (some companies provide a limited quota for students) and require high processing capacity due to their high spatial resolution, conditions that limit their broader use.

Furthermore, SAR images have many advantages when analysing river movements, since they are able to monitor water bodies regardless of the presence of cloud cover (Hensley and Farr, 2013). However, the literature so far has tended to use this technology to map river and reservoir areas (Goumehei et al., 2019; Mitidieri et al., 2016; Pappas et al., 2020; Zhang et al., 2020), rather than to study the variation of river planform characteristics over time and space. Nonetheless, new SAR satellites and constellations of SAR satellites are being planned that might be used to detect the evolution of fast and low-scale migration rates. The RADARSAT-Constellation (launched in 2019), for example, is capable of monitoring water extents at 5 m spatial resolution every 4 days (Dabboor et al., 2022), which might be used to study how river geomorphology is impacted during flooding events. The Surface Water and Ocean Topography (SWOT) mission, an altimeter satellite that was launched in December 2022 and which is designed to offer water level estimation for inland and ocean waters (Nair et al., 2021), has great potential for water-related morphology studies. Furthermore, the great capacity of SAR to detect ships (Dechesne et al., 2019), such as provided by the Sentinel-1 satellite, might also be used to study the impact of illegal gold (which increases sediment availability) and sand mining (decreases sediment availability) on river meander migration process.

Although these new satellites have different resolutions and other capability advantages when compared to Landsat, they inevitably, at least at their initial introduction, will offer only a short historical database of images. As a result, the data provided by these satellites might best be used to support and supplement Landsat analyses of river morphodynamics. The combination of Landsat's long and growing historical database with other sensors that have higher spatial and temporal resolution will increase the availability of data to study meandering rivers on a global scale. To discern patterns within extensive datasets, often referred to as "big data," artificial intelligence algorithms, particularly deep learning, can be harnessed to analyse landscape patterns and numerical relationships (Bishop and Giardino, 2021). Additionally, to computationally process this growing available data, cloud computing such as GEE might be used to advance our knowledge and test theories which have lacked suitable empirical evidence to do so. However, cloud platforms such as GEE must include other satellite datasets to improve the cloud potential and democratize cloud access, especially the ones developed outside the European and American Space programs, such as the Indian IRS and the Brazilian CBERS. Other new theories might be developed and classic concepts reexplored using cloud computing multitemporal analysis (Boothroyd et al., 2021) of multiple sensors, benefiting greatly our knowledge of river geomorphology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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