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RESEARCH ARTICLE

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Open-access remote sensing data for cooperation in transboundary water management

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ABSTRACT

Open-access remote sensing products provide data for transboundary water management. This study presents a comprehensive overview of the applications, uncertainties and implications of these remote sensing data products in the context of transboundary water management. Focusing on different stages within the transboundary cooperation continuum, we delineate the potential role and application of remote sensing data at the various stages of this cooperation. Despite the uncertainties and capacity requirements for data acquisition, processing and interpretation, we argue that remote sensing broadens opportunities to monitor, assess, forecast, track or validate compliance in transboundary basins, thereby challenging traditional notions of water data exclusivity.

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Remote sensing; transboundary water management; water conflict; cooperative water management; water data sharing

Introduction

Sustainable development in transboundary basins requires cooperation and operational arrangement on water management among riparian states (Bernauer & Böhmelt, 2020; McCracken & Meyer, 2018; Yalew et al., 2021). Such cooperation requires data and information exchange across political and/or administrative boundaries. A 'regular exchange of data and information' between riparian states was outlined as a duty in the 1997 United Nations' 'Convention on the Law of the Non-Navigational Uses of International Watercourses' (United Nations, 1997). In practice, however, only 30–50% of transboundary agreements in different continents include a direct mechanism for information sharing (Gerlak et al., 2011). The need for regular data and information exchange is again emphasized in the United Nations' Sustainability Development Goals (SDGs) on transboundary water management (United Nations, 2015). Many transboundary basins, however, still lack operational arrangements for water cooperation and data-sharing mechanisms. As the sole indicator of transboundary water cooperation in SDG 6.5.2 considers the 'Proportion of transboundary basin area with an operational

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arrangement for water cooperation' (United Nations, 2015). However, only a small number of countries reported that all their transboundary basins are covered by cooperation and data exchange arrangements with respect to the SDG 6.5.2 indicator (UNECE, 2021).

There are many cases where there is disagreement over data and models used for transboundary water management, as well as on the water availability and/or use in a basin (Heggy et al., 2021). Such disagreements can negatively influence negotiations and delay agreements over the management of shared waters. Assessment studies on transboundary basins sometimes present biased overviews based on the data and perspective of only one or two of the riparian countries (Uereyen & Kuenzer, 2019). Lack of timely and accurate data or lack of willingness to share it among riparian states – a major challenge for operational as well as strategic planning in transboundary water management – leads to suspicion, conflict and confrontation (Carius et al., 2004; Mianabadi et al., 2020).

In recent decades, information from remote sensing data has served as a complementary source of data for water management, thanks to improvements in remote sensing data coverage, accuracy and resolution. Sensors onboard satellites can now provide time-series of spatially distributed data that can be used to derive key hydrological variables such as rainfall (Beck et al., 2017; Stisen & Sandholt, 2010), evapotranspiration (ET) (Irmak, 2012; Zhang et al., 2016), changes in the water levels of lakes and rivers (Frappart et al., 2006; Morris & Gill, 1994), extent of lakes and reservoirs (Cai et al., 2016; Duan & Bastiaanssen, 2013; Gao, 2015; Pekel et al., 2016), and groundwater storage anomalies (Castellazzi et al., 2018; Sun, 2013). Continuing advancements in remote sensing technology and data acquisition as well as data assimilation approaches can therefore improve efforts to assess natural resources for conservation and sustainable water management.

More importantly, many of the remote sensing data or products are open access. These open-access data or products present an opportunity for supporting transboundary water management. While remote sensing data can be used for water resources management in general, its application for water management in transboundary basins may play an important role in addressing unique challenges such as data-sharing problems and regulation/compliance monitoring issues between riparian states. Furthermore, remote sensing challenges the exclusivity of transboundary water data by government bodies. The availability of such open-access remote sensing data to individual, non-governmental organisations (NGOs) and/or researchers accelerates the 'democratization' of water data (Craglia & Shanley, 2015). Nevertheless, it is important to recognize that the journey towards a complete data democracy can be obstructed by challenges such as power and resource imbalances, particularly in transboundary settings.

In this study, we offer an updated summary of the utilization of open-access remote sensing products for transboundary water management. We specifically focus on water bodies that span multiple sovereign nations, a context where such data are vital due to the absence of a unified authority enforcing data sharing. Our emphasis is on 'basins' as defined by the 1997 UN Watercourse Convention, which includes both surface water flows and underlying groundwater resources. We delve into the application of remote sensing-derived data through a review of the latest literature, highlighting key examples of remote sensing-derived estimates of basic water balance components such as precipitation (P), evapotranspiration (E) and changes in water storage ($\Delta S/\Delta t$). The study evaluates the applicability, accuracy and uncertainty associated with these remote sensing-derived data products and discusses their implications in fostering cooperation in transboundary water management. The study targets water experts, diplomats and other stakeholders involved in transboundary water challenges, aiming to bridge the gap between the technical understanding of remote sensing and its practical policy applications.

Data needs and the role of remote sensing

Data needs for transboundary water management are essentially the same as any other basin except that the data acquisition across borders is often challenging. Data required for water management in general relate to applications such as estimation of the basin water balance, water budget or water accounting for deciding on water entitlements, the monitoring and management of floods and droughts, the monitoring of water quality and water pollution in particular, groundwater assessment, agricultural water management including irrigation water use assessment, and monitoring of ecological conditions. Some of the most important variables needed for estimating the above include data on water availability, stream flow, water abstractions, use and consumption from groundwater and surface water, water quality and groundwater recharge (Sheffield et al., 2018). Such data are often required at different spatial and temporal resolutions in different contexts. Short latencies or long time-series of data are required for various applications, such as long-term planning and infrastructure design, disaster forecasting and response or real-time operational management. In transboundary contexts, hydrological variables related to a water-sharing agreement (e.g., inflow to a country or water level in a specific reservoir) may require dedicated monitoring. Furthermore, water resources are also strongly linked with the management of land and other resources (Leb, 2020), and thus additional data such as land-use and land cover change, vegetation health, biomass accumulation and land degradation, are important data requirements.

Remote sensing provides the opportunity to directly or indirectly derive the data and information required to meet data needs on these and related hydrological components, such as precipitation, ET, water storage (surface/ground) and water level. Sheffield et al. (2018) provide a comprehensive description of the data required for water resources management, including data derived from remote sensing, *in-situ* measurements and modelling, and their limitations. In this section, we focus our review on existing information based on remote sensing-derived data from some of these major hydrological components required for water resources assessment in transboundary basins, including associated uncertainties.

Precipitation

Precipitation is one of the primary hydrological variables in the water cycle. Ground-based measurements of rainfall (rain gauges) are often sparsely located. Satellite remote sensing has been used to estimate precipitation on the global scale, covering diverse areas of the Earth's surface, including deserts, high mountains and oceans which are infeasible to monitor using conventional rain gauges or meteorological radars (Sun et al., 2018; Tian & Peters-Lidard, 2010). A continuous and open-access availability of precipitation datasets is an important criterion for transboundary water management. Only a few satellite precipitation products meet these criteria. These include GPM (Global Precipitation Measurement Mission), CHIRPS (Climate Hazards Group InfraRed Precipitation with Station), PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), CMORPH (Climate Morphing technique), and MSWEP (Multi-Source Weighted-Ensemble Precipitation). Passive microwave sensors, such as those on board the TRMM and GPM satellites, measure the natural microwave emissions from the Earth's surface and atmosphere. The detected microwave radiation is directly related to the temperature and moisture levels in the atmosphere, which can be used to estimate precipitation (Lettenmaier et al., 2015). Remote sensing is a valuable source of precipitation data, not only because it enables data gathering in areas where stations are sparse and unevenly distributed, but also because the low level of collaboration in most transboundary waters makes the collection of precipitation data more difficult, restricting a comprehensive understanding of hydrological processes in shared basins. It is also important to note that most remote sensing precipitation products are based on assimilation of satellite data and gauge data (Sheffield et al., 2018). While remote sensing data provide extensive coverage, gauge data offer localized accuracy. This synergy aims to maximize the strengths of both data types. However, in regions where gauge data are scarce or unavailable, the calibration and validation of remote sensing precipitation estimates may be compromised, potentially leading to larger errors in precipitation estimates (Gleason et al., 2018).

Evapotranspiration (ET)

ET is another primary component of the water cycle with important implications in transboundary river basins, particularly in the context of agricultural water management, such as for irrigation. It is one of the most important hydrological components, functioning as a water depletion mechanism, and its key role in moisture flux (Kalma et al., 2008; Srivastava et al., 2013). ET is often estimated indirectly using potential ET and a variety of land surface parameters derived from climatological data (Liou & Kar, 2014). Remote sensing-derived ET products primarily make use of thermal infrared and optical remote sensing data, in addition to climatological data, to estimate parameters such as land surface temperature and vegetation indices, which are incorporated into models like the surface energy balance and the Penman–Monteith equation to estimate ET (Bastiaanssen et al., 1998; Pelgrum et al., 2010). Direct measurements of ET are mainly based on a variety of complex measurements such as lysimeters and/or eddy covariance techniques (Ghiat et al., 2021). In addition to the limited utility of such measurements at local, field or landscape levels, their accessibility is also constrained (Ashouri et al., 2016; Singh et al., 2021). Some of the continuous and open-access ET products include SSEBop (Operational Simplified Energy Balance), MODIS (Moderate Resolution Imaging Spectroradiometer) ET, and WaPOR (Water Productivity through Open access of Remotely sensed derived data). Remote sensing data can be used to estimate actual ET of river basins (Gonzalez-

Dugo et al., 2009; Vinukollu et al., 2011; Zhang et al., 2016). Accurate ET data are essential to understand the water balance of a basin, to monitor and forecast droughts, as well as to estimate agricultural water consumption so as to improve the efficiency of irrigation systems.

Surface water and groundwater storage

The use of remote sensing data for surface and reservoir water detection, delineation and/or monitoring changes is an established practice in the literature (Bhangale et al., 2020; Bijeesh & Narasimhamurthy, 2020; Huang et al., 2018). Remote sensing data can be used to derive information on surface water levels using radar altimetry (Frappart et al., 2006; Morris & Gill, 1994), when combined with other datasets, volumes (Cai et al., 2016; Gao, 2015), and reservoir impoundment or water releases from reservoirs (Deng et al., 2020; Muala et al., 2014). Changes in surface water extent are often determined using time series of optical satellite data at various resolutions depending on the scale of application. The Global Surface Water Explorer (Pekel et al., 2016) is an example of the more recent open-access global datasets on surface water dynamics. Techniques such as the Synthetic Aperture Radar (SAR) are used for applications such as to determine inundation extents for mapping floods under cloudy conditions (e.g., Tarpanelli et al., 2022) and/or to detect variations in water levels of lakes, rivers and reservoirs, allowing researchers to indirectly infer changes in water storage (Brisco, 2015). The GRACE satellite system estimates groundwater changes by tracking variations in the Earth's gravitational field, a technique that enables indirect measurement of total terrestrial water storage, including groundwater, by assessing changes in the gravitational pull between twin satellites (Rodell et al., 2004; Wahr et al., 2004). This provides data on total water storage variations including surface water, snowpack, soil and groundwater (Tapley et al., 2004). Overall, remote sensing data can be used to detect and monitor changes in surface water bodies, such as the volume and surface area of lakes, groundwater recharge and storage.

Other remote sensing data

In addition to the major hydrologic components often required for water budget assessment in river basins, remote sensing-derived data products are also applied for measuring other important components for basin water assessment, including snow cover, depth and/or snow water equivalent (Shi et al., 2016; Xu et al., 1993), soil moisture content (Mohanty et al., 2017), water level-derived streamflow (Michailovsky et al., 2012), and flood inundation extent and/or depth (Rosser et al., 2017). The application of remote sensing data for land-use/land-cover and soil characterization, important variables in most basin water assessment models, is a well-documented practice in the water resources literature (Brown et al., 2022; Gómez et al., 2016; Kussul et al., 2017; Pareeth et al., 2019). Other remote sensing applications include water pollution/water quality observation (Ritchie & Cooper, 2001; Wang & Yang, 2019), wetland assessment and monitoring (Munyati, 2000; Perennou et al., 2018), water productivity and/or water-use efficiency (Cai et al., 2013; Karimi et al., 2013), and biomass productivity (Qi et al., 2019).

Uncertainties associated with remote sensing data

The availability of open-access and spatially and temporally continuous remote sensing data significantly aids in managing water resources, transboundary or otherwise. However, the quality of the varied remote sensing data products is subject to several factors. These include the spatial and temporal resolution of the data, the algorithms used in estimating variables, and the presence of ground-truth data that can be used for validation (Figure 1). In the context of transboundary basin agreements and practices, stakeholders have traditionally depended on conventionally collected hydrological data (Leb, 2020). This reliance often results in a certain level of resistance or scepticism towards adopting data from newer sources such as remote sensing. As such, it becomes imperative to offer accurate and thorough reporting on the uncertainties and error margins tied to remote sensing-derived data. Such information is particularly important when comparing the data's reliability with those sourced from conventional methods.

Remote sensing-based measurement and/or data can introduce several sources of errors during data acquisition, processing, analysis, conversion and presentation (McMillan et al., 2018; Tian & Peters-Lidard, 2010). Data processing errors in remote sensing occur during the initial stages of handling and refining raw data obtained from satellite sensors. These include radiometric errors (sensor inconsistencies, atmospheric effects or variations in surface reflection), geometric rectification errors (distortions in

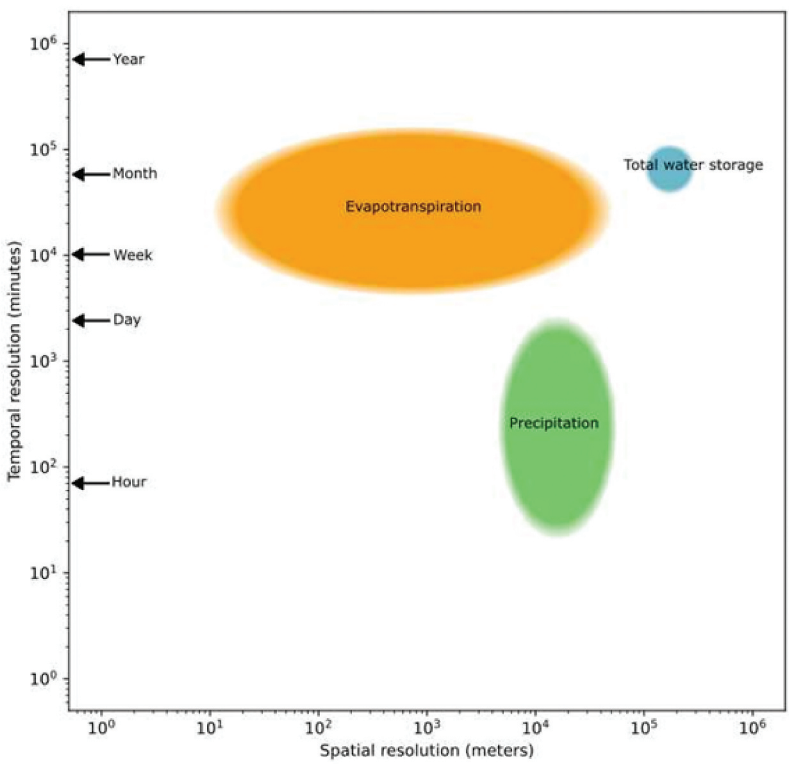

Figure 1. Spatial and temporal resolution of remote sensing data products for major hydrologic components.

the spatial positioning of pixels in the image), and bias correction errors (systematic inaccuracies introduced by the sensor (Slater, 1985) or the processing chain (Povey & Grainger, 2015). Data analysis errors occur during the interpretation and evaluation of the processed data, which include classification errors, generalization errors, parametrization errors and data gaps (Mayr et al., 2019). For example, the data obtained from optical sensors are often contaminated by clouds (which can introduce radiometric errors) resulting in data gaps which for many applications are statistically filled (which can introduce data analysis errors; Siabi et al., 2022). These gap filling approaches can introduce uncertainties in the estimates depending on the geographical location and the ability of cloud-masking algorithms to accurately detect clouds (Foody, 2002). The undetected clouds and the cloud shadow after applying cloud masks are also a key source of uncertainties. Modelling based on remote sensing data can further introduce errors including on spatial and temporal representation and interpretation.

The remote sensing methods employed to estimate precipitation from spaceborne instruments are, for example, affected by both relative errors (difference between the remote sensing data estimate and ground observations) and uncertainties (range of values within which the estimated value lies with some level of confidence from the ground observation data; Massari & Maggioni, 2020). According to Massari and Maggioni (2020), the most common sources of uncertainty in remote sensing precipitation data are related to sampling uncertainty due to limited satellite overpasses, processing errors (parameter calibration, gap filling) and/or errors in the a priori databases. Such uncertainties are challenging to quantify, particularly over a large area in data-scarce regions, and remain largely unknown, limiting the usefulness of remote sensing precipitation data. Additionally, the inherent discrepancy between point-based gauge measurements and area-based (or pixel-based) remote sensing measurements presents another challenge. While gauge data provide precise measurements at specific locations, remote sensing data provide averaged measurements over a larger area (the pixel size). This fundamental difference can introduce additional uncertainties when comparing or combining these two types of data, and needs to be carefully considered in data analysis and interpretation. Some studies, however, report that satellite-derived products sometimes outperform gauge data during calibration of conceptual models (Awange et al., 2016; Stephens et al., 2022).

Uncertainties in ET products are mainly attributed to the discrepancies in the forcing datasets such as meteorological data, solar radiation, soil moisture stress and water storage changes (Ali et al., 2022). Furthermore, model structural limitations of the water and energy balances and vegetation processes can contribute to this (Jung et al., 2019). Although non-remote sensing-derived ET data generated with, for example, hydrological models are arguably equally uncertain and come with their own intrinsic flaws (Puy et al., 2022), it is still difficult to conduct a comprehensive and systematic evaluation of remote sensing-derived ET products due to limited ground data (Weerasinghe et al., 2020). The reported uncertainties of remote sensing ET data vary widely. For example, Velpuri et al. (2013) reported a mean uncertainty of up to 50% on point and 25% on basin scale ET, while Rodell et al. (2011) found that water budget-based estimates of monthly ET are often too large to be of use. Furthermore, Badgley et al. (2015) reported that choice of forcing data can produce up to 20% difference in global monthly mean ET, while Karimi and Bastiaanssen (2015) reported an overall 95%

accuracy on seasonal ET estimates from remote sensing-based models for a particular water accounting case.

With regard to water storage and groundwater data, uncertainties remain large. For example, while GRACE data are useful for tracking total water storage variations (Tapley et al., 2004), the coarse spatial and temporal resolutions – pixel sizes of roughly 300–400 km at approximately monthly scale – present a large uncertainty in total storage assessment (Long et al., 2014; Richey et al., 2015).

Overall, the level of accuracy of remote sensing data for water resources management depends on a variety of factors, including the specific data products being used and the methods employed to analyse and interpret the data. The main uncertainties generally depend on the spatial and temporal resolution of specific datasets, accuracy of the specific sensor, cloud cover and other atmospheric conditions, and data processing methods applied to the estimation or quantification of these datasets.

Opportunities and challenges of remote sensing data in transboundary cases

As remote sensing data have become increasingly pivotal in transboundary water management over recent decades, it has begun to transform how data access is viewed. This non-exclusive open-access data encourage broad participation, allowing various stakeholders such as NGOs, academics and individuals to join in the process of data analysis and decision-making. As it does not allow a single riparian country to monopolize, it provides opportunities to foster an inclusive and cooperative attitude towards water management. The realization of this potential, however, hinges on adequate internet access, suitable infrastructure, and the ability to process and interpret this data, highlighting the need for capacity-building in this regard.

Besides the data required for water resources management in general, such as for water budget assessment (P, ET, $\Delta S/\Delta t$) as described above, remote sensing data have the potential to support cooperation in transboundary basin management. As described by Sadoff and Grey (2002, 2005), the process of cooperation in transboundary river basin can be represented as a continuum framework, from unilateral action/dispute to coordination, collaboration and joint action/integration (Figure 2). In this 'Continuum of Cooperation', the initiation of cooperation, that is, the transition from unilateral action towards cooperation can involve information sharing and regional assessments of water resources. Then a transition from cooperation to collaboration can involve converging national agendas in adapting plans to mitigate regional costs or to capture regional gains as well as join preparation and investment. Finally, a transition from joint collaboration to joint action can involve joint equity ownership of assets, institutions and/or project design and assessment.

In situations where cooperation is just starting, for example, remote sensing data and applications such as general precipitation assessment and ET mapping and monitoring (Figure 2, left side) are more relevant. For example, in the case of the Mekong basin, which is shared by six countries in Southeast Asia, cooperation has progressed to the stage of joint management through the establishment of the Mekong River Commission (MRC) to coordinate and manage the shared water resources (Hensengerth, 2009). In such cases, remote sensing data can be used to

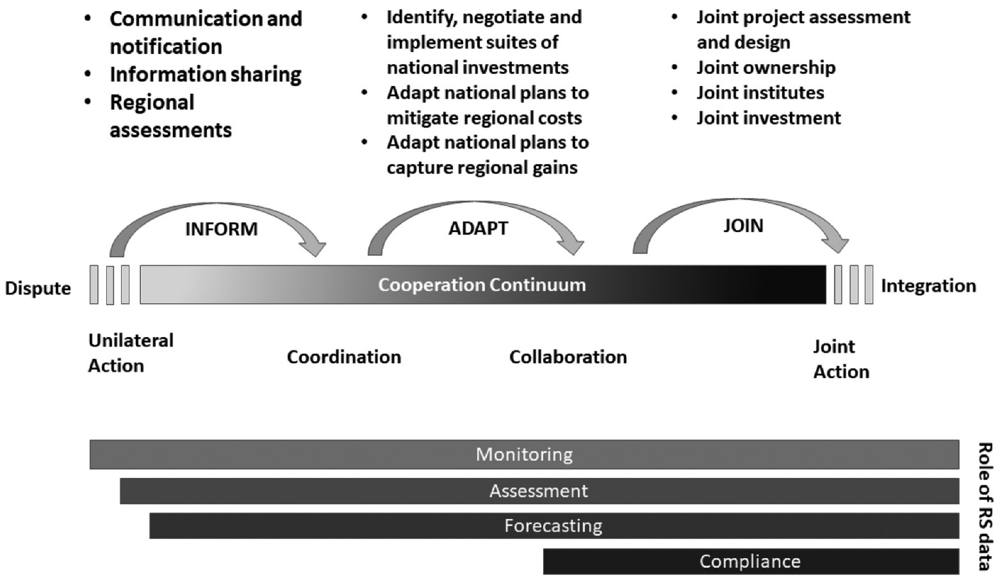

Figure 2. Continuum of cooperation in transboundary basins.

monitor general water resources assessment to inform water management decisions by providing a spatially and temporally continuous record of water balance, water levels, flow rates, etc. Remote sensing data are applied in the Mekong transboundary basin for assessing general water balance (Dinh et al., 2020), stream flow variability (Mohammed et al., 2018), monitoring of reservoir inundation dynamics (Shin et al., 2020), monitoring and assessment of water pollution (Tran-Thanh et al., 2022).

In the case of fully fledged transboundary cooperation (Figure 2, right end), more targeted and precise information on transboundary water quantity and quality may be required. The Senegal River basin, which is shared by four countries in West Africa, is a good example of a relatively advanced level of cooperation on transboundary basins. Governed by the Senegal River Basin Development Authority (OMVS), the cooperation in this transboundary basin is considered to have progressed into a level of structured cooperation through joint investment and the development of common policies and strategies for the management of the shared river (Nguyen, 1982; Varis et al., 2008). In this transboundary basin, remote sensing data are applied, for example, to simulate discharge (Stisen et al., 2008), to forecast flood and reservoir operation (Bruckmann et al., 2022), and to monitor compliance with transboundary water use agreements (Merem & Twumasi, 2008; Ragettli et al., 2017).

Ultimately, remote sensing data can play a pivotal role in monitoring potential sources of transboundary water, including rivers, lakes and aquifers, during the initial stage of cooperation. Progressing along the cooperation continuum (Figure 2), these data can then be applied to assessing the quantity and quality of transboundary water resources. Furthermore, remote sensing data can be instrumental in the forecasting of transboundary water resources, including in real-time hydrological modelling, early warning systems for droughts and floods, predictions of potential water quality issues, and predicting changes in ecosystem health and biodiversity. As cooperation strengthens in transboundary basins, remote sensing data can play a crucial role in enforcing compliance with water agreements and conservation measures, providing open-access and spatially distributed data to support equitable resource management and conflict resolution.

It is important to note, however, that the stages or phases of cooperation outlined in Figure 2 are not necessarily sequential and may not necessarily be achieved by all transboundary river basins. Furthermore, the level of cooperation among countries can vary depending on a variety of factors, including the level of conflict or political tensions between the countries, the level of trust between them, and the availability of resources for cooperation (Martin et al., 2011).

A wide range of remote sensing applications for transboundary water management exist in the literature (Table 1). Some of these applications involve, for example, the use of remote sensing data for monitoring compliance of transboundary agreements (Bretreger et al., 2021), water level of reservoirs and rivers (Biancamaria et al., 2011; Seyler et al., 2008), flood inundation modelling and forecasting (Amarnath et al., 2016; Dubey et al., 2021), and monitoring and assessment of transboundary aquifer storage changes (Fallatah et al., 2017; Voss et al., 2013). Further applications include monitoring of land cover change (Khoshnoodmotlagh et al., 2020; Schulte to Bühne et al., 2017).

Overall, remote sensing data can be a valuable source of information for transboundary water management, as it provides timely and cost-effective data over large areas on various hydrological, meteorological and land cover variables. Existing earth observation and remote sensing based geospatial decision support systems on transboundary basins, for example, SERVIR tools (SERVIR-Amazonia, 2023; SERVIR-Mekong, 2023), part of the SERVIR-Global initiative (Flores et al., 2018), provide valuable information for water resources management for riparian states beyond their political border, thereby presenting viable alternatives whenever on-ground observations are lacking or unavailable. The SERVIR-Mekong decision support tools, for example, enable the MRC and its member states monitor flood and drought for decision-making and planning processes in the

Table 1. Studies on remote sensing applications in transboundary basins (note that the colour shade the message conveyed in Figure 2).

Broad categories	Applications	References
Monitoring	Water level of reservoirs	Gao (2015); Muala et al. (2014); Seyler et al. (2008)
	Water level of rivers	Biancamaria et al. (2011); Hossain et al. (2013)
	Reservoir operation rules (construction/filling of dams), monitoring	Muala et al. (2014); Eldardiry and Hossain (2019); Kim et al. (2022); Das et al. (2022)
	Pollution/water quality	Ritchie and Cooper (2001); Wang and Yang (2019)
	Wetland/environmental/ecological flow	Munyati (2000); Perennou et al. (2018)
Assessment	Water use/consumption estimation/efficiency, e.g., irrigation	Bretreger et al. (2022); Akbari and Torabi Haghighi (2022)
	Water resources assessment/water accounting/ water budget	Karimi et al. (2013); Kumar et al. (2022); Chen et al. (2021)
	Storage change of transboundary aquifers	Voss et al. (2013); Fallatah et al. (2017); Khaki and Awange (2019)
	Water productivity, water use efficiency, net primary productivity	Karimi et al. (2013); Cai et al. (2013); Qi et al. (2019)
Forecasting	Flood forecasting	Dubey et al. (2021); Biancamaria et al. (2011)
	Drought forecasting	Zhang et al. (2020); Das et al. (2022)
Compliance	Enforcement of transboundary water agreement/regulation	Merem and Twumasi (2008); Ragettli et al. (2017); Bretreger et al. (2021)

Mekong basin (Das et al., 2022). Remote sensing data can cover large areas at relatively high spatial resolutions; some satellite sensors can provide estimates of P and ET at resolutions as fine as 1 km or less, much finer than the resolution of most ground-based weather stations. Therefore, remote sensing data can provide spatially distributed information of areas where most of the water is generated and of those locations where most of the water is consumed. On the other hand, temporal resolution of P can be as high as 3 hourly and near real time, which provides opportunity in establishing flood and drought forecasting models at basin level. This information can be compared with existing plans and agreements on water allocation and use among countries and competing sectors.

Using remote sensing data in models and frameworks such as the WA+ (water accounting plus; Karimi et al., 2013), for example, one can further produce an assessment of water resources availability and use, as well as evaluate the impact of future development plans in transboundary basins. Furthermore, open-access remote sensing data supports transparency and allows for re-examinability of data and information compared with traditional measurements: in case of disagreements on assessment results, riparian states can reprocess the raw data retroactively and examine the results. The characteristics of remote sensing data are therefore instrumental for establishing a dialogue in transboundary water management. The evaluation of remote sensing data, the assessment of its accuracy and related uncertainty can therefore be joint processes to foster such a dialogue. Furthermore, while countries may occasionally contest the validity and accuracy of remote sensing data, its universally accessible nature fosters non-governmental cooperation in transboundary water management, even regardless of formal governmental consensus.

While generally cost-effectiveness, wide and repeatable coverage, and reasonably favourable accuracy make remote sensing data valuable sources of environmental data (Zhang et al., 2016), challenges related to consistency under diverse conditions, and limited availability of calibration and validation datasets remain important (Bhattarai & Wagle, 2021). Furthermore, the presence of open-access remote sensing data does not automatically mean that they will be used for transboundary water management. Cooperation in transboundary water management is also influenced by other considerations such as differences in legal frameworks, historical practices, technical abilities, and cultural backgrounds (Ibrahim, 2020; Timmerman & Langaas, 2005).

Besides the more measurable aspects of uncertainty related to remote sensing data which can be very large in some products and cases, however, there is also scepticism and perceived uncertainty associated with the utility of remote sensing data (Povey & Grainger, 2015). *In-situ* data, which, while also subject to errors and uncertainties, tend to be regarded as 'truth'. However, it is important to note that there is no agreed convention to systematically report uncertainty when reporting hydrological data even when using *in-situ* data. Furthermore, the level of error or uncertainty in remote sensing data is location and climatic zone specific (Awange et al., 2016; Zhang et al., 2016). The same data product may perform badly in some location but may give good validation results elsewhere. Perceptions, however, can pose further challenges towards the uptake of some remote sensing data in transboundary water management.

The impact of uncertainty of remote sensing products in transboundary basins depends on the position of riparian states in the cooperation process. Under low cooperation condition, for example, any error can be politicized or, even worse, remote sensing data can be used to mislead the public opinion (e.g., the 'water panic' in Wheeler et al. (2020, p. 6) 'people feel losses much more acutely than gains of comparable size'; and they 'feel water losses more acutely than they do losses of almost any other commodity'). It is, therefore, important that transboundary water management practitioners understand which remote sensing products are most appropriate for their situation and also identify the most important remote sensing data uncertainties. Notwithstanding the many promising potentials outlined earlier, remote sensing data may not be sufficient on its own for transboundary water management, as it does not provide detailed information about the physical, chemical and biological characteristics of water resources. Furthermore, it also lacks information on various social and hydropolitical drivers in a shared basin. Remote sensing data are, therefore, likely to remain a complementary product in the near future, not least due to inaccuracy (real and/or perceived), uncertainty, limited validation datasets, and difficulty to rely on remote sensing data with respect to cloud cover and other atmospheric interferences. Ongoing research on technologies such as the SAR (Brisco, 2015), which can 'see through' clouds, aims to detect variations in the water levels of lakes, rivers and reservoirs. This could indirectly improve the estimation of remote sensing-derived hydrological components such as changes in water storage.

The human capacity for remote sensing data gathering, processing, analysing and storing information on shared waters is another challenge and could be a key priority for riparian states to develop (a certain level of) confidence in remote sensing data itself. This could, in turn, help to facilitate dialogue and promote joint factfinding in situations where remote sensing data give rise to unexpected, surprising, differing or even conflicting interpretations. Since remote sensing is capable of providing information about water use across political borders, it may be, and has been, perceived as a potential security concern because it enables the observation of water use in neighbouring countries. Ironically, and perhaps surprisingly, this may also create a new motivation for riparian states to share conventional (ground-observed) data. In any case, riparian states should ideally have an interest in building and maintaining strong technical capacity and competence in collecting, validating, interpreting and critically assessing data derived from remote sensing to be able to interrogate and corroborate any application with an impact on their shared waters. Such interrogation and corroboration of remote sensing data, including the assessment of its accuracy and related uncertainty, can be joint processes. This collaboration could ideally foster further dialogue on transboundary water management. Strengthening and promoting inter-institute and/or inter-university cooperation on remote sensing applications in specific transboundary river basins could prepare the grounds for a more formal intergovernmental transboundary cooperation on a more robust application of remote sensing data for transboundary water management.

Conclusions

The increasing availability of open-access, timely remote sensing data presents an opportunity for water resources management in general. Such data are particularly useful for addressing unique transboundary water assessment challenges such as data-sharing and monitoring of compliance to transboundary water allocation agreements. Remote sensing data complements existing models and could encourage riparian states to share conventional data, knowing other states may use these datasets.

The primary challenges to remote sensing data use in transboundary water management involve uncertainty, data collection and processing capacity, and other considerations such as legal and political perspectives. Despite its great potential for transboundary water management, the role of remote sensing data will most likely remain limited to a complementary one due to these challenges.

Despite this, remote sensing data present a real opportunity for transboundary basin management, particularly in data-scarce regions. However, for such an opportunity to materialize, it presupposes a strong technical capability for validating, interpreting and critically assessing remote sensing data on shared waters. It is thus in the interest of riparian states to build strong technical capacity and competence in remote sensing to be able to apply, interrogate and corroborate any application with an implication on their shared waters.

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