remote sensing

MDPI

Review

Inland Water Level Monitoring from Satellite Observations: A Scoping Review of Current Advances and Future Opportunities

Stylianos Kossieris *, Valantis Tsiakos, Georgios Tsimiklis and Angelos Amditis

Institute of Communication and Computer Systems, National Technical University of Athens, 157 73 Athens, Greece; valantis.tsiakos@iccs.gr (V.T.); georgios.tsimiklis@iccs.gr (G.T.)
* Correspondence: stelios.kossieris@iccs.gr; Tel.: +30-210-772-3865

Abstract: Inland water level and its dynamics are key components in the global water cycle and land surface hydrology, significantly influencing climate variability and water resource management. Satellite observations, in particular altimetry missions, provide inland water level time series for nearly three decades. Space-based remote sensing is regarded as a cost-effective technique that provides measurements of global coverage and homogeneous accuracy in contrast to in-situ sensors. The advent of Open-Loop Tracking Command (OLTC), and Synthetic Aperture Radar (SAR) mode strengthened the use of altimetry missions for inland water level monitoring. However, it is still very challenging to obtain accurate measurements of water level over narrow rivers and small lakes. This scoping systematic literature review summarizes and disseminates the research findings, highlights major results, and presents the limitations regarding inland water level monitoring from satellite observations between 2018 and 2022. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline and through a double screening process, 48 scientific publications were selected meeting the eligibility criteria. To summarize the achievements of the previous 5 years, we present fundamental statistical results of the publications, such as the annual number of publications, scientific journals, keywords, and study regions per continent and type of inland water body. Also, publications associated with specific satellite missions were analyzed. The findings show that Sentinel-3 is the dominant satellite mission, while the ICESat-2 laser altimetry mission has exhibited a high growth trend. Furthermore, publications including radar altimetry missions were charted based on the retracking algorithms, presenting the novel and improved methods of the last five years. Moreover, this review confirms that there is a lack of research on the collaboration of altimetry data with machine learning techniques.

Keywords: inland water level; inland water bodies; satellite; altimetry; Sentinel-3; SAR; retracking algorithms; ICESat-2; PRISMA

check for updates

Citation: Kossieris, S.; Tsiakos, V.; Tsimiklis, G.; Amditis, A. Inland Water Level Monitoring from Satellite Observations: A Scoping Review of Current Advances and Future Opportunities. *Remote Sens.* **2024**, *16*, 1181. https://doi.org/10.3390/rs16071181

Academic Editors: Sergei Badulin, Xiaoli Deng, Stelios Mertikas and Jérôme Benveniste

Received: 20 September 2023
Revised: 4 March 2024
Accepted: 22 March 2024
Published: 28 March 2024

1. Introduction

Inland water bodies, wetlands, and their dynamics have a key role in a variety of scientific, economic, and social applications. As rivers, lakes, and wetlands form the main freshwater recourses, are crucial to water resource management [1], biodiversity [2,3], climate change impacts [4–7], agricultural productivity [8], and modeling between land and atmosphere interactions [9,10]. Thus, inland water bodies are an integral part of the global water cycle and there is a need for a globally homogeneous, continuing monitoring system for an effective management of terrestrial water resources. However, there is limited understanding of the distribution of the global hydrological cycle. Both the water surface elevation of inland water bodies and the spatial and temporal dynamics of water storage, are not sufficiently known.

Historically, observations for understanding the global hydrological cycle and the Earth system in general rely on in situ gauge measurements. In situ sensors help to retrieve water level heights, but the network is sparse, particularly in areas with difficult access. The

Global Runoff Database Centre has established a network with gauge stations providing river discharge data in 159 countries [11]. The spatial distribution of rain gauge measurements is not dense enough to represent the input with high accuracy to the hydrological cycle. Also, the water storage estimates from traditional in situ observation show great uncertainty [12,13]. Moreover, the prohibitive cost of state-of-the-art sensors is a significant factor that hinders their global widespread installation, and as a result, it contributes to the inadequate monitoring of the hydrological cycle, while in some cases the scientific community faces restricted access to in situ data, often due to political circumstances or agreements pertaining to transboundary water sharing [14].

In this context, space-based remote sensing could be considered an innovative cost-effective technique that provides up-to-date measurements from various sensors with global coverage and homogeneous accuracy. Spaceborne sensors designed for monitoring terrestrial water levels can provide measurements with high temporal coverage. Space-based water cycle monitoring is entering a new era in view of the wealth of present and future spaceborne missions. This scoping review paper examines the performance of satellite altimetry missions used to retrieve inland water surface heights. Satellite altimetry constitutes the dominant technique for inland water level monitoring. The principle of altimetry is to emit wave pulses and to receive the reflected echoes recording the round-trip time of the pulse. The measured backscatter energy as a function of time is called the waveform. Altimetry, originally aimed in the 1960s at oceanography and geodesy using a radar altimeter to extract sea water level [15], has demonstrated its potential for monitoring other components of the hydrosphere such as rivers, lakes, and wetlands. The concept of using satellites to observe water surface heights was initially proven successful through various missions launched by NASA in the 1970s, such as the Skylab-3 in 1973, the GEOS-3 in 1975, and the Seasat in 1978 [16–18]. A total of 20 altimetry satellites have been launched in the last three decades. In the 1980s, the altimetry Geosat mission was launched [19], while the real upsurge of altimetry came after the launch of the very successful NASA-CNES Topex-Poseidon (T/P) mission in the 1990s [20]. Especially, the significant upsurge of altimetry for inland water came after the launch of the ERS-1 mission, which had three tracking modes which was very efficient over non-ocean surfaces. However, the use of altimetry for monitoring inland water bodies was facilitated by the advent of two different developments: The Open-Loop Tracking Command (OLTC), first implemented by the Jason-2 satellite mission [21], and the Synthetic Aperture Radar (SAR) mode, first used in the CryoSat-2 mission [22,23]. The first mission operated both in OLTC and SAR mode was the Sentinel-3A, launched in 2016 [24]. The timeline of modern radar altimeters from the nineties to the next decade is shown in Figure 1. Past missions are in red and satellites in operations are in orange, while future missions and unconfirmed mission extensions are in yellow.

The latest altimetry mission named SWOT was launched in December 2022 and is the first mission specifically dedicated to the observation of continental surface water bodies. This mission was developed by NASA and CNES with contributions from the Canadian Space Agency and the United Kingdom Space Agency. The SWOT mission can acquire 2-D swaths as opposed to conventional 1-D profiles used for approximately 50 years. It might be the most important technological breakthrough in the history of altimetry missions since the T/P mission's capability to reach centimetre-level accuracy. The SWOT mission has opened a new era of scientific advances for continental hydrology, and therefore the extraction of inland water levels [25].

Inspired by the launch of so many altimetry missions, and the development of services to provide inland water level time series to supply data for Earth system understanding, hydraulic studies are becoming more important than ever. After the launch of GEOS-3 and Seasat missions in the 1970s, two reviews focused on marine geodesy and ocean circulation [26,27]. Other reviews focused on continental surface waters [28], and specifically on surface water storage [14]. The role of satellite altimetry in monitoring the world's inland water resources is highlighted in [29–31], while another study presents the capabilities of

ESA altimeters to monitor inland water heights [32]. Furthermore, the various achievements made by altimetry missions, and their key contribution to global climate change monitoring are presented in [33], while a different analysis emphasized the importance of radar altimeters in terms of water level and discharge [34]. Moreover, a comprehensive analysis summarizing the progress of 25 years of satellite altimetry was made by more than 300 co-authors [35], while the most recent review paper, summarizes the scientific achievements of altimetry using a total of 8541 publications covering the years from 1970 to 2021 [36].

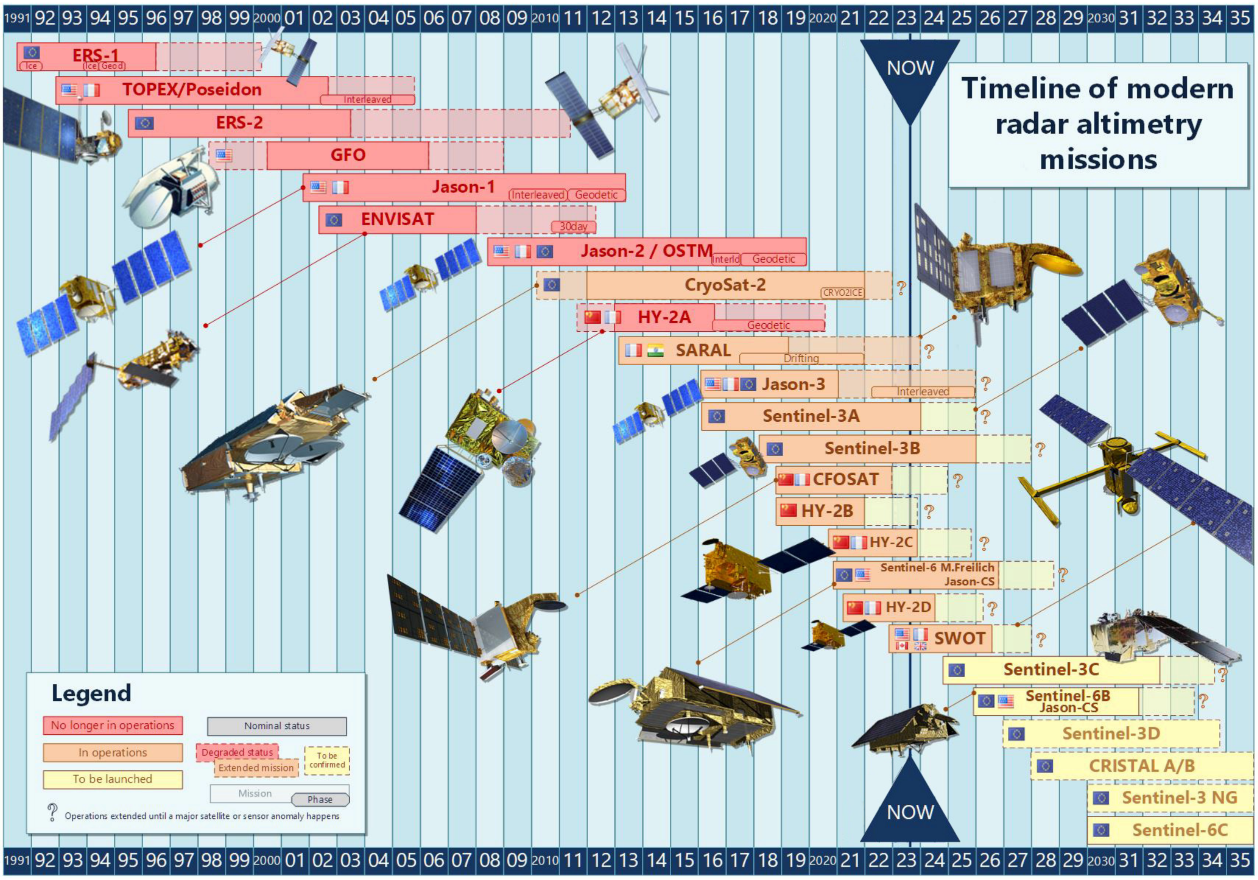

Figure 1. Timeline of modern radar altimetry missions. https://www.aviso.altimetry.fr/en/missions/timeline-altimetry.html (version 2023/08), accessed on 21 March 2024.

Scoping studies have become a progressively more prevalent approach for systematically searching the literature to address a specific research question [37]. The current scoping review paper presents the achievements made by satellite missions, and hence by altimetry missions to the field of inland water level monitoring between 2018 and 2022. Following the methodological framework developed by Arksey and O'Malley [38], the purpose of this review is to summarize research findings in inland water surface height monitoring, while for the analysis of the current research question five electronic literature databases are used. Researchers used the PRISMA statement to improve the reporting of scoping review and meta-analyses [39]. This study includes data related to the different literature databases and the number of publications per year. Moreover, both the publications associated with specific satellite missions and the different algorithms used to retrack the waveforms are analyzed to mirror the trend in the field of inland water level monitoring. This study provides a comprehensive review using spaceborne missions during the past 5 years, aids new researchers in their study of this specific field, and assists experienced researchers in keeping their knowledge up to date. The remainder of this paper is organized as follows: Section 2 describes the methodological framework of the scoping review. In Section 3, the results of the review are presented and analyzed, while Sections 4 and 5 focused on the conclusion of this study emphasizing research gaps and future opportunities.

2. Methodological Framework

In this section, the methodological framework of the scoping review is described, based on the stages followed by Arksey and O'Malley [38] and Daudt et al.'s [37], to analyze the current state of different satellite missions, altimetry, or others, regarding the highly focussed research questions [40,41]. The performances of different satellite missions are examined as well as the different retracking algorithms used over inland water bodies. The research protocol described in the following paragraphs was proposed by Arksey and O'Malley [38] and Peters et al. [42].

2.1. Search and Selection Strategy

For the analysis of satellite missions used for inland water level monitoring, five electronic literature databases were employed. We used Google Scholar, Scopus, ScienceDirect, IEEE Xplore, and Taylor & Francis databases to search English-language peer-reviewed scientific journals and proceedings. The searching period of the current scoping review paper is between 1 January 2018 and 31 December 2022, since until 2018 Sentinel-3 was operated in the OL tracking mode in specific areas of interest, having a low number of hydrological targets [24]. Then the research team established the exclusion and inclusion criteria for the evaluation of the literature. We excluded studies characterized as "*grey literature*" including presentations, books or book chapters, commentary, preprints, thesis, abstracts, as well as report deliverables. Based on pre-determined research questions, we searched for the best combination of keywords relevant to the research topic. The multiple keywords combined with the appropriate Boolean operators were queried in the aforementioned five literature databases. The multiple keywords with the Boolean operators are presented in Table 1. Then, all results were uploaded to Mendeley software (Version 1.19.4) [43] to remove the duplicates between the literature databases.

Table 1. Group of the selected keywords used in the five selected databases.

Question Components	Search Keywords
Inland Water Level Satellite	("Inland Water Level" OR "Inland Water Level Monitoring" OR "Inland Water Monitoring" OR "Monitoring Inland Water") AND (Satellite)–"Monitoring Inland Water Quality"–"Water Quality Monitoring"

Afterward, the review team accomplished a two-level screening (abstract screening and full-text screening). The systematic review software, Swift Review [44], was used to provide tools for assistance in the literature prioritization during the screening. Swift-Review software uses the latent Dirichlet allocation (LDA) model to probabilistically assign the publications to the topic. The papers assigned to Swift Review were manually labeled as "Relevant" or "Non-Relevant" and were used to predict the probability of each publication as "Relevant" [45]. This stage of screening includes the title and the abstract of each document. Swift Review uses a machine learning method to compute a score which attempts to prioritize the documents such that the documents similar to the "Included" papers are ranked at the top of the list. Thus, the most "representative" publications get the highest scores and are presented at the top of the list. Having completed the triage of documents in "Relevant" and "Non-Relevant" and performing the priority ranking, the second stage of screening has to be performed. The second stage includes the evaluation of predicted ranking scores, denoting the threshold of relevance. For the objectivity of data sample, the training and test documents were split to a 50-50 ratio. For the evaluation process, we denoted as "Relevant" the corpus of a prioritization ranking score of 0.6 or higher. Also, the confusion matrix based on visual inspection analysis, as well as the sensitivity score are analyzed to evaluate the results. The sensitivity score, depicted in Equation (1) is a measure of how many 'Relevant' documents are selected, and it is calculated as the proportion of True Positive with True Positive and False Positive documents. TP stands for 'Relevant' publications correctly identified as Relevant, and FP stands for 'Non-Relevant' publications incorrectly identified as Relevant.

$$Sensitivity = \frac{TP}{TP + FP} \tag{1}$$

Afterward, the dataset was updated including the validated "Relevant" articles and the remaining articles, which were denoted as "Included" during the first stage of screening. Then, the final dataset was confirmed, ascertaining the corpus selection efficiency through the full-text screening procedure.

2.2. Selection Criteria

The initial perusal of the citations indicated that the search strategy had picked up a high number of irrelevant studies. This highlights the importance of defining terminology at the outset of the scoping study. Thus, our scoping study adopted inclusion and exclusion criteria, based on the specific research question. These criteria were defined at the beginning of the analysis and before the selection process, ensuring the thematic consistency of the analysis, as well as the reduction of bias [46]. Then, the research team applied the inclusion and exclusion criteria to all scientific papers during the full-text screening process. The final consensus among all researchers needed to be reached before each publication was finally included. The inclusion and exclusion criteria are presented below:

Inclusion criteria:

1. Peer-reviewed scientific journals, proceedings, and review papers have to be published between 1 January 2018 and 31 December 2022;
2. Publications must be written in the English language;
3. Publications encompass data from satellite missions with in-situ sensors or other spaceborne missions for the validation/assessment of the proposed methods;
4. Studies that include statistical accuracy metrics for the validation/assessment of the performances of satellite missions.

Exclusion criteria:

1. Publications that are not mainly oriented in inland water level monitoring but generally in the water cycle, water dynamics (such as water volume variations, surface water extent, and river discharge), or in hydrologic/hydrodynamic models of a river;
2. Any article that is mainly oriented in sea surface, coastal, or ocean water level monitoring, and not in inland water level monitoring;
3. Exclusion of publications that do not calculate water level heights but are focused only on the analysis of a satellite mission.

2.3. Charting the Data: Transformation, Analysis, and Interpretation

The next stage of the scoping review involved "charting" key items of information. "Charting" refers to a technique for synthesizing and interpreting qualitative data by sorting and charting data according to key themes and issues [38,47]. The charted information should include a mixture of general information about the study and specific data related to the study question [37]. Thus, each team member worked independently to chart the included articles, and then all reviewers compared their results to agree upon the categories to chart for the study.

Initially, included articles were charted using specific data relating to the literature databases, the year of publication, and the aim of the study. Apart from the publications in which the performances of different satellite missions are evaluated over inland water bodies using existing and known retracking algorithms, some articles aim for deployment and the evaluation of novel and improved retrackers that can derive stable and accurate inland water levels. By developing new retracking algorithms, researchers aim to overcome the limitations of existing retrackers to accurately measure inland water levels [48]. Consequently, the publications were categorized into two groups based on the utilization of only existing retracking algorithms or also of novel and improved ones. Moreover, the publications associated with specific satellite missions (e.g., Sentinel-3, Jason-2/3) were analyzed in order to examine the literature based on the use of different satellite missions. Although satellite altimetry missions are mainly used to monitor the inland water levels, there are also different techniques, such as Global Navigation Satellite System-Reflectometry (GNSS-R), and gravimetry which could also provide accurate water level measurements. Thus, the yearly number of publications, between 2018 and 2022, associated with specific missions were analyzed since each satellite mission has its own characteristics and applications. The trend of specific missions may mirror the trend of the current research field, inland water level monitoring [36]. In the last years, the publications on radar altimetry missions (e.g., Sentinel-3, CryoSat) and laser altimetry missions (e.g., ICESat-1/2) have exhibited a high growth trend. Therefore, the publications associated with radar and laser altimetry missions were charted in order to illustrate any possible trend in the monitoring of inland water levels.

Also, the return waveform, the fundamental measurement of radar altimetry, is contaminated over inland water bodies due to the large size of the radar footprint. Thus, the extracted ranges are corrupted which leads to inaccurate water level measurements. As can be understood, to overcome this problem, proper algorithms need to be used to retrack the waveforms. Therefore, publications were charted based on the retracking algorithms (i.e., retrackers): either they are novel and improved or existing and known ones, applied to the waveforms deemed to be from inland water bodies [48]. There are different types of retracking algorithms, such as Ocean, Ice, and Sea-ice, according to the type of waveforms re-tracked. The different retrackers can be more suited to a specific surface. Therefore, due to the fact that each retracking algorithm has its own characteristics, the trend of one retracker may mirror the trend of inland water level monitoring.

Moreover, in the current study data were organized with respect to the continent and the specific study region, river, lake, or reservoir, where the different satellite missions and retracking algorithms are evaluated so as to examine the different study regions around the world [36].

2.4. From Data to Information, towards Decision Making

For the analysis of charted data, both quantitative and descriptive analytics were used [49]. Both analytics allow the reviewers to summarize and describe the important characteristics of the studies included in the current review, as well as to identify trends and patterns in the literature highlighting areas that have been extensively studied and areas that require further research. Therefore, for the quantitative analysis, graphical representations were created using open-source Python visualization libraries, such as Plotly and Matplotlib. Also, for the descriptive analysis, a visualization map was generated using the VOSviewer open-source software (version 1.6.20) [50]. A network of keywords and terms was created based on the included documents determining the level of relevance between predicted keywords and their frequency of occurrence.

2.5. Bias Control

Two different types of bias were controlled in the scoping review: publication bias and rater bias [51]. For the minimization of publication bias, five electronic literature databases were searched and three types (scientific papers, conferences, and review papers) of publications were included enabling the authors to obtain a more comprehensive and wide range of publications [52]. For the minimization of rater bias, four researchers from a variety of disciplines were involved in the scoping review providing a large perspective on the selection and the charting processes [37].

3. Review Results

As described in the preceding chapter, the study selection process consists of four steps: (1) *identification* of relevant scientific studies from the five literature databases, (2) *screening* the abstracts of publications applying the relevant criteria, (3) *eligibility* applying both the inclusion and exclusion criteria to the full papers, and finally (4) *inclusion* re-applying criteria to the full papers [42]. For the first step, using the multiple keywords with the Boolean operators presented in Table 1, the number of published articles retrieved by the five electronic literature databases is 531. The current scoping paper refers to the period between 1 January 2018 and 31 December 2022. The number of publications was reduced to 386 by excluding the "grey literature". Another 136 documents were excluded by removing duplicates. Thus, the number of remaining documents for the title and abstract screening process is 250. Afterward, the Swift Review uses a definition of "Relevant" by considering a prioritization ranking score of 0.6 or higher. This Threshold of Relevance was empirically selected. As a result, the remaining documents are 72 and thus implementing the exclusion criteria during the full-text screening, a total number of 48 scientific articles were finally selected. The PRISMA flowchart [39], illustrated in Figure 2, depicts the different phases of the current scoping review paper and the number of selected publications at each stage of the process.

Moreover, performing the priority ranking at the Swift Review, the ranking scores of the examined literature varied from 0.11 to 0.87. As can be seen in Figure 3, the ranking performance curve displays the percentage of the included documents (blue line) occurring in each quantile of the ranked list. Nearly 80% of the included documents occur in the top 30% of the ranked list and virtually all the included documents occur in the top 60% of the ranked list. In addition, documents at the top of 25% of the ranked list are included in the "Relevant" list. Also, the yellow line shows the baseline performance we should expect if the ranking score had been generated completely at random such that included publications were uniformly distributed in the ranked list, while the green line depicts the performance for items in the "test set". Finally, it can be understood that the ranking performance on the training documents will typically exceed the performance on the unlabeled document set.

Also, as can be seen in Table 2, the confusion matrix as well as the sensitivity score shows that around 83% of the publications, with a prioritization score of 0.6 or higher, are included in the list of "Relevant" publications.

The 48 scientific publications that were finally selected for the current scoping review paper are mainly published in seven scientific journals which are presented in Figure 4. Apart from the 33 scientific papers published in 7 scientific journals, a total number of 15 scientific journals appeared only once and are aggregated to the "Other" category. As can be seen, the majority of scientific publications (n = 12) have been published in Remote Sensing peer-reviewed open-access academic journals. Moreover, the other six scientific journals focus on environmental monitoring, and their research is mainly oriented toward Remote Sensing and Water (Journal of Hydrology | n = 5, Remote Sensing of Environment | n = 5, Advances in Space Research | n = 4, IEEE Transactions on Geoscience and Remote Sensing | n = 3, Hydrology and Earth System Sciences | n = 2, and Water | n = 2). Also, Figure 5 illustrates the number of publications per year between 2018 and 2022. As can be seen, the number of published articles in 2021 and 2022 was higher than the number of publications in 2019 and 2020, showing the increased interest in the water level monitoring over inland water bodies by spaceborne missions in the last two years.

In addition, the percentage of selected papers per main aim is depicted in Figure 6. Articles were categorized into two groups based on the presentation or not of novel retracking algorithms for the retrieval of inland water levels. As can be seen, there is a significant number of articles in the category of evaluating satellite mission performances using existing retracking algorithms (77% | 37 articles) compared to the category showcasing novel and improved retracking algorithms (23% | 11 articles) for inland water level monitoring. More findings regarding this research question are presented in Section 3.2.

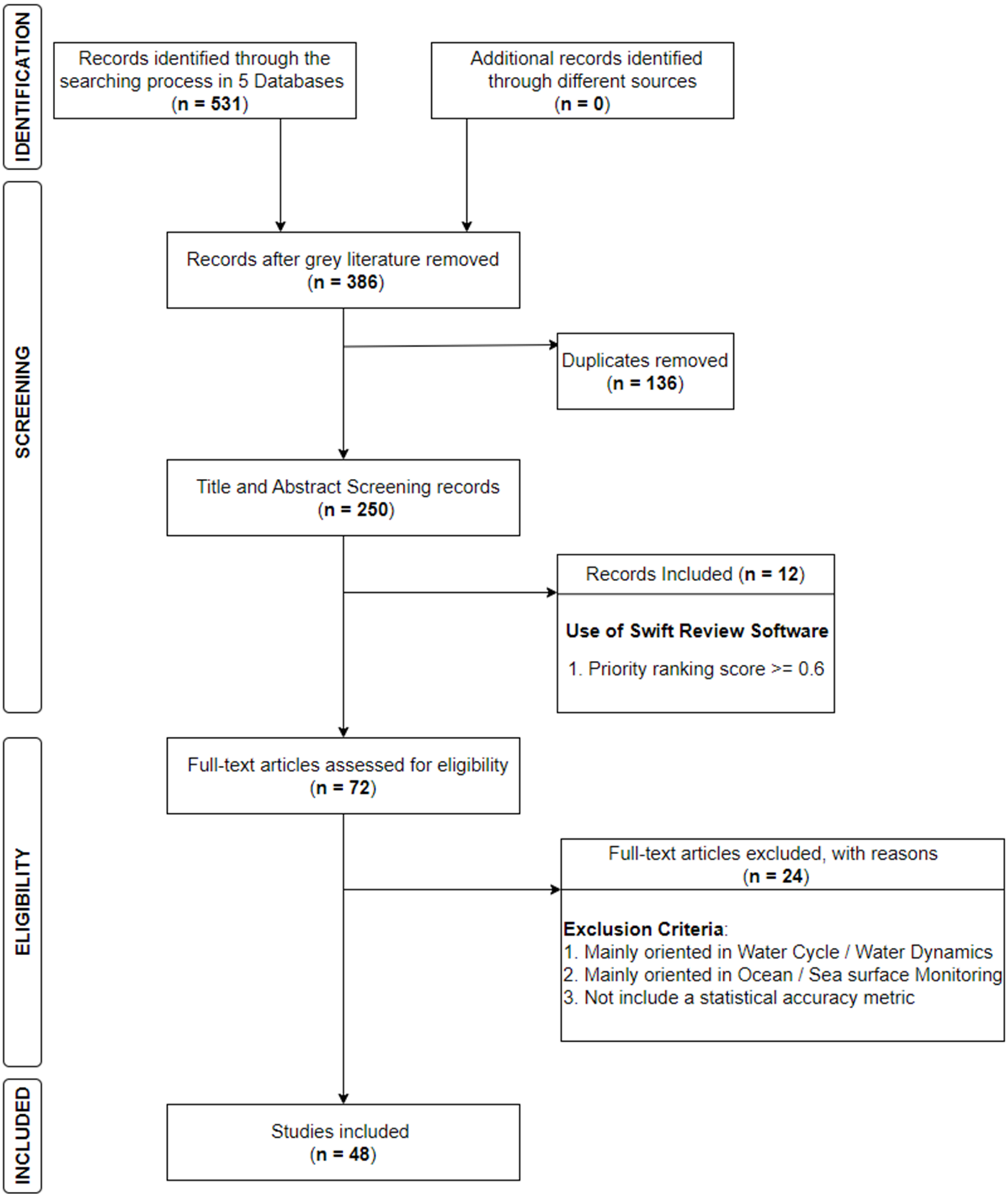

Figure 2. Modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart illustrates the different phases of the scoping review paper and the number of selected articles at each stage of the process.

Table 2. Confusion Matrix based on visual inspection analysis, indicating the percentage of predicted publications, with a prioritization score of 0.6 or higher, included in the final dataset.

	Total Number of Publications	Relevant Publications Classified as Relevant	Non-Relevant Publications Classified as Relevant	Sensitivity Score
Relevant publications classified as Relevant	69	57	12	82.6%

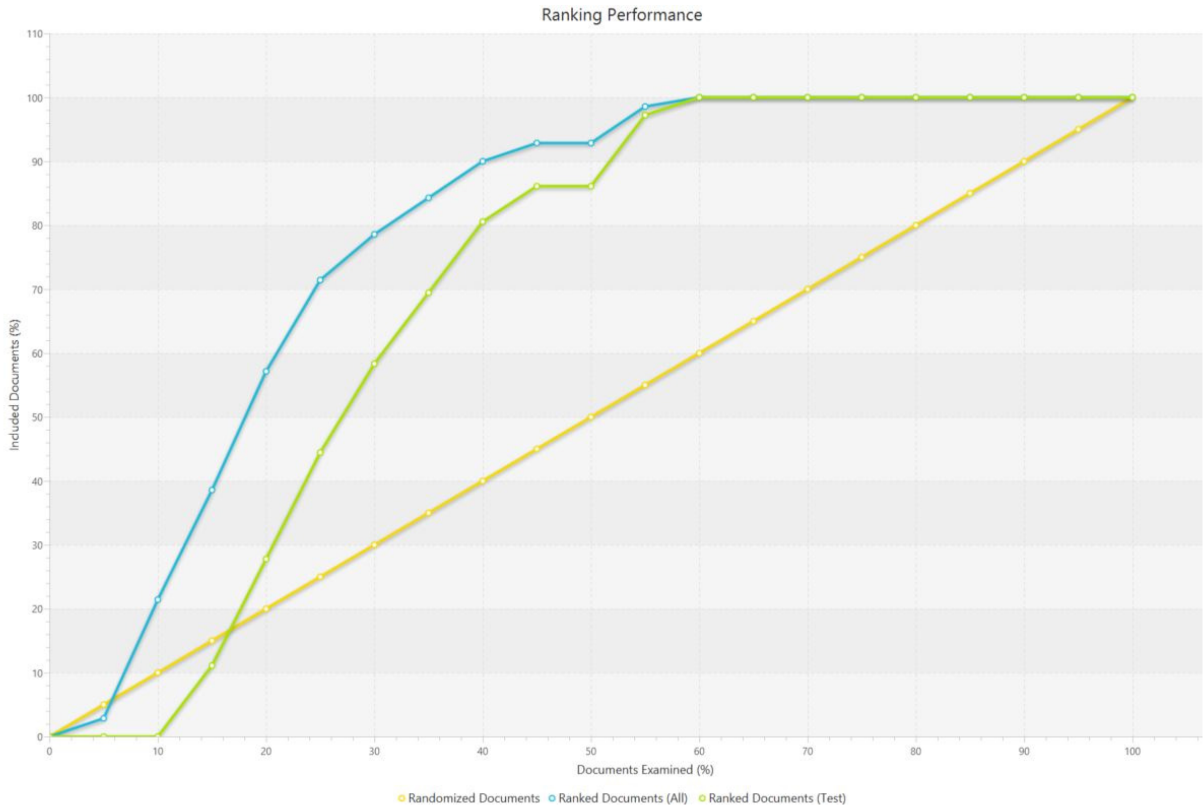

Figure 3. The ranking performance curve determined by randomly selecting a training-test dataset using a 50/50 split in the prioritization modeling. The yellow line represents the baseline performance we should expect if the ranking score had been generated completely at random. The green line shows the performance based on the test dataset, while the blue line denotes the training set.

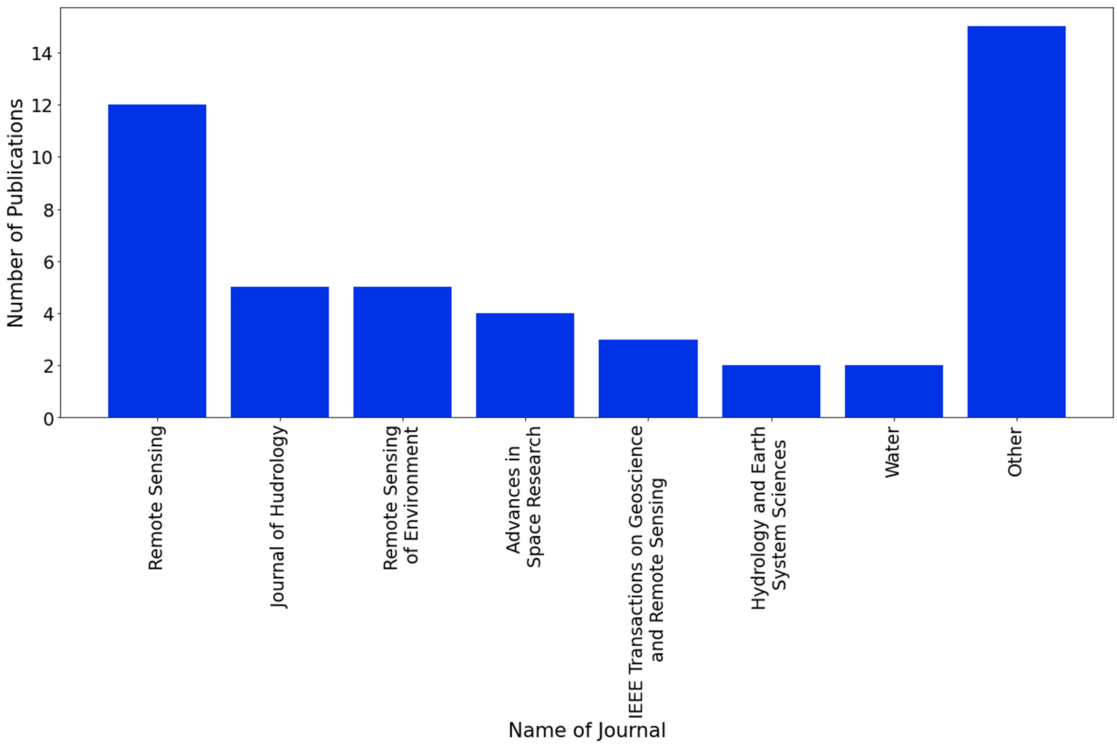

Figure 4. Number of publications per peer-reviewed journal between 2018 and 2022. In terms of simplicity, journals that appeared only once were homogenized in the 'Other' class.

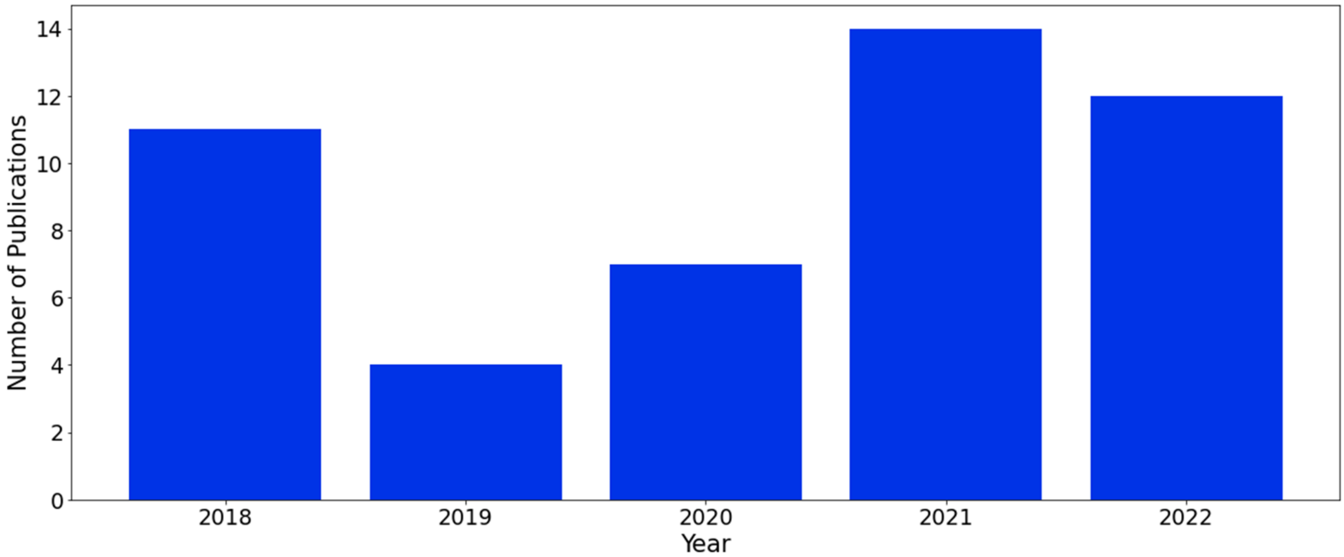

Figure 5. Number of published articles per year.

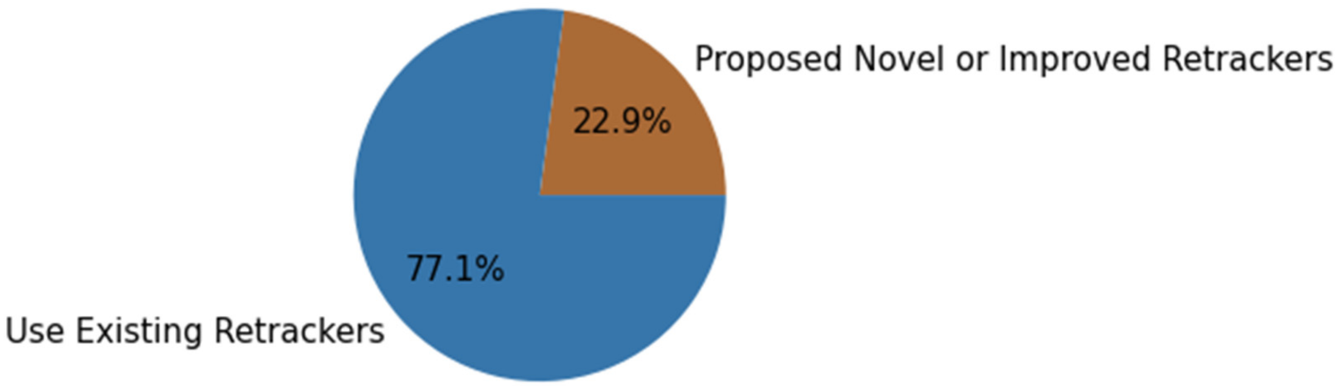

Figure 6. Percentage of published articles that present or not novel or improved retrackers.

3.1. Satellite Missions for Inland Water Level Monitoring

During the last three decades, spaceborne missions have been used as a key tool for the monitoring of inland water surfaces, as well as the hydrological cycle. Especially satellite altimetry has been widely used to monitor water levels since GEOS-3 and Seasat missions are considered the first altimetry satellites that provided exploitable data for the ocean. However, the trend of a particular research field, such as inland water level monitoring, may be reflected in the trend of a specific satellite mission or in a category of satellites, such as radar or laser altimetry missions, since each mission has its own unique characteristics. In the last fifteen years, the use of satellite altimetry has been facilitated by the advent of two different developments: Open-Loop Tracking Command (OLTC), and operation in Synthetic Aperture Radar (SAR) mode [53]. These developments have established altimetry as the prevailing spaceborne technique for inland water level monitoring. Thus, an analysis was conducted on our 48 included publications in order to demonstrate the distribution of literature based on satellite missions. Figure 7 displays the annual number of publications for altimetry missions used for the inland water level monitoring, while in the following subsection different types of satellite missions used for water level monitoring are depicted, such as gravimetry and GNSS-R missions.

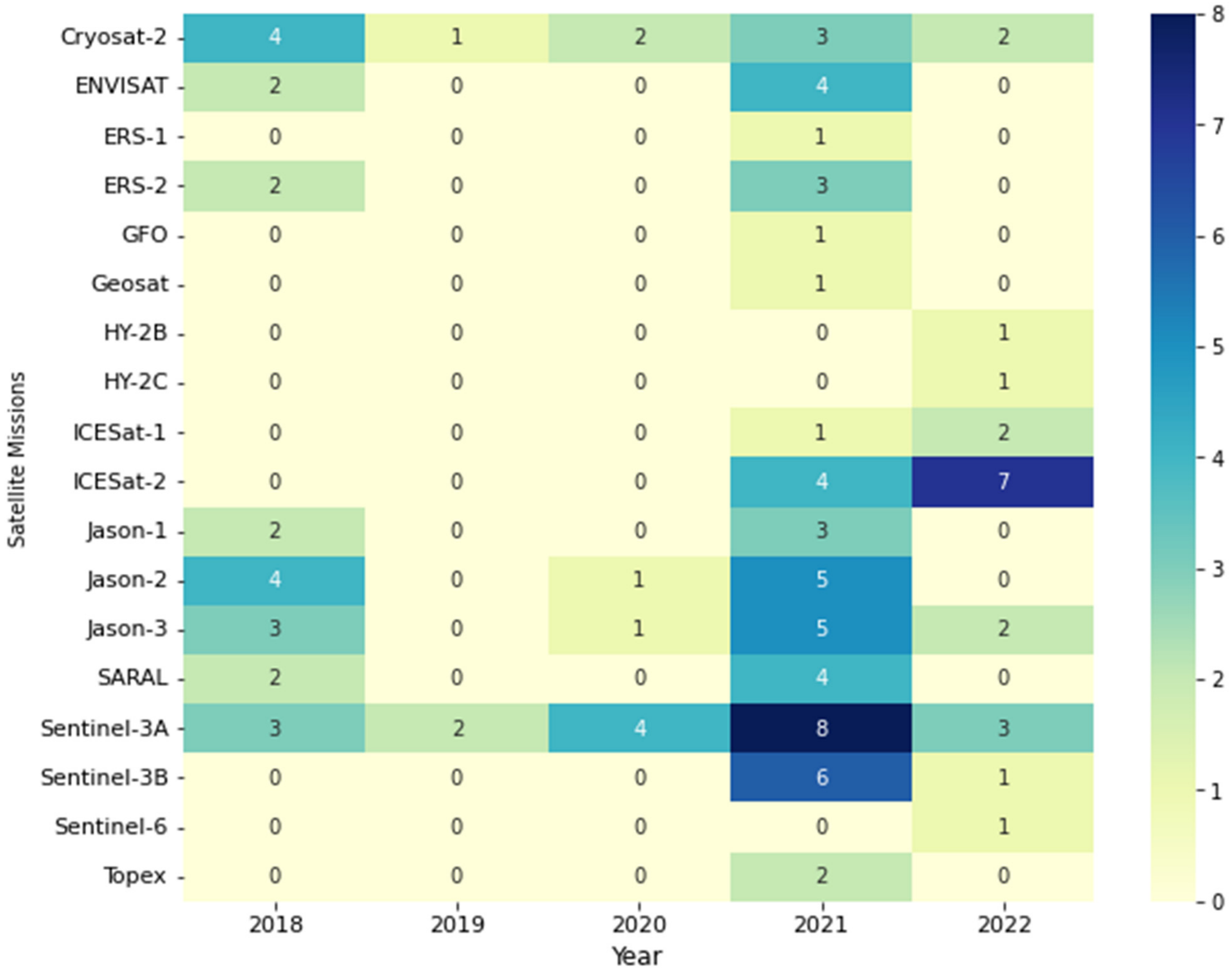

Figure 7. Number of applications per altimetry mission and year, from 2018 to 2022.

3.1.1. Radar Altimetry Satellite Missions

The Sentinel-3 mission has exhibited a high growth trend since Sentinel-3 was the first mission operated both in SAR mode and in OLTC over almost all Earth surfaces. The data from the Sentinel-3 mission was utilized in nearly half of the publications included in the current scoping review paper, 20 out of 48, establishing this mission as the dominant for monitoring inland water levels. Sentinel-3A and Sentinel-3B satellites were launched by the European Space Agency (ESA) in February 2016 and April 2018 respectively. The satellite ground track repeats in a 27-day cycle [54].

Moreover, Sentinel-3 satellites can be operated either in Closed-Loop (CL) or in Open-Loop (OL) tracking mode. In OL tracking mode, also called Diode/Digital Elevation Model (DEM), the altimeter uses an elevation prior uploaded onboard the altimeter as a function of longitude and latitude to position its receiving window. This information is provided by the OLTC [55]. In 2008, the first OLTC was implemented in the POSEIDON-3 altimeter on the Jason-2 satellite as an experimental mode [21]. Also, until 2010, all altimeters onboard satellites utilized a type of altimeter known as conventional pulse-limited Low-Resolution Mode (LRM). In 2010, Synthetic Aperture Radar (SAR) was implemented in the CryoSat-2 mission, which was launched by the ESA. The CryoSat-2 mission offered the opportunity to showcase the advantages of SAR mode or "Delay-Doppler altimeter" over the conventional pulse-limited LRM for various applications and also over inland waters [23,56]. In addition, the SRAL instrument of Sentinel-3 operates in both modes: LRM and SAR mode. The LRM is a backup mode working as a conventional pulse-limited radar altimeter. In contrast, in the SAR mode, it employs SAR technology inherited from CryoSat-2 to increase the along-track sampling resolution and elevation measurement accuracy. In SAR mode, the altimeter has a higher along-track resolution of 300 m compared to several km in LRM [54].

Out of the twenty publications, only two of them utilized Sentinel-3 data in LRM mode to assess the performance of the Sentinel-3 mission in retrieving water levels [57,58]. In both documents, it is highlighted that with the higher resolution of SAR mode, it is possible to obtain inland water surface elevations from smaller water bodies than with LRM, as well as to provide estimations with higher accuracy.

As depicted in Figure 7, data only from the Sentinel-3A and CryoSat-2 missions were utilized consistently throughout the five-year period covered by this paper (2018–2022). Therefore, CryoSat-2 emerges as the second most widely used mission since its data was utilized in 12 different publications, highlighting the significance of this mission for inland water level monitoring. SIRAL carried by CryoSat-2 is the first space-borne altimeter featuring delayed Doppler technology providing an orbital footprint of 300 m, and its reference ellipsoid in WGS84 [23,59]. Thus, CryoSat-2 ushered in a new era in radar altimetry. CryoSat-2 offers the opportunity to make comparisons of SAR and conventional altimeters by a multi-mode altimeter, since depending on the geographical mask it has three measurement modes, namely LRM, SAR, and Interferometric SAR (InSAR) [60]. Moreover, depending on the sensor mode SIRAL has different footprint sizes on the ground. The width of the footprint is several km for LRM, depending on the roughness of the terrain, while both SAR and InSAR modes have ~300 m along-track resolution. Furthermore, in contrast to the 27-day repeat cycle of Sentinel-3, CryoSat-2 has a long repetitive cycle (369 days) [61]. Thus, CryoSat-2 crosses a river many times during the long repeat cycle, albeit at different locations. CryoSat-2 offers a very dense spatial sampling pattern [60]. Although CryoSat-2 has a lower temporal resolution over a fixed Virtual Station compared to Sentinel-3, it provides measurements made upstream and downstream of a specific location that could be assimilated in a model.

Also, Figure 8 depicts the number of applications per measurement mode, i.e., SAR, LRM, and InSAR among the twelve publications in which CryoSat-2 data was used. As can be seen, there is no apparent preference by researchers for a specific measurement mode of the CryoSat-2 mission. Among the twelve publications, researchers utilized all measurement modes to evaluate the water level derived by CryoSat-2 over inland water bodies in two of them [62,63]. Based on their analysis, the quality of water level measurements depends on the measurement modes, shape, and size of inland bodies but also on the retracking algorithms analyzed in the following subsection. For very large lakes, the accuracy achieved between the different measurement modes is the same, in contrast to the small inland water bodies, where SAR and InSAR measurement modes achieve more accurate measurements. Moreover, in four publications researchers utilized only InSAR mode either to test the retracking performance of different algorithms [64–66] or to evaluate the performance of different satellite missions [67]. Furthermore, the quality of inland water level measurements is tested using only SAR mode [68,69], while in [70] some study regions were observed in SAR mode, and some other lakes were covered in LRM. In addition, in [71,72] LRM is utilized to evaluate the performance of different missions for measuring inland water levels, whereas both LRM and InSAR modes are used to test different retracking algorithms [73] showing that CryoSat-2 InSAR mode data can be used to monitor small inland water bodies that have not been measured by other altimetry missions. Based on these publications, the CryoSat-2 mission can deliver useful water level observations over inland water bodies worldwide, as even the conventional LRM mode of the altimeter delivers good results. However, the appropriate retracking algorithms are able to greatly improve the accuracy of CryoSat-2 water levels having a major impact on inland water level monitoring.

Moreover, comparing data from CryoSat-2 and Sentinel-3, the most widely used missions, it is shown that Sentinel-3 demonstrates superior overall performance. Sentinel-3, thanks to OLTC and its orbit configuration, is superior to CryoSat-2 in capturing water level changes and temporal resolution [65,67,71,72].

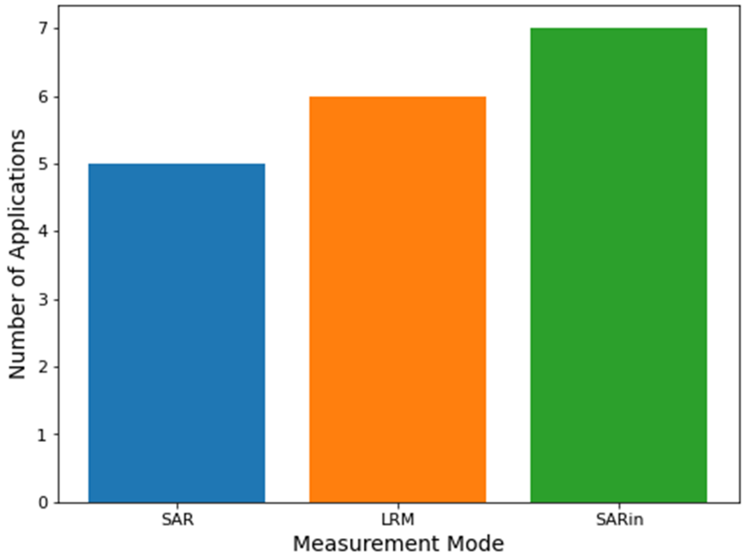

Figure 8. Number of applications per measurement mode of CryoSat-2.

Except for the Sentinel-3 and CryoSat-2 missions, the 10-day-revisiting Jason series are substantially used for monitoring the inland water level. Jason-1, Jason-2, and Jason-3 provide observations with a 10-day repeat cycle. This orbit has been used since 1992 by the T/P mission. Jason-1 satellite was launched in December 2001 as a cooperation between the Centre National d'Etudes Spatiales (CNES) and National Aeronautics and Space Administration (NASA). However, Jason-1 was decommissioned in June 2013 [74]. Furthermore, the Jason-2 mission was launched in June 2008 by a cooperation between NASA, CNES, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and the National Oceanic and Atmospheric Administration (NOAA). In addition, Jason-2 was deactivated in October 2019. Its payload was composed of the Poseidon-3 radar altimeter [21]. Jason-3 was launched in January 2016. Its payload consists of the Poseidon-3B radar altimeter, which is operating in OL tracking mode over land surfaces [57].

Comparisons conducted among the Jason missions revealed that water level changes obtained by Jason-2 and Jason-3 missions, thanks to OLTC, are more accurate than the Jason-1 missions. Also, the correlation between water level estimates acquired by Jason-2 and Jason-3 missions is higher than the correlation between measurements obtained by Jason-1 and Jason-2 [57,75–78]. In contrast to Jason-2 and Jason-3, the altimeter of the Jason-1 mission was not operating in OL tracking mode [74]. So, the use of the Jason-1 mission is limited for the extraction of water surface elevation compared to most recent missions, such as Jason-3 and Sentinel-3 [57,76,77]. Also, Jason-3 demonstrates better performance compared to Jason-2 in mitigating the effects of the surrounding topography, thereby enhancing the accuracy of measurements over inland water bodies [72,79,80].

Furthermore, as a follow-up mission to Jason-3, Sentinel-6 satellite has the highest accuracy among CryoSat-2, Jason-3, and Sentinel-3 missions [71]. Sentinel-6 is superior to Sentinel-3 in temporal resolution thanks to its 10-day repeat cycle. However, the Sentinel-6 Michael Freilich (S6-MF) satellite was launched in November 2020 and as a result its altimetry data has not been widely used for the inland water level monitoring, but only in one publication. S6-MF sensor consists of a Poseidon-4 dual-frequency SAR altimeter. Poseidon-4 is designed to operate in an interleaved (open burst) mode, allowing for simultaneous operation of SAR and LRM acquisitions. As a result, the altimeter offers twice the number of observations compared to the Sentinel-3 altimeter, leading to a substantial enhancement in the domain of water level monitoring [81]. This mission is critical for maintaining the continuity of accurate measurements over inland water bodies. Furthermore, although the use of the S6-MF mission's data is limited, Refs. [71,82] show the great potential of this state-of-the-art mission.

In addition, ENVISAT and SARAL mission data have been used in the same six publications to assess the performance of historic missions in comparison to the newest altimetry missions for measuring inland water levels. Both missions have a 35-day repeat cycle. The ENVISAT mission was launched in March 2002 by ESA, and it has been inactive since 2012. Its payload included the advanced radar altimeter (RA-2) [83]. Also, SARAL was launched in February 2013 by CNES and the Indian Space Research Organization (ISRO) [84]. Its payload included the AltiKa radar altimeter, achieving higher accuracy performance than the previous radar altimeters [85–87]. Moreover, the SARAL mission is the second radar altimeter, after the Jason-2 mission, operating in OLTC. A comprehensive evaluation of seven different radar altimeters indicates that very good agreement was found between the most recent missions such as SARAL, Jason-3, and Sentinel-3 than for the older ones, such as ENVISAT and Jason-1/-2 [77]. The use of SARAL data provides more accurate inland water level measurements than using ENVISAT satellite's dataset, resulting from the use of the Ka-band with its smaller footprint and higher chirp frequency of 500 MHz [57,72]. Also, a thorough evaluation of eight radar and 2 laser altimeters over Swiss lakes shows that the highest correlations between in situ measurements and altimetry missions are obtained with SARAL, Jason-3, and Sentinel-3 satellites. However, results obtained with the Sentinel-3 mission outperform the results obtained with any other mission [77]. Furthermore, among the satellite missions used in [76], SARAL gave the second-best performance and more accurate results than ENVISAT, while ENVISAT has slightly better lake water level estimates than Jason-1/-2, but its data missing rate is higher. However, among the eleven missions, the most recent Sentinel-3 has the best performance, while the accuracy of the SARAL mission was equivalent to the ENVISAT mission [79]. Moreover, in [58], the SARAL mission achieved higher accuracy measurements over Indian reservoirs than the ENVISAT satellite, and together with Sentinel-3 showed the highest accuracy.

Furthermore, the ERS-2 mission's data have been used in the same publications in which ENVISAT and SARAL mission's data have been used for the evaluation of the performances of historic and operational altimeters for water level retrievals [57,58,72,76,77]. ERS-2, a follow-on mission of ERS-1, has a 35-day repeat cycle such as ENVISAT and SARAL missions. ERS-1 and ERS-2 were launched in July 1991 and April 1995 by ESA, and retired in March 2000 and September 2010, respectively. ERS-2 payload carried a radar altimeter (RA) operating at Ku-band [77]. The thorough evaluations of the performances showed that for larger waterbodies, higher RMSE, and lower R values than usual are obtained using ERS-2 and ENVISAT [57,77]. Moreover, a comprehensive analysis of Indian reservoirs shows that SARAL and Sentinel-3A provide the highest accuracy of water level retrieval, followed by ENVISAT and then by ERS-2 [58]. In addition, it is indicated that classical LRM altimeters operating at Ku-band without OLTC (i.e., ERS-1, ERS-2, ENVISAT, and Jason-1) are highly affected by the hills and mountains in the surrounding inland water bodies. Due to the radar remaining fixed on the hills and mountains, there is a lack of data acquisition, while for ERS-2 and ENVISAT, the data loss rates over small lakes are slightly higher than those over large lakes. Also, Refs. [72,77] provide an estimate of the altimeter biases for SARAL, ERS-2, and ENVISAT. On the other hand, for smaller inland water bodies, the ERS-1 and ERS-2 missions provide more accurate results than the T/P mission in contrast to large lakes, where T/P is more accurate thanks to its lower data missing rate and shorter repeat cycle [76]. T/P, the predecessor of the Jason series, has the same 10-day repeat cycle. T/P was launched in August 1992 and decommissioned in October 2005 [20].

In the past 3 decades a total of 20 altimetry satellites, radar and laser missions, have been launched with different altimeters on board. Between 1985 and 1990 Geosat was the sole radar altimetry mission in operation [19]. Geosat was launched in March 1985 by the US Navy, and retired in January 1990. Also, the successor of Geosat, the Geosat Follow-On (GFO) mission, was launched in February 1998 and decommissioned in October 2008. GFO retained the Geosat exact repeat mission's orbit with a repeat cycle of 17 days [88].

Both Geosat and GFO have an extremely high data missing rate of inland water level measurements hampering their usefulness for retrieving water levels [76]. Although contemporary radar altimetry missions provide more accurate estimates than Geosat, its measurements are still valuable since it was the sole radar altimeter from 1985 to 1990. Also, GFO is the least desirable choice for the lakes overpassed by GFO, ERS-2, and T/P in the same period. The comprehensive evaluation of eleven radar altimeters over different lakes in four countries shows that for the period prior to 2002, the order of selection priority should be ERS-2, ERS-1, and TOPEX/Poseidon. From 2002 to 2013, the order of selection priority should be ENVISAT, Jason-2, Jason-1, ERS-2, and GFO, while between 2013 and 2020, the order of selection priority should be Sentinel-3, SARAL, Jason-3, and Jason-2 [76].

Finally, in spite of the fact that the HY-2 mission has a total of four satellites (HY-2 A, B, C, and D), the number of publications associated with the HY-2 mission is rather low when compared to other contemporary missions. The thorough evaluation of seven ongoing altimeters for measuring inland water levels is the only one that includes information about HY-2B and HY-2C performance [71]. HY-2B and HY-2C were launched in October 2018 and in September 2020 respectively. HY-2B is equipped with dual-frequency altimeters (Ku and C bands), with a revisit period of 14 days in the early stage of the mission and 168 days at the end of the mission [89]. Also, the orbit revisit period of HY-2C is 10 days at the initial stage of the mission and it will become 400 days at the final stages [90]. In [71] is indicated that HY-2C has the highest temporal resolution among seven altimeters, with a temporal resolution of 7.5 days at one station, although it has the largest RMSE and therefore the lowest accuracy. However, the overall accuracy of HY-2C has a certain improvement compared with HY-2B satellite, while based on its temporal resolution it has great potential for more detailed inland water level measurements. Moreover, it is expected that the follow-up satellites of the HY series will attain greater accuracy. The quantitative assessment of radar altimetry satellite missions is included in Sections 3.2.1 and 3.2.2 together with the relevant waveform retracking algorithms.

3.1.2. Laser Altimetry Satellite Missions

Existing altimetry satellites can be divided into radar and laser altimetry missions. Although radar altimetry is now commonly used to provide long-term monitoring of inland water levels in complement to or for replacing disappearing in situ networks of gauge stations, spaceborne laser altimeters have also been demonstrated to be an essential source of data. Compared to radar altimeters, laser altimeters have smaller footprints and higher sampling densities, making laser altimeters more suitable for small inland water bodies monitoring. As can be seen in Figure 7, ICESat-2 is the most extensively utilized laser altimetry mission. Its altimetry data are used in an equal number of research publications as the Jason-3 mission's data. ICESat-2, a follow-on to the ICESat-1 mission, was launched in September 2018 by NASA. ICESat-1 was launched by NASA in January 2003 and deactivated in August 2010 [91]. ICESat-2 carries the Advanced Topographic Laser Altimeter (ATLAS). ATLAS has a total of six laser beams, divided into three pairs, and each beam pair laser includes a strong energy beam and a weak energy beam [92]. In [93] is highlighted that the measurements by strong beam are more accurate than the weak beam. Furthermore, the key advancement of ICESat-2 is that it generates individual laser footprints of around 14 m diameter on the Earth's surface, with each footprint separated by only 70 cm in contrast to the ICESat mission with 70 m diameter laser footprints and 170 m along-track footprints [91]. As can be understood ICESat-2 has high spatial resolution and high density of observation. Thus, ICESat/ICESat-2 has a unique role in monitoring water level changes in most rivers and lakes, especially for small ones benefitting from their small footprints [93–96]. However, the water levels from ICESat-2 are much more accurate than those from ICESat [97]. Also, comparing ICESat-2 with radar satellites, such as Jason-3 and Sentinel-3, is shown that ICESat-2 has the smallest variability in deviations between satellite-measured water level and the in-situ data. Moreover, the accuracy of the ICESat-2 mission is comparable to Sentinel-3 and Jason-3 satellites, but it has lower accuracy than

S6-MF [71]. When available, ICESat-2 data show a strong potential for the monitoring of inland water bodies [77]. Furthermore, in [98,99] it is highlighted that the use of night-time observations by the ICESat-2 mission achieved slightly higher accuracies than day-time measurements. On the other hand, the temporal resolution of the ICESat-2 satellite (91-day repeat cycle) is low and significantly lower than the radar altimeter satellites. Also, another basic limitation of ICESat and ICESat-2 laser altimeters is that clouds and aerosol have an impact on the quality of data because of attenuation and scattering effects [94].

Apart from the ICESat and ICESat-2 missions, the most recently launched spaceborne laser sensor is the Global Ecosystem Dynamics Investigation (GEDI). GEDI launched in December 2018 and has been acquiring data since April 2019 on board the International Space Station (ISS). GEDI is equipped with three identical lasers, and it generates laser footprints of 25 m in diameter on the Earth's surface, with 60 m along the track and 600 m across the track [100]. However, GEDI's main mission is to observe the forest canopy height and canopy vertical structure to characterize important carbon cycling. In [99,101,102] is indicated that the combination of GEDI and ICESat-2 mission data presents a valuable resource for hydrological and climatic studies, especially for frequent and accurate inland water dynamics monitoring. Thus, the combined dataset allows us to capture the seasonal, and annual dynamics of inland water levels. As these two missions are operating simultaneously can provide a mutual accuracy verification and increase the temporal density of measurements. The evaluation of Lake Qinghai highlights the dense temporal resolution of the GEDI dataset, while the accuracy of these data is inferior to that of the ICESat-2 mission. Moreover, the factors affecting the accuracy extraction need to be further improved [102]. The factors that have an effect on the accuracy of GEDI elevations using two different data product releases were and analyzed in [103]. The results showed that the best criterion to filter less accurate GEDI data is based on the viewing angle, while the newest product release provides better precision of water levels. Also, a comparison between the three laser altimeters over the Great Lakes and Mississippi River showed that ICESat-2 provided water level measurements with an unprecedented accuracy (RMSE = 0.06 m, biases = -0.01 ± 0.05 m), followed by ICESat-1 and then by GEDI missions [99]. In addition, the more accurate performance of ICESat-2 compared to GEDI data is shown in [102]. Furthermore, a comprehensive evaluation of the performances of radar and lidar altimetry missions over mountainous areas shows that very accurate results could be obtained using ICESat-2 data in contrast to GEDI data which need to be analyzed over longer time periods to clearly indicate their capability for inland water level monitoring [77]. As can be understood, the applications and the validation of ICESat-2 and GEDI data over inland water bodies are limited, since only 4 years of ICESat-2 and 3 years of GEDI data are provided. Table 3 showcases the publications analyzed in the current scoping review paper that employ laser altimeters for inland water level monitoring.

Table 3. Laser altimeter applications that were found across the literature. RMSE stands for Root-mean-square-error, r: Pearson correlation, MAPE: mean absolute percent error, MAD: median of absolute deviation, ubRMSE: unbiased RMSE, std: standard deviation.

Publication	Satellite Mission	Data	Validation	Accuracy Metrics
[94]	ICESat-2	ATL13 products–version V003	In situ gauge and ATL08 products	RMSE = 0.08 m, r = 0.999 (RMSE = 0.28 m, r = 0.999 for ATL08 product)
[104]	ICESat, ICESat-2	GLAH14–V034 (ICESat), ATL13 products V005 (ICESat-2)	In situ gauge and G-REALM and HYDROWEB	For In situ: RMSE = 0.06 m/yr., MAPE = 15.58%, r = 0.98. For databases: RMSE = 0.06 m/yr., MAPE = 22.79%, r = 0.92
[77]	ICESat-2, GEDI	ATL13 (ICESat-2), L1B and L2A (GEDI)	In situ gauge	ICESat-2: RMSE $\leq$ 0.06 m, R $\geq$ 0.95, bias (0.42 ± 0.03) m, GEDI: RMSE: 0.16–0.51 m, R > 0.75, bias std: 0.08–0.3 m

Table 3. *Cont.*

Publication	Satellite Mission	Data	Validation	Accuracy Metrics
[97]	ICESat, ICESat-2	L2-GLAH14 (ICESat), ATL13 products V005 (ICESat-2)	In situ gauge	ICESat: R = 0.85, RMSE = 0.15 m, MAE = 0.1 m, MAD: 0.05–0.25 m, σ: 0.078–0.37 m and for ICESat-2: R = 0.69, RMSE = 0.05 m, MAE = 0.06 m, MAD = 0.03–0.05 m, σ = 0.04–0.07 m
[95]	ICESat-2	ATL13 products	In situ gauge	R^2 = 0.28–0.99, RMSE = 0.4–1 m
[102]	GEDI, ICESat-2	ATL13–V004 (ICESat-2), L2A (GEDI)	In situ gauge	ICESat-2: R = 0.96–0.99, MAE = 0.03–0.1, RMSE = 0.04–0.13 m and GEDI: R = 0.56–0.95, MAE = 0.31–0.38, RMSE = 0.35–0.46 m
[99]	ICESat, ICESat-2, GEDI	GLA14, ATL13–V003, L2B	In situ gauge	ICESat-2: RMSE = 0.06–0.12 m, biases = −0.08 ± 0.07 m, ICESat: RMSE = 0.10–0.25 m, biases = −0.18 ± 0.16 m, GEDI: RMSE = 0.28–0.40 m, biases = −0.24 ± 0.24 m
[71]	ICESat-2	ATL13	In situ gauge	RMSE = 0.05–0.14 m, R = 0.74–0.95
[98]	ICESat-2	ATL13	In situ gauge	RMSE = 0.24 m, bias = −0.11 m, MSD = 0.04
[101]	ICESat-2, GEDI	ATL13–V004 (ICESat-2), L2A (GEDI)	In situ gauge, DAHITI, and Hydroweb	ICESat-2: std = 0.03 m, GEDI: std = 0.11 m, Combining two missions: R > 0.8
[96]	ICESat-2	ATL13–V003	In situ gauge	RMSE = 0.32 m, R > 0.99
[103]	GEDI	L1B and L2A	In situ gauge	ubRMSE = 0.27–0.43 m, R = 0.34–0.66, bias = 0.35–0.54 m

3.1.3. Other Satellite Missions

Except for radar and laser altimetry missions, there are a few different techniques that can also perform altimetry with quite good coverage, such as Gravimetry [105] and GNSS-R [106]. Figure 9 depicts the annual number of applications per these satellite missions.

Initially, the GNSS-R field has gained exponential growth thanks to its increasing relevance across a wide range of applications [107]. A research investigation conducted on Lake Qinghai highlighted the altimetry potential of space-based GNSS-R, specifically of the Cyclone GNSS mission (CYGNSS) [106]. The CYGNSS mission consists of eight satellites, whose primary objective is to measure wind speed within and around the inner core of tropical cyclones over the ocean [108]. Using CryoSat-2 InSAR mode products for the validation of inland water level estimates is shown that water level time series derived by GNSS-R follows the CryoSat-2 one quite well. The root-mean-square deviation between CYGNSS and CryoSat-2 water levels is 0.70 m, while between CYGSS measurements and In situ data is 0.68 m [106]. Also, the GNSS Interferometric Reflectometry (GNSS-IR) technique is used to estimate ten years of lake surface heights, assessing its reliability by comparisons with gauges and satellite radar altimetry water level heights [109]. The relative RMS differences between gauges and GNSS-IR water level heights range from ±0.027 m to ±0.028 m, while between radar altimetry and GNSS-IR range from ±0.069 m and ±0.124 m showing that GNSS-IR technique can provide reliable water level estimates. Although a continuously operating GNSS station within a lake is uncommon, GNSS-IR presents an opportunity for satellite altimetry calibration/validation. Moreover, a method is proposed for the water level estimates in reservoirs using Sentinel-1 SAR data and Shuttle Radar Topography Mission (SRTM) surface models. Sentinel-1A/-1B satellites, with a 12-day return period, generate high-resolution backscatter images. This research marks a significant advancement in the worldwide assessment of inland water bodies, regardless of their size or geographical location, as long as a DEM is available. Also, while radar altimeters are more accurate, the combination of Sentinel-1 and SRTM missions can be used to monitor water level changes with relatively high temporal resolution, providing estimates every three to twelve days, as well as to monitor water bodies that are not directly located at the satellite's nadir and water bodies substantially smaller in area [110]. Furthermore, inland water levels were estimated by Interferometric Imaging Radar Altimeter (InIRA) carried out by the Tiangong-2 mission. The water levels obtained by InIRA are compared with surface levels derived by CryoSat-2 InSAR data showing that InIRA data is more stable and level estimates can be obtained with higher precision using the further processing InIRA data [111]. However, CryoSat-2 can measure the larger inland water levels with higher accuracy due to more observations, while InIRA obtains more observations in smaller lakes due to its three-dimensional imaging capability. Additionally, a comprehensive evaluation of inland water levels based on satellite gravimetry indicates that GRACE, and specifically its derived index GRACE-DSI can obtain water level estimates with RMSE values ranging from 0.88 to 1.12 m compared to gauge water levels [105]. Water level measurements results based on GRACE are superior to those reconstructed from traditional remote sensing indices, such as Palmer's Drought Severity Index (PDSI), and El Niño Southern Oscillation (ENSO) indices. GRACE is widely used to infer large-scale terrestrial water storage variations [112,113]. Finally, an approach based on the differences between daytime and nighttime land surface temperatures (LST) observations of Moderate Resolution Imaging Spectroradiometer (MODIS) shows a strong relationship both with in-situ and with Jason-2 water levels [114]. The LST difference from the thermal infrared (TIR) measurements of MODIS is shown to have the potential to produce high temporal resolution water levels. In this research four simple statistical models were used to explore the most effective model structure to predict daily river water levels and therefore to improve the temporal resolution of the Jason-2 mission.

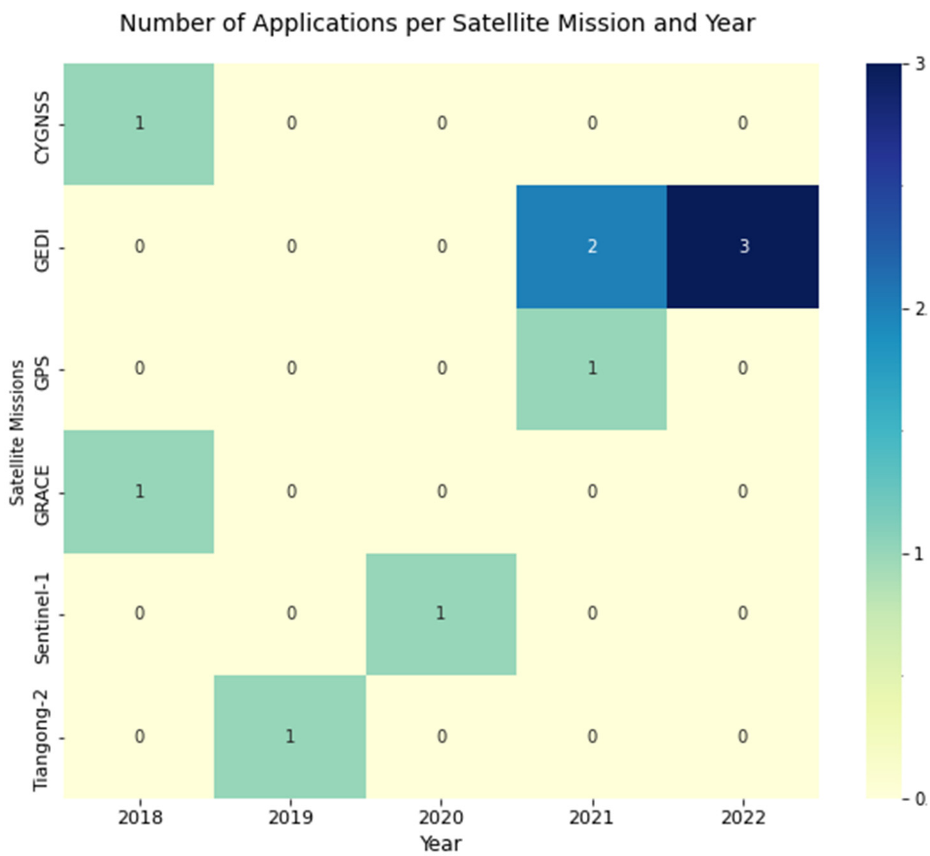

Figure 9. Number of applications per satellite mission and year.

3.2. Waveform Retracking

Although satellite radar altimetry is an important technique for inland water level monitoring, the issues related to waveform contamination because of its relatively large footprint restrict its use for narrow rivers and small lakes [115]. Therefore, to overcome this problem, the waveforms need to be retracked with appropriate retracking methods. The analysis of a waveform provides valuable information for water level monitoring since it provides the distance between the satellite and the reflecting surface, hereafter range. Except for the range, other physical parameters such as the amplitude of the backscattered signal (Sigma0), and the significant wave height are deduced from the waveform thanks to retracking algorithms that consist of fitting a physical or an empirical model to the waveform. Different retracking algorithms are used on different surfaces since the waveform's shape highly depends on the reflecting surface characteristics, in particular surface roughness [24].

The water surface orthometric height (WSH) is computed by the following Equation (2):

$$\text{WSH} = \text{altitude} - \text{range} - \text{corr} - \text{geoid} \tag{2}$$

Where altitude is the distance between the satellite's center of gravity and the reference ellipsoid (e.g., WGS84), computed by precise orbit determination, the range is the distance between the altimeter's antenna and the reflective surface estimated by the retracking algorithms, augmented by the distance between the altimeter's antenna and the satellite's center of gravity, corr represents the geophysical corrections, and geoid stands for the distance between the reference ellipsoid and the geoid model (e.g., EGM2008). Therefore, the water level is referenced relatively to the geoid model. Also, the geophysical corrections account for the variation of wave pulses because of atmospheric effects and the tides. The corrections are computed as can be seen in Equation (3), in which dry corr and wet corr represent the dry tropospheric and wet tropospheric correction respectively, while the iono corr stands for ionospheric correction.

$$\text{Corr} = \text{dry corr} + \text{wet corr} + \text{iono corr} + \text{pole tide} + \text{solid earth tide} \tag{3}$$

The retracker's waveform model fitted the acquired waveform to measure the mean range from the multiple facets within the instrument footprint could be separated into two categories. The model could have either a mathematical form derived from the expected statistics of the physical processes producing the return signal or an empirical form based on getting a robust estimate of the delay in the return signal. In physical waveform retracking, the models are based on the physics of the electromagnetic interaction between the transmitted wave pulse and the scattering surface. On the other hand, empirical models are simple and can be applied to all waveforms. Consequently, some approaches for determining the range of inland water bodies have an inheritance of the physical retrackers, while others are more empirical [48].

As it can be understood, the quality of water surface height observations obtained from radar satellite altimetry can be improved by waveform retracking. That can be achieved by modifying the initial range derived from the two-way travel time of radar pulses [116]. Therefore, many studies are dedicated to waveform retrackers. In 1986, the Offset Centre of Gravity (OCOG) retracking method was proposed [117], also known as Ice1 or Ice, while nine years later the Threshold retracking algorithm was developed, which turned out to be superior to the 5-β and 9-β algorithms [118]. Apart from the different official retrackers of each satellite mission, other novel algorithms have been developed through the years to estimate the range from the altimeter to the water surface. Thus, the novel and improved retracking algorithms included in the publications for monitoring inland water levels are initially presented.

3.2.1. Novel and Improved Retracking Algorithms

In 2018, a novel and improved empirical algorithm was presented to estimate water surface heights from processing CryoSat-2 InSAR waveforms [64]. The ImpMWaPP algorithm integrates the advantages of the Multiple Waveform Persistent Peak (MWaPP) retracker and the error mixture model [22,23]. They used in situ gauge data of seven lakes, as well as five existing retrackers for the evaluation of the performance of the proposed ImpMWaPP algorithm. The five existing algorithms used for the evaluation are The Narrow Primary Peak Threshold retracker (NPPTR) with a 50% threshold level (NPPTR [0.5]) [119], NPPTR with an 80% threshold level (NPPTR [0.8]) [119], the Narrow Primary Peak OCOG retracker (NPPOR) [119], the MWaPP retracker [23], and ESAL2 [117]. The root-mean-squared errors (RMSEs), between CryoSat-2 and in-situ data, obtained by the proposed algorithm range between 0.085 m and 0.159 m. Also, ImpMWaPP outperforms the other five algorithms in handling multi-peak waveforms since it obtains the lowest mean RMSE (0.175 m) and the lowest standard deviation (Std) (0.23 m) among all lakes. Therefore, they conclude that the new retracker can effectively process multi-peak waveforms over inland water. It can also extract accurate results independently of ice existence but is more proper for lakes frozen in winter.

The next year, a new approach to selecting an optimal peak in a given waveform retracked by the Threshold method was developed [120]. The Threshold algorithm was presented in the study of ice sheet elevation changes. Its implementation is easy, but it is sensitive to surface topography [118]. In this research, data from Sentinel-3A was used to extract water level heights. Instead of the threshold algorithm, the Ocean, OCOG, Ice-sheet, Sea-ice, and Tracker were used for the evaluation of water heights. Also, the results using the new optimized peak selection (optimal and mean-all sub-waveforms) methods show a significant improvement of 50% in RMSEs and 22% in correlations compared to level-2 data relative to in situ gauge measurements. Also, the first meaningful sub-waveform has a contribution of more than 90% in the measurements of precise water heights.

Furthermore, a modified retracker was used to determine inland water surface heights from the first altimetric sub-waveform [75]. They used T/P and Jason series missions to retrieve suitable waveforms, as well as in-situ data and other retrackers for the evaluation of the novel method. The retrackers used are Ice, MLE3, MLE4 [121], T, ST, and MST. Jason-2 Sensor Geophysical Data Records (SGDR) provide levels using Ice, MLE3, and MLE4 retrackers. Using the new methodology, the Std of differences between water levels extracted from Jason-2 and in-situ data is 0.06 m compared with Std using Ice Retracker which ranges between 0.08 m and 0.11 m. Also, T/P is less accurate than the combined Jason missions with Std equal to 0.07 m using the new modified retracker. As it is shown, the Ice algorithm is more precise than the oceanic MLE retrackers over inland waters. Moreover, the sub-waveform retracker with threshold 0.1 extract water levels of marginally higher accuracy than the SGDR retrackers.

In addition, an automatic multiscale-based peak detection retracker (AMPDR) was presented, suitable for CryoSat-2, Sentinel-3, and Jason-2/-3 missions [67]. The retracker extracts a robust threshold level for each track and using a shortest-path algorithm can obtain the surface water level from the multipeak waveforms. Its implementation is easy and computationally efficient, extracting accurate results. To evaluate the performance of the AMPDR algorithm in-situ gauge data as well as seven existing retrackers were used. The retrackers used for the evaluation are (NPPTR [0.5]), (NPPTR [0.8]), NPPOR, MWaPP, ESA L2/WWMFW, SAMOSA, and ALES+ [23,117,119,122,123]. The AMPDR retracker appears to provide the best and most robust results, having the lowest mean Std of all tracks, while using Sentinel-3 data obtained the lowest mean-RMSE (0.139 m) of all inland water bodies. It should be noted that AMPDR is called AMPDTR when using a 50% threshold retracker, while using the OCOG retracker is called AMPDOR. Also, it is proven that AMPDTR has the most inaccurate results for the Sentinel-3 and Jason-2/-3 missions, while AMPDOR has the lowest results for CryoSat-2 data. AMPDR provides the most stable results and it has the potential to monitor surface water heights of small inland water bodies as well as to be applied to other altimeters. Moreover, having common study areas, seven lakes in the Tibetan Plateau, AMPDR using CryoSat-2 InSAR data outperform the ImpMWaPP retracker. Furthermore, in the same year, a new retracker called APD-PPT was presented using also CryoSat-2 data to monitor inland water level variations [73]. This new algorithm combines the adaptive peak detection (APD) with the PPT retracker since the sub-waveform is formed based on the APD-detected primary peak, and retracked by the PPT algorithm. However, the APD was originally developed to detect peaks of the LRM waveform [124,125]. Also, Jason-2 LRM, in-situ gauge data, and five different retrackers (OCOG, PPT, WWMFW, MBP, ALES) were used to evaluate the performance of APD-PPT method using CryoSat-2 data. Both MBP and ALES have been successfully used to retrack LRM waveforms. As it is shown, APD-PPT retracker is the most appropriate for InSAR mode waveforms achieving the smallest mean-std of two lakes (0.186 m and 0.303 m), while Ice is the most accurate for LRM mode waveforms achieving the smallest mean-std (0.254 m). However, AMPDR is slightly more accurate than the APD-PPT method since the smaller the std, the better the retracking algorithm [23]. Furthermore, in 2022 a new retracking algorithm, named INPPTR was presented for InSAR waveforms to obtain stable water levels, such as in cases of ImpMWaPP, AMPDR, and APD-PPT retrackers [66]. INPPTR algorithm is based on NPPTR [22]. Also, for the evaluation of the accuracy of the novel INPPTR, the inland water levels were calculated by three more algorithms (NPPTR, NPPOR, MWaPP) and compared with in-situ data. In summary, the RMSE (0.17 cm–0.58 cm) and std (0.08 m–0.52 m) obtained by INPPTR are the lowest compared with the other retrackers, and therefore the accuracy of INPPTR is significantly higher than the other algorithms. Moreover, INPPTR can obtain retracking points from the reflected waveforms of complex terrains with high accuracy.

Furthermore, from 2018 to 2022 two different modified multiple waveform persistent peak (MWaPP+) retrackers, both based on the MWaPP [23] method, were proposed to obtain accurate inland water levels. The first modified retracker uses the median of all available waveforms to form a new waveform and instead of the first sub-waveform, they extract the sub-waveform with the largest peak [126]. This retracker was evaluated for Sentinel-3 data. Also, the three other algorithms used to evaluate the modified retracker are the OCOG, SAMOSA+ [127], and primary peak COG (PPCOG) [119]. The comparison revealed that SAMOSA+, OCOG, and PPCOG are unable to handle multi-peak waveforms in contrast to modified MWaPP+, which obtains the highest accuracy in most cases. In the majority of virtual stations MWaPP+ retracker obtains really small RMSE values, between 0.13 m and 0.6 m, but in some other stations, RMSE values range from 0.9 m to a few meters. Also, it is important to obtain accurate results that MWaPP+ is less sensitive to off-nadir bright targets. Moreover, a few months later another modified MWaPP+ retracker was adopted for CryoSat-2 InSAR and Sentinel-3 data [65]. Also, for Jason-2/-3 data products the ALES+ retracker was used to extract retracking heights. For the evaluation of the performance of the modified retracker were used also the OCOG, NPPTR, NPPTR [0.5], NPPTR [0.8], NPPOR, and MWaPP. It can be seen that the water levels obtained by MWaPP+ are more robust for both Sentinel-3 and CryoSat-2 than the other algorithms having the lowest std (0.25 m–0.30 m). Also, MWaPP+ is capable of processing poor quality complex waveforms obtaining robust water surface heights in contrast to MWaPP.

In the following three publications, all novel or improved retracking algorithms proposed were evaluated using Sentinel-3 data. Initially, a new waveform portion selection method with consideration of the DEM was proposed together with the Threshold, OCOG, and two-step SAR physical-based retrackers [128,129]. Although there was no significant difference in the results of the three retrackers, the use of the novel selection method greatly improved the accuracy of measurements. The RMSEs for different water bodies range between 0.17 m and 1.39 m, while all retrackers gave better results than the Level-2 ocean retracked data without the waveform portion selection method. Moreover, a new bimodal correction algorithm was proposed for the retrieval of inland water surface elevation, mainly over ice-covered lakes [130]. The four standard SRAL SAR retrackers used to retrieve water level measurements are Ice-sheet, SAMOSA-3, OCOG, and Sea-Ice [59,131]. However, these retrackers generated erroneous measurements when inland water bodies were covered by ice, and therefore to address the negative measurements a new algorithm was proposed. The evaluation of this study shows that the Sea-Ice retracker fails to provide continuous measurements of water levels, while the accuracy of the other three retrackers is similar. The mean-RMSE over lakes is 0.12 m for OCOG, 0.11 m for SAMOSA-3, and 0.11 m for Ice-sheet. Also, correlation coefficients r, with ice-affected estimates to be excluded, are higher than 0.87 for Ice-Sheet, greater than 0.79 for OCOG, and higher than 0.87 for SAMOSA-3. Moreover, with the use of the new bimodal correction algorithm including the ice-affected estimates is shown that the accuracy of measurements over ice-covered lakes is extremely higher than without the use of the new method. Using the new algorithm over Great Slave Lake is shown that r = 0.93 and RMSE = 0.05 m instead of r = 0.13 and RMSE = 0.6 m using SAMOSA-3 retracker. As it can be seen the new method provides accurate continuous water level measurements over also ice-covered water bodies. Finally, in 2022 a physical retracking algorithm based on a priori numerical simulations was proposed for water level retrievals over lakes [132]. The novel retracker takes as input both the lake contour and the instrument characteristics. The methodology was inherited from previous developments [133]. They used in-situ data and OCOG retracker to evaluate the performance of the new retracker. The results indicated that the unbiased RMSE is better than 0.07 m over medium-sized lakes, while even over small lakes, the unbiased RMSE is better than 0.14 m showing that the proposed method retrieves water level measurements with high accuracy. On the other hand, for inland water bodies with very narrow widths of less than 200 m, the OCOG algorithm did not provide accurate results. The publications including the performance of novel or improved retracking algorithms are presented in Table 4.

Table 4. Publications that include novel or improved retracking algorithms for the measurements. RMSE stands for Root-mean-square-error, r: Pearson correlation, MAD: median of absolute deviation, ubRMSE: unbiased RMSE, std: standard deviation.

Publication	Satellite Mission	Data	Retracker	Validation Data	Accuracy Metrics
[64]	CryoSat-2 (InSAR)	Baseline C Level-1b (L1b) and Level-2 (L2)	ImpMWaPP	Retrackers (NPPTR [0.5], NPPTR [0.8], NPPOR, MwaPP, ESAL2) and in-situ	RMSEs = 0.085 m–0.573 m, lowest mean RMSE = 0.175 m and lowest Std = 0.23 m obtained by ImpMWaPP
[75]	T/P, Jason-1/-2/-3	SGDR versions-T/P: MGDR-B, J-1: E, J-2: D, J-3:D	Modified algorithm to use the first subwaveform	Retrackers (Ice, MLE3, MLE4, T, ST, MST) and in-situ	Jason-2: Std = 0.06 m with new retracker. Std = 0.08 m–0.11 m with Ice. T/P: Std = 0.07 m
[120]	Sentinel-3A	L1b and L2	A new approach to selecting an optimal peak of a waveform	In-situ gauge, Level-2 data, and retrackers (Ocean, OCOG, Ice-sheet, Sea-ice)	RMSE = 0.07 m and R = 87% using optimal sub-waveform, RMSE = 0.08 m and R = 85% using Mean-all sub-waveform. RMSE= 0.14 m and R = 65% using L2
[67]	CryoSat-2 (InSAR), Sentinel-3, Jason-2/3	-	AMPDR (AMPDTR + AMPDOR)	In-situ gauge and 7 Retrackers (NPPTR [0.5], NPPTR [0.8], NPPOR, MWaPP, WWMFW/ESA L2, SAMOSA, ALES+)	mean-RMSEs = 0.149, 0.139, and 0.181 m and Std = 0.16, 0.16, and 0.24 m obtained by Cryosat-2, Sentinel-3, and Jason-2/3 respectively.
[73]	CryoSat-2 (LRM, InSAR)	Baseline-C L2 for LRM and L1B for InSAR	APD-PPT	Jason-2 LRM, In-situ gauge, and Retrackers (WWMFW, PPT, OCOG, MBP, ALES)	Smallest mean-Stds (0.186 m and 0.303 m). R > 0.7 for Jason-2 and Cryosat-2 using APD-PPT. MAD = 0.23–0.43 m
[66]	CryoSat-2 (InSAR)	L1b	INPPTR	Retrackers (NPPTR, NPPOR, MWaPP) and In-situ gauge data	RMSE = 0.17–0.58 m, std = 0.78–0.52 m

Table 4. *Cont.*

Publication	Satellite Mission	Data	Retracker	Validation Data	Accuracy Metrics
[126]	Sentinel-3A	L1b	MWaPP+	Retrackers (OCOG, SAMOSA+, PPCOG, MWaPP) and In-situ gauge data	RMSE = 0.13–2.08 m
[65]	CryoSat-2 (InSAR), Jason-2/-3, Sentinel-3A	InSAR L1b, S-GDR, LAN L2	another modified MWaPP+	Retrackers (OCOG, NPPTR, NPPTR [0.5], NPPTR [0.8], NPPOR, MwaPP), In-situ gauge and Hydroweb product	mean-RMSEs = 0.08–0.16 m, std = 0.25–0.30 m, R > 0.79,
[128]	Sentinel-3	L1b	New waveform portion selection method	L2 Ocean retracked data, In-situ gauge, Retrackers (Threshold, OCOG, two-step SAR physical-based)	OCOG: RMSEs = 0.29–1.39 m and ubRMSE = 0.28–1.38 m, Threshold: RMSEs= 0.30–1.39 m and ubRMSE = 0.16–1.38 m, Physical: RMSEs= 0.18–1.39 m and ubRMSE = 0.16–1.39 m,
[130]	Sentinel-3	L2	Bimodal correction algorithm	In-situ gauge, Retrackers (Ice-sheet, SAMOSA-3, OCOG, Sea-Ice)	r = 0.93, RMSE = 0.05 m instead of r = 0.13, RMSE = 0.6 m using SAMOSA-3 retracker
[132]	Sentinel-3	L1b	Novel retracker based on numerical simulations	In-situ gauge data, OCOG	ubRMSE = 0.03–0.07 m and biased-RMSE = 0.10–0.13 m

3.2.2. Official Retracking Algorithms

Apart from the novel or improved algorithms described in the previous subsection, in the majority of publications official retrackers were used for the evaluation of the performances of radar altimetry satellite missions over inland water bodies. Between 2018 and 2022, official retrackers from different radar altimetry missions are used in twenty-one publications. In five publications [134–138] only data from the Sentinel-3 mission were used and its performance was validated by comparing in-situ gauge data with the altimetry-based water levels. In [134] it is shown that water level variations based on the empirical OCOG [117] retracker are significantly better than the physical Ocean [122] method. Generally, the OCOG retracker has obtained results with higher accuracy for inland waters compared to other LRM methods [77]. Also, in the L2 product used in [134], the Ocean retracker is the SAMOSA2.5 retracker which has been developed for SAR altimeter echoes [122,139]. On the other hand, the water level results using the SAMOSA+ physically based retracker of the Grid Processing on Demand (GPOD) platform are slightly more accurate than using the OCOG method of the Copernicus Open Access Hub (SciHub) platform over Zambesi River in terms of relative RMS deviation [137].

Furthermore, there are eight publications where water level measurements from the Sentinel-3 mission are compared with measurements from other radar altimetry missions employing different retrackers [57,58,71,72,76,77,79,115]. In [57] the evaluation of the performances of seven radar altimeters shows an overall very good agreement between in situ and altimetry extracted water levels, especially for the most recent missions SARAL and Sentinel-3 applying the OCOG retracker. Although this research was conducted using only one year and a half of measurements from Sentinel-3, the results obtained from the OCOG retracker confirm the strong potential of this algorithm for inland water bodies monitoring. The OCOG method is very well adapted for the specular echoes from a single reflector obtained in SAR mode. In addition, research about the performance of the same seven radar altimeters was conducted in [77]. They also concluded that measurements of water level obtained with the OCOG retracker of the Sentinel-3 mission outperform the results obtained with the other missions. Also, a comprehensive evaluation of the same seven radar altimetry missions, but the CryoSat-2 mission instead of the Jason-1 mission, was conducted in [72] to assess the extracted inland water levels. Missions operating in SAR mode (Sentinel-3, CryoSat-2) with the OCOG retracker exhibit the best accuracy, while the combination of data from all the radar altimeters significantly improved the extracted water levels.

Moreover, among the eleven radar altimetry missions used in [76], the Sentinel-3 mission has the best performance using empirical/model-free retrackers (e.g., OCOG). As can be seen, all retrackers of each mission have similarly good performance over large inland water bodies, apart from the ERS-1 sea ice retracker. On the other hand, over small inland water bodies, the empirical retrackers, such as the Ice1 (OCOG) of SARAL, ENVISAT, ERS-1/-2, and Jason series missions, obtain more accurate results than the physical/model-based algorithms, such as the MLE4 retracker of Jason missions, the ocean algorithm of SARAL, ENVISAT, ERS-1/-2 missions or the non-model-based sea ice retracker. Also, the OCOG retracker produced the lowest mean RMSEs and the lowest mean data loss rate, while the SAMOSA-2 algorithm achieves slightly greater RMSE and lower bias than OCOG. However, it would be really interesting to see the results comparing the OCOG retracker with the SAMOSA+, which is customized for inland water. Following these two algorithms of Sentinel-3, the OCOG algorithm of SARAL obtained the second-best performance among the eleven radar altimetry missions. In addition, using the Ice-1 retracker the ENVISAT had slightly better performance than Jason-1/-2 missions. However, due to the 35-day repeat cycle of ENVISAT and its higher data loss rate compared to the Jason-1/-2 missions, Jason missions (with a 10-day repeat cycle) offered more frequent and continuous estimates of water levels compared to ENVISAT. As a result, the empirical retrackers are recommended for inland water level monitoring in combination with the Sentinel-3 mission, which gave the most accurate results. Also, in [79] OCOG retracker of Sentinel-3B outperforms the other altimeters (Envisat, SARAL, Jason-2/-3) as well as Sentinel-3A with a maximum RMSE of 0.21 m over small reservoirs in the Brazilian semiarid region. In [115], research was conducted to determine the absolute bias of Sentinel-3 and Jason-3 altimeters as well as the accuracy of these two altimeters. It is highlighted that the accuracy of Sentinel-3A with OCOG retracker was the best in terms of RMS. Furthermore, although [58] used the LRM mode of Sentinel-3A, the OCOG retracker with Sentinel-3 and SARAL mission's data retrieved the measurements with the highest accuracy in terms of RMSE and R^2, followed by ENVISAT and ERS-2. Also, in the only publication where Sentinel-6 mission data were used, the results show that Sentinel-6 with the Ocean retracker has higher accuracy than Sentinel-3 with the Ocean algorithm in terms of RMSE and R [71]. Together with the Ocean algorithm of Jason-3, these two missions extract the most accurate water levels.

Also, the evaluation of CryoSat-2 water level measurements from different retracking scenarios over inland water bodies was conducted in five publications [62,63,68–70]. The use of Full Bit Rate (FBR) SAR data in combination with the use of five proposed empirical retrackers show that the use of proposed retrackers is preferable to the OCOG and Threshold retrackers with a threshold of 0.75 [68]. In addition, it is shown that the use of the SAMOSA2 retracker is not recommended for inland water level monitoring since it is designed for oceanic applications. CryoSat-2 measurements with the empirical retrackers are superior to T/P and Envisat estimates but less accurate than those from SARAL [68]. SAMOSA+ and Threshold algorithms were used to derive the water levels from the Fully Focused-SAR (FF-SAR) waveforms with additional either pulse-peakiness or waveform-fit filtering [69]. Thus, they show the potential of the FF-SAR algorithm to extract inland water levels of really narrow canals, with high accuracy. This was the first time that satellite radar altimetry data were used to measure water levels in ditches a few meters wide. In [62] is shown that the use of Threshold and SAMOSA3 retrackers at the first and the mean-all sub-waveforms of SAR mode is appropriate to retrieve water level variation of complex shaped and small lakes, while over larger lakes the full-waveform retracking leads to better results. Also, the evaluation of the SAMOSA+ retracker, which is recommended for inland water level monitoring, would be really interesting. On the other hand, the most precise result for Envisat retrackers was obtained from the Ice-1 algorithm. Also, the importance of outlier detection before applying CryoSat-2 data is highlighted by [70]. Thus, the RMSE of CryoSat-2 water levels using SAMOSA2 retracker was greatly improved from 0.70 m to 0.27 m. In the last research, CryoSat-2 data were retracked with an empirical Narrow Primary Peak Retracker (NPPR) [23], showing that the RMSE between satellite and in situ observation is 0.38 m.

Furthermore, the Jason satellite measurements using Ice-1/ICE retracker were validated from different retracking scenarios in three publications [78,80,140]. In [80] are highlighted the significant advantages of OL tracking mode using Jason-2 and Jason-3 data over French rivers and its high accuracy measurements over inland water bodies. Also, using the same retracker with Jason-1 and Jason-2 satellite water level measurements showed that the water level was highly correlated with measurements obtained by Landsat images [78]. Finally, Convolutional Neural Networks (CNN) using Jason-3 data obtain water level measurements [140]. It is the only research, among the 48 publications examined at the scoping review, in which a machine learning approach was used to extract water level heights. The results indicate the strong potential of CNN to measure surface water levels since they are more robust than using the OCOG/Ice-1 algorithm time series. Table 5 summarizes all the previous publications that use official retracking algorithms of radar altimeters for inland water surface height monitoring.

Table 5. Publications including radar altimetry missions with their official retracking algorithms. RMSE stands for Root-mean-square-error, r: Pearson correlation, MAD: median of absolute deviation, ubRMSE: unbiased RMSE, std: standard deviation.

Publication	Satellite Mission	Data	Retracker	Validation Data	Accuracy Metrics
[134]	Sentinel-3	Level-2 (L-2)	Ocean, OCOG	In-situ gauge	Ocean: median-RMSE = 0.25–0.30 m, R = 0.86 and for OCOG: median-RMSE = 0.19–0.24 m, R = 0.93. Percentage of outliers is 11–16%.
[135]	Sentinel-3	Acquired by G-POD	OCOG	In-situ gauge	R = 0.937–0.941, RMSD = 0.43–0.45 m, ubRMSE = 0.37–0.42 m
[136]	Sentinel-3	Acquired by CTOH	OCOG	In-situ gauge	R> 0.79, RMSE = 0.15–1.39 m
[137]	Sentinel-3	L-1b, L-2	SAMOSA+ (G-POD), OCOG (SciHub)	In-situ gauge	RMSD = 0.03–0.31 m, WRMSD = 4.9%–18.9% of the in-situ std, and R > 0.98
[138]	Sentinel-3	Altimetric data acquired by Hydroweb	OCOG	In-situ gauge	RMSE = 0.12–0.44 m, mean-RMSE = 0.22 m, NSE = 0.40–0.98, mean-NSE = 0.84
[57]	ERS-2, ENVISAT, SARAL, Jason-1/-2/-3, Sentinel-3	GDRs data: E for Jason-1, D for Jason-2/-3, ERS-2 (CTOH), ENVISAT (V2.1), SARAL (T), Sen-3 (ESA IPF 06.07 land)	OCOG	In-situ gauge	R > 0.8 in 80% of cases and RMSE < 0.4 m in 48% of cases.
[76]	GeoSat, ERS-1/-2, T/P, GEOSatFO, Jason-1/-2/-3, ENVISAT, SARAL, Sen-3	ERS-1 (REAPER), T/P (GDR-M), ERS-2 (CTOH), GFO (GDR), J-1 (GDR-E), ENVISAT (V3), SARAL (GDR-T), J-2/-3 (GDR-D), Sen-3 (Baseline 2.45)	See Table 2	In situ gauge	Sen-3 OCOG: RMSE = 0.06 m, r = 0.93, data loss rate = 2.32% (best performance). GeoSat: data loss rate = 65.42%. ERS-1: mean-RMSE = 0.35 m. Jason-2 ice: r = 0.93, RMSE = 0.08 m
[77]	Jason-1/-2/-3, ERS-2, ENVISAT, SARAL, Sen-3	GDRs data: E for Jason-1, D for Jason-2/-3, ERS-2 (CTOH), ENVISAT (V2.1), SARAL (T), Sen-3 (ESA IPF 06.07 land)	OCOG	In situ gauge	Sen-3: RMSE< 0.07 m, R > 0.85, bias = (-0.17 ± 0.04) m. ERS-2: RMSE = 0.28–0.41 m, R = 0.45–0.65. ENVISAT: RMSE = 0.52 m. SARAL: RMSE $\leq$ 0.08 m, R> 0.8.
[79]	Envisat, SARAL, Sen-3, Jason-2/-3	Envisat (GDR-V3), SARAL(GDR-T), J-2 (PISTACH), J-3 (GDR-D), Sen-3 (O_NT_003)	OCOG	In situ gauge	Sen-3B: max-RMSE = 0.21 m, Sen-3 A: RMSE = 0.14–1.01 m, Envisat: RMSE = 0.28–0.40 m, SARAL: RMSE = 0.17–0.40 m, J-2: RMSE = 0.21–0.86 m, J-3: RMSE = 0.14–0.84 m

Table 5. *Cont.*

Publication	Satellite Mission	Data	Retracker	Validation Data	Accuracy Metrics
[115]	Sentinel-3, Jason-3	Jason-3: GDR-D, Sent-3: ESA Land_IPF_06.07_V1.5	Jason-3: (Ocean, OCOG) Sen-3: (OCOG, SAMOSA)	In situ gauge	Absolute biases: Jason-3: −0.03 ± 0.04 m (Ocean), 0.2± 0.03 m (OCOG) and Sen-3: −0.01± 0.02 m (SAMOSA), 0.29± 0.02 m (OCOG). Lowest RMS = 0.02 m for Sen-3 with OCOG. RMS of J-3 > 0.03 m.
[71]	CryoSat-2, HY-2B, HY-2C, Jason-3, Sen-3, Sen-6	CryoSat-2: LRM_L2, HY-2B/-2C: SDR_L2, J-3: GDR_L2, Sen3A: SAR_NTC_L2, Sen-6: LR_L2	Jason-3, Sen-3A, CryoSat-2, Sen-6 (Ocean)	In situ gauge	RMSEs: CryoSat-2 (0.05–0.30 m), HY-2B (0.04–0.23 m), HY-2C (0.07–0.26 m), J-3 (0.04–0.14 m), Sen-3A (0.04–0.13 m), Sen-6 (0.04–0.14 m) and R: CryoSat-2 (−0.70–0.94), HY-2B (0.34–0.97), HY-2C (0.83–0.92), J-3(0.69–0.99), Sen-3A (0.18–0.99), Sen-6 (0.87–0.98)
[72]	Jason-2/-3, ERS-2, ENVISAT, CryoSat-2, SARAL, Sen-3	Jason-2/-3 (GDR-D), Envisat (GDR v2.1), SARAL (GDR-T), CryoSat-2 (GDR-C), ERS-2 (CTOH), Sen-3 (ESA IPF 06.07 land)	OCOG	In situ gauge	Sen-3: R > 0.94 and RMSE < 0.4 m, CryoSat-2: R = 0.98 and RMSE = 0.25 m, Envisat: R > 0.9 and RMSE < 0.5 m, SARAL: R > 0.95 and RMSE < 0.4 m
[58]	ERS-2, ENVISAT RA-2, SARAL, Sen-3	ERS-2: ERS_ALT_2 L2, Envisat RA-2: GDR V3, SARAL: L2, Sen-3: NTC L2 LRM	OCOG	In situ gauge	Sen-3: RMSE = 0.19–0.79 m, ERS-2: RMSE = 0.26–2.77 m, ENVISAT: RMSE = 0.44–4.57 m, SARAL: RMSE = 0.03–1.67 m
[68]	CryoSat-2	Full Bit Rate SAR L-1A	5 Empirical retrackers, SAMOSA2, OCOG, Threshold	In situ and T/P, Envisat, J-2, SARAL data	RMS: Tonle Sap: 0.4 m for CryoSat-2, 0.4 m for J-2. 0.6 m for CryoSat-2, Mekong: 0.35–0.52 m for Envisat. Amazon: 0.27 m for CryoSat-2, 0.26 m for SARAL.
[69]	CryoSat-2	L-1b, L-2 (FF-SAR)	SAMOSA+ and Threshold	In situ gauge	SAMOSA+: std = 0.05–0.15 m, Precision = 0.03–0.14 m and Threshold retracker: std = 0.04–0.14 m, Precision = 0.04–0.14 m.
[62]	CryoSat-2	L-1b, L-2 (LRM, SAR, InSAR)	OCOG, threshold, b-parameters and SAMOSA3	In situ and L2 products of Envisat and J-2	SAR mode: RMS = 0.13–0.15 m, while 0.28–1 m for Envisat. InSAR mode: RMS = 0.16–0.25 cm, while for Envisat: 0.19 and J-2: 0.54 m. LRM mode: RMS = 0.13–0.15 m, while Envisat: 0.17 m
[70]	CryoSat-2	GDR L-2(SAR, LRM)	SAMOSA	In-situ gauge. DAHITI and Hydroweb to validate in-situ	absolute mean difference = 0.09 m, absolute std difference = 0.04 m, mean RMSE = 0.27 m, mean R = 0.84
[63]	CryoSat-2	L-2, based on 20 Hz level 1b baseline C (LRM, SAR, InSAR)	NPPR	In situ gauge	RMSE = 0.38 m
[80]	Jason-2/-3	GDR-D	OCOG	In situ gauge	RMSE = 0.20–0.30 m,
[78]	Jason-1/-2	GDR-C (Jason-1), GDR-D (Jason-2)	OCOG	Landsat TM/ETM/OLI_TRIS images	RMSE = 0.237 m, R = 0.986
[140]	Jason-3	-	OCOG (also for validation)	In-situ gauge	R > 0.95, RMSE = 0.26–0.43 m

3.3. Study Regions

As shown in Figure 10, lakes around the globe are the most common type of inland water bodies used for the evaluation of the performances of satellite missions for water level retrievals, while the use of rivers is limited only to 18 out of 48 publications. The return waveforms are contaminated over narrow rivers and small lakes due to the size of the radar footprint, and the extracted ranges are corrupted leading to inaccurate water level measurements [141]. In the near future, more researches are expected to be conducted on rivers benefiting from the technological achievements of state-of-the-art missions. Publications incorporating multiple types or continents in their applications are included in the relevant categories on the heatmap. The most used study area is the Qinghai-Tibetan Plateau in China [58,62,64–67,73,97,98,102,104–106,111].

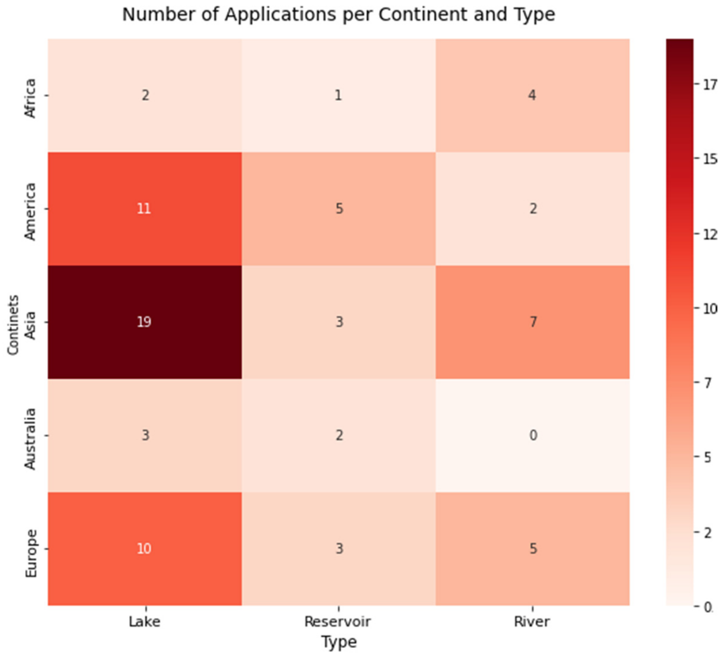

Figure 10. Number of applications per continent and type.

4. Discussion

The development of services to provide inland water level time series from satellite missions is getting more attention than ever before, which is motivated by the urgent need for global water cycle monitoring. Due to the absence of perspective for improving in situ networks worldwide, space-based remote sensing could be considered a unique technique that provides up-to-date observations with global coverage and homogeneous accuracy. The existence of a high quantity of operational altimetry satellites, and the prospect of cutting-edge missions, such as HY-2E, S3-NG, CRISTAL, as well as SWOT, a swath interferometric altimeter providing high spatial resolution and river slope, intensify the use of altimetry for inland surface water monitoring, and therefore for global water cycle monitoring. Although satellite radar altimetry was primarily designed for ocean monitoring, altimetry data has proven extremely important for inland water studies. Altimetry missions have been used for inland water surface height and hydrological cycle monitoring in the last three decades. In particular, since the launch of the T/P and Envisat missions, monitoring of lakes and rivers has been the goal of research and the quantity of altimetry research publications has substantially increased. However, the use of altimetry missions for inland water level monitoring was facilitated by the advent of OLTC, first implemented by the Jason-2 mission [21], and SAR mode developments, first used in the CryoSat-2 mission [22,23], and was confirmed in 2016 with the launch of Sentinel-3A mission, which was the first mission operated both in OLTC and SAR mode nearly globally [24].

In this work, we addressed the role of spaceborne remote sensing in estimating inland water surface heights, a key component of the water cycle, and of land surface hydrology. We reviewed the studies, over the last five years, between 2018 and 2022, which described the advances made by satellites, and hence by altimeters to characterize the dynamics of inland water level. The quality of water level determination depends on the measurement modes of each mission, the retracking algorithm, as well as the shape and size of inland water bodies. Thus, due to the fact that each mission has its own characteristics, the publications associated with specific missions were examined in order to depict the trend of each mission in inland water level monitoring. Also, publications including radar altimetry data were charted based on the retracking algorithms, whether they are novel and improved or existing and known ones, applied to the waveforms deemed to be from inland water bodies [48]. Proper algorithms are important to be used to retrack the waveforms since extracted ranges over inland water bodies are contaminated due to the magnitude of the radar footprint.

This research shows that data from the Sentinel-3 mission, in SAR mode, were used in nearly half of the publications included in the current review, 20 out of 48, establishing this mission as the dominant for monitoring inland water levels. The OLTC feature significantly increased the data availability, while the SAR mode substantially increased along-track the spatial resolution. Sentinel-3, SAR mode, also delivers significantly higher precision measurements (std around 15 cm) than the previous generation of altimeters, such as ERS-2, Envisat, T/P, and Jason-1, while it provides also higher accuracy inland water level time series than current altimeters, such as CryoSat-2, and Jason-3. Also, both Jason-3 and Sentinel-3, perform better than the previous generations of altimeters in terms of data availability. However, in [71], the only publication where S6-MF mission's data was used, is shown that S6-MF as a follow-up mission to Jason-3, has the highest accuracy among CryoSat-2, Jason-3, and Sentinel-3 missions. S6-MF is superior to Sentinel-3 in temporal resolution and capturing water level changes of inland water bodies, but worse in global spatial resolution due to its orbit configuration. Moreover, by adopting the OLTC, the latest altimetry missions, S6-MF and SWOT, are expected to significantly increase the valid observation rates as well as the data availability over inland water bodies. Furthermore, data only acquired by Sentinel-3 and CryoSat-2 missions were used consistently throughout the five-year period covered by this paper. CryoSat-2 emerges as the second most widely used mission since its data were used in 12 different publications, highlighting the significance of this mission for inland water level monitoring. Researchers use all different modes of the Cyosat-2 mission, LRM, SAR, and InSAR, to evaluate inland water levels showing that for very large lakes LRM and SAR modes can achieve the same RMS [62]. However, for small inland water bodies, the quality depends also on the retracking scenario. Also, applying the Fully-Focused SAR algorithm to CryoSat-2 data permits the retrieval of inland water levels of narrow rivers smaller than 300 m in width, with a precision between 4 and 11 cm [69]. The future mission Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), builds upon the CryoSat-2, S6-MF, SARAL, and SWOT missions and it will carry, for the first time, a dual-frequency (Ku-Ka) SAR radar altimeter having the capability for FF-SAR processing so as to further enhance the along-track sampling resolution [142].

Also, in spite of the fact that the HY-2 mission consists already of four satellites (HY-2 A, B, C, and D), data only from HY-2B and HY-2C missions are used to evaluate its performance over inland water bodies in one documentation [71]. The upcoming launch in 2024 of the HY-2E altimetry mission will provide valuable measurements over continental water surfaces and thus will open a new era of scientific advances for inland water level monitoring. Also, the last launch of an altimetry mission in December of 2022, named SWOT [25], is the first mission specifically dedicated to the monitoring of continental waters. Its Ka-band radar Interferometer is extremely useful for comprehensive global monitoring of water bodies. The recent launch of the advanced SWOT mission shows already a tendency of research interest [143,144]. SWOT, as a swath-based SAR altimetry mission, provides high along-track and cross-track resolution. Therefore, it is capable of producing images of high-resolution water surface elevation measurements, hence surface water slope, that is necessary for estimating streamflow.

Apart from the radar altimeters, laser altimetry missions, e.g., ICESat and ICESat-2, and GEDI instruments, have been used for inland water level monitoring. Laser altimeters exhibit a high growth trend, while ICESat-2 is the most extensively utilized laser altimetry mission. In 2022, its data were used in seven studies for the extraction of inland water levels, a number substantially higher than any other mission's application. It is shown that laser altimeters have a unique role in monitoring water level changes in most rivers and lakes, especially for small ones, benefitting from their higher sampling densities and much smaller footprint than radar altimeters [93–96]. However, a significant limitation to their use is the temporal resolution, e.g., 91-day repeat cycle for ICESat-2 satellite, which is significantly lower than in radar altimeters. Also, another basic limitation of laser altimeter is that clouds and aerosols have an impact on the quality of data because of attenuation and scattering effects [94]. Furthermore, although satellite altimetry missions are mainly used to monitor inland water levels, there are also different techniques, such as GNSS-R [106], and gravimetry [105] which also provide accurate water level measurements, but are less accurate than altimetry missions. The public agency websites and the hydrological databases, which provide inland water height data, used for the evaluation of satellite missions are presented in Tables A1 and A2 respectively.

Furthermore, one of the main limitations of satellite missions to monitor inland water surface heights is the onboard tracking system. Land contamination, the main issue of altimetry missions over inland water bodies, is closely related except for the altimeter spatial resolution to the onboard retracking algorithms. This paper provides a comprehensive analysis of different algorithms used to retrieve inland water levels from different missions between 2018 and 2022. To retrieve water level data with higher accuracy, efforts are required to develop advanced retrackers to process the complex waveforms. Retrackers usually treat the first peak as the returned echo from the different targets. However, when there are inland water bodies with complex shapes or other bright targets nearby, this presumption may not be true. Thus, advanced retracking algorithms may be developed under certain use cases and conditions to detect the peak that corresponds to the correct target of interest [140]. From 2018 to 2022, 11 publications included novel or improved algorithms for inland water surface height monitoring, such as the ImpMWaPP [64].

Moreover, although Neural Networks (NN) have proven their efficiency for image processing and image classification tasks, the concept of NN is not yet completely clear what advantages can be derived from it in the field of altimetry [145]. This is quite obvious since only one publication used supervised learning to train a deep Convolutional NN for the extraction of water surface heights [140]. Therefore, it is recommended to explore the concept of NN in the field of altimetry further.

Despite the recent advances in satellite altimetry missions, there is still much to be learned regarding inland water level changes. As it can be understood, in future missions the enhancement of spatial resolution and along-track sampling resolution of current missions should be also accompanied by an enhancement in temporal resolution. The development of state-of-the-art altimeters, such as SWOT altimeters with a 21-day period, is not enough to monitor applications such as flood events, or even weekly or more frequent dynamics of inland water bodies. Thus, altimeters should be accompanied by a larger altimetry constellation, including swath and conventional altimetry, and/or the use of an integrated altimeter and a Doppler Wave and Current Scatterometer such as SKIM. Future missions, such as SMall Altimetry Satellites for Hydrology (SMASH) [146], Sentinel-3C/-D/-NG Topo, and Sentinel-6 NG with higher spatial and temporal resolution will play a key role in a better understanding of the global water cycle and hence of inland water level monitoring.

Many future altimetry missions are dedicated to inland waters hydrology significantly increasing the hydrology targets over rivers, with higher than 10 days revisit time. SMASH will be a constellation of 10 satellites, in the same orbit plane, providing daily measurement over each target and twice a day revisit for large watersheds. They will carry a single-frequency Ka radar altimeter. It will be able to provide measurements for rivers wider than 50 m and for lakes with areas larger than 100 m $\times$ 100 m. Sentinel-3C/-D will follow in approximately 2025 and 2028, respectively, to ensure the continuity of the Sentinel-3A/-B missions. Sentinel-3NG Topo aims to provide continuity of the Sentinel-3 mission, while increasing the quantity and quality of products and services. S3NG-T incorporates both a nadir and a wide swath altimeter. S3NG-T altimeters will be able to improve the spatial sampling of the SMASH constellation.

Lastly, the terrestrial water level is a useful component of the river discharge essential climate variable (ECV), among the 55 variables that were carefully selected and defined by the Global Climate Observing System (GCOS) to help in understanding and tracking the changes and progress of various components within the Earth system. Therefore, the current study contributes also to the call by remote sensing and hydrological communities for inland water level monitoring in the framework of the ongoing development of the concept of essential climate variables (ECVs) [147,148]. Additionally, future research should be conducted summarizing and disseminating the research findings concerning river discharge monitoring through satellite observations.

5. Conclusions

In this scoping literature review, following PRISMA guidelines, a comprehensive analysis of spaceborne missions for inland water level monitoring is provided for the last five years. Using five electronic literature databases, a double screening process found 48 scientific publications to meet the eligibility criteria. This review summarizes and disseminates the research findings, and presents both major results and limitations of satellite observations for inland water surface heights monitoring. Among the satellite missions that provide inland water level time series, it is shown that altimetry is the dominant technique. There are also a few alternative techniques that can measure water surface heights with quite good coverage, such as Gravimetry and GNSS-R. Sentinel-3, as the first altimetry satellite operated both in OLTC and SAR mode, is the dominant mission for monitoring inland water levels, achieving the most accurate results. Only the Sentinel-6 mission's data outperforms the Sentinel-3 mission, capturing water level changes with higher accuracy and in higher temporal resolution. However, Sentinel-6 altimetry data has not been widely used for the inland water level monitoring, since the satellite was launched in November 2020. Except for the Sentinel-3/-6 missions, CryoSat-2 and Jason-3 advanced radar altimetry missions show high capability in acquiring accurate inland water level time series. Also, the ICESat-2 laser altimetry mission has exhibited a high growth trend thanks to its higher sampling density than radar altimetry missions. Furthermore, the FF-SAR method is able to retrieve inland water levels of narrow rivers of smaller than 300 m in width, with precision between 4 and 11 cm. The dual-frequency (Ku-Ka) SAR radar altimeter of CRISTAL future mission, will have the capability for FF-SAR processing to further enhance the along-track sampling resolution. Thus, in the upcoming years, more research for the evaluation of the performance of missions is expected over narrow rivers and small lakes. Apart from the measurement mode of each mission, the quality of water level determination depends on the retracking algorithm, as well as the shape and size of inland water bodies. Novel or improved retrackers are presented in 11 publications to provide more accurate inland water level measurements than the conventional retrackers of each mission. However, despite the advances of state-of-the-art altimeters and advanced algorithms, there is still much to be learned regarding the monitoring of inland water levels by satellite observations. In future missions, the enhancement of spatial resolution and along-track sampling resolution should be also accompanied by an enhancement in temporal resolution to meet the data requirements for applications such as flood monitoring and warning systems. Advancements in future missions such as CRISTAL, SMASH, Sentinel-3C/-D/-NG Topo, and Sentinel-6 NG missions with higher spatial and temporal resolution will play a major role in inland water level monitoring and the derivation of river discharge, and therefore contribute to a better understanding of the global water cycle. In the future, it is expected that more research focused on inland water level monitoring and river discharge derivation, related to new advances in altimetry missions, such as the Sentinel-6 and SWOT missions, will be conducted. Finally, advanced machine and deep learning techniques have not yet been tested in the field of altimetry. The collaboration of altimetry, in-situ, and various proxy data with machine learning techniques can be a promising solution to calibrate spaceborne water level measurements and river discharge derivation algorithms, and potentially augment their spatial and temporal resolution.

Author Contributions: Conceptualization, S.K., V.T. and G.T.; methodology, S.K.; software, S.K.; validation, S.K., V.T. and G.T.; formal analysis, S.K.; investigation, S.K. and V.T.; resources, A.A.;

writing—original draft preparation, S.K.; writing—review and editing, S.K., V.T. and G.T.; visualization, S.K.; supervision, G.T. and A.A.; project administration, G.T.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the ReNEW project supported by the European Union's Horizon Europe research and innovation program, under Grant Agreement 101069682.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Public agency websites and water height data availability included in the publications analyzed in this scoping review. Last access in webpages on 15 September 2023.

Agency	Webpage
National Water Information System, America	https://maps.waterdata.usgs.gov/mapper/index.html
National Hydrometric Network, Canada	https://wateroffice.ec.gc.ca/
Meteorological and Hydrological Institute, Sweden	https://www.smhi.se/data/meteorologi/
Center for Operational Oceanographic Products and Services, U.S.	https://tidesandcurrents.noaa.gov/
River Water and Snowpack Data, Colorado	http://lakemead.water-data.com/
Water Data, Texas	https://www.waterdatafortexas.org/reservoirs/
Water Data, Australia	http://www.bom.gov.au/waterdata/
Finnish Environment Institute (SYKE), Finland	https://www.syke.fi/en-US
Ministry of Water Resources, China	http://www.yellowriver.gov.cn/
Chinese Academy of Sciences, China	http://www.tpedatabase.cn/
Sindh Irrigation and Drainage Authority, Pakistan	https://sida.org.pk/
Environmental Protection Agency, U.S.	https://www.epa.gov/climate-indicators/great-lakes
Federal Office for the Environment, Hydrology Department, Switzerland	https://www.hydrodaten.admin.ch/
National Service of Meteorology and Hydrology of Peru	https://www.gob.pe/senamhi
Mekong River Commission	https://portal.mrcmekong.org/time-series/water-level
Ministry of Infrastructure and Water Management, Netherlands	https://waterinfo.rws.nl/#!/kaart/waterhoogte-t-o-v-nap/
Rivers Agency Coleraine	https://www.dardni.gov.uk/rivers-agency
Electricity Supply Board	https://www.esb.ie/
Data Center for Eco-Environment Protection in the Qinghai Lake	http://qhh.qhemdc.cn/
Jiangsu Provincial Department of water resources	http://jssslt.jiangsu.gov.cn/
Ma'anshan water management system	http://www.masswj.net:9009/ahwater/website/index.html
Hydrologic Information System, Ebro data hub, Spain	http://www.saihebro.com/saihebro/index.php
Brazilian Water Agency ANA	http://www2.ana.gov.br
Malian Hydrological Service, Ministry of Energy and Water	https://dnhmali.org/
US Army Corps of Engineers	https://rivergages.mvr.usace.army.mil/WaterControl/new/layout.cfm
India-Water Resource Information System (WRIS)	https://indiawris.gov.in/wris/#/
Water resources data of the Qinghai Tibet Plateau	https://data.casearth.cn/en/sdo/detail/614c6a4008415d75145ecb9e

Table A1. *Cont.*

Agency	Webpage
Water resources data of France	https://www.hydro.eaufrance.fr/
Changjiang Water Resources Commission, China	http://www.cjh.com.cn/
Interregional Agency of Po River, Italy	https://www.agenziapo.it/

Table A2. Hydrological Databases used for the evaluation of the performances of satellite observations including inland water level time series. Last access in websites on 15 September 2023.

Database/Product	Website	Operated by
DAHITI	https://dahiti.dgfi.tum.de/en/	German Geodetic Research Institute-Technical University of Munich (DGFI-TUM)
Hydroweb	https://hydroweb.theia-land.fr/	CNES
Hydrosat	http://hydrosat.gis.uni-stuttgart.de	Institute of Geodesy-University of Stuggart
G-REALM	https://ipad.fas.usda.gov/cropexplorer/global_reservoir/	United States Department of Agriculture
GRRATS	https://doi.org/10.5067/PSGRA-SA2V1	Ohio State University
C3S LWL	https://doi.org/10.24381/cds.5714c668	Copernicus and European Commision
Water Level by CGLS	https://land.copernicus.eu/global/products/wl	Copernicus Global Land Operations CNES, CLS, and LEGOS

References

1. Postel, S.L. Entering an Era of Water Scarcity: The Challenges Ahead. *Ecol. Appl.* **2000**, *10*, 941–948. [CrossRef]
2. Albert, J.S.; Destouni, G.; Duke-Sylvester, S.M.; Magurran, A.E.; Oberdorff, T.; Reis, R.E.; Winemiller, K.O.; Ripple, W.J. Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio* **2021**, *50*, 85–94. [CrossRef]
3. Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liermann, C.R.; et al. Global threats to human water security and river biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef] [PubMed]
4. Bastviken, D.; Tranvik, L.J.; Downing, J.A.; Crill, P.M.; Enrich-Prast, A. Freshwater Methane Emissions Offset the Continental Carbon Sink. *Science* **2011**, *331*, 50. [CrossRef]
5. Shao, C.; Chen, J.; Stepien, C.A.; Chu, H.; Ouyang, Z.; Bridgeman, T.B.; Czajkowski, K.P.; Becker, R.H.; John, R. Diurnal to annual changes in latent, sensible heat, and CO_2 fluxes over a Laurentian Great Lake: A case study in Western Lake Erie. *J. Geophys. Res. Biogeosci.* **2015**, *120*, 1587–1604. [CrossRef]
6. Stephens, G.L.; Slingo, J.M.; Rignot, E.; Reager, J.T.; Hakuba, M.Z.; Durack, P.J.; Worden, J.; Rocca, R. Earth's water reservoirs in a changing climate. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2020**, *476*, 20190458. [CrossRef] [PubMed]
7. Chahine, M.T. The hydrological cycle and its influence on climate. *Nature* **1992**, *359*, 373–380. [CrossRef]
8. Blango, M.M.; Cooke, R.A.; Moiwo, J.P. Effect of soil and water management practices on crop productivity in tropical inland valley swamps. *Agric. Water Manag.* **2019**, *222*, 82–91. [CrossRef]
9. Tranvik, L.J.; Downing, J.A.; Cotner, J.B.; Loiselle, S.A.; Striegl, R.G.; Ballatore, T.J.; Dillon, P.; Finlay, K.; Fortino, K.; Knoll, L.B.; et al. Lakes and reservoirs as regulators of carbon cycling and climate. *Limnol. Oceanogr.* **2009**, *54*, 2298–2314. [CrossRef]
10. Trenberth, K.E.; Fasullo, J.T.; Mackaro, J. Atmospheric Moisture Transports from Ocean to Land and Global Energy Flows in Reanalyses. *J. Clim.* **2011**, *24*, 4907–4924. [CrossRef]
11. GRDC: Global Runoff Database Center—River Discharge Data. Available online: https://www.bafg.de/GRDC (accessed on 28 February 2024).
12. Riegger, J.; Tourian, M.; Devaraju, B.; Sneeuw, N. Analysis of grace uncertainties by hydrological and hydro-meteorological observations. *J. Geodyn.* **2012**, *59–60*, 16–27. [CrossRef]
13. Strassberg, G.; Scanlon, B.R.; Rodell, M. Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). *Geophys. Res. Lett.* **2007**, *34*, L14402. [CrossRef]
14. Papa, F.; Frappart, F. Surface Water Storage in Rivers and Wetlands Derived from Satellite Observations: A Review of Current Advances and Future Opportunities for Hydrological Sciences. *Remote Sens.* **2021**, *13*, 4162. [CrossRef]
15. Massachusetts Institute of Technology. *Williamstown Report, NASA CR-1579*; Massachusetts Institute of Technology: Cambridge, MA, USA, 1970. Available online: http://ilrs.gsfc.nasa.gov/docs/williamstown_1968.pdf (accessed on 28 February 2024).

16. Pierson, W.J.; Mehr, E. Average Return Pulse Form and Bias for the S193 Radar Altimeter on Skylab as a Function of Wave Conditions. *Use Artif. Satell. Geod.* **1972**, *15*, 217–226. [CrossRef]
17. Fu, L. Recent progress in the application of satellite altimetry to observing the mesoscale variability and general circulation of the oceans. *Rev. Geophys.* **1983**, *21*, 1657–1666. [CrossRef]
18. Vignudelli, S.; Birol, F.; Benveniste, J.; Fu, L.-L.; Picot, N.; Raynal, M.; Roinard, H. Satellite Altimetry Measurements of Sea Level in the Coastal Zone. *Surv. Geophys.* **2019**, *40*, 1319–1349. [CrossRef]
19. McConathy, D.R.; Kilgus, C.C. The navy geosat mission: An overview. *Johns Hopkins APL Tech. Dig.* **1987**, *8*, 170–175.
20. Fu, L.; Christensen, E.J.; Yamarone, C.A.; Lefebvre, M.; Ménard, Y.; Dorrer, M.; Escudier, P. TOPEX/POSEIDON mission overview. *J. Geophys. Res. Ocean.* **1994**, *99*, 24369–24381. [CrossRef]
21. Desjonquères, J.D.; Carayon, G.; Steunou, N.; Lambin, J. Poseidon-3 Radar Altimeter: New Modes and In-Flight Performances. *Mar. Geod.* **2010**, *33*, 53–79. [CrossRef]
22. Nielsen, K.; Stenseng, L.; Andersen, O.B.; Villadsen, H.; Knudsen, P. Validation of CryoSat-2 SAR mode based lake levels. *Remote Sens. Environ.* **2015**, *171*, 162–170. [CrossRef]
23. Villadsen, H.; Deng, X.; Andersen, O.B.; Stenseng, L.; Nielsen, K.; Knudsen, P. Improved inland water levels from SAR altimetry using novel empirical and physical retrackers. *J. Hydrol.* **2016**, *537*, 234–247. [CrossRef]
24. Taburet, N.; Zawadzki, L.; Vayre, M.; Blumstein, D.; Le Gac, S.; Boy, F.; Raynal, M.; Labroue, S.; Crétaux, J.-F.; Femenias, P. S3MPC: Improvement on Inland Water Tracking and Water Level Monitoring from the OLTC Onboard Sentinel-3 Altimeters. *Remote Sens.* **2020**, *12*, 3055. [CrossRef]
25. Biancamaria, S.; Lettenmaier, D.P.; Pavelsky, T.M. The SWOT Mission and Its Capabilities for Land Hydrology. *Surv. Geophys.* **2016**, *37*, 307–337. [CrossRef]
26. Wunsch, C.; Gaposchkin, E.M. On using satellite altimetry to determine the general circulation of the oceans with application to geoid improvement. *Rev. Geophys.* **1980**, *18*, 725–745. [CrossRef]
27. Fu, L.; Cheney, R.E. Application of satellite altimetry to ocean circulation studies: 1987–1994. *Rev. Geophys.* **1995**, *33*, 213–223. [CrossRef]
28. Calmant, S.; Seyler, F.; Cretaux, J.F. Monitoring Continental Surface Waters by Satellite Altimetry. *Surv. Geophys.* **2008**, *29*, 247–269. [CrossRef]
29. Berry, P.A.M.; Garlick, J.D.; Freeman, J.A.; Mathers, E.L. Global inland water monitoring from multi-mission altimetry. *Geophys. Res. Lett.* **2005**, *32*, L16401. [CrossRef]
30. Berry, P.A.M.; Wheeler, J.; Smith, R.G. Inland Water Monitoring from Multi-mission Satellite Radar Altimetry—Current Status and Future Capability. In Proceedings of the Symposium Earth Observation and Water Cycle Science, Frascati, Italy, 18–20 November 2009; ISBN 978-92-9221-238-4.
31. Benveniste, J.; Berry, P.A.M. 2004 Monitoring River and Lakes from Space. *ESA Bull.* **2004**, *117*, 36–42. Available online: https://earth.esa.int/eogateway/documents/20142/37627/Monitoring-River-and-Lake-Levels-from-Space.pdf/5a14ce2e-3a67-e165-b525-cdd161590d7a?t=1624448249272 (accessed on 28 February 2024).
32. Berry, P.A.M.; Freeman, J.A.; Garlick, J.D.; Smith, R.G.; Benveniste, J. A Decade of Global River and Lake Heights from ESA Altimeter Missions. In Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry, Venice, Italy, 13–18 March 2006; Available online: https://altimetry.esa.int/riverlake/rl_docs/493_ber.pdf (accessed on 28 February 2024).
33. Berry, P.A.M.; Benveniste, J. Measurement of Inland Surface Water from Multi-mission Satellite Radar Altimetry: Sustained Global Monitoring for Climate Change. In *Gravity, Geoid and Earth Observation. International Association of Geodesy Symposia*; Mertikas, S., Ed.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 135. [CrossRef]
34. Michailovsky, C.I.; McEnnis, S.; Berry, P.A.M.; Smith, R.; Bauer-Gottwein, P. River monitoring from satellite radar altimetry in the Zambezi River basin. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 2181–2192. [CrossRef]
35. Abdalla, S.; Kolahchi, A.A.; Ablain, M.; Adusumilli, S.; Bhowmick, S.A.; Alou-Font, E.; Amarouche, L.; Andersen, O.B.; Antich, H.; Aouf, L.; et al. Altimetry for the future: Building on 25 years of progress. *Adv. Space Res.* **2021**, *68*, 319–363. [CrossRef]
36. Yang, L.; Lin, L.; Fan, L.; Liu, N.; Huang, L.; Xu, Y.; Mertikas, S.P.; Jia, Y.; Lin, M. Satellite Altimetry: Achievements and Future Trends by a Scientometrics Analysis. *Remote Sens.* **2022**, *14*, 3332. [CrossRef]
37. Daudt, H.M.L.; Van Mossel, C.; Scott, S.J. Enhancing the scoping study methodology: A large, inter-professional team's experience with Arksey and O'Malley's framework. *BMC Med. Res. Methodol.* **2013**, *13*, 48. [CrossRef] [PubMed]
38. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 19–32. [CrossRef]
39. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med.* **2009**, *6*, e1000097. [CrossRef] [PubMed]
40. Munn, Z.; Peters, M.D.J.; Stern, C.; Tufanaru, C.; McArthur, A.; Aromataris, E. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Med. Res. Methodol.* **2018**, *18*, 143. [CrossRef]
41. Tricco, A.C.; Lillie, E.; Zarin, W.; O'Brien, K.; Colquhoun, H.; Kastner, M.; Levac, D.; Ng, C.; Sharpe, J.P.; Wilson, K.; et al. A scoping review on the conduct and reporting of scoping reviews. *BMC Med. Res. Methodol.* **2016**, *16*, 15. [CrossRef] [PubMed]
42. Peters, M.D.J.; Godfrey, C.M.; Khalil, H.; McInerney, P.; Parker, D.; Soares, C.B. Guidance for conducting systematic scoping reviews. *JBI Evid. Implement.* **2015**, *13*, 141–146. [CrossRef] [PubMed]

43. Mendeley Ltd. Mendeley Desktop (Version 1.19.4) [Computer Software]. Available online: https://www.mendeley.com/ (accessed on 3 November 2023).
44. Howard, B.E.; Phillips, J.; Miller, K.; Tandon, A.; Mav, D.; Shah, M.R.; Holmgren, S.; Pelch, K.E.; Walker, V.; Rooney, A.A.; et al. SWIFT-Review: A text-mining workbench for systematic review. *Syst. Rev.* **2016**, *5*, 87. [CrossRef] [PubMed]
45. Jonnalagadda, S.; Petitti, D. A new iterative method to reduce workload in systematic review process. *Int. J. Comput. Biol. Drug Des.* **2013**, *6*, 5–17. [CrossRef]
46. Levac, D.; Colquhoun, H.; O'Brien, K.K. Scoping studies: Advancing the methodology. *Implement. Sci.* **2010**, *5*, 69. [CrossRef]
47. Bryman, A.; Burgess, B. *Analyzing Qualitative Data*, 1st ed.; Routledge: London, UK, 1994. [CrossRef]
48. Quartly, G.D.; Rinne, E.; Passaro, M.; Andersen, O.B.; Dinardo, S.; Fleury, S.; Guillot, A.; Hendricks, S.; Kurekin, A.A.; Müller, F.L.; et al. Retrieving Sea Level and Freeboard in the Arctic: A Review of Current Radar Altimetry Methodologies and Future Perspectives. *Remote Sens.* **2019**, *11*, 881. [CrossRef]
49. Cavanillas, J.M.; Edward, C.; Wahlster, W. (Eds.) *New Horizons for a Data-Driven Economy*; Springer, Cham, Switzerland, 2005. [CrossRef]
50. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
51. Lapierre, N.; Neubauer, N.; Miguel-Cruz, A.; Rincon, A.R.; Liu, L.; Rousseau, J. The state of knowledge on technologies and their use for fall detection: A scoping review. *Int. J. Med. Inform.* **2018**, *111*, 58–71. [CrossRef] [PubMed]
52. Liberati, A.; Altman, D.G.; Tetzlaff, J.; Mulrow, C.; Gøtzsche, P.C.; Ioannidis, J.P.A.; Clarke, M.; Devereaux, P.J.; Kleijnen, J.; Moher, D. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLoS Med.* **2009**, *6*, e1000100. [CrossRef] [PubMed]
53. Tourian, M.J.; Elmi, O.; Shafaghi, Y.; Behnia, S.; Saemian, P.; Schlesinger, R.; Sneeuw, N. HydroSat: Geometric quantities of the global water cycle from geodetic satellites. *Earth Syst. Sci. Data* **2022**, *14*, 2463–2486. [CrossRef]
54. Donlon, C.; Berruti, B.; Buongiorno, A.; Ferreira, M.-H.; Féménias, P.; Frerick, J.; Goryl, P.; Klein, U.; Laur, H.; Mavrocordatos, C.; et al. The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission. *Remote Sens. Environ.* **2012**, *120*, 37–57. [CrossRef]
55. Le Gac, S.; Boy, F.; Blumstein, D.; Lasson, L.; Picot, N. Benefits of the Open-Loop Tracking Command (OLTC): Extending conventional nadir altimetry to inland waters monitoring. *Adv. Space Res.* **2021**, *68*, 843–852. [CrossRef]
56. Nielsen, K.; Stenseng, L.; Andersen, O.B.; Knudsen, P. The Performance and Potentials of the CryoSat-2 SAR and SARIn Modes for Lake Level Estimation. *Water* **2017**, *9*, 374. [CrossRef]
57. Normandin, C.; Frappart, F.; Diepkilé, A.T.; Marieu, V.; Mougin, E.; Blarel, F.; Lubac, B.; Braquet, N.; Ba, A. Evolution of the Performances of Radar Altimetry Missions from ERS-2 to Sentinel-3A over the Inner Niger Delta. *Remote Sens.* **2018**, *10*, 833. [CrossRef]
58. Thakur, P.K.; Garg, V.; Kalura, P.; Agrawal, B.; Sharma, V.; Mohapatra, M.; Kalia, M.; Aggarwal, S.P.; Calmant, S.; Ghosh, S.; et al. Water level status of Indian reservoirs: A synoptic view from altimeter observations. *Adv. Space Res.* **2021**, *68*, 619–640. [CrossRef]
59. Raney, R. The delay/Doppler radar altimeter. *IEEE Trans. Geosci. Remote Sens.* **1998**, *36*, 1578–1588. [CrossRef]
60. Wingham, D.; Francis, C.; Baker, S.; Bouzinac, C.; Brockley, D.; Cullen, R.; de Chateau-Thierry, P.; Laxon, S.; Mallow, U.; Mavrocordatos, C.; et al. CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. *Adv. Space Res.* **2006**, *37*, 841–871. [CrossRef]
61. Jiang, L.; Schneider, R.; Andersen, O.B.; Bauer-Gottwein, P. CryoSat-2 Altimetry Applications over Rivers and Lakes. *Water* **2017**, *9*, 211. [CrossRef]
62. Roohi, S.; Sneeuw, N.; Benveniste, J.; Dinardo, S.; Issawy, E.; Zhang, G. Evaluation of CryoSat-2 water level derived from different retracking scenarios over selected inland water bodies. *Adv. Space Res.* **2021**, *68*, 947–962. [CrossRef]
63. Schneider, R.; Tarpanelli, A.; Nielsen, K.; Madsen, H.; Bauer-Gottwein, P. Evaluation of multi-mode CryoSat-2 altimetry data over the Po River against in situ data and a hydrodynamic model. *Adv. Water Resour.* **2018**, *112*, 17–26. [CrossRef]
64. Xue, H.; Liao, J.; Zhao, L. A Modified Empirical Retracker for Lake Level Estimation Using Cryosat-2 SARin Data. *Water* **2018**, *10*, 1584. [CrossRef]
65. Chen, J.; Liao, J. Monitoring lake level changes in China using multi-altimeter data (2016–2019). *J. Hydrol.* **2020**, *590*, 125544. [CrossRef]
66. Chen, P.; An, Z.; Xue, H.; Yao, Y.; Yang, X.; Wang, R.; Wang, Z. INPPTR: An improved retracking algorithm for inland water levels estimation using Cryosat-2 SARin data. *J. Hydrol.* **2022**, *613*, 128439. [CrossRef]
67. Chen, J.; Liao, J.; Wang, C. Improved Lake Level Estimation from Radar Altimeter Using an Automatic Multiscale-Based Peak Detection Retracker. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2021**, *14*, 1246–1259. [CrossRef]
68. Moore, P.; Birkinshaw, S.; Ambrózio, A.; Restano, M.; Benveniste, J. CryoSat-2 Full Bit Rate Level 1A processing and validation for inland water applications. *Adv. Space Res.* **2018**, *62*, 1497–1515. [CrossRef]
69. Kleinherenbrink, M.; Naeije, M.; Slobbe, C.; Egido, A.; Smith, W. The performance of CryoSat-2 fully-focussed SAR for inland water-level estimation. *Remote Sens. Environ.* **2020**, *237*, 111589. [CrossRef]
70. Liu, Z.; Yao, Z.; Wang, R. Evaluation and Validation of CryoSat-2-Derived Water Levels Using In Situ Lake Data from China. *Remote Sens.* **2019**, *11*, 899. [CrossRef]

71. An, Z.; Chen, P.; Tang, F.; Yang, X.; Wang, R.; Wang, Z. Evaluating the Performance of Seven Ongoing Satellite Altimetry Missions for Measuring Inland Water Levels of the Great Lakes. *Sensors* **2022**, *22*, 9718. [CrossRef] [PubMed]
72. Bogning, S.; Frappart, F.; Blarel, F.; Niño, F.; Mahé, G.; Bricquet, J.-P.; Seyler, F.; Onguéné, R.; Etamé, J.; Paiz, M.-C.; et al. Monitoring Water Levels and Discharges Using Radar Altimetry in an Ungauged River Basin: The Case of the Ogooué. *Remote Sens.* **2018**, *10*, 350. [CrossRef]
73. Deng, X.; Wang, R.-B.; Peng, F.; Yang, Y.; Mo, N.-M. Retracking Cryosat-2 Data in SARIn and LRM Modes for Plateau Lakes: A Case Study for Tibetan and Dianchi Lakes. *Remote Sens.* **2021**, *13*, 1078. [CrossRef]
74. Perbos, J.; Escudier, P.; Parisot, F.; Zaouche, G.; Vincent, P.; Menard, Y.; Manon, F.; Kunstmann, G.; Royer, D.; Fu, L.-L. Jason-1: Assessment of the System Performances Special Issue: Jason-1 Calibration/Validation. *Mar. Geod.* **2010**, *26*, 147–157. [CrossRef]
75. Yang, Y.; Moore, P.; Li, Z.; Li, F. Lake Level Change From Satellite Altimetry Over Seasonally Ice-Covered Lakes in the Mackenzie River Basin. *IEEE Trans. Geosci. Remote Sens.* **2020**, *59*, 8143–8152. [CrossRef]
76. Shu, S.; Liu, H.; Beck, R.A.; Frappart, F.; Korhonen, J.; Lan, M.; Xu, M.; Yang, B.; Huang, Y. Evaluation of historic and operational satellite radar altimetry missions for constructing consistent long-term lake water level records. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 1643–1670. [CrossRef]
77. Frappart, F.; Blarel, F.; Fayad, I.; Bergé-Nguyen, M.; Crétaux, J.-F.; Shu, S.; Schregenberger, J.; Baghdadi, N. Evaluation of the Performances of Radar and Lidar Altimetry Missions for Water Level Retrievals in Mountainous Environment: The Case of the Swiss Lakes. *Remote Sens.* **2021**, *13*, 2196. [CrossRef]
78. Li, S.; Chen, J.; Xiang, J.; Pan, Y.; Huang, Z.; Wu, Y. Water level changes of Hulun Lake in Inner Mongolia derived from Jason satellite data. *J. Vis. Commun. Image Represent.* **2018**, *58*, 565–575. [CrossRef]
79. Neto, A.R.; Behnia, S.; Tourian, M.J.; da Costa, F.A.; Sneeuw, N. Satellite altimetry over small reservoirs in the Brazilian semiarid region. *RBRH* **2021**, *26*, e21. [CrossRef]
80. Biancamaria, S.; Schaedele, T.; Blumstein, D.; Frappart, F.; Boy, F.; Desjonquères, J.-D.; Pottier, C.; Blarel, F.; Niño, F. Validation of Jason-3 tracking modes over French rivers. *Remote Sens. Environ.* **2018**, *209*, 77–89. [CrossRef]
81. Donlon, C.J.; Cullen, R.; Giulicchi, L.; Vuilleumier, P.; Francis, C.R.; Kuschnerus, M.; Simpson, W.; Bouridah, A.; Caleno, M.; Bertoni, R.; et al. The Copernicus Sentinel-6 mission: Enhanced continuity of satellite sea level measurements from space. *Remote Sens. Environ.* **2021**, *258*, 112395. [CrossRef]
82. Jiang, M.; Xu, K.; Wang, J. Evaluation of Sentinel-6 Altimetry Data over Ocean. *Remote Sens.* **2022**, *15*, 12. [CrossRef]
83. Benveniste, J.; Roca, M.; Levrini, G.; Vincent, P.; Baker, S.; Zanife, O.; Zelli, C.; Bombaci, O. The radar altimetry mission: RA-2, MWR, DORIS and LRR. *ESA Bull.* **2001**, *106*, 25101–25108.
84. Dibarboure, G.; Lamy, A.; Pujol, M.-I.; Jettou, G. The Drifting Phase of SARAL: Securing Stable Ocean Mesoscale Sampling with an Unmaintained Decaying Altitude. *Remote Sens.* **2018**, *10*, 1051. [CrossRef]
85. Verron, J.; Sengenes, P.; Lambin, J.; Noubel, J.; Steunou, N.; Guillot, A.; Picot, N.; Coutin-Faye, S.; Sharma, R.; Gairola, R.M.; et al. The SARAL/AltiKa Altimetry Satellite Mission. *Mar. Geod.* **2015**, *38*, 2–21. [CrossRef]
86. Steunou, N.; Desjonquères, J.D.; Picot, N.; Sengenes, P.; Noubel, J.; Poisson, J.C. AltiKa Altimeter: Instrument Description and In Flight Performance. *Mar. Geod.* **2015**, *38*, 22–42. [CrossRef]
87. Vignudelli, S.; Kostianoy, A.G.; Cipollini, P.; Benveniste, J. *Coastal Altimetry*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2011; pp. 3–50.
88. Barry, R.; Finkelstein, J.; Kilgus, C.; Mooers, C.N.K.; Needham, B.; Crawford, M. Geosat follow-on satellite to supply ocean sciences data. *Eos Trans. Am. Geophys. Union* **1995**, *76*, 33–36. [CrossRef]
89. Yang, L.; Xu, Y.; Lin, M.; Ma, C.; Mertikas, S.P.; Hu, W.; Wang, Z.; Mu, B.; Zhou, X. Monitoring the Performance of HY-2B and Jason-2/3 Sea Surface Height via the China Altimetry Calibration Cooperation Plan. *IEEE Trans. Geosci. Remote Sens.* **2021**, *60*, 1002013. [CrossRef]
90. Guo, H.; Guo, J.; Yang, Z.; Wang, G.; Qi, L.; Lin, M.; Peng, H.; Ji, B. On Satellite-Borne GPS Data Quality and Reduced-Dynamic Precise Orbit Determination of HY-2C: A Case of Orbit Validation with Onboard DORIS Data. *Remote Sens.* **2021**, *13*, 4329. [CrossRef]
91. Schutz, B.E.; Zwally, H.J.; Shuman, C.A.; Hancock, D.; DiMarzio, J.P. Overview of the ICESat Mission. *Geophys. Res. Lett.* **2005**, *32*, L21S01. [CrossRef]
92. Neuenschwander, A.; Guenther, E.; White, J.C.; Duncanson, L.; Montesano, P. Validation of ICESat-2 terrain and canopy heights in boreal forests. *Remote Sens. Environ.* **2020**, *251*, 112110. [CrossRef]
93. Dandabathula, G.; Rao, S.S. Validation of ICESat-2 Surface Water Level Product ATL13 with Near Real Time Gauge Data. *Hydrology* **2020**, *8*, 19. [CrossRef]
94. Xu, N.; Zheng, H.; Ma, Y.; Yang, J.; Liu, X.; Wang, X. Global Estimation and Assessment of Monthly Lake/Reservoir Water Level Changes Using ICESat-2 ATL13 Products. *Remote Sens.* **2021**, *13*, 2744. [CrossRef]
95. Narin, O.G.; Abdikan, S. Multi-temporal analysis of inland water level change using ICESat-2 ATL-13 data in lakes and dams. *Environ. Sci. Pollut. Res.* **2022**, *30*, 15364–15376. [CrossRef] [PubMed]
96. Guo, X.; Jin, S.; Zhang, Z. Evaluation of Water Level Estimation in the Upper Yangtze River from ICESat-2 Data. In Proceedings of the 2021 Photonics & Electromagnetics Research Symposium (PIERS), Hangzhou, China, 21–25 November 2021; Volume 2021-Novem, pp. 2260–2264. [CrossRef]

97. Han, W.; Huang, C.; Gu, J.; Hou, J.; Zhang, Y.; Wang, W. Water Level Change of Qinghai Lake from ICESat and ICESat-2 Laser Altimetry. *Remote Sens.* **2022**, *14*, 6212. [CrossRef]
98. Lao, J.; Wang, C.; Nie, S.; Xi, X.; Wang, J. Monitoring and Analysis of Water Level Changes in Mekong River from ICESat-2 Spaceborne Laser Altimetry. *Water* **2022**, *14*, 1613. [CrossRef]
99. Xiang, J.; Li, H.; Zhao, J.; Cai, X.; Li, P. Inland water level measurement from spaceborne laser altimetry: Validation and comparison of three missions over the Great Lakes and lower Mississippi River. *J. Hydrol.* **2021**, *597*, 126312. [CrossRef]
100. Dubayah, R.; Blair, J.B.; Goetz, S.; Fatoyinbo, L.; Hansen, M.; Healey, S.; Hofton, M.; Hurtt, G.; Kellner, J.; Luthcke, S.; et al. The Global Ecosystem Dynamics Investigation: High-resolution laser ranging of the Earth's forests and topography. *Sci. Remote Sens.* **2020**, *1*, 100002. [CrossRef]
101. Zhang, Z.; Bo, Y.; Jin, S.; Chen, G.; Dong, Z. Dynamic water level changes in Qinghai Lake from integrating refined ICESat-2 and GEDI altimetry data (2018–2021). *J. Hydrol.* **2022**, *617*, 129007. [CrossRef]
102. Zhang, Z.; Chen, G.; Bo, Y.; Guo, X.; Bao, J. Performance evaluation of combining ICESat-2 and GEDI laser altimetry missions for inland lake level retrievals. *Geosci. Lett.* **2022**, *9*, 35. [CrossRef]
103. Fayad, I.; Baghdadi, N.; Frappart, F. Comparative Analysis of GEDI's Elevation Accuracy from the First and Second Data Product Releases over Inland Waterbodies. *Remote Sens.* **2022**, *14*, 340. [CrossRef]
104. Xu, N.; Ma, Y.; Wei, Z.; Huang, C.; Li, G.; Zheng, H.; Wang, X.H. Satellite observed recent rising water levels of global lakes and reservoirs. *Environ. Res. Lett.* **2022**, *17*, 074013. [CrossRef]
105. Fok, H.S.; He, Q. Water Level Reconstruction Based on Satellite Gravimetry in the Yangtze River Basin. *ISPRS Int. J. Geoinf.* **2018**, *7*, 286. [CrossRef]
106. Li, W.; Cardellach, E.; Fabra, F.; Ribó, S.; Rius, A. Lake Level and Surface Topography Measured with Spaceborne GNSS-Reflectometry From CYGNSS Mission: Example for the Lake Qinghai. *Geophys. Res. Lett.* **2018**, *45*, 13332–13341. [CrossRef]
107. Rodriguez-Alvarez, N.; Munoz-Martin, J.F.; Morris, M. Latest Advances in the Global Navigation Satellite System—Reflectometry (GNSS-R) Field. *Remote Sens.* **2023**, *15*, 2157. [CrossRef]
108. Ruf, C.S.; Chew, C.; Lang, T.; Morris, M.G.; Nave, K.; Ridley, A.; Balasubramaniam, R. A New Paradigm in Earth Environmental Monitoring with the CYGNSS Small Satellite Constellation. *Sci. Rep.* **2018**, *8*, 8782. [CrossRef]
109. Holden, L.D.; Larson, K.M. Ten years of Lake Taupō surface height estimates using the GNSS interferometric reflectometry. *J. Geod.* **2021**, *95*, 74. [CrossRef]
110. Park, E.; Merino, E.; Lewis, Q.W.; Lindsey, E.O.; Yang, X. A Pathway to the Automated Global Assessment of Water Level in Reservoirs with Synthetic Aperture Radar (SAR). *Remote Sens.* **2020**, *12*, 1353. [CrossRef]
111. Liao, J.; Xue, H. Estimation of lake level using Tiangong-2 InIRA data. In *Proceedings of the 2019 Tiangong-2 Remote Sensing Application Conference*; Springer: Singapore, 2019; Volume 541, pp. 333–343. [CrossRef]
112. Wahr, J.; Swenson, S.; Zlotnicki, V.; Velicogna, I. Time-variable gravity from GRACE: First results. *Geophys. Res. Lett.* **2004**, *31*, L11501. [CrossRef]
113. Tapley, B.D.; Bettadpur, S.; Watkins, M.; Reigber, C. The gravity recovery and climate experiment: Mission overview and early results. *Geophys. Res. Lett.* **2004**, *31*, L09607. [CrossRef]
114. Pham, H.T.; Marshall, L.; Johnson, F.; Sharma, A. Deriving daily water levels from satellite altimetry and land surface temperature for sparsely gauged catchments: A case study for the Mekong River. *Remote Sens. Environ.* **2018**, *212*, 31–46. [CrossRef]
115. Cretaux, J.; Berge-Nguyen, M.; Sensing, S.C. Absolute Calibration or Validation of the Altimeters on the Sentinel-3A and the Jason-3 over Lake Issykkul (Kyrgyzstan). *Remote Sens.* **2018**, *10*, 1679. [CrossRef]
116. Birkett, C.M. Contribution of the TOPEX NASA Radar Altimeter to the global monitoring of large rivers and wetlands. *Water Resour. Res.* **1998**, *34*, 1223–1239. [CrossRef]
117. Wingham, D.J.; Rapley, C.G.; Griffiths, H. New techniques in satellite altimeter tracking systems. In Proceedings of the IGARSS, Zürich, Switzerland, 8–11 September 1986.
118. Davis, C.H. Growth of the Greenland ice sheet: A performance assessment of altimeter retracking algorithms. *IEEE Trans. Geosci. Remote Sens.* **1995**, *33*, 1108–1116. [CrossRef]
119. Jain, M.; Andersen, O.B.; Dall, J.; Stenseng, L. Sea surface height determination in the Arctic using Cryosat-2 SAR data from primary peak empirical retrackers. *Adv. Space Res.* **2015**, *55*, 40–50. [CrossRef]
120. Roohi, S.; Amini, A.; Battles, D. Lake Monitoring from a Combination of Multi Copernicus Missions: Sentinel-1 A and B and Sentinel-3A. *J. Hydrogeol. Hydrol. Eng.* **2019**, *8*, 3.
121. Mostafavi, M.; Delpeche-Ellmann, N.; Ellmann, A. Accurate Sea Surface heights from Sentinel-3A and Jason-3 retrackers by incorporating High-Resolution Marine Geoid and Hydrodynamic Models. *J. Géod. Sci.* **2021**, *11*, 58–74. [CrossRef]
122. Ray, C.; Martin-Puig, C.; Clarizia, M.P.; Ruffini, G.; Dinardo, S.; Gommenginger, C.; Benveniste, J. SAR Altimeter Backscattered Waveform Model. *IEEE Trans. Geosci. Remote Sens.* **2015**, *53*, 911–919. [CrossRef]
123. Passaro, M.; Rose, S.K.; Andersen, O.B.; Boergens, E.; Calafat, F.M.; Dettmering, D.; Benveniste, J. ALES+: Adapting a homogenous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters. *Remote Sens. Environ.* **2018**, *211*, 456–471. [CrossRef]
124. Peng, F.; Deng, X. Validation of Sentinel-3A SAR mode sea level anomalies around the Australian coastal region. *Remote Sens. Environ.* **2020**, *237*, 111548. [CrossRef]
125. Peng, F.; Deng, X. A New Retracking Technique for Brown Peaky Altimetric Waveforms. *Mar. Geod.* **2017**, *41*, 99–125. [CrossRef]

126. Jiang, L.; Nielsen, K.; Dinardo, S.; Andersen, O.B.; Bauer-Gottwein, P. Evaluation of Sentinel-3 SRAL SAR altimetry over Chinese rivers. *Remote Sens. Environ.* **2020**, *237*, 111546. [CrossRef]
127. Dinardo, S.; Fenoglio-Marc, L.; Buchhaupt, C.; Becker, M.; Scharroo, R.; Fernandes, M.J.; Benveniste, J. Coastal SAR and PLRM altimetry in German Bight and West Baltic Sea. *Adv. Space Res.* **2018**, *62*, 1371–1404. [CrossRef]
128. Gao, Q.; Makhoul, E.; Escorihuela, M.J.; Zribi, M.; Seguí, P.Q.; García, P.; Roca, M. Analysis of Retrackers' Performances and Water Level Retrieval over the Ebro River Basin Using Sentinel-3. *Remote Sens.* **2019**, *11*, 718. [CrossRef]
129. Makhoul, E.; Roca, M.; Ray, C.; Escolà, R.; Garcia-Mondéjar, A. Evaluation of the precision of different Delay-Doppler Processor (DDP) algorithms using CryoSat-2 data over open ocean. *Adv. Space Res.* **2018**, *62*, 1464–1478. [CrossRef]
130. Shu, S.; Liu, H.; Beck, R.A.; Frappart, F.; Korhonen, J.; Xu, M.; Yang, B.; Hinkel, K.M.; Huang, Y.; Yu, B. Analysis of Sentinel-3 SAR altimetry waveform retracking algorithms for deriving temporally consistent water levels over ice-covered lakes. *Remote Sens. Environ.* **2020**, *239*, 111643. [CrossRef]
131. Dinardo, S.; Lucas, B.; Benveniste, J. Sentinel-3 STM SAR ocean retracking algorithm and SAMOSA model. In Proceedings of the 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Milan, Italy, 26–31 July 2015; pp. 5320–5323.
132. Boy, F.; Cretaux, J.-F.; Boussaroque, M.; Tison, C. Improving Sentinel-3 SAR Mode Processing Over Lake Using Numerical Simulations. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 5220518. [CrossRef]
133. Boy, F.; Crétaux, J.-F.; Boussaroque, M.; Tison, C. Estimation of Lake Heights from Sentinel-3 Sar Mode Through Numerical Simulations. In Proceedings of the 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, Brussels, Belgium, 11–16 July 2021; pp. 6128–6131. [CrossRef]
134. Nielsen, K.; Andersen, O.B.; Ranndal, H. Validation of Sentinel-3A Based Lake Level over US and Canada. *Remote Sens.* **2020**, *12*, 2835. [CrossRef]
135. Zaidi, A.Z.; Vignudelli, S.; Khero, Z.; Ghauri, B.M.; Muzaffer, R.; Naeem, B.; Panhwar, V.; Zafar, S.; Haque, S.U. Indus river water level monitoring using satellite radar altimetry. *Adv. Space Res.* **2020**, *68*, 641–651. [CrossRef]
136. Diepkilé, A.T.; Egon, F.; Blarel, F.; Mougin, E.; Frappart, F. Validation of the altimetry-based water levels from Sentinel-3A and B in the Inner Niger Delta. *Proc. Int. Assoc. Hydrol. Sci.* **2021**, *384*, 31–35. [CrossRef]
137. Kittel, C.M.M.; Jiang, L.; Tøttrup, C.; Bauer-Gottwein, P. Sentinel-3 radar altimetry for river monitoring—A catchment-scale evaluation of satellite water surface elevation from Sentinel-3A and Sentinel-3B. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 333–357. [CrossRef]
138. Halicki, M.; Niedzielski, T. The accuracy of the Sentinel-3A altimetry over Polish rivers. *J. Hydrol.* **2022**, *606*, 127355. [CrossRef]
139. Ray, C.; Roca, M.; Martin-Puig, C.; Escola, R.; Garcia, A. Amplitude and Dilation Compensation of the SAR Altimeter Backscattered Power. *IEEE Geosci. Remote Sens. Lett.* **2015**, *12*, 2473–2476. [CrossRef]
140. Nino, F.; Coggiola, C.; Blumstein, D.; Lasson, L.; Calmant, S. Monitoring of Inland Water Levels by Satellite Altimetry and Deep Learning. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 4205814. [CrossRef]
141. Crétaux, J.-F.; Birkett, C. Lake studies from satellite radar altimetry. *Comptes Rendus Geosci.* **2006**, *338*, 1098–1112. [CrossRef]
142. Kern, M.; Cullen, R.; Berruti, B.; Bouffard, J.; Casal, T.; Drinkwater, M.R.; Gabriele, A.; Lecuyot, A.; Ludwig, M.; Midthassel, R.; et al. The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) high-priority candidate mission. *Cryosphere* **2020**, *14*, 2235–2251. [CrossRef]
143. Frasson, R.P.d.M.; Schumann, G.J.; Kettner, A.J.; Brakenridge, G.R.; Krajewski, W.F. Will the Surface Water and Ocean Topography (SWOT) Satellite Mission Observe Floods? *Geophys. Res. Lett.* **2019**, *46*, 10435–10445. [CrossRef]
144. Wang, J.; Fu, L.-L.; Qiu, B.; Menemenlis, D.; Farrar, J.T.; Chao, Y.; Thompson, A.F.; Flexas, M.M.; Farrar, T. An Observing System Simulation Experiment for the Calibration and Validation of the Surface Water Ocean Topography Sea Surface Height Measurement Using In Situ Platforms. *J. Atmos. Ocean. Technol.* **2018**, *35*, 281–297. [CrossRef]
145. Fablet, R.; Verron, J.; Mourre, B.; Chapron, B.; Pascual, A. Improving Mesoscale Altimetric Data From a Multitracer Convolutional Processing of Standard Satellite-Derived Products. *IEEE Trans. Geosci. Remote Sens.* **2018**, *56*, 2518–2525. [CrossRef]
146. Blumstein, D.; Biancamaria, S.; Amiot, T.; Guérin, A.; Le Gac, S.; Maisongrande, P.; Cherchali, S.; Picot, N.; Coutin-Faye, S.; Rey, L.; et al. SMASH: A Mission to Better Monitor Inland Waters and Esturaies. 2021. Available online: https://www.hydrospace2021.org/ (accessed on 15 September 2023).
147. Giuliani, G.; Egger, E.; Italiano, J.; Poussin, C.; Richard, J.-P.; Chatenoux, B. Essential Variables for Environmental Monitoring: What Are the Possible Contributions of Earth Observation Data Cubes? *Data* **2020**, *5*, 100. [CrossRef]
148. Bojinski, S.; Verstraete, M.; Peterson, T.C.; Richter, C.; Simmons, A.; Zemp, M. The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bull. Am. Meteorol. Soc.* **2014**, *95*, 1431–1443. [CrossRef]