water

Systematic Review

Investigation and Quantification of Erosions in the Margins of Water Bodies: A Systematic Review

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Abstract: Erosive processes along the margins of water bodies are driven by various phenomena. Understanding and quantifying these processes require multidisciplinary approaches spanning across geology, ecology, and engineering. Accordingly, a variety of quantification approaches and techniques have been previously applied. To this end, the objective of the present research was to conduct a systematic review of the subject literature, with an aim to identify the techniques adopted in the quantification of erosion in the margins of water bodies. This study used a systematic review strategy based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses—PRISMA. The results showed that the primary focuses of the investigations were channel dynamics and the use and coverage of riparian soils. Two of the identified research focuses remain scarcely discussed due to the logistical difficulties surrounding continuous monitoring: (1) the direct impacts of rain on the removal of soil from the margin, and (2) the influence of water content on soil surfaces. Seven field techniques for measuring erosion in the margin were identified and summarily compared in this review. There is a consensus in the literature that the application of each technique is dependent on the characteristics of the study site, as well as the available resources for analysis; however, to overcome certain limitations, different techniques have been used simultaneously for a combination of data. The use of models has stood out in relation to the use of field techniques.

Keywords: erosion; erosive processes; quantification of erosion; reservoir margins; riverbanks; systematic reviews; water bodies

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1. Introduction

Erosion processes on banks are an important geomorphological mechanism for river ecosystems, controlling the succession of vegetation and habitat dynamics; however, excessive and accelerated erosion can cause impacts beyond the provision of suspended sediment, such as changes in channel morphology, increased turbidity, as well as altered aquatic habitats via changes in water quality, flood risk, and loss of arable land [1–4].

Studies on monitoring and measuring erosion in the margins are important for assessing the risks imposed by this process, in addition to defining conservation and restoration practices [5]. Accordingly, correlated studies can maintain multiple investigational focuses across the factors that control margin erosion, such as subaerial factors (associated with moisture conditions within the material [6]), river entrainment, and mass failure. Approaches are often selected according to river environmental characteristics and study objectives. Additionally, some approaches can focus on direct measurements of erosion processes [3,7], or the direct assessment of channel changes over large spatial scales [8].

Three primary categories of erosive processes and their interrelations have been detailed by Grove et al. (2013) [5]; these are subaerial processes, fluvial entrainment, and mass failure processes. Subaerial processes decrease the shear resistance of the margin surface and include factors such as ice and thaw cycles, wetting and drying cycles, as well as the direct impact of rain on the margin surface. Fluvial entrainment involves the detachment of particles or aggregates from the margin face by flow force, which occurs when the shear stress of the water exceeds that of the soil. Mass failure processes occur when gravitational forces exceed the shear strength of the margin materials and are commonly influenced by the weight of vegetative cover or an increase in soil water content [5].

In a review of field techniques used to measure riverbank erosion, Lawler (1993) [9] identified seven main methods: botanical evidence, sedimentological evidence, planimetric surveys, historical sources, repeated cross-profiling, terrestrial photogrammetry, and erosion pins. Since then, the development of remote sensing and geographic information system (GIS) technologies has allowed for significant advancement in the spatiotemporal analysis of margin erosion processes.

More recently, several additional techniques are used to quantify bank erosion; some employ a more conventional approach (e.g., erosion pins) [10,11], whereas others take advantage of contemporary technologies (e.g., photogrammetry with movement structure algorithms—SFM) [1,12–15]. The consensus in the literature is that the application of each technique depends on analysis objectives, site conditions, as well as data and resource availability [16]. For example, to analyze erosive processes by seepage, techniques with high spatiotemporal precision are required because of the timescale at which these processes occur, as well as their spatial distribution. The seepage erosion process often lasts less than a few hours [17].

Accordingly, the present systematic review arises from the need to understand the research focus of recent studies based on the monitoring techniques for quantifying erosion in margins, which potentially provides a direction to future studies by identifying any gaps in the literature. Furthermore, the identification and evaluation of the most common techniques used can aid field researchers in selecting the appropriate techniques based on their applicability and limitations. Here, emphasis was placed on both field techniques, as in the studies of Lawler (1993) [9], as well as model-based analyses and experiments in soil laboratories, thereby providing insight into technological advancements over time.

In summary, the present systematic review aimed to identify: (1) the focus of investigations on erosion processes in margins over the past decade, and (2) the main techniques used to quantify erosion in the margins.

There is a consensus in the literature that the application of each technique is dependent on the characteristics of the study site, as well as the available resources for analysis; however, to overcome certain limitations, different techniques have been used simultaneously for a combination of data.

2. Materials and Methods

2.1. Research Strategy and Study Identification

This study used a systematic review strategy based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses—PRISMA [18], and included articles published between 1 January 2010 and 31 July 2020.

The Web of Science Core Collection database was used as the primary search engine owing to the quality of indexed scientific journals, and the scope of the publication number. The employed search terms were “bank erosion,” “margin erosion,” “reservoir margin,” or “reservoir border”, and were selected based on previous research related to margin erosion. These terms were searched in the topic field (search for title, abstract, author keywords, and keywords plus).

2.2. Study Screening and Eligibility

The State of the Art through Systematic Review (StArt) software (Laboratory of Research on Software Engineering, Federal University of São Carlos, Brazil; v. 2.3.4.2) was used to conduct the systematic review [19], as it represents a free tool capable of supporting the planning and execution of systematic reviews, thus allowing for the selection of studies and data extraction to be carried out using a previously established and implemented protocol [20,21]. The VOSviewer program (Centre for Science and Technology Studies, Leiden University, The Netherlands; v.1.6.15) was used to view keyword networks [22].

The following selection criteria were implemented for article selection: addresses erosive processes on the banks of rivers, reservoirs, or through laboratory experiments; quantifies/estimates erosion in margins; and originally published in English (Table 1). Articles were selected based on their title and abstract information.

Table 1. Inclusion criteria for reviewed studies.

Criterion	Inclusion	Exclusion
Type of literature	Original paper	Conference proceedings, review articles, early access, and editorial material
Timeline	2010 to 2020	Before 2010
Study location	River or reservoir banks	Coastal zone
Investigation focus	Use and coverage of riparian soils, physical characteristics of the margin, soil characteristics, floods, channel dynamics, river hydraulic force, direct impact of rain on the bank surface, soil wetting and drying cycle, abrasion by suspended sediment particles, changes in the flow regime caused by dams, more than one of these factors, other investigation focuses, methodological investigations (i.e., not directly addressing the impacts of these factors, but rather the application or comparison of techniques)	Wave effects. Anthropogenic activities (e.g., cattle grazing) Ice–thaw cycle
Language	English	Other languages

Subsequently, the full texts of all selected articles were evaluated. For data extraction, each eligible study was compiled in StArt according to the following techniques: quantification/estimation of margin erosion, investigation focus, type of procedure (field study and/or laboratory experiment), study location (river or reservoir), and country where the study was conducted. The focuses of each investigation were identified based on the factors that control the erosion processes in the margins, as emphasized by the authors. Lastly, the results were summarized using StArt-generated reports, and interpreted via descriptive statistics.

3. Results and Discussion

In total, 882 articles were identified in the database. After verification of the titles and abstracts, 139 articles were considered eligible for the full-text evaluation. Following the removal of 8 articles which did not present measurements of margin erosion, the summary of results was based on information from 131 studies that successfully met the inclusion criteria corresponding to the review's objectives. Figure 1 shows the systematic review strategy based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

3.1. Focus of Margin Erosion Research

From 2010 to 2020, studies on margin erosion have emphasized channel dynamics (19.1%), the use and coverage of riparian soil (16%), and inundation (8.4%; Figure 3).

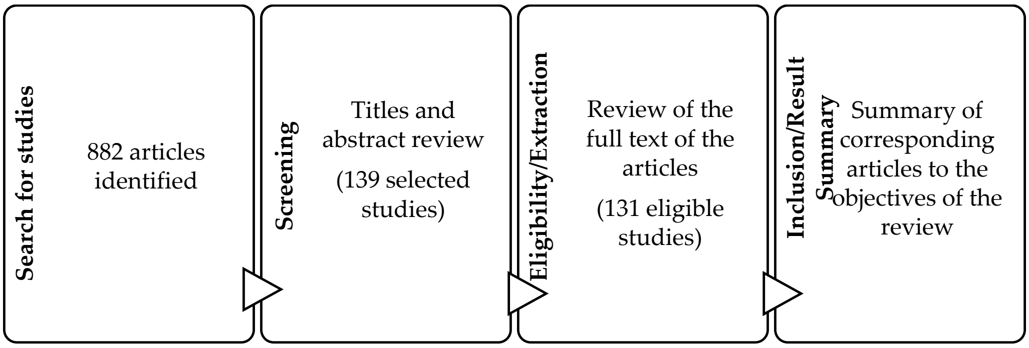

Figure 1. Stages of the systematic review on erosion processes in margins.

The most frequently used keyword in the 882 articles analyzed was "bank erosion" (*n* = 146 studies; 16.6%). Figure 2 shows the 25 main keywords used, as well as the three colored groups formed by their connection corresponding to the main research areas on this topic.

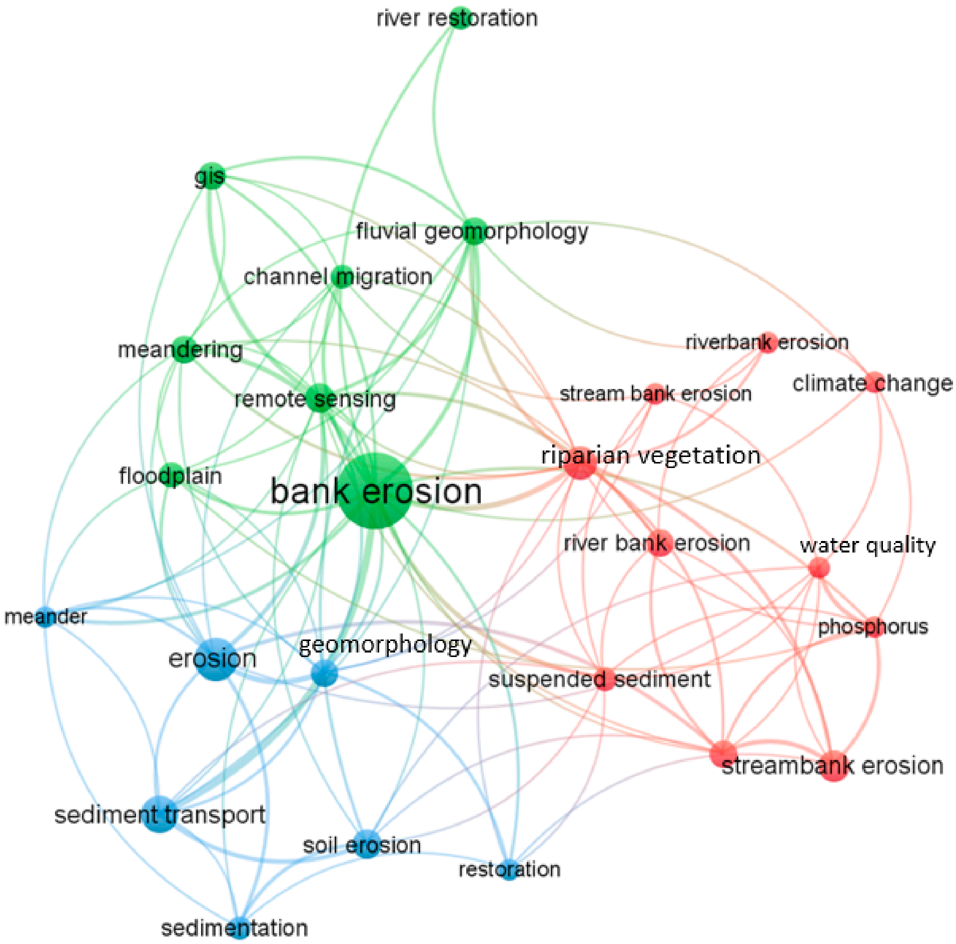

Figure 2. Distribution of keyword occurrences in the relevant literature.

Accordingly, there is a consensus among researchers regarding the importance of channel dynamics, with an emphasis on understanding the processes of erosion and accretion, as well as the definition of management strategies [8,15,23]. The characterization of winding and braided rivers is related to variations in runoff patterns, which in turn are dependent upon floodplain characteristics, hydrodynamic forces, flow regime, and sediment transport. These factors must be considered when mapping morphological changes and quantifying erosion in riverbanks [8,23].

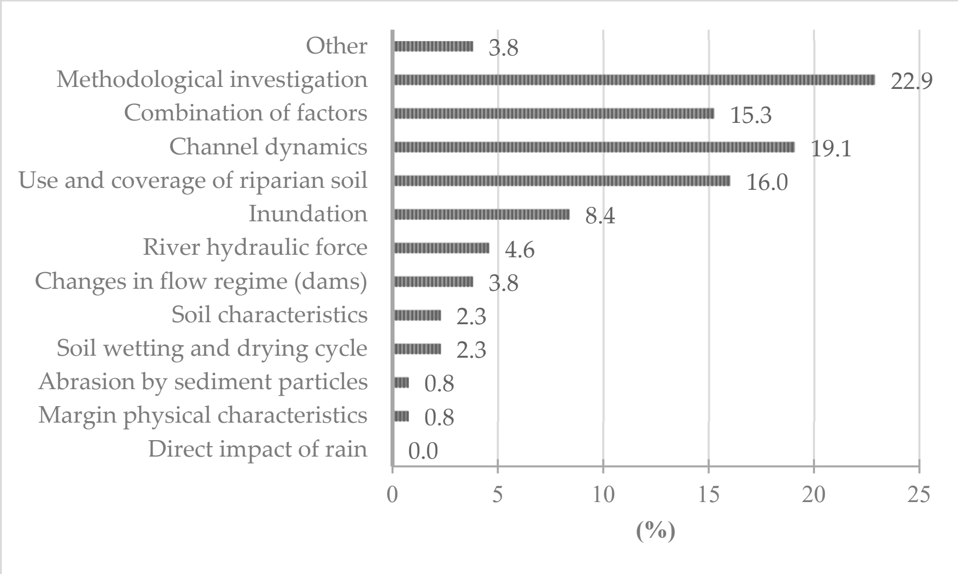

Figure 3. Distribution of investigative focuses in the literature.

Several studies have investigated the influence of riverside vegetation on bank erosion [24–27]. According to these investigations, vegetation type, density, and depth of the root system affect margin stability. For example, Mcmahon et al. (2020) [27] concluded that a 1% increase in tree canopy cover reduced the magnitude of erosion by 2–3%. Alternatively, Purvis and Fox (2016) [28] showed a three-fold reduction of margin retreat in areas protected by vegetation when compared to margins without vegetation.

Riparian vegetation with extensive and deep root systems provides structural support to the margin material, thereby limiting the action of flow force [26]. Pizzuto et al. (2010) [29] noted the importance for corresponding studies to consider the interactions between flow and the spatial structure of riparian vegetation. In addition, Zaimes and Schultz (2015) [26] added the need for assessments of soil temperature and humidity, and Purvis and Fox (2016) [28] highlighted the need to analyze the width of the riparian vegetation buffer when determining the variability of erosion rates.

Additional research focusing on flooding impact [5,13,30] has shown that extreme precipitation events enhance flow strengths, and channel flooding may therefore increase erosion rates. These studies have also highlighted the importance of managing environmental flows, as riverbank morphology depends on monitoring and management actions [4,31]. The hydraulic force of the flow can trigger other processes (e.g., mass failure) through destabilizing mechanisms at the bottom of the margin [32]. Fluvial entrainment has a significant impact on margin set-aside rates; however, the type of riparian vegetation can make this category of erosion process non-dominant [26].

Regarding soil composition and properties, approaches have focused on the influences of margin material characteristics as they relate to the erosive processes along hydrographic basins. For example, Motta et al. (2012) [33] examined the influence of alluvial soil heterogeneity on the migration of meanders; however, Beck et al. (2018) [34] investigated the contributions of alluvial unit materials during margin recession, and the resulting transport of sediment and phosphorus.

Subaerial processes related to water content on the margin surface have also been the focus of some investigations. The relationship between the infiltration gradient and the time to break the margin was investigated in the field by Karmaker and Dutta (2013) [35], and laboratory analyses were carried out by Masoodi et al. (2018) [17]. Other subaerial processes, such as those related to the direct impact of rain on margin materials, still constitute a notable gap in the literature, and therefore require further investigation. According to Grove et al. (2013) [5], subaerial processes have a significant cumulative impact, but are more difficult to monitor continuously; thus, they are often assessed indirectly by considering their influence on other categories of erosive processes, such as mass failure and river entrainment.

Some studies maintained more than one investigation focus, such as the characteristics of soil and riverside vegetation [36], channel dynamics, physical characteristics of the margin and land use-land cover [37], channel dynamics and riparian vegetation [38], and river water depth close to the bank and bank height [39]. Other themes have also been investigated, such as the contribution of margin erosion to sediment transport [40–42].

3.2. Techniques for Quantifying and Monitoring Margin Erosion Processes

Over the past decade, researchers have primarily employed five field techniques to quantify erosion in margins: erosion pins, satellite imagery analysis, photogrammetry (classical or photogrammetry with SFM), laser scanning (aerial or terrestrial), and the dendrogeomorphological technique. Most studies, however, were based on the application of models (n = 43 studies; 32.8%; Figure 4), followed by field studies using erosion pins (n = 21 studies; 16%), and satellite imagery analyses (n = 20; 15.3% of studies). The dendrogeomorphological technique has also been used to estimate erosion rates, although there are relatively few application examples (n = 2 studies; 1.5%).

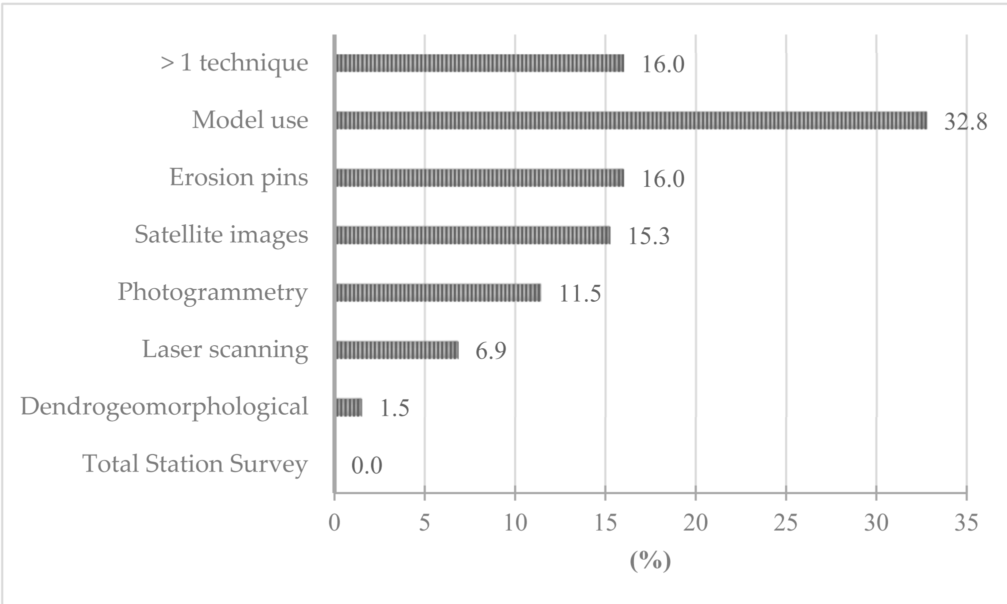

Figure 4. Distribution of investigation techniques used to quantify margin erosion in the literature.

The global distributions of all such studies are listed in Table 2. Notably, most were concentrated in the United States (28.2%), followed by China (13%), and India (9.2%). Within the United States, the most commonly employed techniques were erosion pins and models, whereas models were predominant in China. In India, satellite imagery-based investigations have become more common.

Among the 131 publications selected in this review, the techniques used to quantify margin erosion, and their investigative focuses are summarized in Table 3. For example, monitoring with erosion pins is considered a conventional method of measuring margin erosion, and is carried out by installing metal pins perpendicular to the face of the margin, and subsequently measuring the exposed rods. According to Lawler 1993 [9], this technique has been applied since 1970, and remains widely used in a variety of fluvial environments and geomorphological contexts [3,7].

Table 2. Study locations and techniques used for measuring erosion in margins.

Study Site	Technique							
	>1 Technique	Model Application	Biological Evidence	Direct Measurement	Remote Sensing			
			Dendrogeomorphological Technique	Erosion Pins	Laser Scanning	Photogrammetry	Total Station	Satellite Images
Australia	1			2	2			
Bangladesh	1	1						7
Bosnia	1							
Brazil					1			
Canada		3						
China	2	10		2		2		1
Colombia		1						
Czech Republic		1				2		
Denmark				3				
Ecuador				1				
Egypt								1
England		1						
France	2	1				2		
Greece		1						
Holland	1							
Hungary	1					1		
India		5						7
Iran			1			1		1
Italy	1	1						
Japan		2						
Malaysia		1						
Mexico		2						
Morocco								1
Mongolia		1						
New Zealand	1	2						
Pakistan	1							2
Poland	1				1			
Serbia						1		
Slovakia		1						
South Korea		1						
Switzerland				1				
Turkey				1				
United Kingdom				1				
United States	8	7	1	10	5	6		
Vietnam		1						
Total	21	43	2	21	9	15	0	20

Table 3. Techniques used to quantify and estimate margin erosion, as well as the focus of each study.

Investigation Focus on Bank Erosion	**Technique/Study**							
			Biological Evidence	**Direct Measurement**	**Remote Sensing**			
	>1 Technique	**Model Application**	**Dendrogeomorphological Technique**	**Erosion Pins**	**Laser Scanning**	**Photogrammetry**	**Total Station**	**Satellite Images**
Other				[42–44]	[40,41]			
Methodological investigation	[16,39,45–50]	[51–60]		[61]	[62]	[1,14,63,64]		[65–67]
Combination of factors	[36,68]	[37–39,69–75]		[3,76–79]	[80,81]	[82]		
Channel dynamics	[83–85]	[23,86–91]				[8,15,92–94]		[95–104]
Use and coverage riparian soil	[105,106]	[24,107–109]	[110,111]	[10,26,112–115]	[27,29,116]	[25,28]		[117,118]
Inundation	[5,12,13,119,120]			[31]		[30]		[4,121–123]
River hydraulic force		[32,124–126]		[11,127]				
Changes in flow regime	[128]			[7,129]	[130]	[131]		
Soil characteristics		[33,132]		[34]				
Soil wetting and drying cycle		[35,133]				[17]		
Abrasion by sediment particles		[134]						
Margin physical characteristics		[135]						
Direct impact of rain								

Over the years, there has also been an increase in the use of photoelectronic erosion pins [26]. The technique presents itself as an alternative in locations where the margin retreat rate tends to be low, as it allows the detection of small changes. Zaimes and Schultz (2015) [26] considered the daily erosional rates greater than 3 cm as major erosion events. In some circumstances, the use of erosion pins may not be satisfactory, as shown in Jugie et al. (2018) [12] who compared this technique with SFM photogrammetry. The results indicated that erosion pins underestimated the volume of the eroded margin by twice the volume quantified by photogrammetry in periods of higher morphological activity.

No studies using only the total station survey were found during analysis; however, this traditional technique was compared with terrestrial laser scanning in Resop and Hession (2010) [45], and combined with photogrammetry in Blanka and Kiss (2011) [119]. Using the total station, it is possible to monitor margin retreat by measuring the angles and distances based on the control points defined by a global positioning system (GPS). Notably, this technique has some measurement limitations based on margin shape, as lower cut margins can be a source of error in erosion rate estimates [16].

Technological advancements related to remote sensing have also expanded the possibility of analyzing margin erosion. Lawler (1993) [9] elaborated upon the need for improvements in the temporal resolution of erosion distribution for determining the moments of erosion occurrence, in addition to its relationship with promoter variables. This would allow inferences to be made regarding the main variables responsible for erosion. In addition, there was a need for techniques capable of detecting the spatial variability of erosion. At that time, advances in photogrammetry and the use of photoelectronic erosion pins were considered promising for resolving these limitations.

Photogrammetry has been widely used since 1990 and includes the application of classic [48], short-range [17,64], and SFM photogrammetry [15,63]. Innovations with unmanned aerial vehicles (UAVs) have enabled the development of a new generation of SFMs, permitting the restoration of the three-dimensional geometry of surfaces using randomly positioned images; however, classical photogrammetry was dependent upon overlapping strips of images acquired in parallel flight lines [136]. To this end, Hemmelder et al. (2018) [15] mapped erosion on the Buech River, France using SFM photogrammetry, and obtained a high-resolution time series of data (centimeter resolution). Mirijovsky and Langhammer (2015) [63] analyzed the applicability of SFM photogrammetry for tracking flood effects on channel changes in the Czech Republic, supporting the applicability of this technique in studies that require high levels of spatial detail, as well as highlighting the advantage of rapid mapping of flooding effects on rivers from a multitemporal perspective.

Some studies have explored the potential of UAVs to analyze channel dynamics, morphology, and margin erosion [1,14,15,63]. According to Hamshaw et al. (2019) [14], UAVs provide cost-effective and efficient data obtaining to monitor erosion processes in margins, capable of providing high spatiotemporal resolutions. Furthermore, limitations related to vegetation cover can be minimized through seasonal surveys, thereby enhancing data accuracy.

In satellite imagery analyses, the use of Landsat imagery was most common. Indeed, this technique has been applied with different emphases: channel migration and flood risks [4], assessment of channel morphological changes associated with river width and sinuosity [98], analysis of riverbank retreat line using a continuous wavelet transform [65], and estimation of changes in erosion area and accretion over time [99].

There was an equal balance between the number of studies that applied aerial and land laser scanning (four each), with one other study using a combination of these techniques [130]. Terrestrial laser scanning provides a detailed 3D point cloud, making it possible to detect changes in margin relief across multiple datasets. Compared with aerial laser scanning and photogrammetry, terrestrial laser scanning is more advantageous, as it allows for the analysis of steep margins. When compared with traditional methods, such as surveys with erosion pins and total stations, terrestrial laser scanning offers superior spatial resolutions and data collection time [137].

Notably, analyses of erosive processes in reservoir margins remain incipient. Studies have mainly focused on the reservoir influence area [7,128,130,131], whereas only one study has directly investigated reservoir bank erosion. Moraes et al. (2016) [62] monitored the erosion rates along the margins of Brazilian reservoirs using bat-mounted mobile laser-scanning equipment, allowing for the orthogonal visualization of erosive processes, as well as the analysis of areas obstructed by vegetation.

In dendrogeomorphological studies, erosive processes have been analyzed through anatomical changes in the roots, in addition to tree ring data. Dick et al. (2014) [110] conducted studies on the Michigan River in the United States, estimating the average annual erosion rates using this technique, and established a relationship between the Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS). The BEHI has as its parameters bank height, bank full height, root depth, root density, surface protection, and bank angle; NBS includes near bank maximum depth and mean bank full depth [138]. Hosseinzadeh et al. (2020) [111] investigated erosion rates in the Lavij River, Iran through micro- and macroscopic dendrogeomorphological analyses. Statistical tests confirmed that there were no significant differences in the results, indicating the advantage of applying macroscopic analyses, as they facilitate survey and subsequent analyses.

Donovan et al. (2015) [41] highlighted the importance of spatiotemporal studies for evaluating bank erosion, and their contribution to sediment transport; however, the hydraulic and geotechnical processes related to margin erosion have been modeled (e.g., the Bank Stability and Toe Erosion Model—BSTEM [24,57,91,133], and Bank Assessment for Non-Point Source Consequences of Sediment Model—BANCS [51,58].

Field measurements are necessary to acquire hydrological, hydraulic, and geomorphological variables when applying the BSTEM. This model estimates erosion based on the excess shear stress equation, and safety factor [57]. Alternatively, the BANCS is based on the evaluation of margin stress (NBS) and erodibility (BEHI) for estimating erosion rates [58]. According to the findings of this review, BSTEM use was primarily confined to the United States, but has also been applied in China and Mongolia, whereas the BANCS has been tested across different countries such as the US, India, Slovakia, and the Czech Republic. This suggests the possibility of calibrating and modifying the model parameters according to the characteristics of different regions.

Some studies have focused on the application of more than one field technique, such as aerial photogrammetry and satellite imagery analyses [46,47], laser scanning and aerial photography [5,68,128], erosion pins and laser scanning [49], SFM photogrammetry and erosion pins [12], and SFM photogrammetry and scanning lasers [13]. In some cases, a comparison was made between the techniques, while in others, combinations of the two methods were applied. For example, a combination of techniques was used by Foucher et al. (2017) [49] to analyze the dynamics of margin erosion over time, where erosion pins were used for short-term analyses during winter, and a differential global positioning system combined with laser scanning was employed to estimate the average loss of margin material long term.

The literature is relatively limited regarding the comparability between techniques. Notably, each technique maintains some form of advantage according to the analysis location conditions [16,17]. For the terrestrial laser scanning technique, the presence of dense vegetation close to the margin can limit accuracy. In open streambanks with little vegetation, the terrestrial laser scanning can detect small erosion rates with a sub-centimeter error [16]. Comparably, limitations of total station surveys relate to the morphology of the margin (e.g., lower cuts). A comprehensive list of advantages and disadvantages for each of the primary techniques employed can be found in Table 4.

Table 4. Comparative analysis of field techniques for measuring erosion in margins.

Technique	Advantages	Disadvantages	References
Total station survey	High precision. Technique can analyze the evolution of margin changes over time, and can be used on margins with vegetation with decreased risk of data loss. It is not necessary to leave the instruments in the field, thereby decreasing the possibility of research losses (compared to erosion pins).	Difficulties in analyzing steeper margins or those with a lower cut. Lower spatial resolution.	[16,119]
Direct measurement with erosion pins	Can be used in margins with vegetation with decreased risk of data loss. More cost effective (i.e., cheaper). Data processing does not require familiarity with software.	Possibility of destabilizing the margin during installation and subsequent turbulence. Possible losses in research data due to pin loss via natural processes or human interference. Provides only a point estimate of erosion rate. Longer data collection times.	[16,110]
Classical photogrammetry	High spatial resolution. High precision.	Decreased visibility from tree canopy. Limitations for evaluating margins with sloping surfaces. Relative inflexibility in image acquisition. Higher technology and processing costs when compared to SFM photogrammetry.	[14,48]
SFM photogrammetry	High spatial resolution. High precision (cm). High levels of image detail allow for the quantification margin retreat, and identification of erosive processes characteristics. High image operability and relatively lower operating costs. Rapid image acquisition and data processing. Technology allows the filtering of margin images with sparse vegetation.	The presence of dense vegetation along the margins can generate error. Further difficulties imposed by solar glare on the water surface and shadows. Restrictive legislation. Requires technical knowledge for analysis and interpretation of certain phenomena. Camera resolution can be a limiting factor.	[1,14,15,63]
Satellite images	Technique allows for multitemporal analysis. Enables large-scale investigations. Rapid data collection.	Cloud cover can generate missing data. Image availability limited to specific time periods. Limited in separating the riverbank from water boundaries (water level fluctuations).	[99,123]
Terrestrial laser scanning	Provides a high-resolution data set. Multitemporal analysis. Allows for the analysis of steep margins. Ability to collect large data sets quickly.	Equipment costs. Requires technical skills for GIS data processing. Limitations when scanning underwater topography, or measuring surfaces with dense vegetation.	[16,137]
Aerial laser scanning	Provides a high-resolution data set. Multitemporal analysis. Enables analysis in difficult-to-access areas. Helps detect margins that are the main sources of sediment. Ability to rapidly collect large data sets.	Equipment costs. Limitations for evaluating margins with sloping surfaces.	[27,40,80,130]
Dendrogeomorphological study	Rapid field survey and ability to measure erosion over comparatively longer periods.	Technique limited to areas with arboreal vegetation. Analyses depend on tree species. Lack of existing knowledge regarding how various species respond to root exposure.	[110,111]

4. Conclusions

Over the analysis period, there has been a significant evolution in the use of photogrammetry, with an emphasis on the use of images with high spatial resolutions, as well as new technologies, such as photogrammetry-based UAVs (i.e., drones) for measuring margin retreat. This technique also overcomes some limitations of classical photogrammetry, allowing for a more cost-effective method of analysis in terms of economics, technology, and processing requirements, as well as the ability to analyze photos taken from different positions. UAVs also offer a much better/more flexible temporal resolution than conventional imagery. The use of photoelectronic pins has also been consolidated, allowing for continuous erosion records, although they are notably less frequently applied than conventional pins.

There is consensus in the literature that the application of each technique is dependent on the characteristics of the study site, as well as the available resources for analysis; however, to overcome certain limitations, different techniques have been used for a combination of data, such as erosion pins for point analyses, laser scanning for spatiotemporal analyses, and aerial photographs for assist in the densification and classification of point clouds when filling gaps in laser scanning data.

The analysis of steep margins and dense vegetation is a challenge that is gradually being addressed via advancements in laser scanning and improvements in filtering techniques. The use of boat-mounted mobile laser scanning represents a promising technique for the orthogonal visualization of erosive processes and analysis of areas obstructed by vegetation. Novel research can be carried out focusing on topics that have not been addressed in the literature, including subaeroerosive processes, such as the direct impacts of rain on the removal of soil from the margin, and the influence of water content on soil surfaces. Such erosive processes can result in a significant cumulative impact but remain scarcely discussed due to the logistical difficulties surrounding continuous monitoring.

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