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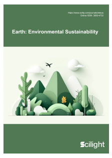

Review

The Sustainable Earth Screened through the Lens of Catchment Water Services

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Abstract: Water has shaped the Earth's surface into catchments that support a diversity of ecosystem services, such as water and nutrient cycling, soil formation and habitat. Besides supporting, catchments regulate services like flood attenuation and water quality improvements through organism-mediated chemical processes. Catchments are also the geosphere where the water is stored in lakes, wetlands, reservoirs or underground, to be later provided as service to the economic activities such as agriculture or industry, as well as to the humans as drinking water. Finally, catchments may incorporate unique landscapes that leverage recreational and cultural services targeting tourism and social well-being. But catchments are also the geographical domain where humans and meteorological agents dynamize ecosystem services though land use changes and climate shifts. Consequently, catchments are disturbed through amplified soil erosion, water balance reconfigurations, etc., and eventually adapt overtime, either evolving towards a pre-disturbance condition or towards new landscapes. Disturbance and adaption are research questions in the spotlight, with growing published literature on the subject. Thus, a review focused on the latest findings (last couple of years) is worth of consideration and was the motivation to write this opinion paper. While gathering relevant papers from the Science Direct, Web of Science and Scopus databases, we realized that current research essentially shows how disturbance and natural feedbacks of catchments challenge the sustainable physical Earth by shaking support, regulation and provision hydrologic services. Thus, using the PRISMA methodolgy we assembled papers on these dimensions and discussed their roles in separate sections. Key results retrieved from the reviewed articles (41 in total, including contributions from all the continents) comprised new methods of preferential flow and turnover times in the soil layer and concurrent impacts on stream flow generation, including intermittence analyses. Important results also comprehended global assessments of lake contamination related to urbanization, as well as reports about exacerbation of water-rock interactions caused by increasing temperatures and concomitant raise of stream water solute concentrations. A common headlight to most articles was reforestation as measure to improve catchment water storage and quality, with focuses put on catchment's physico-chemical processes such as infiltration, properties such as porosity or root development, and water yields, depending on whether the reviewed article was dealing with support, regulation or provision services, respectively. Articles on wetlands and climate shifts were not forgotten and exposed the need to expand mangrove systems to handle water purification in lowlands, as well as the role of mediation among competing interests to mitigate water shortfalls resulting from extreme and prolonged and prolonged droughts. We believe that, altogether, the findings reported in the selected papers and summarized in the discussion allowed a panoramic view over catchments as pools of cycling water and elements, as well as on the services and disservices they can be linked to.

Keywords: characterization and monitoring; forests; wetlands; revegetation; storage infrastructure; payments for ecosystem services

1. Introduction

The sustainable Earth requires catchments to function normally, whatever the concept of normality can represent. A key function of catchments is keeping the water cycle running, setting up the water balance components in the sequel. Anthropogenic action and climate shifts all over the planet have changed various components in the recent past, namely infiltration through urbanization, runoff via the exacerbation (frequency, intensity) of extreme events (floods, droughts) or through forest to agriculture and urban conversions, evapotranspiration in the course of deforestation or reforestation, among others [1,2]. The changes to the water cycle have impacted the cycle of elements, namely through increased erosion as well as surface and groundwater pollution [3,4]. Besides supporting multiple water services, catchments can regulate various of them. Key regulation services of undisturbed catchments include enhanced aquifer recharge and water erosion prevention (including of contaminants) in the highlands where they are typically covered by forests, but also flood attenuation and water purification in the lowlands where they are frequently occupied by wetlands [5,6]. The problem is that undisturbed catchments are a utopia these days, the reason why a growing number of papers on these topics focuses on nature-based solutions to bring catchments back to an undisturbed status [7]. The "golden" catchment water services are, however, the provision services, because they have a direct reflex on the functioning of economic activities (e.g., water supply to irrigation) and well-being of people (e.g., drinking water supply) [8,9]. Although they stand out from the rest, the provision services are fully provided by the catchments only if the formerly mentioned support and regulation services are not jeopardized. So, there is a close interaction among the three kinds of services, with continuous feedbacks between them.

The concerns about catchment water services brought into the spotlight in the last paragraph are all important when the background subject is a sustainable Earth, justifying a review to update these matters in the scientific literature. Thus, the general purpose of this study was to provide a review about catchment water services aligned with the contextual subject of Earth's sustainability. The specific purposes were to review relevant research papers, preferably published in the last couple of years (i.e., make a rapid review in the context of Randles and Finnegan [10]) and specifically addressing the following catchment water services: (a) support services; (b) regulation services; (c) provision services. After selecting scientific articles that addressed the aforementioned topics, the review discussed each one of them in its own section. On the other hand, the sections were presented in a specific order, which, to the authors' view, generated a smooth flow of information that will help the reader track the story straightforwardly. At this point, we also refer the novelty transported to the scientific literature by this rapid review. There is a growing number of papers talking about catchment water services from a diversity of standpoints, either focused on global- or local-scale problems, either touching one or all of its dimensions, either considering current or future land use and climate settings. However, to our best knowledge, a review of newly published papers addressing catchment water services from the Earth's sustainability standpoint is lacking. With the current study, we believe have produced a summary involving a scrutiny of innovative articles at the forefront of knowledge on this topic, which, with the alignment provided in this review, fill the aforementioned gap.

2. Methodology

The articles included in the review were compiled from the Science Direct ((https://www.sciencedirect.com/ (accessed on 6 June 2025)), the world's biggest database of articles that other scientists also use to perform reviews. It includes almost all journals that are indexed to the most well-known and reputable science rankings, like Clarivate's Web of Science (https://www.webofscience.com/ (accessed on 6 June 2025)) and Elsevier's Scopus (https://www.scopus.com/ (accessed on 6 June 2025)). In this study, the Science Direct database was searched using short, simple sentences that were designed to cover the three physical dimensions of topic "catchment water services". The sentences targeting the topics were: (1) "catchment water support services"; (2) "catchment water regulation services"; (3) and "catchment water support services". The three searches were executed separately, and the results of each search sorted by how relevant they were to the article. The fifty most relevant articles for each query were then checked again, which made a total of 150 articles. This extra analysis was done by hand. It tried to include in the review only studies closely related to the topic. These studies also had to present new methodological insights or important results. Further, they should have been published in the last couple of years (2024–2025 period), preferably. In the end, a total of 41 articles were included in the review and assessed for their contribution to the corresponding topic. Finally, we refer that the literature review followed the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [11,12], an approach used in many recent review studies [13–15]. Systematic reviews conducted this way comprise 6 steps: (1) scoping; (2) planning; (3) identification and search; (4) screening; (5) eligibility assessment; and (6) presentation and interpretation. Steps 1 to 5 were outlined above and are summarized in Figure 1, where some technical details about the Science Direct's database inquiries are included. Step 6 is presented in Section 3 (presentation of general information about the reviewed articles) and Section 4 (discussion of key findings and integrated analysis of outcomes from different but related articles).

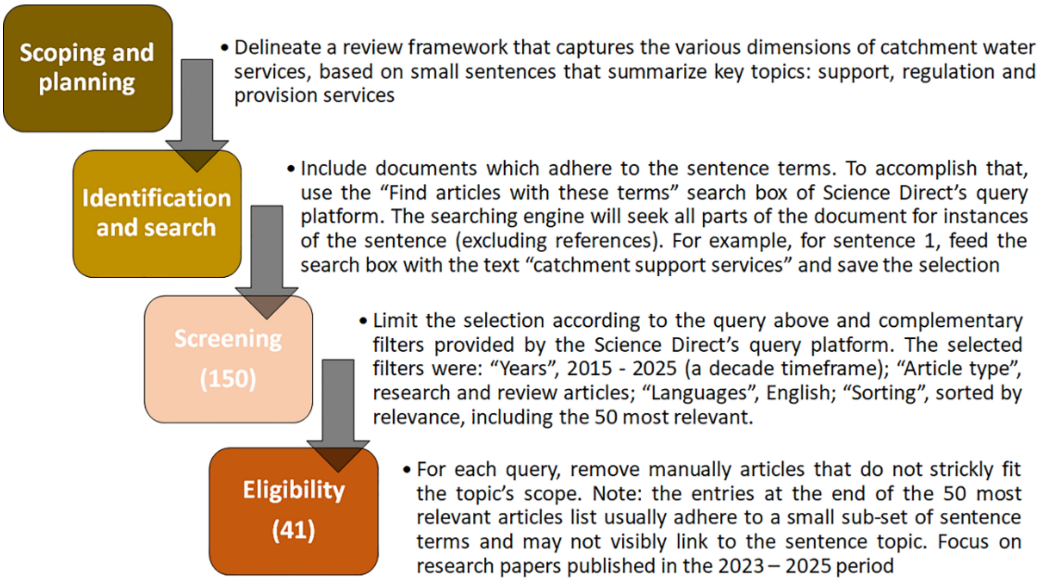

Figure 1. PRISMA workflow used in the selection of articles for the current review.

3. Results

The search results of papers to include in the current review about catchment water services are indicated in Table 1. The supportive data processing file is provided as Supplementary Materials in Excel file format. As deduced from the numbers in Table 1, the large share (83%) of papers was indeed published in the last couple of years. The seven papers published outside this period were three from 2023, two from 2022, one from 2020 and one from 2017, meaning all newer than one decade and mostly newer than three to five years. The studies were well distributed by the searched topics, namely 15 addressing support services, 16 regulation services and 10 provision services. Finally, all continents were represented in the review, with a predominance of studies conducted in Asia (18), followed by studies developed in Europe (7), Africa (6) and the Americas *s.l.* (5). Four studies provided global assessments.

The reviewed studies covered the three physical dimensions of catchment water services, namely support, regulation and provision services, spanning a diversity of topics. Despite the presentation in independent sections (Sections 4.1–4.3), the topics from the various dimensions overlap and therefore have connections and trigger feedbacks. For example, reforestation stood out among the topics of reviewed articles. However, the standpoints differed. Reviewed articles interested in the support services put the emphasis on the understanding of physical processes in the soil and the aquifer and how they support water services like stream flow. On the other hand, the articles dealing with the regulation services highlighted the physical and biological properties of soils developed underneath the forest stands, such as total porosity and root development, and especially how they regulate water quantity in the catchment through infiltration and recharge. Finaly, when the interest was on provision services the accent changed to the metrics of reforestation, i.e. to the answer of how much water can be kept in the catchment via reforestation? Overall, the reviewed articles form an integrated assessment of catchment water services and hence a robust and updated view about Earth's sustainability screened through this topic.

Table 1. Articles included in the rapid review of papers addressing catchment water services (support, regulation and provision) from an Earth's sustainability standpoint.

Year and Continent	Catchment Water Service			Total
	Support	Regulation	Provision	
<2024		**2**	**5**	**7**
Africa			1	1
Asia		2	1	3
Global			2	2
South America			1	1
2024	**10**	**6**	**5**	**21**
Africa	1		2	3
Asia	3	4	1	8
Australia	1			1
Central America	1			1
Europe	4		1	5
Global		1		1
North America		1		1
South America			1	1
2025	**5**	**8**		**13**
Africa	1	1		2
Asia	1	6		7
Europe	2			2
Global	1			1
South America		1		1
Total	**15**	**16**	**10**	**41**

4. Discussion

4.1. Catchments' Support Services

The most recent scientific literature has addressed the catchments' support services through innovative analysis on groundwater flow and geochemical cycles, as well as through reports of land use and climate change impacts on catchments' functions, including recovery assessments (Figure 2). Among the relevant papers interested on groundwater flow, the work of Kaffas et al. [16] stands out for its contribution about preferential flow in the soil and concomitant role in stream flow generation. Using weather and rain gauge stations, soil moisture probes, and stream gauges installed in two small catchments located in Tuscany (Italy), they detected sequential (from top to bottom) and non-sequential (from bottom to top) soil moisture profiles, the latter of which were related with preferential flow. Further, using a random forest machine learning model the authors quantified the contribution of preferential flow to the total stream flow to be in the range of 37.2–50%, in the dry season, and 29.6–37.5% in the wet season, relating these values with controlling factors such as antecedent (pre-rainfall event) soil moisture and bulk density (soil compaction) conditions. The work of Ying et al. was also relevant for the assessment of groundwater-surface water interactions, because the authors were able to design and implement a creative multi-proxy approach to assess groundwater—surface water connectivity in the upper, middle and low reaches of a shallow aquifer catchment located in Germany, in dry and wet periods [17]. The authors combined hydrometrics, geophysics, isotope tracers and geochemistry to confirm the presence of alluvial aquifers with shallow (<3 m deep) water tables where groundwater flows for no longer than 5 years, and to show how declining water levels since 2011 led to intermittent stream flows in the succeeding years. Overall, the results exposed the vulnerability of shallow fast-flowing unconfined aquifers to drought events and the necessity of detailed water resource management strategies to mitigate the situation in these sensitive catchments, such as evapotranspiration reductions via vegetation cover conversions. These strategies are particularly relevant in the tropical regions where high precipitation combined with high temperature generate thick soil layers in vast areas, which are shallow unconfined aquifers from the hydrologic standpoint. In the catchments hosting these aquifers, the stream flow ages are invariably short, ranging from hours to a few (<5) years as determined by Quichimbo-Miguitama et al. [18] in various catchments from Australia, Costa Rica and Ecuador ranging in area from 1.6 to 990 km^2 and in rainfall from 958 to 5117 mm/year, which exacerbate their exposure to drought events.

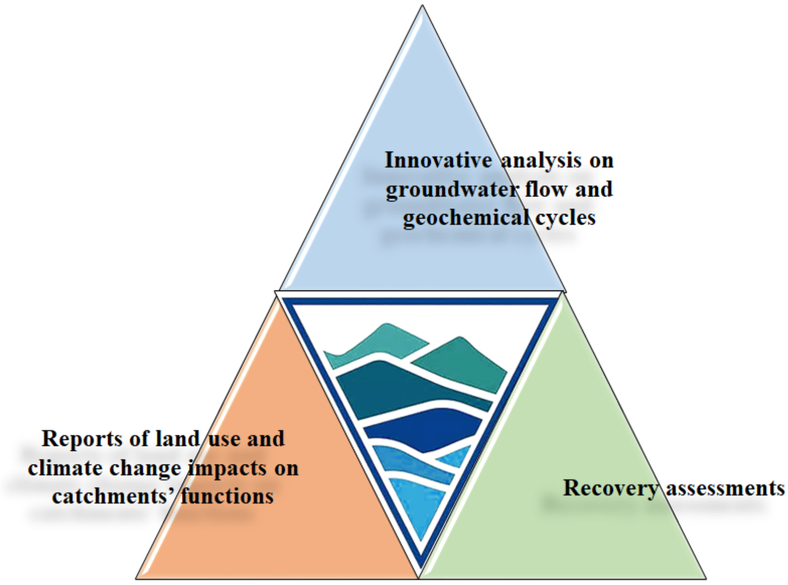

Figure 2. Key topics of recent scientific research on water-related support services.

The recent scientific contributions to geochemical cycles in catchments were mostly interested on showing how natural variations in the water cycle, either seasonal or interannual, affected the element distribution between the vegetation, soil, rock and water compartments. Among the published articles, the work of Wang et al. stands out for its very detailed analysis [19]. According to these authors, rainy periods rise the water table and set up connections between groundwater and the drainage network of hillslopes. The blooming groundwater wets the riparian forests and mobilize particles and solutes previously trapped in the vegetation, changing water quality. If the water table rises even higher, the groundwater becomes fully connected to the soil horizons and stream water receives contaminant loads (e.g., nitrate) washed off from the nearby agriculture and livestock areas. On the other hand, during the dry periods, the water table drops and shuts down the previously opened hydraulic connections. Stream flow becomes intermittent and restricted to riverbeds of larger streams where reduced oxygen levels may prevail. In those cases, redox-sensitive elements such as metals tend to mobilize from sediment particles into the aquatic phase affecting water quality. The assessment of geochemical cycles in catchments was also key to realize the support service of producing pristine groundwater, regarded as water with dissolved elements sourced from water-rock interactions. In this context, the work of Renzo et al. used geologic mapping and hydro chemical modeling to illustrate how the weathering of evaporite, carbonate and dolomite rocks developed $Ca\text{-}SO_4$, $Ca\text{-}HCO_3$ and $Ca\text{-}Mg\text{-}HCO_3$ facies, respectively, in the groundwater from the Pordenone Plain of Northeastern Italy [20]. Hydro chemical signatures were also assessed in the Chinese Loess Plateau, where Liu et al. used mass balance models to link the $Mg\text{-}Ca\text{-}HCO_3$ facies in this region to weathering of silicate rocks [21].

The disruption of water and geochemical cycles by anthropic and climate action is evident across the globe for decades, and for that reason continues rising the attention of academics, water resource management institutions and the general public. The recent scientific literature on water cycle disruptions caused by human action was particularly concerned with the support of natural ecosystems by environmental flows, and with the influence of man-created hydrologic connections (e.g., ditches, roads, industrial activity) on the surface water flow and transport of eroded materials. Important contributions are summarized in this review. One is the work of Mengistie et al., who estimated environmental flows to represent 31% of the mean annual flow in the Big Akaki catchment of Ethiopia, and revealed unmet scenarios caused by excessive demands by the urban supply and crop irrigation [22]. The unmet flows reached > 50% in the worst cases but, according to the authors, could be mitigated through catchment-wide water resources management based on mediation of competing interests, because the catchment's annual surface water potential exceeded the global water demand. The study of Kaptein et al., on the other hand, assessed the impact of plantations on the stream flow, in the KwaZulu-Natal province of South Africa where *Acacia mearnsii* and *Eucalyptus dunnii* are used as source of various wood products [23]. In particular, these authors were interested on the effect of tree age on the stream flow, and concluded that afforestation with mature trees impacted more the stream flow than with younger specimens, because the leaf area was larger in the first case raising interception losses and hence reducing effective precipitation and ultimately the stream flow. The impact of human action on the hydrologic connectivity of catchments and consequences derived therefrom was discussed in the works of Zhao et al. [24] and Barbosa-Briones et al. [25]. In the first case, the authors modeled flow connectivity in a terraced watershed used for rice production located in the Honghe Hani Rice Terraces World

Heritage Site of China. They ran the model with and without incorporation of roads and man-made ditches and concluded that roads impacted lateral flows rising landslide risk and road instability in high connectivity areas. Moreover, man-made ditches impacted lateral as well as longitudinal flow allowing more effective distribution of catchment water among rivers, reservoirs, and farmland. Nevertheless, soil-built ditches were revealed prone to ridge collapse and hence a source of increased soil erosion. In the second case, the authors showed how the destruction of vegetation around the mining areas of Cerro de San Pedro and Villa de la Paz located in Mexico, increased the catchments' hydrologic and sediment connectivity amplifying the potential of erosion and sediment delivery to downstream areas. The disturbance of geochemical cycles by the human kind was also addressed in the recent scientific literature, which alerted for the global problem of lakes. For example, Caroni et al. used remote sensed data retrieved from the European Space Agency Climate Change Initiative to reveal a positive correlation between increased chlorophyl-a and turbidity concentrations in 349 shallow lakes (depth < 3 m) distributed globally with increased population and gross regional product around the lakes [26].

Climate variations are also a source of water and geochemical cycles disturbance addressed by the scientific community through publications. The research focus in the last couple of years was put on the effects of more frequent and prolonged droughts on the hydrodynamics of catchments and composition of stream water, as well the impact of increasing temperatures on the weathering of rocks and consequent export of elements from catchments to the sea. In that regard, the monitoring of Girnock Burn catchment (Scotland) for 17 years conducted by Stevenson et al., showed a clear shift from high flows sourced by young (<0.5 years) atmospheric solute composed (Na^+, Cl^- SO_4^{2-}) shallow groundwater, towards low flows sourced by weathering product composed (Ca^{2+}, Mg^{2+}, SiO_2) older (> 3 years) groundwater, over the period [27]. The study of Sun et al., on the other hand, conducted in the Artic's Lena River, showed how temperature rises over the past 20 years have doubled the total inorganic solids exported to the sea and derived from carbonate, silicate and evaporite rock weathering, which reached 112 Tg/yr in 2015 [28].

The reset of ecosystem's functioning after catchment restoration through afforestation projects has been investigated in the past two years to shed light over their efficacy. The research groups were mostly interested on evaluating the projects' benefits for soil functions like infiltration and water retention capacity. The current review included two important monitoring studies of Xu et al. conducted in China after the implementation of reforestation projects around the Three Gorges reservoir [29,30]. The reforestation strategies were planted forests, naturally regenerated forests and deforested pastures. In the two studies, the results were clear about the more effective use of naturally regenerated forests in the restoration projects, as they ensured improved cumulative infiltration during storm events and hence increased soil water storage and resilience to seasonal droughts.

In summary, the recent literature on catchment support services provided new and important insights about preferential flow in the soil and concomitant role in stream flow generation, improved the understanding of shallow aquifer dynamics, namely about turnover times and stream flow intermittence with effects on droughts, and moved forward the knowledge on how catchments dynamize the chemical evolution of rainwater into groundwater through water-rock interactions. Besides advancing knowledge on catchment functioning, the relevant literature on catchment support services published in the recent past (mostly the last couple of years) have also concerned about catchment disturbance. Important contributions in this regard were interested on measures to keep or restore environmental flows capable of supporting the natural ecosystems, namely through mediation of competing interests and selection of adequate species in the context of reforestation programs. In addition, attention was given to the disturbance of hydrological connectivity by man-built infrastructure and consequences derived therefrom, such as exacerbated erosion and sediment delivery into surface water bodies, as well as disturbance of geochemical cycles caused by urbanization with consequences for turbidity and chlorophyl-a levels of lakes globally. A third viewpoint of recent scientific literature on catchment support services was the role of climate change. The working questions were now about how changes in precipitation and temperature are affecting the water cycle. The answers were as expected, for example that climate shifts are intensifying extreme events of water scarcity and may be feeding rivers with more concentrated water derived from enhanced water-mineral reactions. A final look was put over catchment restoration, whereby publications reporting the results of monitoring programs conducted after the implementation of reforestation programs unequivocally concluded that naturally regenerated forests behaved better as regards the recovery of infiltration and soil water storage, relative to planted forests, with benefits for drought resilience. Taken together, the recent studies on catchment support services stepped on various important hydrologic and geochemical routes and shed light over relevant issues, namely catchment functioning, disturbance, role of climate and restoration.

4.2. Catchments' Regulation Services

The most recent studies tackling the topic of catchment regulation services move around two central domains: the source areas of watersheds and their role as safeguards of regulation services such as aquifer recharge and water quality preservation through forest occupation, and the catchment outlets as keepers of flood mitigation and water quality purification through wetlands. A smooth transition between the two domains, via an undisturbed well-managed intermediate sector, is seen as ideal model for a naturally regulated watershed (Figure 3).

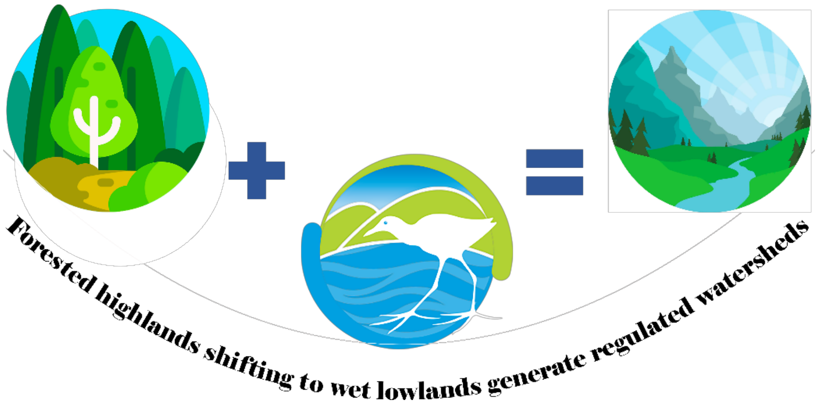

Figure 3. Dominant vision of recent scientific research on catchment regulation services. The concept illustrated in the figure, of coupling forested highlands with wet lowlands to get a regulated watershed, applies to undisturbed catchments. A definition of undisturbed catchment could be those that preserve forests in the source areas and wetlands in the catchment outlets, but also those where the human occupation and activities, which usually concentrate in the region between the source areas and the outlets, do not deregulate the catchment's hydrological functioning and do not impact the quality of water.

Forest ecosystems are unequivocally spaces of good water quality, as documented in numerous studies. For example, Jaikawna and Pagdee correlated the increase of forest lands in the Pong River Basin located in Thailand with higher concentrations of dissolved oxygen in stream waters, and simultaneously the increase of farmlands with higher levels of fecal coliform bacteria [31]. Another study, conducted by Xintong Cui et al. in the Tumen River Basin located in China, showed how nitrogen losses from forests, especially during rainfall events, are mostly organic (litter) and hence have limited impact on stream water quality, while losses from farmlands occur in the form of nitrate, which means dissolved in the water column of streams and likely impactful to downstream lakes or reservoirs through eutrophication [32]. Finally, Dou et al., while working in the Yellow River Basin (China), showed how the aggregation of grassland patches has an inhibitory effect on the propagation of nitrogen and phosphorus contamination from farmlands during extreme rainfall effects [33]. These three examples highlighted the role of forests on the regulation of stream water quality, meaning that reforestation can help catchments to reset this regulation service. Some recent studies documented how catchment restoration strategies through reforestation coped with stream water quality improvements. One is the work of Oliveira et al. conducted in the Vale do Paraíba do Sul basin (São Paulo state, Brazil), where the authors investigated the relationship between water quality and various pastureland to forest conversions [34]. The authors identified a gradient of water quality improvement, ranging from degraded catchments dominated by pasture, to catchments with forest remnants around springs and pioneer vegetation in riparian buffers, to more conserved catchments with young and old forest restoration and old-growth forests.

Forested ecosystems are also documented safeguards of enhanced soil water infiltration and aquifer recharge. For example, the detailed study of Liao et al. conducted in the Huanjiang County, Northwest Guangxi, Southwest China, revealed a cumulative total infiltration (CTI = 380–3152 mm), as well as preferential flow infiltration (PFI = 176–2755 mm; representing 42.8–82.4% of CTI), following the sequence: woodland > orchard land > abandoned land > secondary forest land > cultivated land [35]. On the other hand, the cumulative matrix infiltration (CMI = 169–268 mm) followed the sequence: cultivated land > woodland > secondary forest land > orchard land > abandoned land. The authors related the sequences and the differences among them with variations in the total porosity of soils developed underneath the various land use types, complemented with tillage at the cultivated land that improved matrix infiltration in that environment. On the other hand, total porosity and pore characteristics that allow preferential infiltration to occur are usually determined by plant root development, as documented in the experimental work of Zhu et al. [36]. Thus, the large preferential flow infiltration of woodlands and secondary forest lands observed in the work of Liao et al. can be mostly justified by macropores created in these environments by well-developed root systems, while the large matrix infiltration of cultivated land is mostly explained by well-developed texture, structure and organic matter influenced by tillage. The soil physical properties that affect infiltration and water storage capacity of forested ecosystems are also dependent on the forest type. In the work of Zhang et al. developed in the Dinghushan Biosphere Reserve located in Zhaoqing City, south China, the results were clear: broadleaf forests showed 2 to 3 times larger infiltration rates than pine forests, which were supported by corresponding larger hydraulic conductivities likely linked to differences in the root systems [37]. As mentioned for the water purification service of forests, the results of characterization and monitoring studies discussed above show that reforestation can help catchments to regain the regulation service of infiltration and recharge. And that has indeed been documented. For example, in the study conducted by Wang et al. [38] in the Laotudingzi National Nature Reserve of Liaoning Province (China), forest restoration was implemented with planted and natural secondary forests. The results showed that both reforestation strategies confirmed the development of preferential flow infiltration, and that differences among the studied sites were mostly explained by variations in the soils' total porosity and root volume development, with some share by clay content. It is worth mentioning, however, that real-world catchments are frequently threaten by land use conversions that reduce infiltration instead of increasing it. An example was documented by Zhu et al. [39] in the Dabie mountainous area (China) following the conversion of natural to economic forests. The authors showed significant decreases in the initial, average and steady infiltration rates in the range 35–76%, caused by that conversion.

Wetlands are unique environments for their capacity to regulate and provide services in the multiple geospheres, namely the atmosphere through carbon sequestration, the hydrosphere through flood and drought mitigation as well as stream water purification, and the biosphere through providing habitat and food to an ample variety of fauna and flora. The role of wetlands in stabilizing the environment has been discussed for long but continues advancing with recent publications, mostly because wetlands are shrinking and degrading worldwide in the course of climate change and anthropogenic pressures, and scientists want to understand the big picture and predict and protect the future. Global wetland conservation has recently been assessed by Yi et al. [40]. As regards the mitigation of floods through management of wetlands, various recent studies relied on the creation of scenarios whereby rejuvenation of existing or settlement of new wetlands are anticipated and the corresponding effects on flooding evaluated. Authors like Enu et al. and Donnelly et al. worked the scenarios in the urban environment and agricultural systems, respectively, while others like Gupta et al. or Wu et al. did it at the river basin scale [41–44]. In the work of Enu et al. [41], the authors integrated spectral indices retrieved from satellite imagery (e.g., MNDWI) with hydrologic modeling based on the TELEMAC-2D software, to forecast how floodplain restoration and new wetland creation would affect the duration and intensity of floods in the rapidly urbanizing Greater Kumasi Metropolitan Area located in Ghana. One scenario combined floodplain restoration and wetland creation and achieved peak flow reductions of 16–19% in prolonged storms. A second scenario predicted full floodplain network restoration and reduced peak flows by 24% in short-duration events. Finaly, the scenario of wetland creation in available spaces yielded reductions of 1–3%, which are marginal and thereby underscore the limited efficacy of space-dependent approaches and the paramount importance of spatial targeting. In the work of Gupta et al., the scenarios aimed to help managing flood-risk in the Brahmaputra River basin (area > 600,000 km^2) located in Meridional Asia, which is affected by monsoon climate [43]. Wetlands in this basin may fill their maximum volume early in the monsoon season losing their flood-regulation capacity in the sequel, especially because over the last two decades they have shrunk by nearly 25% and reduced their depth by 1 to 3 m in the course of soil erosion, anthropogenic encroachments, and farming. Thus, the proposed scenario consisted of rejuvenating wetlands through interventions that would restore their area and depth to original values or close. In complement, a precautious water release would be implemented for a threshold precipitation, to improve the wetland storage capacity immediately before heavy rainfall events. The modeled results revealed peak flow reductions of 30% at the outlet of rejuvenated wetlands and threat flow reductions of 60% around the major cities within the basin. This is a remarkable achievement for a large-scale watershed hosting millions of people.

The role of wetlands in the purification of inflowing waters has a longstanding acknowledgement. However, scientific contributions to this topic remain at the spotlight because wetlands are degrading worldwide and, unfortunately, they are not sufficiently integrated in the political and investment agendas of governments. Attention of recently published papers has been given to wetland contamination through atmospheric microplastic deposition [45], but especially to coastal areas where pollution has exacerbated in the course of urban and industrial concentration, land reclamation for aquaculture development, among other factors. In coastal areas, mangroves are wetland ecosystems that regulate pollution derived from human presence and activities, but have been severely threaten in the last decades. The study of Rahman et al. conducted in China showed how heavy metals such as Cd, Cr, Mn, Pb, Hg, and As impacted the health of mangroves across the country, hampering their capacity to detain from biotic and abiotic stressors [46]. Firstly, these metals accumulated in mangrove sediments, thereby clogging the physiological and biochemical functioning of mangrove species. Secondly, the excessive bioaccumulation of these contaminants in the mangrove diversity extended all over the food chain, potentially damaging marine organisms and human health in the sequel. The authors recognize the efforts of policy and industry to reduce the emissions at the source, as well as natural adaptions and phytoremediation mechanisms of mangrove species like limiting metal uptake, excreting metal binding proteins, among others. They both avoided the mangrove ecosystem from being completely compromised. However, they are not enough to keep their regulation role in the long-term, because the pace of pollution is overwhelming. In the view of Rahman et al., only the implementation of restoration and mangrove expansion projects can offer a promising and durable solution to rise the eco-resilience of these ecosystems [46].

In summary, recent scientific literature on regulation catchment services reported new case studies about restoration of highlands through reforestation programs. In general, these enterprises led catchments to enhanced water quality manifest through higher levels of dissolved oxygen, lower levels of organic contaminants, among other enhancements. In addition to water quality issues, recent papers addressing the regulation of water services in the source areas of watersheds, highlighted the role of forests in improved preferential infiltration triggered by total porosity of soils developed underneath the trees and better developed root systems, especially in broadleaf forests. The recent literature did not bring new issues to the aforementioned research topics, but advanced substantially in the methodological approaches. Now, the mainstream research is based on remote sensed data and hydrologic models coupled with artificial intelligence optimization and prediction algorithms, which bring detail to the results in the spatial and temporal domains. Moreover, the datasets are progressively available in higher spatio-temporal resolution. Taken together, the outcomes from recent studies are more reliable and workable by the stakeholders, allowing a smoother confluence between science and decision-making. And that is a remarkable achievement. With focus on wetlands, on the other hand, the current research dedicated efforts to simulate the benefits for flood mitigation, of creating or rejuvenating these systems, at various scales and spanning various meteorologic settings as well as urban and rural environments. It also alerted for the loss of capacity of mangroves from many coastal areas, to regulate metal and other kinds of pollution (e.g., microplastics), because the pace of contamination is overwhelming. The general perception is that mangrove expansion is the best route to mitigate the problem, but that will depend on political awareness and action.

4.3. Catchments' Provision Services

The recent scientific literature on catchment's provision services is abundant and diverted across characterization, anthropic- and climate-related impacts, benefits from catchment restoration, and economic issues including payments for water services (Figure 4). Some studies tackled more than one topic. For example, the study of Sumarga et al. conducted in the Watuputih groundwater basin, located in the North Kendeng Mountain (a karst system in Indonesia), identified the Sumber Seribu, Brubulan and Kalutan springs, which discharge 1080, 85 and 0.76 L/s, respectively, representing 34.06 billion L/year of freshwater resources [47]. This volume is mostly used for irrigation of paddy fields (93%), the remaining 7% being used to supply households. The catchment seems to provide enough water for these needs, but the authors were concerned with limestone mining activities, which reduce infiltration to residual values, threatening spring water discharge rates in the long-term. For that reason, they suggested converting the basin into a water catchment or geological protection area, and cumulatively implementing payment for water services programs that would help communities living in the service provision area to actively protect the karst ecosystem. Another important assessment of water provision services was published by Ebrahim et al. [48] while working in the Shashe catchment located in the Limpopo River Basin (Botswana, and Zimbabwe). The authors described the catchment as highly seasonal relative to rainfall and hence stream water availability, which induce recurrent shortfalls (demand exceeding the availability). Building on this reality, they assessed water storage across various sources, namely: 42,000 mm^3 in aquifers, 1500 mm^3 in the soil system, 700 mm^3 in dam reservoirs, 45 mm^3 in ponds or weir's reservoirs, and 0.13 mm^3 in sand dams. Besides, they evaluated seasonality of storage across these sources and suggested optimizing the use from them to improve water availability and resilience to climate.

The largest share of recent scientific studies interested on catchment water provision services describes impacts to supply, either caused by anthropic action or related with climate variations. This is not surprising because provision of water services is recognized to suffer multiple threats from fast-growing and environmentally uncontrolled societal development. For example, Eekhout et al. projected threats to water security in the Campo de Cartagena catchment (1280 km^2) located in the South-East of Spain, namely if future development follows the SSP5-8.5 shared socioeconomic pathway (Fossil-fueled Development) [49]. The scenario was proposed by the authors to anticipate a shift from rainfed to irrigation agriculture, aiming the increase of crop yields. However, the irrigation water demand in this case would increase from 199.8 hm^3/year to 279.4 hm^3/year (+39.8%), mostly supplied by increased groundwater abstraction, watershed transfers, and use of desalinized water. Thus, allowing the society to follow the SSP5-8.5 in that region seems challenging for water security, besides being implemented at high economic and environmental costs, nonetheless the food-security purpose. The pressure of water demand on water security was also emphasized by Dlamini et al. [50] in their study of Buffalo River catchment located in KwaZulu-Natal (South Africa). The catchment covers an area of 9803 km^2, being characterized by 1465.8 mm/year of evaporation, 801.6 mm/year of precipitation and just 89.7 mm/year of runoff. The supply of water resources to domestic, agriculture and industrial uses is ensured by a storage infrastructure capable to provide 136.9 mm^3/year. However, the historical demands are close to 185 mm^3/year leading to recurrent shortfalls. A simulation of future water availability and demand based on the RCP8.5 scenario from CMIP5 projected an increase in the catchment's water availability to 287.5 mm^3/year accompanied by an increase in the demand to 250 mm^3/year, by 2100. So, in the long-term, a perspective of shifting the availability-demand balance from negative to positive exists, because by 2100 the expected surface water availability will exceed the corresponding water demand. However, the shift will only occur if adjustments are also made to the storage capacity, namely through construction of micro dams, ponds or check dams.

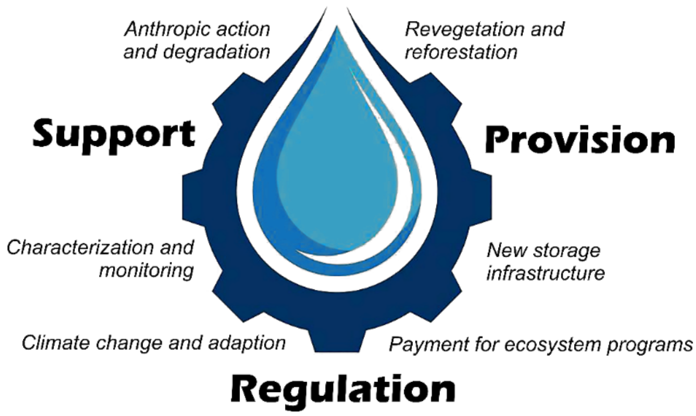

Figure 4. Research trend of recent scientific literature on catchments' provision water services: integration and feedbacks with support and regulation services, with main topics focused on service characterization, human- and climate related impacts on their long-standing maintenance, sustainable economic implementation through payment for ecosystem services programs, among others.

Construction of infrastructure is the anthropic pathway for increasing water availability in the catchments. The natural route is through reforestation or re-naturalization, but the outcomes of reforestation depend on the species used and many studies reported decreases of availability instead of increases [51]. For example, Li et al. modeled the provision of freshwater in the Yellow River Basin (China) after the implementation of a large revegetation program (the Grain for Green Program) [52]. The modeling exercise spanned the 1958–2014 period and the results were clear: the freshwater availability (assessed by a freshwater provisioning index) decreased by 11.9% in the upper part and by 3.6% when the entire basin was considered. The reason was mostly ascribed to increased evapotranspiration losses from new planted vegetation. Similar results were obtained by Yohannes et al. while modeling the Akaki River catchment, which is a tributary of Awash River basin located in Ethiopia [53]. The modeling framework involved a business as usual and a forest patch protection scenario, which ran in the 2021–2051 period. In both cases, the forested areas increased during that timeframe, but the growth was larger in the second (66.4%) relative to the first (42.6%) case. Starting from a baseline yield set up at the year of 2021 (6707 m^3/ha), the business-as-usual scenario showed an increase to 6996 m^3/ha by 2051, while the patch protection scenario showed a decrease to 6667 m^3/ha. In both studies, the authors concluded that reforestation may not improve provision water services as could be whished. Studies describing hydrologically successful restoration projects are in fact rare, but the existing ones refer the use of native trees plantation and natural regeneration as key ingredients for the success [54]. It is worth mentioning, however, that reforestation programs usually target several ecosystem services besides provision water services, such as soil erosion / sediment export reductions, flood control and carbon sequestration improvements, among others, in which cases the results of previously mentioned studies have confirmed the optimistic expectations, like improved carbon sequestration [51–54].

The execution of revegetation programs frequently represents a suppression of areas used for production purposes, namely food production. Consequently, it is expected a certain loss of income by landowners who decide or are encouraged/enforced to convert land uses within their properties [55], like converting monocultures into agroforestry systems to restore water yields and quality. As compensation for this loss, payments for ecosystem services (PES) programs can be implemented. The compensation is a monetary incentive to cover the conversion costs, which must be parsimonious and have a limited timeframe. There are PES programs for all sorts of services, including for restoring water availability in catchments. In the last couple of years, studies addressing this topic were interested in prioritizing areas for revegetation within the studied catchments considering the limited financial resources allocated to the PES programs. One study directly related to the provision of water services occurred in the Jacaré-Guaçu River basin (area: 4172 km^2), located in the state of São Paulo (Brazil). The work was conducted by Anjinho et al. [56] and spanned the 1985–2019 period. In this period, the basin experienced significant land use and cover changes, namely increases in the agriculture area (from 975 to 2112 km^2; 27% increase) and concurrent reductions in the pastures (from 2136 to 931 km^2; 29% decrease). As consequence, the runoff increased from 128 to 154 mm/year (17%), being accompanied by increases in sediment export (from 25,920 to 39,087 ton/year; 33%) as well as in nutrient exports (nitrogen: from 471,413 to 571,889 kg/year, 17.5%; phosphorus: from 55,239 to 84,690 kg/year, 35%). Conversely, the catchment's baseflow decreased from 279 to 202 mm/year (27%). To revert the situation, meaning reduce erosion and restore the baseflows, a planned use scenario was elaborated based on the conversion of nearly 10% of agriculture area into natural vegetation. The simulated results revealed sediment exports reducing by nearly 65%, and phosphorus and nitrogen exports declining by 60 and 49%, respectively. Finally, the surface flows decreased by 2% and the baseflow increased by 4%. Overall, the simulation results showed that revegetating the area would significantly contribute to reduce erosion and pollution in the river basin, but the replenishment of aquifers to restore the baseflow would require additional measures.

In summary, the catchment provision services benefit or are negatively impacted by the good- or malfunctioning of support and regulation services, respectively. The reviewed recent publications revealed impacts for spring discharge of mining that affected agriculture and public water supply. They also showed how integrated use of various sources can help mitigating the effects of prolonged and recurrent water shortfalls in arid regions. In this regard, some studies simulated availability and demand under various socio-economic development scenarios, while others addressed the need to expand storage infrastructure to prolong water resources availability in time, preferably through natural-based solutions such as reforestation programs. Repeatedly, the authors alerted that is key to success the selection of native species to prevent unwanted decreases of water yields, instead of increases. A last topic discussed in the recent scientific literature about provision catchment water services was the payments for water services, as financial incentive to help activities conducted in headwater catchments, namely monoculture agriculture, to shift towards variants where forest stands are included to promote the recovery of water yields and quality. The financial contribution, to be provided by water users, water resource management institutions or specific programs, should be time-limited and the water enhancement results monitored, to keep the contribution as incentive and not as a regular parcel of income. Overall, the reviewed studies showed that managing catchments to bring or keep them under normal functioning, whereby water services are provided to the society and future generations with no interruption, is a multifaceted never-ending enterprise that the human kind needs to embrace if the ultimate objective of its presence on Earth is to preserve its habitability. The future will tell.

5. Unresolved Issues and the Prospect of Future Scientific Research

A number of pivotal issues persist as unresolved uncertainty with regard to catchment water services. The worries include the effective management of trade-offs between upstream and downstream users, the assurance of equitable access to water resources, and the integration of natural capital thinking into water resources management. Furthermore, there is a paucity of consensus regarding the long-term ramifications of diverse interventions on water quality and quantity, and the optimal methodology for implementing integrated water resource management approaches [57,58].

The balancing of upstream and downstream interests involves incentive divergences and trade-offs in land use practices. In the first case, the question that rises is that catchment management frequently triggers a divergence of interests between upstream landowners and downstream water users. And the problem to solve is how policies and economic scenarios can be designed to ensure that interventions benefit both groups without compromising the long-term distribution of benefits. In the second case, the issue is that land use practices do not invariably correspond with the objective of sustainable water management. And the problem needing solution is how these trade-offs can be managed effectively to ensure both economic viability and the protection of ecosystem services. The concerns about the assurance of equitable access to water resources spans various specific issues: water metering and pricing, water transfers and recharge, water quality impacts. The unresolved questions in this case may be put this way: How can universal water metering and efficient pro-poor water pricing be implemented to promote water conservation and efficiency, while also ensuring access for all? What are the possibilities and challenges of using water transfers and artificial recharge to strategically sustain aquifers, particularly in the face of climate change and increasing water demands? How do poor water quality and subsequent environmental impacts affect the well-being of local populations? Finally, the integration of natural capital thinking into water resources management faces the following challenges: mainstreaming green solutions, natural capital thinking, and investment in green infrastructure. In more detail, the first challenge relates to the resistance of mainstreaming effective environmental solutions like wastewater treatment plants and desalination, instead of keeping them niche technologies. The second challenge hinges on the struggle to embed capital thinking into the water industry to ensure that green solutions are considered a legitimate alternative to traditional "end-of-pipe" solutions. And the third challenge derives from the resistance to use green and private investments more effectively to support sustainable water resources management, including ecosystem restoration and nature-based solutions.

The governance issue of implementing integrated water resources management approaches comprises a diversity of challenges. Firstly, catchment partnerships must be revisited to ensure success in achieving multiple objectives at once. Secondly, watershed management must be reinvented to address the problem of long-term spatiotemporal evolution of catchment water quality under the persistence of pollution sources. Thirdly, management plans must adapt to capture hydrologic and ecologic responses under rapidly changing environmental conditions.

Taken together, the aforementioned unresolved questions and governance issues confronting the field of catchment water services, highlight the need to push scientific research forward. It is of paramount importance that further research and innovation be undertaken in order to address them and others to come, to ensure the sustainable management of our water resources.

6. Conclusions

This study reviewed 41 publications in the forefront of knowledge about catchment water services, mostly published in the last couple of years and representing contributions from all the continents. The reviewed articles contained methodological innovation, important results or global assessments on the three physical dimensions of catchment water services—support, regulation and provision services, framed in the context of Earth's sustainability.

The key findings of reviewed articles with regard to support services, comprised a better understanding on the relationships between preferential flow in the soil and stream flow generation, and between shallow aquifer turnover times and intermittent stream flows, and had the ultimate purpose of advancing drought management. In addition to shed light over these catchment functioning issues, the reviewed articles tackled a number of topics related to catchment disturbance processes and their handling. These topics included the mediation of competing interests and selection of proper species in the context of reforestation programs, to succeed in ensuring environmental flows and ecosystem integrity. The assessment and disturbance of geochemical cycles at the catchment level was also in the spotlight. In this regard, some articles described water-mineral interactions and concomitant evolutionary pathways of water composition from rainwater towards groundwater, while others analyzed the global effect of urbanization on lake contamination via increased levels of turbidity and chlorophyll-a. Finally, with no surprise, reviewed articles addressed climate shifts and how they affect catchments via the intensification of extreme events and exacerbation of water-rock interactions with concomitant raise of stream water solute concentrations, as well as catchment reforestation programs and the important role of native vegetation for the success of expected improvements in infiltration, soil water storage and aquifer recharge.

The articles which addressed catchment regulation services also had a strong focus on reforestation programs, but now the emphasis was not on the understanding of catchment physical processes and how they support water services like abundant and good quality stream flow. Rather, the prominent viewpoint was how physical and biological properties of soils developed underneath the forest stands, such as total porosity and root development, promote water quantity through improved infiltration and water quality through enhancement of parameters like dissolved oxygen. In these studies, the benchmark was the use of remote sensed data compiled from big data sources and processed with artificial intelligence algorithms. Other studies moved attention from the source areas of catchments, where reforestation programs typically occur, to catchment outlets occupied with wetlands. In these studies, the analyses of regulation services covered the topics of flood mitigation and water purification in mangroves, especially in coastal areas.

The discussion on catchment provision services completed the current review, and was presented after the other two topics because provision services benefit or are negatively impacted by the good- or malfunctioning of support and/or regulation services, respectively. The key findings covered reports and simulations of supply-demand balances, especially in arid regions where prolonged water shortfalls are recurrent, and how nature-based solutions like reforestation programs properly implemented with native species can mitigate the unbalanced situations. Again, reforestation was the headlight of catchment water services assessment, but now the crux were the metrics—How much water can be kept in the catchment via reforestation? As corollary to this question, some reviewed articles discussed concurrent governance problems like payments for water services (PWS). Reforestation or other land use conversion projects aiming at raising the volume of water stored in catchments has a financial cost. The question is: who is going to pay and how and why? In that regard, reviewed articles reported new methods and pilot applications focused on PWS, which are worth of replication.

In spite of being a review with a substantial contribution to the understanding of catchment water services, some relevant topics were missing, either because they escaped our search or did not develop in the last couple of years. The missing topics comprise the effective management of trade-offs between users, ensuring universal access to water and integrating natural capital thinking into water resources management.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2509121535578959/EESUS-2508000062-supplementary.zip.

Author Contributions

F.A.L.P: conceptualization, methodology, software, data curation, writing—original draft preparation; L.F.S.F.: visualization, investigation, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

This is a review paper with no data or statistical reporting, besides the information and analysis of all reviewed papers.

Conflicts of Interest

The authors declare no conflict of interest.

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