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Review

Impounding Reservoirs, Benefits and Risks: A Review of Environmental and Technical Aspects of Construction and Operation

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Abstract: The operation of multi-functional reservoirs, together with their benefits and risks, is a complex issue. The scientific and social discussion has been burgeoning recently, and all the more so as no planning and technological solutions for the realisation of storage reservoirs have yet been worked out that could represent a universal approach, assuming ecologically and socially sustainable operations, maximising economic returns and supporting the development of the region concerned. Although the creation of each reservoir facility involves different engineering and environmental considerations, this article attempts to isolate the key benefits of impounding reservoirs and to summarise the risks associated with their operation, considering flood protection, retention, environmental and social aspects and water quality. Based on a review of the scientific literature for each of these aspects, various sub-categories representing intensively developing sectors of research were distinguished, and the published results were used to formulate a register taking into account the spectrum of impact of a given factor and a proposal for remedial action. As a basic conclusion of this review, it can be pointed out that the current development of scientific research, technological progress in hydrotechnical engineering and information technology, as well as advanced data analysis capabilities, provide the basis for developing sustainable solutions to avoid or mitigate the negative impact of all the identified risks. In addition, remedial measures in the catchment area and the reservoir should be taken on board to counteract the negative effects of reservoirs. The results presented can be a valuable source of information for institutions responsible for the planning and implementation of investments in the construction of multi-functional reservoirs.

Keywords: multi-functional reservoirs; flood protection; retention; water management; environmental impact; social impact; water quality

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1. Introduction

Although water occupies most of the planet's surface, freshwater accounts for about 2.5% of the total, of which only a small proportion is a source of drinking water. In addition to domestic use, water is a key raw material used for manufacturing and industrial purposes, for energy, and is essential for the proper functioning of agriculture and forestry [1–4]. It should also be stressed that water resources are not evenly distributed and are often not managed rationally either. The Food and Agriculture Organization (FAO) reports that the total annual freshwater withdrawal in the United States is approximately 440 million m^3, compared to 12.5 million m^3 and 0.7 million m^3 in Nigeria or the Democratic Republic of Congo, respectively. Considering climate change, rising global temperatures and the increased frequency of extreme atmospheric phenomena, countries in Africa and Asia in particular are experiencing reduced levels of water safety, a particularly worrying circumstance given the growing number of people on these continents and the estimated 60% increase in food demand by 2050 [5]. It is, therefore, necessary to place emphasis on counteracting water scarcity through a series of measures resulting in increasing the capacity to retain water periodically in the catchment area of a region, of which the construction of storage reservoirs can be mentioned as one of the basic ones [6,7].

In addition to the accumulation of increasingly valuable water resources, the creation of impounding reservoirs is driven by various socio-economic needs, i.e., anti-flood, tourism, navigation, energy and drought-mitigation functions [8,9]. More than 36,000 dams characterised as "larger" have been identified worldwide, with the largest number (about 28%) located in Asia [10]. Although artificial damming facilities were constructed as early as antiquity, the greatest expansion of such investments occurred in the second half of the 20th century [11], of which a gradual shift away from such projects in developed countries has been observed since the 1970s, with a simultaneous intensification of such activities in the African, Asian, and South American regions [10]. Poland can be cited as an example of such circumstances, where of the ten largest storage reservoirs, eight were built between 1933 and 1986, and the Świnna Poręba facility, which also belongs to this ten and was built in 2017, is an exception among the hydrotechnical investments carried out in recent decades, which focus on dry reservoirs with only flood-control functions [12]. This approach is primarily due to greater public awareness of environmental impacts, the promotion of projects that are at least environmentally neutral, and national or international regulations, the latter of which apply, for example, to European Union countries. Another issue of equal importance is the fact that the implementation of large hydrotechnical investments can be very difficult without obtaining external funding, e.g., from the institution commonly referred to as the World Bank or related institutions. Obtaining funds from such organisations requires the fulfilment of numerous demands, with one of the key ones being absolute respect for environmental and social aspects [13]. It is easy to conclude that, even in the case of rational economic needs, the above-mentioned circumstances favour the moving away from attempts to implement solutions with a potentially negative impact on the environment and the implementation of less-complex projects for which it is easier to demonstrate limited ecological interference [14,15]. However, the complete abandonment of the development of a multi-functional reservoir structure conflicts with the needs of many countries in terms of increasing water demand [5]. Continuing with the example of Poland—despite its favourable geographical location in a climate described as temperate—Poland is a country with relatively limited water resources, ranking further down the list than other European Union countries. The amount of freshwater from storage reservoirs per capita in Poland is about 1.6 thousand cubic meters, and based on the "Water Exploitation Index+", which determines the average annual total freshwater demand divided by the long-term average freshwater resources, Poland is among the countries exposed to water stress [16]. For many countries facing similar problems, an appropriate approach could be the review process of the policy of abandoning the construction of multi-functional reservoirs while using scientific developments and technological advances as a basis for planning and implementing new hydroelectric investments that allow the full socio-economic potential of damming structures to be realised. This would maintain not only a sustainable or neutral approach to environmental issues, but also ultimately reap significant environmental benefits.

Since scientific articles usually deal with one selected segment of research and often highlight its importance by omitting only seemingly unrelated issues, a review of the literature on the subject is justified to correctly reflect the complexity of the issue under consideration, which is the functioning of impounding reservoirs. It is also advisable to take a comprehensive approach to the publications analysed, considering not only the results obtained, but also the area of research and its methodology. The aim behind this paper is to review the current state of knowledge in the field of multi-functional reservoirs: (1) to collect and collate a selection of scientific publications describing the functioning of multi-purpose reservoirs in flood control, retention, environmental and water-quality aspects; (2) to identify developing sectors of research and innovative technological, planning or operational solutions; (3) to discuss and identify the main benefits and risks; and (4) to use the analysed findings to make proposals for actions that can prevent the occurrence of particular events and circumstances or reduce their negative impacts. This paper focuses on the challenges primarily related to the planning of storage reservoirs, their operation, as well as their impact on flood-wave reduction, environmental and social impacts, water quality and the use of reservoirs in water resources management, which is crucial. A graphical abstract of the research paper is shown in Figure 1.

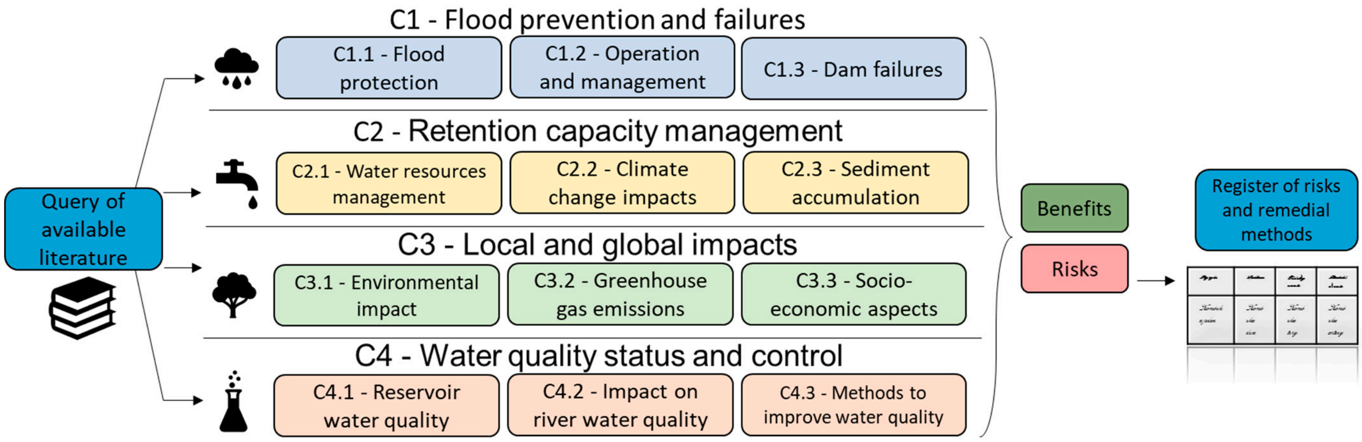

Figure 1. Graphical abstract of the research paper.

The different categories and subcategories under review are numbered using the letter C and the relevant colour, as summarised in Figure 1. This numbering and designation will be used throughout the rest of the article. After the introduction covered in the first chapter, the following part of the article, in the second chapter, describes the trend of scientific publications in the field of reservoir operations and the methodology of the query of available literature. Section 3 is divided into five subchapters, the first four of which describe the results of the review carried out (in turn for each of the issues analysed), and the fifth of which summarises the risks identified in the form of a register including the spectrum and extent of their impact, as well as remedial methods. In addition, a diagram proposed by the authors showing the most relevant issues to be considered during the planning and construction of storage reservoirs is included in Section 3.5.

2. Materials and Methods

The work of searching for publications to meet the objective of this publication began using the Web of Science database, appropriately typing the phrase "water reservoir" or "retention reservoir" (bearing in mind that the word "reservoir" has very many meanings in other, different scientific fields) obtaining a total of 452 results for articles published since 2000, in categories:

- Water Resources.
- Climate Change.
- Water Treatment.
- Geotechnical Engineering.

Of the results received, 103 items were more- or less-precisely related to issues of the ongoing literature review. Table 1 and Figure 2 summarises the different aspects of the research with the number of publications corresponding to them.

Table 1. Number of publications in a given field retrieved from the WoS database.

Category	No. of Publications
C1—Flood prevention and failures	10
C2—Retention capacity management	44
C3—Local and global impacts	17
C4—Water-quality status and control	32

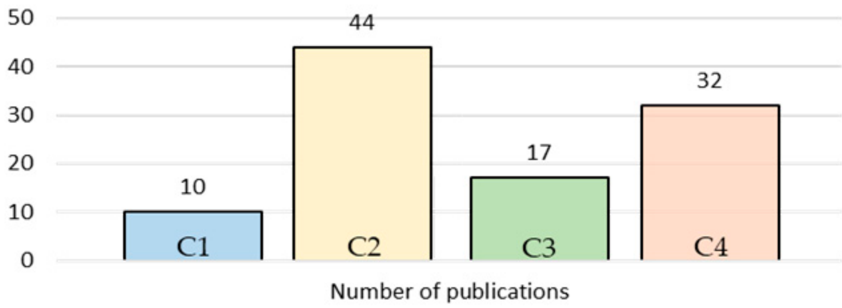

Figure 2. Number of publications in a given field retrieved from the WoS database.

Such a search of the database reveals a predominance of research into the retention capacity and influence of bottom sediment accumulation on the operation of the facility, as well as analyses of the quality of water stored in the reservoir or its influence on changes in hydrochemical parameters in watercourses flowing through the canopy of the facility. However, the values obtained do not fully reflect the scientific involvement of the authors of the publications in the sectors mentioned, as articles on retention reservoirs often only have the word "reservoir" in the title and abstract, without an adjective specifying its function. In addition, many of the publications searched had limited access or their content did not adequately correspond to the issues sought to be presented in this paper, i.e., the conclusions of these publications would not show the benefits or risks associated with the construction and operation of reservoirs. Therefore, it was decided to use other databases as well as search engines available directly on the websites of scientific journals. In parallel, a different search method was used by using the words "reservoir" and an additional phrase targeting the issue:

- "reservoir" and "flood";
- "reservoir" and "retention" or "water resources";
- "reservoir" and "environment" or "social" or "impact";
- "reservoir" and "water quality" or "pollution" or "contamination".

On the basis of this method, publications have been selected for review that, in the opinion of the authors, comprehensively explore the issue in question, are based on valuable case studies in their methodology and use modern and innovative engineering solutions or advanced data analysis techniques. The conclusions of the literature review were not only treated superficially, but all the publications analysed were tabulated (in Supplementary S1–S4 to the article), where, in addition to a precise presentation of the research result, the scope of the research, the size of the object under analysis, the location of the case study and an outline of the methodology used were also included. It should be emphasised here that, in determining the size of the reservoirs described in the individual articles, the definition given by the International Commission of Large Dams (ICOLD), which defines reservoirs with, among other things, a volume of more than 3 million m^3 as 'large', has been taken into account. In order to describe the size of the facilities more precisely, reservoirs up to 3 million m^3 are classified as 'small', up to 10 million m^3 as 'medium', up to 500 million m^3 as 'large' and those with a capacity above 500 million m^3 as 'very large'. For each pledge, covering flood control, retention, environmental/social and water-quality aspects in turn, a discussion of the issue in question was carried out and the main benefits and risks of the reservoirs were identified in its area. A register was compiled for these risks, including countermeasures formulated based on the review.

3. Results and Discussion

3.1. Flood Prevention and Failures

Table 2 presents a summary of the analyses assigned to category C1 (flood prevention and failures). For each of the subcategories (C1.1, C1.2 and C1.3), the benefits (numbered B1–B4) and risks (numbered R1–R4) diagnosed in the area are distinguished. The spectrum of analyses on the basis of which these conclusions were drawn is also cited.

Table 2. Summary of scientific publications concerning flood protection and failures of reservoirs.

Research Papers	Spectrum of Analysis	Benefits Diagnosed	Risks Diagnosed
C1.1—Flood protection			
[17–23]	The analyses concern 1 very large and 17 large reservoirs in Asia, 4 large and 2 small reservoirs in Europe and 2 medium-sized reservoirs in Africa. In addition, publication [20] operated on a large dataset, and in [22] reservoir capacity was a variable value.	B1—The most effective form of flood protection. B2—Significant wave reduction with a relatively small occupied area. B3—Flood protection on a supra-local scale.	R1—Limited importance of the object with too small a capacity.
C1.2—Operation and management			
[24–35]	The analyses concern 11 very large and 11 large reservoirs in Asia, 1 very large reservoir in Europe, 2 very large reservoirs in Africa and 1 large reservoir in the USA. In addition, in publication [28], reservoir capacity was a variable value, and in [35], a review based on a large dataset was performed.	B4—Possibility of effective real-time management.	R2—Lack of proper operating guidelines.
C1.3—Dam failures			
[36–42]	The analyses concern 1 large reservoir in Asia, 1 large and 3 small reservoirs in Europe and 2 large reservoirs in the USA. In addition, in publication [39] the reservoir capacity was a variable value, and in [36,42] a review based on a large dataset was performed.	n/a	R3—Dam failure as a result of water overflow. R4—Internal erosion in an earthen embankment.

The articles summarized in Supplementary S1 and Table 2 indicate the important role of reservoirs in flood control in the region under analysis [17–23]. However, the design of multi-purpose reservoirs requires careful research to produce a facility that allows a balance between effective flood control and other facility objectives [17,20]. It is also important to determine the precise technical specifications [18] as well as the most favourable location of the facility in terms of maximising scale and efficiency while maintaining a viable economic approach [21–23].

Due to ongoing climate change and the more frequent occurrence of extreme weather events, the role of flood-control reservoirs may become more important. At the same time, this involves analysing the risk of failure of damming facilities that were designed based on flow rates that were too low and did not take time to consider other things, such as climate change and the associated increase in the occurrence of higher flow rates [36,38,40,41]. Particularly important is also the modernisation of old hydrotechnical facilities that have been in operation for a long time, for which the basic technical specifications have not been maintained. This is due to the selection of unsuitable soil and construction technology, as well as the failure to consider the phenomenon of internal water filtration [37]. In the case of reservoirs for which a risk of insufficient capacity or lack of capacity of the discharge facilities has been identified, appropriate action should be taken. This should start with detailed monitoring and inspection of the facility, resulting in the development of a programme for land use below the dam, the establishment of a system to warn residents of areas at risk, and ultimately the development of a system to discharge water from the reservoir [39–43].

There are also studies in the scientific literature on optimising the management of reservoir operations according to the hydrological year [24,25], as well as publications proposing tools and models to improve real-time decision making, depending on weather forecasts or prevailing weather conditions [26–35]. This direction can be described as leading the way in terms of innovative research into flood-control reservoirs, for which the latest developments in the field of artificial intelligence are also being used [34,35]. Analyses based on the case studies confirm the feasibility of implementing models with sufficiently fast computation times [27,30]. They show a significant increase in the effectiveness of minimising the negative effects of flooding, assuming rational management of available resources with the support of appropriately designed IT tools [28–33]. With the provision of accurate hydrometeorological data in the reservoir catchment, these tools can also serve as (1) emergency population warning, (2) guidelines for the co-operation of a system of different flood-control facilities, (3) support for decision makers to minimise fluctuations in reservoir water levels, and (4) guidelines to maximise hydropower production. Figure 3 illustrates the key benefits and risks of reservoirs during high-water stages and flood risk.

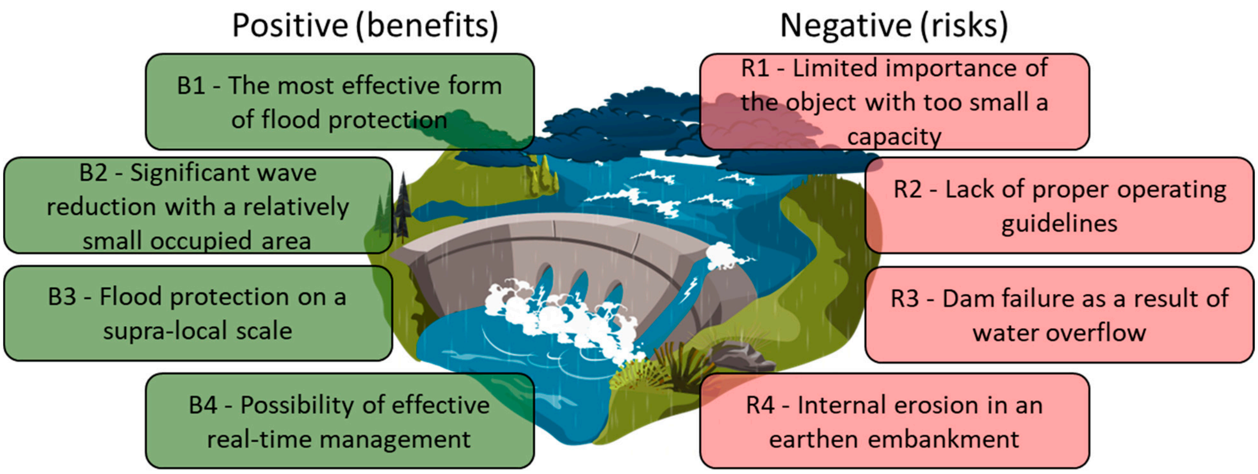

Figure 3. Main benefits and risks associated with the operation of reservoirs during high-water stages and flood risk.

3.2. Retention Capacity Management

Table 3 presents a summary of the analyses assigned to category C2 (retention capacity management). For each of the subcategories (C2.1, C2.2 and C2.3), the benefits (numbered B5–B8) and risks (numbered R5–R8) diagnosed in the area are identified. The spectrum of analyses on the basis of which these conclusions were drawn is also cited.

The publications analysed highlighted the crucial importance of reservoirs in increasing water resources, while pointing out the need for a complex approach to their management [44–52]. To ensure a stable and uninterrupted water supply, it is assumed that improved reservoir-operation criteria [44] or predictive models using widely available hydrometeorological data can be introduced. This will also allow for proper real-time monitoring and assessment of the risk of water shortages [45]. A considerable number of approaches have emerged to provide IT support to decision makers managing reservoirs, providing the opportunity to choose the most effective method that corresponds to the original characteristics of each facility [48]. Establishing comprehensive and flexible water management instructions, assuming adaptation to different atmospheric scenarios, will also maximise resource efficiency and economic benefits [46]. Retention reservoirs may also have problems maintaining their intended capacity due to technical reasons (e.g., seepage) or inadequate management of the catchment area in which they are located. In both the planning and operation stages of a reservoir, consideration must be given to whether expanding the farming economy and the creation of public housing will negatively impact the retention capacity of the facility (pollution, siltation, etc.) [47,49]. Although arid and desert regions primarily experience water supply problems, they require alternative approaches to regulatory development, through, for example, the creation of underground reservoirs to reduce evaporation losses [50]. Cross-border cooperation between countries crossed by the same river, which is a key water source for each actor, is also an important issue in water resources management. In such a situation, there may be a risk of interfering too much with the upper course of the watercourse without regard to the consequences felt downstream, especially if it is in another country [51]. Restricting access to surface waters can also be a tool in armed conflict, an example of which is the suspension of the flow of water to the Crimean Peninsula, as a result of Russia's war with Ukraine. This resulted in a loss of capacity in the reservoirs there and the need to seek alternative methods of filling them [52].

Table 3. Summary of scientific publications on the retention function of reservoirs.

Research Papers	Spectrum of Analysis	Benefits Diagnosed	Risks Diagnosed
C2.1—Water resources management			
[44–52]	The analyses concern 4 very large, 12 large and 2 small reservoirs in Asia and 26 large or small reservoirs in Europe. In addition, publication [48] reviews based on a large dataset.	B5—Provision of water for domestic, industrial and social purposes. B6—Enabling the development of dry regions.	R5—No update of water management instructions. R6—Possible negative impact on the morphology of the watercourse and the region downstream of the dam cross-section
C2.2—Climate change impacts			
[53–60]	The analyses concern 2 very large and 6 large reservoirs in Asia, 4 large reservoirs in Europe and a large reservoir system in South America. In addition, in [56] the reservoir capacity was a variable value, and in [60] a review based on a large dataset was performed.	B7—Counteracting the effects of drought. B8—Reducing the negative impact of climate changes.	R7—The need to respond to ongoing climate and urban change (in the context of new construction and the refurbishment of old facilities).
C2.3—Sediment accumulation			
[61–68]	The analyses concern 1 very large and 9 large reservoirs in Asia, 1 large reservoir in Europe, 1 large reservoir in Africa, 5 small reservoirs in the USA and 1 large reservoir in South America. In addition, publications [66,67] review based on a large dataset.	n/a	R8—Sediment accumulation and loss of facility capacity.

An intensively developing sector of research is the analysis of the scale of progressive climate change, the importance of hydraulic structures in this context and the impact of potentially different atmospheric conditions on their operation [53–57]. A reservoir can effectively serve as a tool to counteract the negative effects of climate change [53]; however, its operation must presuppose the need to adapt to new hydrometeorological circumstances and adopt a modernised strategy for operational activities [54,55,57]. When new facilities are built, different parameters defining the characteristics of the project should be considered, particularly regarding the increase in average annual temperatures and the uneven distribution of precipitation [56]. The exact effect of climate change for future decades is not accurately recognised, and, moreover, its intensity is closely linked to a particular region of the Earth. In the publications analysed [57–60], there were discrepancies in the estimation of the magnitude of changes in temperature and precipitation, as well as different conclusions regarding the amount of evaporation. The paper [58] found a significant correlation between an increase in atmospheric CO_2 concentration and a decrease in average evapotranspiration, while other studies indicated a general increase in water loss from reservoirs due to evaporation [57]. To improve the quality of the research in question, analyses involving the evaluation of the use of individual models, including those advanced and based on artificial intelligence, are important. It is advisable to test them under different conditions and with the availability of limited datasets [59]. The development of new technologies to technically reduce evaporation from storage tanks is also noticeable. However, studies have indicated that shade covers are not universally and widely applicable due to the high energy and water consumption in the production process, which translates into a high cost of implementing such a solution [60].

A major challenge, since ancient times, has been the problem of sediment accumulation in the reservoir bowl causing loss of capacity or complete siltation [61–68]. The suspension of sediment movement is associated not only with the loss of functionality of the facility, but also with the disturbance of the channel morphology below the dam cross-section [65]. Various methods of measuring sediment accumulation rates and sediment transport rates are described, based on a Geographic Information System (GIS), mathematical models, field surveys, historical data and photographic documentation [61–64]. When a problem is diagnosed, remedial action can be taken by identifying and eliminating the source of erosion [64], scouring sediment by intensifying the outflow from the reservoir [68], and using a range of other technological treatments [67]. It should be stressed that it may not be economically justifiable to take remedial action if the problem is already progressing. In this case, the only (albeit rarely appropriate) solution may be to decommission the dam [66], particularly if the facility's sediment permeability was not considered at the planning stage, or it was decided to build in a location highly vulnerable to increased debris transport [67]. Figure 4 shows the main benefits and risks of using reservoirs for water management.

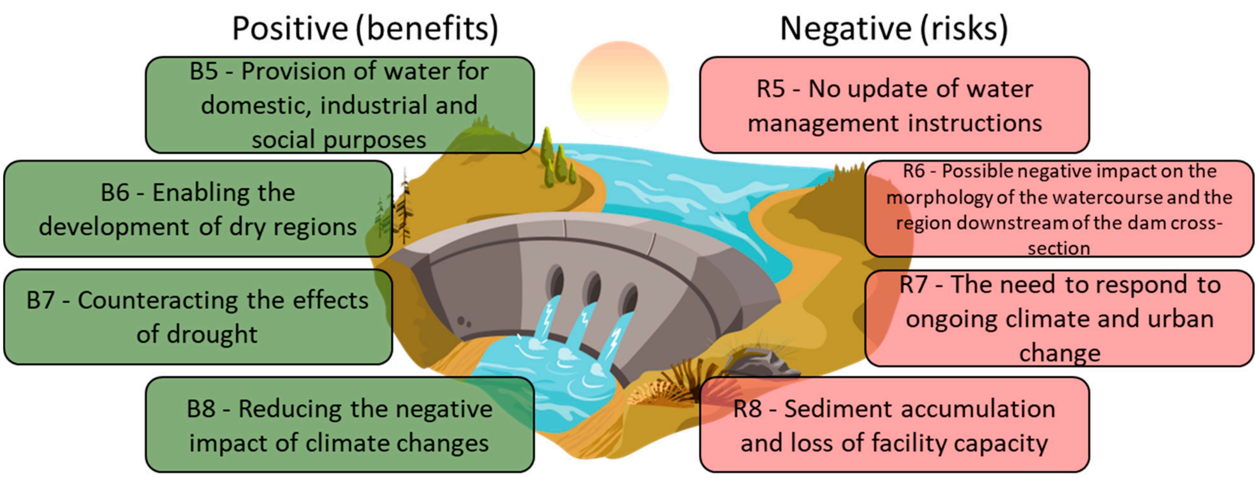

Figure 4. Main benefits and risks of using reservoirs to manage water resources.

3.3. Local and Global Impacts

Table 4 presents a summary of the analyses assigned to category C3 (Local and global impacts). For each of the subcategories (C3.1, C3.2 and C3.3), the benefits (numbered B9–B12) and risks (numbered R9–R12) diagnosed in the area are identified. The spectrum of analyses on the basis of which these conclusions were drawn is also cited.

Table 4. Summary of scientific publications on environmental and social impacts of reservoirs.

Research Papers	Spectrum of Analysis	Benefits Diagnosed	Risks Diagnosed
C3.1—Environmental impact			
[69–83]	The analyses concern 6 very large and 5 large reservoirs in Asia and 1 very large, 1 large, 1 small and a reservoir system in Europe. In addition, publications [69,70] review based on a large dataset.	B9—Beneficial microclimate changes to support vegetation expansion. B10—Creation of habitats and nesting sites for birds.	R9—Changes in species structure of flora and fauna, good conditions for invasive species. R10—Possible negative impact on groundwater. R11—Socially and ecologically unjustified degradation of the floodplain area (in the context of species losses).
C3.2—Greenhouse gas emissions			
[84–87]	The analyses concern 8 large reservoirs in Asia, and 1 very large reservoir in South America. In addition, publications [84,85] review based on a large dataset.	n/a	R11—Socially and ecologically unjustified degradation of the floodplain area (in the context of increasing CO_2 emissions rather than reducing it).
C3.3—Socio-economic aspects			
[88–94]	The analyses concern 1 very large, 2 large and 1 small reservoir in Asia, 2 large and 4 small reservoirs in Europe and 1 large reservoir in Africa.	B11—Socio-economic development of the region. B12—Facilitated control and regulation of fish populations.	R12—The need to resettle people from the occupied area.

The issue of the environmental impact of reservoirs is the subject of numerous discourses. There is a clear division between those in favour of the construction of these facilities and those individuals or organisations stating the environmental harm of hydroengineering projects of this type. This state of affairs leads to social conflicts at the investment-planning stage. Due to the high complexity of the problem, there is a lack of comprehensive studies in the literature that consider all related aspects and can provide an irrefutable argument in the ongoing discussion. The publications summarised in Table 4 usually focus on one or a few selected issues, and only a review of them provides a broader view of such a complex issue as the impact of retention structures on environmental change. The main conclusion of this review is that priority should be given to implementing sustainable planning and technological solutions to build facilities whose social benefits will largely outweigh any environmental losses. These should be subject to the most effective possible compensation [69–83]. The need for ex ante impact assessments is emphasised, but also for studies to be repeated after a longer period of reservoir operation [69]. Such analyses provide a broader view of the problem described and may indicate a potentially flawed site management strategy and the possibility of taking remedial action through pro-environmental regulation of water management in the reservoir and its catchment area [70,71]. In this aspect, it is also important to determine the minimum water discharges in a given period and to intensify them temporarily if necessary to preserve the natural balance of the region below the dam cross-section [72]. It is not insignificant to maintain baseflows (biological) on the outflow from the reservoir. The construction of large facilities of strategic importance for the whole country or region will always involve environmental impacts; however, studies of the large Alqueva reservoir have shown that many other factors have been superimposed on changes to the vegetation structure in its catchment, and that the recovery of important assemblages of endemic species is possible by adopting ecological-restoration solutions [73]. Such a measure has been implemented in the case of the Three Gorges Reservoir catchment, where there has been a change in microclimate favourable to the spread of vegetation [74]. An inappropriate approach to the planning process was indicated in the case of the Chotiari Dam, where the conversion of wetlands into a reservoir worsened the condition of the surrounding land, causing an increase in salinity [75]. A different view is presented in the publications [76,77], where the reservoirs were assessed as naturally valuable locations for bird habitats, including those threatened with extinction. However, it was pointed out that the level of water damming should be regulated so as not to submerge nesting sites or to allow nesting on special artificial islands [77]. Some European artificial reservoirs are becoming such important habitats for avifauna that they are being included in special regulations as Natura 2000 (special bird protection) areas, an example being the Jeziorsko reservoir in central Poland [95]. As dams significantly interfere with the continuity of rivers and provide a habitat and breeding ground for ichthyological fauna, it is necessary to carry out monitoring in this regard. An example is the study carried out on the Feitsut Reservoir [78], where the risks arising from the emergence of invasive species and the displacement of native ones have been confirmed, which is detrimental to the local ecosystem as a whole. The removal of older facilities [79] or very often the construction of fish ladders [80] are sometimes cited as ways of ensuring the permeability of watercourses. However, the publication [79] emphasises that dam removal alone would not have the desired effect in every case. The provision of a fish ladder with optimal parameters may allow for the sustainability and diversity of the ichthyological fauna, which, however, requires studies carried out on the native fish species of the region [80]. Due to the different geological characteristics of the various dam reservoir locations, each project requires an individual approach to the issue of groundwater impact [81–83]. Due to the nature of lowland urban areas, the damming of water in the reservoir results in a general and long-term increase in local groundwater levels and its significant correlation with fluctuations in the level of dammed water [81]. In mountainous areas, the situation is more dependent on the terrain and geological structure, and, in certain circumstances, the creation of a reservoir can result in a significant and undesirable lowering of groundwater levels downstream [83]. The publications analysed [81–83] demonstrate the significance of the impact of storage reservoirs on groundwater quality and the possibility of rapid movement of contaminants, and, therefore, emphasise the need for regular monitoring of the state of dammed water quality, the use of technology to reduce possible seepage, and the afforestation of adjacent land.

Global warming is prompting considerations that include a wide range of greenhouse gas emissions, including from inland water surfaces and storage reservoirs. Estimating the CO_2 equivalent emitted is a difficult task, requiring an appropriate methodology; a combination of complex field and modelling studies; as well as the consideration of many components, such as the ratio of removals to emissions, the lost potential of flooded areas after water damming, the amount of energy produced if the facility is equipped with a hydroelectric power plant, the change in the local socio-economic structure and others. Consequently, presenting precise results is an unfeasible task and the current research focuses on achieving relatively realistic estimates [84–87]. This global task was undertaken in the publication [84], where global greenhouse gas emissions from reservoir surfaces were determined to be in the range of 0.5 to 1.2 Pg CO_2 equivalent per year, most of which relates to CH_4 and is significantly correlated with water quality. A similar analysis was conducted for the Indian area, concluding that 4% of India's greenhouse gas emissions come from inland waters, indicating, however, a predominance of CO_2 (56%) [85]. It also highlighted important gaps in this sector of science and the need to further improve models to achieve more precise results [85]. More detailed studies on a smaller scale, carried out for a system of eight reservoirs and one large one, were carried out successively in the publications [86,87]. They pointed out the need to consider components such as the timing and height of the damming level [86], as well as the increased outgassing of CO_2 at the outlet of the power plant turbines and the inundation of previously rainforest areas [87].

When analysing the regional impact of reservoirs, it is also important not to overlook the socio-economic aspects, which are a key component in determining the rationale for the facility or ultimately holding back the feasibility of the investment [88–93]. At the planning stage, it is necessary to identify the interrelation of the role of the reservoir with economic, ecological and socio-cultural issues [88]. Surveys indicate that although the public sees the benefits behind the construction of dams, the whole project is of concern to people, and they would rather not live in the immediate vicinity of such facilities [89]. Measures are, therefore, needed to make the public aware of the economic basis of construction, and of any compensation that may be due for loss of land or resettlement, but this requires a well-thought-out and sustainable compensation policy [90]. Resettlement is a particularly sensitive issue, causing much emotion. The publication [91] distinguishes between three groups of people, i.e., those displaced long or short distances and those remaining on their lands despite the proximity of the facility. The last group was identified as the most disadvantaged, especially in comparison to the second mentioned, who ultimately recorded even relative material gains. An interesting example is the construction of the Racibórz Dolny reservoir in Poland, where two villages with a total of about 700 inhabitants were relocated to a new site about 7 km away. Surveys carried out a few years after the relocation found a mostly neutral view of the impact on material status and a largely positive attitude towards the completed investment [92]. A proper policy geared towards improving the interests of local communities is crucial in order not to marginalise the needs of residents at the expense of making businessmen and managers rich. To this end, the local community should be involved in the investment process from the very beginning of the planning stage and have a real say in its direction [93]. However, legislation should not only protect the public from losses due to reservoirs, but also safeguard the ecosystem of these facilities from overexploitation by humans, especially in terms of regulating fishing [94] and pollution discharges [96,97]. Figure 5 shows the main benefits and risks associated with the environmental and socio-economic impacts of reservoirs.

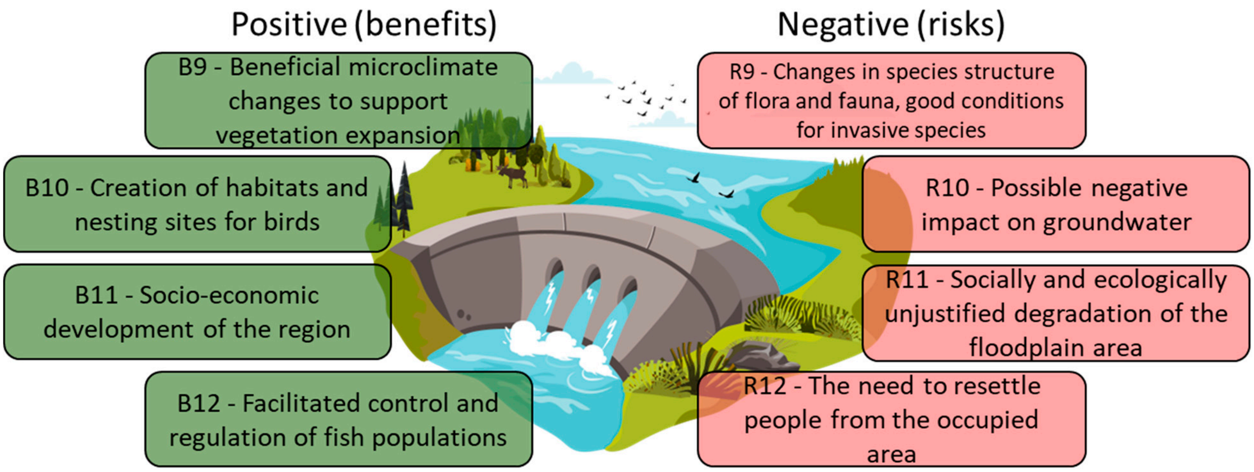

Figure 5. Main benefits and risks associated with the impact of reservoirs on environmental and socio-economic issues.

3.4. Water-Quality Status and Control

Table 5 presents a summary of the analyses assigned to category C4 (water-quality status and control). For each of the subcategories (C4.1, C4.2 and C4.3), the benefits (numbered B13–B16) and risks (numbered R13–R16) diagnosed in the area are identified. The spectrum of analyses on the basis of which these conclusions were drawn is also cited.

The assessment of the ecological status of surface waters consists of numerous organoleptic criteria, physico-chemical parameters and biological indicators. Water-quality tests concern, among other things, water transparency, oxygen conditions, acidification, salinity, occurrence of bioindicator organisms, as well as the content of heavy metals and organic or biogenic substances, including above all the concentrations of various forms of nitrogen and phosphorus, which leads to eutrophication of waters. Artificial reservoirs are vulnerable to changes in water quality that may adversely affect the function of the facility, particularly in the case of recreational or potable water storage reservoirs [96–108]. Research confirms the high sensitivity of the ecological status of reservoirs to land use in their catchment, with growth in built-up or agricultural areas significantly contributing to increased concentrations of undesirable elements [96,97,110]. In the case of small reservoirs located in ecologically sustainable and forested areas, such a risk is lower [98]. Internal sources of pollution can be accumulated bottom sediments releasing, among other things such as phosphorus in the pelagic zone [99] or the phenomenon of seasonal stratification causing mobility of negatively impacted elements and deoxygenated bottom waters [100,113]. Water blooms caused by cyanobacteria are widespread in various climate zones, causing public dissatisfaction; however, due to the complexity of the issue and the lack of a single determining factor, the search for a solution to the problem requires the active participation of the scientific community and a synergy of different research methods [101,102]. Furthermore, in addition to field studies, the use of appropriately selected and calibrated IT models is important in the water-quality-monitoring process. These make it possible to predict progressive changes in biogenic compound concentrations and the frequency of eutrophication phenomena, as well as the spatial distribution of pollutants [103–105]. The latter is particularly important for potable and municipal water reservoirs, where the determination of the characteristic migration of hazardous elements offers the possibility of taking water from other locations. This reduces the cost of treatment or the cancer risk to the local community [106,107]. A developing line of research is the analysis of the presence of microplastics in water and bottom sediments; however, the assessment of the global and local impact of this factor and the identification of the most effective field-survey methodology remains an open question [108].

Table 5. Summary of scientific publications on water quality in reservoirs.

Research Papers	Spectrum of Analysis	Benefits Diagnosed	Risks Diagnosed
C4.1—Reservoir water quality			
[96–108]	The analyses concern 3 very large and 14 large reservoirs in Asia, 3 large and 5 small reservoirs in Europe and 1 large reservoir in South America. In addition, publications [101,108] review based on a large dataset.	B13—Good water quality in reservoirs in ecologically sustainable areas. B14—Advanced opportunities for synergy between model and field studies.	R13—Excessive accumulation of biogenic compounds or heavy metals. R14—Contamination of water for utility purposes. R15—Accumulation of microplastics in water and bottom sediments.
C4.2—Impact on river water quality			
[109–114]	The analyses concern 6 small reservoirs in Europe and 1 very large reservoir in South America. In addition, publications [112,113] review based on a large dataset.	B15—Interception of pollutants from the catchment area.	R16—Negative impact on the richness of the ecosystem and river water temperature.
C4.3—Methods to improve water quality			
[115–120]	The analyses concern 1 large and 4 small reservoirs in Europe. In addition, publication [116] reviews based on a large dataset.	B16—Availability of technological solutions to improve water quality (especially in smaller reservoirs).	n/a

The impact of reservoirs on water quality in the watercourse downstream of the dam cross-section is relatively straightforward to determine in field studies; however, it is impossible to establish a universal pattern of impact due to the diversity in the specifics of each site [109–114]. In terms of halting the downstream transport of biogenic compounds and heavy metals, the impact of the reservoirs in the cases analysed can be described as positive or at least neutral [109,110,112,120]. In extreme cases, however, there may be excessive uptake of bottom sediments and binding of phosphorus in them, resulting in oligotrophication of the water below the reservoir with a negative impact on the local ecosystem [112,113]. The relationship between the operation of hydroelectric power plants located on the reservoir dam and changes in water quality in the dammed watercourse needs to be investigated in more detail [111]. The stratification phenomenon already mentioned adversely affects the quality of the water in the reservoir, but can also cause cold and deoxygenated hypolimnion waters to escape from the reservoir, disrupting the optimal physicochemical parameters of the river [113]. The risk of negative impacts is also present during the construction phase and the initial filling of the facility's canopy, and if the water stays in the reservoir for too long, i.e., stagnant or significantly delayed runoff [114,115].

In addition to planning measures and continuous monitoring of surface water quality, technical solutions can also be applied for reservoirs to achieve the expected ecological status or to revitalise neglected facilities (or parts of them) [115–120]. Increasing the feeding to the reservoir and reducing the time of water transport is an action that has the potential to remove a significant proportion of the pollution and counts as water reclamation [115]; however, this is not in every case technologically feasible or economically justified. Depending on the characteristics of the site in question, it is possible to use artificial floating islands designed to make a positive contribution to a chosen aspect, such as through absorbing biogens, improving the habitat for aquatic organisms or optimising the temperature and aeration of the water [116]. To achieve improvement of water quality in the reservoir, chemical interference and interference with the structure of ichthyofauna species is acceptable, but this requires sustainable and long-term action to achieve lasting effects [117]. Local water purification (e.g., in an area used for tourism) can be achieved using point treatment systems [118], while a global improvement in the water quality of the entire site is achievable through the systematic discharge of deoxygenated hypolimnion water [119]. A very promising technology that is not widely reported in the scientific literature is also the use of pre-tanks, managed with biogenic compounds absorbing aquatic vegetation [120]. Figure 6 shows the main benefits and risks of maintaining proper water quality in and below the reservoir.

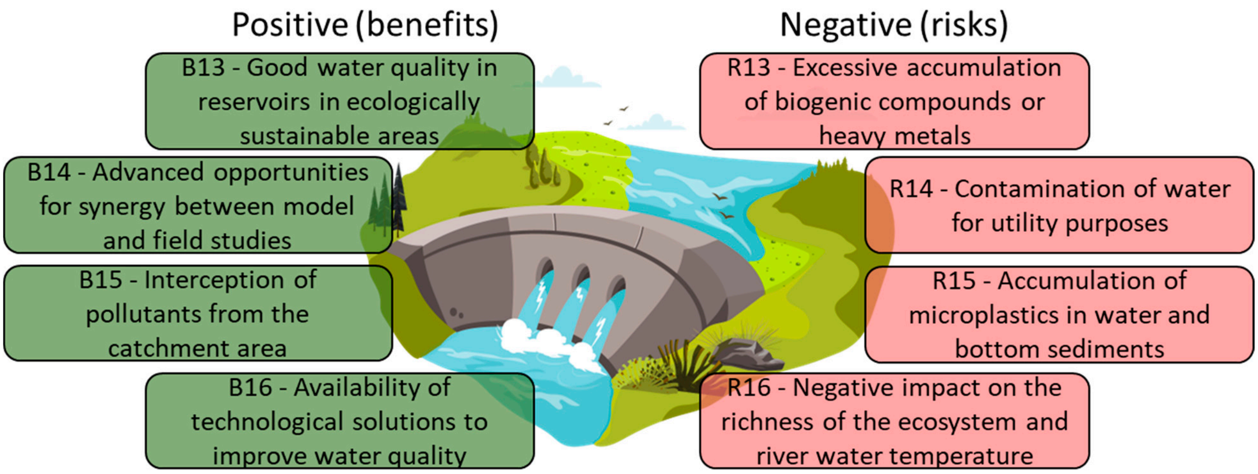

Figure 6. Main benefits and risks of maintaining proper water quality in and below the reservoir.

3.5. Register of Risks and Remediam Methods

Based on the studies collected in Supplementary S1 and S2 and Tables 2–5, the main risks concerning the establishment and operation of storage reservoirs are listed. Due to the currently changing climatic conditions and the more frequent occurrence of extreme atmospheric and hydrological phenomena. It is important to carry out such an analysis of the risks based on current research and bearing in mind modern technological possibilities. Table 6 includes a register of risks including their description, spectrum, and extent of impact, as well as remedial methods.

Table 6. Register of risks associated with the construction and operation of storage reservoirs.

Category	Risk	Spectrum	Influencing	Counteracting
C1.1	R1	Facilities developed in wrong locations or with limited capacity in relation to potential hydrometeorological conditions.	Effects economically disproportionate to the resources invested, negative impact of the reservoir on a larger spatial scale.	At the planning stage: adopting an appropriate methodology to select a location that maximises the efficiency of the facility [21–23].
C1.2	R2	Reservoirs in uncontrolled catchments, no meteorological data available.	Reduction in the functionality of the facility. Loss of flood capacity, achievable with optimal management. Increased risk of dam failure.	Development of guidelines for suggested damming levels at a given time [24,25]. Implementation of models to support real-time operations [26–35].
C1.3	R3	Facilities designed for too low flows, or poorly managed.	Intensification of flooding rather than minimisation of its effects. Induction of a chain reaction of failure of facilities operating in the system. Significant economic losses, damage to infrastructure and risk to human life or health.	Operational activities described in the cell above, early warning schemes, increasing the capacity of overflow facilities [39–41].
	R4	Old embankments created without optimal safety parameters.		Inventorying and upgrading existing facilities through the use of seepage or infiltration screens [36,37]. Implementation of a seepage control system [121].
C2.1	R5	Multi-purpose reservoirs, in drought-prone regions, providing water for social, industrial and agricultural needs.	Failure to store enough water for the drought period, causing the development of a region to stall or leading to social conflict.	Estimation of the actual water demand in the region. Updating the reservoir management scheme, developing a hydrological model that offers decision makers results that are easy to interpret [44–46].
	R6	Operation of facilities that completely stop sediment transport or limit water flow. Transboundary rivers, competition for water resources.	Causing increased erosion of the watercourse, and loss of the economic importance of the region and reduced retention capacity of downstream reservoirs.	Construction of facilities in which the permeability of sediment transport and gradual filling of reservoirs are considered, while maintaining optimum flow rates in the river. Adoption of trade-offs between water use objectives, while maintaining international cooperation [51,65].
C2.2	R7	Older reservoirs, designed because of outdated data.	Inability to achieve target water storage levels. Low regulatory efficiency and low strategic importance of the facility.	At the planning stage: Estimating design parameters based on climate models and catchment development changes [49,56]. Reducing evaporation through "shade curtains" when economically justified [60,122].
C2.3	R8	Upstream facilities without anti-debris infrastructure.	Loss of facility capacity or complete siltation and the need for costly decommissioning.	At the planning stage: Analysis in terms of the scale of sediment transport at the location [47,123] and the possibility of implementing preventive measures [67]. Dredging operation or scouring of sludge from existing facilities [68].

Table 6. *Cont.*

Category	Risk	Spectrum	Influencing	Counteracting
C3.1	R9	Reservoirs being built around nature-rich areas with fragile ecosystems. Lack of respect for legislation.	Emergence of invasive species, decline of native species, and loss of ecological permeability of the watercourse.	Conducting a comprehensive environmental impact assessment, regulating damming management procedures, ensuring environmental flow in the river, ecological restoration, construction of fish ladders and overseeing sustainable operation of the facility [69–74,94].
	R10	Reservoirs not well sealed, and in areas potentially exposed to fluctuations in groundwater levels.	Undesirable lowering of groundwater levels downstream, collecting pollutants and transporting them to groundwater.	Taking this phenomenon into account in the models at the planning stage, monitoring of groundwater levels in exposed locations, control of water quality in the watercourse above the reservoir, technical protection of the facility against seepage and afforestation near the reservoir [81–83].
C3.1 C3.2	R11	Large reservoirs directly in areas of natural value.	Total loss of areas important for the habitat of regional animal species, and total increase in greenhouse gas emissions from the region.	A holistic approach to the planning process by balancing socio-economic gains and environmental losses [74,75]. Locating reservoirs without exposing them to pollution to reduce greenhouse gas emissions and considering sequestration [84,85,87].
C3.3	R12	Reservoirs arising in inhabited or occupied areas.	Social conflicts, lack of objectively high compensation and displacement over a considerable distance.	Talking to residents, involving them in the planning process, implementing sound regulations and compensation or resettlement procedures [90,91,93].
C4.1	R13	Reservoirs in catchments with proportionally large built-up area (residential or industrial) and agricultural use. Stagnant waters.	Water blooms in the reservoir (eutrophication) due to proliferation of algae/cyanobacteria. Reduction in oxygen concentration and negative impact on water-dwelling organisms. In the case of heavy metals, which impact on benthos. Threat to human health and decrease in tourist value of the site.	At the planning stage: long-term water-quality monitoring of potential tributaries to the reservoir, modelling studies and forecasting of catchment development as factors determining the viability of the investment [96–98,102–104,124,125]. For existing facilities: use of technical, chemical or biological solutions to reduce or discharge pollutants [115–120].
	R14	Potable or municipal water reservoirs subject to heavy metal accumulation. Older facilities for which revitalisation has not been carried out.	Risk to human health in regions using water stored in a contaminated reservoir. Potential for the emergence of carcinogens.	Synergy of field and modelling studies to determine the spatial distribution/migration of pollutants in different seasons, and development and implementation of guidelines on the issue of water intake site selection [100,105–107].

Table 6. *Cont.*

Category	Risk	Spectrum	Influencing	Counteracting
C4.1	R15	Reservoirs in highly urbanised regions subject to drain water inflows.	Possible negative impacts on the health of aquatic organisms and humans—an open question in scientific research.	Developing an effective methodology for sampling and testing for the presence of microplastics and identifying the process by which they enter reservoirs. Introduce regulations to limit the spread of this type of pollution [108,126].
C4.2	R16	Large reservoirs at low latitudes subject to stratification and facilities that accumulate excessive amounts of bottom sediment.	Negative impacts on dissolved oxygen concentrations and water temperature, resulting in undesirable changes to the structure of the ecosystem below the reservoir and impairment of the species that live there.	Conduct a comprehensive environmental impact assessment and hydrochemical monitoring for facilities for which stratification and sedimentation phenomena cause potential damage to the river ecosystem [113]. Implement investments that regulate water temperature [116] or allow sediment movement [67].

The set of countermeasures indicates that the risk of negative impacts from a reservoir can be reduced in a given area primarily by taking appropriate action at the planning stage of the project. During the preliminary analysis of the needs to be met by the new facility, it is essential to assess the existing condition, which includes economic aspects, water quality, debris movement and the hydrology of the area. In addition, the scale of the potential impact in terms of the environment, the local community, the morphology of the dammed river and the groundwater must be recognised. In Figure 7, a diagram summarising this review is presented, where for each of the above-mentioned issues, the previously identified risks are matched with their category, and a summary description of the countermeasures to achieve a multi-purpose and sustainable impounding reservoir is shown.

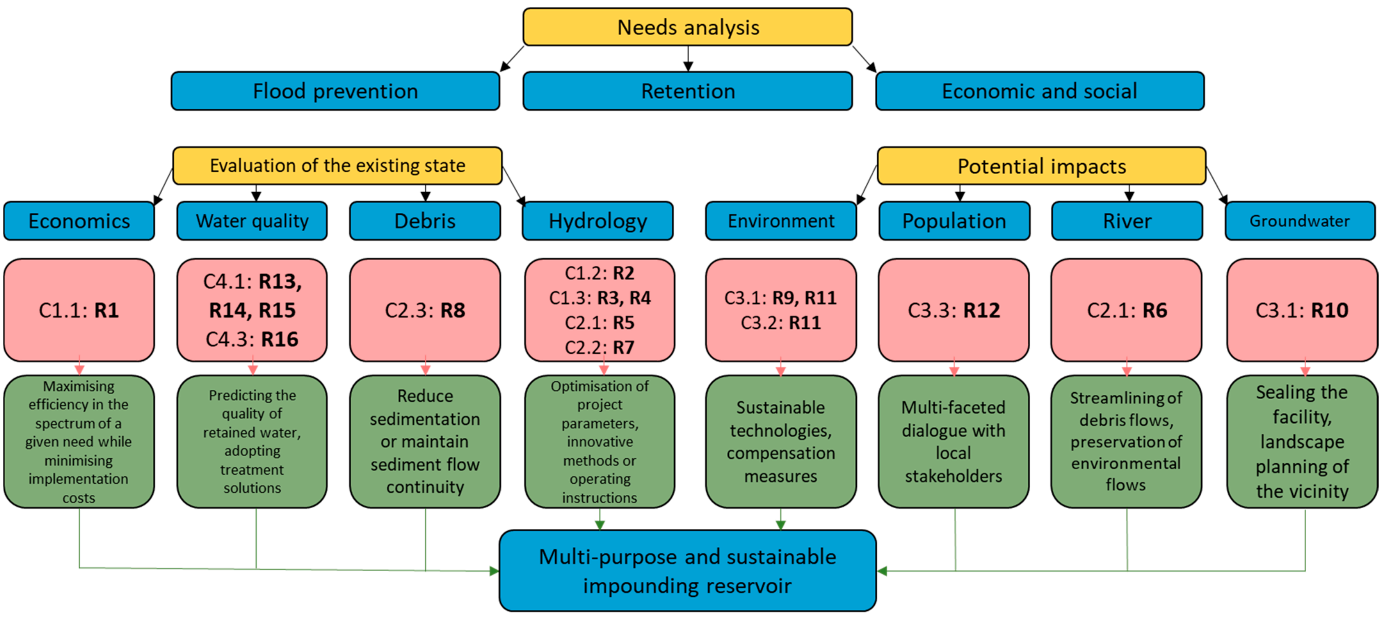

Figure 7. The most important issues to be considered during the planning and construction of reservoirs.

4. Conclusions

The study directly analysed 104 publications, of which 17 were review articles and 87 research articles. The review presented in this paper addressed four aspects related to the operation of multi-purpose reservoirs: (C1) flood prevention and failures, (C2) retention capacity management, (C3) local and global impacts, and (C4) water-quality status and control. For each of these aspects, key benefits or positive circumstances have been identified, as well as risks arising from the operation of multi-purpose reservoirs, for which countermeasures have been proposed. The following conclusions emerge from the work:

C1. Reservoirs are the most effective form of flood protection, also on a supra-local scale, while occupying a relatively small area. The risks relate to the reduced significance of the facility as a result of erroneous planning assumptions or progressive climate change; the lack of proper operational guidelines; and the failure of the dam as a result of overflow or the occurrence of internal erosion of the embankment. The primary remedial actions are to carry out comprehensive simulations of reservoir operation at the assumed site of formation, to implement models to support real-time operations, and to monitor inventory and upgrade older facilities.

C2. Reservoirs offer the possibility of storing water for their intended purpose and any further use, while counteracting the effects of drought and supporting the development of water-scarce regions. In addition, they reduce the negative impacts of climate change by, among other things, stabilising the water flow in the watercourse below the dam. Risks are associated with the potential failure to update the water management manual and the ongoing urban developments in the reservoir catchment area. Sediment accumulation in the reservoir canopy causing loss of retention capacity and negatively affecting the morphology of the dammed river is also a major problem. Particularly important countermeasures are updating the water resources management scheme based on monitoring actual demand, designing facilities based on predictive hydrometeorological data, and ensuring the permeability of downstream debris transport through planning and engineering measures.

C3. Reservoirs contribute to the socio-economic development of the region, enable the control and regulation of populations of aquatic organisms and create optimal conditions for the establishment of avifauna habitats, while having a positive impact on the development of local vegetation. Their formation, however, requires the degradation of selected sites through inundation, through which it may involve the displacement of people, interference with fauna and flora species structure and impacts on groundwater. A disproportionate amount of negative impacts relative to the benefits can be avoided by involving local communities in the planning process. This includes selecting less ecologically valuable locations for the construction of the facility, implementing appropriate guidelines for the height of damming at a given time, and using technological solutions to ensure the biological permeability of the dam.

C4. Reservoirs provide the opportunity to reduce the downstream transport of, among other things, biogenic compounds and heavy metals by capturing and retaining in the canopy pollutants from the catchment area. For sites located in ecologically sustainable areas, the problem of poor hydrochemical parameters is greatly reduced. The advanced development of field and IT survey technology offers the opportunity to synergise these analyses to obtain accurate models of water-quality changes with their spatial distribution. If the reservoir is located in a heavily urbanised or agriculturally exploited area, there is a risk of excessive accumulation of pollutants in the stored water, worsening the usability and tourism value of the site. The phenomenon of stratification and sediment accumulation can negatively affect the biological productivity of water reservoirs and temperature in the watercourse below the dam cross-section, and studies indicate a high potential for reservoirs as sites prone to microplastic accumulation. To avoid the construction of a facility highly exposed to poor-water-quality problems, long-term hydrochemical monitoring of potential tributaries should be carried out and projected catchment development should be considered. Potable and municipal water reservoirs should be equipped with a system that allows extraction from different locations and depths. It is also important to reduce the residence time of water in the canopy and to make proper use of technical, chemical and biological methods to reduce biogenic compound concentrations and improve selected water-quality parameters. This is where catchment management measures, initial reservoirs and biogeochemical barriers will come into play.

In addition, it should be noted that the largest number of available studies conducted after 2000 were identified for reservoirs located in Asia and Europe, and to a lesser extent on other continents. Studies on sites in Asia have overwhelmingly focused on 'large' or 'very large' reservoirs (as defined in the methodology), whereas in Europe, studies have focused on 'small' reservoirs, which is most likely due to the high density of larger reservoirs on Asian rivers [10]. Regardless, the problems accompanying the construction and operation of such facilities are largely the same for all sizes, and what differs is mainly the scale of the impact, not the type of impact. Likewise for the scale of remedial measures, these will require more-extensive efforts when larger reservoirs are planned. However, in undertaking this review, no risks have been identified for which there are no effective countermeasures, and the adoption of appropriate countermeasures could result in a multi-purpose and sustainable dam reservoir.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152216020/s1. Supplementary S1. Extended summary of scientific publications concerning flood protection and failures of reservoirs. Supplementary S2. Extended summary of scientific publications on the retention function of reservoirs. Supplementary S3. Extended summary of scientific publications on environmental and social impacts of reservoirs. Supplementary S4. Extended summary of scientific publications on water quality in reservoirs.

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