Journal of Water Resource and Protection, 2024, 16, 233-263
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Restoration or Rehabilitation of the Faleme River Affected by Mining Activities: What Methods?

Mor Diop[1]*, Ibrahima Mall[2], Elhadji Mamadou Sonko[1], Tidiane Diop[3], Birane Niane[4], Cheikh Mbow[1]

[1]Environmental Sciences Institute (ISE), Cheikh Anta Diop University of Dakar, Dakar, Senegal
[2]Higher School of Mines, Geology and Environment, Amadou Mahtar Mbow University of Diamniadio (UAM), Dakar, Senegal
[3]Department of Chemical, Cheikh Anta Diop University of Dakar, Dakar, Senegal
[4]Departmentof Engineering Sciences, Iba Der Thiam University of Thiès, Thiès, Senegal
Email: *mor31.diop@ucad.edu.sn

How to cite this paper: Diop, M., Mall, I., Sonko, E.M., Diop, T., Niane, B. and Mbow, C. (2024) Restoration or Rehabilitation of the Faleme River Affected by Mining Activities: What Methods? *Journal of Water Resource and Protection*, **16**, 233-263.
https://doi.org/10.4236/jwarp.2024.164014

Received: February 16, 2024
Accepted: April 9, 2024
Published: April 12, 2024

Abstract

The Faleme River, a West Africa long transboundary stream (625 km) and abundant flow (>1100 million m^3) is affected by severe erosion because of mining activities that takes place throughout the riverbed. To preserve this important watercourse and ensure the sustainability of its services, selecting and implementing appropriates restorations techniques is vital. In this context, the purpose of this paper was to present an overview of the actions and techniques that can be implemented for the restoration/rehabilitation of the Faleme. The methodological approach includes field investigation, water sampling, literature review with cases studies and SWOT analysis of the four methods presented: river dredging, constructed wetlands, floating treatment wetlands and chemical precipitation (coagulation and flocculation). The study confirmed the pollution of the river by suspended solids (TSS > 1100 mg/L) and heavy metals such as iron, zinc, aluminium, and arsenic. For the restoration methods, it was illustrated through description of their mode of operation and through some case studies presented, that all the four methods have proven their effectiveness in treating rivers but have differences in their costs, their sustainability (detrimental to living organisms or causing a second pollution) and social acceptance. They also have weaknesses and issues that must be addressed to ensure success of rehabilitation. For the case of the Faleme river, after analysis, floating treatment wetlands are highly recommended for their low cost, good removal efficiency if the vulnerability of the raft and buoyancy to strong waves and flow is under control.

Keywords

Faleme River, River Restoration, Constructed Wetlands, Dredging, Floating Treatment Wetlands, Coagulation-Flocculation

1. Introduction

Rivers are part of the freshwater ecosystems that play an important role in people's living, aquatic and terrestrial living organisms, and agricultural production [1]. Rivers serve many functions such as electricity generation, water supply, sediment transport, shipping, food production, sightseeing, and more. Consequently, they play an important role in people's living and agricultural production [2]. Compared to other ecosystems, rivers support a disproportionately large number of plant and animal species [1]. The importance of rivers and streams for fresh water, food, and recreation is well known, yet there is increasing evidence that degradation of running waters is at an all-time high [3]. Indeed, intense human activities have broken the original ecological balance, and affected structures and functions of the river ecosystem [2]. Recognition of the degraded state of rivers across the world has prompted the development of management programs which promote river repair through rehabilitation practices [4]. To restore the damaged river ecosystem back to a healthy status, effective ecological restoration measures need to be implemented. Fortunately, streams and rivers restoration can lead to species recovery, improved inland and coastal water quality and new areas are defined as for wildlife habitat and recreation activities.

River restoration refers to a large variety of ecological, physical, spatial and management measures and practices. These are aimed at restoring the natural state and functioning of the river system in support of biodiversity, recreation, flood management and landscape development [5]. By restoring natural conditions, river restoration improves the resilience of the river systems and provides the framework for the sustainable multifunctional use of estuaries, rivers, and streams. Many different terms have been put forward to define and describe efforts to manage and adjust rivers, with three of the more common and relevant ones being restoration, rehabilitation, and enhancement [6] [7] [8] [9] [10]. The concept of a return to the preexisting natural state, as free from human interference as possible, is referred to as "river restoration" [6] [11]. Ideally, it means taking a river that has been disturbed or degraded by a specific human action (or set of actions) and altering the river back to a pre-action natural state. The natural state would not be defined simply in terms of structural descriptive characteristics or visually perceived stability, but in terms of the degree of functionality of essential, linked abiotic and biotic processes [12] [13] [14]. More specifically, river restoration is defined as "assisting the recovery of ecological structure and function in a degraded river ecosystem by replacing lost, damaged or compromised elements and re-establishing the processes necessary to support the natural ecosystem and to improve the ecosystem services it provides" [15]. River rehabilitation means changing a river from a degraded state to an improved state with more functional abiotic-biotic processes reminiscent of what existed prior to degradation [16]. River enhancement is defined as changing a river from a degraded state to an improved state based on identified ecological potential, regardless of site history. Some consider this a form of rehabilitation and do not make a distinction [6] [10]. With regards to river rehabilitation or enhancement, there may be a limited opportunity to eliminate underlying human perturbations, no matter how important they are, so the longevity of project benefits may be uncertain and limited or require active maintenance in perpetuity.

River restoration has become important as people have come to realize that alteration of hydrology, water chemistry, and biology of rivers has unintended consequences in urban and other areas. Such efforts require restoration of natural hydrology and understanding of how the dynamic equilibrium of geomorphology can be restored to lead to long-term stability of the system [17].

The Faleme, a West Africa transboundary river, rises from the northern part of Fouta-Djalon (in the Republic of Guinea), and flows in the direction of the North-North Est (NNE) to enter Mali. The river provides food and water needs for the people living near a "landlocked area". The same is true of the agricultural and pastoral potential it offers in addition to the seaworthiness that could make it economically profitable to exploit the mineral deposits of the basin. In addition, the Faleme also contributes an important part of the Senegal River to its estuary [18]. This large tributary of the Senegal River has experienced a serious pollution problem (due to mining) and a change in its hydrological regime.

In the Faleme basin, industrial exploitation by large gold mining companies such as Barrick gold, B2 gold, Iamgold, AngloGold Ashanti Limited etc.) and artisanal exploitation coexist. These gold-bearing activities contribute a significant way to the three countries economy but seriously degrade the environment, particularly water resources. Indeed, exploitation (especially artisanal gold) has caused terrible consequences on the river, particularly by disrupting the hydrological functioning of the river through withdrawals, direct discharges, dredging, pollution related to chemicals etc. Considering this situation, it is necessary to reflect on the means of restoration possible to ensure the sustainability of the services offered by the river.

Regarding this scientific context, the main objective of this paper is to present an overview of the actions and techniques that can be implemented for the restoration/rehabilitation of a West African river, the Faleme. The specific objectives are:

- Establishing the hydrological and hydrochemistry state of the river,
- Identifying the factors and causes of the perturbation of the river,
- Reviewing a series of natural and engineering methods for the rehabilitation and/or restoration of the Faleme river,
- Analyzing all methods to identify their strengths and weaknesses.

2. Material and Methods

2.1. Study Area

The Faleme catchment is situated between latitudes 14˚42'N and 11˚42'N and longitudes 12˚30'W and 10˚50'W in Western Africa (see Figure 1). The Faleme

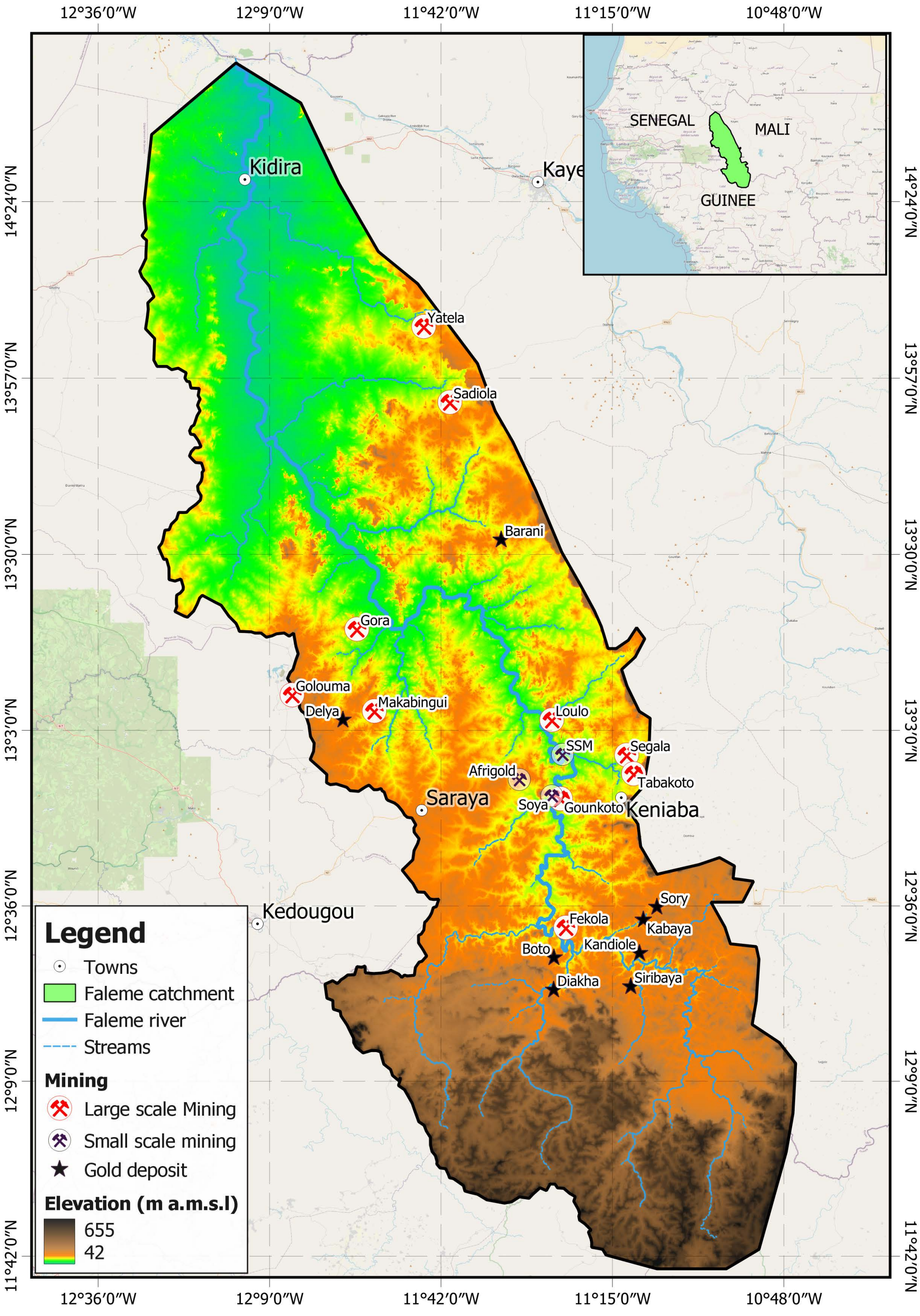


Figure 1. Study area.

is one of the main tributaries on the left bank of the Senegal River. Its watershed covers an area of 28,900 km^2, and is shared between three countries (Senegal, Mali, and Guinea). The river rises at an altitude of 800 m in an area of lateritic plateaus at the foot of the Fouta Djalon Mountains and extends for about 625 km until it meets the Senegal River. The Faleme covers three geographical and climatic domains (Guinean, Soudanian, and Sahelian) [19]. As the area have a south-north rainfall gradient with maximum in southern basin and minimum in northern basin, the Guinean domain is the wetter zone (highest rainfall average, above 1500 mm), followed by the Soudanian (intermediate rainfall average between 500 and 1500 mm) and the Sahelian (lowest rainfall average, below 500), respectively. The area is characterized by the alternation of two different seasons: a dry season from November to May and a rainy season from June to October with a rainfall of around 1000 mm/year and a maximum rainfall intensity in August (data from Senegalese national agency of meteorological, 2020).

As shown in **Figure 1**, the study area (The Faleme catchments) is subject to intense gold activity with world-class deposits and Artisanal and small-scale gold mining (ASGM) which proliferate along the rivers. The area contains several significant gold mines including Sadiola, Yalea, Segala, Tabakoto, Loulo-Gounkoto deposits in Mali, and Boto, Gora and Golouma in Senegal. For example, the Loulo-Gounkoto gold complex located in the investigated area, very adjacent to the Faleme river is an operating mine managed by Barrick Gold Corporation. It comprises two underground mines (Yalea and Gara) and a processing plant (5 million tonnes per annum (Mtpa) capacity) producing gold doré bars at Loulo, with a third underground mine and open pit operation at Gounkoto, in addition to a number of satellite deposits all located on the Faleme basin.

Within these large mines, mining is carried out using complex and sophisticated processes and techniques. The ore is mined from open pit or underground mines followed by transporting, stockpiling, crushing, and grinding, and then gold leaching using a standard carbon leaching method, to conclude with elution and electro recovery operations. The water supply is made from a pumping of the waters of the Faleme, even though for most companies a recycling system is set up. Mining waste made up of the extracted rock not used in the mining process is stacked in massive blocks, up to several tens of meters high in some cases. The leaching of these waste often causes environmental damage especially on the waters of the neighborhood by the phenomenon of acid mine drainage (if the leached rocks are sulphides).

Artisanal small-scale and semi-mechanized gold mining are also abundant in the study area (both in Senegalese territory and Malian territory). The gold washing techniques and tools used by the alluvial diggers are often very rudimentary; however, larger operations have become more sophisticated (e.g., use of pumps and digger-loaders to excavate material). The use of chemicals, particularly mercury and cyanide, is common at these sites where working hundreds of people of various nationalities are. **Figure 2** below illustrates some images of gold mining activities in the study area.

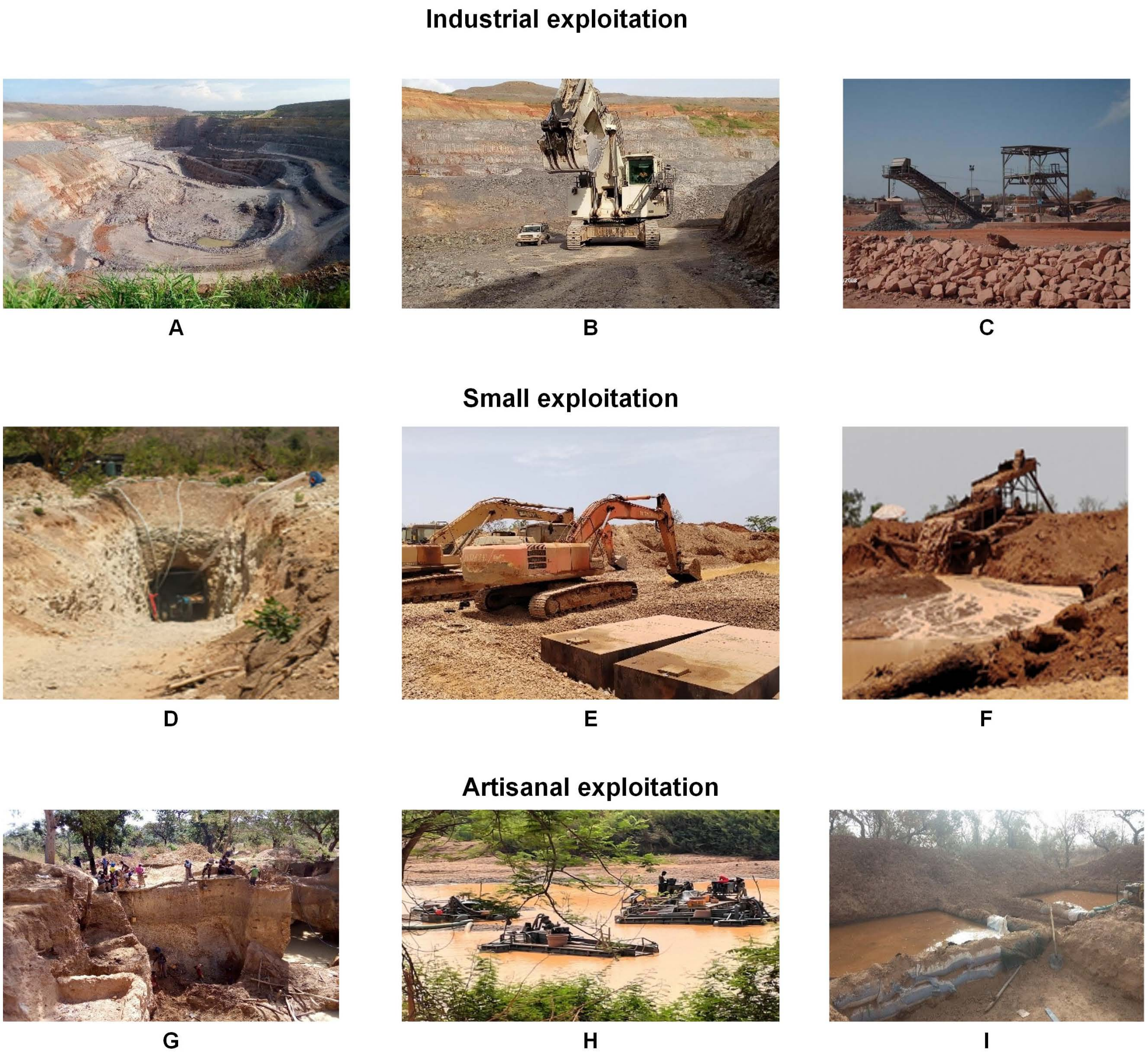


Figure 2. Illustrative images of gold mining in the study area: open industrial pit (A), ore loader machine (B), ore processing crusher (C), small scale underground gold mining (D, Excavator (E), Sluice (F), Artisanal gold mining site (G), River dredging (H), artisanal cyanidation basins (I).

2.2. Research Methodology

This paper uses a mixed methods approach to present an overview of the best actions and techniques that can be implemented for the restoration of the Faleme.

- First, it was conducted an in-depth literature review. Data and information were collected via a literature search through the internet from July to December 2023. The main key words used were: "River restoration", "River rehabilitation", "Restoration methods", "Remediation dredging", "constructed wetlands", "Faleme River" etc. For inclusion criteria considered it can be noted the quality of the document, the language of publication of the document (French or English exclusively) and also the presence of keywords in the document. Therefore, articles, books, and other publications were included in our review (see **Figure 3**).

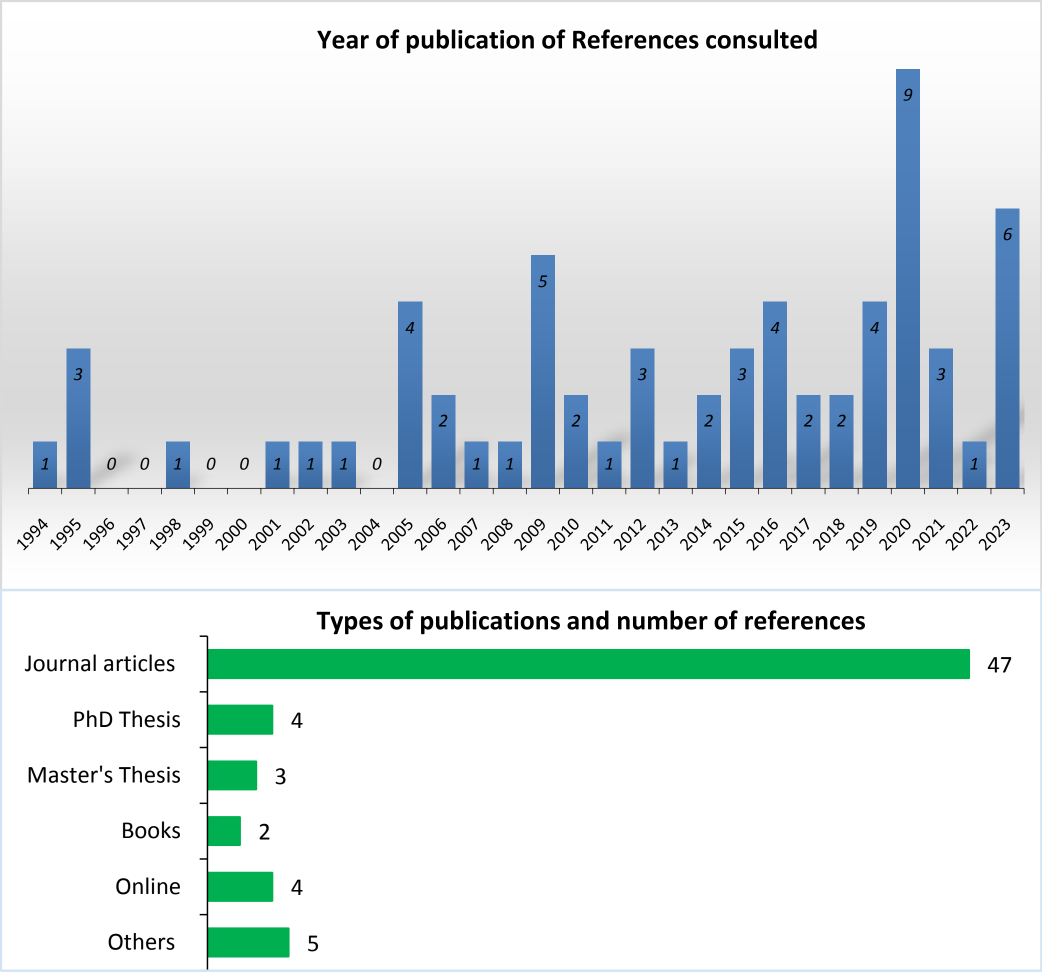


Figure 3. References review characteristics.

- Field missions are done to identify and characterize the typology of anthropogenic activities carried out alongside the river and the riverbanks which disrupt the quality and therefore, their availability of water resources (see **Figure 4**).
- In addition, surface water and stream sediments sampling were conducted during field campaigns in September 2022 and May 2023 in a total of eleven (11) sites (**Figure 5**). Standard sampling procedures have been used with blank and duplicate as quality assurance measures. The equipment used included: sampling bottles, coolers for sample storage etc. Once the samples are collected, they are stored in containers to stabilize the temperature at less than 4˚C until they are sent to the ALS lab in Prague (Czech Republic) where analysis are been undertaken. In this lab, water quality parameters are determined through Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-MS) and the stoichiometric calculations of the concentration of the compounds are made from the measured values following their internal process CZ_SOP_D06_04_001, standardized and certified by US EPA 200.7, ČSN EN ISO 11885.

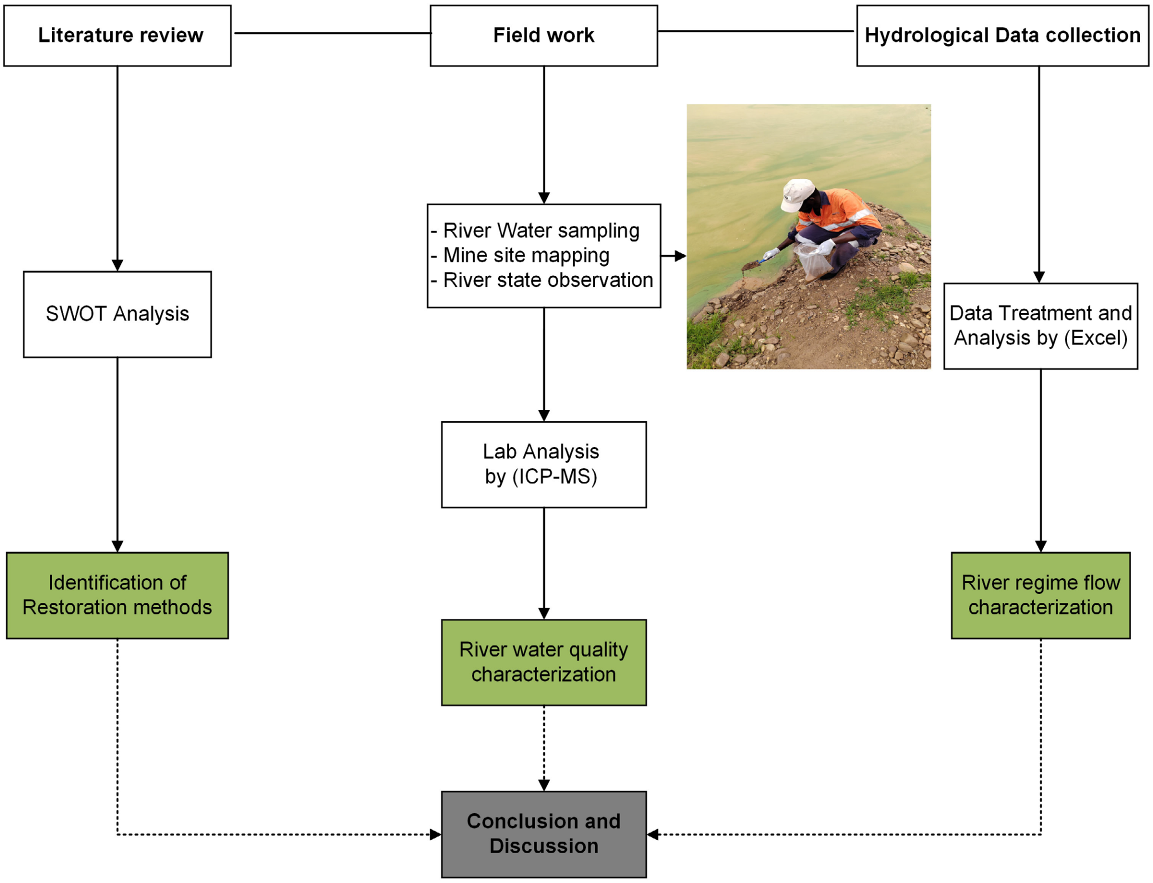


Figure 4. Global flowchart of the research methodology.

3. Results and Discussion

3.1. Characteristics of Faleme River

3.1.1. Flow Regime

The Faleme is a well-fed river on average, but extremely irregular with very large disparities in measured flows between the rainy and dry seasons [20]. The average monthly flow observed in May (low water level minimum) is only 0.5 m^3/second (500 liters), more than 1500 times less than the average flow in September (785 m^3/s), which shows its large seasonal irregularity (see **Figure 6**).

Over the 30-year observation period (1992-2022), the average annual flow varies from 34.89 m^3/s to 219.5 m^3/s at the Kidira station, a locality located 35 kilometers upstream of the final outlet of the basin. Similarly, the volumes of water flowing at this station vary from 1100 million m^3 to 6941 million m^3 which can be considered abundant. At the station of Gourbassi, located in the middle of the river, the flows are more modest and vary between 30 and 151 m^3/s. According to [19], the discharge at Gourbassi is influenced by climatic conditions in the Guinean and the Soudanian Zones, and the discharge measured at the main outlet of the basin (Kidira) which is more downstream, is under the influence of the all-climate domains of the basin. This justifies that Kidira has the highest values of river discharge than those at Gourbassi (**Figure 7**).

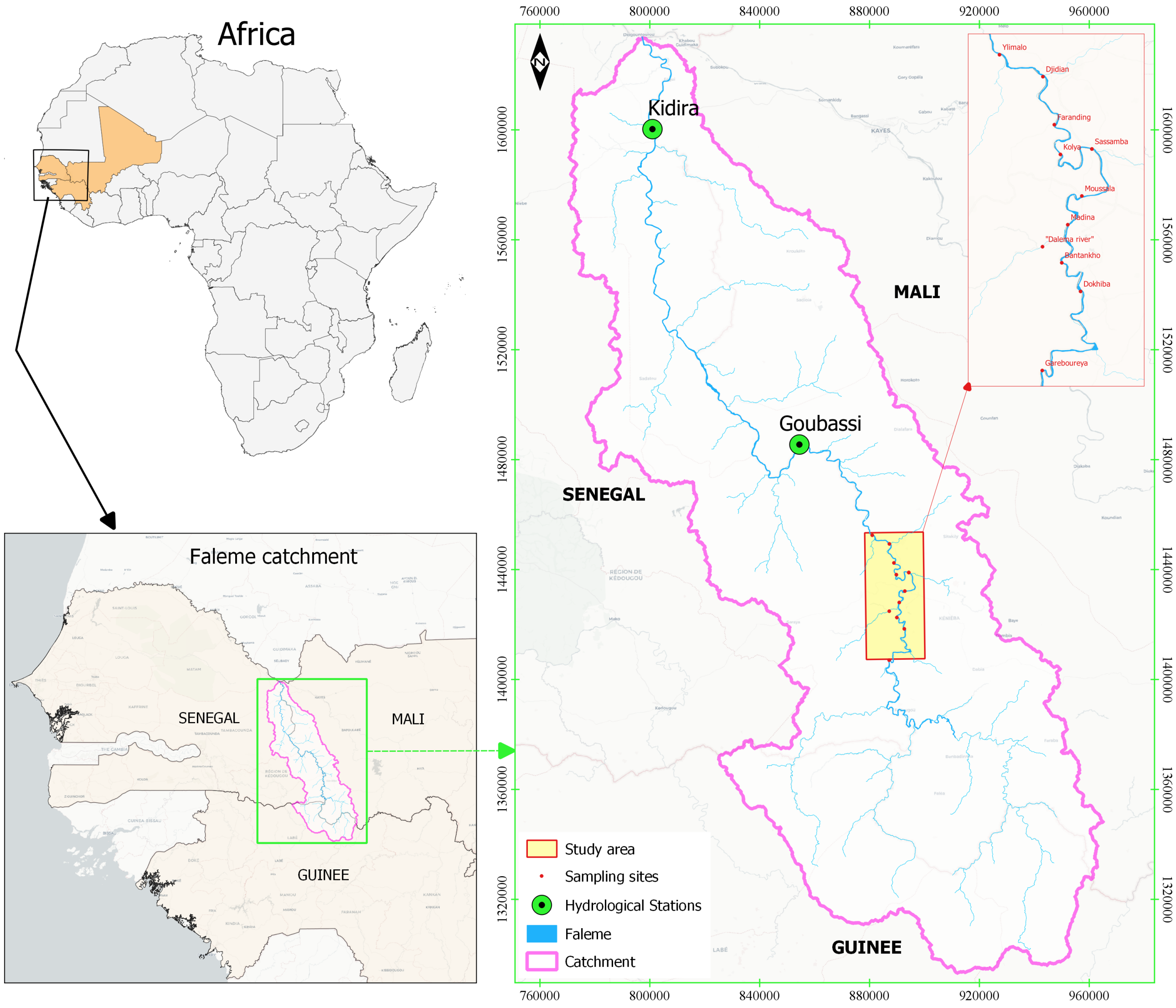


Figure 5. Map of the sampling area.

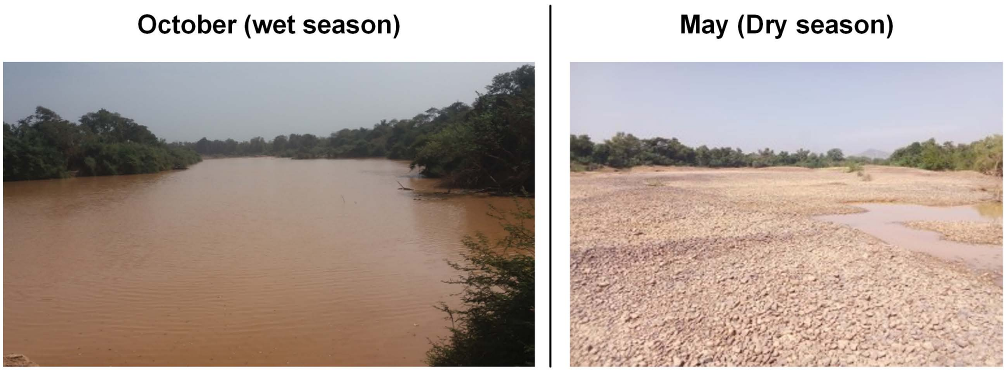


Figure 6. Irregularity of flow in the river between wet and dry season.

3.1.2. Hydromorphology

From a hydromorphological point of view, the Faleme River faces several major problems, the main ones being the erosion of the banks, the incision of the channel

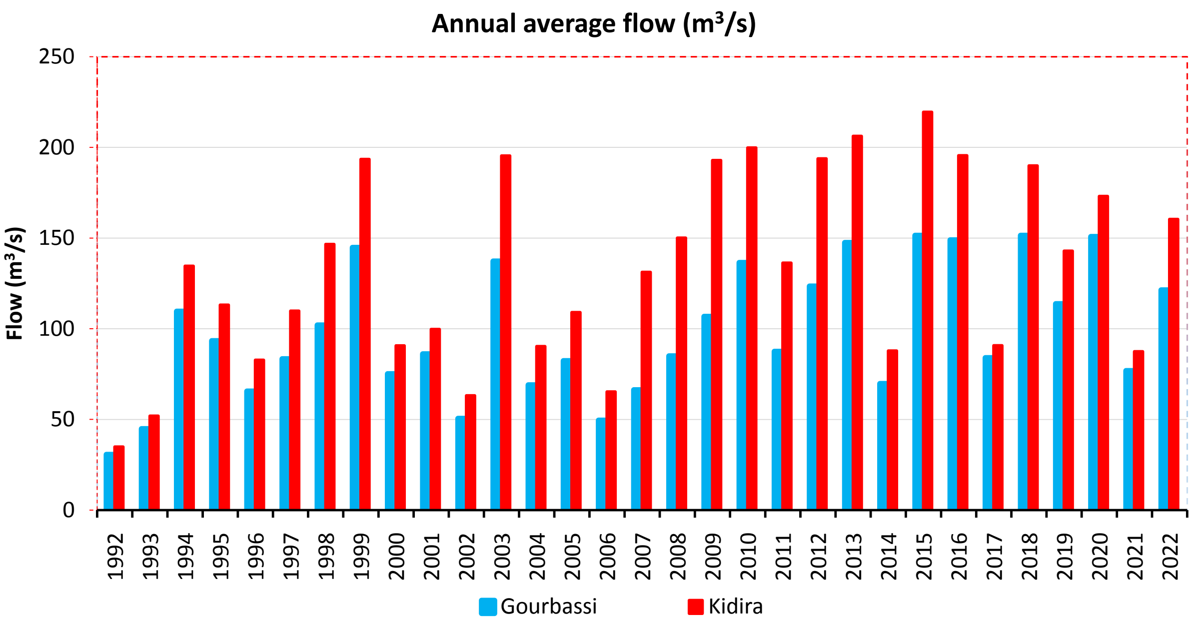


Figure 7. Annual average flow (m^3/second) in two stations of the Faleme River (data from Senegalese Direction of Water Resources Management and Planning (DGPRE)).

and the disconnection of the river annexes (e.g., dead arms, secondary channels). According to several authors [21] [22], erosion along the Faleme brings together a set of natural and anthropogenic factors that promote its appearance and accentuation in the locality.

- **Natural factors:** topography, lithology, pedology, vegetation and climate
- **Anthropogenic factors:** deforestation, overgrazing and unsuitable agricultural practices, bush fires, alluvial exploitation.

Along the Faleme, shoreline erosion is a worrying phenomenon [21]. Among the factors is the regression of vegetation cover along the banks accentuated by mining activities and its excessive tree cutting. Indeed, the presence of vegetation is a major element to be considered in the study of erosion and its impacts. According to the Food and Agriculture Organization (FAO) cited by [21] the role of vegetation acts in 2 ways: first the leaves break the kinetic energy of the drops and prevent them from hitting the soil directly, which is important in the fight against erosion. Also, the spreading of its roots attenuates the speed of runoff and increases the porosity of the soil. This prevents the formation of surface runoff. Finally, the falling leaves cover the ground and avoid the "splash effect". This gives it an antierosive function.

In addition to this, the bed of the Faleme has for the very long-time sheltered activities of extraction and washing of minerals because of the resources that it contains; but the phenomenon has experienced a considerable rise in recent years. According to [23], the impact of extractions in minor bed has been the subject of several studies that have shown that this activity can be the cause of severe hydromorphological and ecological degradation. Indeed, the imbalance between the available load and the carrying capacity of the stream which produces an incision of the channel and results in a change in the profiles across and along the stream. This alluvial extraction (**Figure 8**) therefore leads to a decrease in the frequency of flooding, the decline of riparian habitats, a degradation of aquatic habitats or water quality.

3.1.3. Hydro-Chemical Quality of the Faleme River

The laboratory results of water sampled in the dry and wet season showed that the Faleme River is affected by a constant deterioration of its quality. This results in contamination with heavy metals (iron, aluminum in all points) as well as zinc and arsenic in Sassamba (5.34 ppm) and Moussala (12.3 ppm). More importantly, there is an extraordinary presence of solid elements (**Figure 9**). These solid elements (dissolved and suspended) are present in exceptionally large quantities in water at all stations.

This pollution of surface water would be strongly linked to mining. Indeed, the extraction of alluvial ore, ore washing and leaching of mine waste are accompanied by a destruction of the banks and of massive contributions in sediments which can potentially enrich the water in suspended matter and metals (iron, al, Arsenic). In addition, the land disturbance undertaken by mining operators also promote the erosion of banks, which increases water pollution by solid elements.

For other elements such as mercury, nitrate and cyanides, the levels are low, which proves that mining uses these chemicals (or their derivatives), but that the proportions are low enough to change the quality of the stream. Thus, in the Faleme river the main problem is the quality of water and the presence of suspended matter. The figure below shows the levels of suspended solids in some stations in September 2023.

According to [23], the deposition of fine sediment in stream ecosystems is detrimental to aquatic organisms because of reductions in streambed substrate composition, permeability, and stability. For example, concentrations of suspended sediments that significantly reduced fish growth ranged from 100 to 1000 mg·L^{-1} [24], while higher rates were recorded on the river.

Figure 8. Alluvial gold mining on the bed of the Faleme.

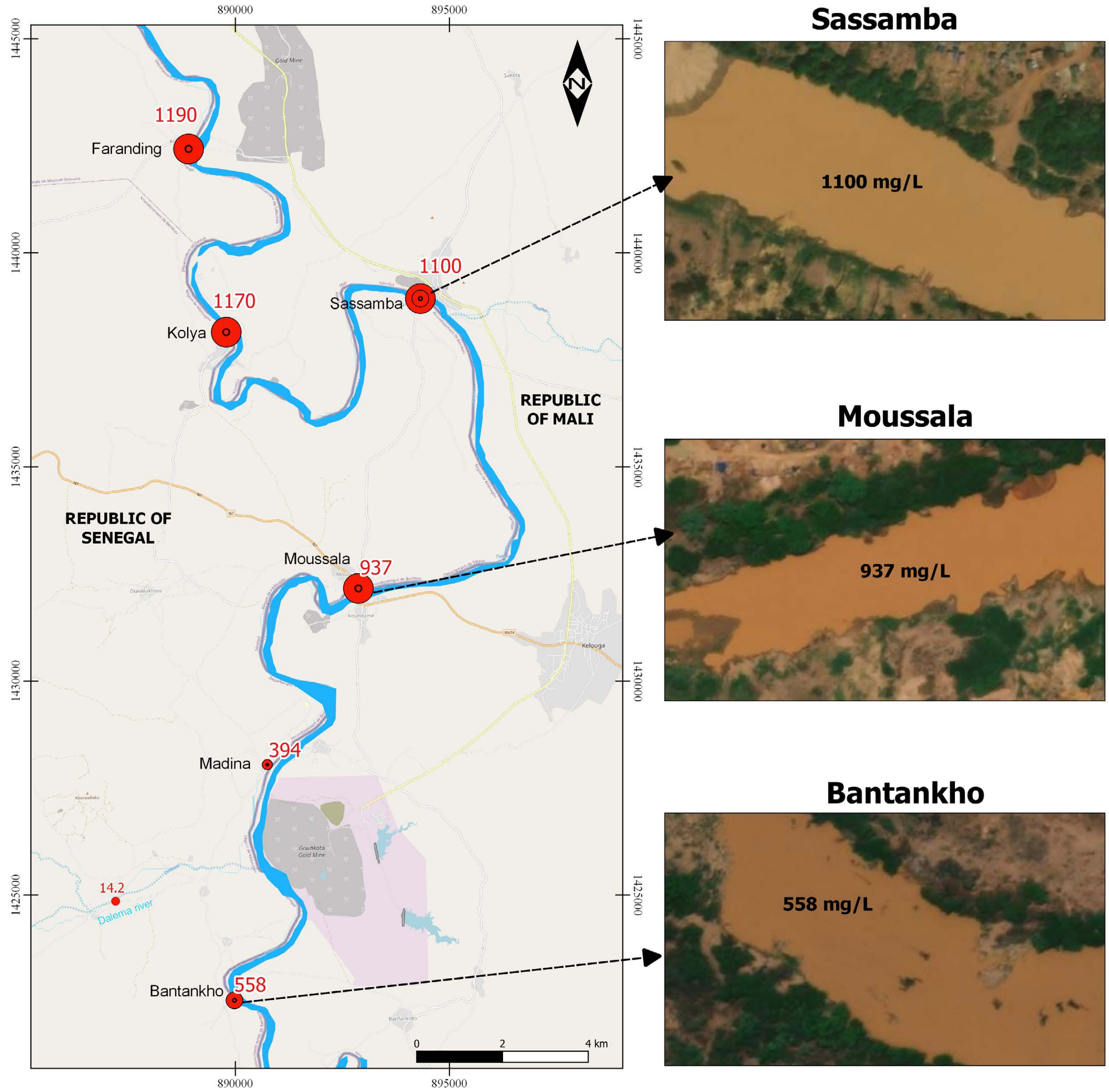


Figure 9. Total suspended solids (mg/L) in some stations of the Faleme River.

3.2. Restoration Methods

River restoration does not imply that rivers should be restored to a pre-industrial revolution state, which can be impossible because rivers naturally change over time and because of societal constraints [25]. With the improvement of people's awareness of ecological protection, new ecological restoration methods which meet multiple requirements (*i.e.*, flood control, ecological health, landscape, etc.) have been used. River restoration can be expensive, and yet its scientific foundations are often weak or of questionable validity [26]. River rehabilitation aims to protect biodiversity or restore key ecosystems services, but the success rate is often low. Most so-called restoration projects are, more properly, attempts to rehabilitate selected sections of riverine systems to a predetermined structure and function [27]. Contaminated Rivers can be restored by using different restoration methods. The selection of the preferred restoration methods depends on the physical, chemical, and biological characteristics of the river [1]. So, commonly used techniques for restoration of polluted rivers around the globe can be categorized into physical methods, chemical methods, and biological methods [1] [2].

- **Physical methods** which include sewage interception and dredging, covering, algae removal by mechanical methods, water diversion, etc.
- **Chemical methods** which include chemical flocculation, adding chemical algaecide, dosing lime, and in-situ chemical reaction technique; and
- **Biological-ecological methods** which include aquatic plant restoration, biomanipulation technique, aeration, microbial enhanced technique, bio membrane technique, activated sludge technique, land treatment technique, and so on.

Polluted river water exhibits odor, turbidity, lack of water transparency, high concentrations of chemical oxygen demand (COD), biological oxygen demand (BOD) and organic and inorganic contaminants. Selection of appropriate river water treatment methods is important for the restoration of river ecosystems.

In this article, the focus will be on 04 treatment systems that could be used in the context of the Faleme River. These four remediation techniques will be worked out to describe the processing, analysis their effectiveness and evaluate their benefits and limitations.

3.2.1. Remediative Dredging

Dredging means the process of removing accumulated sediment from the bottom or banks of bodies of water, including rivers, lakes, or streams. Dredging is also performed to reduce the exposure of fish, wildlife, and people to contaminants and to prevent the spread of contaminants to other areas of the water body. This environmental dredging is often necessary because sediments in and around cities and industrial areas are frequently contaminated with a variety of pollutants [28]. Remediation dredging, sometimes called environmental dredging, helps responsible authorities comply with present environmental standards for the removal of dangerous contaminants. The Sediment dredging technology refers to the removal of pollutants in contaminated sediment or sediment by physical methods (mechanical dredging or hydraulic washing), to reduce the release of sediment pollutants upward overlying water body and alleviate endogenous pollution, which is the most widely used treatment technology at present. This technique involves extracting sediments deposited at the bottom of the stream. The aim is to improve overall water quality and restore the health of aquatic ecosystems. The equipments used for this kind of operation called dredges are specialized pieces of equipment that create a vacuum to suck up and pump out the unwanted sediment and debris [29].

❖ **Operation process**

According to [30], the three main stages of dredging activities include excavation, transport, and disposal of sediments (**Figure 10**). These are successively repeated until a target quantity of sediments is dredged with each stage requiring different technologies. Dredging starts with the excavation of sediments at a site with hydraulic and/or mechanical cutter. Diverse types of dredgers are required for different sediments and depths, but similar extraction methods may be required for both capital and maintenance dredging, whether through suction or grab. Dredged sediments are then transferred into hopper barges or pipelines using suction pipes, conveyor belts, buckets, or grab.

❖ **SWOT analysis of river dredging techniques**

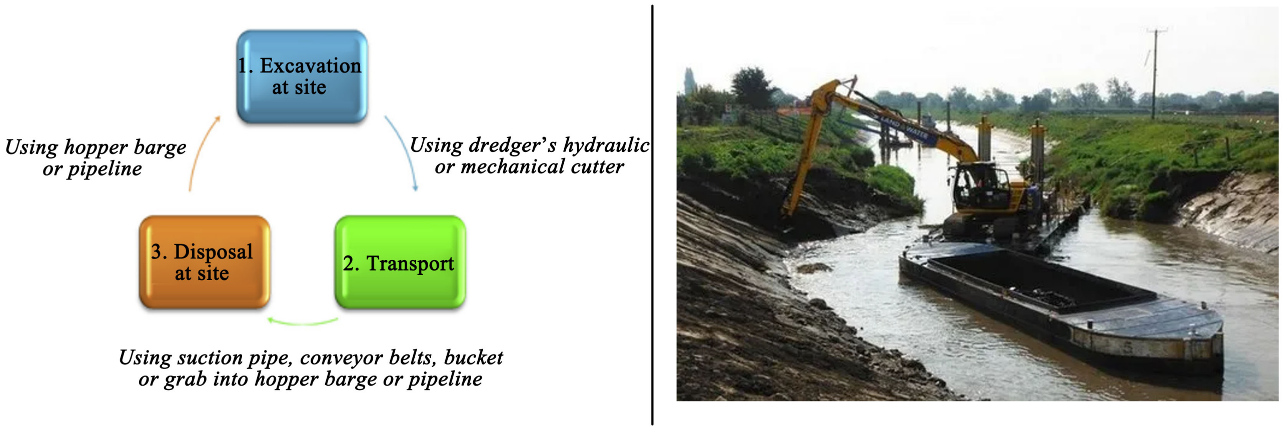
The technology has a quick effect on pollution treatment, but it is difficult to control the dredging depth accurately due to the large amount of engineering, high investment and easy to cause sediment re-suspension pollution of water. It is suitable for the restoration of some seriously polluted river sections with sediment [31]. Dredging is itself a highly complex industrial operation involving risks to human health and possibly the environment [32]. Due to the potential content of toxic substances in the sediment a key problem of dredging is how to dispose of the sediment. **Table 1** below summarizes the strengths and weakness of the dredging technique.

3.2.2. Biological-Ecological Methods

Ecological engineering-based techniques, such as plant purification treatment, ecological floating beds, artificial floating islands, and constructed wetlands, have attracted the greatest attention due to their overall economic, environmental, and ecological benefits, but these methods demonstrate variable performances to remediate polluted river water [33] [34] [35] [36]. The remediation of river water is a critical process which needs the combination of engineering and ecological technologies for successful treatment of river water.

❖ **Constructed wetlands**

Constructed wetlands are artificial and nature-based solutions designed to improve water quality while preserving biodiversity [37]. They are configured to



Stages of dredging (Highley et al., 2007; Verbeek, 1984 in Manap, 2015)

River dredging operations (source: www.indiamart.com)

Figure 10. Stages of dredging [30], river dredging operations.

Table 1. SWOT analysis of river dredging techniques.

Strengths	Weaknesses
- Reduces the amount of nutrients in sediments that are beneficial to plant development. - Prevents infilling of the stream - Slows the eutrophication dynamics of the stream. - Improves airworthiness in the river. - Positive impacts in long terms (6 to 24 months after dredging) for heavy metals reduction.	- Excessive cost of operation. - Short term negative impacts (turbidity, Resuspension of sediment, saturation of water with toxic metal).
Threats	**Opportunities**
- Potential effects of dredging on living organisms. - Problems of treatment and disposal of extracted sediments.	- Environmental assessments of the removed sediments - Need to develop process environmentally friendly: - Dredging techniques are often costly; however precise dredging can lower the dredging cost by determination of dredging depth based on the pollution level prior dredging. This method can also provide a favorable environment for the benthos, - Re-use or remediation of contaminated dredged sediments.

enhance the processes and interactions that occur in natural wetlands between water, plants, microorganisms, soils, and the atmosphere to remove contaminants from polluted waters in a relatively passive and natural manner. Constructed treatment wetlands typically involve flow of contaminated water through the shoots (surface-flow or free-water surface) or root-zone (subsurface-flow or submerged bed) of emergent species of sedges, rushes, and reeds. Constructed wetland systems can also be combined with conventional treatment technologies to provide higher treatment efficiency [38]. **Figure 11** below presents a Schematic diagram of Constructed wetlands.

❖ Floating treatment wetland

This system that has several other calls (Ecological floating beds, artificial floating islands etc.) is a relatively new technology that does not use soil for a plant growth medium [40]. Instead, it uses a synthetic buoyant mat, which acts as a substrate for the growth of plants and roots extending into the water body. It uses ecological processes and can be used as decentralized in-stream water reclamation technology [41]. It's a popular and sustainable technology for the treatment of river water, particularly for polluted rivers that experience water level fluctuations and waves [34]. These techniques need minor engineering works, but their maintenance is easy, and they show significant efficiency in the treatment of polluted river water without any secondary pollution problem [42]. The plants and microbes grown in and around the plant roots of floating beds help to remove pathogenic microorganisms, nutrients, heavy metals, and organic compounds from water [43] [44]. The primary removal mechanisms in these plants-microbe's interactions are decomposition, assimilation, denitrification, sorption and entrapment in roots and sedimentation [45].

Figure 12 presents a description of floating treatment wetland processing.

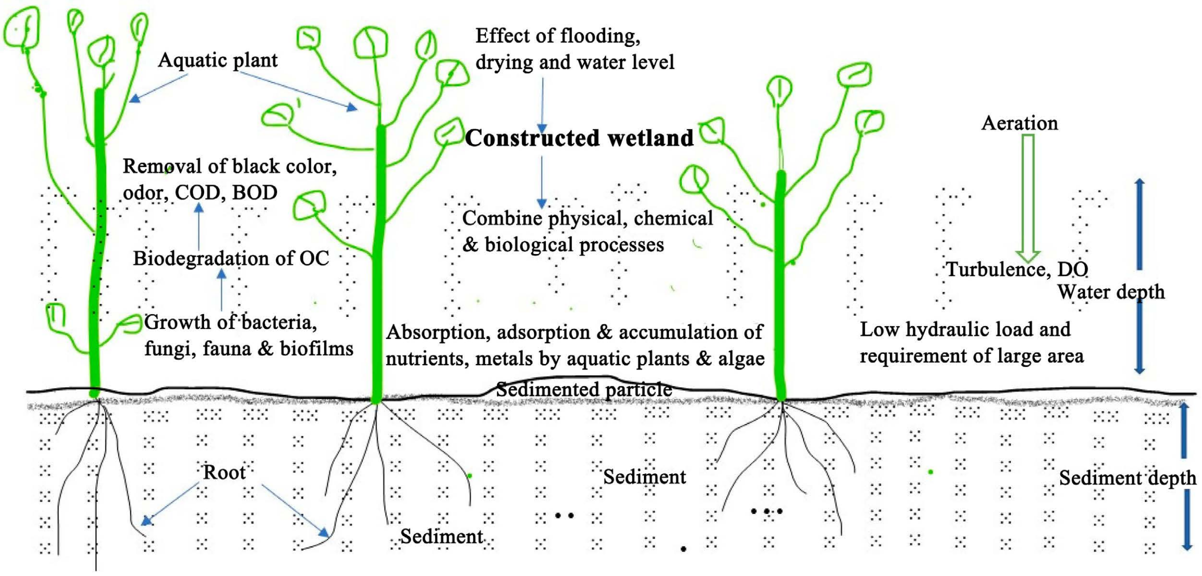


Figure 11. Schematic diagram of constructed wetlands [39].

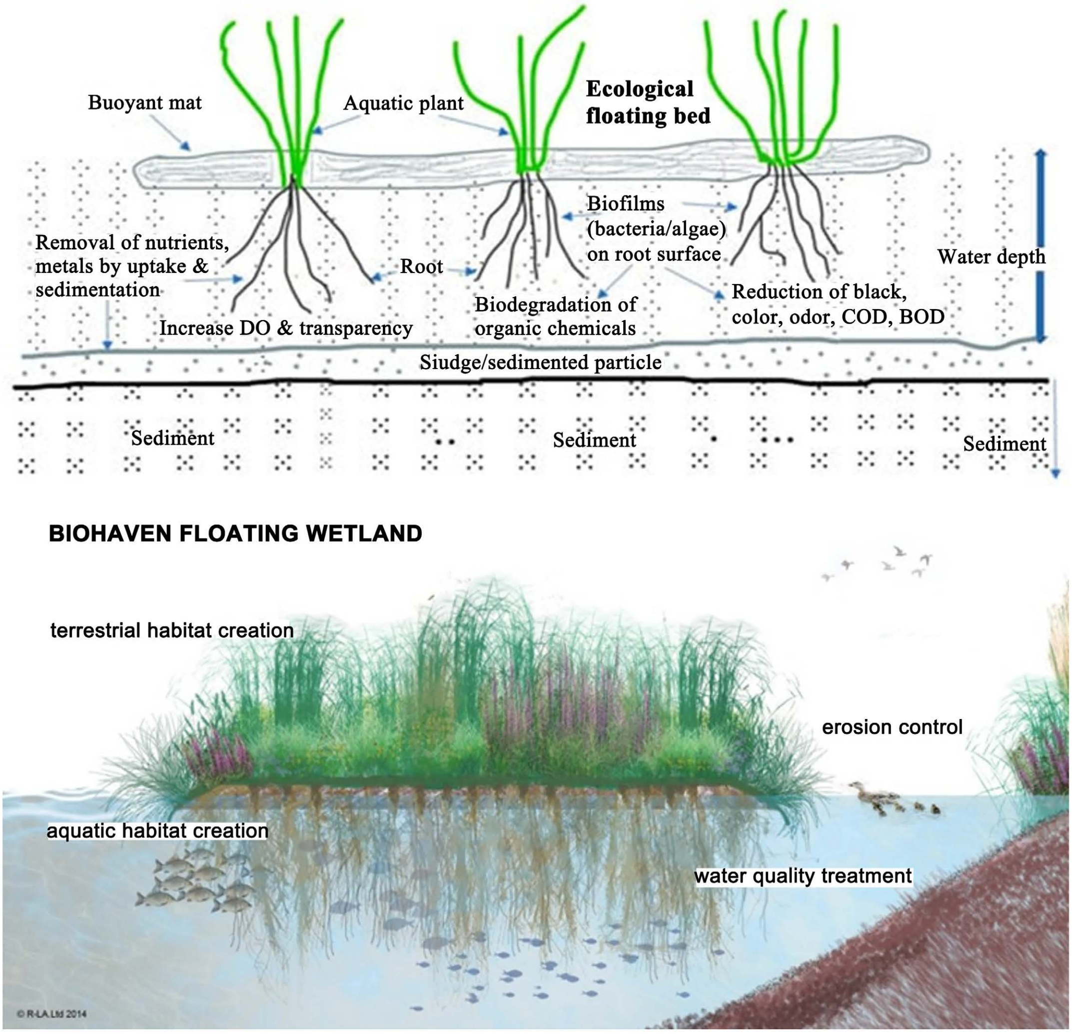


Figure 12. Floating treatment wetlands [39] [46].

❖ Biological-ecological Processes descriptions

Constructed wetland systems entail a properly designed and constructed basin that holds water, a substrate that provides filtration pathways, habitat/growth media for the needed organisms, and communities of microbes and aquatic invertebrates, which in most cases develop naturally. Most importantly, constructed wetlands also hold vascular plants whose nature depends on the intended purification role and efficiency [47]. Depending on their location, constructed wetlands are divided into two categories: off-stream and in-stream wetlands (**Figure 13**). Off-stream wetlands are constructed near a river or stream where only a portion of the river flow enters the wetland. On the other hand, in-stream wetlands are constructed within the riverbed, and all flows of the river enter into the wetland [48]. Constructed wetlands remove the emerging contaminants through the complex physical and biogeochemical processes that include volatilization, sorption, sedimentation, phytoremediation, uptake by plants, and microbial destruction. The microbial degradation and adsorption of contaminants in soil, mineral surfaces, and biofilms depend on the physicochemical properties of the chemicals, sorbent properties, pH, temperature, ionic strength, redox species, and the presence of cosolutes [49].

For floating treatment wetlands, the raft can be constructed in several ways, if they provide buoyancy, support to the plants, and anchoring possibility. Typical materials are various plastics, as in commercially available Beemats (Beemats

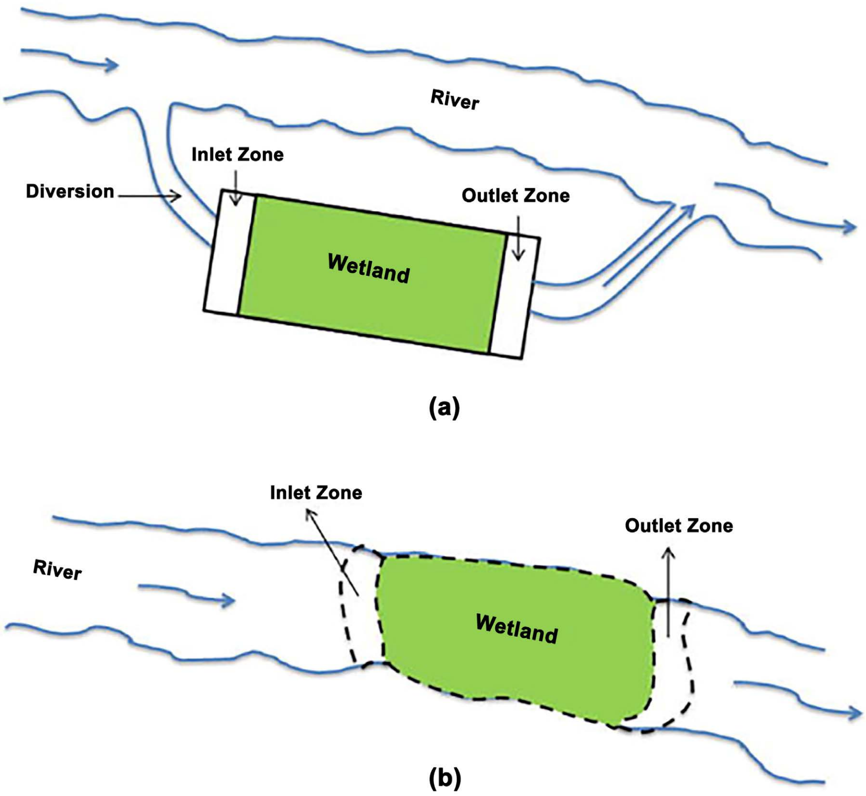


Figure 13. (a) Off-stream river diversion wetland and (b) in-stream river diversion wetland [48].

LLC, New Smyrna Beach, FL) and Bio Haven floating islands (Floating Island International, Inc. Shepard, MT). Other types of constructions, predominately used in research projects, are buoyant frames consisting of drainage pipes, bamboo, glass foam or stainless-steel pipes, surrounding a plastic or metal net which supports the substrate. The substrate supports and stabilizes plant roots, provides surface area for biofilms together with the plant roots, and can, dependent on the material, also absorb pollutants. Organic substrates, such as soil, coconut coir, or peat, also provide nutrients and water-retaining capacity for newly established plants [50].

FTWs improve water quality by several mechanisms that are based on macrophytes, root systems, microorganisms, and floating rafts like a constructed wetland, nutrients and other pollutants are incorporated gradually into biomass and withdrawn from the aquatic ecosystem [51].

Plant roots are believed to play a key role in treatment processes within floating wetland systems because the water passes directly through the extensive root system hanging beneath the floating mat (**Figure 12**). Hence, one of the key pathways for contaminant removal in floating wetland systems is believed to occur via the sequential processes of release of extracellular enzymes, development of biofilms and promotion of flocculation of suspended matter, at the surface of the submerged plant organs. Other processes that may be important include plant uptake of nutrients and metals, enhancement of anaerobic conditions (and associated biogeochemical processes) in the water column beneath the floating mat, and promotion of settling and binding of contaminants in the sediment pool [52]. Gravitational settling is responsible for most of the removal of suspended solids.

- **SWOT analysis of bio-ecological techniques**

Table 2 and **Table 3** describe the strengths, weaknesses, opportunities, and threats of the 2 bio-ecological techniques.

- **Examples of application**
  - **Constructed wetlands**

In their study, [33], built a sequential combination system of the floating bed constructed wetland (FBCW) + horizontal subsurface flow constructed wetland (HSFCW) + surface flow constructed wetland (SFCW) to purify the polluted water of Yitong River, using the favorable terrain of the park on the shore (**Figure 14**). Given the low removal rate of single constructed wetland, they sequentially constructed floating bed wetland, horizontal subsurface flow constructed wetland and surface flow constructed wetland for the treatment of urban river water. The combination of three wetland systems effectively removed COD, NH_4^+-N, TN (total nitrogen), TP (total phosphorus) and SS (Suspended Solids) from river water. In the Yitong River, the designed capacity and the hydraulic loading of the system were 100 m³/d and 0.10 m³/m²d, respectively. The hydraulic retention time was approximately 72 h. The monitoring results, from April to October in 2016, showed the multiple wetland ecosystem could effectively remove chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total

Table 2. SWOT analysis of constructed wetlands techniques.

Strengths	Weakness
- High potential for the remediation of physics and organic pollutants [33] [49] [53]. - low running cost, - easy maintenance, - no secondary pollution, - CW can tolerate fluctuations in flow, - sustainably facilitate water recycling and reuse, - Provide favorable habitat for many wetlands organism [47].	- Require a large area. - have low hydraulic load and - exhibit intolerance to heavy pollutant loading rate [33], - Seasonal death and plant diseases - Seasonal variation of the treatment efficiency
Threats	**Opportunities**
- Continuous input of pollutants can cause an exceedance of the wetland and reduce the system's ability to perform treatment efficiently.	- Use of CW for river treatment is a recent development, therefore, there is yet no consensus on the optimal design of wetland systems, and not much information on their long-term performance. - Need to reinforce the choice of plants species, - Resolve the problem of saturation, - Optimize the treatment to reduce the large area required.

Table 3. SWOT Analysis of floating treatment wetlands.

Strengths	Weaknesses
- cost effectiveness, - Good removal efficiency and better plant accommodation facilities. - Planted floating bed systems effectively remove nutrients and increase dissolved oxygen (DO) and transparency in urban river water [54]. - Show ability to remove organics, nutrients, heavy metals, and emerging trace pollutants such as antibiotics, pesticides, and hormones without land requirement [55]. - Contribute to carbon sequestration. - Systems movable can be deployed anywhere in the river. - Provides refuge for birds, macroinvertebrates, and fish. - Adaptability to a variety of environmental conditions [51].	- Chemical properties of water bodies can be affected by the floating rafts. Low dissolved oxygen (DO) conditions may occur in the water column under the floating wetland. - Vulnerability of raft and buoyancy to strong waves which may seriously damage the structure. - Risk that biomass accumulation may exceed the buoyancy provided by floating rafts. - Water purification efficiency may be limited by the performance of plants and microorganisms. - Oil contaminants if present in river water can damage the plant roots system.
Threats	**Opportunities**
- Risk to ecosystem integrity: for example, if invasive species were introduced by FTWs and other practices, these plants could form monotypes and significantly affect biodiversity, ecosystem function, and human uses of the affected environments [51].	- Improve the raft stability and resistance to high water flow, - Increase FTW processing capacity to accommodate large rivers.

nitrogen (TN), total phosphate (TP), and suspended solids (SS) at average removal rates of 74.79%, 80.90%, 71.12%, 78.44%, and 91.90%, respectively. The removal rate of SS in floating-bed wetland was the largest among all the indicators (80.24%), which could prevent the block of sub-surface flow wetland effectively.

○ **Example of floating treatment wetlands**

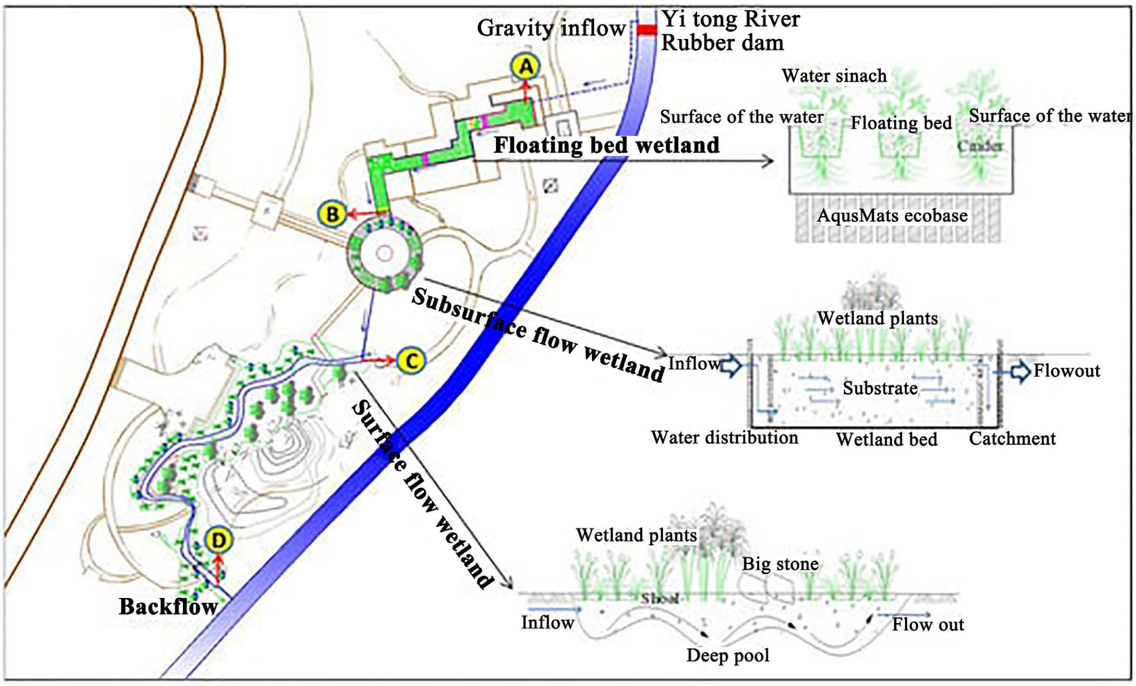
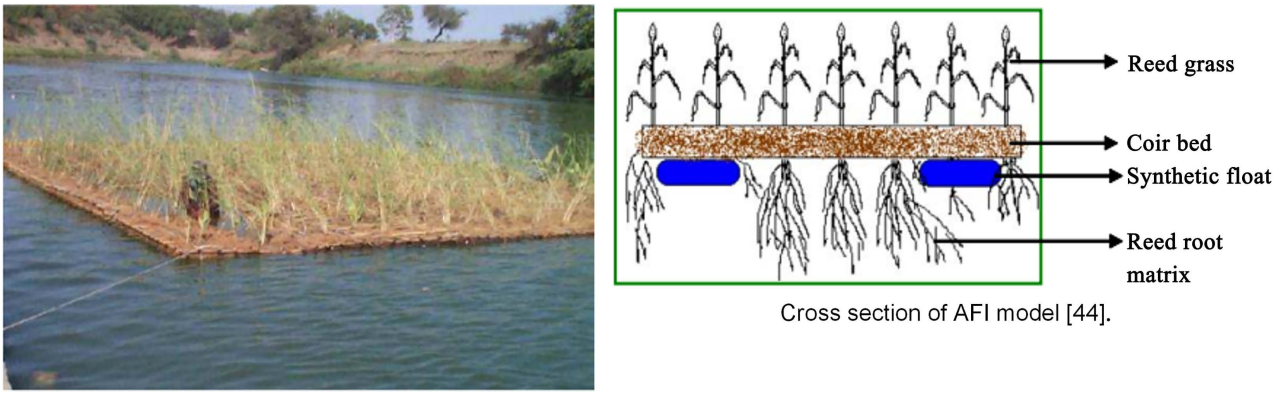


Figure 14. Floating tratment wetland (FTW) design [33].

Floating treatment wetlands also called artificial floating islands (AFIs) are artificial buoyant superstructures vegetated with riparian plant species, especially reed grass (*Phragmites karka*) floating on waterscape. These structures are mostly installed in lakes and stagnant systems as a green technology for water quality improvement. In his study, Professor Billore of Vikram University in Ujjain, has installed an AFI (Artificial floating islands) in the River Kshipra, Ujjain city at a point where wastewater nullah meets the river. The AFI of 200 m^2 (20 × 10 m) of floating wetlands was constructed and installed with close networking of 100 small platforms unit of size 2 m^2, in the least turbulent part of the river Kshipra (**Figure 15**). The floating rafts are constructed locally using low-cost materials such as bamboo. Onsite treatment methods like artificial floating islands (AFIs) are the latest innovations in restoration of degraded water bodies [56] [57]. The concept of reed beds evolved from constructed wetlands and natural floating islands that are similar to hydroponics [58]. In 2009, the experiment with the mesocosms with treatment of River water resulted that floating unit was reducing pollution load by 55% - 60% of TS, 45% - 55% of NH4-N, 33% - 45% of NO_3-N, 45% - 50% of TKN (Total Kjeldahl Nitrogen) and 40% - 50% of BOD. The Artificial floating islands may be recommended as an in-situ, eco-friendly river water treatment structure for small shallow, slow flowing (or slightly stagnant) water bodies [59].

In 2020, experiments showed that the installation of AFIs improved the underneath water quality: reducing the pollution load by 46% of total suspended solids (TSS), 51% of turbidity, 37% of total Kjeldahl nitrogen (TKN) and 39% of biochemical oxygen demand (BOD) and formed an additional floating niche for aquatic macroinvertebrates [58].



Cross section of AFI model [44].

Figure 15. Design of the FTW (AFI) model.

3.2.3. Chemical Treatments

Chemical remediation is to inject chemical modifiers into polluted rivers, through chemical reactions between chemicals and pollutants to produce neutral substances without pollution to the environment, to remove pollutants in the water and repair the ecological environment of rivers. The chemical purification method is quick in effect, high in repair efficiency and easy to operate. However, since the chemical agent is added, the treatment cost is large, and it is easy to cause secondary pollution. It is applicable to the restoration of water bodies that require emergency treatment, generally only as an emergency measure [31]. The technology of chemical remediation includes many techniques such as flocculation-coagulation, adding chemical algaecide, dosing lime, and in-situ chemical reaction technique [2].

❖ **Flocculation and coagulation**

Coagulation-flocculation is a conventional pre-treatment method (typically in combination with sedimentation and rapid sand filtration) used to separate the suspended and dissolved compounds (turbidity) from the water in (semi-) centralized drinking water treatment plants. The flocculation and sedimentation method could be used to treat water with many suspended solids and algae, which was simple to operate, easy to maintain and effective to treat. Coagulation-flocculation processes facilitate the removal of suspended solids and colloids by collecting them in the form of floc whose separation is then carried out by settling, flotation and/or filtration systems. Thus, by applying flocculation-coagulation, the objective is: total elimination of suspended matter and complete discoloration.

❖ **Coagulation-flocculation mechanism**

Suspended particles are destabilized by addition of a clarifying agent leading to the neutralization of their charges. Particles thus agglomerate (flocs formation) and can decant. In industrial processes where it is usually used, coagulation process consists of two different steps: 1) rapid mixing for coagulant dispersion into water/wastewater with severe agitation, 2) slow mixing to convert small particles into clear flocs. The purpose of the coagulation is instability of the suspension, which causes agglomeration, while flocculation forms larger agglomerates. After flocs settling and its elimination as sludge, supernatant wastewater is moved to next treatment processes or discharged into a watercourse [60]. Coagulation-flocculation yield strongly depends on the process parameters. Optimization of important parameters, such as initial pH, coagulant, or flocculant dosage, settling time, mixing parameters, and temperature are required for efficient coagulation-flocculation. Initial contaminant concentration is also one of the process parameters. Coagulation is therefore the destabilization of colloidal particles by the addition of a chemical reagent, the coagulant, which provides multivalent cations, free or bound to an organic macromolecule. To be effective, the coagulant must be immediately dispersed in water to obtain a homogeneous distribution of the latter and before any precipitation of hydroxide [61].

Table 4 below summarizes some coagulants and flocculants used in industrial water processing.

❖ SWOT analysis of COF techniques

Chemical treatment of polluted water by flocculation, precipitation, oxidation, and algaecides can remove suspended solids (SS) and algae. Chemical processes provide a quick remediation of polluted river water, but it is only temporary and significant, not a permanent remediation measure [34], and may produce secondary wastes, which can create other hazards. Therefore, flocculation or precipitation processes should focus on the use of environmentally safe chemicals for destruction of suspended solids and algae by chemical treatment [39]. **Table 5** below summarizes the strengths and limitations of coagulation-flocculation technology.

❖ Examples of application

Table 4. Coagulants and flocculants used in industrial processing.

Coagulation: destabilization of colloids by neutralization of electrical charges. Common reagents:	**Flocculation**: agglomeration of neutralized particles. This phenomenon is naturally slow. It can be accelerated by the addition of reagents called flocculation adjuvants.
- Aluminum sulphate (alum) - WAC (Basic aluminum chloride) - Ferric chloride - Ferric chlorosulfate	- Activated silica. - Alginate - Mineral Charges - Starch - Anionic polyelectrolytes

Table 5. SWOT analysis of COF techniques.

Strengths	**Weaknesses**
- Simple technology - High efficiency in removing charged suspended and dissolved particles. - Low cost - Removes solids and improves filtration.	- The infrastructure costs and pharmacy costs were high, meanwhile, it is noted that use of flocculants can result in secondary pollution [62] - Continuous input of chemicals required. - Skilled operators required.
Threats	**Opportunities**
- waste maybe toxic if contains heavy metals	- Specific components can be removed.

[63] applied chemical oxidation-flocculation technology (COF) for enhanced treatment of polluted river water in Dongguan, China. Through jar tests and plant scale experiments, they successfully evaluated the efficiency of this technique. The outcomes of their study show that the removal rates of COD, BOD_5, TP and NH_3-N by COF process were 71.2%, 77.4%, 91.1% and 68.7%, respectively, which can meet the municipal wastewater discharge standard [2].

3.2.4. Administrative and Management Measures

River restoration measures are divided into management measures and engineering technical measures. The management measures can effectively control the pollution from land sources into rivers and strengthen the protection of river ecological environment. The engineering technical measures are to repair and restore the degraded river ecosystem. In the context of the Faleme river, regulations services (Senegal River Development Organization (OMVS)) can adopt following measures inspired by those proposed by [31]:

First, the prohibition of certain forms of exploitation: alluvial exploitation, dredging, use of chemical goods for ore processing.

Second, it should strictly enforce administrative law and resolutely put an end to the indiscriminate dumping of garbage and sewage into rivers and lakes. Water administrative departments in all the three states should conscientiously implement relevant laws and regulations, conscientiously enforce laws and regulations, strictly enforce the law, investigate violations of the law, and do a decent job in river to prevent pollution.

Third, it should strengthen the monitoring and assessment of river section water quality. Environmental protection departments and water departments at all States should strengthen the monitoring and management of river water quality, set up water quality monitoring stations scientifically, carry out full-time and dynamic monitoring of river water quality in time and space, formulate measures for water quality assessment and management, set up reward and punishment measures and punish administrative areas where rivers do not meet the standards in accordance with relevant regulations.

Fourth, it should regulate rivers, ensure the ecological base flow of rivers, and enhance river connectivity. Over-exploitation and monopoly control of surface water resources should be curbed. The OMVS should exercise its jurisdiction to formulate water resources dispatching plans, water distribution plans and water system dam management and dispatching plans in accordance with the river basin distribution map, so as to ensure the basic ecological base flow of rivers and maintain the water system self-purification capacity, and at the same time strengthen the planning and construction of water system connection projects, so as to realize the goal of incorruptibility of running water and continuous improvement and enhancement of river water quality.

4. Discussion

The Faleme River, a 625 km long transboundary stream, has an abundant flow

(>1100 million m^3) but extremely irregular. In addition, the river is affected by severe erosion and degradation of its quality by suspended elements (TSS > 1100 mg/L) and heavy metals such as iron, zinc, aluminium, and arsenic. Therefore, selection of an appropriate river water treatment is important for the restoration of the Faleme river. The 04 methods presented in this paper inherently have each of the advantages and limitations. All methods have proven their effectiveness in treating rivers, the differences will lie mainly in costs, the durability of the technique (causes a second pollution?) and social acceptance. In the case of the Faleme River, however, some obstacles or blocking factors must be considered to ensure the success of operations. The first blocking factor is the extent of the river. In fact, most restoration projects are small scale (implemented on less than 1 km of stream length), and information on their implementation and outcome is not readily accessible.

As the Faleme River is disturbed over tens of kilometers, the complete restoration may be exceedingly difficult, long, and extremely expensive. Regarding costs, it appeared from the literature that restoring a river can be excessively expensive. According to [64], in France as in Germany, the average "restored" river length is shorter than 1 kilometer. In contrast, the project costs are high (the median cost is over 100,000 Euros). In Switzerland, the government budget allocated for river restoration (CHF 1200/meter) is insufficient to cover the cost of local restoration project [65]. These costs, however, depend on the option chosen. From the SWOT analysis that was performed and according to [39] it is recognized that:

- River dredging is effective but is cost intensive and detrimental to river ecosystems.
- Chemical treatments are high cost and are short-term solution and potential for secondary pollution.
- Ecological engineering-based techniques are preferable due to their high economic, environmental, and ecological benefits, their ease of maintenance and the fact that they are free from secondary pollution. Constructed wetlands and ecological floating beds (floating treatment wetlands) are the most widely applicable ecological techniques, although some variabilities are observed in their performances. In fact, constructed wetlands require a large area, have low hydraulic load and exhibit intolerance to heavy pollutant loading rate.
- Floating treatment wetlands are highly recommended for their low cost, high effectiveness, and optimum plant growth facilities. However, Vulnerability of raft and buoyancy to strong waves and flow is the main weakness that must be mastered to ensure the success of operations.

Beyond the method, any restoration project depends on several other factors including local site conditions. The Faleme River is characterized from this point of view by several constraints like the high channel erosion from natural and anthropogenic origin, enormous quantities of sediments and by the heterogeneity of ecosystems and substrates (gravelly, muddy etc.) which could make remediation more expensive. In addition, the high occupation of the riverbed is almost incompatible with some restoration initiatives such as dredging and the establishment of constructed wetland or artificial floating island. The success of a restoration project must require full ownership by all stakeholders: States, local authorities, technical and financial partners, local economic actors (for example gold miners), natural area conservation structures, research institutions and especially communities. In fact, according to [4], community and stakeholder involvement is a key component of effective practice. Integration of knowledge and understanding of the interactions between the biophysical and social dimensions of river rehabilitation are integral considerations in this process. The context of Transboundary River is a priori a major constraint.

5. Conclusions

The objective of this study was to present an overview of the actions and techniques that can be implemented for the restoration/rehabilitation of a West African river, the Faleme which is facing a major problem of degradation. However, this river provided important services for the human communities in the three countries, for domestic uses and in agriculture, fauna and livestock drinking source and artisanal and industrial mining activities. The river once housed an important aquatic biodiversity many fish species and mammals (hippos in particular). To ensure the sustainability of these services, it is important to take measures to rehabilitate it. In this context, this study has investigated first the river water quality and regime flow to establish the hydrochemical and hydrological state of the river. It appears that, the stream is not contaminated by chemical substances from mining activities but is seriously by physical pollution with high rate of suspended solids and the presence of iron, aluminium, arsenic, zinc. For the remediation, the study has explored 4 methods: river dredging, constructed wetlands, floating treatment wetlands and chemical precipitation (coagulation and flocculation). It was illustrated through description of their mode of operation, some case studies presented and SWOT analysis performed, that all the four methods have proven their effectiveness in treating rivers (in particular may reduce suspended solids in water) but have differences in their costs, their sustainability (detrimental to living organisms or causing a second pollution) and social acceptance. They have also weaknesses and issues that must be addressed to ensure success of rehabilitation. For the case of the Faleme river, after analysis, floating treatment wetlands seem to be the best for their low cost, good removal efficiency if the vulnerability of the raft and buoyancy to strong waves and flow is under control.

This study presents scientific limitations: for example, the failure to compare the results of chemical analyses with other previous studies (related to the absence of data), the research area that is too limited has the scale of the watershed and finally the uncritical approach to information on remediation systems. However, from the mixed Methods Approach and the SWOT analysis performed, the findings presented in this paper can help scientific communities regulations agencies (States, OMVS) to strengthen their understanding of the river water quality and more important, the methods to restore it. Future research directions can focus on the ways to improve and optimize the processing capacity of all the methods, especially the floating treatment wetland to accommodate it to large rivers. It passes by improving the stability of the raft and resistance to high water flow as is the case at the Faleme River.

Funding

This work has received financial and logistic support from Endeavour Mining/Sabodala Gold Operations and Barrick Gold Corporation Senegal.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Yenew, C. (2021) Key Restoration Methods of a Polluted River Ecosystem: A Systematic Review. *Health Science Journals*, **15**, 832.

[2] Pan, B., Yuan, J., Zhang, X., Wang, Z., Chen, J., *et al.* (2016) A Review of Ecological Restoration Techniques in Fluvial Rivers. *International Journal of Sediment Research*, **31**, 110-119. https://doi.org/10.1016/j.ijsrc.2016.03.001

[3] Bernhardt, E.S., Palmer, M.A., Allan, J.D., *et al.* (2005) Synthesizing US River Restoration Efforts. *Science*, **308**, 636-637. https://doi.org/10.1126/science.1109769

[4] Spink, *et al.* (2010) Has River Rehabilitation Begun? Social Perspectives from the Upper Hunter Catchment, New South Wales, Australia. *Geoforum*, **41**, 399-409. https://doi.org/10.1016/j.geoforum.2009.12.003

[5] European Centre for River Restoration (ECRR) (2023) What Is River Restoration? https://www.ecrr.org/river-restoration/what-is-river-restoration

[6] Sear, D.A. (1994) River Restoration and Geomorphology. *Aquatic Conservation*: *Marine and Freshwater Ecosystems*, **4**, 169-177. https://doi.org/10.1002/aqc.3270040207

[7] Wyant, J.G., Meganck, R.A. and Ham, S.H. (1995) The Need for an Environmental Restoration Decision Framework. *Ecological Engineering*, **5**, 417-420. https://doi.org/10.1016/0925-8574(95)00007-0

[8] FISRWG (Federal Interagency Stream Restoration Working Group) (1998) Stream Corridor Restoration: Principles, Processes, and Practices.

[9] Jungwirth, M., Muhar, S. and Schumtz, S. (2002) Re-Establishing and Assessing Ecological Integrity in Riverine Landscapes. *Freshwater Biology*, **47**, 867-887. https://doi.org/10.1046/j.1365-2427.2002.00914.x

[10] Shields, F.D., Cooper, C., Knight, S.S. and Moore, M. (2003) Stream Corridor Restoration Research: A Long and Winding Road. *Ecological Engineering*, **20**, 441-454. https://doi.org/10.1016/j.ecoleng.2003.08.005

[11] Roni, *et al.* (2008) Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques in North American. *Journal of Fisheries Management*, **28**, 856-889. https://doi.org/10.1577/M06-169.1

[12] Muhar, S., Schmutz, S. and Jungwirth, M. (1995) River Restoration Concepts—Goals and Perspectives. In: Schiemer, F., Zalewski, M. and Thorpe, J.E., Eds., *The Importance of Aquatic-Terrestrial Ecotones for Freshwater Fish*, Springer, Berlin, 183-194. https://doi.org/10.1007/978-94-017-3360-1_17

[13] Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L. and Tarboton, D. (2005) River Restoration. *Water Resources Research*, **41**, W10301. https://doi.org/10.1029/2005WR003985

[14] Sawyer, A.M., Pasternack, G.B., Merz, J.E., Escobar, M. and Senter, A.E. (2009) Construction Constraints for Geomorphic-Unit Rehabilitation on Regulated Gravel-Bed Rivers. *River Research and Applications*, **25**, 416-437. https://doi.org/10.1002/rra.1173

[15] Speed, R., Li, Y., Tickner, D., Huang, H., Naiman, R., Cao, J., Lei, G., Yu, L., Sayers, P., Zhao, Z. and Yu, W. (2016) River Restoration: A Strategic Approach to Planning and Management. UNESCO, Paris.

[16] Roni, P., Hanson, K., Beechie, T.J., Pess, G.R., Pollock, M.M. and Bartley, D.M. (2005) Habitat Rehabilitation for Inland Fisheries. Global Review of Effectiveness and Guidance for Rehabilitation of Freshwater Ecosystems. FAO (Food and Agriculture Organization of the United Nations) Fisheries Biology Technical Paper 484.

[17] Dodds, W.K. and Whiles, M.R. (2020) Physiography of Flowing Water. In: Dodds, W.K. and Whiles, M.R., Eds., *Freshwater Ecology*, Elsevier, Amsterdam, 121-153. https://doi.org/10.1016/B978-0-12-813255-5.00006-5

[18] Diop, B. (2012) Monographie de la station hydrologique de kidira du bassin versant de la falémé.

[19] Mbaye, M.L., *et al.* (2020) Impact of 1.5 and 2.0˚C Global Warming on the Hydrology of the Faleme River Basin. *Journal of Hydrology*: *Regional Studies*, **31**, Article ID: 100719. https://doi.org/10.1016/j.ejrh.2020.100719

[20] Wuilleumier, A., Théveniaut, H., Mall, I. and Ndiaye, P.M. (2010) Notice explicative de la carte hydrogéologique à 1/500 000 du sénégal oriental. Ministère des mines, de l'industrie, de l'agro-industrie et des pme, direction des mines et de la géologie, Dakar.

[21] Ndour, C. (2016) L'érosion et ses impacts naturelles le long de la falémé: Cas de la commune de ballou.

[22] Gueye, M. (2015) Etude de l'érosion et ses impacts le long de la falémé à kidira de ary hara à sinthiou dialiguel.

[23] Jantzi, H. (2018) Incision fluviale et transition d'une rivière alluviale vers une rivière à fond rocheux: formation et évolution des seuils molassiques de la moyenne garonne toulousaine au cours du 20e siècle. Géographie. Université Toulouse le Mirail-Toulouse II, Toulouse.

[24] CCME (2001) Canadian Water Quality Guidelines for the Protection of Aquatic Life.

[25] Dufour, S. and Piégay, H. (2009) From the Myth of a Lost Paradise to Targeted River Restoration: Forget Natural References and Focus on Human Benefits. *River Research and Applications*, **25**, 568-581. https://doi.org/10.1002/rra.1239

[26] Feld, C.K., *et al.* (2009) From Natural to Degraded Rivers and Back Again: A Test of Restoration Ecology Theory and Practice. *Advances in Ecological Research*, **44**, 119-209. https://doi.org/10.1016/B978-0-12-374794-5.00003-1

[27] Gore, J.A. and Shields Jr., F.D. (1995) Can Large Rivers Be Restored? Most Restora-

tion Projects Are Only Attempts to Rehabilitate Selected River Sections to a Predetermined Structure and Function. *BioScience*, **45**, 142-152. https://doi.org/10.2307/1312553

[28] NOAA. What Is Dredging? National Ocean Service Website. https://oceanservice.noaa.gov/facts/dredging.html#:~:text=dredging%20is%20the%20removal%20of,gradually%20fills%20channels%20and%20harbors

[29] Dredging 101: What It Is, How It Works, Benefits & More. https://geoforminternational.com/sediment-removal-101/#what-is-dredging

[30] Manap, N. and Voulvoulis, N. (2015) Environmental Management for Dredging Sediments—The Requirement of Developing Nations. *Journal of Environmental Management*, **147**, 338-348. https://doi.org/10.1016/j.jenvman.2014.09.024

[31] Zhang, X.M., *et al.* (2020) Measures, Methods and Cases of River Ecological Restoration. *IOP Conference Series*: *Earth and Environmental Science*, **601**, Article ID: 012025. https://doi.org/10.1088/1755-1315/601/1/012025

[32] Kvasnicka, J., Burton, G.A., Semrau, J. and Jolliet, O. (2020) Dredging Contaminated Sediments: Is It Worth the Risks? *Environmental Toxicology and Chemistry*, **39**, 515. https://doi.org/10.1002/etc.4679

[33] Bai, X.Y., Zhu, X.F., Jiang, H.B., Wang, Z.Q., He, C.G., Sheng, L.X. and Zhuang, J. (2020) Purification Effect of Sequential Constructed Wetland for the Polluted Water in Urban River. *Water*, **12**, Article No. 1054. https://doi.org/10.3390/w12041054

[34] Ge, P.L., Chen, M., Zhang, L.C., Song, Y.J., Mo, M.H. and Wang, L.Y. (2019) Study on Water Ecological Restoration Technology of River. *IOP Conference Series*: *Earth and Environmental Science*, **371**, Article ID: 032025. https://doi.org/10.1088/1755-1315/371/3/032025

[35] Sun, S.L., Sheng, Y.Q., Zhao, G.Q., Li, Z.R. and Yang, J. (2017) Feasibility Assessment: Application of Ecological Floating Beds for Polluted Tidal River Remediation. *Environmental Monitoring and Assessment*, **189**, Article No. 609. https://doi.org/10.1007/s10661-017-6339-y

[36] Kamble, R. and Patil, D. (2012) Artificial Floating Island: Solution to River Water Pollution in India. Case Study: Rivers in Pune City. *International Conference on Environmental*, *Biomedical and Biotechnology* (*IPCBEE*), **41**, 136-140.

[37] Samaei, S.R. and Ghodsi, M. (2023) Innovations in Water Treatment: Navigating Sustainable Solutions for the Future.

[38] Van-Biervliet, O., McInnes, R.J., Lewis-Phillips, J., *et al.* (2020) Can an Integrated Constructed Wetland in Norfolk Reduce Nutrient Concentrations and Promote *in Situ* Bird Species Richness? *Wetlands*, **40**, 967-981. https://doi.org/10.1007/s13157-019-01247-7

[39] Md Anawar, H. and Chowdhury, R. (2020) Remediation of Polluted River Water by Biological, Chemical, Ecological and Engineering Processes. *Sustainability*, **12**, Article No. 7017. https://doi.org/10.3390/su12177017

[40] Faulwetter, J.L., Burr, M.D., Cunningham, A.B., Stewart, F.M., Camper, A.K. and Stein, O.R. (2011) Floating Treatment Wetlands for Domestic Wastewater Treatment. *Water Science and Technology*, **64**, 2089-2095. https://doi.org/10.2166/wst.2011.576

[41] Jamwal, P. (2017) Remediation of Contaminated Urban Streams: A Decentralized Ecological Wastewater Treatment Approach. In: Bhattacharya, S., *et al.*, Eds., *Water Remediation*, Springer, Berlin, 29-41. https://doi.org/10.1007/978-981-10-7551-3_3

[42] Headley, T.R. and Tanner, C.C. (2012) Constructed Wetlands with Floating Emergent Macrophytes: An Innovative Stormwater Treatment Technology. *Critical Reviews in Environmental Science and Technology*, **42**, 2261-2310. https://doi.org/10.1080/10643389.2011.574108

[43] Kadlec, R.H. and Wallace, S. (2009) Treatment Wetlands. 2nd Edition, CRC Press, Boca Raton. https://sswm.info/sites/default/files/reference_attachments/kadlec%20wallace%202009%20treatment%20wetlands%202nd%20edition_0.pdf

[44] Billore, S.K., Prashant and Sharma, J.K. (2009) Treatment Performance of Artificial Floating Reed Beds in an Experimental Mesocosm to Improve the Water Quality of River Kshipra. *Water Science and Technology*, **60**, 2851-2859. https://doi.org/10.2166/wst.2009.731

[45] Ijaz, A., Imran, A., Anwar Ul Haq, M., Khan, Q.M. and Afzal, M. (2015) Phytoremediation: Recent Advances in Plant-Endophytic Synergistic Interactions. *Plant and Soil*, **405**, 179-195. https://doi.org/10.1007/s11104-015-2606-2

[46] Biohaven Floating Treatments Wetlands. https://www.frogenvironmental.co.uk/product/biohaven

[47] Oscar Omondi, D. and Caren Navalia, A. (2021) Constructed Wetlands in Wastewater Treatment and Challenges of Emerging Resistant Genes Filtration and Reloading. In: Devlin, A., Pan, J.Y. and Shah, M.M., Eds., *Inland Waters—Dynamics and Ecology*, IntechOpen, London. https://doi.org/10.5772/intechopen.93293

[48] Dauda Ahmed, S., Kwaku Agodzo, S. and Amaning Adjei, K. (2021) Designing River Diversion Constructed Wetland for Water Quality Improvement. In: Devlin, A., Pan, J.Y. and Shah, M.M., Eds., *Inland Waters—Dynamics and Ecology*, IntechOpen, London. https://doi.org/10.5772/intechopen.92119

[49] Anawar, H.M., Ahmed, G. and Strezov, V. (2019) Long-Term Performance and Feasibility of Using Constructed Wetlands for Treatment of Emerging and Nanomaterial Contaminants in Municipal and Industrial Wastewater. In: Mishra, A.K., Anawar, H.M.D. and Drouiche, N., Eds., *Emerging and Nanomaterial Contaminants in Wastewater*, Elsevier, Amsterdam, 63-81. https://doi.org/10.1016/B978-0-12-814673-6.00003-6

[50] Schück, M. (2022) Floating Treatment Wetlands for Stormwater Management. Plant Species Selection and Influence of External Factors for Heavy Metal and Chloride Removal in a Cold Climate. Doctoral Thesis in Plant Physiology, Stockholm University, Stockholm.

[51] Wang, C.-Y. (2013) Floating Wetlands for Urban Stormwater Treatment. Dissertation, Virginia Tech, Blacksburg. https://vtechworks.lib.vt.edu/bitstream/handle/10919/52036/wang_c_d_2013.pdf?sequence=1

[52] Headley, T.R. and Tanner, C.C. (2006) Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review. Prepared for Auckland Regional Council.

[53] Abi Saab, M.T., Jammoul, D., Makhlouf, H., Fahed, S., Lebbous, N., Hajjar, C. and Todorovic, M. (2018) Assessing the Performance of Constructed Wetland for Water Quality Management of a Southern Mediterranean River. *Water and Environment Journal*, **32**, 508-518. https://doi.org/10.1111/wej.12348

[54] Ning, D., Huang, Y., Pan, R., Wang, F. and Wang, H. (2014) Effect of Eco-Remediation Using Planted Floating Bed System on Nutrients and Heavy Metals in Urban River Water and Sediment: A Field Study in China. *Science of the Total Environment*, **485**-**486**, 596-603. https://doi.org/10.1016/j.scitotenv.2014.03.103

[55] Vo, T., *et al.* (2023) Pilot and Full-Scale Applications of Floating Treatment Wetlands for Treating Diffuse Pollution. *Science of the Total Environment*, **899**, Article ID: 165595. https://doi.org/10.1016/j.scitotenv.2023.165595

[56] Bi, R., Zhou, C., Jia, Y., Wang, S., Li, P., Reichwaldt, E.S. and Liu, W. (2019) Giving Water Bodies the Treatment They Need: A Critical Review of the Application of Constructed Floating Wetlands. *Journal of Environmental Management*, **238**, 484-498. https://doi.org/10.1016/j.jenvman.2019.02.064

[57] Billore, S.K. and Prashant (2006) Floating Islands Treat Polluted Water. *Appropriate Technology*, **34**, 53-54.

[58] Chen, Z., Cuervo, D.P., Müller, J.A., Wiessner, A., Köser, H., Vymazal, J. and Kuschk, P. (2016) Hydroponic Root Mats for Wastewater Treatment—A Review. *Environmental Science & Pollution Research*, **23**, 15911-15928. https://doi.org/10.1007/s11356-016-6801-3

[59] Prashant and Billore, S.K. (2020) Macroinvertebrates Associated with Artificial Floating Islands Installed in River Kshipra for Water Quality Improvement. *Water Science & Technology*, **81**, 1242-1249. https://doi.org/10.2166/wst.2020.219

[60] Teh, C.Y., Budiman, P.M., Shak, K.P.Y. and Wu, T.Y. (2016) Recent Advancement of Coagulation-Flocculation and Its Application in Wastewater Treatment. *Industrial and Engineering Chemistry Research*, **55**, 4363-4389. https://doi.org/10.1021/acs.iecr.5b04703

[61] Duguet, J.-P. (2005) Degrémont suez-mémento technique de l'eau, 10e Édition Française.

[62] He, N., Li, Y., Chen, J. and Lun, S.-Y. (2002) Identification of a Novel Bioflocculant from a Newly Isolated *Corynebacterium glutamicum*. *Biochemical Engineering Journal*, **11**, 137-148. https://doi.org/10.1016/S1369-703X(02)00018-9

[63] Pan, L.T., Wu, L. and Tu, X.Q. (2007) Chemical Oxidation-Flocculation Technology Applied for Enhanced Treatment of Polluted River Water. *Chinese Journal of Environmental Engineering*, **1**, 54-57.

[64] Morandi, B. (2014) La restauration des cours d'eau en france et à l'étranger: De la définition du concept à l'évaluation de l'action. Eléments de recherche applicable. Géographie. Ecole normale supérieure de lyon-Ens Lyon, Français.

[65] Logar, I., Brouwer, R. and Paillex, A. (2019) Do the Societal Benefits of River Restoration Outweigh Their Costs? A Cost-Benefit Analysis. *Journal of Environmental Management*, **232**, 1075-1085. https://doi.org/10.1016/j.jenvman.2018.11.098

Abbreviations

AFI	Artificial floating Islands	**FAO**	Food and Agriculture Organization
ASGM	Artisanal and Small Gold Mining	**FTW**	Floating treatment wetland
BOD	Biological oxygen demand	**ICP-MS**	Coupled Plasma-Atomic Emission Spectrometry
CW	Constructed wetlands	**OMVS**	Senegal River Development Organization "Organisation pour la mise en valeur du fleuve Sénégal"
COD	Chemical oxygen demand	**SWOT**	Strengths, weakness, opportunities and Threats
COF	Coagulation-flocculation	**TSS**	Total suspended solids