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Sustainable sediment management in Jordanian dams: Feasibility, economic viability, and agricultural reuse potential

Ahmed Al-Taani*[1),2)], Nazem El Radaideh[2)], Wesam Al Kateeb[2)], Fares Howari[1),3)], Yousef Nazzal[1)], Jibran Iqbal[1)], Abeer Al Bsoul[4)]

[1)] Zayed University, College of Natural and Health Sciences, Department of Environmental Sciences and Sustainability, 144534, Abu Dhabi, United Arab Emirates

[2)] Yarmouk University, Science Faculty, Department of Earth and Environmental Sciences, 21163, Irbid, Jordan

[3)] Ajman University, College of Humanities and Sciences, P.O. Box 346, Ajman, United Arab Emirates

[4)] Al-Balqa Applied University, Al-Huson University College, Department of Chemical Engineering, 50, Irbid, Jordan

* Corresponding author

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Abstract: Jordan has long faced severe water scarcity, which has significant implications for agriculture, industry, and domestic consumption. This crisis is further exacerbated by climate change, population growth, regional conflicts, and unsustainable water use. In response, Jordan has focused heavily on dam construction to secure water supplies, despite the high financial and environmental costs. However, rapid sedimentation threatens dam storage capacity and operational efficiency, reducing their lifespan and long-term sustainability. This study evaluates the feasibility of sediment removal as an alternative to constructing new dams, considering environmental, technical, agricultural, and economic factors. The research is based on case studies from King Talal and Mujib dams, integrating water and sediment quality assessments, cost analyses, and comparisons with regional studies from similar climatic and hydrological conditions. The findings suggest that while sediment removal presents logistical and economic challenges, it can restore lost reservoir capacity and provide valuable agricultural benefits. The potential reuse of dredged sediments for soil enhancement offers an opportunity for sustainable farming, reducing reliance on costly fertilisers. Given the increasing costs and environmental concerns associated with new dam construction, sediment management emerges as a viable, cost-effective strategy for optimising Jordan's existing water infrastructure, enhancing water security, and promoting sustainable resource management.

Keywords: dam, dredging, Jordan, quality, sediment removal

INTRODUCTION

Jordan has long struggled with water shortages, significantly impacting agriculture, industry, and domestic sectors (Al-Taani, 2014; Khawajah *et al.*, 2023). The issue of water scarcity is further aggravated by multiple factors such as climate change, population growth, limited natural water sources, and regional conflicts (Al-Rawabdeh *et al.*, 2014; Al Shwayatt *et al.*, 2019; Muhaidat *et al.*, 2019). In addition, unsustainable water consumption triggered by high population growth, following the influx of Syrian refugees, has worsened the water crisis and put a great burden on the country's limited resources (Al-Taani, 2019; Al-Harahsheh *et al.*, 2020). In 2022, the per capita share of water in Jordan has declined to about 61 m^3.

The response to the growing demand for water has focused on dam building, among other alternatives (Al-Taani *et al.*, 2018; Al-Taani, Radaideh and Al Khateeb, 2018; Al-Taani, Nazzal and Howari, 2020). While this is a costly approach to alleviating water shortage (Karami and Karami, 2020), Jordan is planning to invest heavily in storage reservoirs to maintain reliable water supplies at times of water stress (Al-Taani, 2013; Al-Taani, 2014). However, the high sedimentation rate remains the major threat to the productivity and longevity of dams (Al-Taani, 2013; Al-Taani *et al*., 2015; El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b; Gruca-Rokosz and Cieśla, 2021).

Owing to the naturally continuous erosion processes and sediment influx to the reservoir (even with conservation measures in the upstream watershed), reservoir siltation is inevitable; limiting the lifespan and reducing the long-term benefits of the reservoir (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b; Huang *et al*., 2021; Zhang *et al*., 2022). With changing rainfall patterns, due to climate change, Jordan has observed frequent flash floods which accelerated soil erosion and increased sediment accumulation in dams (Al-Taani, 2013).

Catchment-based measures like afforestation and land use changes are effective for reducing sediment yield but require significant long-term investment (Trimble, 1981; Mahmood, 1987; El-Radaideh *et al*., 2014). Improved vegetation cover was recommended as a strategy to reduce sedimentation, despite the decreased water yield (Shi *et al*., 2022). Shrestha *et al*. (2021) examine sediment management strategies to maintain reservoir sustainability amidst uncertain land use and cover changes. The study emphasises that balancing sediment inflow control with removal methods is crucial for cost-effective and sustainable reservoir management.

While building new reservoirs has long been cheaper than removal and disposal of sediment (Al-Taani *et al*., 2015; Al-Taani *et al*., 2018; Al-Taani, Radaideh and Al Khateeb, 2018), this economic balance has changed. In addition to the social and environmental issues, the siting constraints, the growing cost of building a new dam, and expensive alternative water resources, all have shifted the concept of managing both water and sediment for reservoir sustainability to generate long-term benefits than the construction of new reservoirs (Al-Taani, 2014; Karami and Karami, 2020).

Social and environmental costs include resettlement, negative impacts on upstream and downstream ecology, and downstream loss of silt and fertility, among others (Sumi, Nakamura and Hayashi, 2009). Also, the cost of dam decommissioning can be quite substantial. Therefore, these benefits and costs should be properly considered when a decision is to be made on building a new dam and planning an operating strategy.

The removal and disposal of sediments to restore the storage capacity of reservoirs are becoming a viably feasible option (El-Radaideh *et al*., 2014), and an engineering requirement to avoid dam failure (Kondolf *et al*., 2014). Having said this, the excavation of sediment deposits is still a relatively costly operation which may be justified in certain circumstances by the economic value of the water, as in Jordan, and the unfeasibility of replacing lost reservoir capacity (Shrestha *et al*., 2021).

The disposal of excavated sediment remains an issue of concern unless the sediments are used, for example, to improve the adjacent agricultural land, and subsequently reducing the cost of operation (Palermo and Hays, 2013; El-Radaideh *et al*., 2014; El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b). However, once sediments are deposited in a reservoir, excavation may be the best management option available. Sediments are significant sinks for heavy metals and other contaminants, which can bind to particulate matter and accumulate over time. They can cause phytotoxicity in plants, reduce microbial activity, and bioaccumulate in aquatic organisms (Peijnenburg and Jager, 2003). Sediments often contain pharmaceutical residues that may disrupt microbial processes and pose risks to aquatic and benthic organisms (Cooper and Corcoran, 2010). Microplastics physically damage sediment-dwelling organisms and chemically harm ecosystems by leaching toxins (Rochman *et al*., 2015).

This study aims to evaluate the feasibility of removing accumulated sediments from Jordan's King Talal Dam (KTD) and Mujib Dam (MD) to mitigate the impacts of siltation on reservoir storage capacity. It focuses on analysing sediment characteristics, assessing the economic viability of sediment removal compared to constructing new dams and exploring the reuse potential of these sediments in agriculture to improve soil fertility. By integrating environmental, technical, and cost analyses, the study provides insights into sustainable sediment management practices tailored to Jordan's water-limited environment.

MATERIALS AND METHODS

STUDY SITES

The King Talal Dam (KTD) is an earth-fill structure and the second largest reservoir in Jordan. Located within the Zarqa River basin (Fig. 1), where intense agricultural activities and significant industrial operations in Jordan are concentrated near the Zarqa River, with wastewater frequently discharged into the river. Effluents from three wastewater treatment plants (Khirbet As-Samra, Jerash, and Baqa'a) collectively account for approximately 50% of the water reaching KTD. The average annual inflow into the reservoir is around 113 mln m^3 (RSS, 1984–2005). The summary characteristics of KTD are tabulated in Table 1. The steep topography of the KTD catchment accelerates the erosion of topsoil and rock, leading to the direct transport of chemicals, organic matter, and nutrients into the reservoir.

The Mujib Dam (MD) (Fig. 1), located in central-western Jordan, was designed to capture flood and base flows from Wadi Mujib which would otherwise drain into the Dead Sea. Constructed on limestone in deeply incised valleys, the dam utilises roller-compacted concrete gravity. The Mujib catchment area is fed by several wadis that form the base flow of the dam. These flows mainly originate from a network of springs within the Dead Sea escarpment. The key characteristics of MD dams are summarised in Table 1.

DATA COLLECTION AND SOURCES

This study evaluates the feasibility, economic viability, and reuse potential of dam sediments by integrating sediment quality data, agricultural application experiments, and cost analyses. These approaches aim to identify sustainable sediment management practices that enhance soil fertility and inform cost-effective solutions for sediment removal and reuse. Data on dam sediment removal in Jordan is relatively sparse, so this study drew extensively from previously published work on the KTD and MD. Our prior studies (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b; Al-Taani *et al*., 2018; Al-Taani, Radaideh and Al Khateeb, 2018; Al Khateeb

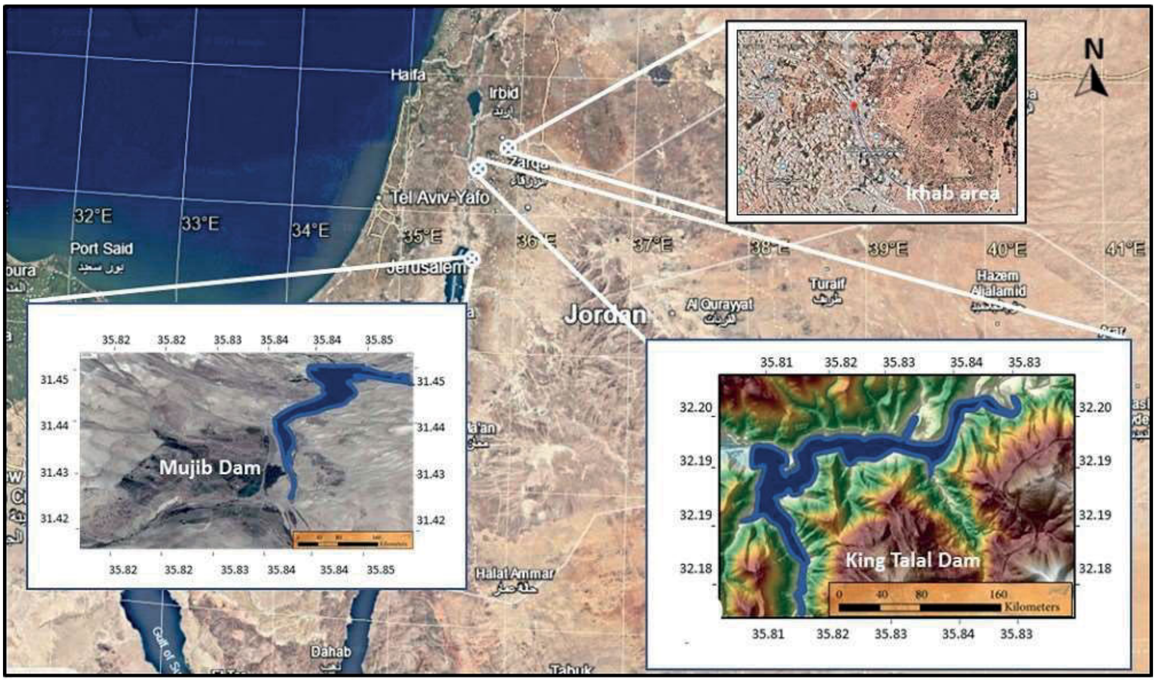

Fig. 1. Location map of Jordan illustrating King Talal Dam (KTD) and Mujib Dam (MD) along with Irhab area (identified as a potential site for sediment reuse); source: own elaboration

Table 1. Summary characteristics of King Talal Dam (KTD) and Mujib Dam (MD)

Feature	KTD	MD
Type of dam	earth-fill	roller-compacted concrete gravity
Year of completion	1978	2003
Purpose	irrigation, electricity generation	irrigation, industrial, domestic, and drinking water
Catchment area (km^2)	33.75	4,500
Reservoir length (km)	7.6	5
Maximum reservoir width (m)	450	1,100
Total storage capacity (mln m^3)	88.5	31.2
Live storage capacity (mln m^3)	80.5	29.8
Dead storage capacity (mln m^3)	8	1.4
Annual yield (mln m^3)	not specified	16.6
Average annual inflow (mln m^3)	113	–

Source: own elaboration.

et al., 2019) provided key insights into water and sediment quality assessments, focusing on the potential for reusing dam sediments in agriculture and examined the practical effects of mixing dam sediment with soil and tested its suitability for planting various crops, highlighting its potential to enhance soil fertility. Also, cost data from the Jordan Valley Authority on sediment removal, along with input from the Ministry of Irrigation and expert consultations, informed the economic analysis. Relevant studies from regions with similar climatic and hydrological conditions also contributed comparative data to this feasibility study.

RESULTS AND DISCUSSION

TECHNICAL FEASIBILITY OF DAM SEDIMENT REMOVAL

Dredging techniques

Various dredging techniques are commonly used, including hydraulic and mechanical methods. These methods are primarily categorised as "dredging and excavation." However, a significant limitation of both techniques is the requirement to lower the water level in the reservoir, which poses challenges in water-scarce regions like Jordan (Kondolf *et al.*, 2014).

When sediment removal occurs in a fully water-logged reservoir, the resulting dredged materials often exhibit high moisture content, adding complexity to the disposal process and inflating associated costs (Batuca and Jordaan, 2000). This issue is particularly pertinent in Jordan, where water resources are both scarce and highly valued, compounded by limited financial resources. The high demand for reservoir water, especially in supporting agricultural and industrial activities, makes it imperative to consider cost-effective sediment removal strategies that minimise disruption to water supply.

To mitigate the impact of sediment removal on water availability, it is generally more economical to perform desilting operations while the reservoir water level is drawn down. However, in Jordan, the consequences of lowering the water level can be notable. For instance, reservoirs such as KTD and MD are crucial for local agriculture and industry, and temporarily reducing water levels could disrupt these vital activities for an extended period, potentially lasting for at least two years. Such interruptions could lead to economic losses for communities reliant on consistent water access.

Given these considerations, it is essential for water management authorities in Jordan to explore innovative dredging solutions that balance sediment removal needs with the imperative to maintain water levels. Techniques such as selective dredging, which targets specific sediment deposits without necessitating a complete drawdown, may provide viable alternatives. Also, advancements in dredging technology and practices can enhance operational efficiency while minimising environmental impacts, thereby supporting the dual goals of effective sediment management and sustainable water use.

Availability of equipment

The availability of hydraulic dredgers, essential for effective sediment removal from KTD and MD, presents challenges in Jordan. This specialised equipment is not commonly utilised or readily available within the country. While small-sized dredgers may be located in the Gulf of Aqaba, primarily for waterways dredging, the hydraulic dredgers required for deep reservoir sediment removal are absent from local markets. This scarcity not only adds logistical challenges but also increases operational costs due to the need to import such equipment from other countries. Importation would likely include additional expenses related to shipping, customs duties, and potential tariffs, ultimately escalating the financial burden of sediment removal operations.

The physical characteristics of hydraulic dredgers add further challenges to their use in Jordan. Weighing over 50 Mg and measuring up to 21 m in length, these machines require special arrangements for transportation. The road infrastructure surrounding KTD and MD may impose weight and size limits that could restrict the movement of such heavy machinery. Transporting a hydraulic dredger to these sites requires careful planning to ensure compliance with local regulations and safety standards, as well as the capability of the existing road network to accommodate the weight of the equipment. The complexity of transportation logistics can lead to delays and increased costs.

Also, the maintenance and repair of hydraulic dredgers should be considered. In the absence of a local support network for these machines, the interruption associated with repairs could extend project timelines and increase costs due to lost operational capacity. This situation underscores the need for comprehensive planning and the establishment of a maintenance framework to ensure that any imported dredgers can be effectively supported throughout their operational lifecycle.

Given these circumstances, dry excavation methods may be more appropriate for sediment removal in Jordanian dams. This technique involves scrapers, dump trucks, and other heavy equipment to extract accumulated sediment. However, dry excavation requires the reservoir to be completely drawn down, leading to a loss of water that could infringe on established water rights. In a region where water is an increasingly scarce and valuable resource, such actions could lead to legal ramifications and disputes over water allocation. The implications of temporarily reducing water supply must be thoroughly assessed, especially as water is critical for both agricultural irrigation and industrial activities in the vicinity of KTD and MD. Partial mitigation can be achieved by utilising treated wastewater and groundwater resources.

While hydraulic dredging is typically viewed as a more effective method for sediment removal, studies indicate that dry excavation, even with its associated challenges, may prove to be the most economically feasible solution. Research by Sumi, Nakamura and Hayashi (2009) suggests that the financial benefits of dry excavation outweigh the costs of reduced water production. Mechanical removal of sediment, while still expensive, may offer a more manageable financial pathway compared to the high operational costs of hydraulic dredging, particularly given the current equipment availability challenges.

Recent events have highlighted the urgent need for sediment removal from the MD reservoir, which was completely drained last year. This unprecedented situation was attributed to a combination of factors, including severe drought conditions, below-average annual rainfall, frequent heatwaves, and mismanagement of water resources. The drying of the MD reservoir has sparked significant discussions regarding the potential for sediment excavation and removal, particularly as the reservoir suffers from moderate siltation rates. The dramatic depletion of water in MD has brought sedimentation issues to the forefront of water management discussions, revealing an opportunity for proactive sediment removal strategies.

The current state of the MD reservoir presents both a challenge and an opportunity. It emphasises the necessity of establishing a reliable and cost-effective sediment removal strategy while addressing the legal, environmental, and operational considerations inherent in such processes. Ensuring that any sediment removal approach aligns with Jordan's water management policies and protects the rights of local water users will be critical to the success of future projects.

Therefore, the availability of appropriate equipment for sediment removal from KTD and MD remains uncertain, driving the need for alternative approaches such as dry excavation. This situation highlights the importance of strategic planning and collaboration among stakeholders to address the complex interplay of equipment availability, cost management, and water rights, ultimately facilitating effective sediment management in Jordanian reservoirs.

ECONOMIC VIABILITY OF DAM SEDIMENT REMOVAL

Estimating the cost of sediment removal from reservoirs in Jordan is a complex process that necessitates careful consideration of various factors, including the specific mechanical methods employed, the logistics of temporary storage, disposal site proximity, and potential material reuse strategies. Given that the specialised equipment required for effective sediment removal is not currently available in Jordan, it must be imported from other countries, adding another layer of complexity to the cost analysis.

As highlighted by Niu and Shah (2021) and Warrick *et al.* (2019), the cost of sediment removal can vary significantly based on the chosen method and local conditions. For example, hydraulic dredging may entail different costs compared to mechanical excavation, impacting the overall budget. Also, the logistics involved in sediment disposal, such as transportation distance and the nature of the disposal method, play critical roles in shaping cost estimates.

A key study conducted by the Jordan Valley Authority in 2016 provided insights into the costs associated with sediment removal from Shuaeb Dam in northwestern Jordan, which has suffered substantial loss of storage capacity due to sedimentation. The study indicated that dry excavation for sediment removal and subsequent disposal upstream incurred costs of approximately Jordanian dinar (JOD) 3–4 per m^3 of sediment (JOD1 = USD1.41, in 2016). Moreover, if the sediment were to be disposed of downstream, costs increased to about JOD6 per m^3. These figures underscore the importance of site selection for disposal in minimising costs.

In comparison, estimates for constructing new dams were approximately 5JOD per m^3 of reservoir capacity in 2016, which encompasses expenses such as design engineering, construction oversight, legal fees, and land acquisition (Jordan Valley Authority, 2016). This translates to a substantial investment; for instance, constructing a new 10 mln m^3 dam would amount to approximately JOD50 mln.

The economic implications of sediment removal are further compounded by the water rights associated with Jordan's reservoirs. The KTD and MD dams support vital irrigation rights for surrounding agricultural areas and provide essential water supplies to industrial enterprises, including the Southern Ghor Irrigation Project, the Arab Potash Company, and the Jordan Bromide Company. Given these critical functions, any dredging or excavation efforts must carefully navigate the complexities of water rights to avoid disrupting agricultural and industrial operations (Hadadin, 2015). For example, undertaking dry excavation under reservoir drawdown conditions could pose practical challenges if water rights for adjacent agricultural lands and industrial facilities are not adequately protected. As noted by Gosden, Dutton and Hart (2014), the interplay between sediment removal and water availability makes planning for such operations a significant concern for Jordanian water management authorities.

Moreover, the variability in the cost of desilting operations must be considered, particularly as sediment removal activities may not be executed for several decades. As such, cost estimates must account for inflation and escalation in pricing for labour, construction equipment, and fuel over this extended timeframe. A typical escalation rate of about 5% compounded annually is a common industry benchmark (Mack, 2012).

This forward-looking approach is essential to ensuring that funding and resources are adequately allocated for future sediment removal operations, as costs may significantly rise by the time these activities are implemented. By projecting future costs, stakeholders can better plan for the financial implications of sediment management strategies, thus ensuring that Jordan's water reservoirs remain functional and capable of meeting the needs of its agricultural and industrial sectors.

ENVIRONMENTAL CONSIDERATIONS OF DAM SEDIMENT REMOVAL

The removal of sediment from reservoirs such as KTD and MD dams necessitates careful planning and consideration of environmental impacts, particularly regarding the disposal of mechanically removed sediments. One of the foremost challenges is identifying suitable locations for sediment containment that are in close proximity to the reservoirs. As noted by Kondolf *et al.* (2014), cost-effectiveness in sediment disposal is highly dependent on the distance to these locations. However, the regions surrounding KTD and MD have undergone significant development for agricultural, industrial, and residential purposes. This makes it more challenging to identify large parcels of publicly owned land suitable for sedimentation basins. The limited availability of land for containment adds considerations regarding the logistics and feasibility of sediment disposal operations. Having said this, the land is needed as a temporary storage site until the sediment is transported to a potential location for agricultural reuse, as discussed later.

The environmental complications of sediment disposal extend beyond the logistical challenges. The establishment of sediment containment areas poses a risk to local flora and fauna. The construction and maintenance of these sites can lead to habitat destruction, resulting in the burial and loss of wildlife and plants. Also, the clearing of land for sedimentation basins can lead to the loss of native vegetation and disrupt local ecosystems, which are vital for maintaining biodiversity (Erftemeijer *et al.*, 2012). Such impacts underscore the importance of conducting thorough environmental assessments before determining sediment disposal strategies.

Furthermore, the dredging operations themselves can have effects on the surrounding ecosystems. The process of mechanically removing sediments may inadvertently affect habitats and disturb existing wildlife. In addition to the immediate environmental concerns associated with sediment containment, the logistics of transporting excavated sediments can result in short-term disruptions for local communities. The transport of sediments from the reservoirs to disposal sites will likely generate noise and air pollution, impacting the quality of life for residents in the vicinity. Community engagement and communication about potential disturbances will be critical in managing public perception and minimising conflict.

In addition, contaminants in sediments may disrupt soil functionality, making it less capable of supporting plant and microbial life. Heavy metals such as Pb, Cd, and Hg in dam sediments may be detrimental to plant and microbial life (OEHHA, 2008). They disrupt physiological processes (nutrient uptake and photosynthesis) in plants and interfere with enzymatic and metabolic pathways in microbes. Kan *et al.* (2023) observed that heavy metals and organics in dam sediments may significantly alter microbial ecosystems. This includes reductions in nitrogen-fixing bacteria and mycorrhizal fungi, which are crucial for nutrient cycling and plant health. Also, runoff carrying pesticides and nutrients from agricultural areas accumulates in reservoir sediments, leading to reduced enzymatic activity, biodiversity, and overall soil health (Materu and Heise, 2019).

Another significant concern is the impact of sediment removal on reservoir water quality. Mechanical removal techniques often increase the levels of suspended sediments in the water column, particularly when fine-grained sediments are present in high concentrations (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b). The implications of such water quality changes are particularly pronounced during hydraulic dredging, which can mobilise substantial quantities of fine sediment into the water column (Lee *et al.*, 2019). However, it is important to recognise that, on a long-term basis, sediment removal may improve overall water quality within the reservoir. By eliminating contaminated sediments, whether they contain inorganic or organic pollutants, there exists the potential for enhanced ecological health and resilience. Nevertheless, care must be taken to monitor for potential groundwater contamination from leaching at disposal sites, which can introduce new environmental challenges (Prieto-Espinoza, Susset and Grathwohl, 2022).

To address these multidimensional environmental concerns, a comprehensive management plan is essential. This plan should include ecological assessments prior to sediment removal, mitigation strategies to minimise habitat destruction, and monitoring programs to track the impacts of sediment removal on both terrestrial and aquatic environments. Collaboration with local stakeholders, including environmental agencies and community organisations, will be vital to ensure that sediment management strategies are aligned with broader environmental goals and community needs.

SEDIMENT QUALITY

The quality of sediments within reservoirs serves as a crucial indicator of their suitability for various applications, including agricultural use. In the case of the MD and KTD in Jordan, sediment yields have been observed to be relatively low, with MD experiencing a higher rate of silting (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b) (Tab. 2). This implies that immediate concerns regarding reservoir siltation may not be pressing. However, recent climatic observations have indicated significant shifts in precipitation patterns, characterised by increased frequency of flash floods. Such events necessitate a re-evaluation of sedimentation rates for both dams, suggesting that sediment yields could be underestimated and might increase in the future. This change in sediment dynamics highlights the need for continuous monitoring to assess the impact of climate variability on sediment accumulation.

Table 2. Sediment characteristics of King Talal Dam (KTD) and Mujib Dam (MD)

Feature	KTD	MD
Grain size distribution (%)	gravel (1.38), sand (32.38), silt (32.35), clay (32.38)	granules (1.6), sand (30.7), silt (45), clay (23.2)
Total organic matter (average, %)	7.0	5.9
pH (average)	7.3	7.5
Carbonates ($CaCO_3$) (average, %)	35.9	25.8
Cation exchange capacity (average, $mmol \cdot kg^{-1}$)	1005	880
Dominant minerals	quartz, calcite, dolomite, clay minerals, feldspar	calcite, quartz, dolomite, clay minerals (montmorillonite, illite, kaolinite), feldspar
Key trace metals ($mg \cdot kg^{-1}$)	Fe (44,446), Cu (30.3), Zn (373.5), Pb (76.5), Cd (17.9)	Fe (39,621), Cu (55.5), Zn (278.4), Pb (55.5), Cd (6.3)
Annual sedimentation rate (mln $m^3 \cdot y^{-1}$)	0.4061	0.4633

Source: own elaboration based on El-Radaideh, Al-Taani and Al Khateeb (2017a) and El-Radaideh, Al-Taani and Al Khateeb (2017b).

The composition of sediments in both reservoirs predominantly consists of fine-sized grains, which has implications for their chemical and physical interactions with surrounding waters (Tab. 2). Fine sediments, particularly those rich in clay and silt, play a vital role in the adsorption and desorption of trace metals, including essential micronutrients. This characteristic makes them particularly valuable for agricultural applications, as these fine fractions contribute significantly to soil fertility and nutrient availability (Al-Taani *et al.*, 2018; Al-Taani, Radaideh and Al Khateeb, 2018).

Further analysis reveals that the bottom sediments in the KTD and MD reservoirs exhibit properties that render them suitable for enhancing agricultural soils (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b). The presence of abundant clay minerals, including montmorillonite, vermiculite, and kaolinite, contributes to the high cation exchange capacity (CEC) of these sediments. The CEC is an essential property that reflects the ability of soil to retain and exchange nutrients, ultimately influencing plant growth and productivity (Tab. 2). Also, the neutral pH levels found in these sediments align with optimal conditions for the availability of most nutrients, facilitating their uptake by plants (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b).

Heavy metal analysis of the sediments revealed that most heavy metals are present at concentrations within the normal global ranges for soils, except for Cd and Zn, which exhibited slightly elevated levels (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b). These findings suggest that the sediments from KTD and MD could be safely utilised in agricultural contexts, provided that careful management practices are employed to mitigate any potential risks associated with heavy metal accumulation. Moreover, studies utilising the comet assay have indicated no significant deoxyribonucleic acid (DNA) damage in plants grown in soil amended with dam sediments (Al Khateeb *et al.*, 2019). This points to the non-genotoxic nature of the sediments, further reinforcing their suitability for agricultural use. The DNA fingerprinting profiles for spinach plants grown in either pure soil or sediment-amended soil showed no significant differences, suggesting that the incorporation of sediment does not adversely affect plant genetic integrity (Al Khateeb *et al.*, 2019).

Despite the promising characteristics of these sediments, the analysis also revealed slightly higher concentrations of Fe, Cu, Zn, Cd, and Pb in spinach grown in sediment-amended soil compared to control samples (Al Khateeb *et al.*, 2019). While the presence of these metals warrants further investigation, the overall results suggest that the beneficial effects of sediment incorporation, such as improved nutrient availability and enhanced soil structure, may outweigh potential risks, particularly when appropriate guidelines and monitoring are in place.

The beneficial properties of sediments not only enhance the physical and chemical characteristics of soil but also significantly improve its fertility when mixed with agricultural land. The high levels of available micronutrients found in these sediments, such as Fe, Cu and Zn are essential for healthy plant growth (Javed *et al.*, 2022). By utilising dam sediments as soil amendments, farmers can capitalise on the natural nutrient reservoir present in these materials, potentially reducing their reliance on synthetic fertilisers, which are often costly and environmentally detrimental.

Furthermore, the integration of sediment reuse into agricultural practices can play a crucial role in promoting sustainable land management. The reapplication of sediments can contribute to soil conservation efforts by improving soil structure, enhancing water retention capabilities, and reducing erosion. In a region like Jordan, where agricultural land is under significant pressure from overexploitation and desertification, the strategic use of dam sediments can provide a dual benefit of improving soil fertility while addressing the challenges of land degradation.

The quality of sediments in the KTD and MD reservoirs offers a promising indicator of their suitability for agricultural applications. While the current sedimentation rates suggest that siltation is not an immediate concern, the changing precipitation patterns call for ongoing assessment and management strategies. The favourable physical and chemical properties of these sediments, coupled with their potential to enhance soil fertility, position them as valuable resources for farmers seeking sustainable agricultural practices in Jordan. As research continues to elucidate the long-term effects of sediment reuse on soil health and crop productivity, it is essential for stakeholders to engage in collaborative efforts to implement sediment management strategies that align with environmental sustainability and agricultural resilience.

AGRICULTURAL POTENTIAL OF SEDIMENT REUSE

In recent years, a notable trend among farmers is the adoption of low-input farming practices, which seek to enhance net benefits while minimising environmental impact (Al-Hamad *et al*., 2024). This shift toward sustainable agriculture indicates low-input farming can yield economic returns comparable to, or even exceeding, traditional farming methods One key point for evaluating the economic viability of any new agricultural production system is the analysis of production costs. By comparing the costs associated with different cropping systems, farmers can better assess the advantages and profitability of alternative practices.

Recent studies have highlighted the potential of using sediments as soil additives, demonstrating promising results for crop growth and yield (El-Radaideh, Al-Taani and Al Khateeb, 2017a; El-Radaideh, Al-Taani and Al Khateeb, 2017b). For example, our research found that crops such as *Chrysanthemum* L. and wheat showed yields that were comparable to, and in some cases better than, those grown in soil treated with conventional organic or inorganic fertilisers (Al Khateeb *et al*., 2019). These findings underscore the viability of sediment reuse as a beneficial alternative in agricultural practices, offering farmers an innovative approach to sediment management while simultaneously enhancing soil fertility and crop productivity.

However, the utilisation of dam sediments as agricultural amendments is not without its challenges, with transportation costs being a significant constraint (Jacobsen, 1997). Previous assessments indicated that transporting excavated sediment from dam sites to agricultural areas is essential for realising these benefits. One proposed destination is Irhab City, located in the Mafraq governorate of northeastern Jordan. This region, characterised by its semi-arid climate and relatively low population density, presents a strategic opportunity for sediment reuse. The area suffers from poor-quality soils, making it an ideal candidate for the addition of dam sediments to improve fertility and physical properties (Al Khateeb *et al*., 2019). However, the haulage distance is a logistical concern; transporting sediment from KTD entails approximately 47 km while transporting from MD can reach about 155 km. However, other potential sites closer to the dams are also available, as land degradation is a prevalent issue in Jordan.

The use of dam sediments offers advantages over conventional commercial fertilisers. In Jordan, the rising costs of inorganic fertilisers, driven by high energy prices and limited availability, further incentivise the exploration of alternative soil amendments (Mohsen, 2007). The financial burden of fertilisation is significant, with estimates indicating that costs can range from JOD50 per 1000 m^3 for wheat to JOD110 for *Chrysanthemum* L. As farmers seek ways to reduce production costs, sediment reuse emerges as an attractive option, especially in light of these escalating expenses.

In contrast, organic fertilisers, primarily sourced from local chicken and animal farms, provide another alternative but come with their own set of challenges. While these fertilisers are typically more affordable due to their proximity to croplands (Al-Hamad *et al*., 2024), they can lead to issues such as weed proliferation, necessitating the use of additional herbicides and potentially increasing overall production costs. Furthermore, concerns over contamination – particularly the risk of groundwater pollution from agrochemicals and organic fertilisers – underscore the need for careful management practices (Lampkin, Padel and Foster, 2000; Bergstrand, 2022).

When evaluating the agricultural impacts of sediment reuse, it is essential to consider not only the economic performance but also the environmental implications of adopting new production systems (Ciaian, Paloma and Delincé, no date). The application of dam bottom sediments can enhance soil quality by increasing the availability of macro- and micronutrients, improving soil organic matter content, and enhancing soil structure and water retention capacity (El-Radaideh *et al*., 2014; Ferrans *et al*., 2022). Also, incorporating sediments into the soil can mitigate issues such as soil crusting and erosion while ensuring a slow, consistent release of nutrients, which is critical for sustained crop health and productivity.

The benefits of utilising dam sediments extend beyond immediate agricultural gains. By recycling these materials, farmers can contribute to more sustainable land management practices, which are vital in a region like Jordan that faces challenges related to soil degradation and water scarcity. The integration of sediment reuse into farming systems can foster a circular economy within agriculture, where waste materials are repurposed to enhance productivity rather than being discarded.

With its potential to improve soil fertility, reduce reliance on costly fertilisers, and promote sustainable agricultural practices, sediment reuse offers a viable solution for farmers seeking to enhance their economic returns while also addressing environmental concerns. While challenges such as transportation costs and logistical hurdles remain, the advantages of utilising dam sediments as soil amendments could play a pivotal role in shaping the future of agriculture in the region. Continued research and collaboration among stakeholders will be essential in overcoming these barriers and maximising the benefits of sediment reuse for Jordanian farmers.

POLICY RECOMMENDATIONS FOR SEDIMENT MANAGEMENT

Financial and operational support

Subsidising sediment removal equipment. Governments should provide financial incentives or subsidies for procuring advanced sediment removal equipment to reduce operational costs for dam operators and agricultural users. Establish grant programs to support small-scale farmers in utilising sediment as a soil amendment.

Promoting public-private partnerships. Encourage partnerships between public agencies and private companies to create value-added products, such as nutrient-rich compost or construction materials, from dam sediments. Incentivise private sector investments in sediment processing facilities and reuse technologies.

Regulatory frameworks

Establishing water rights guidelines. Develop clear regulations to protect downstream water users during sediment removal activities, ensuring equitable access to water resources. Incorporate stakeholder consultations into the process to balance ecological, agricultural, and industrial water needs.

Developing sediment quality standards. Set national guidelines for sediment quality, specifying permissible levels of contaminants for agricultural reuse, construction, or disposal. Implement regular monitoring programs to ensure compliance with these standards.

Research and capacity building

Investing in research. Support research on innovative sediment reuse applications, including biochar production, soil restoration, and construction materials. Collaborate with universities and research institutes to assess long-term impacts of sediment reuse on soil health and crop productivity.

Building local capacity. Provide training programs for dam operators, farmers, and local stakeholders on best practices for sediment removal and reuse. Raise awareness about the economic and environmental benefits of sediment reuse to foster community participation.

Environmental and social considerations

Incorporating ecosystem-based approaches. Promote nature-based solutions such as afforestation in catchment areas to reduce sediment inflow into reservoirs. Encourage sustainable agricultural practices upstream to minimise erosion and nutrient runoff.

Engaging local communities. Include community representatives in decision-making processes to ensure sediment management strategies address local needs and priorities. Create employment opportunities in sediment removal and reuse projects to support local economies.

Economic incentives

Tax incentives for sediment reuse. Provide tax breaks for industries that incorporate reused sediment into their production processes, such as brick-making or land reclamation.

Market development. Establish marketplaces or exchanges for sediment-based products to link producers with potential buyers, such as farmers or construction companies.

CONCLUSIONS

The high siltation rates in many water dams and reservoirs across Jordan pose a significant threat to their productivity and longevity. As the country aims to heavily invest in dam construction, among other solutions, to meet the increasing water demands, the removal of sediment from these dams to restore their storage capacity has become a focal point of discussion. This approach contrasts with the traditionally costly option of building new dams. Utilising sediments as soil additives has shown potentially positive results in enhancing the growth and yield of various crops, particularly in regions with low soil fertility. However, the economic and technical feasibility of sediment removal and its reuse in agriculture in Jordan remains challenging due to factors such as a lack of necessary equipment, water rights complications, and transportation costs. Nevertheless, there is significant potential for future research and innovation to tackle these challenges. We believe that the short- and long-term benefits of sediment removal and reuse are likely to outweigh the associated economic costs.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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