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RESERVOIR SEDIMENTATION MANAGEMENT IN TAIWAN

BY HSIAO-WEN WANG AND WEI-CHENG KUO

With many dams reaching the end of their design life, sediment accumulation has become an increasingly important stake in reservoir management. Feasibility studies conducted for existing reservoirs did not address the costs of dam decommissioning and sediment management at the end of the design life, but these costs are substantial, as has been demonstrated for more than 1000 dam removals[1]. The potential benefits of managing sediment to maintain the storage capacity of reservoirs has widely been recognized[2], but to date it has been implemented at relatively few sites. This article summarizes sediment management strategies in Taiwan, providing lessons to help guide planning and design of new dams, and establish design standards for sustainable reservoir management. This article is complementary to other articles in this and the previous issue of Hydrolink on reservoir sedimentation, such as those by Kondolf and Schmitt, Annandale *et al*., Kantoush and Sumi, Lyoudi *et al*. who present diverse experiences and policies in managing reservoir sedimentation worldwide.

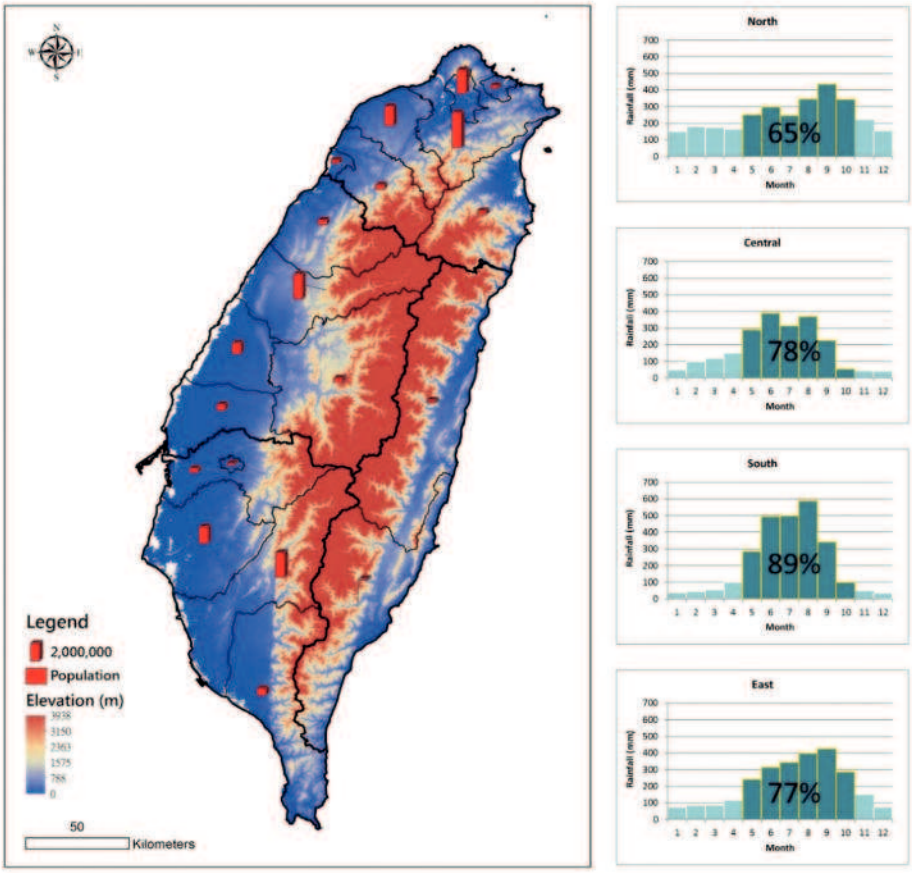
Background

The island of Taiwan (36000 km^2) supplies the Pacific Ocean with 384 million tonnes of suspended sediment per year (Figure 1), which means that 1.9% of the global fluvial suspended sediment discharge is derived from only 0.024% of Earth's subaerial surface[3]. Tectonically subduction zones, rapid uplifts, intense monsoon and typhoonal rains generate rapid erosion rates that make Taiwan's sediment yield to be among the highest in the world.

Taiwan counts 61 major reservoirs which impound a total initial storage capacity of 2,200 Mm^3 of water for domestic, industrial, agricultural and hydropower needs. However, with its highly seasonal precipitation and erodible landscapes, the ability to store water is seriously threatened by sedimentation, calling therefore for the implementation of sustainable sediment management strategies[4]. The annual capacity loss due to sedimentation of reservoirs in Taiwan is 22 Mm^3. By 2011, almost 30% of the total initial capacity of reservoirs had been lost according to the Water Resources Agency, with some reservoirs having lost more than 80% of their initial volumes. Figure 2 shows a selection of reservoirs in Taiwan, and their corresponding sediment management strategies.

For the benefit of gathering helpful information for existing and future reservoir sediment management, six cases, spanning a range of river and dam sizes, geographical contexts, and management objectives, have been examined[5] (Figures 2). These reservoirs, Shihmen, Zengwen, Ronghua, Wujie, Agongdian and Jensanpei, are facing severe sedimentation problems (Table 1 and Figure 3), thereby requiring extensive interventions for maintaining/restoring the reservoir storage capacity and dam functions.

Figure 1. (a) Map of Taiwan and general information, (b) Monthly average rainfall from 1949 to 2017. Data courtesy of National Development Council Government Website Open Information Announcement and Central Weather Bureau

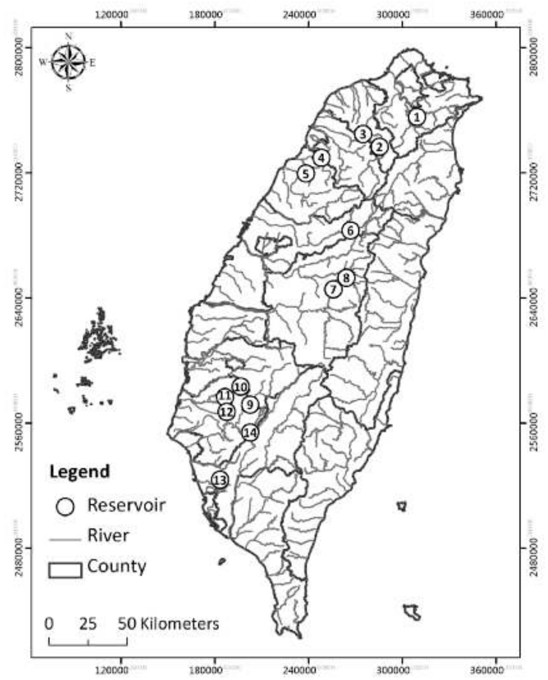


SEDIMENT MANAGEMENT STRATEGIES

Examining the selected six reservoirs, through the perspective of sediment management framework described by Annandale *et al*. (*cf*. first Hydrolink issue on reservoir sedimentation), some strategies were more commonly applied (Figure 2), such as reducing sediment yield from the catchment, trapping sediment above the reservoir by check dams (*i.e*. *Sabo* dams, Figure 4a), modifying dam operating rules, and hydraulic dredging of accumulated sediment near the dam. However, these practices represent the 'low-hanging fruit', generally characterized by low capital costs but also have limited effectiveness in maintaining and/or restoring the reservoir capacity.

Table 1. Overview of case studies. Reservoir purposes are Municipal and Industrial (M&I), Irrigation (IR), Industrial (ID), Hydropower Generation (HP), Recreation (R), Sediment Control (SC), and Flood Control (FC). (data

Figure 2. Selected reservoirs and associated sediment management strategies in Taiwan[5]. The study cases are 2: Ronghua, 3: Shihmen, 7: Wujie, 11: Jensanpei, and 13: Zengwen. (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation) (data courtesy of Water Resources Agency (WRA), Taipower Company, Taiwan Sugar Corporation, and Taiwan Water Corporation)



Strategies associated with each reservoirs

1	Feitsui: AF, ME
2	**Ronghua: AF**
3	**Shihmen: AF, HD, ME, SL, VT, DT**
4	Tapu: AF, EF, HD
5	Minte: AF, HD
6	Techi: AF, ME
7	Wujie: AF, DF
8	Wusheh: AF, ME
9	**Zengwen: AF, HD, ME, OS, SL, (SB), VT**
10	Paiho: AF, HD, ME, (SL), (SB)
11	**Jensanpei: AF, EF, ME**
12	Wusantou: AF, HD
13	**Agongdian: AF, EF, ME**
14	Nanhua: AF, ME, HD, VT

Description

AF:	*AFforestation*
DF:	*Drawdown Flushing*
DT:	*Desilting Tunnel*
EF:	*Empty Flushing*
HD:	*Hydraulic Dredging*
ME:	*Mechanical Excavation*
OS:	*routing Off-Stream reservoir*
SL:	*Sluicing*
SB:	*Sediment Bypass*
VT:	*routing Venting Turbidity currents*

Table 1. Overview of case studies. Reservoir purposes are Municipal and Industrial (M&I), Irrigation (IR), Industrial (ID), Hydropower Generation (HP), Recreation (R), Sediment Control (SC), and Flood Control (FC). (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation)

Reservoir (River)	Service year	Reservoir purposes	Initial Storage Capacity (Mm^3)	Live storage (Mm^3)	Mean annual runoff(Mm^3)	Mean Annual inflow Sediment (Mm^3)
Shihmen (Dahan)	1964	M&I, IR, HP, FC, R	309	208.3	1,468 (1964–2015)	3.5
Ronghua (Dahan)	1984	HP, SC	12.4	0.9	1086 (2001–2015)	2.8
Wujie (Jhuoshuei)	1934	HP	14	0.7	1,279 (2001–2015)	1.7
Jensanpi (Chiesui)	1938	IR, ID; after 2001, only R	8.1	1.5	7 (2001–2015)	0.25
Agongdian (Agongdian)	1953 2005	FC, IR, M&I (2011~)	36,700 18,370	17.2 16.3	54 (2001–2015)	0.38
Zengwen (Zengwen)	1973	M&I, IR, HP, R, FC	748,400	468	1,153 (1975–2015)	5.60

courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation)

In lieu of the aforementioned techniques, more efficient approaches requiring larger up-front capital investments are available. Dredging is relatively easy to implement, has low capital investment requirements, and offers potential value added from selling coarse aggregate for use in construction (when there is demand for such material). However, the effectiveness of dredging for maintaining the reservoir capacity relative to the annual sediment inflow is very low. For instance, in the multipurpose Shihmen Reservoir, approximately US$160 million was spent on hydraulic dredging operations over 31 years (1985 to 2015, Figure 4b), resulting in removal of only 8.1 Mm^3 of sediment at a unit cost of approximately US$20/m^3. In contrast, turbidity current venting and sediment sluicing through the renovated power plant penstocks, the renovated low-level Permanent River Outlet (PRO), which releases downstream water supply during power plant failures, and the spillway tunnel renovation projects (Figure 4c) effectively resulted in the removal of 12.6 Mm^3 of sediment in a period of 10 years (2005-2015), with a total initial engineering cost of about US$67 million, for a unit cost of approximately US$5/m^3. Thus, the infrastructure retrofits had a much higher economic efficiency than the hydraulic dredging.

The time horizon of sediment management is an important metric in comparing sediment management strategies. At the Shihmen Reservoir, dredging over 31 years removed the same amount of sediment as the PRO, turbidity venting, and spillway tunnel did in only 8 years. The cost of the power plant modifications (US$29 million) at Shihmen to facilitate turbidity current venting and sluicing, calculated over a 25-year design life of the tunnel, yielded a smaller unit cost for sediment removal (US$3/m^3) than did hydraulic dredging (US$20/m^3). Desilting tunnels are a high economically efficient technique compared to traditional dredging. The planned Amuping Desilting Tunnel will require an initial investment of US$133 million, and is expected to remove 0.64 Mm^3/year for a duration of 25 years of the dam operation[6]. Its total cost is therefore US$33 million less than the hydraulic dredging induced cost to remove the same material volume.

Some of the most effective sediment management strategies (*i.e.* sediment bypass, sediment pass-through) were implemented at only two sites, Shihmen Reservoir and Agongdian Reservoir. Sluicing, turbidity venting and flushing in Taiwan's reservoirs have been shown to discharge only 30 to 40% of the incoming sediment, calling for the use of other complementary methods. Thus, dredging continues to be an essential component of efforts to prolong reservoir life.

The lack of sediment management plans and monitoring for most of the reservoir sites is striking. While intakes and hydraulic structures have been refitted for the Shihmen, Zengwen, and Agongdian reservoirs, or are under consideration for modification for the Ronghua Reservoir, only the Shihmen and Zengwen reservoirs have comprehensive plans placing these renovations within the longer-term context of sediment management. For instance, a comprehensive plan at Shihmen Reservoir (Figure 5) was developed to identify the management strategies that may be used over time to combat sedimentation. In addition to the current practices, the design of desilting tunnels from the reservoir itself is ongoing[7,8]. A desilting tunnel (Amuping) will divert discharge and sediment from the midpoint of the reservoir into a 3.7 km-long tunnel with a gradient of 2.86% to transport 0.084–0.104 mm sized sediment[6]. After completing the Amuping desilting tunnel in 2021, there are plans to construct the Dawanping desilting tunnel to vent turbidity currents through two 10-m-diameter steel pipes via an intake structure, a 0.9-km tunnel, and two outlets, rejoining the river 1 km downstream of

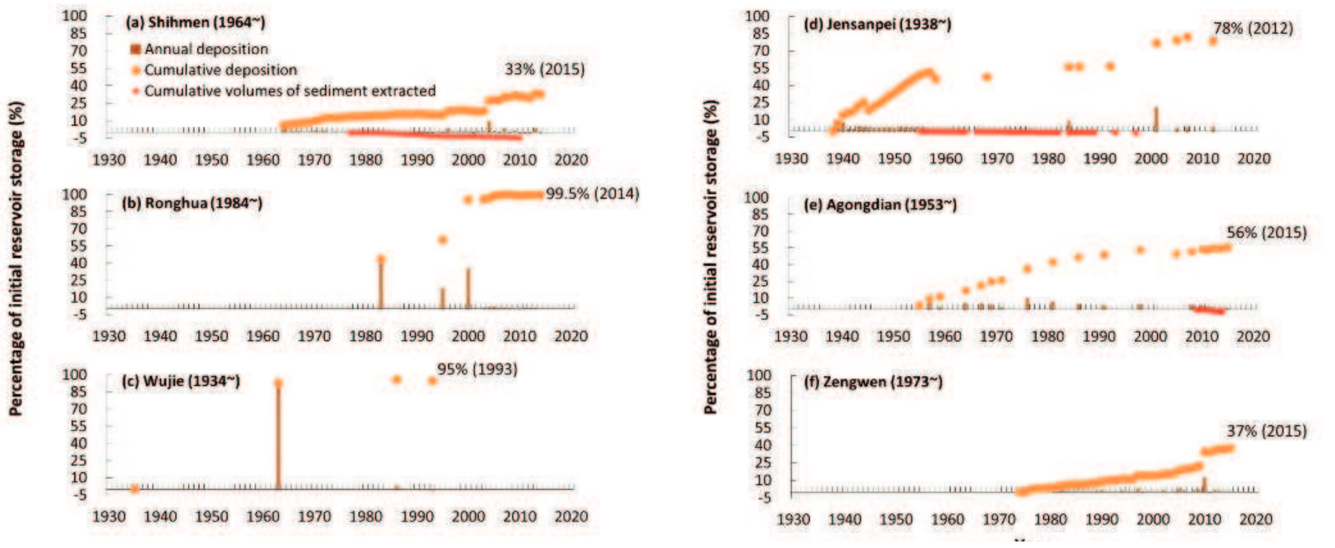


Figure 3. Reservoir sedimentation and material extraction over time[5]. The capacity loss due to sedimentation is reported along with the year of last reservoir survey on each plot (e.g. 33% and 2015, respectively, for Shihmen Reservoir). (a) Shihmen Reservoir; (b) Ronghua Reservoir; (c) Wujie Reservoir; (d) Jensanpei Reservoir; (f) Zengwen Reservoir. (data courtesy of WRA, Taipower Company, and Taiwan Sugar Corporation). Most important events include Typhoon Gloria in 1963, Typhoon Herb in 1996, Typhoon Mindulle and Typhoon Aere in 2004, and Typhoon Morakot in 2009. Due to the high sediment yield, the Wuji reservoir was almost filled six years after its completion in 1934

the dam. The two tunnels are expected to remove approximately 1.35 M tonnes/year, representing 39% of the mean annual sediment inflow.

Suitability of sediment management techniques

The characteristics of a site can strongly influence the suitability of different sediment management techniques. For example, despite its effectiveness, drawdown flushing has been conducted during floods in the Wujie (Figure 4d), Agongdian and Jensanpei reservoirs. Drawdown sediment flushing during the non-flood season is limited to hydrologically small reservoirs, where the residence time (*i.e.* ratio of storage capacity to mean annual runoff) does not exceed a certain value[13]. Different values for the residence time for characterizing a reservoir as small have been proposed in the literature, ranging from 0.04[14] to 0.3[15]. In hydrologically “large” reservoirs, where drawdown is not an option, major infrastructure modifications may be needed to manage sediment by venting turbidity currents or bypassing incoming sediment.

Similarly, bypass tunnels are best-adapted to situations where the geometry of the river and reservoir make possible a steeper short-cut route for the tunnel, such as where the reservoir occupies a river bend. A feasibility study at the Zengwen Reservoir proved that the unfavorable geometry, the high construction cost, and the engineering difficulty make the construction of a sediment bypass tunnel unlikely[16]. Furthermore, understanding the interactions between flow and sediment in sediment bypass tunnels is needed to avoid the need for frequent maintenance as bedload induces abrasion of the tunnel concrete bed (*cf.* Albayrak *et al.*’s article in the current issue).

Needs for and barriers to sustainable reservoirs

Sustainable reservoirs, from a sediment management perspective, have been defined as those a) whose life and reservoir capacity is maintained indefinitely, b) whose economic value is positive when taking a full life cycle approach that considers dam decommissioning and sediment management at the end of the project life, and c) provide intergenerational equity by not burdening future generations with the social, environmental, or economic costs of natural resources use by previous generations[13]. All these three concepts, either directly or indirectly, support the need for managing sediment throughout the reservoir life.

Shihmen and Zengwen are the most important reservoirs of Taiwan, supplying more than 25% and 40% of the water demand for the northern and southern regions, respectively. However, sedimentation was not taken seriously in these reservoirs until they lost a large portion of their respective capacity during a single typhoon event (*i.e.* 9% of initial storage capacity lost due to Typhoon Aere in 2004 for Shihmen Reservoir, 12% of initial storage capacity lost due to Typhoon Morakot in 2009 for Zengwen Reservoir). For Ronghua and Wujie, the two reservoirs with almost no remaining storage capacity, the originally stated design lives were short. For instance, the Ronghua Reservoir was commissioned in 1984 on the Dahan River with design life of only 25 years, as one of the 120 sediment-control dams (*i.e. Sabo*) reducing the sediment inflow to the Shihmen Reservoir. As of

Figure 4. Sediment management strategies in Taiwan[5]: (a) mechanical dredging from a sabo dam in Yixing, Shihmen basin, (b) hydraulic dredging at Shihmen reservoir (photo courtesy of WRA), (c) Sluicing at Shihmen Reservoir during Typhoon Soulik in 2013 (WRA), (d) Drawdown flushing at Wujie Reservoir

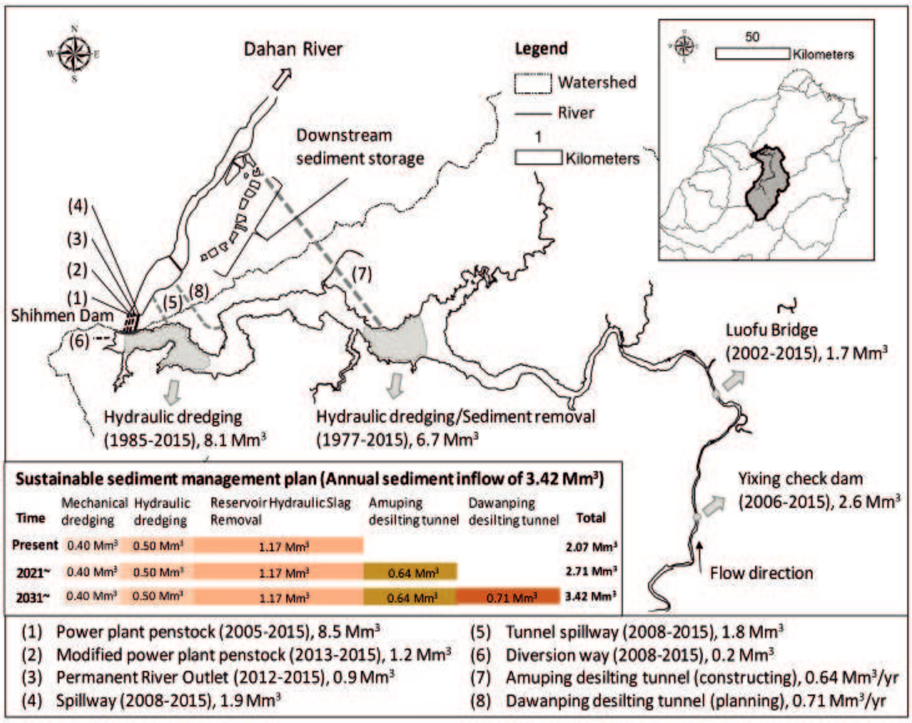


Figure 5. Diagrammatic map showing management strategies at Shihmen Reservoir[5]. Data are from WRA[9-12]

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2003, the reservoir was almost filled with sediment and its remaining capacity as of 2014 was less than 1% (Figure 3b). For dams whose primary objective was sediment retention, the expected timeframe for their benefit has been short. Moreover, sediment-filled dams can either fail catastrophically[17] or become expensive engineering problems upon decommissioning[18], creating hazards and burdens for future generations. Reservoir sedimentation demonstrates the critical need to take a full life cycle approach during design and construction of any dam, accounting for decommissioning and sediment management at the end of the project life.

For Agongdian and Jensanpei, the two reservoirs where drawdown flushing operations are conducted, conflicts with the competing use the reservoirs for recreation led managers to decide against emptying them. Public education on the importance of sediment flushing may help reduce conflicts between recreational and sedimentation operations. However, this must be complemented by strong leadership from reservoir managers and politicians to ensure that the key benefits of flood regulation and water supply are not compromised by the promotion of tourism and recreational activities.

Classifying the conflicts associated with sustainable sediment management in the Taiwan case studies highlights how social, technical, environmental, and economic barriers all inhibit effectively addressing reservoir sedimentation. Social barriers can be local (*e.g.* traffic concerns, tourism impacts, flood hazards) to global (*e.g.* design-life engineering paradigm, disregarding intergenerational equity). Among them, social concern about increased flood hazard risk due to aggradation downstream of the dam is also a technical issue. While the evaluation of increased sediment concentrations and aggradation of the bed downstream due to sediment passed through the bypass and desilting tunnels were conducted for Shihmen Reservoir[7,8], few such systematic evaluations exist for other sites.

A variety of technical concerns may emerge in any individual project. The methodological and financial challenges associated with monitoring sediment inflows has been the most common technical barrier, though methods for monitoring sediment are well established[19]. The loss of water supply associated with sediment flushing and sediment pass-through has also been a common technical barrier across our case studies. The primary environmental impact of sediment management is associated with high turbidity, even though it was identified as a concern at only two of the sites, Shihmen and Zengwen, and the literature on this impact is still immature. For instance, large pulse releases of sediment during flushing operations can impact downstream aquatic organisms through abrasion, burial, and in cases of organic sediments, anoxia[20]. Besides, dredging is known to impact aquatic organisms in the reservoirs in a variety of adverse ways[21] that range from direct mortality over the short term to transgenerational effects over the long term. Engineering and ecological research could evaluate operational and mechanical sediment management based on deviations from background concentrations, or behavioral or toxicity thresholds for aquatic organisms[22]. The most obvious economic impacts are associated with the capital costs of modifying water infrastructure to accommodate sediment pass-through, but ancillary impacts, such as foregone hydropower revenue, may also pose real barriers to implementing some of the most sustainable sediment management solutions. It is worth noting that the most commonly identified conflicts (*e.g.* design-life, capital costs, monitoring, impacts to water supply) tend to be addressed by more short-term strategies (*e.g.* mechanical dredging, check dams) instead of implementing long-term solutions (*e.g.* infrastructure retrofits).

Conclusion

Given the high sediment yield, several strategies for managing reservoir sedimentation have been implemented in Taiwan, offering insights into their effectiveness, tradeoffs, and barriers.-The selected case studies highlight the social barriers to reservoir sustainability, including the crisis-response approach to addressing sedimentation and the low priority for sediment

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