RESERVOIR DREDGING: A RISK-BASED APPROACH

Reservoirs are large natural or artificial lakes created by constructing a dam to store fresh water. Sedimentation in a reservoir both diminishes its storage capacity and compromises its purpose and safety. Reservoir dredging is a curative sediment management strategy, which, if planned effectively, is a sustainable solution. Most reservoirs have multiple users leading to competition and potential conflicts among user groups. Reservoirs are associated with complex and sensitive ecosystems and large volume of sediments that need to be removed. A risk-based approach for reservoir dredging involving all stakeholders from an early stage will help to identify and mitigate risks with minimal damage to the associated ecosystems.

Reservoir sedimentation

A reservoir is defined as an artificial lake constructed for storing water. Most reservoirs are formed by constructing dams across rivers. A reservoir can also be generated from a natural lake by constructing a dam at its outlet to control water. Large reservoirs without dams often present similar challenges as reservoirs associated with dams for sediment management and removal processes. Coastal reservoirs are freshwater reservoirs in the tidal limits, near the river mouth to capture sustainable river flow (S.Q. Yang et al., 2005). Coastal reservoirs can be located inside, outside or beside the river mouth. In this article, a reservoir is referred to both artificial and natural reservoirs including coastal reservoirs.

Reservoirs and lakes form a vital part of the Earth's usable and available fresh water supply system. According to the World Meteorological Organisation (WMO) report (2021), only 0.5% of water on Earth is usable and available freshwater. Based on the current data published by the International Commission on Large Dams (ICOLD), the present storage capacity of reservoirs is about 8,767 km³ of fresh water. The demand for global fresh water is steadily increasing and could reach 2-3% per year over the coming decades (ICOLD). Water reservoirs also guarantee steady water supply for irrigation, domestic and industrial use during droughts and reduce the negative impacts of floods.

Reservoir sedimentation not only diminishes its storage capacity but also compromises the purpose of reservoirs and the safety of dams. With the challenges of climate crisis, the planet is experiencing both drought with reservoirs and lakes drying up, as well as floods resulting from excessive rainfall as extreme weather events become more frequent. Soil erosion and hence reservoir sedimentation are also accelerating due to the severity of storms and rains associated with climate change. Sediment management and removal strategies need to be developed urgently to tackle the problems of reservoir sedimentation as well as the worldwide water crisis resulting from climate change.

To formulate suitable sediment management strategies for reservoirs, historic and current data on dams and reservoirs are necessary. No complete database of the world's reservoirs is available to date. Lehner and Doll (2004) present a global database of lakes, reservoirs and wetlands. This database is superseded by Global Reservoir and Dam Database (GRandD v1.3) (Lehner et al., 2011) that records 7,320 reservoirs and associated dams, with a global reservoir storage of 6,863.5 km³. Based on ICOLD, the current estimate of large dams is now around 58,000 worldwide with an estimated storage capacity of 7,000-8,300 km³. A large dam is a height of 15 metres or greater from the lowest foundation to the crest or a dam between 5 m and 15 m impounding more than 3 million m³ (ICOLD). There are many more small dams and impoundments, which are not recorded in the global databases.

Global Georeferenced Database of Dams (GOODD, 2020) is a global dataset of more than 38,000 georeferenced dams. GeoDAR (2022) presents nearly 25,000 geo-referenced dam and reservoir data. Other existing global and regional dam databases are AQUASTAT and World Resources Institute (WRI) databases. The Global Dam Tracker (GDTA, 2018) is a geo-referenced global dam database of 35,140 dams in all continents except Antarctica.

Primary information required to develop effective and sustainable sediment management and removal strategies for reservoirs are:

- the location and associated catchment and discharge areas;
- year the reservoir was built;
- current capacity of the reservoir: and
- material characterisation.

Data about present day reservoir capacity is often not available. Numerical modelling techniques assessing the sedimentation rates of reservoirs can be used to estimate the current volume of sediments present in reservoirs (Khorrami and Banihashemi, 2019).

Curative sediment management strategy

Sediment management strategies for reservoirs can either be "preventive sediment management strategies" i.e. adopting measures to reduce the inflow of sediments in the reservoirs or "curative sediment management strategies" i.e. removal of sediments from the reservoirs. This article discusses only the curative sediment management strategy of sediment removal by dredging.

The location and type of reservoirs presents challenges in terms of selection, transportation and launching of suitable dredging equipment. The volume of sediments to be removed from reservoirs is significant when compared to the volume of sediments removed from annual maintenance dredging works. Availability of a suitable disposal area for such volumes of sediments is often challenging. With contaminated sediments, disposal and encapsulation methodologies require carefully designed processes. While developing sediment management and removal strategies for reservoirs, emphasis should be given to circular economy and beneficial uses of the dredged sediments.

Most reservoirs have multiple users leading to competition and potential conflicts among user groups. Reservoirs are associated with complex and sensitive ecosystems. The timing of dredging and the rate of dredging activity should be such that it minimises the disturbance to the associated ecosystems (Sarkar, 2013). The sediment management and restoration of reservoirs often involves public resources. All these challenges increase the risks associated with any reservoir dredging activities.

This article discusses the importance of adopting a risk-based approach for reservoir dredging activity by identifying the major risks associated with different types of reservoirs and with various phases of the reservoir dredging life cycle (Sarkar and Sarkar, 2024). Identification of stakeholders and decision makers from the planning phase as well as early stakeholder involvement will result in a stakeholder driven process, which is effective in identifying, managing and mitigating reservoir dredging risks.

The recognised industry standards for risk assessments are ISO 45001:2018 and ISO 14001. ISO 45001 replaced the BS OHSAS, the globally recognised standard for

ORIGIN	SIZE	POSITION	LOCATION	PURPOSE
Manmade Natural	Small Area < 10 km² Medium Area 10-50 km² Large Area > 50 km²	Valley dammed Bank side Coastal	Wet/arid/cold Plain/hilly Rural/urban Surrounded by trees/open areas	Flood control Hydroelectricity Agriculture/ Pisciculture Minicipal

FIGURE 1

Classification of reservoirs.

SEDIMENTS	
Sediment source	Bank erosion
	Clastic sediments – transported
	Waste disposal
Sediment transport mode	Transported by water
	Transported by wind
	Transported by glacier/ice
Sediment size (PIANC Classification, 2016)	Gravel
	Sand
	Silt
	Clay
CONTAMINANTS	
Natural contaminants	From sub-soil
	Eroded and transported
Artificial contaminants (the level of contamination generated from these activities is important)	Washing and bathing of humans and animals
	Industrial effluents and solids/agricultural run-off and sewage discharges
	Religious ritual and wastes
AQUATIC PLANTS	
Type of aquatic plants	Free floating plants
	Floating and attached plants
	Semi-aquatic plants
	Submerged plants
	Emergent plants
	Partly decomposed thawed vegetation (e.g. in reservoirs that can be frozen during winter months)

TABLE 1

Material characterisation within reservoirs (Sarkar and Sarkar, 2024).

FIGURE 2

Small reservoir dredging equipment: A) auger cutter for contaminated sediments; B) rotovator cutter for aquatic weeds; C) water injection dredger; and D) submersible walking dredger.

occupational health and safety management. ISO 45001 includes bidding on contract, especially internationally, commitment to social sustainability (ESG benchmarking) commitment to UN SDGs (United Nations Sustainable Development Goals), and providing safe and healthy workplace free from injury and disease. ISO 14001 is the environmental management system standard that also needs to be considered.

Reservoir sediment management

The type of reservoir determines the morphological, hydrological and material (sediment, contaminants and aquatic plants) characteristics of any reservoir. Reservoirs can be classified based on their origin, size/storage volume, position, location and purpose of the reservoir. A simplified classification scheme for reservoirs is presented in Figure 1.

Extensive research and literature is available on morphology and hydrology of reservoirs, and is therefore not discussed in this article. Material characterisation is very important for developing sediment management and removal strategies, and selection of suitable dredging equipment. Material present in reservoirs can be grouped into three categories, i.e. sediments, contaminants and aquatic plants (see Table 1).

The type and volume of sediments are determined by the source of the sediment, sediment transportation mode, prevailing climate controlling the rate of precipitation and evaporation in the area. The rate of seepage through the bed rock/soil also impacts the type and volume of sediments present in the reservoir.

The sediment management strategies can be preventive sediment management strategies by sediment control at the source (e.g. construction of embankments, sediment traps and afforestation measures) and sediment control during transportation (e.g. construction of pre-settling structures/weirs/dams/barrages in the upstream or construction of silt traps). The type (natural or artificial) and amount of contaminants present in the reservoir needs to be assessed for defining sediment management strategies. The curative sediment management strategies include dry excavation where the reservoir is dry during the excavation process or dredging where the reservoir cannot be dried up. Surface floating mechanical or hydraulic dredgers can be used for shallow reservoirs. For deep-water reservoirs, submersible tracked or walking dredgers (Sarkar, 2007) and submersible floating dredgers (Sarkar, 2012) can be used. Specially designed submersible pumps can also be used for deep-water reservoirs.

Figure 2 shows small scale dredgers with specialised cutters for aquatic plants and contaminated sediments present in small reservoirs. A water injection dredger and a submersible walking dredger suitable for deep-water reservoirs are also shown.

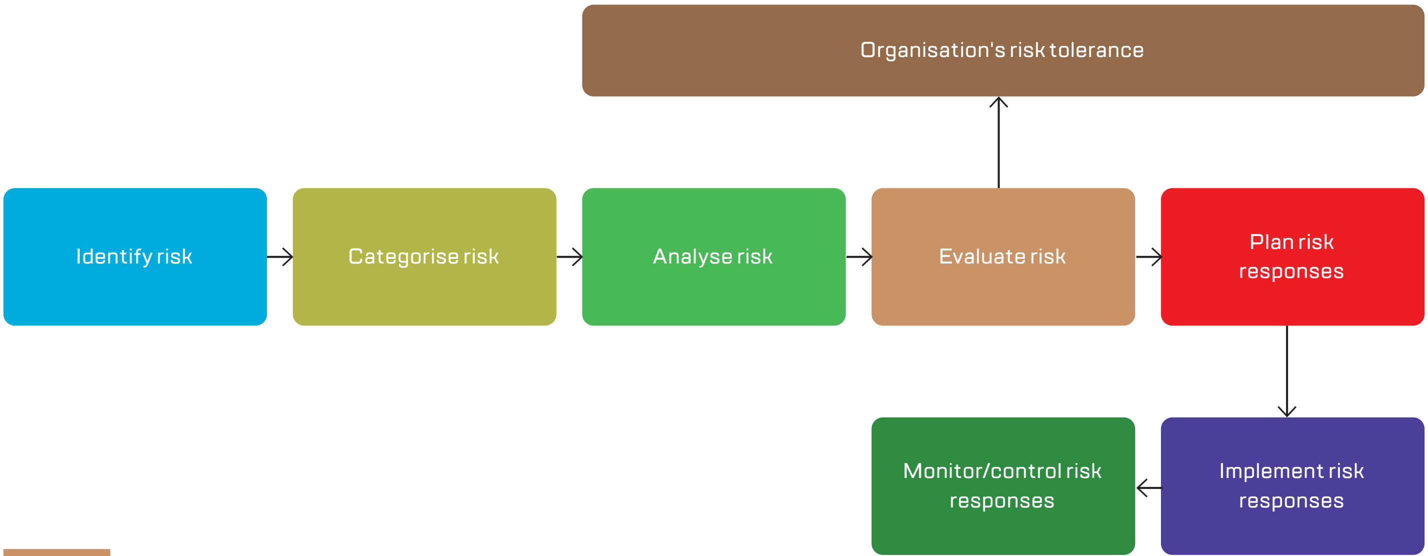

FIGURE 3
Risk management response steps.

FIGURE 4
Risk tolerance of an organisation.

Risk management

Risk can occur at any phase of the reservoir dredging life cycle. A "risk" is an uncertain event, activity or a set of circumstances that, should it occur, has a positive or negative impact on at least one of the reservoir dredging project objectives, i.e. scope, schedule, cost and quality. There can be multiple impacts and one or more stakeholders can be affected. The various phases of the reservoir dredging life cycle are: 1) pre-tendering; 2) tendering; 3) mobilisation; 4) execution; and 5) site restoration and demobilisation. The risk categories that can occur during reservoir dredging life cycle phases are: 1) technical; 2) economic; 3) commercial; 4) organisational; 5) political; and 6) social (nearby residents). Environmental risks will be generated by dredging activities. An Environmental Impact Assessment (EIA) should be performed prior to any dredging activities to provide sufficient knowledge about the associated ecosystems and flora and fauna thriving in the reservoir and surrounding areas.

Risk management for reservoir dredging is a continuous process performed throughout the various phases of the reservoir dredging life cycle. For each phase, the steps shown in Figure 3 should be applied to reduce the likelihood of an identified risk occurring and/or to reduce the potential impact of the risk on the reservoir dredging project.

To identify, categorise and analyse risks, the hazards associated with activities for each phase of the reservoir dredging life cycle are to be identified. The consequences of a hazard can be on people, equipment, environment and reputation of relevant stakeholders. Risk is calculated as:

$$\text{Risk} = \text{consequence} \times \text{likelihood} \quad [1]$$

The calculated risk needs to be evaluated with the risk tolerance of an individual organisation. Each organisation has its own unique risk profile based on assets it wants to protect, goals it wants to achieve and its ability and willingness to handle risks. Figure 4 shows the factors considered for calculating the risk tolerance of an organisation.

Risk response is the action taken to reduce the probability of a hazard arising or to reduce the impact of the hazard if it arises. Standard control and reduction measures are taken to reduce the risk rating (see Equation 1). These are referred to as "proactive responses or mitigations" and are usually funded by the project budget. If "reactive responses or mitigations" are required, then these are funded by the contingency budget. The contingency budget is dependent on the risk tolerance of the relevant organisation.

Early identification and involvement of stakeholders and decision makers are necessary in order to mitigate reservoir dredging risks. Stakeholders care about or have a vested interest in the project, while decision makers are legal authorities or groups that have accountability for management action. All decision makers are stakeholders, but not all stakeholders are decision makers. The importance of the stakeholders during various phases

All decision makers are stakeholders, but not all stakeholders are decision makers.

Potential stakeholders	Likelihood that stakeholder will affect decision	Likelihood that the stakeholder will be affected by decision	Reservoir dredging life cycle
Company (reservoir owner or operator) (COM)	High	High	All phases
Government and policy makers (G&PM)	High	Low	All phases
Contractor and sub-contractor (CON/SUB-CON)	Low	High	All phases
Political representatives (P)	Medium to high	Low	All phases
End-users and consumers (EU)	Low	High	Pre-tendering and post-completion phases
Groups with economic interests e.g. local business or landowners affected by the activity (LG)	Low	High	Execution, restoration and post-completion phases
Natural resource management agencies (RMA)	Medium	Low	Pre-tendering, execution and restoration phases
Relevant Non-Governmental Organisations (NGO)	Low to medium	Low	Pre-tendering, execution and restoration phases
Tourism department (TD)	Low	Low	Execution and post-completion phases

TABLE 2

Importance of stakeholders versus various phases of reservoir dredging life cycle (Sarkar and Sarkar, 2024).

	Reservoir type	Major risks for dredging
Position	Valley dammed	• Transportation of dredging equipment. • Most of the time, large dredger with higher capacity cannot be used. • Availability of suitable disposal area.
	Bank side	More sediment inflow above predicted levels due to bank erosion.
	Coastal	Coastal reservoirs at river mouth have a potential to collect all contaminants yielded from catchment.
Purpose	Flood control/hydroelectric generation	Assessment of dredging volume and location of dredging.
	Domestic/agriculture/pisciculture	• Insufficient dredging will affect the quantity and quality of water for the specific purpose of the reservoir. • Flora and fauna population will be reduced or extinct.
	Municipal	Required quantity and quality for the water supply system may not be met with less dredged volume and incorrect dredging location.
	Industrial	Financial loss for reduced or zero production in the relevant industry without planned dredging.
	Tourism/creating habitat for birds and animals	• Financial loss with reduced tourists. • Environmental impact resulting in decrease and even extinction of bird and animal population.
Location	Wet regions	Constant flow of sediments from catchment areas and eroded from surrounding areas.
	Arid regions	Loss of moisture and water due to evaporation and dredging activities; Restriction on use of transport water for hydraulic dredging methods.
	Cold regions	Thawed vegetation which are difficult for hydraulic dredging.
	Plain land	Increased cost for embankment construction for disposal area.
	Hilly region	Transportation of large equipment.
	Rural areas	Narrow roads and often inaccessible roads.
	Urban areas	Surrounded by houses and human settlement – social pressure on dredging activity.
	Surrounded by trees	Branches and leaves falling in the reservoir and getting decomposed.
	Open areas	Increased evaporation rates, especially in arid areas, resulting in fall of water level below the required draft of dredging vessel.

TABLE 3

Major risks of reservoir dredging verses type of reservoirs (Sarkar and Sarkar, 2024).

Activities	Hazards (Examples)	Risk category	Stakeholders affected*	Stakeholders who can mitigate risks
Determine sediment volume, distribution and classification	Inadequate or wrong survey data Inadequate or wrong survey data	Technical, economical, commercial.	COM/CON/SUB-CON	All decision makers formulating the reservoir dredging strategy
Determine volume to be dredged				
Define dredge scope	Large error margin on the calculation			
Select equipment	Incorrect specification of equipment			
Identify disposal location	Unavailability of disposal area	Technical, economical, commercial, social, political.	COM/CON/SUB-CON/ EU/LG	COM/RMA/NGO
Disposal methodology	Selecting wrong disposal methods			
Define liability period of dredging	Defining too short or too long liability period	Technical, economical, commercial.	COM/CON/SUB-CON	COM

TABLE 4

Pre-tendering phase – risk categorisation and stakeholders. Note * refer to Table 2.

Activities	Hazards (Examples)	Risk category	Stakeholders affected*	Stakeholders who can mitigate risks
Tendering process	Poorly written contract.	Technical, economical, commercial.	COM/CON/SUB-CON	COM/G&PM/P/ CON/ SUB-CON
Select contractor	Contractor selected with wrong track record.			
Obtaining information about "company"	Incomplete and inadequate information.	Economical, commercial.		
Deliverables by "company"	Delayed decision in awarding the contract.	Technical, economical, commercial.		
Deliverables by "contractor"	Reliability/availability of equipment.		COM/EU/LG	

TABLE 5

Tendering phase – risk categorisation and stakeholders. Note * refer to Table 2.

of the reservoir dredging life cycle are presented in Table 2.

Risks of reservoir dredging

Reservoir classification is presented in Figure 1. There are risks associated with different reservoir types, which can affect the overall risk of reservoir dredging. Major risks associated with dredging each type of reservoir are presented in Table 3.

The risks associated with the various phases of the reservoir dredging life cycle are presented next. Risk categorisation and stakeholders affected by the hazard and stakeholders who can mitigate the risks are shown in Tables 4-7.

Risks associated with demobilisation of the dredging equipment are similar to those mentioned for mobilisation activities. However, the risk to the overall project is lower as the works have been completed before demobilisation commences. The main consequences for site restoration are damage to the environment and associated ecosystems. The end users, local business groups and tourism department are affected if the site restoration steps taken are inadequate. During the site restoration phase the following checks are to be performed as a minimum:

1. Post-dredging monitoring of reservoir water quality and comparison with pre-dredging water quality;
2. Migration and extinction of any species not identified in the Environmental Impact Assessment, which is usually performed before the execution of any dredging activity;

Activities	Hazards (Examples)	Risk category	Stakeholders affected*	Stakeholders who can mitigate risks
Data collection during site setup	Information not collected regarding local maintenance and repair facilities.	Technical, economical, commercial, organisational.	CON/SUB-CON	CON/SUB-CON
Site setup for execution of dredging work	Wrong location and methodology selected for launching of dredger/ dredge pipelines.	Technical, economical, organisational.	CON/SUB-CON/EU/LG	
Supporting equipment setup – electrical	Improper electrical connection leading to electrical shock.	Technical, economical, political, social.		
Supporting equipment setup – diesel	Solids particle discharge in case of improper combustion.			
Supporting equipment setup – hydraulic power pack	Hydraulic oil leak leading to slips/trips.			
Surveying activities	Snake bites/ scorpions/ wasps.	Organisational, social.	CON/SUB-CON	
Paperwork for transportation	Improper paperwork for transportation from contractor's facilities to operational sites.	Economical, organisational.	CON/SUB-CON	
Mob/demob by land	• Uneven roads/ narrow roads • Steep roads/ diversions • Weather conditions • Extremists along driving routes • Night-time driving • Over-speeding • Driver fatigue • Improper and inadequate lashing, leading to asset damage	Technical, economical, political, social.	COM/CON/SUB-CON	
Mob/demob by waterways	• Size limitations • Towing/container transport • Improper and inadequate fastenings, leading to asset damage	Technical, economical, political, social.	COM/CON/SUB-CON	
Lifting and launching operation	• Wrong selection of crane/lifting gear/ rigging • Lift point design • Failure of crane/ lifting devices/rigging • Collision during lifting and launching • Oil spill from cranes • Noise pollution	Technical, economical, commercial, social.	COM/CON/SUB-CON, EU/LG	

TABLE 6

Mobilisation and site set-up phase – risk categorisation and stakeholders. Note * refer to Table 2.

Activities	Hazards (Examples)	Risk category	Stakeholders affected*	Stakeholders who can mitigate risks
Assembly of dredgers/ dredging equipment	• Incorrect assembly • Missing components/ tools required for assembly • Incompetent personnel	Technical, economical, organisational.	COM/CON/SUB-CON	CON/SUB-CON
Disposal line setup	• Wrong routing of the disposal line • Improper connection of disposal line components • Damage or leak from disposal line	Technical, economical, commercial, social, political.	COM/CON/SUB-CON, EU/LG/TD	
Equipment testing prior to operations	• Inadequate/ incomplete test plans • Not all components tested	Technical, economical, commercial.	COM/CON/SUB-CON	
Dredging operations	• Change in material to be dredged as mentioned in contract • Turbidity generation (hydraulic dredging) • Effect on associated ecosystems	Technical, economical, commercial.	COM/CON/SUB-CON	
Disposal of dredged material	• No nearby disposal site available • Disposal site available but not adequate for the volume of dredged sediments • Sudden influx of material from surrounding areas to dredge area • Ecological/ environmental damage • Contaminated sediments	Technical, economical, commercial, social, political.	COM/CON/SUB-CON, EU/LG/TD/RMA	RMA/COM/ NGOs
Survey during dredging work	• Survey equipment not calibrated • Survey equipment not working	Technical, economical, commercial.	COM/CON/SUB-CON	COM/CON/SUB-CON
Knowledge about local labour laws	• Inadequate training of local resources	Technical, economical, commercial, political.	CON/SUB-CON	P/COM

TABLE 7

Execution phase – risk categorisation and stakeholders. Note * refer to Table 2.

Beneficial uses of dredged material and circular economy should be considered to reduce risks.

3. Timeline for return and resettlement of species either disturbed or moved due to reservoir dredging activity (Sarkar, 2013);
4. Effect of reservoir dredging on downstream ecosystems and associated flora and fauna;
5. Dredged material in the designated disposal area is not generating any environmental damage and ecological risks to the local community and existing flora and fauna;
6. Disposal, encapsulation or further transport of contaminated sediments in not generating any additional risks; and
7. Any change in landscape of the area surrounding the reservoir to be inspected and brought back to the state as close as possible to the original.

Conclusions

A holistic approach is necessary for reservoir dredging operations by considering the associated water systems and the morphological and hydrological characteristics of the catchment and downstream areas. Identification and early involvement of stakeholders is necessary for a stakeholder driven process, which will help to identify and effectively manage and mitigate risks associated with reservoir dredging. Adequate data should be collected about the reservoir either from existing databases or suitable surveys to develop reservoir sediment management and restoration strategies and methodologies. The sedimentation pattern and material characteristics present within the reservoir is fundamental for any dredging activity. An Environmental Impact Assessment should provide sufficient knowledge about the associated ecosystems and flora and fauna present in the reservoir and surrounding areas. The volume of dredged sediments from the reservoirs can be of significant volume compared to capital dredging. Hence, identification of suitable disposal location, disposal methodology is very important. At planning stages, beneficial uses of dredged material and circular economy should be considered to reduce risks and have minimum impact from the dredged spoil. If contaminated sediments are present, handing and treatment of such material needs to be considered as early as possible.

Summary

According to the World Meteorological Organization (WMO) report published in 2021, only 0.5% of water on Earth is useable and available freshwater, of which reservoirs form a vital part. Sedimentation in reservoirs not only diminishes the storage capacity but also compromises the purpose of a reservoir and safety of a dam. Developing appropriate sediment management strategies for reservoirs is therefore necessary to cope not only with sedimentation problems but to also tackle the water crisis resulting from climate change. This article addresses the risks associated with reservoir dredging activities from planning, execution as well as restoration phases.

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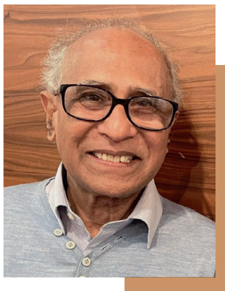

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