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REVIEW PAPER

Advanced Remote Sensing versus Traditional Techniques for Reservoirs and Dams Monitoring: A Comprehensive Review

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Abstract

Remote sensing (RS) involves acquiring and analyzing information about a target, area, or phenomenon without direct physical contact. Satellite spaceborne and airborne sensors can capture spectral and spatial data for Earth's surface monitoring with high precision. In addition, photogrammetry is used for environmental monitoring, as it offers cost-effective and spatially vast data acquisition. These technologies make large-scale observations and analyses of infrastructure and natural resources with remarkable accuracy. This review paper assesses the application of remote sensing techniques (satellite imagery and photogrammetry), to monitor dams and the effect of reservoir storage on dams. It evaluates the advantages and limitations of various RS technologies on dams and reservoir monitoring. The review focuses on three main applications of remote sensing: structural health monitoring of dams, water quality assessment in reservoirs, and sedimentation tracking that affects storage capacity. The objective of this paper is to highlight how remote sensing can improve dam monitoring efficiency, reduce inspection costs, and support sustainable water management by synthesizing recent advancements and drawing conclusions on their practical value. This paper highlights the importance of remote sensing in enhancing dam management and promoting water resource sustainability by examining current advancements and challenges.

Keywords: Dam structure integrity; Remote sensing application; Reservoir monitoring; Sedimentation assessment.

1. Introduction

Dams are important structures built across rivers to control and manage water for a long time. They help people by providing water for farming, making electricity, supplying drinking water, and protecting areas from floods. Keeping dams safe and strong is important because many people depend on them. Around the world, efforts like the Sustainable Development Goals (SDGs) encourage careful use of water. They aim to make sure everyone has clean water, enough food, renewable energy, and uses water wisely [1].

By 2050, farmers will need much more water, but there will be less fresh water available. So, it is important to carefully watch and manage water resources. Satellites like the European Union's

Copernicus program help by giving valuable information about the environment. This helps people make better decisions and use water wisely [2], [3].

In the past, people checked dams using tools like inclinometers, extensometers, clinometers, leveling surveys, and total stations [4], [5], [6]. Leveling surveys and total stations worked well to measure vertical movements but took a lot of time and effort [7]. Hydrostatic leveling is another method that can automatically check dams all the time, but it's difficult to use everywhere[8].

Remote sensing uses multi platforms to collect information about the Earth's surface such as aircraft, balloons, and satellites [9]. Satellites provide spatiotemporal images that are widely used to detect changes in the environment. These images offer large-scale coverage and can be collected frequently, allowing for continuous monitoring over time. However, the spatial resolution of satellite images can be limited by the sensors used and the distance from the Earth's surface. In contrast, aircraft and balloons can capture images with higher spatial resolution because they operate closer to the ground. These platforms can be deployed to specific locations and times, which makes them more flexible and accurate for certain applications. However, the use of aircraft and balloons requires careful planning, including flight paths, weather considerations, and regulatory approvals [10]. Moreover, Synthetic Aperture Radar (SAR) is a remote sensing technology that uses microwave signals to capture images of the Earth's surface. Unlike optical sensors, SAR can penetrate clouds, smoke, and even vegetation, making it useful for monitoring the environment in all weather and lighting conditions. This capability allows SAR to provide reliable data both during the day and at night, regardless of atmospheric conditions. SAR has become an important tool for applications such as land cover mapping, disaster assessment, and environmental monitoring [7].

Interferometric Synthetic Aperture Radar (InSAR) is used to measure ground movements. It can detect tiny movements until a few millimeters over large areas [11], [12]. At first, InSAR was used for mapping the shape of the land but now it could be used for many approaches. There are special types of InSAR methods. These include Differential InSAR (DInSAR), Ground-Based InSAR (GBInSAR), Persistent Scatterer InSAR (PSInSAR), Multi-Temporal InSAR (MTInSAR), Quasi-Persistent Scatterer InSAR (QPSInSAR), and Small Baseline Subset (SBAS) [13], [14], [15], [16], [17].

DInSAR finds ground movement by comparing the difference between two radar images [13]. GBInSAR uses equipment set up on the ground to get more detailed information. This method is useful for small area [14]. PSInSAR focuses on points that stay mostly the same. This methos is more accurate for measuring the ground movements over a long period [15]. MTInSAR uses several radar images taken at separate times. This helps show how the ground changes over time and in different places [16]. QPSInSAR is like PSInSAR but can work even if there are not many stable points. This make it useful in more areas[17]. Finally, SBAS chooses images carefully to get better results. It works well in areas if there fewer images are available [17].

This review carefully looks at diverse ways of checking dams and reservoirs, especially using remote sensing (RS). It compares older methods with newer RS method like radar, optical, and multispectral technologies. Recent studies show that RS is becoming more popular for checking dams, especially for hydropower dams, water supply conditions, and their strength [18], [19]. The review highlights how important and useful remote sensing and photogrammetry have become for keeping dams safe, checking how well they perform, and managing water wisely.

2. Importance of Dam Monitoring

Experts usually put dams into three main groups. They do this based on how the dam is made and what materials are used. The first type is rockfill dams with concrete faces. These dams are built by placing compacted rocks on the side where the water comes from. A concrete slab is added on top to stop the water from leaking through. The second type is earth-filled dams. These dams are mostly made from soil or tightly packed earth. The weight of the earth keeps the stored water from leaking out of these dams. They usually have a waterproof core in the middle. This core helps stop water from leaking through the dam. The third type is concrete dams. They are made fully from concrete. These are built entirely out of concrete and are often used where there are strong foundations. There are three main types of concrete dams: gravity dams, arch dams, and buttress dams. These names come from the shape of the dam and how it moves water pressure to the foundation. These categories help engineers choose the best design for certain geological, environmental, and hydrological conditions [20], [21]. The type of dam and outside forces determine the materials and designs. There are two main types of concrete dams: gravity dams and arch dams. These types of dams have a big effect on how well they can resist forces. Forces affecting dams are typically divided into normal and abnormal types.

Normal forces include temperature changes from air and sunlight, and water pressure from reservoirs [21], [22]. Abnormal forces involve earthquakes[22], [23] and geotechnical forces such as ground movements or soil pressure [23].

Dams can also deform due to internal stress changes over time. This deformation is called plastic deformation. Other problems include water seepage, internal erosion, and sliding. Earth-fill dams are particularly prone to these issues, especially when water seeps through or erodes the ground beneath, affecting stability.

Monitoring dam movements typically involves tracking horizontal (side-to-side) and vertical (up-and-down) shifts. When multiple forces act simultaneously, monitoring movement in all three dimensions is necessary. Horizontal movements usually result from water pressure or temperature changes, frequently occurring at the dam's top [24]. In concrete dams, temperature and water-level changes affect the central area, where plumblines placed in vertical shafts or inspection galleries monitor horizontal shifts at various heights. Horizontal deformations may also impact specific structural areas like the downstream faces of dams. In such cases, Automated Deformation Monitoring Systems (ADMS) are important for real-time detection of unusual displacement patterns.

Vertical movements often occur at the dam crest, within inspection galleries, at foundation levels, and along the interfaces between the dam and valley slopes. Differences in elevation between monitoring points may indicate rotational deformation or overall settlement of the structure and surrounding ground. Early detection of vertical movements, such as local sinking or uneven uplift, can signal structural instability, particularly when closely monitored at the dam-bedrock interface.

Monitoring systems must differentiate between permanent long-term changes and short-term fluctuations. Short-term changes often occur due to temperature variations or changing water levels. Environmental data like weather and water level records are essential for understanding these movements. In earth dams, variations in the water table significantly affect internal soil pressure, potentially causing settlement over time.

3. Literature Review

3.1 Geodetic and Traditional Sensors

Large dams use geodetic methods to monitor their stability and movement. Common methods include optical collimators, optical leveling (OL), geometric leveling, trilateration, robotic total stations (RTS), and Global Navigation Satellite Systems (GNSS).

Optical collimators measure horizontal displacements (HD) by observing targets from a fixed reference point. These sensors are highly precise under ideal conditions but are limited by atmospheric conditions and distance [25][24]. Automatic collimators provide continuous monitoring but require careful placement to minimize atmospheric interference.

Optical leveling reliably measures vertical displacements but is labor-intensive and unsuitable for continuous monitoring. Digital autonomous levels improve efficiency but still require manual operation[26]. Hydrostatic leveling allows continuous high-precision measurements but needs costly and complex pipe networks [27].

Geometric leveling, trilateration, and intersection are crucial methods for dam monitoring. Trilateration uses distance measurements for accurate spatial positioning, beneficial in challenging terrain. Intersection measures angles and distances to locate targets. Geometric leveling, although precise, is time-consuming for broad areas [28], [29] [30].

Robotic total stations (RTS) provide automated, frequent, millimeter-level measurements. However, accuracy can be impacted by atmospheric refraction, necessitating calibration models [31], [32]. Terrestrial laser scanning (TLS) is considered a remote sensing technology used for the high-precision three-dimensional modelling of small topographic features. It provides millimeter-level detail for monitoring dams. TLS can be conducted on the ground, on a moving vehicle, or from an aircraft [33], [34]. Global Navigation Satellite system (GNSS) delivers accurate 3D measurements without line-of-sight restrictions but may encounter interference from reflective surfaces and environmental factors [35], [36], [37].

3.2 Remote Sensing Techniques

Remote sensing (RS) methods use satellites to collect data without direct contact. There are two types of RS as illustrates in Figure 1 .Passive sensors detect naturally emitted or reflected energy (sunlight), useful for environmental monitoring. Active sensors emit energy and measure its reflection, suitable for structural assessments.

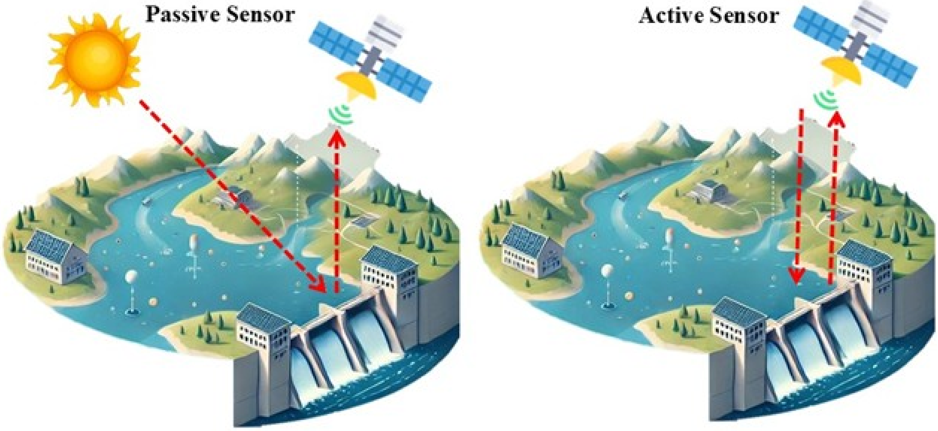

Figure 1: *The difference between active and passive RS.*

SEASAT was the first satellite equipped with a spaceborne Synthetic Aperture Radar (SAR) system. Launched by NASA from the United States in June 1978, SEASAT was primarily designed to see and collect data about the world's oceans, including wave patterns, sea surface winds, and ice coverage. Although the mission ended in October 1978 due to a technical failure, SEASAT demonstrated the value of SAR technology for environmental monitoring from space.

Coupled missions were expanded after SEASAT. For example, the TOPEX/Poseidon satellite was a cooperative mission with NASA, the United States, and French space agency CNES. The mission was launched in August 1992 and studied ocean surface topography. This satellite carried a radar altimeter that measured the height of the sea surface and could be used to infer water storage for a variety of lakes and reservoirs around the world.

Other satellites to carry radar altimeters have included JASON-1, JASON-2, GEOSAT, ERS-1, ERS-2, TOPEX/Poseidon, ENVISAT, and GFO. Radar altimeters have been successful in providing repeatable, accurate estimates of water levels and surface changes for broad areas.

Recent and near-real time missions such as LANDSAT, MODIS, RADARSAT, JERS-1, and the newer SAR satellites and sensors provide even better spatial resolution, temporal frequency, and accuracy. This enables higher precision in estimating surface water area, bathymetric information, water storage variability, and accuracy of water storage. All the information listed in Figure 2 is critical in effective water resource management and monitoring.

Satellites have proved to be an invaluable tool in dam and reservoir monitoring. Satellite information can be used to effectively monitor water levels, changes in structure, ecosystem changes, water quality, and more. As Figure 2 shows, an integrated strategy using multiple RS techniques and several satellite data sources to provide a suite of applications ranging from water storage to structural health to sedimentation monitoring to ecosystem evaluation has been effectively demonstrated in various case studies.

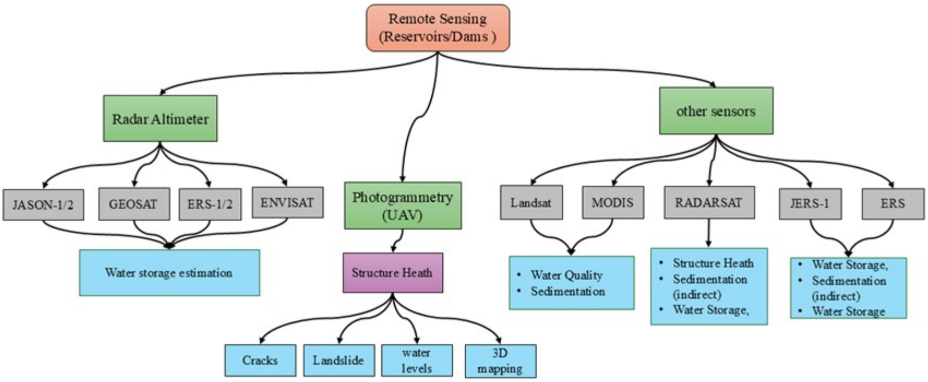

Figure 2: *Remote Sensing Applications for Dam and Reservoir Monitoring.*

Figure 2 shows a variety of remote sensors and technologies used for dam and reservoir monitoring. The figure also indicates major types of sensors: radar altimeters, photogrammetry, and other satellites (Landsat, MODIS, RADARSAT, JERS-1, ERS). Each group of sensors is represented by several key missions (ovals). These remote sensors provide various data used for management of dams and reservoirs.

Radar altimeters such as JASON-1/2, GEOSAT, ERS-1/2 and ENVISAT are used for water storage estimation, and photogrammetry including UAVs for detailed assessments of structural health (detecting cracks and monitoring of landslides, measuring water levels, and three-dimensional (3D) mapping of dam surface). Other sensors (e.g., Landsat and MODIS) provide water quality and sedimentation data which can be used for ecosystem changes and reservoir capacity. Synthetic aperture radar (e.g., RADARSAT) provides data for structural health monitoring, indirect assessment of sedimentation, and estimation of water storage. Finally, other platforms, including JERS-1 and ERS, can be used to obtain data for water storage and sedimentation.

The integration of these diverse data sources enables comprehensive monitoring and analysis. Advanced remote sensing methods, including interferometric SAR (InSAR), persistent scatterer SAR (PS-SAR), and other radar-based techniques, enhance the detection of surface deformation and structural movement. Environmental factors and ecosystem variations can be assessed using vegetation indices and precipitation datasets.

Continuous advancements in data processing, algorithm development, and automation are improving the accuracy and efficiency of remote sensing applications for dam and reservoir monitoring.

Figure 3 shows the number of studies that used remote sensing to study dams and reservoirs in different continents. Most of the studies were done in Asia (19 studies). This is because many large dams are built in Asia, and satellite data is often used to watch how they affect the environment and

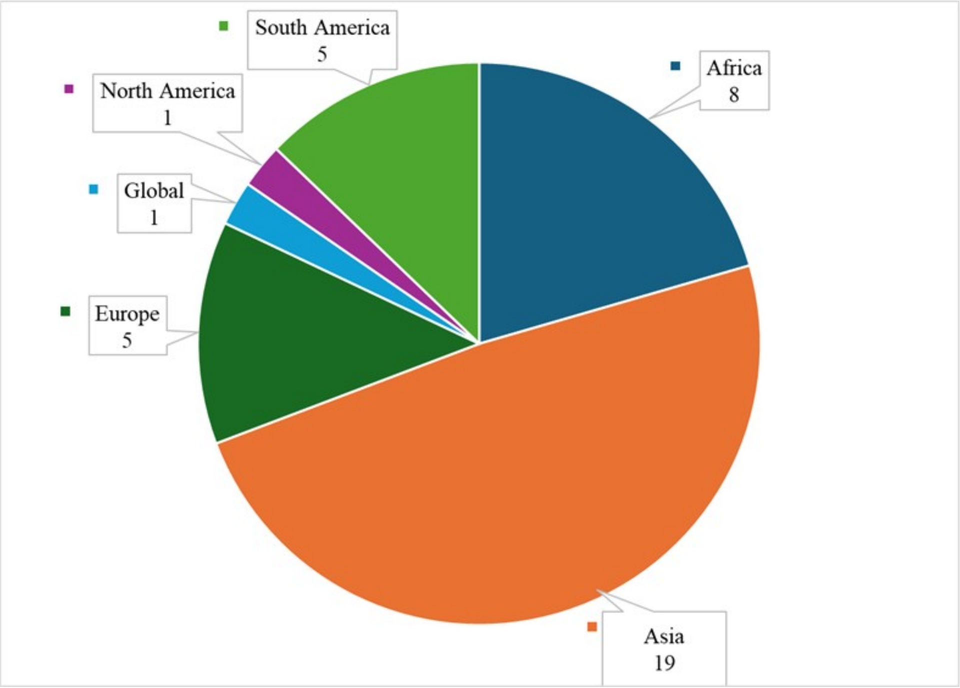

Figure 3: *Pie charts show the number of study areas categized by continent.*

water. Africa had eight studies, focusing on water storage, rainfall, and dam safety. South America and Europe each had five studies, mostly in Brazil and countries in southern Europe. Only one study was done in North America, and one study looked at dams around the world. No studies in this chart came from Australia or Oceania. This chart shows that most research is focused on Asia, while other parts of the world have fewer studies. It also shows how satellite data is used where there are many dams or not enough ground data.

Table 1 summarizes global studies that applied satellite data to monitor dams and reservoirs. It includes details on the sensors used, study locations, research focus, methods, and countries. Commonly used satellites include Landsat, MODIS, Sentinel, ICESat, and ENVISAT, which supported investigations into dam deformation, water surface area, rainfall patterns, and structural stability. Most studies were conducted in Asia and Africa, with others from South America, Europe, and some global assessments. Frequent study locations included China, India, Brazil, Egypt, and Spain. Techniques such as InSAR, NDWI, altimetry, supervised classification, and regression models were used to monitor ground movement, water levels, and environmental changes. These findings highlight the growing role of satellite platforms in dam safety, water management, and environmental research.

Several studies also addressed key applications such as Structural Health Monitoring (SHM), water quality, and sedimentation tracking. SHM used remote sensing methods like InSAR, SBAS, and PSI to detect structural changes over time. Water quality assessments focused on indicators such as color, temperature, and turbidity. Sedimentation studies tracked soil and debris buildup in reservoirs, which can reduce storage and affect dam operations. These applications show how remote sensing supports broader aspects of dam and reservoir management.

Table 1: *Satellite platforms in many sites of dams and reservoirs all over the world.).*

Sl. no	Sensor	Dam/Reservoir	Type of Study	Techniques	Country	Citation	Continent
1	ERS 1/2, Envisat, Sentinel	Aswan High Dam, BenÃ¬nar, La ViÃuela, El Arenoso	Vertical displacement; Consolidation rating	MT-InSAR	Egypt - Spain	[38]	Africa - Europe
2	Landsat satellite altimetry	Aswan High Dam/Lake Nasser	Estimate discharges	Satellite Altimetry Analysis	Egypt - Sudan	[39]	Africa
3	Hydroweb satellite altimetry, Landsat 8	Lake Nasser	Water volume variations (WL and surface areas)	Areas–WL model; Heron method	Egypt	[40]	Africa
4	ENVISAT	Twenty-one small reservoirs	Reservoir deformation	ENVISAT	Ghana	[41]	Africa
5	Landsat 1-5, MODIS Terra	Kariba Dam	Rainfall patterns; Water level relationships	Automated satellite data extraction	Zimbabwe	[42]	Africa
6	Landsat 8, Sentinel-2, ICESat-GLAS	Mekong River dam	Dam characteristics; Reservoir storage	Time-series remote sensing; Hydrological modeling	China	[43]	Asia
7	Sentinel, Landsat 8	Baihetan Reservoir	Ground deformation; Slope stability	SBAS-InSAR	Chian	[44]	Asia
8	Sentinel-1 SAR, Landsat 8-9	Three Gorges Dam	Dam stability monitoring; Surrounding landscape	SAR interferometry	China	[45]	Asia
9	Sentinel-1, TerraSAR-X	Xiaolangdi Dam	Deformation monitoring	PS-InSAR	China	[46]	Asia
10	ICESat-2, Sentinel-2	Lakes	Water storage changes; Depth exploration; Resource assessment	Bathymetric models	China	[47]	Asia
11	Sentinel-1	Three Gorges Reservoir area	Predict landslide displacement; 3D time series	InSAR; GNSS; ML; SBAS	China	[48]	Asia
12	Landsat (5-8)	Sobradinho dam	Estimate water surface area; Calculate drought	NDWI Index Calculation; Surface Area Estimation	Brazil	[49]	South America

13	Envisat RA3, ICE-Sat GLAS	Thirteen reservoirs in eastern Brazil	Estimate reservoir volume dynamics	Regression models; Modeled volume changes	Brazil	[50]	South America
14	MODIS	Six hydropower dams in the Paranapanema River	Impact of hydropower dams on turbidity and sedimentation	MODIS surface reflectance algorithm	Brazil	[51]	South America
15	Sentinel 2/3	Yliki reservoir	Water level, area, and storage variations	NDWI; Situ Observation	Greece	[52]	Europe
16	Sentinel-1A	Baglihar Dam Reservoir	Monitoring and mapping landslides	PSI	India	[53]	Asia
17	Sentinel (1A, 1B)	Rim dam and reservoir	Monitor deformations	SBAS-InSAR	India	[54]	Asia
18	Landsat DEM, Sentinel	Yarmouk basin	Monitor storage variations	Elevation-area relationship	Syria	[55]	Asia
19	Landsat 7	Duhok dam	Change in water surface area	NDVI	Iraq	[56]	Asia
20	Landsat 8	Mosul Dam reservoir	Monitor and estimate water volume	Supervised classification	Iraq	[57]	Asia
21	Landsat-TM, Landsat-ETM+	Ede-Erinle and Eko-Ende reservoirs	Mapping and monitoring reservoir area	Unsupervised classification; land use	Nigeria	[58]	Africa
22	Landsat and ASTER	Alkhod Dam	Mapping clay siltation	ASTER VNIR SWIR; Spectral Angle Mapper	Oman	[59]	Asia
23	Sentinel-1, Sentinel-2, Landsat-8,	Sardoba Dam	Assessing dam risks and failure	PS network; SBAS; NDWI	Uzbekistan	[60]	Asia
24	MODIS and Landsat imagery	Dale Hollow Reservoir	Reservoir surface water tracking	Pixel analysis; Spectral unmixing	USA	[61]	North America

25	Sentinel 1	Gilgel Gibe, Xiowan, Jirau, Bansagar, Vueltosa, Three Gorges	Measure reservoir levels; Elevation estimates.	Area-Elevation (A-H); DEM	Ethiopia, China, Brazil, India, Venezuela, China	[62]	Africa, Asia, South America, Asia, South America, Asia
26	ERS-1/2, Envisat, Sentinel-1A/B	La ViÃuela dam	Deformation monitoring	GNSS; optic fiber; Terrestrial Laser Scanning (TLS); MT-InSARM	Spain	[63]	Europe
27	Sentinel-1A, Landsat 8	Castello dam's crest	Displacement and forcing factors	Quasi-PSI-SAR; Thermal; Classification	Italy	[64]	Europe
28	PS-InSAR and Electronic Corner Reflectors	Eight dams in Ruhrverband, Germany	Dam deformation	PS-InSAR; CR Index	Europe	[65]	Europe
29	Sentinel-1 /2	Two dams and three reservoirs	Water body detection; Water quantity	Speckle filtering; Object detection (Otsu, K-means, etc.)	Korea	[66]	Asia
30	Sentinel-3, ICESat-2	Six reservoirs in the Krishna River	Water level monitoring	Wet tropospheric correction; Back-substitution	India	[67]	Asia
32	ICESat and ICESat-2	Global lakes and reservoirs	Global water level change analysis	Filters and quality flags for ICESat data	World	[68]	World
32	MODIS	Five Reservoirs in South Asia	Flood monitoring; Water resource management	MODIS-DEM storage time series	South Asia (INDIA)	[69]	Asia

3.2.1 Water Resource Monitoring

Monitoring reservoir storage through changes in water level and surface area depends on remote sensing data with frequent temporal resolution. Landsat offers high spatial resolution with a consistent 16-day revisit cycle, while MODIS provides more frequent coverage at 8-day, 16-day, monthly, seasonal, and annual intervals. These datasets are widely used to detect temporal variations in surface water due to seasonal cycles, drought, and human activities. In addition to optical imagery, satellite altimetry missions such as ICESat-1, ICESat-2, and Jason series provide precise water level measurements that, when combined with surface area data, enable volume estimation.

The monitoring of reservoirs with such satellite sources has been carried out in many different regions with different hydrological conditions. For example, Landsat and MODIS were used for water dynamics monitoring in Egypt, Brazil, and the United States. Several investigations have shown that altimetry data provides a major contribution for reservoir volume estimation when the in-situ information is non-existent or lacking accuracy and completeness. Since the altimetry consistently measures water surface elevation of these reservoirs over time, storage change can be more accurately followed. Furthermore, radar technologies such as Sentinel-1 provide a great benefit for water detection in areas where cloud or dense vegetation can be a common occurrence. Radar sensors can "see through" atmospheric and vegetation cover, providing the ability to monitor these conditions. By using the fusion of optical imagery, radar information and altimetry data a higher accuracy and spatial coverage has been achieved. Radar systems can penetrate atmospheric and surface obstacles, allowing for continuous monitoring regardless of weather or vegetation conditions.

The integration of optical imagery, radar data, and altimetry measurements has led to increased accuracy and broader spatial coverage for hydrological monitoring. This combined approach is particularly effective for observing surface water dynamics in remote, inaccessible, or data-poor regions, where ground-based surveys are not feasible.

These advanced remote sensing methods have been applied in various countries to study water resources. For example, in Egypt, researchers have used these technologies to monitor reservoir storage and assess changes in water availability [39], [40]. In Brazil, similar techniques have been adopted to examine water variability and investigate the impacts of droughts and seasonal fluctuations on reservoir levels [49], [50], [51]. In the United States, satellite data have been used to analyze water level variations and to understand the effects of drought and seasonal cycles on storage capacity [61]. Moreover, studies have explored how population density influences the selection and effectiveness of different water storage monitoring methods, highlighting the importance of matching remote sensing techniques to local needs[68]. These examples demonstrate the value of integrated satellite data for managing water resources and understanding hydrological changes under various environmental and social conditions.

Satellite altimetry missions have played a key role in the estimation of reservoir and lake volumes, particularly in areas where ground-based observations are scarce or unavailable [43], [47], [50], [70]. These missions provide continuous measurements of water surface elevation, which are essential for tracking variations in water storage over time. The use of altimetry data allows for a more accurate assessment of volume changes, especially during periods of drought or flood.

Optical satellite systems, such as Landsat and MODIS, have contributed extensively to the monitoring of surface water extent and distribution [49], [55], [57]. Their long-term data archives enable the observation of seasonal and interannual fluctuations in water bodies, supporting studies of hydrological cycles and climate impacts on freshwater resources.

In addition, the application of Sentinel satellites and radar sensors has improved water mapping in regions that are challenging to survey using traditional methods. These radar systems are capable of acquiring data through clouds, vegetation, and at night, which makes them effective for detecting surface water in remote or heavily vegetated areas [43], [52], [55], [69]. By combining data from altimetry, optical, and radar sources, researchers can achieve more comprehensive and reliable monitoring of water resources across a wide range of geographic and environmental conditions.

3.2.2 Structural Integrity Monitoring

Sentinel-1, ERS, and Envisat, combined with advanced INSAR techniques, have proven to be a cornerstone technique in the interpretation of ground deformation and the evaluation of the structural integrity of dams. These techniques of remote sensing are also able to identify even very slight changes in the earth sub-structure: such as land subsidence, slop-value instability and even deformation in the structure of a dam. The application of interferometric methods, such as SBAS-InSAR, SBAS, SBAS PS-InSAR and PS-InSAR, permits obtaining enhanced accuracy and identification of slow movements on long time intervals.

Combining the analysis of InSAR data with other geospatial techniques additionally increases the potential for monitoring activities. For instance, Global Navigation Satellite System (GNSS) observations offer accurate ground displacement at discrete spots and optically based satellites like Landsat furnish high-resolution images for visual inspections. By combining these technologies, researchers can obtain a more comprehensive understanding of dam movements, enable early detection of potential risks, and support effective management and safety evaluation of critical infrastructure.

The capability of remote sensing and spatial technologies for dam monitoring and safety evaluation has been documented in numerous studies from different countries. InSAR is extensively used for monitoring the deformation of dams as well as the ground movement in India, Spain, Egypt, and Uzbekistan. The failure mechanisms and the contributory factors of the Sardoba Dam were understood through change analysis of the dam using Sentinel-1, Sentinel-2, Landsat-8, and PlanetScope data. With these methods, a complete evaluation of surface displacement and the structural changes is possible, including the assessment of risk.

The impacts of vegetation, sedimentation, and other environmental factors are studied using satellite optical missions such as Landsat and MODIS, focusing on the safety of the dam and its associated works. These studies are necessary in determining the possible limiting factors on the long-term stability and the capacity of the reservoir.

The increasing access to satellite data is accompanied by new techniques and algorithms created to process large datasets more efficiently. These enhancements assist in the estimation of water storage, detection of ground deformation, and monitoring other changes in the environment with higher precision. Geospatial tools like Google Earth Engine have eased the extraction and analysis of satellite imagery such that these tools are now more accessible to researchers and even decision makers. The growing use of Geographic Information Systems (GIS) and their cloud-based processing capabilities enable more efficient and timely surveillance, risk assessment, and management of the dams [38], [44], [45], [48], [49], [51], [53], [54], [60], [61], [62], [63], [64], [71]. More advanced GIS tools such as Google Earth Engine have provided new opportunities for innovation in data processing and analysis which will result in enhanced systems for dam monitoring [42].

3.2.3 Photogrammetry Techniques

Unmanned Aerial Vehicles (UAVs) provide detailed 3D models for identifying dam issues such as cracks, water stains, and structural failures. Structure from Motion (SfM) is a helpful way to make 3D models, however it doesn't work all the time. It can't be accurate to within a millimeter, thus it might not find microscopic cracks or motions. The pictures you use will affect how good the results are. The model may not be clear if the pictures are grainy or taken in bad light. SfM also needs a lot of pictures from different angles that overlap well. It can only see what's on the outside of the structure and can't find harm inside. It can take a long time and demands a powerful computer. The effects can potentially be worse if the weather is bad or the drone is unsteady. The Software can have trouble with smooth or glossy surfaces, such glass or water [72], [73], [74].

UAV photogrammetry and thermal imaging, combined with laser scanning, effectively assess dam conditions, moisture levels, and sedimentation. Challenges include achieving millimeter precision and optimal Ground Control Point (GCP) placement. Figure 4 shows an example of various damages identified on a dam structure such as cracks, calcified deposits, water stains,[75].

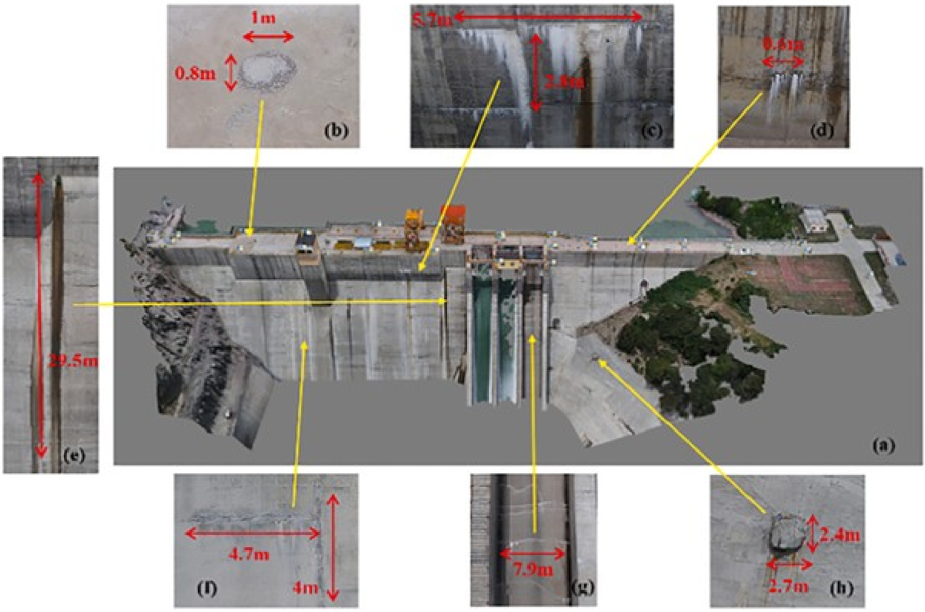

Figure 4: *Many different measured damage [75].*

Table 2 presents a summary of studies that use UAVs and drones for dam monitoring. The table outlines the main goals, benefits, and limitations of each approach. These methods include 3D mapping, crack detection, moisture and sediment analysis, and visual inspection. UAVs have a lot of benefits, like being cheap, safe, and able to collect high-resolution data. But there are also some problems, like not being very accurate in some cases, being sensitive to the weather, or needing extra tools to confirm results. This summary shows how UAV technology is used and what problems still exist when it is used in the real world.

3.2.4 *Integration of Multi Techniques*

Dams can change shape or move because of earthquakes, floods, or damage over time. To study these changes, researchers use different tools together. Common tools include Synthetic Aperture Radar (SAR), Global Positioning System (GPS), and leveling. Using them together helps give more accurate results.

Table 2: *The literature of using UAV and Drone for dam monitoring.).*

Aims	Advantages	disadvantage	Reference
Generate 3D models for monitoring cracks, stains, and structural damage.	Cost-effective; suitable for large areas.	Limited precision; not millimeter accuracy.	[75]
3D mapping and hazard detection of small targets in reservoirs.	Combines SfM, thermal imaging, laser rangefinder, and AI for high accuracy.	Higher cost approach.	[76]
Autonomous photogrammetry for 3D mapping and hazard identification in small dams.	Safe non-contact method.	Does not support intelligent health monitoring.	[77]
Moisture monitoring combining UAV thermal images and photogrammetry.	Effective for surface moisture and suspended solids.	Limited to surface moisture detection only.	[78]
Sediment volume estimation and spatial variability via sUAS and photogrammetry.	Enhances accuracy and spatial detail.	Calibration challenges; errors possible in complex terrain.	[79]
Historic dam analysis with UAV, thermal imaging, photogrammetry, and ERT.	Detects erosion and internal stratification well.	ERT is less effective with low seepage; requires complementary methods.	[80]
Compaction quality monitoring in dam construction using UAV photogrammetry.	Faster than traditional methods; useful for small scales.	Scalability issues: traditional methods still needed for validation.	[81]
Measuring water levels at dams using drones.	Accurate (mean error 0.05 m); rapid measurements.	Sensitive to lighting, camera movement, and condensation.	[82]
Topographic mapping of landslide dams.	Cost-efficient, detailed terrain capture.	Data quality is affected by difficult terrain and weather.	[83]
Crack detection and monitoring using aerial imagery and numerical analysis.	Integrates image processing and structural analysis.	Time-consuming and resource intensive.	[84]
AI-based automatic crack detection with drones.	Uses advanced deep learning for accurate crack segmentation.	Limited defect types detected; exclude other damage forms.	[85]
Evaluating dam removal impacts with UAV, SfM, and machine learning.	Effective integration for vegetation classification.	Classification errors affect accuracy.	[86]
Monitoring dam deformation using UAV laser scanning and point cloud comparison.	High spatial resolution; comparable to TLS data.	GNSS signal issues; point cloud optimization affected by structure and flight paths.	[87]
Visual inspection of concrete dams via UAV imagery and anomaly detection.	Captures detailed images and point clouds.	Limited to surface anomalies; no internal defect detection.	[88]
Dam inspection combining UAV photogrammetry and traditional methods.	Enhances safety for downstream populations.	Limits accessibility for maintenance; lacks anomaly detection focus.	[89]

For instance, looking at the Darbandikhan Dam after a strong earthquake in 2017. The researchers used SAR, GPS, and leveling to measure how much the dam moved. GPS showed the largest movement was 0.27 meters. The left and right sides of the dam moved 0.14 and 0.12 meters. All points on top of the dam moved toward the center. Measurements were taken in March and again in November 2017. They showed both up-and-down and side-to-side movement. One path, from point C7 to C1, showed clear changes in both directions. This study shows that using several tools together gives better results. It helps engineers understand how dams respond to natural events and how to keep them safe. Figure 5 presents the ground movement caused by the earthquake, based on GPS and leveling data collected in March and November 2017. The figure displays both up-and-down (vertical) and side-to-side (horizontal) movements. Red lines mark the paths where the measurements were taken. One of these paths, between points C7 and C1, shows clear changes in both directions[90].

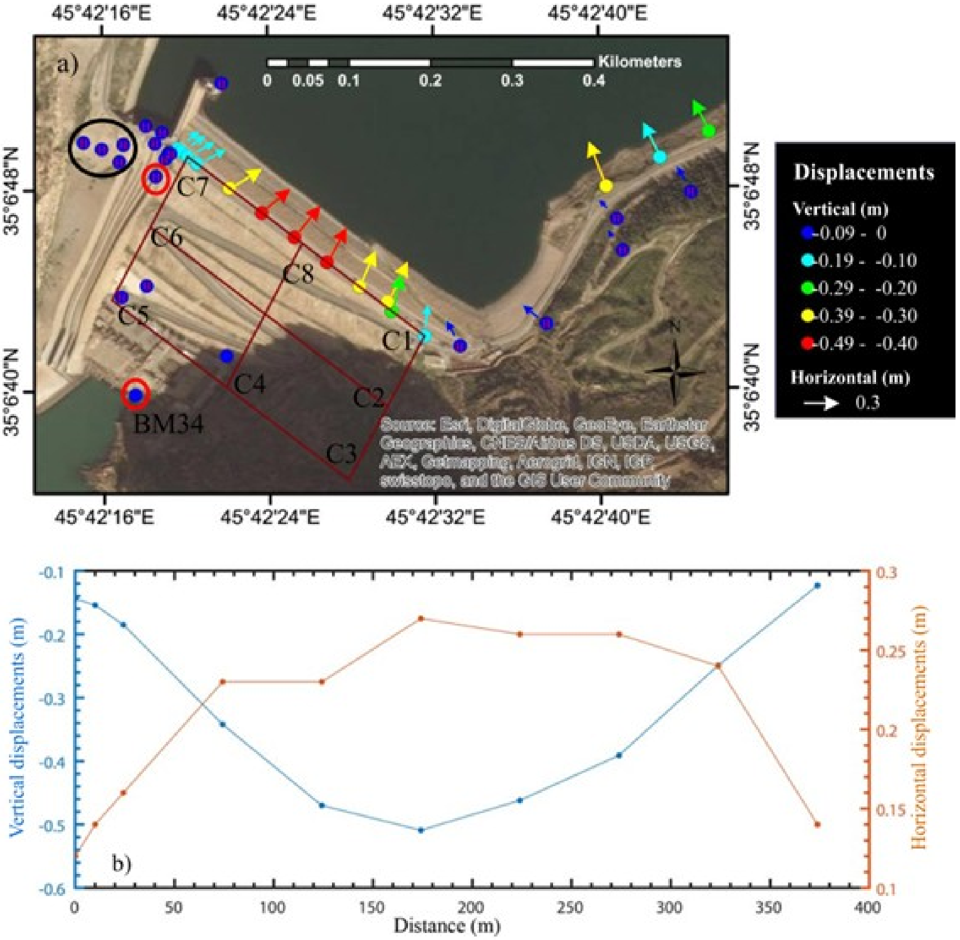

Figure 5: *The earthquake effect on the horizontal and vertical displacement [90].*

Estimating dam displacement has improved using automated models that can manage enormous amounts of data. These models combine different monitoring techniques to find the best fit and improve accuracy. For example, some models use satellite and ground-based data together to track how dams move over time.

One study used Persistent Scatterer InSAR (PSI) to improve the accuracy of GNSS-based displacement measurements. This method reduced the error to just 3 mm along the radar direction. Another study combined optical and SAR satellite images to extract the water surface, while GNSS data were used to measure how much the dam had moved. These examples show that combining data sources gives more reliable results for dam monitoring [91], [92].

4. Analysis of Dam Monitoring Techniques

4.1 Geodetic and Traditional Sensors

Both geodetic and conventional survey methods are fundamental for monitoring dam displacements and maintaining structure safety. These methods give precise horizontal and vertical details regarding the movements of the dam structures, which helps in problem detection. As shown in Table 3, the effectiveness and accuracy of each method differs based on specific conditions and objectives. Many geodetic methods have remarkably high precision and are effective in measuring minute deformations, while some other methods are better suited for sustained monitoring over extended regions.

Selection of a proper monitoring method is determined by a set of criteria including the physical features of the dam, ease of access to the site, and the kinds of movements to be monitored. Engineers tend to blend techniques to optimize the balance between precision, measurement frequency, and spatial coverage. This approach ensures the integrated methods used help with maintaining the safety of the dam while enhancing efficiency in detecting risks and structural changes in time.

Table 3: *Summary of geodetic and conventional methods for dam movement monitoring, highlighting key strengths and limitations.*

Method	Advantages	Disadvantages
Optical Collimators	Very accurate for side-to-side movement	Affected by weather, needs manual use
Automatic Collimators	Continuous tracking, very accurate	Needs careful setup, sensitive to weather
Optical Leveling	Accurate for up-and-down movement, no need for direct line of sight	Takes a lot of time, not good for continuous checks
Hydrostatic Leveling	Can track movement all the time, very precise	Expensive, hard to install in old dams
Trilateration	Works in tough areas, no need for line of sight.	Needs accurate distance measures, errors can be added up.
Geometric Leveling	Very good for up-and-down checks.	It takes a long time, needs a clear view.
Robotic Total Stations (RTS)	Fast, automatic 3D data collection.	Weather can affect it, needs calibration.
GNSS	Fast, accurate 3D positions, no line of sight needed.	Can have signal problems, needs good planning.

4.2 Remote Sensing and Photogrammetry Techniques

Remote sensing and UAV photogrammetry are useful tools for checking dam conditions. They help monitor dams over large areas and over time. Each method has strengths and weaknesses. Table 4 shows the main methods, what they are good at, and their limits.

Table 4: *Main remote sensing and UAV-based methods for dam monitoring, with their advantages and disadvantages.*

Method	Pros	Cons
Passive Optical Sensors (MODIS, Landsat)	Cover large areas, frequent updates, low cost.	Medium resolution can be affected by clouds and weather.
SAR and InSAR Techniques	Detect small movements, work in clouds, good for big areas.	Hard to process data, sensitive to weather in the air.
UAV Photogrammetry	Detailed 3D maps, safe and fast checks.	Only accurate to a few centimeters, needs good setup.
Thermal Infrared (TIR)	Good for finding leaks or hot spots.	Results change with weather; equipment can be expensive .
Satellite Altimetry (ICESat)	Measures water levels well, can be used anywhere.	Less frequent data, not good for small lakes.
Multispectral Sensors (Sentinel, MODIS)	Track water quality and environment.	Medium detail, depends on weather.

4.3 Comparison of Geodetic and Remote Sensing Methods in Dam and Reservoir Monitoring

Engineers use the methods in Tables 3 and 4 to check dam safety. Each method has its own strengths and weaknesses which used for different purposes. By understanding what each method can do, engineers can choose the best one for their needs.

Geodetic and traditional tools supply accurate data at certain points on the dam. They can detect slight changes, such as sinking, rising, or shifts in the structure. For example, optical and hydrostatic levelling help check if the dam is going up or down. Collimators and total stations are used to track side-to-side movements. These tools can help find problems early before they get worse. GNSS and trilateration are useful in hard-to-reach or hidden areas. They are perfectly accurate, but they take more time, cost more, and need trained people to use them. Also, they cover smaller areas compared to other methods that watch the whole dam over time.

Remote sensing and UAV tools can watch large areas and collect data often. Satellite images like MODIS, Landsat, and Sentinel show changes in water, land, and plants. They are useful for checking big areas and seeing how things change over time. SAR and InSAR can spot small movements in the ground or dam, even when it is cloudy or dark. This helps find landslides or slow shifts near the dam.

UAV photogrammetry creates detailed 3D images. It is useful for checking dam faces or slopes after heavy rain or earthquakes. Thermal infrared tools help find leaks or hot spots by showing changes in surface temperature. Satellite altimetry is good for measuring water levels in large lakes, but it does not work well for small ones. Multispectral sensors help monitor plant health and water quality around the reservoir.

In short, traditional methods give exactly accurate results in certain spots. Remote sensing gives a wider view and can collect data repeatedly over time. Using both methods together gives a clearer and safer understanding of the dam and reservoir.

4.4 Real-World Challenges in Using Monitoring Methods

Both traditional and remote sensing methods are useful for checking dams and reservoirs. But in real life, there are some problems that can make it hard to use these tools. These problems include cost, rules, and technical limits. Cost is a big issue. Tools like UAVs, thermal cameras, and radar systems can be expensive to buy and keep working. Some traditional tools, like GNSS and hydrostatic leveling systems, also cost a lot, especially when used for a long time.

Rules and permissions can also make things harder. For example, UAVs are not allowed to fly in some areas without special permission, especially near dams. In some countries, using satellite data is limited by law, which can slow down work or block access to the data.

Technical problems are also common. Some methods, like InSAR, need special software and train people to use them. Cloudy skies, weak signals, or rough land can make it hard to get good data. Traditional tools may need power, clear views, or good weather, which are not always available in remote or risky areas.

These problems can make it hard to use certain tools often or in some places. Knowing about these limits helps engineers and planners pick the right tools and make better plans for dam safety.

4.5 Application of Remote Sensing and Photogrammetry in Dam Monitoring

Remote sensing and photogrammetry are effective techniques for monitoring dams and their surroundings. These methods allow engineers to detect changes in dam structures or the nearby environment by analyzing data collected from satellites, unmanned aerial vehicles (UAVs), or aircraft. The images obtained can reveal surface movements, cracks, shifts in water levels, and other early indicators of structural issues. Early detection of these signs is important for assessing potential risks and maintaining dam safety (Figure 6).

Remote sensing and photogrammetry offer several advantages. They can cover wide areas in a single survey and do not require direct access to the dam site, which increases safety for personnel and efficiency in data collection. These techniques are practical and can be applied regularly to track changes over time and support informed decision-making in dam management.

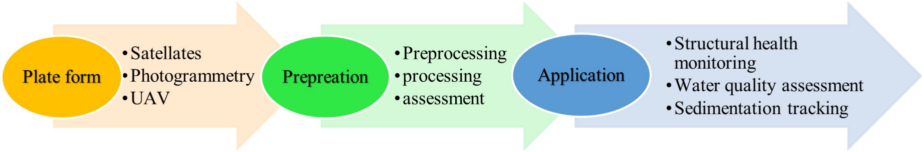

Figure 6: *Workflow Diagram of Remote Sensing Data Acquisition, Processing, and Application in Dam and Reservoir Monitoring.*

The core components of monitoring dams and reservoirs are illustrated in Figure 6: Platform, Preparation and Application. These include satellites, photogrammetry, and UAVs. In the ground preparation phase, the gathered data undergoes various processing steps like filtering to ensure that it is free from errors and meets the quality standards. For the Application stage, the refined data is put to effective use for any of its numerous applications. These activities improve overall dam security as well as promote impact mitigation. This involves remote sensing evaluations of the dam's structural health, water quality control, and monitoring of sedimentation rates.

4.5.1 Structural Health Monitoring (SHM) Using Remote Sensing

Dams necessitate active monitoring to mitigate disasters that can take on substantial economic ramifications and an endangerment to human life. Remote sensing is becoming increasingly accepted, safe, and accurate for monitoring the condition of dam structures as a SHM method. Remote sensing can also provide several advantages over conventional methods of inspection, including, but not limited to, non-contact, safety, and the capacity for quick inspection (without having to inspect on foot) in more significant or dangerous areas. Also, repeated data collection can occur without having to be physically on-site.

Recent advancements in computer vision, machine learning, and deep learning have also increased the accuracy of detecting structural damage in dams, and all these technologies' operational definitions are synthesizing the areas of identifications, classifications, and measurement of damage with a higher accuracy rate than observed by conventional inspectors, or in terms of reliability. This review will discuss using remote sensing as an SHM method, including detailed video from UAVs and broad-area observations from SAR. InSAR is an advantageous remote sensing method for monitoring large-scale ground deformation. DInSAR has been successfully applied to evaluate long-term stability and deformation including major dam monitoring efforts including Three Gorges, San Liberato and Plover Cove dams [93]. InSAR can also be used to observe the effects of temperature fluctuations and changes in water pressure on dam structures. This method remains effective even when data acquisition is not continuous[94]. UAVs provide perfectly accurate inspections by capturing high-resolution images and generating three-dimensional models of dams. Structure-from-Motion (SfM) is a photogrammetric technique that employs overlapping images captured from various viewpoints to reconstruct a 3D model of a scene. When integrated with UAVs, it offers a cost-effective and efficient method for acquiring high-resolution imagery of structures and surfaces. SfM techniques are used with UAV imagery to detect surface cracks and structural changes. SfM offers detailed 3D data and generally achieves better accuracy than older stereoscopic imaging methods[75].

Recent improvements in sensor technology and data processing make it possible to use laser scanners with statistical and modeling methods. This approach increases the accuracy of structural monitoring and analysis. This improves the accuracy of deformation measurements using 3D point clouds [95].

Machine learning further enhances monitoring. One approach uses an incremental extreme learning machine to detect and fix major errors in deformation data. This method handles outliers and complex data patterns to improve accuracy [96] . Another study combined robotic total stations, GNSS, laser scanning, SAR, and artificial intelligence to monitor small real-time movements, showing how Artificial intelligence (AI) can solve difficult problems in SHM [97]. Despite these advances, some challenges remain. Remote sensing data can be complex to process, and optical sensors may be affected by weather conditions. SAR resolution can limit detailed analysis in some cases. Current trends focus on combining multiple data sources for better accuracy and using deep learning for automatic damage detection. The integration of real-time monitoring systems with IoT sensors and remote sensing is also gaining attention. IoT sensors are devices that can collect information like temperature, pressure, or water levels and send it over the internet in real time. They are often used to help monitor buildings, machines, and the environment.

4.5.2 Water Quality Assessment and Management

Assessing water quality is critical for understanding the state of aquatic environments and ensuring safe water for human and ecosystem use. Remote sensing of water quality using satellite observations provides an innovative option for tracking water quality indicators at broad spatial extents. There are several benefits of using remote sensing, including: 1) remote observations (non-contact data), 2) frequent and continued observations, and 3) relative ease of accessing remote or challenging locations.

Important water quality parameters monitored by satellites include turbidity, total suspended solids (TSS), chlorophyll-a, Secchi disk depth, dissolved oxygen, nutrient conditions (nitrates and phosphates), and total dissolved solids (TDS). The choice of medium or high resolution will depend on the size and characteristics of the site [98], [99]. Recently, researchers have focused on improving the accuracy of remote sensing methodologies for water quality assessments. Researchers are now much more likely to couple their ground-based measurements (water surface temperature, rainfall, etc.) to satellite images and ultimately use machine learning models to identify a more accurate estimation of the water quality indicators of interest [100], [101], [102]. Further, deep learning methods have begun to help distinguish water bodies from surrounding areas in images to increase the reliability of water quality assessments [103].

Water quality is dynamic; it changes over time and can vary due to specific pollution sources and land use patterns. To better manage reservoirs, these changes have been documented [104], [105]. Developing spatiotemporal maps of water quality parameters helps water resource managers make informed decisions [101]. To check the accuracy of remote sensing methods, their results are compared with direct field measurements. Common statistical measures for this comparison include R^2, root mean square error (RMSE), and mean absolute percentage error (MAPE) [106], [107], [108].

4.5.3 Sedimentation Tracking

Remote sensing is a valuable method for tracking sediment accumulation in reservoirs and upstream dams across large areas. It allows for the estimation of sediment buildup and storage capacity loss over time. Medium-resolution satellites such as Landsat have been widely used to monitor reservoir storage and measure sedimentation rates. For example, Landsat 8 OLI data were used to assess sedimentation in the Jayakwadi reservoir, and the findings matched those from traditional hydrographic surveys [109]. In another case, using Landsat images together with data from lake observation stations made it possible to accurately estimate both water depth and sediment layer thickness [110].

MODIS data, due to its specific spatial and temporal resolution, is effective for monitoring turbidity and sediment movement in reservoirs. For example, MODIS was used to observe suspended sediment and turbidity levels in the Bagre reservoir, capturing seasonal and long-term changes that aligned with hydrographic survey results [111]. In another study, combining MODIS and Landsat data made it possible to identify sediment changes in the Yangtze River caused by the Three Gorges Dam. This approach shows the value of remote sensing for monitoring and forecasting sediment patterns over large areas [112].

Unmanned Aerial Vehicles (UAVs) and photogrammetry provide high-resolution data that enhance the accuracy of sediment monitoring. UAVs have been used to measure sediment stored by dams and to confirm estimates of sediment changes [113], [114]. Recent UAV-based techniques also allow for precise analysis of silt sedimentation behind check dams, showing the increasing value of UAV technology in sediment studies [114].

Remote sensing is being used more often in studies of sediment budgets and water quality assessment. For example, researchers have suggested using a comprehensive sediment budget approach with remote sensing for East African hydropower reservoirs. This method highlights the importance of long-term satellite data [115]. In addition, models that combine Markov chains with remote sensing information have been created to support large-scale monitoring of water quality [116].

Recent research has introduced new models for sedimentation monitoring. One novel parameter for reservoir sediment trapping efficiency (Te) was developed using remote sensing data across 222 dams in the contiguous United States. This study found that large reservoirs have widespread trapping efficiencies, which is contrary to previously presumed perspectives. The model coded for twenty-two explanatory variables. The best predictions were accomplished with four variables: age, construction type, volume, basin area [117].

5. Limitations and Recommendations

First, in most studies researchers use one method in isolation, geodetic tools, satellites, or UAVs for example, but never use the different datasets in unison. Because of this, it is difficult for researchers to understand the interactions of structural changes, water quality, and sediment accumulation in relation to most dams and reservoirs [51], [95].

Second, each monitoring tool has its own limits. Geodetic tools, while accurate, can be slow and need a lot of work. They can also be affected by weather and other conditions [26], [32], [36]. Satellite images like Landsat and MODIS cover large areas, but they might miss slight changes or early warning signs. These sensors can have errors due to sunlight and the atmosphere[118]. UAV photogrammetry gives clear and detailed images, but it is not used often, and it depends on good weather and careful planning [75], [78].

Third, most research focuses on just one topic, like water level or cracks. Not many studies look at issues such as sediment build-up, changes below the surface, or water quality, even though these are important for dam safety [51], [109]. There are also few studies that combine different technologies, like LiDAR or radar, which could improve monitoring [48], [95].

Fourth, collecting high-detail images and frequent data over time produces a large amount of information. This makes it hard to store and analyze all the data, especially when using manual or partly automatic methods. Not all research teams have access to cloud computing or advanced data analysis tools [119].

There are several recommendations were inspired out of the current survey and can be listed as follows:

- Integrate Different Methods: Future research should combine UAVs, GNSS, InSAR, and satellite remote sensing to improve both the detail and timing of dam and reservoir monitoring.
- Improve Accuracy: It is important to make UAV and remote sensing methods more accurate, especially for finding slight changes. Better placement of ground control points (GCPs) will also help with georeferencing.
- Advance Technology: New and better technologies are needed to overcome current limits, such as InSAR's sensitivity to only certain types of movement and the signal problems that can affect GNSS accuracy.
- High-Resolution Model Development: The use of very high-resolution satellite imagery (e.g., WorldView-3, PlanetScope) should be prioritized for developing long-term monitoring models that improve change detection and structural assessment.
- AI-Driven Analytical Frameworks: Continued development of deep learning, machine learning, and artificial intelligence models is crucial for managing large-scale, heterogeneous datasets and enhancing predictive monitoring capabilities.

6. Conclusion

This paper reviews how geodetic tools, remote sensing, and Unmanned Aerial Vehicles (UAV) photogrammetry are used to monitor dams and reservoirs. We looked at many recent studies and found that these methods help collect useful information about dam movement, water storage, sediment build-up, and water quality. Landsat and MODIS satellites are used often because they have a long record of data and can take pictures often. UAVs and ground tools help find cracks and other small problems on dams. Our review shows that using different methods together, like satellites, UAVs, and ground sensors, gives a better understanding of dam safety and environmental changes. Newer tools like Interferometric Synthetic aperture Radar (InSAR), Global Navigation Satellite System (GNSS), and laser scanning make it easier to find small movements in dams. We also found that remote sensing and UAVs help track water areas, water levels, sediment, plants, and even some human activities near dams. Time series analysis, change detection, and simple machine learning can help separate the effects of dams from those caused by climate. There are still some challenges, such as needing better ways to combine data, more accurate tools for slight changes, and easier ways to handle big sets of data. Using new sensors, faster computers, and working together across different fields will help solve these problems. In summary, geodetic, remote sensing, and UAV methods are important for keeping dams safe, managing water, and helping researchers and engineers study the effects of dams, which have a major human impact on nature.

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