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REVIEW PAPER

# A Comprehensive Review on the Influence of High Aswan Dam on Hydrometeorological and Geoscience Perceptions

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**Abstract**

The High Aswan Dam (HAD), completed in 1971, is an important engineering project that has changed the Nile Valley in many ways. HAD provides benefits like controlling floods and producing hydroelectric power. However, HAD also has caused several problems such as loss of sediment, changed river flow, and effects on both aquatic and land ecosystems. Studies report measurable impacts on groundwater, fish habitats, and energy production—especially during the GERD filling period. Climate change, population growth, and increased water demand have added new pressure to the system. Despite these issues, water quality remains generally acceptable, and renewable energy options like floating solar panels show promise. This review highlights the need for integrated and adaptive water management strategies. By examining the environmental, hydrological, geotechnical, and energy-related impacts of the HAD in the 21st century, the study aims to guide more informed decisions for the sustainable future of the Nile Valley.

**Keywords:** High Aswan Dam (HAD); Environmental impacts, Hydrological impacts, Geotechnical impacts.

## 1. Introduction

### 1.1 Research Background

In Egyptian mythology and religion, the Nile River played a significant role. It was frequently connected to deities like Hapi, the god of the yearly floods, and Osiris, the god of the afterlife. Religious activities included festivals and rituals that focused on the flooding of the Nile and its importance. Northeastern Africa's lifeline, the Nile River, has supported civilizations for thousands of years thanks to its yearly floods that are predictable and deposit silt that is rich in nutrients over its floodplains, fostering agricultural prosperity. The Nile is the world's longest river, flowing through eleven countries for a total distance of roughly 6695 km. Its basin has a catchment region of around 3*106 $km^2$, making up around 10% of the African continent [1] However, the building of the High Aswan Dam (HAD), one of the most ambitious engineering projects in the world, in the middle of the 20th century brought about a radical change in the river's hydrological regime. Earth and rock are the natural materials used in the construction of the HAD. Egypt's strategy to water management underwent a dramatic change with the completion of the HAD in 1970, moving away from a concentration on water supply through "control structures" and toward an emphasis on water conservation [2]. The Nile River, Egyptian agriculture, water management, and the ecology have all been significantly impacted by the HAD. The HAD is roughly 364 feet high and 12,570 feet long. As seen in Figure 1, it produces one of the biggest manmade lakes in the world (the second largest artificial reservoir on Earth), Lake Nasser (HADR), which extends from northern Sudan into southern Egypt [3].

HADR has a capacity of about 162.0 BCM, measures 500 km in length and 12.0 km in breadth on average and has a surface area of about 6.5x$10^3$ km$^3$ [4]. The HADR was separated into three distinct parts. The first part, which has a total volume of 30.0 BCM, is below the 147.0 m threshold for silt buildup. The second part, designated for live (active) storage, is located from levels 147.0 m to 175.0 m. This part has a 90.0 BCM overall capacity. The final part is for high floods and is above level 175.0. Between 175.0 and 182.0, the total capacity is approximately 41.0 BCM. In the HADR, the highest level ever recorded was 181.6 m [4]. Many of HADR's embayment's are known locally as khors. Using the bathymetric contours for each Khor, hypsographic curves were created that connected the water elevation to the surface area and volume of each Khor. The primary Khors constituted Khor Toshka (184.8 km$^2$), Khor Abu Askar (36.7 km$^2$), Khor Dahab (13.3 km$^2$), Khor Dahmit (12.0 km$^2$), and Khor Batikh (7.1 km$^2$) [5]. Although the Khors' entire surface area is approximately 4,900 Mm$^2$ , or 79% of the HADR's size, they only hold 86.4 Bm$^3$, or 55% of the HADR's total volume [6]. The HAD's main functions are flood control, the production of hydroelectric power, recreation, irrigation, landscape improvement, fishing activities, navigation, and water supply management. Flood levels in the River Nile during basin irrigation have a long history that has been documented. The average yearly floods of the Nile River from 1870 have been separated into three periods: 1870 to 1899, 1900 to 1955, and 1956 to 2011. The average flood values were 110.4, 84.1, and 87.7 BCM during the three times, respectively. To discharge the excess water of HADR to the Toshka depression (TD), the Toshka Spillway was constructed during the close of the 1970s and the start of the 1980s. The four deep-cut basins or sub-depressions that make up TD are connected by natural sills and are situated roughly 250 km south of HAD [7]. The canal linking the TD to the HADR has an overall length of 22.0 km and a maximum volume of 250.0 MCM/d [8].

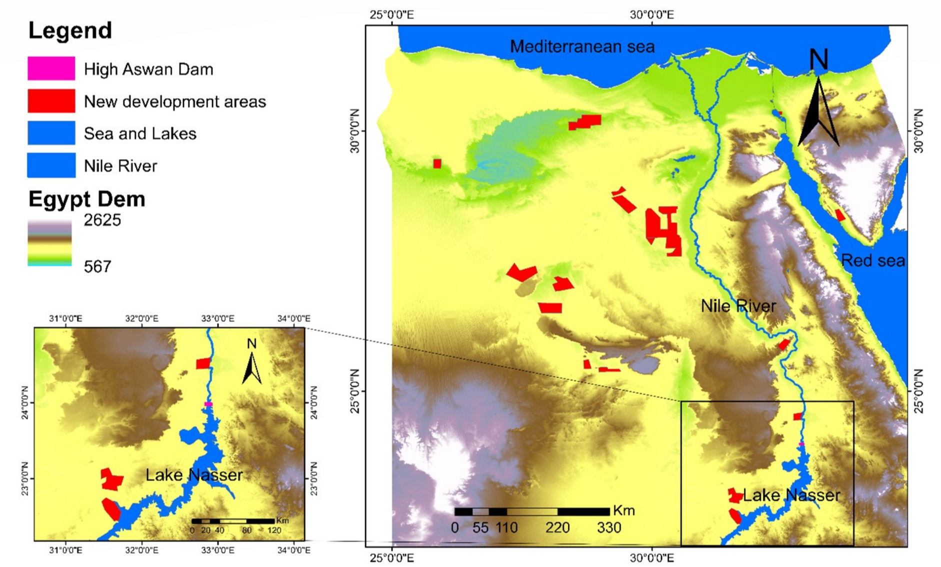

**Figure 1:** *Location map of the High Aswan Dam (HAD) and Lake Nasser (HADR) (This figure was generated using ArcGIS 10.8. URL: https://www.esri.com).*

## 1.2 Motivation for the Current Review

The HAD, a massive engineering project, continues to have a lot of various influences on the ecological balance, hydrological systems, and environmental systems of the Nile River and its delta. However, a number of review studies were conducted on various viewpoints regarding the usefulness of HAD, including economic [9], environmental and health influences [2], and political [10]. However, to date, a comprehensive review that considers all these issues has not yet been conducted. Thus, it is essential to establish a new goal by thoroughly analyzing the current body of literature (88). Hence, this review aims to synthesize the current state of knowledge by examining and compiling a comprehensive collection of research findings across a range of relevant disciplines. The research findings were collected through comprehensive searches on two major academic databases: Scopus and Google Scholar, covering the time span from 1981 to 2024. These platforms were selected due to their broad coverage of peer-reviewed journals and academic literature relevant to the research categories. Specifically, this work draws upon a substantial body of literature, including 35 research papers focused on hydrological perspectives, 20 papers concerning environmental consequences, 11 studies on geotechnical perspectives, and 10 studies related to energy management perspectives. By integrating these diverse perspectives, this review aims to give a comprehensive picture of the long-term influences of the HAD and to pinpoint significant regions for further study and management techniques by combining these many points of view.

## 1.3 Research Objectives

This review synthesises decades of research, offering a thorough analysis of the HAD's environmental, hydrological, energy management, and geotechnical aspects. It elucidates the effects of HAD on downstream watershed management and comprehends the established prior research on how effective water management and sustainability can be achieved. Furthermore, the High Aswan Dam (HAD) is shown as both a great engineering achievement and an example of unexpected hydrological repercussions caused by large projects. One example of such a project is the Grand Ethiopian Renaissance Dam (GERD) (Figure 2) [11]. This review aims to find common views and points out gaps in our understanding. It also wants to give helpful ideas for future water management strategies. In today's world, it is especially important to balance people's needs with the health of the environment. This review highlights the HAD's complex legacy as an engineering achievement and a warning about unexpected hydrological consequences.

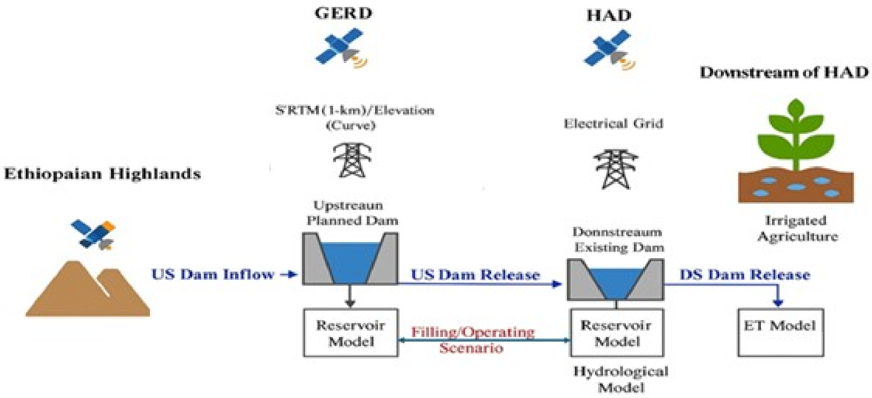

**Figure 2:** *Upstream and downstream HAD simplified chart.*

## 2. Literature Review

The High Aswan Dam (HAD) is unbelievably valuable for Egypt's development. It has impacted hydrological, energy management, and environmental systems in Egypt and the Nile Basin (Figure 3). By controlling the flow of the Nile River, the HAD has helped prevent droughts and floods. This has made water more secure and improved farming [12]. However, building the HAD has also caused serious environmental problems. For example, it traps silt, which has reduced soil fertility downstream and increased erosion in the Nile Delta [13, 14, 15]. From the perspective of hydrological flow, the HAD has changed natural water cycles. This has affected river ecosystems and GW recharge [16, 17]. The HAD's presence has harmed local ecosystems, leading to less biodiversity and the loss of some species. Aquatic life has been affected by changes in water temperature and quality. The health of Mediterranean marine ecosystems has also declined due to less nutrient flow [18]. By 2025, the long-term effects of the HAD will be important for understanding how to manage water better in the future, highlighting the need for sustainable approaches to balance environmental conservation and human development.

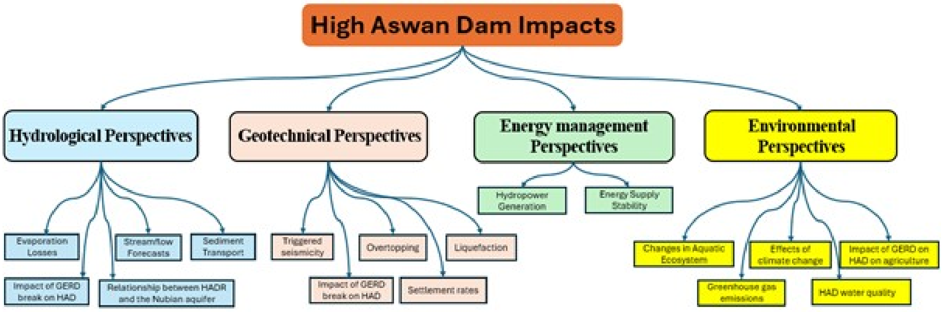

**Figure 3:** *Flowchart delineates the effects of HAD chart.*

### 2.1 Hydrological Perspective

The High Aswan Dam (HAD) was built to control the Nile River's flow, generate hydroelectric power, provide steady irrigation, and reduce severe flooding. This development has helped Egypt's economy and society. However, the HAD has also changed the natural flow of the Nile, leading to various hydrological, ecological, and economic effects that are widely discussed in policy and research circles. One of the largest reservoirs in the world, the High Aswan Dam Reservoir (HADR), shows both the benefits and challenges of large-scale hydrological projects [19, 20]. The HAD changed how sediment moves in the river. Sediment is important for keeping soil fertile and maintaining the delta. By stabilizing the river's flow and stopping seasonal floods that lasted for thousands of years, the HAD has affected the natural balance of the Nile's ecosystem [21]. While changed river regimes have affected GW systems and aquatic ecosystems, sediment trapping behind the HAD has caused downstream erosion, coastal retreat, and increased saline intrusion in the Nile Delta because of the shoreline moving inland [22]. Table 1 illustrates the hydrological perspective of HAD. Concurrently, concerns over the long-term sustainability of water resources considering population increase and climate change have surfaced, along with worries about water quality, including sedimentation and eutrophication changes. The Ministry of Water Resources and Irrigation of Egypt employs the Nile Forecasting System, an operational satellite-based distributed hydrological modelling system for the Basin, to predict inflow to the HAD with maximum lead time possible [23]. The Nile River has an annual mean discharge of approximately 2,900 $m^3/s$ for the HADR, with approximately 20 % lost to evaporation. The HADR can supply water to 33,600 $km^2$ of agricultural land [24]. The yearly flood causes HADR to have a retention period of more than a year. Seasonal flow variation is significant and heavily regulated downstream of HAD. Yearly fluctuations in water levels may attain 10 meters, affecting hundreds of hectares in surface area [25]. For instance, Sudan and Ethiopia are currently working on the construction of new hydroelectric dams, which are anticipated to serve as the constitutional source of electricity. Ethiopia's dam will become the Africa's largest hydropower project [26]. The construction of these kinds of dams can drastically influence Egypt's downstream water supply, particularly when the dams are filling [6]. Hydropower and irrigation are pivotal for social and economic advancement in the Nile River Basin; thus, any development by country upstream would generate considerable tensions regarding water usage among the riparian states.

The reviewed literature in Table 1 presents a strong consensus that evaporation from the HADR results in significant water losses, ranging from 0.273 cm/day to over 1 cm/day, depending on methods, locations, and climate scenarios. Several studies propose engineering interventions—such as installing plastic covers and floating solar systems to reduce evaporation. There is also agreement that advanced modelling techniques such as (BREB, MOD16 ET, ANN) offer improved accuracy in evaporation estimation. Similarly, for storage capacity studies most findings highlight a measurable decline in HADR storage due to sedimentation, especially in dead storage zones. Remote sensing techniques and empirical models (such as the Heron method and DEM analysis) were commonly used. Across studies, it is evident that sedimentation significantly impacts both storage volume and operational efficiency, emphasizing the need for continuous monitoring. Studies that model the impact of the GERD on HADR were summarizes. There is general agreement that Egypt's water availability, agricultural land use, and storage volumes will be affected, with the degree of impact varying based on GERD's filling scenarios and cooperative policies. Notably, several authors suggest optimized operation strategies to mitigate these risks. Lastly, GW and Seepage Studies shows that HADR interacts directly with nearby aquifers, and that seepage losses are non-negligible. GW recharge is largely dependent on HADR's water level and may reverse if the reservoir level drops below critical thresholds. These studies confirm the hydraulic linkage between surface and subsurface water systems, underscoring the importance of integrated water resource management.

### 2.2 Geotechnical Perspective

The HAD, an enormous engineering achievement, has significantly influenced geotechnical perspectives, especially in foundation design and seismic considerations. The HAD's geotechnical challenges have been a focal point of research. Because the HAD was constructed on a complex geological environment made up of claystone, siltstone, and sandstone, creative technical solutions were needed to guarantee stability and longevity. Studies show that it is important to understand how the HAD's foundation behaves under different water loads. This behaviour directly affects the HAD's stability. Seismic risks have become more important because the HAD is in an area with moderate earthquakes [54]. Researchers show that the HAD is designed to handle earthquakes, but it is still needed to check for risks from tectonic activity. To monitor the HAD, advanced tools like seismographs and piezometers are used. These tools help find any unusual responses during earthquakes. There are also concerns about the foundation materials becoming too wet and the risk of liquefaction during seismic events. This means ongoing evaluations are necessary. Table 2 illustrates the geotechnical perspective of HAD. As we look ahead to 2025, it is critical to use modern geotechnical technology, like remote sensing and finite element analysis (FEA), to improve the HAD's performance and safety.

**Table 1:** *Synopsis of recent research for hydrological perspective of HAD.*

| Reference | Hydrological parameter | Research Remark |
|---|---|---|
| [27] | Evaporation | Between 1988 and 1989, the evaporation around the HADR was estimated using deuterium and oxygen $^{-18}$ isotopes and to examine the interrelationship between HADR water and the adjacent GW. Approximately $19\%$ of the input water discharge rate was lost due to evaporation from the HADR. The results indicated that GW aquifer recharge is confined to wells in proximity to the HADR, extending to a maximum distance of approximately ten km . Recent Nile water was expected to contribute between $23\%$ and $70\%$ of the GW in these wells. |
| [28] | Evaporation | Estimates the mean annual evaporation from the HADR using water-balance, bulk aerodynamic (Dalton), energy budget, Complementary Relations Lake Evaporation (CRLE) model (Morton), and combination (Penman). According to the results, the average yearly evaporation ranges between 4.65 and $7.95 \mathrm{~mm} / \mathrm{d}$. At the greatest storage level, the discrepancy between these thresholds exceeds 7 billion $\mathrm{m}^3/\mathrm{yr}$ is more than one-third of Sudan's share and almost one-eighth of Egypt's share according to the treaty. |
| [29] | Evaporation | The result indicated that the evaporation depth varied from $0.958 \mathrm{~cm} / \mathrm{d}$ at the edge of the HADR to $0.273 \mathrm{~cm} /$ day at the center, The total volume of evaporated water losses during the entire HADR was approximately $0.86 \mathrm{Bm}^3$ per month. The analysis further indicated that disconnecting two khors, with construction heights of approximately 15 m and 8 m , could result in a reduction of total evaporation volume loss by about $2.4 \mathrm{Bm}^3$ per month, equating to $19.7 \mathrm{Mm}^3$ per year. |
| [31] | Evaporation | The Bowen ratio energy budget (BREB) technique employed by the combination group exhibits superior accuracy, as indicated by the uncertainty results. Over the decade, the error standard deviation of the BREB technique was determined to be 0.07 cm/d, equating to around 11.90% of the average evaporation rate of 0.59 cm/d. The methodologies of Priestley Taylor, Debruin Keijman, and Penman collectively produce an error standard deviation of 1.31 Bm$^3$/yr, corresponding to 13.3%, 13.2%, and 12.7% of the average evaporation rate of the HADR, respectively. |
| [31] | Storage capacity | Investigated the reduction of the water losses from HADR between 1964 and 2010. The result of investigations revealed that the cross-sectional area decreased from 2.5% to 6% and that the sedimentation had place at the Dongola station, which is 782 km from HAD. Additionally, the flow at Dongola decreased from 16% to 19%, according to daily flow measurements. |
| [32] | Evaporation | The ECHAM5 climate model indicates that the removal of the Khors could reduce evaporation losses by more than 2 BCM for Khor Kalabsha, around 450 MCM for El-Alaky, approximately 130 MCM for Khor Sara, and 0.34 BCM for Korosko by the year 2100. Furthermore, to conserve an additional 0.5 BCM by 2100, it is suggested that appropriate plastic covers be installed over Khor Korosko and Khor Sara. |
| [33] | Impact of GERD on HAD | Aswan High Dam, BenÃ¬nar, La ViÃuela, El ArenosoIndicated that without an additional management investment the intended six-year filling interval is adequate to fill the GERD with minimal effects on Egypt's present irrigation water demands from HAD. Over the filling time, the discharge condition in HAD drops by 19%, equating to 13 BCM. As a result of HAD operating at a lower water level, the volume of water lost through evaporation from the exposed surface of the HAD reservoir dropped by 16%. |
| [34] | Seepage | The result indicated that mean water seepage from the HADR to the Nubian sandstone aquifer over a 50-year period (from 1965 to 2014) is $47.46 \mathrm{Mm}^3$ /year and with the highest loss value calculated in 1976 as $68.48 \mathrm{Mm}^3$, when the storage at HADR was $1084 \times 10^2 \mathrm{Mm}^3$ and the discharge to the HADR from the Nile was $815 \times 10^2 \mathrm{Mm}^3$. |
| [35] | Impact of GERD on HAD | The results indicated that streamflow entering HADR is reduced by an average value of 6% and 14% over the first five years when a 10% and 25% filling policy of monthly streamflow behind the GERD is implemented, respectively. |

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| [38] | Storage capacity | Assessed two approaches (the Areas-WL relationship model and the Heron technique) for estimating water storage fluctuation in the southern portion of HADR without the use of in-situ water gauges and bathymetry maps. With an average surface area of around 658 $\mathrm{km}^2$, the results indicated that the RMSE for the first approach was 0.32389 BCM and for the Heron approach, it was 0.31809 BCM. This represents around 13.2% of the average storage fluctuations over the study period's minimal reference water elevation. |
| [39] | Evaporation | According to the results, employing short-term flow reduction scenarios (less than eight years) will result in a 75 BCM drop in the HADR's volume over years, which will lower water levels by 1.5 m per year. Through several flow scenarios, lowering the HADR's water levels through flow reduction scenarios will lower evaporation losses from 1.00 BCM to 4.00 BCM annually. |
| [40] | Evaporation | For the High Aswan Dam Authority (HADA), MOD 16 ET , and SEBS, the average yearly evaporation rate is $0.693, 0.661$, and $0.638\ \mathrm{cm/d}$, respectively. The HADA estimate is marginally greater than the MOD 16 ET and SEBS estimates. A strong connection between MOD16 ET and SEBS was discovered ( $\mathrm{R}_2 = 0.969$ and $\mathrm{P} < .01$ ), which suggests that only one approach (SEBS) based on remote sensing data is employed to assess the evaporation, monthly evaporation rate from HADR. |
| [41], [42] | Storage capacity | The results indicated that a 12% drop in the HADR's overall storage volume as predicted by the DEM through the interval 1964–2013. This decrease is noticeable in the dead and the live storage volume. Due to sedimentation, the HADR's surface area decreased at low water levels. An estimated 78 $\mathrm{km}^3$ of live storage capacity is needed to satisfy yearly water requirements. A new elevation–capacity curve for the HADR is displayed by the results. Using the water balance approach, this recent curve provides an alternative estimate of the storage of water that enters the reservoir and the predicted water losses. Between water levels of 140 and 168 meters above sea level, the surface area is reduced by an average value of 15%, or 10 $\mathrm{km}^2$. |
| [43] | Evaporation | Created and checked a new simulation model and for HADR to assess the HADR sedimentation impacts on the factors influencing the operation of the HAD. The results indicated that, in the minimum scenario, losses from evaporation exceeding 10 km3 accounted for 27.59% of annual withdrawals from HADR when the sedimentation effect was considered. In the same inflow scenario, this percentage increased to 31.03% of annual withdrawals from HADR when the sedimentation influence case was not considered. |
| [44] | Impact of GERD break on HAD | Represent Egypt's flood threats because of the GERD break. The HEC-RAS model was employed to produce outflow hydrographs caused by GERD breaks. After 26 days of GERD break, the mean daily peak inflow at the HADR's inlet approaches 42000 $\mathrm{m}^3/\mathrm{s}$.. The inflow to HADR is almost three times greater than the greatest inflow during the wet season. As a result, it may be harmful to the HAD if precautions are neglected. |
| [45] | Evaporation | Aswan High Dam, BenÃ¬nar, La ViÃuela, El ArenosoDeveloped a method using artificial neural networks to forecast the evaporation of HADR. The results indicated that a 2% rise in HADR evaporation was likely to occur by 2050. It was observed that the July to August months had the highest expected evaporation values, which vary from 0704 cm/day to 0.964 cm/day. The greatest evaporation outlier, or peak value, is around 1.116 cm/day. The lowest expected values, which range from 0.35 cm/day to 0.681 cm/day, occur during the months of December and January. |
| [46] | Evaporation | To lower evaporation value, a floating photovoltaic system (FPVS) was installed over the water surface of a HADR. The HADR's projected evaporation was $12.0 \times 10^3 \mathrm{Mm}^3$/ year. Approximately $2.1, 4.2, 6.3, 7.0$, and $8.4 \times 10^3 \mathrm{Mm}^3$/ year can be saved by installing FPVS over $25\%, 50\%, 75\%$, and $100\%$ of the HADR, respectively. |
| [47] | Streamflow Forecasts | A Forecast-Based Adaptive Reservoir Operation (FARO) methodology was introduced to evaluate the efficacy of long-term climatic forecasts in improving real-time Humanitarian Assistance and Disaster Relief (HADR) operations. The findings revealed that the prediction horizon for HAD operations spans from 12 to 5 months under high and low demand scenarios, respectively; beyond this period, forecast data no longer influences the release decision. The anticipated value for HAD operations is especially significant in the months after the flooding season (October–December). |

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| [48] | Storage capacity | Used a Multi-Sensor Satellite (MSS) technique to learn about the operation of the HADR in the Nile River basin (NRB), with an emphasis on the cooperative operation of TD and HAD. The results indicated that the MSS technique models the TD inflow with a respectable level of skill, as evidenced by its $\mathrm{R}^2$ of 0.79 and its Relative Error of 19.14%, respectively. |
| [49] | Impact of GERD on HAD | The results indicated that GERD implementation over a three-year period is anticipated to cause losses in Egypt of over 19%, 25%, and 51% for the 10-, 7-, and 3-year filling scenarios, respectively. These losses result in an average annual drop in land used for agriculture of 23%, 28%, and 53% in comparison to the baseline scenario. |
| [50] | Storage capacity | During the 1952–2008 simulation interval, the Soil Water Assessment Tool (SWAT) model and the HEC Reservoir Simulation Model are combined to analyse water flows that arrive at HAD because of anticipated water resource development initiatives within the BAS river system. The results indicated that the hydroelectric scenario augmented the flow reaching HAD by a mean of 1.3 $\mathrm{km}^3$ per year by minimising losses in marshes through a regulated flow pattern. The irrigation scenario diminished the flow reaching HAD by a mean of 4.4 $\mathrm{km}^3$ per year. The inflow into HAD decreased by an average of 3.6 $\mathrm{km}^3$ annually under the integrated hydropower and irrigation development scenario. |
| [51] | Impact of GERD on HAD | Determined the best operating strategy that would enable the GERD to produce 87% of its maximum electricity sustainably without creating a further downstream water deficit for an extended period of drought. The proposed modelled GERD operation policies indicate that during a standard operational interval, when the HAD elevation is higher than165 m, to produce the optimum hydropower generation, GERD will run from the ideal operating level of 640 m to 625 m. |
| [52] | Impact of GERD on HAD | Employed to evaluate the impact of the GERD reservoir's filling procedure on surface water resources in Egypt, Sudan, and Ethiopia from 2013 to 2022. A decrease of $35.47 \pm 2.29\% \left(16.57 \pm 1.07\ \mathrm{km}^3\right)$ in Egypt's Nile water allocation could lead to a yearly reduction of 33.14 $\pm 1.81\%$ of agricultural land. |
| [53] | Groundwater management | Investigated the distribution, incidence, and potential correlation between the Nubian aquifer and HADR within a 330 $\mathrm{km}^2$ pilot region. The findings revealed that the GW level at the pilot site varies from 160 m to 166 m above mean sea level, indicating that recharge from HADR will persist as long as the reservoir elevation remains above 160 m. Should the reservoir elevation decline beneath that threshold, the reverse flow from the Nubian aquifer system to HADR may decrease the GW elevation in adjacent regions to less than 160 m. |

The reviewed literature in Table 2 showed that the studies of the HAD is generally safe and stable. Tealeb [55] found that some parts of the HAD settled more than others in the early years, but everything has been stabled since 1975. Abu-Zeid and El-Shibini [56] confirmed that the dam is in a tectonically quiet area, and earthquakes are not likely to damage it. Ibrahim et al [57] looked at what could happen if the dam overtopped. The results showed that serious flooding could occur, but this is only under extreme cases. Other studies, like Dahy Sayed [58] and Hassib et al [63], explained that small earthquakes sometimes happen because of water from the reservoir entering underground cracks. These are called reservoir-triggered earthquakes. They are usually small and shallow. Genidi et al [62] also found small movements in the ground near the dam using satellite data. In short, the dam is strong, but it's important to keep monitoring the ground and water levels to stay safe.

## 2.3 Energy Management Perspective

The HAD's principal energy benefit is the ability to generate hydroelectric power. Prior to HAD construction, Egypt's energy supply was primarily reliant on fossil fuels, specifically coal and oil. The dam's power station, which has 12 turbines, has a total installed capacity of $2.1*10^3$ megawatts (MW), contributing dramatically to Egypt's electricity supply. The HAD generates around 10 billion kilowatt-hours (kWh) of electricity annually, which at the time of its construction accounted for nearly half of Egypt's entire electrical production [64]. This hydroelectric electricity has helped to electrify rural communities, boost industrial development, and reduce reliance on fossil fuels. This hydroelectric initiative conserved 74 million tonnes of diesel, resulting in a reduction of carbon dioxide emissions by 230 million tonnes [4]. Table 3 illustrates the energy management perspective of HAD.

The reviewed literature in Table 3 showed that the energy production at the HAD is affected by many factors. Salema [65] suggested lowering the water level to between 165 and 170 meters to use water for farming and energy. Mulat and Moges [34] found that during the GERD filling, HAD's energy output dropped by up to 24%. Abdelhaleem and Helal [66] also reported a wide drop in yearly energy based on different water flow scenarios. El-Zohri et al [67] showed that older air coolers in the hydropower plant worked less efficiently than new ones. Some studies, like Abd-Elhamid et al [46] and Ilgen et al [69], looked at using floating solar panels (FPV) on the reservoir. They found that FPV can save water and produce large amounts of clean energy. Hafez et al [68] showed that projects upstream can reduce HAD's inflow and cut power generation by up to 35%. In short, water level, cooling systems, and upstream projects all play a big role in how much power HAD can produce. Using solar panels on the water seems to be a smart way to help.

## 2.4 Environmental Perspective

One of the greatest engineering achievements of the 20th century is the HAD. Although HAD has produced many social and economic benefits, including improved irrigation, flood control, and the production of hydroelectric power, its effects on the environment have generated much discussion. International attention to the effects of large dam project on the health, environment, and social is increasing [70]. From an environmental perspective, the HAD has significantly altered the natural ecosystem of the Nile River and its surrounding regions. Communities have been displaced, and archaeological sites have been submerged because of the HAD's creation of HADR but HAD has also disrupted the natural flow of sediments that once enriched the Nile Delta. Farmers now need to use more artificial fertilizers because of soil degradation, coastal erosion, and a drop in agricultural production downstream [37]. Climate change can have an indirect effect on agricultural production by changing weather patterns and worsening extreme weather events that affect crops [71, 72].

**Table 2:** *Synopsis of recent research for Geotechnical perspective of HAD.*

| Study | Research Remark |
|---|---|
| [55] | Different settlement rates were recorded for the HAD building's structural elements between 1970 and 1989. The rock fill component of the HAD exhibited elevated settling rates compared to other regions, especially during the initial measurement period (1970-1975), settling rates in other structural elements of the HAD have remained minimal and stable since 1975 (approximately 15 years). This means that the numerous structural sections now operate as a single entity, which indicates well for the HAD building's stability. |
| [56] | A comprehensive body of work was conducted to analyse the seismic safety of the HAD, and the study determined that the HAD region is located in a tectonically stable area, and future earthquakes that could cause ground vibrations would have no impact on the HAD's integrity or safety. |
| [57] | Evaluated the numerical risk of the HAD breaching because of overtopping. According to the results, the HAD failure's highest peak discharge is $38.9 * 10^4\ \mathrm{m}^3/\mathrm{s}$. This occurred in the event of an overtopping failure when the hydrograph input for 1964-1965 was considered. The water level and HADR contents are $182\ \mathrm{m}$+ MSL and 162.3 BCM , respectively; the first breach in the rock-fill portion of the HAD is thought to be 14.0 m deep and 10.0 m wide. At an elevation of $133.89\ \mathrm{m}$+ MSL, the breach grew gradually for 95 hours, reaching a depth of 62.11 m and a breadth of 666.30 m . |
| [58] | An earthquake with a local magnitude of ML=4.6 was recorded on November 7, 2010, 4.5 km south of HAD. According to the study, induced seismicity in the HADR becomes active as the water level drops from maximum to minimum. The combined focal mechanism of two events in this investigation revealed strike-slip faulting on vertical fault planes. In most cases, the fault planes of the composite groups diverge from the usual east-west and north-south strikes of the western desert set. |
| [59] | Estimated the attenuation characteristics of HADR using microearthquakes records. The results indicated that specific formulas for scattering $\mathrm{Q}\ (\mathrm{Q_{sc}})$ and intrinsic $\mathrm{Q(Qi)}$, which are $\mathrm{Q_{sc}} = (699.30 \pm 334.50)^{*}\mathrm{f}^{(0.130 \pm 0.060)}$ and $\mathrm{Qi^{i}} = (52.90 \pm 5.60) * \mathrm{f}^{(1.090 \pm 0.030)}$ These formulas can be useful for further seismic studies in the region. |
| [60] | The result indicated that a portion of the HAD's upstream shell is prone to liquefaction if the dam is subjected to an earthquake of the magnitude of the El Centro seismic excitation in 1940. |
| [61] | Moment tensors and stress drop values were calculated for six recently induced earthquakes documented by the Egyptian National Seismic Network (ENSN) near HAD, with local magnitudes varying from 3.0 to 5.5. The results demonstrated that the focal depths of the majority of HAD region seismic events analysed in the study are drastically shallower than the expected focal depths for interpolate and intraplate earthquakes in the surrounding region. 80% of triggered events occur at focal depths of less than 10 km, while 80% of tectonic earthquakes are situated at depths greater than 15 km. |
| [62] | Measurements of levelling over a decade (2013-2022) were utilised alongside four years of descending InSAR images from Sentinel-1 (2017-2021) to assess contemporary crustal movements and identify active faults in the vicinity of the HAD. The Spillway fault exhibits a normal velocity of $3 \pm 0.15\ \mathrm{mm}$/ year,, as determined by InSAR and levelling observations. The results are consistent with the seismicity pattern recorded in the study region |
| [63] | The study presented four occurrences of reservoir-triggered seismicity in the HADR, either in a rapid or delayed response. As a result, it is possible to conclude that the increase in seismic activity is due to the infiltration of water from the HADR into the faults or new stressed fractured zones, which causes an increase in pore pressure at the earthquake's hypocenter, that plays an important role in triggering earthquakes in the HADR. Furthermore, it may be stated that the deep and shallow earthquakes in the HADR are caused by tectonic earthquakes. |

The flood control method from HAD protects farmland from flooding. This helps also prevent crop damage and creates a more stable farming environment [71]. However, the energy produced by the HAD has serious environmental effects. The greenhouse gas emissions, mainly $CO_2$, have raised concerns both internationally and nationally [73]. Furthermore, building of HAD for hydropower can release a lot of greenhouse gases, especially methane, due to the decay of organic matter in the flooded areas [74]. The HAD has also affected the biodiversity in the Nile by changing the habitats for fish and other water creatures. It has led to an increase in waterborne diseases. Changes in water flow and temperature have further disturbed the river's ecological balance. Additionally, climate change adds more problems that could affect Egypt's ecosystems, agriculture, social stability, and overall water availability. Table 4 illustrates the environmental perspective of HAD. Egypt is a desert country, and climate models indicate that if global emissions continue, its mean yearly temperature might rise by a sharp 2.1°C by the middle of the century and by a substantial 4.4°C by the end of the century [75]. By 2100, areas including Aswan will be particularly susceptible to extreme temperatures, which will rise by an even higher 5.12°C and 5.49°C. The Mediterranean shoreline in Lower Egypt receives the majority of Egypt's meagre 33.3 mm of precipitation annually. Additionally, Egypt's precipitation will become less predictable due to climate change. In fact, Egypt's overall yearly rainfall has dropped by almost 22% in just the last three decades [76]. Adaptive solutions and integrated water resource management methods will be necessary to address these issues and mitigate their negative impacts on the HAD and the ecosystem. Notwithstanding these challenges, the HAD has also presented opportunities for conservation and environmental management efforts.

The reviewed literature in Table 4 showed that HAD has had many effects on water quality, energy, agriculture, and the environment. Rashad and Ismail [77] explained that power generation sometimes drops, and that leads to more use of thermal energy and more greenhouse gases. Shahat [78] looked at water quality and found that the reservoir sometimes has high algae levels, but fish are still healthy and safe to eat. Rizk et al [80] and Elshemy and Meon [79] said the water is mostly clean and good for use. Salema [65] and Heggy et al [81] showed that managing water levels can support farming, but poor planning could harm crops and the economy. Researchers also looked at plants, sediments, and weathering. They found that the area around the HAD still supports many plant species and crops, but there are concerns about metals like Ni and Cd in the sediments [85]. In short, the HAD affects many parts of life energy, food, water, and the environment. Most studies show that the water, fish, soil, and surrounding environment are currently safe. However, regular monitoring is important to keep them that way.

**Table 3:** *Synopsis of recent research for energy perspective of HAD.*

| Study | Research Remark |
|---|---|
| [65] | Suggests that desired level should be between 165 and 170 meters instead of 175 meters upstream HAD. The water should then be released for agricultural use in the old Delta area between Qattara Depression and Assiut. The results indicated that it would take 20 years to fill the depression to elevation -50 (MSL) and produce $7.1 * 10^3$( million KWH). If it produces $8.0 * 10^3(\mathrm{H})$ each year, the total power produced annually would be $56.80 * 10^3(\mathrm{MW})$. |
| [34] | The results indicated that, as the water elevation at HAD drops, the average manual energy production of HAD will drop from 0.5% to 24% over the duration of the GERD filling phase, from 2015 to 2019. |
| [66] | Explains how the flow reduction downstream of the HAD affects the amount of hydropower generated in the research region. The results indicated that the yearly energy production from the HAD ranged from 11.5% to 44.3% for the scenarios that were proposed, whereas the annual energy generation from the Aswan old dam (AOD) ranged from 6.3% to 25.1%. |
| [67] | Investigated the performance of generator air coolers for the HAD Egypt hydropower plant under various operating situations related to the location of air-water coolers and the daily fluctuations in power unit generation. The outcome demonstrated that the original cooler's representative average values were twice as high as the new cooler's representative average values based on the highest and minimum values of the actual fouling factor for both coolers. Additionally, the reduction in the heat transfer area was equal to the malfunction of several of the original coolers. |
| [46] | Covered the water surface of a HADR with a floating photovoltaic system (FPVS) to generate energy. According to the results, $285 \times 10^7, 567 \times 10^7, 854 \times 10^7$, and $1138 \times 10^7 \mathrm{MWh}$/ year can be produced by covering $25.0\%, 50.0\%, 75.0\%$, and $100\%$ of the lake, respectively. |
| [68] | Evaluated how Egypt's High Aswan Dam (HAD)'s inflow and hydroelectric generation were affected by irrigation projects and hydropower dams in Tekeze-Atbara-Setit. In the hydropower scenarios, the maximum yearly inflow at HAD diminishes by 1.6 km$^3$, resulting in a 9.5% reduction in power generation at HAD. At HAD, the annual inflow for irrigation and hydropower projects may be diminished by a maximum of 4.63 km$^3$, resulting in a power reduction of 35.2%. |
| [69] | Employs the hydrodynamic General Lake Model (GLM) to quantify the volume of water conserved by the HADR from 2005 to 2016 due to FPV. The average annual evaporation loss was calculated to be $11.8{*}10^3$ MCM , with an average evaporation rate of $0.65\ \mathrm{cm/d}$, in the absence of FPV. The inclusion of water level fluctuations in the GLM simulations enabled both short-term fluctuations and seasonal evaporation variations to be accurately estimated. By reducing these evaporation losses to a maximum of $49.7\%$ at $90\%$ FPV occupancy, an average of 5.9 BCM of water was saved annually. An average unique water saving of $7.67\ \mathrm{m^3a^{-1}kWp^{-1}}$ was achieved. A $90\%$ FPV occupancy at the same period produced between 1459 to $1431\mathrm{TWha^{-1}}$ with a 735 GWp capacity installed. |

## 3. Literature Review Assessment and Discussion

The high Aswan Dam (HAD) has been a linchpin of Egypt's development, providing water security, energy, and flood control. However, its long-term Hydrological, Geotechnical, Energy management, and Environmental influences highlight the need for sustainable management practices. Evaporation from the HADR is a significant challenge. The amount of water lost through evaporation varies between 0.273 cm per day and 0.958 cm per day. These losses depend on several locations in the HADR. Research by [29, 33, 46] show that some strategies can help save water. For example, disconnecting certain khors and using floating photovoltaic systems (FPVS) could save billions of cubic meters of water each year. According to predictions from artificial neural networks [45], evaporation may increase by 2% by the year 2050. This highlights the need for new strategies to reduce future water loss. Sedimentation has also reduced the storage capacity of HADR by about 12% over the years. This reduction mainly affects the live and dead storage areas[41, 42]. This reduction is exacerbated by sedimentation at downstream locations like Dongola, where cross-sectional areas have decreased by 2.5% to 6% [48]. Advanced modelling methods, like the Multi-Sensor Satellite (MSS) approach, are important for managing HADR and estimating their capacity accurately. These methods help provide better data for HADR management [48]. Seepage from HADR into the Nubian sandstone aquifer averages 47.46 $Mm^3$/year, with peak losses during high reservoir levels [35]. GW recharge from HADR is significant, but if reservoir levels drop below 160 m, reverse flow from the aquifer could occur, impacting local GW levels [86]. The filling and operation of the GERD will significantly influence HAD, with potential reductions in Nile flow ranging from 6% to 35%, depending on the filling scenario [36, 49, 52, 87]. These reductions could lead to substantial agricultural land losses in Egypt, emphasizing the need for regional cooperation and adaptive water management strategies. Climate change is expected to alter Nile River flows, affecting HAD's hydropower production and irrigation releases [54] Adaptive management frameworks, such as the Forecast-Based Adaptive Reservoir Operation (FARO) proposed by [47], are crucial for optimizing reservoir operations under changing climatic conditions.

Second, from a geotechnical perspective, researchers [55] observed that the HAD experienced significant settling in its rock-fill section during the early years from 1970 to 1975. However, after 1975, the settling rates became stable. This stability shows that the HAD's parts now work together as a single structure, which is a good sign of its long-lasting strength. [56] found that the HAD region is tectonically stable, meaning that future earthquakes are unlikely to harm the HAD's safety. However, [60] noted that some parts of the HAD, especially the upstream shell, could be at risk of liquefaction during strong earthquakes. This highlights the need for ongoing seismic monitoring to ensure the HAD's safety. [61, 63] observed that HADR triggered seismicity (RTS) in the HADR is affected by water infiltration into faults, which elevates pore pressure and induces both shallow and deep tectonic earthquakes. Changes in water levels in the HADR affect seismic activity. [37] predicted that sedimentation and erosion would change the bed elevation of the HADR. This suggests that the shape of the HADR is not fixed and needs to be monitored regularly to manage sediment build-up and erosion effectively. Researchers [44] highlighted the flood risks that could arise if the GERD fails. Such a failure could send water to the HADR that is three times higher than normal wet season levels. This shows the need for safety measures to protect the HAD. Researchers [11] proposed a new plan called the Forecast Based Adaptive Reservoir Operation (FARO). They found that using long-term climate predictions can make HADR management better, especially during and after flooding. Researchers used advanced methods to study active faults and crustal movements near the HAD [62]. Their results matched existing records of seismic activity, providing valuable information about tectonic activity and its impact on dam safety.

**Table 4:** *Synopsis of recent research for environmental perspective of HAD.*

| Study | Research Remark |
|---|---|
| [77] | Calculated the HAD electricity production trend between 1979 and 1997 using linear regression fitting. The curve indicated that there were periods the actual production deviated from the trend, which must have been compensated by more generation of thermal power. The corresponding greenhouse gas emissions must have been taken into consideration in the whole energy chain GHG evaluation. Additionally, over the previous five years, using natural gas has prevented almost six million tonnes of $CO_2$ emissions annually. |
| [78] | The upper layer of HADR occasionally has a high concentration of chlorophyll a , and the area is eutrophic. Transparency varies from 0.2 m in August to 6.1 m in December, dissolved oxygen levels vary from 0.0 to $10.3\text{mg/L}$, and the mean water temperature varies from $15.0^{\circ}\text{C}$ in February to $32.4^{\circ}\text{C}$ in August. The fishes recorded in the HADR originate from the River Nile. The tilapias (especially Oreochromis niloticus), Lates niloticus, Labeo, and Bagrus species are the most common species sold as fresh fish. Alestes species and Hydrocynus forskalii are the two primary salted fishes. In I981, the total amount of fish produced was $34.206 * 10^3$ ton, while in 1966, it was $.751 * 10^3$ ton. |
| [54] | Indicated the yearly production of hydroelectricity and irrigation water releases at HAD to show how climate change is altering the water resources of the Nile River basin. The outcomes demonstrated a change in flow at the HAD ranging from -16 to + 11% using 11 bias-corrected statistically downscaled GCMs with the Variable Infiltration Capacity (VIC) model. |
| [65] | Suggested that 13 million acres of Egypt's old Delta could be used for the cultivation of olives, wheat, alfalfa, barley, and sunflower if the water level was changed to 170 m instead of 175 m upstream HAD and the water was released for agricultural use in the area between Assiut and Qattara Depression. |
| [79] | The results illustrated that the reservoir's water quality state ranges from outstanding to good and that its trophic status is eutrophic, in accordance with Egyptian water quality criteria for surface fresh streams. |
| [80] | Monitored and evaluated the HADR's physico-chemical parameter changes and water quality. Depend on Egyptian Government Decree No. 92/2013, the aquatic environmental indices estimated alongside the HADR demonstrate "excellent" water quality at two sampling locations and "good" water quality at seven sampling locations. |
| [81] | The results illustrated that the unmet yearly shortage throughout the GERD filling interval can be somewhat countered by expanding GW extraction, modifying the HAD operation, and adopting new crop-cultivation laws. If appropriate mitigation is not implemented, the short-term 3-year filling scenario will result in a deficit equivalent to losses of up to $72\%$ on currently agricultural land. This would lower the agricultural GDP by $\$51$ billion over the filling interval. The country's GDP per capita would drop by almost $8\%$ because of these numbers, raising the already high joblessness ratio by $11\%$, potentially leading to significant social instability. |
| [82] | Carried out a study in HAD area to comprehend the weathering conditions and source locations of river sediments as influenced by the HAD construction. The result indicated regarding to the chemical and physical properties, they were within acceptable limits for the cultivation of several crops without problems. |
| [83] | Attempted to present comprehensive details regarding old Aswan dam and the species that have been identified there. There are 246 species in the 172 genera and 56 families that make up the database of the vascular flora of the FRNRR. Among the overall number of species, the predominant floristic categories were Palaetropical, Pantropical, and Cosmopolitan components, accounting for 54.47% of the whole flora. About 31.8% of the Nile region's total flora and 11.60% of all species in Egypt are derived from the FRNRR. |
| [84] | 250 samples were taken from HADR to assess the quality and safety characteristics of HADR fish. With average values varying from 15.92% to 22.89%, the proximate analysis demonstrated that every sample under examination was a useful source of protein. In line with the standards established by the European Union Commission (EC) and the National Food Safety Authority (NFSA), the results indicate that the species under investigation had minimal levels of cholesterol and histamine. |
| [85] | HADR water and sediment quality was evaluated by collecting samples for metal content analysis, as well as the metal pollution load. As demonstrated by the contamination load index, geoaccumulation index (I-geo), and enrichment factor (EF), the HADR sediments are metal-free. The toxic risk and ecological risk indices were primarily influenced by Ni and Cd, while Ni has the greatest I-geo and EF values. The results indicated that organisms in HADR may be threatened by the presence of Ni and Cd in the sediments. |

Third, from the energy management point of view, the studies reviewed highlight various strategies and impacts related to water and energy management at the HADR. [65] proposes optimising the water level to 165-170 m upstream of the HADR to facilitate agricultural activities in the Delta region, anticipating substantial energy production over a 20-year period. [34] suggest a possible decrease in energy output at HADR resulting from water level variations during the GERD filling phase. [67] examine the efficacy of cooling systems in hydropower facilities, demonstrating that antiquated systems exhibit reduced efficiency and increased susceptibility to failures. [46] advocate for the implementation of FPVS on the HADR to produce significant energy, with coverage levels linked to energy output. [88] further investigate FPVS, revealing substantial water conservation and energy generation, with 90% FPV coverage diminishing evaporation losses by nearly 50% and producing up to 1459 TWh annually. These studies collectively highlight the importance of integrated water and energy management strategies, including technological innovations such as FPVS, to enhance the efficiency and sustainability of HADR operations in the face of evolving environmental and operational conditions.

Fourth, Environmental perspective: researchers [77] highlighted the variability in HAD electricity production and the need to account for GHG emissions from supplementary thermal-power generation. The use of natural gas has significantly reduced $CO_2$ emissions in recent years. Researchers [31, 40] emphasized the accuracy of the BREB technique and remote sensing approaches (SEBS and MOD16 ET) in estimating evaporation rates. Researchers [54] indicated potential influences of climate change on Nile River flow, affecting hydropower and irrigation. Researchers [80, 82] reported that the water quality of HADR varies from excellent to good, with a eutrophic trophic status. These findings align with Egyptian water quality standards. Researchers [84] studied the physical and chemical properties of sediments, noting that while most sediments are uncontaminated, Ni and Cd pose potential ecological risks. Aquatic Life and Food Safety: researchers [84] confirmed the safety and nutritional quality of fish from HADR, with low elevations of cholesterol and histamine, meeting national and international safety standards.

## 4. Practical Implementation Strategies for HAD Operation

In the light of the presented literature, there are several possible strategics plans to be followed for the ultimate benefits of practical operations for HAD (Figure 4). They are summarized as follows:

i. The improvement of water resources management and adaptation in current status of climate change. It is recommended to enhance the forecasting and modelling of hydrological and climate models for better understanding of rainfall-runoff mechanics and thus a proactive water storage and release planning can be achieved. In addition, a dynamic strategic plan for water release based on seasonal inflow and the downstream requirement to be adopted of course with the consideration of the reservoir losses (evaporation and infiltration). With respect to the high evaporation rate losses could be best optimized using the floating solar panels or chemical films.

ii. Energy efficiency and hydropower optimization could be upgraded through the improvement of turbine system with more robust and energy productive to maximize the electricity generation. Of course, this shall be adopted with maintaining the optimal water flow. In addition, developing an integrated pumped-storage hydroelectric system for the sake of storing the excess energy and control power generation. Further, combination/integration between solar and wind energy with hydropower to make sure a grid stability in the energy system harvesting.

iii. For every dam structure, sediment is one of the major concerns in the dam reservoir storage as well as the extra loading on the dam structure. Hence, sediment management and erosion control are the other essential elements could be adopted in HAD practical operation. Sediment bypass system should be always operated and maintained for sediment flushing to present reservoir siltation. Also, HAD upstream soil conservation is especially important and thus erosion control measure in the Nile

Basin River is necessary to reduce the sediment flow into the HAD reservoir "Naser Lake." Further, the periodical dredging of sediment reuse can contribute substantially for agricultural purposes, land reclamation and construction material.

iv. Flood and drought risk management is another influential factor on the HAD best practical operation. Hence, maintaining flood buffer zone can provide a manageable strategy for Naser Lake and especially during the extreme rainfall events. Advance technologies depend on the integration of remote sensing and data-intelligence models can offer a reliable early warning system for flood prediction and mitigation detection. Worth to mention, developing contingency plans including inter-basin transfer and water rationing can help in addressing the prolonged dry spells.

v. As per the presented forgoing literature, HAD contributed substantially on agriculture and irrigation. Thus, devoting more sustainable strategic plans on this aspect can enhance crops production. In this avenue, using modern technologies on dripping and precision irrigation can reduce the water wastage. In addition, the selection of the proper crops and rotation can improve the drought-resistant and encouraging the high-yield crops that required less water. Finally, plants can be supplemented with other sources of water instead of HAD freshwater resources such as water recycling and development of desalination plants for wastewater treatment.

vi. The location of HAD is influenced by nearby the upstream countries including Sudan Uganda, and Ethiopia and thus enhance the cooperation with Nile Basin countries can ensure a sustainable Nile water management through a politically strong water-sharing management. This could be benefits as well from the data-sharing between those countries and exchange those real-time datasets for delivering a reliable and sustainable plan for water releases and water demands. Also, mediation and conflict resolution are the concern to be resolved through engaging a diplomatic plan to control the disputes over the GERD and other water project within the Nile Basin.

vii. As finally strategy, socioeconomic and environmental consideration are the constrains that involve the community engagement/education. Hence, it is vital to increase the public awareness about how important HAD project and water conservation and water efficient usage are incredibly important for better freshwater sustainability. In addition, this can contribute to the ecosystem protection through preserving the biodiversity and wetlands surrounding HAD reservoir and of course ensuring and ecological balance. Worth to mention, Egypt is one of the popular destinations for tourism and HAD project can be improved through the fisheries development that can promote the sustainable economic for the region and provide an alternative livelihood.

## 5. Conclusion

The High Aswan Dam (HAD) remains a critical infrastructure project with significant benefits and challenges. By 2025, its influence on the Environment, Hydrology, Energy management, and Geotechnical will continue to evolve, necessitating adaptive management strategies to balance development and sustainability. Addressing these challenges will require interdisciplinary approaches, technological innovation, and regional collaboration to ensure the long-term resilience of the Nile Basin. HAD and HADR are especially important for Egypt's agricultural, water resource management, and energy generation. The HAD has proven to be adaptability and flexible but HAD faces some challenges. These include water loss from evaporation, effects from climate change, and risks of pollution from metals. Because of this, it is important to keep monitoring and managing these issues carefully. Using advanced methods, like remote sensing to measure evaporation and flexible management of the HADR, will help use water and energy resources better. It is also important to keep water quality high and reduce nutrient enrichment in the HADR. This protects the ecosystem and ensures the safety of aquatic life. The research highlights the need for sustainable practices and teamwork to maintain the benefits of the HAD while lowering its environmental impacts. Over the years, the HAD has shown strong structural stability, with settling rates becoming steady after the initial construction. However, it is influenced by environmental and geological factors like sediment

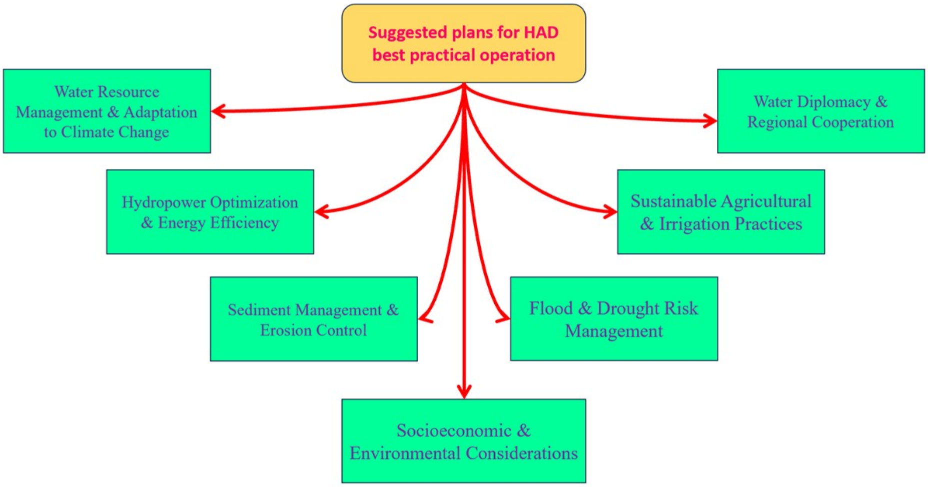

**Figure 4:** *The suggested plans for HAD best practical operation for the upcoming couple of decades chart.*

buildup and climate changes. The Aswan area is generally stable, but there are ongoing risks from earthquakes caused by the HADR and possible flooding from the Grand Ethiopian Renaissance Dam (GERD) failure. Continuous monitoring, flexible management, and cooperation among regions are important for the long-term safety and success of the HAD. Using modern technologies, like InSAR and climate forecasting, will help address these challenges and reduce risks. Following safety regulations and using modern remote sensing methods can greatly improve the management and use of this vital resource.

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