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WATER VOLUME AND 3D TOPOGRAPHIC ANALYSIS OF HUB DAM, KARACHI, USING REMOTE SENSING AND GLOBAL BATHYMETRY DATA

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Background: Karachi one of the largest and fastest-growing cities in the world, the city faces severe water scarcity and aggravated by climate change, excessive groundwater extraction in dense urban areas and inefficient water distribution systems. The Hub Dam, along with the Keenjhar Lake, is the source of water for Karachi's population as well as for the industrial and urban agricultural sectors. It is therefore important to have current information on the dam's storage capacity, its topographic features and the hydrological dynamics of its catchment area, which remains poorly understood to date. **Objectives:** This study's primary objectives are (1) to assess the hydrography of Hub Dam using global bathymetric and remote sensing data and (2) to create a detailed 3D model of the dam to facilitate analysis of its hydrological features. (3) Also generate data-driven insights to guide improvements in Karachi's urban water management policies. **Methods:** The methodology integrates global bathymetric data with remote sensing and Google Earth Engine (GEE) for analysing Hub Dam's hydrological and topographic characteristics. Data processing and visualization were conducted in Google Colab by python codes. This process enabling an efficient workflow for handling and analysing large datasets. **Results:** Hub Dam 3D model is developed. The approaches is enhancing visualization of the dam's water volume and terrain features to support detailed hydrological analysis. 3D volumetric analysis estimates with total water volume at approximately $79.954 \cdot 10^6$ m^3. It was found that currently, the Hub Dam reservoir has enough water to fulfil Karachi needs for 503 days, a critical reserve for urban planning, resource management. Using a topographic analysis that includes surrounding slopes and watershed features, key elements affecting dam performance were identified. This result helps to adjust the filling of the dam with water. The Hub Dam's ability to store water was confirmed through a preliminary volume assessment. **Conclusion:** The study successfully achieved its objectives. The results obtained highlight the importance of adaptive well informed strategies for sustaining well managed water resources in response to environmental pressures. The current study further advance rational water management by integrating remote sensing and data-driven methodologies into this area of knowledge. That is, the effectiveness of Using Remote Sensing and Global Bathymetry Data has been repeatedly proven by other studies in different areas of knowledge. However, in the current study, this scientific approach has successfully demonstrated the efficient and rapid acquisition of accurate, up-to-date information on reservoir capacity and hydrological characteristics, which opens up new opportunities for efficient water management.

Keywords: 3D visualization; remote sensing; global bathymetry; Google Earth Engine (GEE); topographic analysis; Python; resource management.

INTRODUCTION

Water management is an increasingly important issue in urban areas around the world, where rapid population growth, industrial expansion and agricultural demand are putting enormous pressure on available water resources (Carr et al., 2012; Jain et al., 2024). In Pakistan, this problem is evident in Karachi, whose population is over 30 million and growing daily. Karachi one of the largest and fastest-growing cities in the world, the city faces severe water scarcity and aggravated by climate change, excessive groundwater extraction in dense urban areas and inefficient water distribution systems (Khan & Arshad, 2022). Sufficient sustainable water supply for domestic, industrial and agricultural purposes is critical for a city's socioeconomic stability and future growth (Irfan et al., 2018). In distant area the Hub Dam is located on the Hub River about 56 km from Karachi and serves as an important freshwater reservoir for the city and its surrounding areas (Salman et al., 2024). Along with Keenjhar Lake Hub Dam are the sources of water for the people of Karachi and also supports the industrial and urban agricultural sectors (Shaukat et al., 2014).

It is very important to recognize key information about the dam's capacity its topographic features and the hydrological dynamics of its catchment area remain poorly understood. The monsoonal rain accountable for water in the Dam but how much water is present at time of notice, the lack of accurate volume estimates and comprehensive topographic data poses a challenge for urban planners, water managers and policy makers are seeking to effectively manage and optimize urban water supplies (Lioumbas et al., 2023).

There is an urgent need for these challenges for an in-depth and accurate assessment of the Hub Dam's storage capacity and topographical characteristics (Islam et al., 2021). The conservative techniques and methods for estimating reservoir volume, such as in-situ measurements or ground surveys are time-consume, expensive, and often impractical for large reservoirs like the Hub Dam. However, advances in remote sensing, GIS and Geo-informatics are developing more efficient and accessible alternative methods. Modern technologies relying on integration of global bathymetric data and models, along satellite based remote sensing techniques can supply detail and accurate information on dam water amount and topographical context and moreover assist improved water resource management strategies (Kumar et al., 2018; Hameed et al., 2022; Salama et al., 2022).

To perform this assessment, codes and online computation were used to use state of the art remote sensing technologies including global bathymetry and satellite imagery to estimate the water volume of the dam and analyses topographic features affecting its hydrology. Google Earth Engine (GEE) is a powerful cloud platform for large scale geospatial analysis. GEE with Python programming with Google Colab have been used to process data and 3D visualization.

These methods are useful as we can get detailed spatial and hydrological analysis of the Hub Dam and insights that are key to urban water resource management. The integration between Python for proper data handling of large scale satellite and bathymetry data as well as the integration of GEE enhances and facilitates thus efficient data processing (Du et al., 2010; Zhang et al., 2020; Velastegui-Montoya et al., 2023).

Additionally, like its depth profile, surface area and the dynamical evolution of the catchment showing spatial properties of the dam with 3D visualizations (Singla & Padia, 2021). These such visualizations are required for water managers to take refined decisions on water allocation and flood hazard administration (Kilsedar et al., 2019).

The study aims to provide up-to-date information on the Hub Dam storage capacity and its hydrological dynamics and ensure sustainable access to this information by applying remote sensing and bathymetry techniques using the GEE platform and Colab with Python coding. The results of the current study are expected to improve decision-making and the implementation of more sustainable practices and responsible use of water resources in the face of increased pressure on environmental sustainability facing urban water management. Based on the above, the main objectives of the present study were: (1) to find methods and relevant data to estimate the total water storage of the Hub Dam by combining remote sensing data and global bathymetric models, (2) to investigate the terrain, topographic features of the Hub Dam and the surrounding landscape to understand their impact on the hydrological dynamics of the reservoir, (3) to generate proper and comprehensive 3D visualizations of the Hub Dam using satellite remote sensing techniques to improve the spatial awareness of the reservoir, (4) to test the use of modern tools like cloud computing with codes and GEE and Python for efficient processing and analysis of large-scale satellite imagery and bathymetry data, and (5) to generate ideas and recommendations for improving urban water supply management in Karachi based on the findings of the study.

MATERIALS AND METHODS

In this study the methodology with data assessment explain about bathymetry and remote sensing data can be integrated to assess the topography of Hub Dam and its reservoir. The key topographic features such as slope and watershed features, that affect water flow were more easily investigated, this would be recognition to the efficient processing of large geospatial datasets using GEE that included satellite imagery and digital elevation models (Tamiminia et al., 2020). Python is used in conjunction with Google Colab, an online platform that facilitates collaborative development to efficiently utilize and display raster data. This technique not only streamlined data analysis, also improve the representation of complex hydrological dynamics and topography. Extracting information related to dam hydrology, the combination of GEE and Python provided a strong framework also for 3D visualization and storage (Zeng et al., 2023). However, this is also possible using GEE alone.

Data acquisition and pre-processing

The main datasets are high-resolution satellite imagery available through Google Earth Engine (GEE) and global bathymetric models. The GLOBathy dataset, an open-source bathymetry dataset available on the GEE platform, provided bathymetric data for the study. Study area coordinates to GeoJSON coordinates were used to define the study area, which is a polygonal area in Karachi, This data was used to cropped the GLOBathy data to this region of interest (ROI) (Figure 1 – 3). Step by step process used codes and libraries as follows.

Software and tools

The analysis was performed using GEE and Python, with the following libraries:
– *geemap* for interfacing with Earth Engine and visualizing geospatial data;
– *rioxarray* for handling raster data;
– *scipy* and *numpy* for numerical processing and applying filters;
– matplotlib and *plotly* for data visualization, including the 3D bathymetric plot.

Authentication and initialization

The *GEE API* was authenticated and initialized using a custom project ID. This provided access to the GLOBathy dataset and enabled geospatial operations within the ROI.

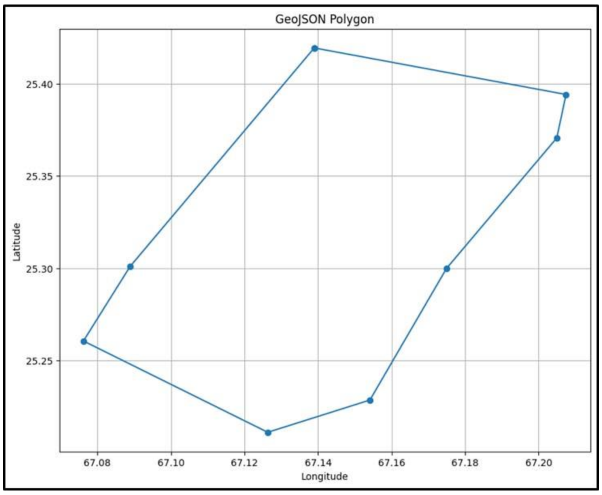

Figure 1. GeoJSON file of the Hub Dam

Figure 2. Study area map on Colab

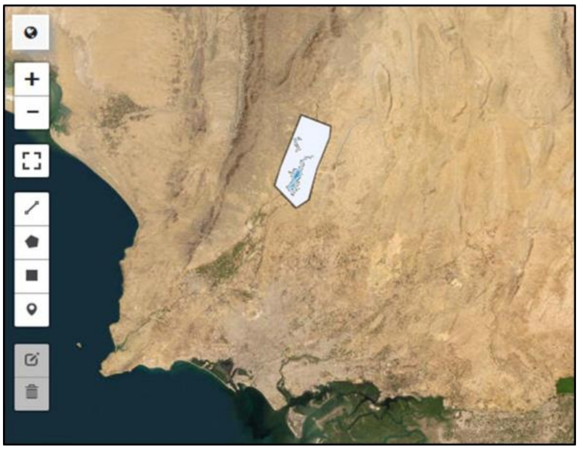

Figure 3. Study area with GLOBathy dataset on Colab with satellite image

Region of interest (ROI) and bathymetric data processing

The *GeoJSON* file with coordinates of the Hub Dam is used to define a polygon of the study area which was then converted to a GEE geometric feature. Later this geometry was used to crop the GLOBathy bathymetry image then a colour palette was used to highlight several depth regions in the data which were determined for display purposes with precise depth values ranging from 0 to 16 m.

Depth and volume calculations

A combination of *GeoJSON*, elevation and bathymetric data to estimate the storage capacity of the Hub Dam. By combining surface calculations from satellite data with depth values from bathymetric models, the volume was determined using the formula for the volume of a prismatic body. The volume of water in the lake estimated and following steps were performed:
– a depth mask was applied to filter out areas where the depth was zero (i.e. areas without water);
– the area of each pixel in the bathymetric dataset was calculated using the *pixelArea()* method in GEE and renamed to 'area_m2';
– the volume of water in each pixel was calculated by multiplying the pixel area by the corresponding depth, yielding the volume per pixel in m^3 (volume_m3);

Total volume estimation

The volume was calculated using the formula with codes. Using the *ReduceRegion* approach, the volume of each pixel within the given region was added to determine the total volume of the lake. For clarity, the resulting volume was converted to m^3. The calculation can be formulated as follows: By adding the volumes of each individual pixel within the region of interest, the total volume was calculated using the following formula:

$$V = \sum_{i=1}^{n}(A_i \cdot D_i), \quad (1)$$

where V is the total volume; A_i is the area of the i-th pixel; D_i is the depth of the i-th pixel; n is the total number of pixels.

Exporting bathymetric data

Analysing topographic features around dams like its topography and land aspect data are important because they reveal how topography affects water storage and movement, this includes hydrologic modelling, slope calculations, and watershed delineation. These are helpful to describe how topography affects hydrologic patterns, including flow routes and storage capacity. Understanding the distribution and storage of water in dam catchments requires knowledge of these factors. Hydrologic studies and accurate terrain modelling require deep bathymetric data representing underwater terrain. This information enables enhanced visualization and analysis of the landscape and is exported through Google Earth Engine (GEE) as a *GeoTIFF* file with a spatial resolution of 30 m.

ArcGIS and other GIS programs can use and open the exported image. Additional processing of bathymetry data helps ensure accurate representation of depth contours and increases the comprehensive knowledge of how the landscape affects aquatic systems and analysed by various software.

Data smoothing and terrain analysis

Around the dam elevation measurements were used to assess topographic features, also to examining depth contours, these assessments also included hydrologic modelling, slope calculations, and watershed delineation to determine how topography affected water flow and storage capacity. The *rioxarray* library was used to read the exported bathymetry data with filters to smooth the data and reduce noise. This smoothing method also preserved significant depth changes while improving the display of topographic features.

3D visualization

Library *Plotly* was used to create a 3D plot of bathymetric data to visualize the Dam topography. The surface plot was created using smoothed depth data with a colour scale indicating different depth levels. Custom colour scales were imported from matplotlib to improve visual appeal.

Finally, the 3D plot had the appropriate calculations to correctly represent the geography of the Hub Dam and its deep and spatial resolution. The final visualization also showed the total estimated water volume in order to better understand the lake's capacity. This methodological framework was used to carefully study the bathymetry of the Hub Dam and to accurately estimate total water volume.

RESULTS AND DISCUSSIONS

The purpose of this study is to analyses characterize the topographic and bathymetric features of the lake so as to gain information on the dynamics of the lake water and its reservoir capacity. Below study present the results of these calculations and discuss how their implications affect hydrological modelling and resource management.

GLOBathy dataset visualization

Below, the visualization of GLOBathy dataset developed using Colab platform (Figure 4). The data is smaller than the dam's full coverage as you see it in satellite images and maps.

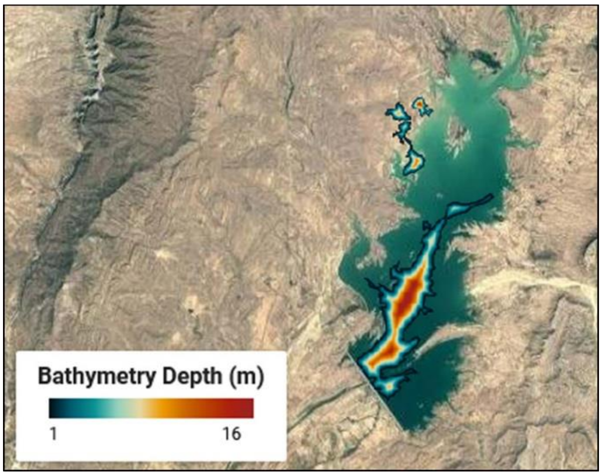

Figure 4. GLOBathy dataset visualization

Volume estimation

Water resource inaccuracy together with a changing climate of reduced water availability and storage necessitate for accurate volume measurements (Mukonza et al., 2024). The study results suggest that Hub Dam holds about $79.954 \cdot 10^6$ m^3. Key elements affecting the performance of the dam were identified through topographical analysis that including surrounding slopes and watershed features that help channel water into the dam. The Hub Dam's ability to store water was confirmed through a preliminary volume assessment (Figure 5, 6). Although this preliminary assessment was simple and it showed that the information could be useful in formulating water management plans. It highlighted the need for further research to improve these estimates by considering variables such as spatial cell size and using more complex hydrological models with proper surveys and time to time assessment.

3D terrain visualization

The 3D visualizations generated for understanding of the function of the dam in urban water supply management. The spatial relationships between the dam its watershed and nearby land uses. The shape of the underwater landscape was well captured by the 3D representation of the topography of the lift dam, which showed clear differences in depth.

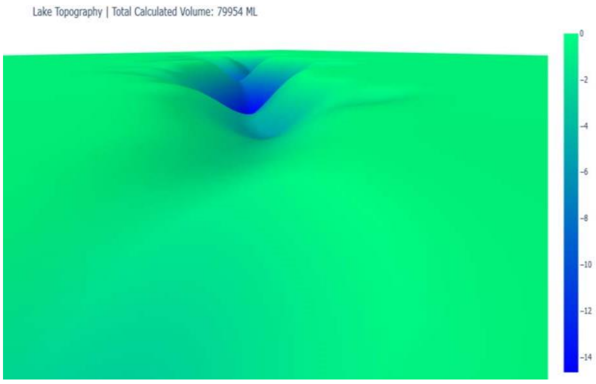

Figure 5. Estimated water volume and 3D Dam orientation

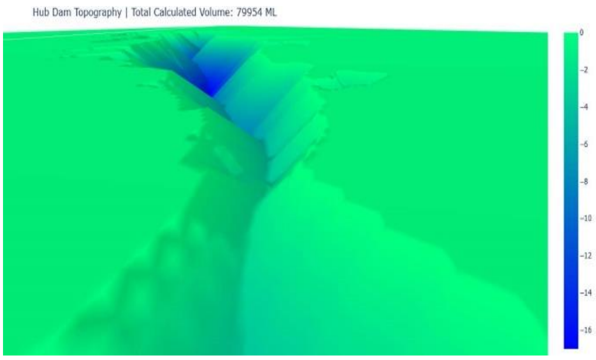

Figure 6. Zoom view (opposite side)

The varying depths were highlighted using a colour scale that highlights both shallow and deeper areas (Figure 7). Slope gradients and submarine contours can be better understood due to the improved visibility of topographic features. This is necessary to determine how these features affect sediment deposition and water movement (Figure 8).

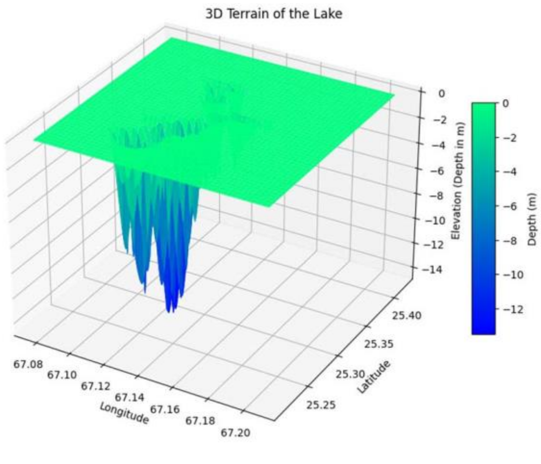

Figure 7. 3D visualization of the Hub Dam's terrain

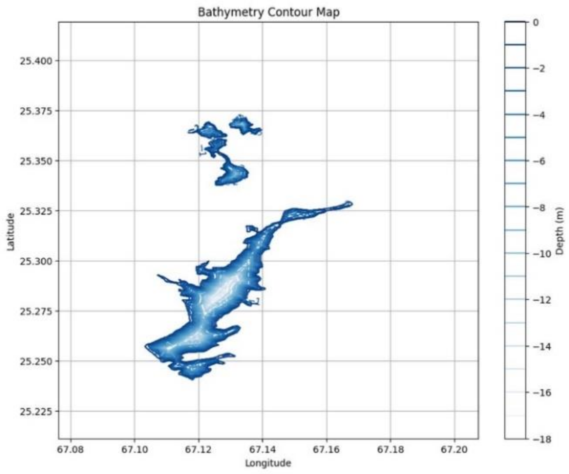

Figure 8. Bathymetry contours

Importance of hub dam

For Karachi and the surrounding agricultural areas, especially Lasbela District, the Hub Dam is an important source of water. The demand for water is constantly increasing to support Karachi's growing population, making Karachi one of the fastest growing cities in Pakistan. This demand is largely met by the Hub Dam, which provides vital water for domestic and agricultural needs. This is an important part of the region's water supply strategy by its huge water capacity and demand of the city (Begum et al., 2013; Salman et al., 2024).

The Main Canal, Bund Murad Minor, Lasbela Canal and Karachi Water Supply Canal are part of the Hub Dam canal system. After about 8.32 km, the main canal, which has a designed capacity of 10.477 m^3/s, divides into two branches at the main regulator where vertical gates regulate the flow of water to Sindh and Balochistan. 20 – 25% of Karachi's municipal and industrial water comes from the 22.4 km long Karachi Water Canal, which has a capacity of 5.947 m^3/s and terminates at the KW&SB Pumping Station. The Lasbela Canal (33.6 km) long has a capacity of 4.531 m^3/s and supplies irrigation to industries in Balochistan for 84.984 km^2 and 68.191 km^3/day, It has 58 structures and 268.219 km^3/day for various purposes. Before the Hub Dam project the Bund Murad Minor Dam, handed over to the Government of Sindh on 1 January 1986 that supplies irrigation water to 10,000 m^2 of agricultural land, replacing the water supplies already available (Zubair et al., 2012).

Due to the growing population in Karachi and surrounding areas existing water resources are coming under increasing pressure. This increase also coupled with the challenges posed by climate change by altered rainfall patterns and higher evaporation rates (Shaukat et al., 2014). This indicates the necessity of capable assessment of the dam's capacity. The dam is also a buffer against the water scarcity, it ensures the agricultural crops and vegetables production in the region, and irrigated crops are used for agricultural purposes (Vorosmarty et al., 2000; Aslam et al., 2024).

Importance of computational methods and remote sensing data in hydrology

With better machines with machine learning and cloud assessment the river, dams and lakes hydrology and storage capacity are being estimated using computational methods. Use of sophisticated computational approaches allows more accurate modelling and analysis of water flow, sediment transport and overall hydrological productivity. Other related techniques, remote sensing, and geographic information systems (GIS) allow researchers to obtain important data to assist in management decisions ensuring greater understanding of hydrological dynamics (Qi & Altinakar, 2012; Kumar et al., 2017).

Dam assessment can be enriched by integrating allied data to give a complete picture of reservoir performance. Useful spatial data and satellite images for monitors temporal changes in surrounding land use, sedimentation rates, and water levels. With high-resolution satellite images dam performance can be monitored and data driven management for decisions (Souza et al., 2021). It facilitates rapid action against potential problem and improves the accuracy of the assessment. Among many studies that have shown the importance of using bathymetry and remote sensing data in order to make accurate water resource management in urbanized environments (Rajendran et al., 2020; Yépez-Rincón et al., 2024).

Using platforms such as Google Colab has completely transformed the way the hydrological assessments are being done. Removing the lockout allows researchers to collaboratively write and run code in this cloud environment, sharing methods and results. If researchers have access to powerful computing and data analysis frameworks (Sharma et al., 2024) they can efficiently process large datasets. Automation of data processing processes is made possible by programming skills that enable the automation of data processing processes which then makes data processing more efficient and result more quickly (Marsal & García-Carpallo, 2024).

Applications and future directions

The results of this study have important implications for the development of water resources management and policy. Understanding of the capacity of Hub Dam and associated hydrological dynamics can help stakeholders to improve management practices aiming sustainable water supply. Quantity estimation can provide important information to planners and policy makers for the strategic management of Karachi's water supply in the face of increased demand. Additionally, the integration of Python with Google Earth Engine (GEE) produces a scalable approach that could be adapted for similar investigations in many geographic places, facilitating their data driven decision making in water resources management (Nakib et al., 2024).

In the future, predictive analytics and hydrological models will become ever more sophisticated, and will be integrated to help improve our understanding of water dynamics in relation to climate change. Additionally, the continuous monitoring and assessment of water resources will be supported by increased use of computational tools and remote sensing technologies. This method will be necessary to develop innovative management plans that can fit both short term water resource availability needs and long term water resource availability problems.

Importance of visualization and analytical techniques

Since, the study results, these sophisticated visualization and analysis techniques are important for hydrological research. Accurate water level assessment is necessary for efficient lake management and conservation, and visualization of complex topographies is equally important.

Future research should focus on several key areas:

1) future research should incorporate advanced volume calculation techniques, including seasonal variations and more complex hydrological models, to improve the accuracy of water resource estimates;

2) conducting longitudinal studies would provide important information on how the volume and topography of the lake have changed over time, particularly in response to human activities and climate change. Adaptive management strategies require this knowledge;

3) the use of interdisciplinary teams integrating knowledge of ecology, hydrology and geo-analysis would increase the sustainability of results and contribute to comprehensive water systems management plans.

By demonstrating the effectiveness of volumetric estimation and visualization approaches, this study advances our understanding of lake systems. The insights gained from this analysis not only complement the existing body of information but also provide the basis for further research on the protection and management of vital water resources in a rapidly changing environment.

With these result and data ($79.954 \cdot 10^6$ m^3) of available water and $159 \cdot 10^3$ m^3 of water is consumed per day), it means that this is approximately half a years' water supply. The implications of this assessment are very important for project of water resource management and planning in Karachi. Water supply sustainability The Hub Dam reservoir is expected to be able to provide more than one and a half years' water supply at current consumption rates. This long time is very important for the urban planning and resource allocation for that, the city can plan out in advance how to allocate and manage water. A greatly useful characteristic especially in dry or low rainfall times when alternative water sources are not suitable.

Sustainability of water supply, risk and planning

Currently, the Hub Dam reservoir has enough water to fulfil Karachi needs for 503 days, a critical reserve for urban planning, resource management. When other water sources are lacking or in the dry seasons, this buffer period is crucial. However, the reservoir's sustainability is threatened by pressures increasing population, industrial growth and fluctuating climate.

The efficient management is crucial to maximize lifespan of the reservoir. By taking actions such as water conservation, leak detection, and infrastructure improvements, supply levels can be sustained. But real factors that structure the reservoir's viability over this period include unexpected drought and possible pollution. Preparedness means regular monitoring of water levels and quality, as well as contingency plans and alternative water solutions. Our evaluation indicates that Karachi's policymakers should take a proactive, long term approach. Such as increasing of water conservation measures, or distribution systems, or other water sources, among others, like desalination or rainwater collection. Public awareness about water saving practices can also increase demand, and thus, provide greater security for resource.

CONCLUSION

Rising water demands in Karachi and the Lasbela region are due to urban expansion, population growth and climate change and this study emphasizes the very important role played by Hub Dam. This research improves the understanding of the reservoir's capacity and hydrological characteristics, with the focus on volume estimation that is accurate and ongoing facilitating effective water management. These results highlight the importance of adaptive well informed strategies for sustaining well managed water resources in response to environmental pressures. Remote sensing data with Google earth engine or with Colab can be useful as these data sets are at global coverage and with various nature and domains.

The results of the current study further advance rational water management by integrating remote sensing and data-driven methodologies into this area of knowledge. That is, the effectiveness of Using Remote Sensing and Global Bathymetry Data has been repeatedly proven by other studies in different areas of knowledge. However, in the current study, this scientific approach has successfully demonstrated the efficient and rapid acquisition of accurate, up-to-date information on reservoir capacity and hydrological characteristics, which opens up new opportunities for efficient water management.

Author's statements

Contributions

Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft: I.A.K.; Formal Analysis: A.HL.; Writing – review & editing: I.A.K., A.H.L.

Declaration of conflicting interest

The authors declare no competing interests.

Financial interests

The authors declare they have no financial interests.

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Data availability statement

The datasets generated during and Codes /or analysed during the current study are available from the corresponding author on reasonable request.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

Not applicable.

Additional information

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