© June 2024 | IJIRT | Volume 11 Issue 1 | ISSN: 2349-6002

Advanced GIS-Based Sediment Analysis for Dam Management

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Abstract— Groundwater is one of the most important natural resources, which supports human health, economic development and ecological diversity. Due to over exploitation, the ground water systems are affected and require management to maintain the conditions of ground water resources within acceptable limits. With the development of computers and advances in information technology, efficient techniques for water management have evolved. Although the use of these techniques in groundwater studies has rapidly increased since last decade the success rate is very limited. This research presents geographic information systems (GIS) based application for investigating sediment deposits of Khadakwasla Dam. Spatial data were collected from aerial photographs, bathymetric data, and satellite images corresponding to the study area. This method for assessment of reservoir sedimentation uses the fact, that the water spread area of reservoir at various elevations keeps on decreasing due to sedimentation. The purpose of the present study is to estimate the amount of suspended sediment in the dam basin using the remote sensing facilities and satellite images of powerful sensors in the field of water studies and then comparing the results with sediment data. Traditional methods are inconvenient, expensive and time consuming. Since applying the remote sensing technique has a greater speed and precision compared to traditional methods.

Index Terms- Geographical Information System (GIS), Sediment Deposition in dam, ARC-GIS software, Satellite Remote Sensing (SRS)

I. INTRODUCTION

Reservoir sedimentation and groundwater depletion are pressing challenges affecting water resource sustainability and ecosystem health worldwide. Effective management strategies are essential to mitigate these issues and ensure adequate water availability for various sectors. Traditional methods for reservoir sedimentation assessment, such as hydrographic surveys, are often time-consuming and expensive, necessitating the exploration of alternative approaches. Remote sensing technologies offer a promising solution, enabling efficient quantification of sediment deposition patterns and storage loss in reservoirs. By leveraging multi-date satellite data, remote sensing techniques provide valuable insights into reservoir dynamics, facilitating informed decision-making for reservoir operations and management. Moreover, Geographic Information System (GIS) tools enhance the spatial analysis of reservoir sedimentation and groundwater resources, offering comprehensive solutions for water resource management.

Reservoir sedimentation poses significant challenges to water resource management, impacting storage capacity, water quality, and ecosystem health. Periodic capacity surveys utilizing remote sensing techniques offer a cost-effective and efficient approach to assess sedimentation rates and storage loss in reservoirs. By analyzing satellite imagery, sediment deposition patterns can be identified, enabling targeted sediment management strategies. Remote sensing data also facilitate the monitoring of reservoir water spread area, providing valuable insights into sediment accumulation trends over time. Integration of remote sensing and GIS technologies enhances reservoir sedimentation management, enabling proactive measures to maintain reservoir capacity and ecosystem integrity.

Groundwater depletion is a global concern, exacerbated by population growth, urbanization, and climate change. Precise assessment of groundwater resources is essential for sustainable water management and conservation efforts. Groundwater recharge estimation, particularly in water-stressed regions, requires accurate spatial data analysis and modeling techniques. GIS tools provide valuable capabilities for groundwater assessment, facilitating the integration of hydrological data, land use information, and precipitation patterns. By combining remote sensing and GIS techniques, comprehensive groundwater recharge maps can be developed, guiding resource allocation and conservation strategies. Moreover, remote sensing data enable the monitoring of land surface changes, aiding in the identification of potential groundwater recharge areas and groundwater-surface water interactions.

1.1 Area of Study

Pune stands as the ninth most populous city in India and the second largest within Maharashtra, trailing only behind the bustling capital, Mumbai. Covering a sprawling geographical area of 16,642 square kilometers, Pune sits on the western edge of the state, gracing the eastern banks of the Mutha River. Nestled nearby is the village of Khadakwasla, home to the eponymous dam that serves as the lifeline for Pune and its surrounding suburbs, boasting a reservoir capacity of 374 million cubic meters and towering at a height of 31.79 meters.

Positioned at a latitude of 18.750 N and longitude of 73.440 E, Khadakwasla experiences a tropical climate, characterized by significantly rainier summers compared to its winters. The average yearly temperature in this region holds steady at 24.70 degrees Celsius, with an annual precipitation rate averaging at 1083 millimeters.

Pune has metamorphosed into a bustling hub, earning renown as an automotive and IT epicenter, alongside housing major industrial zones and esteemed educational institutions. The city pulsates with a constant influx of migrants, drawn by its myriad opportunities and amenities. However, this surge in population, coupled with burgeoning industrial activities, has precipitated a dire need for essential resources, particularly water.

Currently, Pune has secured approximately 2400 plots for groundwater extraction, a number steadily dwindling in the face of escalating demands and swelling population figures. Consequently, the city grapples with acute water scarcity issues, necessitating innovative solutions to augment its water reserves. Addressing this challenge requires strategies to recharge groundwater reservoirs, thereby bolstering storage capacities and ensuring sustained access to water resources for the burgeoning populace and industrial enterprises alike.

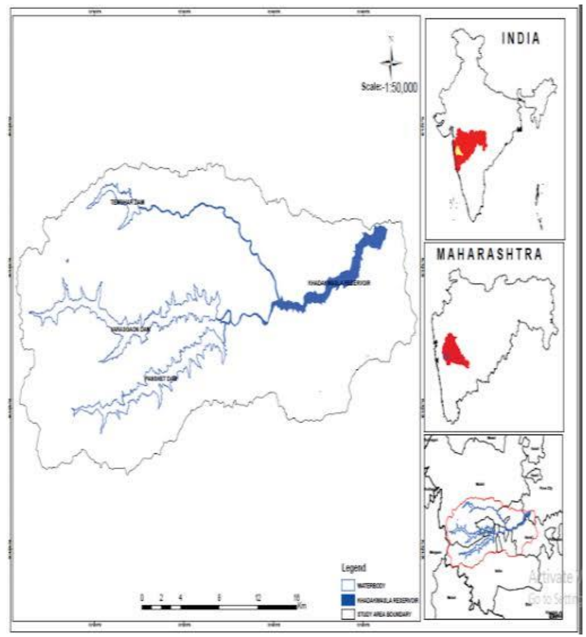

Fig -1: Location of Study Area – Khadakwasla Dam

II. LITERATURE REVIEW

Reservoirs play a critical role in water storage, catering to various societal needs. However, sedimentation poses a significant challenge, reducing their capacity over time. Indian rivers contribute significantly to sediment deposition in water bodies, impacting water availability and operational schedules. To address this issue, researchers have turned to satellite imagery analysis, considering variations in climatic conditions and reflectance properties. Sensitivity analysis techniques, applying coefficients to Landsat bands, reveal insights into sediment changes.

Geographical Information System (GIS) techniques offer valuable tools for sediment source identification and yield estimation. Utilizing ILWIS and ERDAS Imagine, researchers assess land cover and soil characteristics to model erosion and sedimentation in reservoir watersheds. Spatial disaggregation of catchment areas aids in understanding sediment dynamics, while DEM resolution analysis provides further insights.

Studies employing GIS-based models like SWAT demonstrate their efficacy in predicting sediment transport. Calibration and validation against observed data reveal significant reductions in sediment yield with the implementation of check dams. Remote sensing techniques complement GIS, enabling bathymetry and sediment distribution modeling. Ground surveys validate siltation patterns, enhancing reservoir capacity evaluations.

Traditional sedimentation surveys face limitations in mapping reservoir bottoms comprehensively. However, the integration of hydroacoustic systems with GIS revolutionizes sedimentation mapping, offering detailed insights into deposition patterns over time.

Beyond reservoir management, GIS finds applications in groundwater studies. Researchers utilize GIS to identify groundwater recharge zones, analyze groundwater levels, and assess quality parameters. Spatial analysis techniques aid in estimating recharge potential and understanding groundwater variability under different climatic conditions.

Efforts to model groundwater recharge and discharge using GIS contribute to water resource management strategies. Various studies highlight GIS's effectiveness in estimating groundwater dynamics, from recharge assessments to spatial-temporal distribution analyses. These findings underscore GIS's versatility in addressing water resource challenges and informing sustainable management practices.

III. METHODOLOGY

At the first use of ENVI for atmospheric and geometric correction. Removing the influence of the atmosphere is a critical pre-processing step in analyzing images of surface reflectance. Properties such as the amount of water vapor, distribution of aerosols, and scene visibility must be known. Because direct measurements of these atmospheric properties are rarely available, they must be inferred from the image pixels. Hyper spectral images in particular provide enough spectral information within a pixel to independently measure atmospheric water vapors absorption bands. Atmospheric properties are then used to constrain highly accurate models of atmospheric radiation transfer to produce an estimate of the true surface reflectance.

A GIS represents both features and surfaces. Features are geographic objects with well-defined shapes (such as political boundaries). Surfaces are geographic phenomena with values at every point across their extent. Elevation is a common example, but surfaces can also represent temperature, chemical concentrations, and many other things.

Surfaces are usually modeled with raster datasets. A raster is a matrix of cells, also called pixels, organized in rows and columns and covering some part of the world (or even the whole world). Each cell in the matrix represents a square unit of area and contains a numeric value that is a measurement or estimate for that location. Before continuing GIS for pixel values in this step we can use digital elevation.

Satellite images include pixels or the components of image that in this pixel the reflectance values are recorded. In this study, using ARCGIS Software we calculated the reflectance values in each Landsat band and number of repetitions. Then the mean of the reflectance values for each band were calculated in the basin.

The calculation of sediment based on the samples measured at the hydrometric stations. Due to the lack of accurate statistics of the erosion and deposition of sediment at the watershed in most cases the sediment measurement curve prepared by discharge and sediment concentration data or sediment discharge are used. At the hydrometric stations sampling suspended sediment concentration is performed at the base discharges or in low flood discharges. However, the variability of flow and sediment relationships in flood discharges is much higher due to changes in rainfall and catchment (soil moisture, presence of sediment and subcortical water content) and thus, the efficiency of rating curve depends on the accuracy of the obtained data.

Considering the different reservoir levels between dead storage level (D.S.L) and Full storage level

(F.S.L) on various dates in between 2013 to 2020 for covering full range of live storage of reservoir. The original elevation-area capacity curve/table and the reservoir level of year 2014 to 2020 have also been used in the analysis.

Geographical Information System (GIS) techniques offer versatile solutions for understanding and managing water resources. Beyond surface water reservoirs, GIS plays a pivotal role in groundwater studies, aiding in the identification of recharge zones and assessment of groundwater levels and quality parameters. GIS applications extend to analyzing rainfall patterns and spatial distribution, offering insights into recharge mechanisms and groundwater variability. Efforts to estimate groundwater recharge using GIS are complemented by hydrological modeling techniques, enhancing predictions of aquifer behavior under changing conditions. Studies highlight GIS's efficacy in quantifying flow and flux of groundwater discharge, utilizing temperature and velocity data to improve accuracy. Moreover, GIS methodologies facilitate the spatial analysis of groundwater dynamics, providing insights into recharge patterns and resource availability. The integration of GIS with groundwater studies enables comprehensive assessments of aquifer recharge and depletion, guiding effective resource management strategies. GIS-based approaches also enhance understanding of groundwater-surface water interactions, aiding in integrated water resource management initiatives. Research efforts have focused on utilizing GIS to model groundwater recharge in diverse hydrological settings, from humid areas to alluvial plains, providing practical solutions for water resource assessment and planning. Studies utilizing GIS for groundwater assessment underscore its role in estimating spatial and temporal distribution of recharge, contributing to sustainable water management practices worldwide.

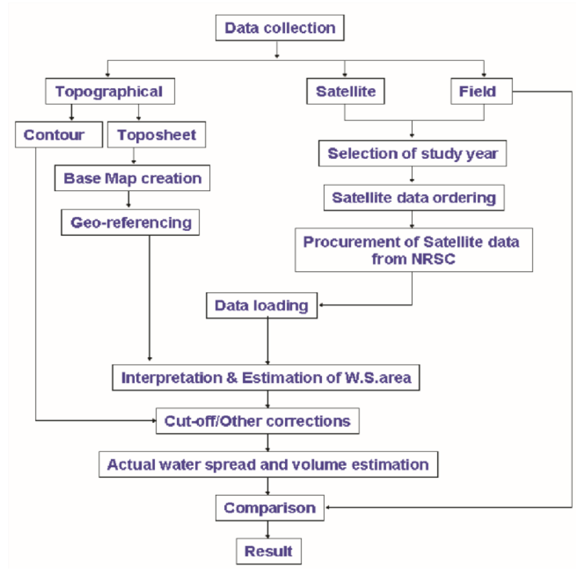

Chart -1: Methodology flow chart

2.2 Procedure for Sedimentation Analysis

The assessment of sedimentation and groundwater potential in the Khadakwasla region has been thoroughly investigated utilizing Geographic Information System (GIS) techniques. A meticulous data collection process involved the compilation of contour maps, rainfall statistics, and groundwater levels during different monsoon phases from the Indian Meteorological Department (IMD) and the Ground Survey and Development Agency (GSDA) respectively, on a yearly basis. Analysis of rainfall data from numerous stations allowed for a detailed understanding of both annual and seasonal patterns. GIS software played a pivotal role in processing and analyzing this data, incorporating digitization, editing, topology building, and the integration of thematic maps. The resulting groundwater prospect map underwent rigorous validation against field data. Furthermore, a consolidation of various sedimentation thematic maps into a unified groundwater prospect zone was achieved using GIS techniques, which entailed spatial database building, analysis, and data integration. This comprehensive approach provides a robust framework for the assessment and management of sedimentation and groundwater resources in the Khadakwasla region, facilitating informed decision-making for sustainable development initiatives.

2.3 Analysis

The creation of thematic maps using ArcGIS plays a crucial role in the representation of spatial data and the distribution of various variables across a region. These maps are instrumental in visualizing patterns and trends that are otherwise not easily discernible, thereby aiding in informed decision-making and research analysis. In this study, thematic maps have been employed to depict the distribution of sedimentation, soil types, slope gradients, land cover, and water depth within a specified area. The data utilized for these maps is gridded, ensuring consistency and accuracy across different temporal surveys. This gridding process involves standardizing the grid extent, cell size, and the horizontal positioning of grid nodes, which is essential for the reliability of comparative analyses.

The sediment deposition mapping, particularly, highlights changes in reservoir bed elevations over the years 1999, 2001, and 2019. By using the Raster Calculator function in ArcGIS, difference grids were generated, enabling the visualization of sediment deposition and erosion. These maps, color-coded by the magnitude of change, reveal significant sediment accumulation, especially in the wider entrance of the reservoir where more than 80 percent of the deposition thickness exceeds 2.50 meters. This level of detail is crucial for understanding sediment migration patterns and for the management of reservoir capacities and lifespans. The data's grid pattern was sufficiently dense to capture the reservoir's bottom features accurately, ensuring high-resolution tracking of sediment movement.

The thematic maps created using ArcGIS 10.2 for the study area also include soil maps that detail the distribution of different soil types such as alluvium, regur (black cotton soil), and hill soil. The region, predominantly covered by alluvial soils, is part of Maharashtra's agricultural landscape, which is well-suited for cotton cultivation due to the presence of regur soil. These black soils are typically found in the basalt regions of Maharashtra and are a product of historical lava flows from the Deccan Traps. The soil map thus provides valuable insights into the agricultural potential and land use planning for the region.

Furthermore, the analysis includes a detailed examination of slope gradients and land cover variations. The slope map is critical for assessing erosion risks, planning construction projects, and managing natural resources. Meanwhile, the land cover map offers a comprehensive view of the vegetation, water bodies, urban areas, and other land use categories. This information is indispensable for environmental monitoring, urban planning, and sustainable development initiatives.

In addition to soil and land cover, the study also focuses on the distribution of groundwater levels. The groundwater maps depict year-wise fluctuations in groundwater levels, categorized into pre-monsoon, monsoon, and post-monsoon periods from 2011 to 2017. These maps are vital for understanding the region's water availability, planning irrigation schedules, and managing water resources efficiently. The data indicates significant variations in groundwater levels, which are influenced by seasonal rainfall patterns and water usage practices. Furthermore, a consolidation of various sedimentation thematic maps into a unified groundwater prospect zone was achieved using GIS techniques, which entailed spatial database building, analysis, and data integration.

IV. RESULTS AND DISCUSSIONS

The analysis of satellite and Google Earth images from 1990 to 2020 using GIS technology reveals significant river migration within the study area's flood plain. Superimposing the bank lines over the years indicates that the central part of the river has experienced notable changes, with more erosion observed on the northern side (right bank) and deposition on the southern side (left bank). This differential behavior highlights the dynamic nature of the river's morphology. Considering the variability in climatic conditions and the timing of satellite image captures, different reflectance values were noted due to changing land conditions. To account for these variations, sensitivity analysis was conducted by applying 10% and 15% coefficients to the average reflectance values of the bands. This approach helped in understanding the potential changes in sediment values, ensuring that the analysis remains robust despite the inherent variability in image acquisition conditions.

CONCLUSION

Based on the study, it is concluded that integrating hydro acoustics, GPS, and GIS technology provides bed elevation maps with accuracy and quality comparable to traditional surveying methods. The GIS approach offers a significant advantage by enabling sediment volume calculations over entire reservoir areas through digital surface comparisons, unlike the traditional method that relies on limited cross-sectional data. This GIS method also holds future potential for tracking sediment changes over time and facilitating automated sediment analysis.

Furthermore, the study highlights the importance of groundwater as an alternative to surface water to meet demand. Groundwater levels in the Khadakwasla area were categorized into good, moderate, and poor zones using various artificial methods and GIS techniques. GIS proved to be a valuable tool for integrating thematic maps, which are crucial for identifying groundwater occurrences and movements. The resulting groundwater prospect maps, also categorized into good, moderate, and poor classes, provide a reliable basis for groundwater assessment and management. The study also notes that urban areas face lower groundwater recharge rates due to soil with low water holding capacity and increased surface runoff from urbanization. Overall, the use of GIS for groundwater level assessment is effective and reliable, supporting better management and development strategies.

Geographical Information System (GIS) techniques offer versatile solutions for understanding and managing water resources. Beyond surface water reservoirs, GIS plays a pivotal role in groundwater studies, aiding in the identification of recharge zones and assessment of groundwater levels and quality parameters

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