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Advanced Integration of Remote Sensing and GIS for Identifying Dam and Reservoir Sites: A Case Study of Manipur, India

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Abstract

This paper investigates the use of Remote Sensing (RS) and Geographic Information Systems (GIS) in identifying the most suitable locations for dam and reservoir construction in Manipur, a state in Northeast India with challenging terrains and varied ecological zones. Using topographical, hydrological, and environmental data, this research applies a multi-criteria decision analysis (MCDA) to determine optimal locations with minimal ecological disruption. The integration of RS and GIS allows for the comprehensive analysis of spatial layers that factor in socio-economic and environmental concerns. The study identifies several potential sites and provides insights into how such methodologies can improve water resource management and sustainable infrastructure development in Manipur and other parts of India.

Introduction

The study begins by discussing the growing need for efficient water resource management in India, particularly in regions like Manipur, where fluctuating monsoon rains and diverse ecological landscapes complicate infrastructure development. Dams and reservoirs play a key role in water conservation, flood control, irrigation, and hydropower generation, but identifying sites with minimal environmental and social impact is critical. The introduction explains how RS and GIS can offer innovative solutions for dam site selection, providing spatial and hydrological data for better decision-making processes. The paper sets the objective to explore how RS and GIS can be used to assess optimal locations for dam and reservoir construction in Manipur.

In the quest for effective water resources management, the identification of suitable sites for dams and reservoirs stands as a pivotal task. This process is greatly enhanced by the integration of remote sensing and Geographic Information Systems (GIS), technologies that have revolutionized how we approach such complex projects. This discussion explores the advanced integration of these technologies, focusing on their application in identifying dam and reservoir sites, with a particular emphasis on Manipur, India.

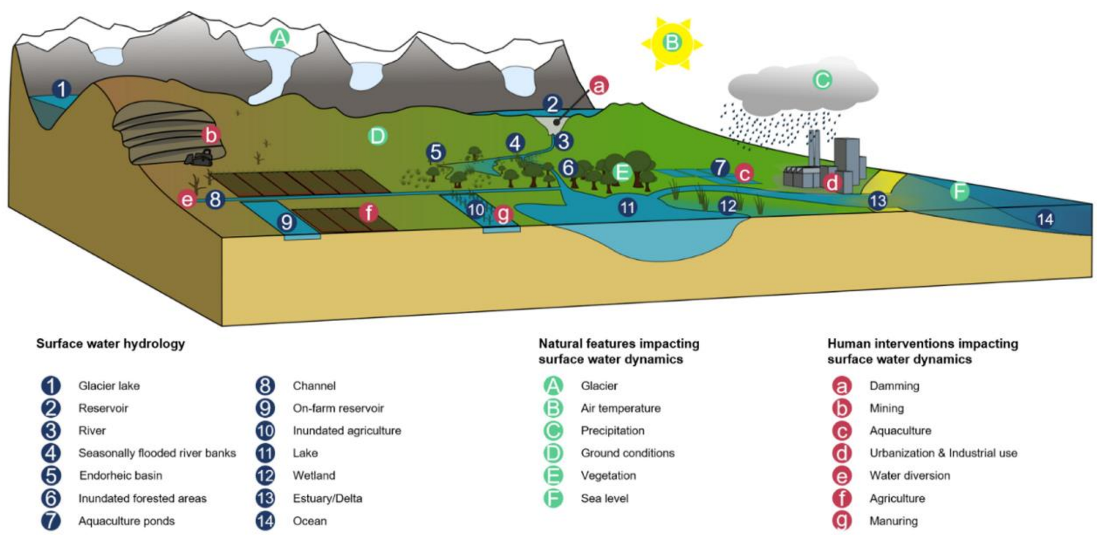

Fig: Model overview of surface water hydrology including natural and anthropological influences that affect surface water dynamics.

Manipur, a state in northeastern India, presents a unique set of geographical and hydrological challenges that influence the planning and development of water infrastructure. The state's terrain is characterized by its rugged hills, valleys, and river systems, which contribute to both its beauty and complexity. The Barak River system and its tributaries play a crucial role in the state's hydrology, and the diverse topography necessitates a nuanced approach to site selection for dams and reservoirs. Here, remote sensing and GIS offer powerful tools to navigate these challenges and optimize site selection processes.

Remote sensing technology involves the use of satellite sensors to capture data about the Earth's surface without physical contact. This data includes information on land cover, vegetation, water bodies, and topography. For identifying dam and reservoir sites, remote sensing provides high-resolution imagery that can be analyzed to assess various factors, such as land use patterns and terrain characteristics. By capturing a broad spectrum of electromagnetic radiation reflected or emitted from the Earth, remote sensing enables detailed analysis of potential sites, offering insights that are crucial for effective decision-making.

GIS, on the other hand, is a robust tool for spatial data analysis and management. It allows for the integration of diverse data layers, such as topographic maps, land use data, and hydrological information, into a cohesive framework. This integration facilitates the analysis of spatial relationships and helps in identifying suitable locations for infrastructure projects. GIS can perform complex spatial modeling, including watershed analysis and flood risk assessment, which are essential for evaluating the feasibility and impact of dam and reservoir sites.

The process of integrating remote sensing and GIS involves several key methodologies and techniques. Initially, remote sensing data is acquired from satellite platforms like Landsat or Sentinel and undergoes preprocessing to correct for atmospheric and geometric distortions. This ensures the data's accuracy and reliability. Subsequently, land cover classification is performed using remote sensing imagery to categorize different types of land use, such as forests, agricultural areas, and water bodies. This classification helps identify regions with minimal land use conflicts or environmental sensitivity, which are ideal for dam construction.

Topographic analysis is another critical component, where elevation data from digital elevation models (DEMs) is used to examine the terrain's suitability. This analysis helps assess factors such as slope stability and floodplain areas, providing insights into the physical characteristics of potential dam sites. Hydrological modeling through GIS involves analyzing watershed characteristics, river networks, and rainfall data to evaluate water availability and storage capacity. This modeling is vital for determining the feasibility of reservoir sites and understanding their impact on local hydrology.

Environmental impact assessment is an integral part of the site selection process. The integration of remote sensing and GIS allows for a comprehensive evaluation of potential environmental impacts, including changes in land use, vegetation cover, and effects on wildlife habitats. Suitability analysis using spatial techniques in GIS helps weigh multiple factors, such as topography, hydrology, and land use, to identify optimal locations for dam and reservoir construction. Suitability maps are generated to highlight areas with the most favorable conditions, facilitating informed decision-making.

In the context of Manipur, the application of remote sensing and GIS has provided significant insights into the identification of potential dam and reservoir sites. The process begins with the acquisition of remote sensing data from satellites like Landsat 8 and Sentinel-2, offering high-resolution imagery of Manipur's diverse terrain. This data is processed using GIS software to create detailed maps and conduct spatial analyses. The topographic and hydrological assessments are performed using digital elevation models and GIS-based hydrological modeling, revealing areas with favorable slope conditions and potential flood risks.

Rainfall is currently the main cause of the severe sedimentation that affects reservoirs. According to Jain et al. (2002), road building, urbanization, deforestation, and cultivation on steep slopes are the other sources of sediment that enter the reservoirs. However, the accumulation of sediment in the reservoirs shortens their useful lives and lowers their capacity to store water. However, water resource planners usually have a challenging task when calculating the amount of silt deposited in the reservoir (Narasayya et al. 2013; Jeyakanthan & Sanjeevi 2013). The most common methods for estimating the amount of sediment deposited are indirect measurements carried out after learning about the inflow-outflow records of a reservoir and direct measurements made using hydrographic surveys (Jain et al. 2002).

Long-term, broad spectrum data collection is the hallmark of remote sensing technology, which often yields timely, repeated, and synoptic information about a reservoir's sedimentation properties. The satellite photos can be used to precisely determine the reservoir's water spread area at a given height.

The decreasing of the water spread area at a given elevation indicates the deposition of sediment. Calculating the amount of storage lost as a result of sedimentation is made easier by integrating this over a range of elevations using multi-date satellite data.

In order to predict the effects of various management practices on water quality, sediment yield, and pollution loading in watersheds, the Soil and Water Assessment Tool (SWAT) was developed (Chen & Adams 2006; Arnold et al. 1998); SWAT was applied with recession methods and a stream flow filter for regional estimation of base flow and groundwater recharge in the upper Mississippi River basin. The SWAT2000 model was used for the Canyonville Reservoir, a water supply reservoir in New York City (Tolson & Shoemaker 2004). Complex models do not always perform better than simpler ones because of the uncertainty around the input parameters (Majid et al. 2013). Kinnell (2010) discovered, however, that a greater extent to the model formula is connected to the issue of USLE and RUSLE over-predicting observed erosion losses, when erosion losses are modest. They discovered that identifying and analyzing the effects of different phosphorus management strategies quantitatively helped to reduce the loading on the reservoir.

In order to replicate every relevant process influencing the amount of water, sediment, and nutrient loads in the Thur watershed in Switzerland, Abbaspour et al. (2007) employed the SWAT model. Excellent discharge and sediment output results were obtained from their study. The SWAT model was employed by Rosenthal et al. (1995) to evaluate the water supply of the lower Colorado river basin in Texas. According to the review, SWAT can be used on a sizable ungauged basin and can reasonably accurately simulate hydrological processes. Consequently, SWAT 2000 with ARCGIS 9.3 is currently utilized to verify the model's ability to determine the reservoir's sediment production.

Review of Literature

The literature review provides an overview of previous research on the application of RS and GIS in water resource management. Studies have demonstrated the effectiveness of these technologies in improving the precision of hydrological and topographical data. The paper reviews key studies that have explored GIS-based decision-making models and RS applications in various parts of India and globally. Special emphasis is placed on the unique topographical and ecological challenges in Manipur and how other researchers have approached similar issues in different regions. The role of multi-criteria decision analysis (MCDA) in integrating spatial data layers for site selection is also highlighted.

In order to estimate runoff, erosion, and sediment output, Dabney et al. (2012) examined the Revised Universal Soil Loss Equation, Version 2, and compared it with data gathered from a watershed close to Treynor, Iowa, between 1995 and 2002. Additionally, it was discovered that the rate of soil erosion on four representative profiles within the watershed is higher than the average rate of sheet and rill erosion as well as more than the observed sediment delivery at the watershed outlet. Overall, it was found that the observed precipitation patterns were generally consistent with the average values in the official NRCS RUSLE2 database. According to the study, since the sample profiles represent the crucial areas of a field where conservation planning efforts are often concentrated, high rates of soil erosion were predicted. The authors come to the conclusion that erosion can be managed if conservation measures are implemented on the crucial slopes.

Kartickumar et al. (2014) employed the widely used Revised Universal Soil Loss Equation (RUSLE) erosion model to investigate the erosion risk of Kothagiri Taluk. They investigated the spatial distribution of the probable annual soil loss in the area by integrating the RUSLE with the Geographic Information System (GIS) environment. In order to ascertain their influence on average annual soil loss, GIS data layers in the watershed, such as rainfall erosivity (R), soil erodability (K), slope length and steepness (LS), cover management (C), and conservation practice (P) parameters, were computed. The rainfall erosive factor was developed using the modified Fournier index; the topographic factor was developed using the Digital Elevation Model (DEM); the K factor was found using data from the soil and geology maps; the land use and land cover factors were obtained from IRS LISS III photos. A maximum soil loss of 27.11 t h-1 y-1 was displayed on the yearly soil erosion map that was created, and this value is related to built-up regions, forest plantations, and crop land on steep side slopes (with high LS). Based on the estimated quantity of soil erosion, the resulting soil susceptibility map from the RUSLE model was divided into five groups, ranging from very low to very high risk (< 3 to > 20 t h-1 y-1).

In order to estimate streamflow in a tropical wet basin located in the Cerrado ecosystem in southeast Brazil, Silva et al. (2018) conducted investigations using the Soil and Water Assessment Tool (SWAT). The Upper São Francisco River basin was the study's location because it needs to manage its water resources effectively during times of drought and high flow. The SWAT model was verified for the years 1999–2007 and calibrated for the years 1978–1998, respectively. Four indices—the coefficient of determination (R2), Nash–Sutcliffe efficiency (NS), p-factor (the percentage of data surrounded by the 95% prediction uncertainty, or 95PPU), and r-factor (the ratio of the average thickness of the 95PPU band to the standard deviation of the corresponding measured variable)—were used to evaluate the calibration and uncertainty of the model. The average monthly streamflow from three gauges—Ponte da Taquara, Pari, and Porto das Andorinhas—was employed in this study. The findings showed that during the calibration, the NS values were 0.68, 0.79, and 0.73, while the R2 values were 0.73, 0.80, and 0.76. Additionally, the validation revealed an adequate performance with NS = 0.61, 0.64, and 0.58 and R2 = 0.80, 0.76, and 0.60. This study shows that the SWAT model is a useful tool for evaluating streamflow and basin management in Brazil's basins.

In order to improve the ecohydrologic process and land management practices representation in the VFS area, Cibin et al. (2018) conducted studies to improve the physical representation of vegetative filter strips in the Soil and Water Assessment Tool (SWAT) model. Water, sediment, and nutrients can be routed from the source region through the VFS area with the help of the suggested framework, which also makes the penetrated water and nutrients available for uptake by filter crops. The SWAT model is improved by utilizing Matlab scripts to alter input files and by modifying SWAT subroutines to allow routing. Three paired watershed experiments in Central Iowa, one with and one without edge of the field VFS, are used to assess the model improvements. With VFS, the better model predicted reductions of 46% runoff, 91% sediment, 83% total phosphorus, and 54% nitrate; these projections nearly matched the observed reductions in VFS. The enhanced model successfully captured crop yields from source and VFS areas and was able to depict elevated infiltration, soil moisture, and denitrification in the VFS area. Overall, the findings point to a better physical depiction of VFS in the SWAT model.

According to studies done by Ijam & Al-Mahamid (2012) on reservoir sedimentation in the Mujib dam, reservoir sedimentation is a serious issue that dams face and results in a decrease in active water storage, which is the primary reason dams are built. The Arc-View Soil and Water Assessment Tool (AVSWAT) model was used to simulate the dam's catchment area. Weather and precipitation data were used as input for this modeling study. The authors determined the amount of water and sediment inflow to the reservoir, excluding areas with high soil erosion, as well as the sediment yield and delivery ratio. They also recommended actions to lower the reservoir's sediment production. According to the study, the Mujib dam reservoir experiences an average of 300x103 m3/year of sedimentation, which poses a serious risk to the dam's ability to function. The authors come to the conclusion that conservation techniques including planting specific types of trees, terracing in hilly areas, and land contouring could lessen soil erosion.

Research Methodologies

This section outlines the methodology used to collect and analyze data. The research incorporates satellite data from sources like Landsat and Sentinel, digital elevation models (DEM) to understand the topographical features, and GIS software to process spatial data. The paper explains the multi-criteria decision analysis (MCDA) technique, which considers factors like slope stability, water availability, proximity to major rivers, soil type, land use, and environmental impact. Additionally, ground truthing through field visits was conducted to validate the identified sites. This methodology ensures a comprehensive approach to identifying dam and reservoir sites in ecologically sensitive regions like Manipur.

Data Preparation for SWAT

The data-driven SWAT model needs a variety of data types, including topography, land use, soil, and climate. As stated below, a variety of sources were used for data collecting, and several procedures were used. For the purpose of defining the Hydrologic Response Units (HRUs) for each of the sub watersheds in the SWAT model, soil types and land use classes were superimposed. The model can represent variations in evapotranspiration and other hydrologic variables for various land covers, crops, and soils by segmenting the watershed into regions with distinct land use and soil combinations.Each HRU's projected runoff values are estimated independently, and the watershed's overall runoff is then determined. By going through this process, forecasts will be more accurate and the physical description of the water balance will be much better. Figure 4.3 displays the reclassified land use map of the Khoupum watershed for the year 2012 (Source: Global land cover facility), which was generated from MODIS satellite images. Figure 3.5 shows the Khoupum slope map. Then a barrier was placed on top of them. The FAO digital soil database was used to get and reclassify the soil map for the year 2012 (Source: International Soil Reference and Information Centre (ISRIC) of Food and Agriculture Organization (FAO/UNESCO)). The resulting soil map is displayed in Figure 3.4. The analysis of the drainage patterns of the land surface terrain is done through watershed delineation, which is mostly dependent on DEM.

Results and Interpretation

The results highlight several areas within Manipur that are suitable for dam construction based on slope stability, hydrological flow patterns, and minimal environmental impact. The study provides maps and models that show the potential dam sites, each ranked according to the environmental and socio-economic criteria. Hydrological analysis demonstrated regions with optimal water retention potential, while topographical analysis identified areas with lower risks of landslides or soil erosion. The results are interpreted in the context of Manipur's specific needs for flood control, irrigation, and water storage.

For calibration and validation, the hydrological observation station's outflow was measured. The results of the calibration and validation processes, which were performed using flows and sedimentation data from 2001 to 2007 and 2008 to 2010, respectively, are displayed in Figures. R2 for calibration and validation was 0.72 and 0.87, respectively, respectively, indicating that the simulated and observed values agreed. These findings show that, with the provided set of parameters, the SWAT model reasonably simulates the basin response at the Khoupum catchment region. In the calibration that is displayed in Figure, the model somewhat overpredicted the flow on the ascending leg and slightly underestimated the flow on the regressing limb. The Curve Number (CN) method that was used to predict the surface runoff is most likely to blame for the minor over and under prediction of the flows, however there could be other explanations as well. For the same antecedent moisture situation, the CN technique assumed that cumulative rainfall and cumulative runoff had a distinct relationship. The amount of moisture held in the watershed determines how the Khoupum reservoir's catchment region behaves.

Discussion and Conclusion

The discussion examines the implications of the findings, emphasizing the importance of using RS and GIS for large-scale infrastructure planning in ecologically sensitive regions. It outlines the potential benefits of these methodologies for long-term water resource management in Manipur, including better flood control and enhanced agricultural productivity. The conclusion suggests that the study's methodology can be replicated in other parts of India with similar environmental and topographical conditions, and recommends future research to include the potential impacts of climate change on dam site suitability.

There have been a few prior initiatives to mitigate the deforestation caused by jhum activities. Nevertheless, they were not adequately organized and carried out. If a farmer were solely dependent on the crop produced by jhum farming, he would not give it up unless presented with a comparable alternative source of income. In order to protect the environment by increasing the amount of forest cover and to give rural residents better and alternative means of subsistence, new land use policies can be created in accordance with the many LULC categories that now exist. NLUP can work in a variety of fields, including agriculture, small-scale businesses, horticulture, sericulture, wildlife, fisheries, soil and water conservation, and animal husbandry and veterinary care. The NLUP can address land management, the resuscitation of dead or shallow streams, the resurgence of forests, the continuous cultivation of broomstick, sugandhmantri, pineapple, and tea, well-planned plantations of cashew, rubber, and litchi, the creation of piggeries, dairy, and chicken husbandry.

On the edges of forests, there were observed issues with forest fires, fuelwood extraction, timber extraction (including pole size), bamboo shoots collection, broom stick collection, and medicinal plant collection. These issues need to be investigated practically and participation is crucial for effective conservation. The outcomes of an examination of forest fragmentation may be crucial in developing conservation policy for native vegetation. An enhanced land use pattern could be implemented using an appropriate agro-forestry model.

By integrating remote sensing data with GIS, the analysis in Manipur has identified several promising sites for dam and reservoir construction. These sites are evaluated based on their hydrological potential, environmental impact, and compatibility with existing land use patterns. The advanced integration of these technologies has enabled a more precise and informed approach to site selection, addressing the unique challenges presented by Manipur's topography and hydrology.

Overall, the integration of remote sensing and GIS represents a sophisticated approach to identifying and managing dam and reservoir sites. By combining satellite imagery with spatial data analysis, these technologies provide valuable insights that enhance decision-making processes. In regions like

Manipur, where geographical and hydrological conditions present significant challenges, the use of remote sensing and GIS offers a comprehensive solution for optimizing water resources management and supporting sustainable development.

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