Developing a sustainable framework for water resources management: GIS-based case study of Central India watershed

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Abstract. Water and land are essential resources for human survival and are critical for sustainable development. These fundamental natural resources play a vital role in environmental preservation, agricultural productivity, environmental stewardship, industrial growth, electricity generation, and the rejuvenation of both land and atmosphere. This study primarily focuses on the sustainable protection and utilization of these natural resources. Due to the increasing demand for food and the shift of farmland to urban and industrial uses, agriculture has been forced to expand into marginal lands and intensively cultivate existing fields. Such intensive practices, particularly on unstable soils, exacerbate soil loss due to water erosion. The study area chosen for the development of the action plan is the Khindsy watershed in the Ramtek taluka of Nagpur district, Maharashtra. Using Survey of India (SOI) topographic sheets and remote sensing data, maps depicting drainage systems, water bodies, contours, land use, and soil types were created. The main objective of this research is to develop a sustainable action plan for identifying potential locations for water recharging facilities to conserve surface runoff. A geographic information system (GIS) was employed to analyze land use factors such as slope steepness and upland drainage areas, integrating sustainability considerations.

1 Introduction

Population, the environment, and resources are the three main issues confronting the world today; nevertheless, as the social economy expands and the population rises swiftly, water resources have become one of the key issues [1]. Human existence, social and economic growth depend on water supplies, which are also a crucial natural resource, a vital economic asset, and a guarantee for sustainable development [2]. As life on the earth depends on the land, water and air for survival, conservation and maintenance of our natural resources should

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be given importance. Unintentional, careless plundering and destructive exploitation of natural resources cause the soil to deteriorate, reduce the availability of water supplies, and eliminate vegetation. Modern civilization had placed heavy demand on land and water due to increased population, urbanization and modernized agriculture and industrial development. The goal of managing water resources is to lessen the negative effects of excessive runoff or a lack of water on a watershed basis. The country's accessible land resources are under pressure from mounting biotic stresses and rising human needs. As a result, one must be aware of the current land use and cover, but also to keep an eye on the changing land use that results from the rising demands brought on by the expanding population. The ecological system and human health are both gravely endangered at the same time. As a result of the onset of water shortages around the world in the 20th century, the struggle for control over water resources started. It will probably lead to enmity between many nations and races in the following century.

There is little doubt that understanding the pertinent physical sciences and technologies is necessary for managing water resources. But the myriad organizational, societal, or political issues that planners and administrators of water resources must address are at least as crucial, if not more so. Certain hydrologic realities must be taken into account when human operations involving rivers, and their floodplains are planned. One of these truths is the fact that aquifer storage volumes and surface water flows are spatially and temporally variable. They also have a limit. There are restrictions on how much water may be taken out of them. Opportunities and issues evolve with time. In order to satisfy shifting demands, expectations, and goals, planning processes alter in response to novel ideas on how to arrange and administer more successfully.

The traditional ground-based techniques for mapping land usage take a lot of time, require a lot of labour, and are not used very often. With time, the maps created in this way become outdated, especially in environments that are dynamic or change quickly. Remote sensing technology has enormous utility in creating landuse maps, landcover maps and helps in periodically checking on changes. One of the main tenets of water management is the efficient distribution of available water resources. Also lack of water at important critical stages of crops and for drinking, results in drought in widespread areas. Thus, it is necessary to increase surface and subsurface water availability by harvesting rainwater, available in plenty during monsoon season. It incorporates scientific procedures to alter the traditional management models and makes use of structured analysis techniques in planning the quantity of water resources in water-scarce locations holistically. The prototype coordination technique was used to construct a prototype for the appropriate distribution of regional water resources and quantity in accordance with the division and coordination method of GIS system concepts.

Nowadays, maximising economic net benefits while maintaining their fair distribution is not the main focus or goal. Environmental and ecological goals should also be taken into account. The majority of management issues are multifaceted, such as how to provide more affordable, high-quality water to the basin's irrigation areas, businesses, and communities. That concern now includes how such withdrawals may change lower hydrological water quality and quantity norms, which will then affect riparian and marine ecosystems [3]. GIS is a tool for converting spatial data into information. It is defined as “The system of computer hardware and software designed to allow users to collect, manage, analyze and retrieve large volume of spatially referenced data”. GIS is made up of several interconnected and linked components that each perform a variety of tasks, including data entry, manipulation, visualisation, combining, analysis, and output generation. Data linking is one of GIS's special features.

The watershed is regarded as the most suitable planning unit for the examination and management of natural resources. The integrated watershed development method is still considered by many to be the best for maximising the use of environmental resources in a region since it helps to preserve the biological foundation of resource exploitation. Both industrialised and developing nations are currently experiencing worrisome rates of degradation of environmental systems like watersheds and natural resources. The available research asserts that the demand for wood in the world's major watersheds already surpasses the ability of forested regions to regenerate. Misuse of wetlands and forest resources within significant watersheds has resulted in a sharp decline in forest cover, which has had a negative influence on natural habitats. It has been demonstrated that in many countries, economic growth and the impact of an increasing population impair the natural resource basis of most watersheds. Decision makers throughout the world have been paying attention to the growing prevalence of global environmental deterioration for a while now, particularly the ozone layer depletion, biodiversity loss, and degradation of vast watersheds brought on by deforestation. The inability to effectively assess, map, and manage the watershed sustainably just makes the issues worse. Despite the seriousness of these trends, resource managers have not made a significant effort to look into these problems in watershed management.

1.1 Watershed and water resources management

Watershed or catchment is a geographic area which catches the water from precipitation and drains it by a river and tributaries to a common point, making it a unit for hydrological interventions for conserving soil and maximizing the utilization of resources to increase production, both by greater irrigation and in-situ moisture preservation using tank and aquifer-based water collection. Development of water resources is required to control floods, lessen droughts, and collect runoff water that would otherwise be wasted. Water conservation methods are a major component of the development of water resources. This entails building subsurface and surface storages that can impound the maximum amount of monsoon rainfall to increase the recharge from precipitation. With the use of various water conservation methods, such as the construction of masonry weirs, excavation tanks, composite dams, etc., collected run-off water can be stored. Water that has been preserved can be recycled and utilised during crucial periods of crop development.

Watersheds are significant sources of both water and bio - diversity, according to numerous studies. Watershed management involves making the best possible use of the soil, water, flora, and other natural resources to minimize soil erosion, boost food, fuel, timber production, and do so in a sustainable manner. The protection of numerous habitats that are necessary to other life-sustaining systems on the globe is improved through watershed conservation. The integrated watershed development method is still considered by many to be the best for maximising the use of natural resource in a region since it helps to preserve the biological foundation of resource extraction. In order to fully understand the role of watersheds, we must first briefly discuss their characteristics and worldwide significance. The protection of watersheds is crucial for preserving the Earth's basic hydrological resources and environmental systems, in part as they are significant in and of themselves, as well as watersheds covering a large portion of the globe in the forms of forests, which bring genetic variety.

The analysis will be useful in locating locations for building various soil and water recharging structures, like check dams, farm ponds, percolation tanks, and drainage network nala expansion and deepening. Under the water resource action plan, many soil and water conservation projects are recommended with specified sites, locations, and maps. In conjunction with the effective implementation of the suggested action plans, the study will aid in the sustainable development of the micro watershed's natural resources. The measuring and quantitative analysis of the earth's surface, shape, and size of landforms is known as morphometry. The researchers present the possibilities of remote sensing (RS) and geographic information system (GIS) procedure for the morphometric analysis of any gauged and ungauged watershed. In circumstances where there is a lack of data, particularly for developing nations like India, remote sensing & GIS have proven be the most effective techniques for morphometric analysis for the creation of regional hydrological models.

2 Literature review

Water management in India is very poor when compared even with some of the developing countries in Southeast Asia. A deep appreciation of rainfall distribution clearly brings out that the country is not poor in water resources. About 74% of the geographical area enjoys over 750mm rainfall and irrigation facilities, though only 48% is assured of water facilities. The country lacks efficient water conservation technology with complementary technical inputs. Water’s role is important because without water the plants cannot be grown on the available lands. According to the literature review, to avoid wasting precipitation from the watershed, water harvest should be prioritised. Along with adding groundwater recharge during the Rabi season, this will also increase irrigation. Farm pond construction and other soil preservation techniques should be advocated among farmers. A few studies have made an effort to analyse and understand the management aspects of collective action, either theoretically or empirically, even though the majority of previous studies have only made a cursory statement that people's participation is essential for sustainable watershed development [3]

Soil types, land cover, and terrain are typically the three main watershed elements that control hydrologic variation in the form of surface runoff and erosion. India's problems are primarily caused by the misuse of its natural resources, namely its land, water, and forests, not by industrialization. Watershed processes vary greatly throughout both time and space. Spatially explicit hydrologic models might be helpful tools for analysing these relationships [4]. More and more studies are preparing geographical data for hydrologic model input using GIS. Hydrology is not a precise science, therefore using hydrologic information effectively calls for a wealth of experience and good judgement. It is common practise to enhance groundwater by using appropriate artificial recharge methods [4-5]. The Central Groundwater Board has conducted studies on percolation tanks and how they affect groundwater. The Integrated Mission for Sustainable Development (IMSD) laid guidelines for water harvesting systems, such as farm ponds, small irrigation tanks, check dams, bundhis, nala bundhis, & groundwater recharge structures, in 1995 [6].

Runoff causes a significant amount of rainwater to be lost, which is a problem made worse by the absence of rainwater harvesting techniques. Groundwater conservation has not received much attention in the past when it comes to locating areas where artificial recharge techniques can be used. In order to create sustainable urban services, water management systems are becoming more crucial. After considering the smart city priorities, digital information for resource management was provided. This primary system, which includes stream modelling, historical information utility and smart supply data, is used to construct the model using open-source software. Las Palmas de Gran Canaria city has also benefited from the creation of these four innovative instruments [7].

GIS as well as an Analytical Hierarch Process-Multi Criteria Decision Analysis used to conduct study on site identification for the disposal of city solid waste of Coimbatore area. Various thematic layers were prepared as the primary data, and multi-criteria analysis was carried out assigning weights to the criteria and sub-criteria. Four acceptable sites were chosen from 17 possible zones in the Coimbatore district that were identified by overlay analysis in a GIS environment, and they were further refined through field research and visual interpretation of satellite images [8]. In Patan 6 District of North Gujarat, India, a study conducted on the use of GIS to assess the suitability of agricultural land for wheat growing.

Various watershed thematic maps were developed using GIS for this study [9]. According to the Food and Agriculture Organization (FAO), the study's findings were divided into four categories: extremely acceptable, moderately suitable, marginally compatible, and unsuitable. These studies are intended to aid decision-makers, farmers, and planners of agricultural growth. The study sought to maximise the use of the few and existing land resources. GIS and remote sensing methods are frequently utilised in literature to explore Earth's resources at different levels. According to the literature, a watershed is a geo-hydrological unit that is drained at one common location by a network of streams. The sensible use of land and water resources for maximum output with the least amount of risk to natural resources is known as watershed management. It is possible to tie the RS & GIS technique to morphometric parameters and use it to efficiently examine the hydrological component of each watershed. Aerial view; basin area and perimeter are important watershed characteristics. The size of a storm hydrograph, the height of a peak, and mean runoff are all directly influenced by basin area. The closeness of stream and channel spacing is shown by the drainage density of the topography. A much rougher drainage texture is seen from the texture ratio. A low value for the form factor indicates longer-lasting peak flows.

This is why many researchers consider the widespread use of GIS and remote sensing techniques in watershed management to be a significant step towards sustainability and resource preservation. There is an urgent need for an integrated GIS and remote sensing applications to provide baseline information about changes in the local ecology of the watershed and to enable future and ongoing monitoring of the delta ecosystem [10]. GIS–AHP techniques are increasingly applied in disaster management, with analyzing flood susceptibility in Nashik [11].

A comprehensive review of GIS applications in various aspects of water resource management, such as flood prediction, drought risk mapping, water quality monitoring, and irrigation planning. The paper emphasized the importance of combining GIS with remote sensing and AI models to increase the accuracy of water-related predictions. It discusses case studies from India, Africa, and Southeast Asia, illustrating the various applications of geospatial tools. The authors advocate standardized, open-access geospatial datasets and highlight the use of GIS in participatory planning. They also proposed a GIS-based monitoring system for policy makers, recommending real-time dashboards for better water governance [12-13].

The application of deep learning models, particularly CNN and LSTM, for predicting groundwater levels using satellite data integrated into GIS frameworks. The study uses parameters like rainfall, land use/land cover, and vegetation indices to train models for places in southern India. These models outperform traditional statistical methods in predicting spatio-temporal variations in groundwater levels. GIS is used to map areas of over-extraction and aquifer recharge, supporting early warning systems and irrigation planning. The study recommends combining these models into policy dashboards for real-time monitoring. The findings highlight the scalability and adaptability of AI-GIS integration in water-stressed regions [13].

3 Study area

A portion of Nagpur district's Ramtek taluka is covered by the Khindsy basin. The Khindsy's catchment is of 183 km^2 area and Fan shaped basin. The Wainganga River is part of Godavari subbasin, including Khindsy basin as a subbasin. It is determined that the basin is 21.17 km long. Located between 21°15'00 to 21°30'00" North latitude and 79°15'00 to 79°30'00" East longitude, this area is covered by top sheets 55 O/3, 55 O/2, 55 O/6, and 55 O/7. In figure 1, the location map is displayed. The elevation generally varies from 320 to 470 m above mean sea level. For the left half of the basin, the overall slope is from North-West to South-East, and for the right half of the basin, from North-East to South-West.

4 Methodology

4.1 Spatial database of the study area

4.1.1 Watershed Boundary

The topo sheets and reference map from the Survey of India (SOI) were utilised to prepare the watershed boundary map through the digitization process, as illustrated in figure 2.

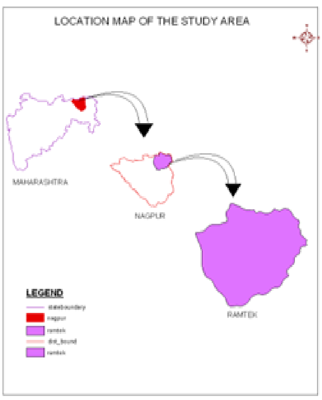

Fig. 1. Location map

Fig. 2. Watershed Boundary

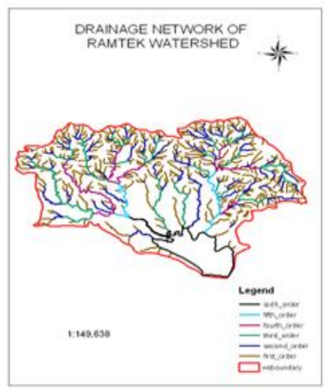

Fig. 3. Drainage network

4.1.2 Drainage Network

The drainage network map was prepared using the SOI topo sheet, as shown in figure 3. The catchment topography is affected by the combined influences of climate and geology, resulting in an erosion pattern that is characterised by a web of channels or streams. Dendrite with fine texture is visible in the drainage network. The Strahler's stream ordering approach was used to order the drainage. Streams in the study region range from the first to the sixth order.

4.1.3 Contour Map

Figure 4 illustrates how the contour map was produced using an SOI topo sheet at a scale of 1:50,000. TIN and the subsequent Digital Elevation Model (DEM) were created using this map. The slope map was created using these maps.

4.1.4 Water bodies

Figure 5 displays the different minor and major water bodies that were recognised and digitised from the drainage network map, contour map, and SOI topo sheet. There are very few water bodies near Khindsy lake's perimeter. This shows that the land slopes are steeper outside the catchments than they are at the outlet.

Fig. 4. Contour map

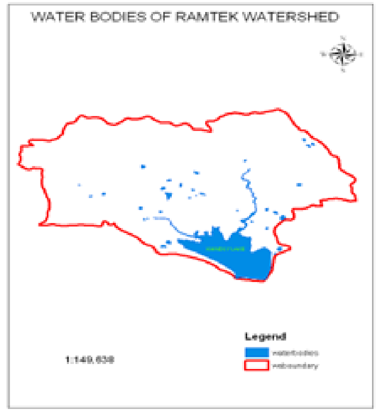

Fig. 5. Water bodies

4.1.5 Settlements and Road Network Map

There are 28 communities in the study area. As seen in figure 6, these village locations were digitised from an SOI topo sheet at a scale of 1: 50,000.

4.1.6 Soil database

NBBS, Nagpur, provided the soil map. Based on the characteristics of the soil, soils were divided into six classes. In the catchment, silty loam and clay loam make up about 35% of the soil textural classifications. figure 7 displays a map of current land use.

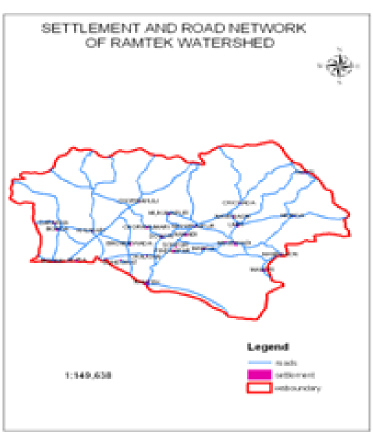

Fig. 6. Settlements and Road Network Map

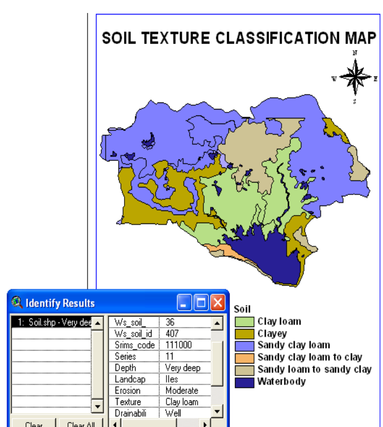

Fig. 7. Soil map

5 Methodology for Action Plan Preparation for Water Resources Management

Water scarcity is a major issue for both urban and rural communities around the world. For home, industrial, and construction use, more and more water is needed. The rate of withdrawal greatly outpaces the rate of water table recharge. Water is referred to as Thirtha and is revered as divine in India. However, the way we handle our water sources is not sacred. Clean, potable water is now only available in trace amounts due to pollution and overuse. The thorough process is displayed in figure 8.

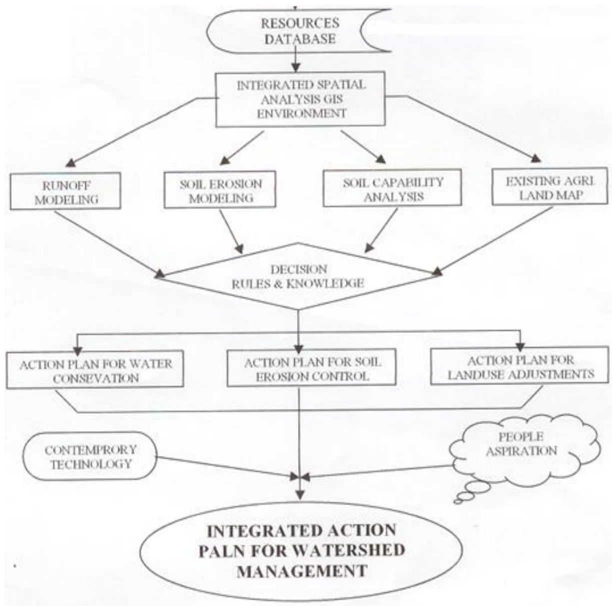

Fig. 8. Methodology

Harvesting rainwater is the process of capturing as well as using runoff from an area with high runoff into a region with low runoff. The water was either held in a water storage facility on the farm for later use in productive activities like irrigation for aquaculture, livestock watering, or residential usage after being collected and sprayed to the agricultural area and stored in the root zone for immediate use by the crop. The water collected can also be utilised to increase groundwater recharge by recharging it and storing it in the aquifer. Water harvesting is done primarily to prevent soil erosion and to conserve rainwater that would otherwise be lost to runoff. For efficacy and better management, water harvesting systems must be implemented on a watershed basis. The structures for harvesting increase soil moisture. When water is abundant (during the monsoon), the structures not only aid in water conservation on the upstream side, but they also improve the soil profile's ability to hold water.

6 Results and Discussions

6.1 Criteria for Selection of Suitable locations for Water Harvesting Structures

To locate the appropriate sites for water harvesting structures Pebble-bed technique, Recharge wells, percolation pits, Furrows and ridges, check dams, structures for gully control or stone walls and contour bunding), formulation of a sound plan would be done by considering the following point:

a) Status of water table and water table fluctuation.

b) Geological sounding to locate water-bearing zones.
c) Development of a groundwater management plan

6.2 Procedure

6.2.1 Selection of theme

After studying themes like soil, slope, and land use/cover, appropriate themes are then chosen. In a GIS context, the chosen topics are merged, and ground verification is carried out.

6.2.2 Drainage condition

Lower order drains are not chosen because they cannot provide the necessary water volume. By not choosing them, higher order drainage's velocity and amount of water are also avoided.

6.2.3 Slope of land and Soil type

The water harvesting structures are not located along the steep slopes. They are generally located along low and medium slopes. The construction of water harvesting structures is avoided in the sandy soils. Slope is a key factor in predicting land capability, erodibility, stability and irrigability.

6.2.4 Roads and Railway Networks

The water harvesting structures should not intercept the network of roadways and railways. They should not obstruct the purpose served by the roads and railways.

6.2.5 Selection of suitable zones

Considering the above factors, the catchment is categorized into three zones, which are- most suitable, more suitable and suitable. Statistics of suitable zone maps were calculated. Determine the accurate catchment area of the watershed at that place using the topo sheet or village map.

7 Conclusion

The proposed action plan for water resources management by way of constructing water harvesting structures after GIS analysis is shown in figure 9. Remote sensing and GIS technologies have proven to be effective tools in characterizing watersheds, building comprehensive databases, and facilitating integrated analysis of information. This supports sustainable water resource conservation efforts at the watershed level. The findings from this study underscore the significant value of GIS in planning regions for optimal, sustainable resource use. They demonstrate that integrating GIS and remote sensing is instrumental in developing watershed management action plans, particularly for identifying sites for water recharging structures, thereby promoting long-term sustainability and resource resilience.

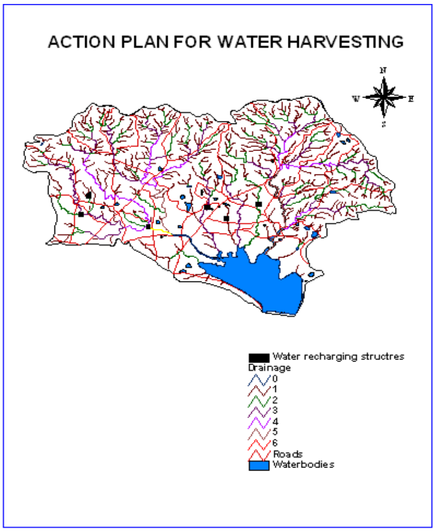

Fig. 9. Proposed Action Plan for Water Harvesting Structures

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