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Final Report

RUNOFF AND WATER STORAGE CAPACITY ESTIMATION FOR DECIDING RAINWATER HARVESTING STRATEGIES

National Institute of Hydrology
Deptt. of WR, RD & GR,
Ministry of Jal Shakti, Govt. of India
Jal Vigyan Bhawan, Roorkee-247 667 (Uttarakhand),
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PREFACE

India’s rainfall regime, shaped by the southwest and northeast monsoons, is characterized by temporal concentration, posing significant challenges for meeting water demands during non-monsoon periods. Rainwater harvesting (RWH) has therefore become a vital strategy for sustainable water resource management, enabling the capture and storage of rainfall for subsequent use. Estimating surface runoff, water availability, and water storage capacity within catchments is central to hydrological modeling, flood risk assessment, and the effective design of RWH structures.

In the present study, a Google Earth Engine (GEE)-based program was developed for application to any region, enabling detailed analysis of water spread areas and corresponding storage at rainwater harvesting (RWH) structures using multiple Digital Elevation Models (DEMs) of varying spatial resolutions. The program allows analysis by simply providing either a probable outlet location or a catchment boundary. A demonstration was carried out in the Henval catchment, Tehri-Garhwal District, Uttarakhand, as a case study. Surface runoff, water availability, water spread area, and water storage were estimated across different resolutions, revealing the impact of data resolution on hydrological outputs. The findings demonstrate that higher-resolution datasets provide more accurate estimates of water availability, storage capacity, and water spread area, while coarser-resolution data introduce greater uncertainty and volumetric errors.

By systematically quantifying these variations, the study underscores the importance of fine-resolution data for reliable hydrological modeling and sustainable RWH design. The outcomes of this work are expected to benefit engineers, the scientific community, and stakeholders by guiding the selection of appropriate topographic inputs, optimizing design and cost, identifying suitable locations for RWH structures, and enhancing decision-making processes.

Y.R.S. Rao
Director

LIST OF ABBREVIATIONS

ALOS PALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
CartoSat	Cartographic Satellite
CGIAR	Consultative Group on International Agricultural Research
CGWB	Central Ground Water Board
CN	Curve Number
Copernicus GLO DEM	Copernicus Global DEM
DEM	Digital Elevation Model
GEE	Google Earth Engine
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
HRU	Hydrologic Response Unit
HSC	Storage Capacity Curve
India-WRIS	India Water Resources Information System
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
LiDAR	Light Detection and Ranging
LULC	Land Use/Land Covers
MCT	Mass Curve Technique
MERIT DEM	Multi-Error-Removed Improved-Terrain DEM
NASA	National Aeronautics and Space Administration
RWH	Rainwater Harvesting
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
UAV	Unmanned Aerial Vehicle
USDA-ARS	United States Department of Agriculture Research Service

EXECUTIVE SUMMARY

The implementation of rainwater harvesting (RWH) strategies is essential for efficiently capturing and storing rainfall for use during dry seasons. Estimating water availability, water spread area, and the storage capacity of structures at catchment outlets is a critical component of hydrological modeling and sustainable water resource management. Open-source topographic data provide valuable insights into these parameters, supporting decisions on the optimal size, cost-effective selection, and number of RWH structures. Such data are particularly useful in ungauged catchments or where field surveys are limited by financial constraints or data unavailability, and they also aid in assessing infrastructural flood risks. Therefore, the objective of the present study is to assess water availability, water spread area, and storage capacity at catchment outlets for RWH structures using multiple open-source topographic datasets, while considering structure heights ranging from 1 m to 15 m.

A Google Earth Engine (GEE)-based program was developed for application to any area, enabling detailed analysis of water spread area and corresponding storage in RWH structures using multiple Digital Elevation Models (DEMs) [SRTM (90 m), Cop30, SRTM30, ALOS30, MERIT, CartoSAT (30 m), and ALOS PALSAR (12.5 m)] and structure heights, simply by providing either a probable outlet location or a catchment boundary. A demonstration was carried out in the Henval catchment, Tehri-Garhwal District, Uttarakhand, as a case study. The topographic datasets for the Henval catchment were obtained from multiple sources.

Initially, morphometric analysis of the Henval catchment was conducted using multiple DEMs at varying resolutions. Key parameters (stream length, stream order, and number of streams) were analyzed using SRTM (90 m), ASTER (30 m), CartoSAT (30 m), and ALOS PALSAR (12.5 m) DEMs. Using these datasets, surface runoff and water availability were estimated across multiple DEM resolutions with the SWAT model, accounting for the catchment's ungauged nature. Finally, the water spread area was estimated in upstream regions of potential storage structures (i.e., check dams), along with storage capacity, by considering different check dam heights (1 m, 2 m, 3 m, 4 m, 5 m, 10 m, and 15 m) and multiple DEM inputs [SRTM (90 m), Cop30, SRTM30, ALOS30, MERIT, CartoSAT (30 m), and ALOS PALSAR (12.5 m)].

The morphometric analysis indicates that higher DEM resolution is associated with higher stream order. It was also observed that small streams are ignored as resolution decreases. Results show variation in stream orders with changes in DEM resolution and area threshold. The study systematically quantifies the impact of DEM resolution on water availability, water spread area, and storage estimation across multiple check dam heights. SWAT model results revealed that while DEM resolution has limited impact on long-term cumulative water availability, higher-resolution datasets better capture short-term variability and peak flows, making them more suitable for flood forecasting and event-based hydrological studies. Results further show that water spread area and storage capacity increase nonlinearly with dam height, and that higher-resolution DEMs provide more reliable estimates. Coarser datasets (e.g., SRTM 90 m) remain useful for broad regional assessments but introduce significant uncertainty at larger dam heights. Comparative analyses highlight the need for a multi-DEM approach to quantify uncertainty and strengthen decision-making.

The study demonstrates that open-source topographic data can significantly reduce costs and improve efficiency in RWH planning, while also enhancing flood risk assessment and ensuring safety in upstream areas of RWH structures. However, variability among DEMs underscores the importance of careful dataset selection. The findings provide actionable insights for policymakers, planners, and water resource managers, emphasizing the role of fine-resolution DEMs in designing resilient and sustainable RWH strategies for India’s diverse catchments.

Key Words: *DEMs, Resolutions, Storage Capacity, Surface Runoff, Water availability*

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1. INTRODUCTION

1.1 Background

India's rainfall regime is shaped by its unique geographical and climatic diversity, resulting in a highly variable precipitation pattern across regions and seasons. The country's monsoon climate, dominated by the southwest and northeast monsoons, delivers rainfall in a temporally concentrated manner. This seasonal concentration creates a pressing challenge: meeting water demands during the prolonged non-monsoon periods. To address this imbalance, rainwater harvesting (RWH) is a vital strategy for capturing and storing rainfall, ensuring its availability for subsequent use.

A critical component of effective RWH planning lies in the estimation of surface runoff, water availability, and the water storage capacity of structures within a catchment. Hydrological modeling and sustainable water resource management depend on accurate assessments of these parameters. Moreover, understanding the spatial distribution of water storage capacity is essential for analyzing saturation-excess runoff and mitigating flood risks. In this context, open-source topographic and hydrological data offer significant potential. Such data can aid in estimating water storage capacity, identifying potential areas for water spread, and guiding decisions on optimal size, cost-effective selection, and the number of RWH structures. Beyond resource management, these datasets also serve as valuable tools for enhancing flood risk estimation.

Given these considerations, this study investigates the applicability of using open-source topographic data at varying resolutions to estimate runoff, water availability, and water storage capacity in catchments and RWH structures (hereafter referred as Check Dam). The findings are expected to provide insights into the practical application of RWH strategies using open-source data, highlighting potential benefits such as cost savings, efficiency, and improved decision-making, thereby contributing to more sustainable water resource planning in India.

1.2 Statement of the Problem

The implementation of RWH strategies is essential for efficiently capturing and storing rainfall for use during dry seasons. Estimating water availability, water spread area, and the storage capacity of structures at catchment outlets is a critical for sustainable water resource management. Open-source topographic data provide valuable insights into these parameters, supporting decisions on the optimal size, cost-effective selection, and number of RWH structures. Such data are particularly useful in ungauged catchments or where field surveys are limited by financial constraints or data unavailability, and they also aid in assessing infrastructural risks related to flooding. The implementation of RWH strategies is deemed necessary to efficiently capture and store rainfall for subsequent utilization. Therefore, the study aims to assess water availability, water spread area, and storage capacity at catchment outlets for check dams using multiple open-source topographic datasets, while accounting for different check dam's heights. The findings will provide insights into the applicability of RWH strategies using open-source data to identify potential benefits (e.g., optimal savings in time and cost). The study will also identify potential limitations and challenges for various stakeholders and decision-makers in selecting suitable RWH and management strategies within the catchments.

1.3 Objectives

The objective of the present study is to assess water availability, water spread area, and water storage capacity using topographic data at varying resolutions from different sources.

1.4 Scope of The Study

The scope of this study is to use open-source topographic data to estimate surface runoff, water availability, and water storage capacity in catchments, with a particular focus on Check dam at varying resolutions and at different heights. The study aims to analyze surface runoff, the spatial distribution of the water-spread area, and water storage capacity, and to explore the role of these data in flood risk estimation. The findings shall be applied to guide decisions on the optimal sizing, cost-effective selection, and number of check dams, thereby supporting stakeholders and policymakers in adopting suitable strategies for water harvesting and management. In addition, the study acknowledges potential limitations, including differences in data resolution, reliability concerns, and applicability across diverse catchments, ensuring that these challenges are critically examined. Overall, the scope extends to providing practical insights into the benefits of open-source data, including time and cost savings, while highlighting its relevance for water resource managers, planners, and decision-makers in advancing sustainable water management practices in India.

1.5 Organization of the report

This report comprises of five chapters. Chapter 1 presents an introduction section where the background, statement of the problem, objectives and scope of the study are presented. Chapter 2 deals with a brief literature review related to different resolutions of topographic datasets used in various hydrological analysis at catchment, and river basins levels in different regions of the world. Chapter 3 presents a description of the study area and data used while Chapter 4 presents the materials and methods adopted in the present study. Chapter 5 presents the results and discussions. Finally, chapter 5 presents conclusions and recommendations drawn from the study and limitations thereof.

2. LITERATURE REVIEW

The water availability, water spread area, and water storage capacity are fundamental considerations in designing effective rainwater harvesting (RWH) strategies. This study reviews the applicability of using open-source topographic data at varying resolutions for estimating water availability in the catchment. The review also examines how data resolution influences water spread area and storage estimates across different datasets and different heights of the structures. By synthesizing existing literature, the study highlights methodologies, key findings, and their implications for sustainable water resource management. The discussion is organized around the following core aspects:

i) Assessment of water availability,
ii) Estimation of water storage capacity,
iii) Accuracy evaluation of datasets,
iv) Influence of topographic data resolution, and
v) Recent techniques.

2.1 Overview

Rainwater stands out as a critical and sustainable water resource that can provide a reliable, high-quality supply, particularly in regions facing surface water scarcity. The stress on surface water resources, both in terms of quantity and quality, has become a pressing concern. Unregulated urbanization and industrial activities contribute to the pollution and depletion of surface water, making the exploration of rainwater crucial for addressing these challenges (Raimondi et al., 2023). RWH has emerged as a promising solution to address the growing water scarcity in many regions worldwide.

The collection and storage of rainwater can be implemented through various technologies and practices, including RWH systems (e.g., Zhang and Li, 2020; Lee et al., 2021). These systems capture rainwater runoff from rooftops and other surfaces, storing it for later use in domestic, agricultural, and industrial applications. By reducing reliance on surface and groundwater, RWH offers a decentralized, environmentally friendly approach to water management. The rainwater emerges as a valuable, sustainable resource that can address the challenges posed by surface water scarcity. By implementing RWH systems, communities can secure a consistent, high-quality water supply, promoting both environmental sustainability and socio-economic development.

In recent years, there has been a growing interest in RWH as a sustainable water management practice. This practice has gained attraction due to its potential to alleviate water scarcity issues and reduce reliance on traditional water sources. Research has demonstrated the potential of RWH in urban areas, where it can significantly reduce the pressure on municipal water supplies and mitigate urban flooding (Khastagir and Jayasuriya, 2010; Palla et al., 2012).

Accurate runoff estimation from catchments and the water storage capacity of RWH structures relies on reliable data on rainfall, temperature, topography, land use/land cover (LULC), soil, and streamflow. By analyzing open-source data, it is possible to obtain valuable information on rainfall patterns, LULC, soil moisture, and other factors; however, data resolution and scale are major concerns and introduce varying levels of error and uncertainty (e.g., Wang et al., 2011; Hari et al., 2018). Despite these challenges, recent advancements have shown promising results. Open-source software and freely available datasets, including those derived from satellite imagery, gridded rainfall data, and soil information, have been successfully employed to model hydrological processes at global scales (Glendenning et al., 2012). For e.g., integrating high-resolution satellite data with hydrological models has enabled the accurate prediction of runoff patterns and water availability, which is crucial for planning RWH systems in areas with complex terrain (Palmer et al., 2015).

The accurate estimation of runoff, water spread area, and storage capacity is crucial for the effective design, implementation, and operation of RWH structures, especially in areas lacking high-quality ground data. For example, topographic data, such as Digital Elevation Models (DEMs), are crucial for analyzing terrain and drainage patterns. DEMs can be sourced from various open sources, such as NASA’s Shuttle Radar Topography Mission (SRTM) data. High-resolution data (e.g., 1 km or less) provides detailed spatial information and is crucial for localized assessments. Moderate-resolution data (e.g., 5 km) might be sufficient for regional analyses. Low-resolution data (e.g., 10 km or more) may be less detailed, but can still offer useful trends, particularly for broader assessments. Higher-resolution data provides more accurate, granular information, which is essential for detailed runoff modeling, water availability assessment and storage capacity estimation and the design of RWH systems. Lower-resolution data might be adequate for preliminary assessments but could overlook localized variability. When assessing the feasibility of using open-source data for estimating runoff and water storage capacity in RWH structures, it’s crucial to identify relevant data types (Winnaar et al., 2007; Lestari et al., 2020; Ratnasari et al., 2022).

The impact of different resolutions of topographic data is necessary to identify reliable datasets, optimizing cost and optimal benefits for deciding RWH strategies and possible uncertainties involved. Therefore, this review aims to investigate the applicability of utilizing open-source data for the estimation of runoff, water spread area and the water storage capacity of RWH structures, drawing from a comprehensive analysis of existing literature and research studies. By leveraging open-source data and integrating it with advanced modeling tools, researchers can assess long-term rainfall trends and catchment area, which are essential for accurately estimating the potential water volume that can be harvested, stored and possible water spread area in the upstream areas of the RWH structures, thus enabling the development of more efficient RWH systems and possible protection and control measures for any risk of the infrastructures available in the catchment areas. This comprehensive approach will ensure accurate and reliable assessments for better and efficient water resource management in the catchment.

2.2 Water Availability Assessment

The Geographic Information System (GIS) based method is a commonly used approach for RWH analysis. It involves utilizing GIS technology to gather, organize, analyze and visualize spatial data related to RWH. This method allows for the integration of various parameters such as topography, LULC, soil types, slope and rainfall data to determine the most suitable locations for RWH structures (Sayl et al., 2020; Khudhair et al., 2020). The GIS-based approach is particularly advantageous in large-scale assessments, where spatial variability plays a critical role in determining the efficiency and effectiveness of RWH systems (Prinz et al., 2019). In addition, remote sensing technologies have been integrated into RWH studies to enhance data accuracy, particularly for mapping surface runoff and identifying potential water-harvesting zones (Chen et al., 2020). Soil and Water Assessment Tool (SWAT) models are commonly employed in RWH studies to simulate the hydrological processes within a catchment. This includes the estimation of runoff, sediment yield and water availability in order to assess the potential for RWH. By calibrating and validating the SWAT model against observed data, researchers assess its performance and use it to evaluate different scenarios and management options for RWH (Tesema and Leta, 2020). Recent advancements in SWAT modeling have enabled the integration of climate change scenarios, which are critical for predicting future water availability and for informing the design of resilient RWH systems (Arnold et al., 2012).

Regression models are commonly used in RWH studies to examine relationships among variables and assess their impacts on rainwater availability and collection efficiency. Statistical methods including regression models can be used in RWH studies to analyze the relationship between various parameters and make predictions about rainwater availability and collection potential (Tesema and Leta, 2020). By utilizing regression models, researchers can identify key factors that influence rainwater availability and collection efficiency, such as rainfall patterns, surface area of collection structures, slope, and vegetation cover. The use of regression models allows for a deeper understanding of the relationship between these variables and can provide insights into how to optimize RWH systems for maximum effectiveness. For instance, regression analysis has been applied to assess the impact of land use changes on runoff patterns, which is crucial for optimizing the placement and sizing of RWH structures (Baldassarre et al., 2015). Incorporating GIS can enhance the analysis by visualizing spatial patterns and identifying optimal locations for RWH systems, thereby facilitating better planning and implementation strategies (Jha et. al. 2014).

Statistical methods play a crucial role in RWH to identify patterns, trends and relationships between different variables, such as rainfall intensity and runoff volume. By using statistical methods, researchers can assess the effectiveness of RWH systems and evaluate different management options. In particular, multivariate statistical techniques have been utilized to analyze complex interactions among climate variables, land use, and topography, providing a more comprehensive understanding of the factors affecting RWH efficiency (Wilk et al., 2021). The statistical methods are essential for gaining insights and making informed decisions in RWH research. Overall, statistical methods are commonly used in RWH studies to analyze and interpret rainfall, runoff, and water availability data (Boers and Ben-Asher, 1982). Furthermore, advanced modeling techniques, such as machine learning algorithms, are increasingly being integrated into RWH research to enhance predictive accuracy and optimize system design (Gaurav et al., 2021). Machine learning approaches, such as random forests and support vector machines, have shown significant promise in predicting runoff and water availability, offering a robust tool for enhancing RWH planning and implementation (e.g., Rahmati et al., 2019; Fan et al., 2025).

2.3 Estimation of Water Storage Capacity

Open-source data is instrumental for providing insights into RWH water storage capacity. By analyzing topographical maps, soil characteristics and vegetation cover, it becomes possible to estimate potential storage capacities within various catchment areas. This analysis is critical for evaluating the feasibility of RWH in different regions and aids in decision making regarding the appropriate size and design of storage tanks (Oweis, et al., 1999; Chiu, et al., 2015). Topographic data, such as that provided by DEMs, is particularly useful for identifying suitable locations for storage structures and predicting runoff patterns, which are essential for accurately determining the potential water yield in a catchment (Pellenq et al., 2015). Additionally, open-source data can be used to assess the groundwater recharge potential through RWH. For instance, combining satellite soil moisture data with local hydrological data can significantly enhance understanding of groundwater recharge dynamics (Rodell et al., 2007). It also supports the evaluation of the effectiveness and efficiency of various RWH strategies and helps in monitoring the impact of these initiatives by comparing water availability and usage before and after implementation (Khanal et al. 1999; Pandey et al., 2011).

Factors such as changing rainfall patterns due to climate change, shifts in land use, and alterations in soil properties due to agricultural practices can significantly impact the performance of RWH structures (Trenberth, 2011). Climate change models, integrated with open-source rainfall data, allow for the simulation of future scenarios, enabling planners to design more resilient RWH systems that can adapt to varying rainfall patterns (Dos Santos et al., 2018). The open-source data offers crucial insights for estimating runoff and storage capacities, as well as for optimizing RWH strategies by considering factors such as rainfall patterns, LULC changes and soil characteristics (Jagadeesha and Palnitkar 2018). For e.g., high-resolution land use maps derived from satellite data can be used to assess the impact of urbanization on surface runoff and the subsequent need for increased storage capacity in urban catchments (Tian et al., 2018). By integrating multiple data sources, including satellite imagery and GIS-based analyses, comprehensive models that predict catchment runoff and storage capacities with greater accuracy (Singh et al., 2013). These models are invaluable for decision-makers, as they provide a detailed understanding of the spatial variability in water availability, which is essential for optimizing the placement and design of RWH systems (Maimaitijiang et al., 2020).

2.4 Accuracy evaluation of datasets

One key consideration in using open-source data to estimate runoff and water storage capacity is the accuracy and reliability of the data. It is important to assess the quality of the open-source data and validate its accuracy against ground-based measurements or other reliable sources. This involves comparing and validating the open-source data with established hydrological models and observations, such as stream gauge readings or field measurements (Steiner et al., 2009; Wang et al., 2021). The accuracy of open-source data can be influenced by several factors, including data resolution, the algorithms used for processing, and temporal and spatial coverage (**Table 2.1**).

For instance, coarse-resolution data might miss small-scale hydrological features, leading to inaccuracies in runoff estimation (Tarekegn et al., 2010). On the other hand, high-resolution data, while more accurate, may require significant computational resources and expertise to process effectively (Schumann et al., 2016). The role of open-source data at different resolutions is crucial to ensure sustainable and efficient water resources management. The role of open-source data at different resolutions is crucial to ensure sustainable and efficient water resources management. Open-source data plays a vital role in improving water resource management by providing essential information for the estimation of runoff and water storage capacity. It also helps in evaluating the feasibility and effectiveness of RWH strategies and assessing the impact of such initiatives (Wisser et al., 2010). Furthermore, continuous advancements in data processing techniques, such as machine learning and artificial intelligence, are being leveraged to enhance the accuracy of predictions derived from open-source data, making it an increasingly reliable resource for hydrological studies (Feng et al., 2021). Therefore, the accuracy assessment of open-source data is a critical step in ensuring that the data used for water resource management, including RWH, is both reliable and effective in supporting sustainable water management practices.

Table 2.1. Literature review on the accuracy assessment of various sources of DEM resolutions

SN	Author (s)	Dataset used	Models	Results
1	Huang et al. 2021	Orthophoto, UAV images	DSM, GIS-based method	Siltation, surface elevation, and storage capacity of check dams are highly reliable.
2	Aristizabal et al. 2022	HAND, USGS 3DEP, USGS NHDPlusHR, FIM, LULC	Regression models	The study found that using high-quality DEMs can improve the accuracy of flood extent maps.
3	Moges et al. 2023	ASTER	SWAT model	The selection of DEMs can affect the accuracy of stream and watershed mapping. This, in turn, can affect the reliability of simulations of water flow in streams.
4	Mukherjee et al. 2012	CARTOSAT, SRTM, ASTER Terrain morphology	CARTOSAT DEM	Physical features of the landscape influence the precision of DEMs in measuring elevation. Specifically, rougher terrain tends to reduce the vertical accuracy of these models.
5	Gangani et al. 2023	ALOS PALSAR, SRTM, ASTER, TanDEM-X	Statistical methods	Cartosat-1 DEM was found to be the most reliable, Manning's n value of 0.02 for the roughness coefficient of the river channel
6	Kaluarachchi & Rajapakse 2023	SRTM, ASTER, TOPO maps, LiDAR data	Algorithm development for accuracy improvement	High-resolution LiDAR and satellite images produce the most accurate DEMs; an algorithm was developed to enhance the performance of low-resolution DEMs in hydrological modeling.
7	Emmendorfer et al. 2024	ALOS-AW3D30, ALOS-	Comparison of DEMs with UAV	TanDEM-X was the most accurate for coastal flooding mapping; it was

		PALSAR, ASTER, SRTM, TanDEM-X	DEM	the only global DEM capable of capturing crucial dune depressions and roads in the studied coastal region.
8	Xu et al. 2024	ALOS PALSAR, SRTM1 DEM, SRTM3 DEM, NASADEM, ASTER GDEM V3	Random Forest model for accuracy improvement	ALOS PALSAR and NASADEM datasets with RMSE improvements are preferred for mountainous urban areas; accuracy decreases with slope steepness.

Note: DSM: Digital Surface Model; GIS: Geographic Information System; SRTM: Shuttle Radar Topography Mission; ASTER: Advanced Space borne Thermal Emission and Reflection Radiometer; ALOS: Advanced Land Observing Satellite; TRMM: Tropical Rainfall Measuring Mission; HAND: Height Above Nearest Drainage; LULC: Land use/land cover; UAV: Unmanned aerial vehicle.

2.5 Influence of topographic data resolution

The different resolution of DEMs plays a pivotal role in the accuracy of hydrologic simulations to assess water availability (**Table 2.2**). High-resolution DEMs such as those derived from LiDAR, provide a detailed topographic information that enhances the precision of runoff and storage capacity estimation. However, their high cost and data-intensive nature pose challenges for widespread adoption. Conversely, lower-resolution DEMs like SRTM (90 m) and ASTER (30 m) data offer more accessible, but less precise alternatives. The studies demonstrated that high resolution data captures micro-topographic features effectively, while medium resolution data can still offer a pragmatic balance between accuracy and resource requirements (Tarboton et al., 1991; Zhang and Montgomery 1994).

Hydrological models including SWAT and Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) are extensively used to simulate runoff. These models integrate topographic data with land use, soil type, and climatic variables to simulate runoff patterns. Gassman et al. (2007) highlighted that high-resolution DEMs significantly improve the model's ability to simulate small-scale hydrological processes. Lin et al. (2010) study indicate that medium-resolution data can be sufficiently accurate for broader watershed management applications, providing a cost-effective alternative without substantially compromising the results. The use of high-resolution DEMs significantly improves the model's ability to simulate small-scale hydrological processes, enhancing the accuracy of predictions for localized areas (e.g., Arnold et al., 2012; Reddy and Reddy, 2015; Zhang and Gao 2020; Gou and Soja 2024).

The integration of runoff and water storage capacity estimations with socio-economic and environmental factors forms the basis of sustainable RWH strategies. Pandey et al. (2003) emphasize the importance of high-resolution topographic data in optimizing the placement and design of RWH structures such as check dams and contour bunds. However, research also indicates that medium-resolution data, when combined with participatory approaches involving local communities can yield sustainable outcomes. For example, Kiggundu et al. (2018) demonstrated the successful application of medium-resolution data in the design of community-based RWH systems in Uganda. This approach has been particularly effective in regions where community involvement is crucial to the successful implementation and maintenance of RWH systems, as demonstrated in Uganda, where medium-resolution DEMs were used to design community-based RWH systems (Mwangi et al., 2015).

Table 2.2. Various open-source data used in studies and their resolutions.

SN	Name of Dataset	Spatial Resolution
1	NASA's Shuttle Radar Topography Mission *(SRTM)*	1 arc-second (30 m) 3 arc-second (90 m)
2	Advanced Space borne Thermal Emission and Reflection Radiometer *(ASTER)* GDEM	1 arc-second (30 m)
3	Global Multi-resolution Terrain Elevation Data 2010 *(GMTED2010)*	30 arc-second (about 1 km) 15 arc-seconds (about 500 m) 7.5 arc-seconds (about 250 m)
4	Global topographic elevation model *(GTOPO30)*	30 arc-seconds
5	Advanced Land Observing Satellite *(ALOS)*	30 m (basically 1 arc-second)
6	Ice, Cloud and land Elevation Satellite-2 (ICESat-2)	25 km x 25 km
7	National Snow and Ice Data Centre	8 m
8	AW3D30	5 m
9	GTOPO30	30 arc seconds (1 km)
10	TerraSAR-X and TanDEM-X (TanDEM-X)	12 m, 90 m global DEM (post-processed data available at higher resolutions)
11	Arctic DEM	2 m to 8 m
12	MERIT DEM (Multi-Error-Removed Improved-Terrain DEM)	3 arc-seconds

2.6 Recent Techniques

Gao et al., (2019) developed a new, straightforward method for modeling runoff generation based on topography, called the Height Above the Nearest Drainage (HAND) based Storage Capacity curve (HSC). This approach uses the HAND index to determine hydrological similarities and identify saturated areas within watersheds. The HSC can be incorporated into various conceptual rainfall-runoff models. By combining the HSC with the mass curve technique (MCT), which calculates root zone storage capacity without calibration, they created a parameter-free runoff generation module named HSC-MCT. This module effectively simulated changes in saturated areas, particularly in terms of correlation and spatial distribution. Despite not requiring calibration, the HSC-MCT module performed similarly to calibrated alternatives. This method shows promise for use in ungauged basins and could enhance global-scale hydrological predictions. Also, Johnson et al., 2019 evaluated National Water Model –Height Above Nearest Drainage (NWM–HAND) for flood mapping using 28 remotely sensed inundation maps and 54 reach-level catchments. The NWM-HAND is developed as part of the National Flood Interoperability Experiment (NFIE) (Maidment, 2016). Results revealed that model under predict inundated cells in 4th order and lower-order reaches but does better with a slight tendency to over predict in high-order reaches.

Researchers have explored various approaches for estimating river runoff as well:

a. Traditional hydrological water balance equation.
b. Satellite altimetry with quantile function-based stage–discharge relationships to estimate river discharge (Sneeuw et al., 2014a).
c. Runoff–storage relationship with time lag Consideration by incorporating time lag effects in runoff estimation (Sneeuw et al., 2014b).
d. The Xin'anjiang model uses the water storage capacity curve to characterize the distribution of water storage capacity for runoff yield calculation (Xu et al., 2022).

These approaches contribute to our understanding of runoff and to the estimation of water storage capacity. These innovative approaches/parameterizations (like HSC, high-resolution data, or hydro-geodetic methods), encourages researchers to continue on enhancing our ability to manage water resources effectively.

2.7 Concluding remarks

Optimizing water conservation efforts can be achieved by leveraging insights from open-source data. For example, by analyzing historical rainfall patterns and open-source water-use data, water management authorities can identify areas with high water demand and potential water scarcity, allowing them to prioritize and implement targeted conservation measures. Furthermore, open-source data can inform the design and implementation of RWH systems by providing insights into local precipitation patterns, soil characteristics, and topography. This data can help determine the optimal size and capacity of rainwater storage tanks, as well as the most suitable locations for their installation. By combining open-source data with advanced modeling techniques, it is possible to accurately estimate runoff volumes and plan for appropriate water storage capacity. By accessing and analyzing open-source data, stakeholders can enhance their understanding of local hydrological conditions, improve the design and implementation of RWH systems, and contribute to the development of sustainable water management practices.

The growing availability of open-source data from various organizations has significantly advanced water resource management by providing accessible datasets related to topography, land use and hydrology. Enhanced remote sensing technologies, such as LiDAR and satellite imagery, now provide higher-resolution data, improving the accuracy of runoff and water storage estimates. However, the challenges still remain, including ensuring data accuracy, quality, standardizing and homogenizing datasets, and adapting models to local conditions. Additionally, climate change introduces uncertainties and the continuous need for data updates and socio-economic considerations.

3. STUDY AREA AND DATA USED

3.1 Study Area

The present study was carried out in the Henval Catchment, located in the Tehri Garhwal district of Uttarakhand. Tehri Garhwal lies within the catchment of the Bhagirathi River and its tributaries, forming an important part of the upper Ganga basin. It is bounded by Rudraprayag District to the east, Dehradun District to the west, Uttarkashi District to the north, and Pauri Garhwal District to the south. Henval River is a first-order tributary that directly feeds the river Ganga and its catchment covers an area of 76 km². The study area map is presented in **Fig.3.1**. The catchment is primarily agricultural, with notable anthropogenic interventions, including the urban settlement at Chamba.

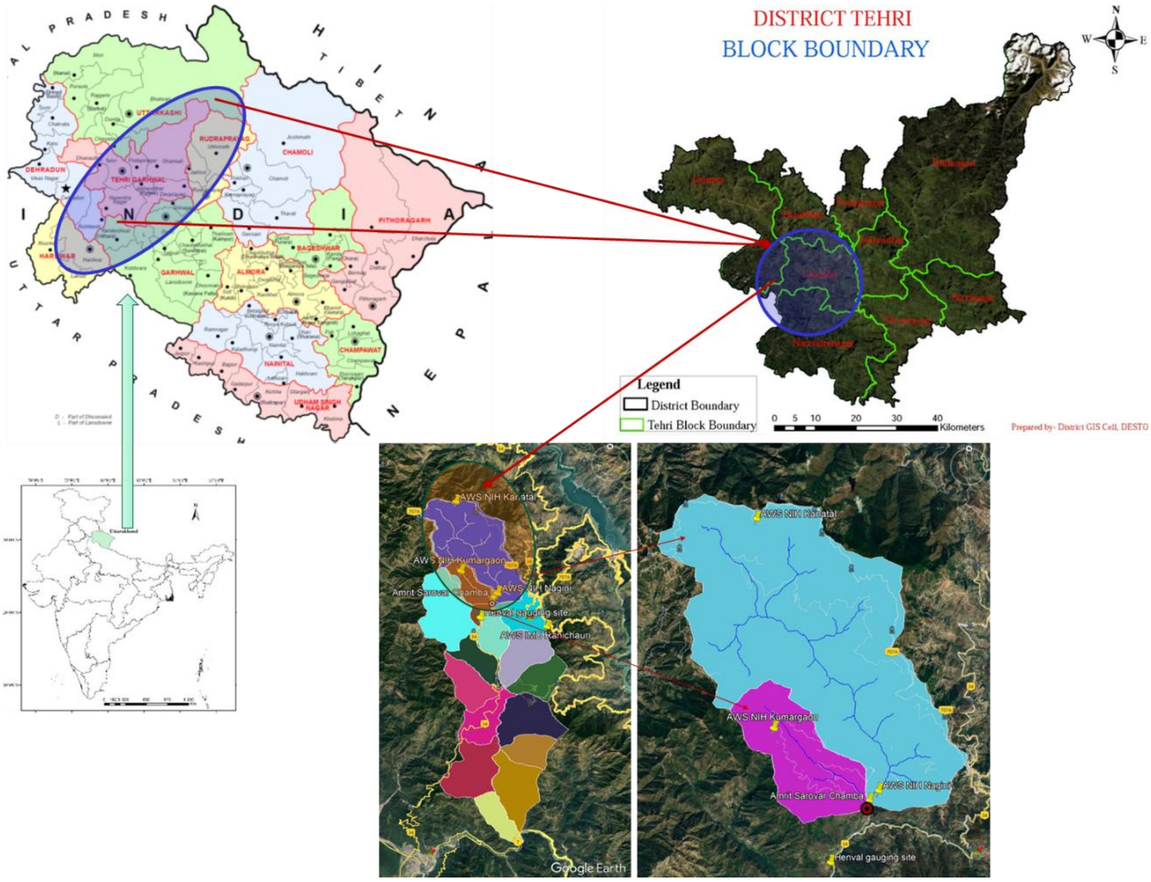


Fig. 3.1. Location of the Henval Catchment in Tehri Garhwal District.

Geographically, the catchment lies between 30°17′N and 30°26′N latitude and 78°16′E and 78°25′E longitude, with elevations ranging from 988 to 2686 m above mean sea level (amsl). The study area represents the climatic conditions of the Lesser Himalaya, with an average annual precipitation of 1200–1400 mm, the majority of which occurs during the monsoon season (approximately 70–80%). The climate is generally humid temperate, though local variations are influenced by various physiographic factors (e.g. altitude, aspect, slope, drainage conditions, vegetation, etc. Summers are typically hot, while winters are cold in the valley region. The drainage network of the study area is well developed, exhibiting a dendritic-to-semi-dendritic pattern. The soils are predominantly sandy loam to loamy sand, derived mainly from metamorphic rocks such as biotite schist and phyllite (Patil et al., 2021).

3.2 Data Used

Data collection methods in this study included both primary and secondary sources. Topographic data for the Henval Catchment, at varying spatial resolutions, were obtained from multiple open-source Digital Elevation Models (DEMs). These datasets include SRTM 90 m, ASTER DEM 30 m cop30, ALOS30, MERIT 30 m, CartoSAT 30 m and ALOS PALSAR 12.5 m (NASA SRTM, METI/ASTER, ISRO/CartoSAT, JAXA/ALOS PALSAR). The gridded daily precipitation dataset (0.25° × 0.25°) from 1901 to 2024 was also obtained from the India Meteorological Department (IMD) (Pai et al., 2014). Aquifer maps were sourced from the Central Ground Water Board (CGWB) and India-WRIS, while lithological formation maps of Tehri Garhwal district were obtained from the Soil and Land Use Survey of India. The LULC map of the year 2024 was used in the present study using Sentinel 1 (10 m resolution).

4. METHODOLOGY

The following overall methodology has been followed in the present study and subsequently presented in **Fig. 4.1**:

- A detailed review was carried out to investigate the application of using open-source data for the estimation of water availability, water spread area, and water storage capacity in RWH structures.
- A Google Earth Engine (GEE) based program was developed for application to any area, enabling detailed analysis of the water spread area and corresponding storage at RWH structures using multiple DEMs and structure heights, simply by providing either a probable outlet location or a catchment boundary (**Fig. 4.2**).
- A demonstration was carried out in the Henval catchment in Tehri-Garhwal District, Uttarakhand, as a case study. The topographic datasets for the Henval catchment were obtained from multiple sources. Various open-source DEMs of different resolutions were used [i.e., SRTM (90 m)-CGIR/SRTM90 V4; cop30-COPERNICUS GLO30, SRTM30-USGS SRTMGL1 003; ALOS30-AW3D30 V3.2; MERIT V1.0.3; CartoSAT (30 m), and ALOS PALSAR (12.5 m)].
- Morphometric analysis of the key parameters (e.g., stream length, stream order, & number of streams) was carried out using different DEMs (i.e., SRTM 90 m, ASTER DEM 30 m, CartoSAT 30 m, and ALOS PALSAR 12.5 m) to evaluate the influence of spatial resolution on morphometric attributes.
- A LULC and soil maps were prepared for the catchment (**Fig. 4.3**). A GIS database comprising DEM, slope, aspect, and contour maps of the study area was created using DEMs from different resolutions using ArcGIS software (**Fig. 4.4 to 4.7**). Additionally, weather data (rainfall, temperature, relative humidity, wind speed, and solar radiation) were prepared in ArcGIS 10.7 environment to obtain the data format required by ArcSWAT database.
- The un-calibrated SWAT model is used in the present study. Since, the primary objective of the study was to evaluate the performance of DEMs with different spatial resolutions in estimating water availability in the catchment. It was assumed that other input parameters would remain constant, and they were kept constant to assess the influence of spatial resolution on water availability at the catchment outlet in the Henval Catchment. The influence of resolution on water availability estimation within the Henval catchment was assessed using the SWAT model in an ungauged catchment, and various hydrological components were simulated at different topographic data resolutions (namely SRTM 90 m, ASTER DEM 30 m, CartoSAT, 30 m and ALOS PALSAR 12.5 m) (**Fig. 4.2**).
- The water spread area and storage capacity analysis were conducted in upstream areas of potential storage structures, considering different RWH structure (i.e., check dam) heights ranging from 1 m to 15 m and DEM inputs using developed GEE Program. The multiple open source DEMs of varying resolution [(i.e., SRTM (90 m), cop30, SRTM30, ALOS30, MERIT, CartoSAT (30 m), and ALOS PALSAR (12.5 m)] were used in the present study (**Fig. 4.2**).

- The quantification and volumetric assessment of water availability, water spread area, and water storage capacity were carried out to support the development of effective rainwater harvesting strategies in the catchment.
- Suitable recommendations were made, and the appropriate resolution of topographic data from different sources was identified to guide RWH strategies in the catchment.

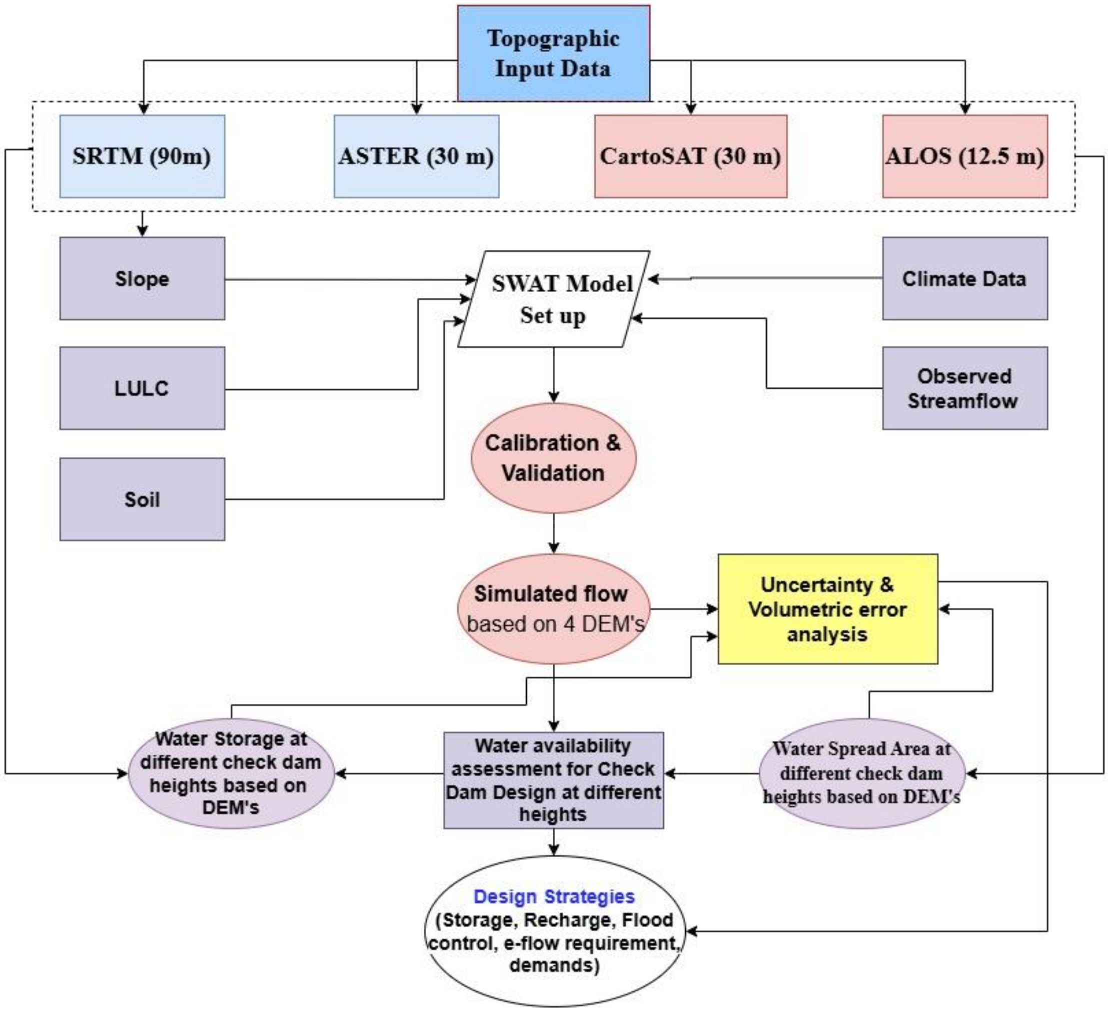
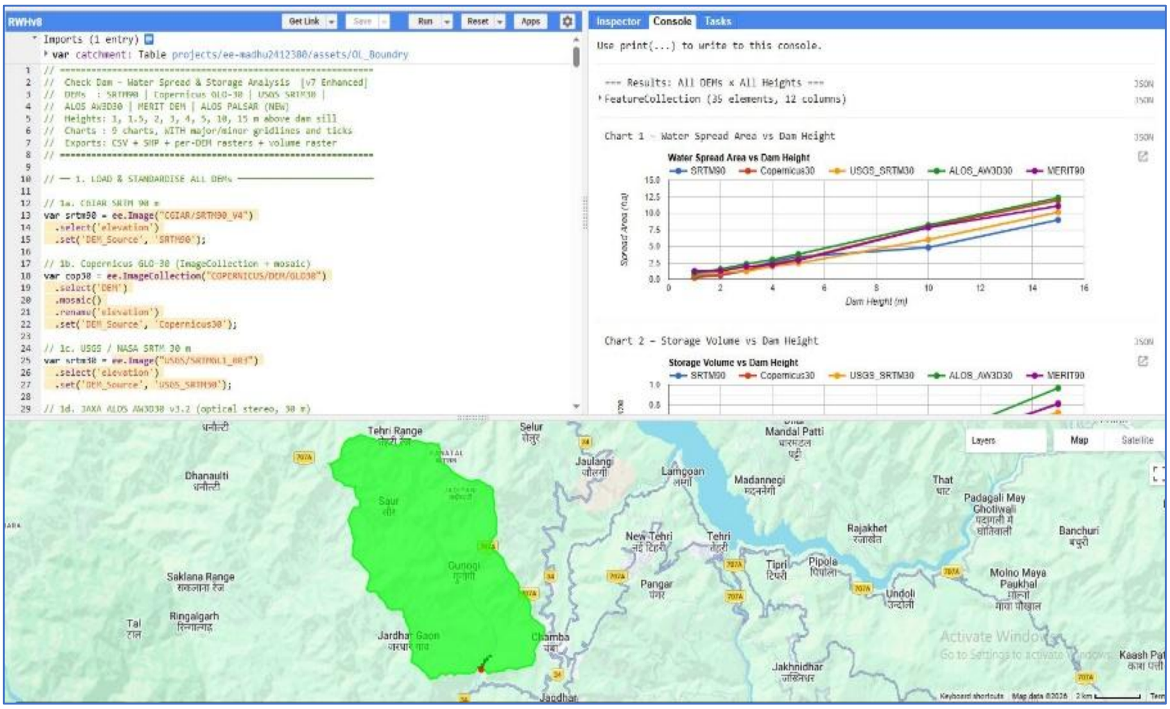


Fig. 4.1. Methodology adapted in the present study.

4.1 Model Description

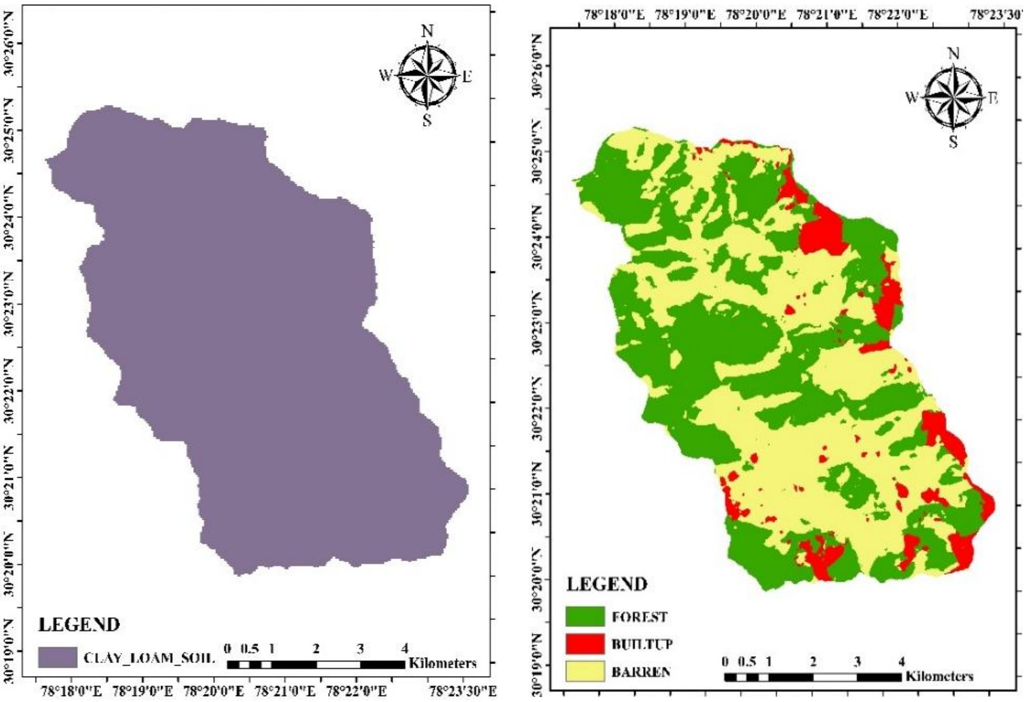
Soil and Water Assessment Tool (SWAT) is physically based continuous, semi-distributed hydrologic model developed by the USDA-ARS and Texas and A&M University. It operates on a daily time step and uses physiographical data such as elevation, land use, and soil properties as well as meteorological data and river discharge data for calibration (Arnold et al. 1998). The SWAT model is mainly used to predict the impact of land-management practices on water, sediment, and agricultural chemical yields in large basins with varying soils, land use, and management over long periods of time (Neitsch et al., 2001). The hydrological processes included in the model are surface runoff, evapotranspiration (ET), percolation, infiltration, aquifers flow, and channel routing (Arnold et al. 1998).



```
Imports (1 entry)
var catchment: Table projects/ee-madhu2412380/assets/OL_Boundry
// ==============================================================
//  Check Dam - Water Spread & Storage Analysis  [v7 Enhanced]
//  DEMs  : SRTM90 | Copernicus GLO-30 | USGS SRTM30 |
//  ALOS AW3D30 | MERIT DEM | ALOS PALSAR (NEW)
//  Heights: 1, 1.5, 2, 3, 4, 5, 10, 15 m above dam sill
//  Charts : 9 charts, WITH major/minor gridlines and ticks
//  Exports: CSV + SHP + per-DEM rasters + volume raster
// ==============================================================

// — 1. LOAD & STANDARDISE ALL DEMs ——————————————————

// 1a. CGIAR SRTM 90 m
var srtm90 = ee.Image("CGIAR/SRTM90_V4")
  .select('elevation')
  .set('DEM_Source', 'SRTM90');

// 1b. Copernicus GLO-30 (ImageCollection + mosaic)
var cop30 = ee.ImageCollection("COPERNICUS/DEM/GLO30")
  .select('DEM')
  .mosaic()
  .rename('elevation')
  .set('DEM_Source', 'Copernicus30');

// 1c. USGS / NASA SRTM 30 m
var srtm30 = ee.Image("USGS/SRTMGL1_003")
  .select('elevation')
  .set('DEM_Source', 'USGS_SRTM30');

// 1d. JAXA ALOS AW3D30 v3.2 (optical stereo, 30 m)
```

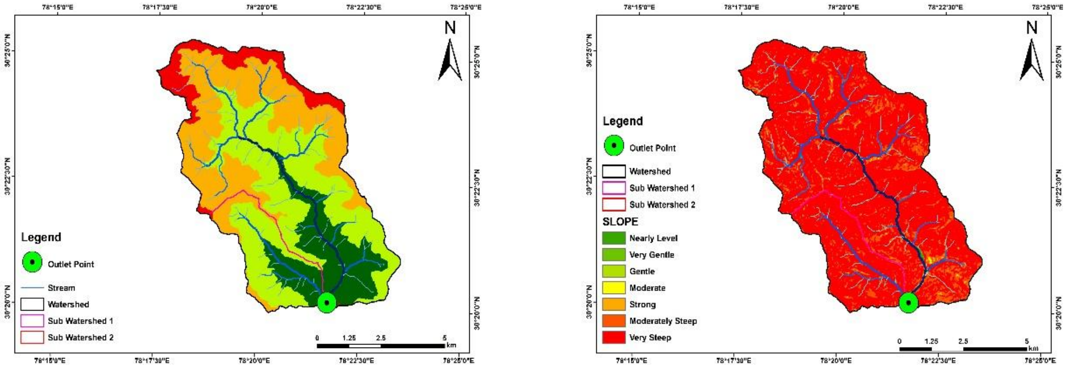
```
Use print(...) to write to this console.

=== Results: All DEMs x All Heights ===
FeatureCollection (35 elements, 12 columns)

Chart 1 - Water Spread Area vs Dam Height

Chart 2 - Storage Volume vs Dam Height
```

Fig. 4.2. Google Earth Engine framework for estimating water spread area and storage capacity at the catchment outlet using multiple DEMs at different structure heights.



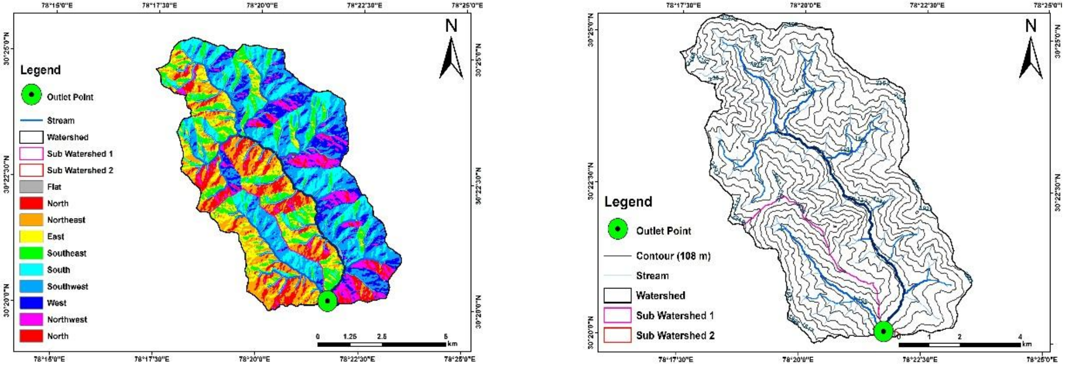
a) Soil map b) LULC map of the year 2024

Fig. 4.3. Soil and LULC used in the present study.



DEM

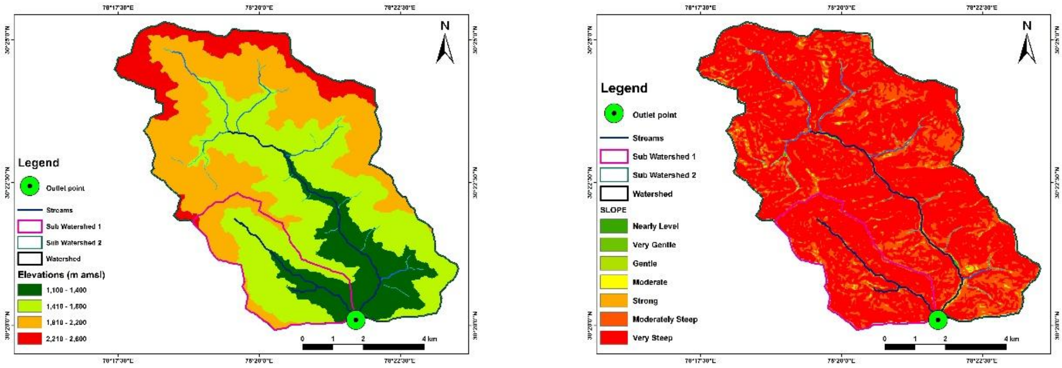
Slope



Aspect

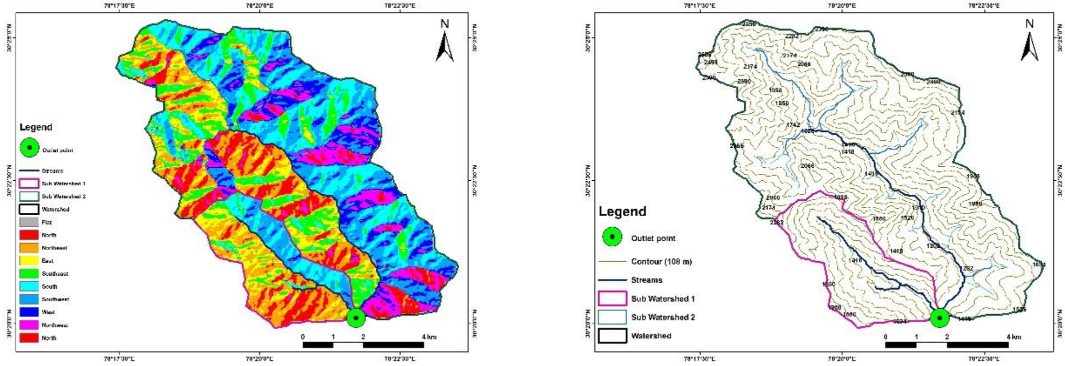
Contour

Fig. 4.4. Topographic maps of Henval catchment derived from ALOS PALSAR DEM (12.5 m).



DEM

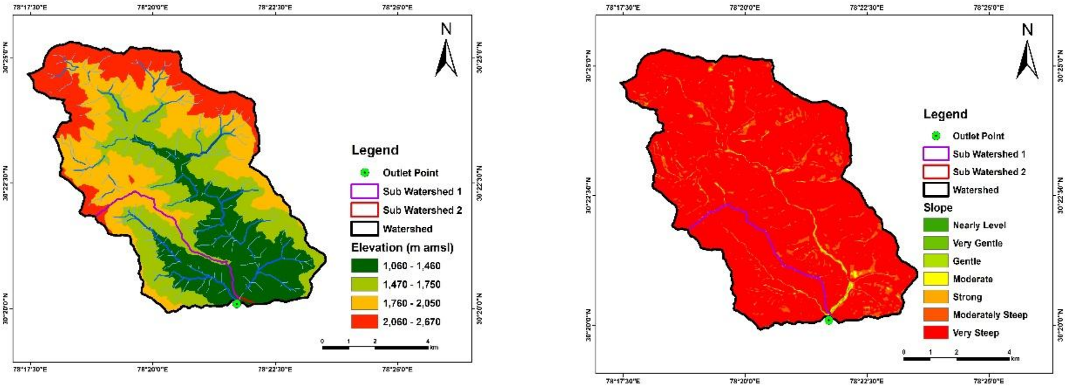
Slope



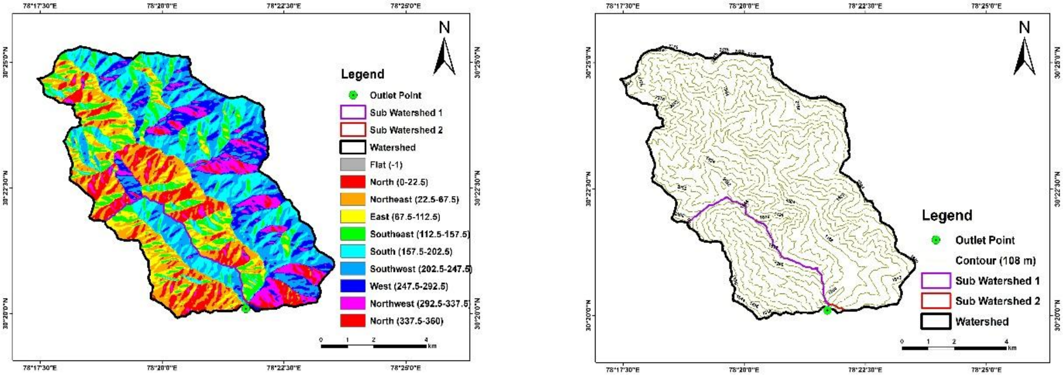
Aspect

Contour

Fig. 4.5. Topographic maps of Henval catchment derived from ASTER DEM (30 m).

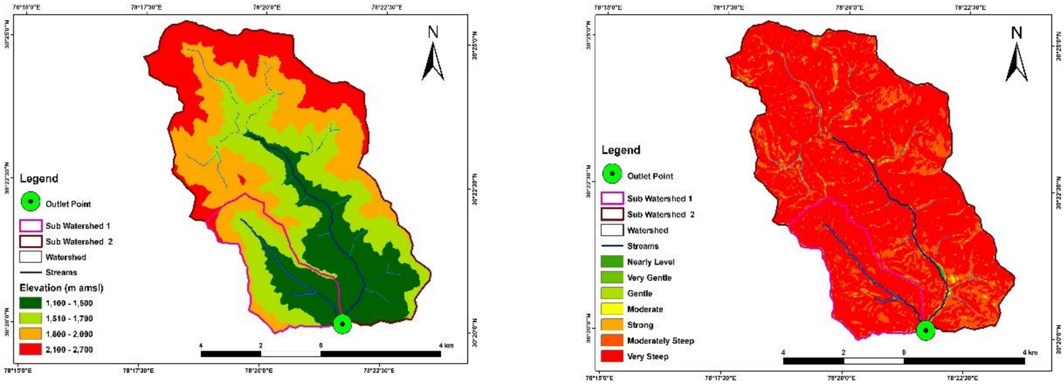


DEM Slope

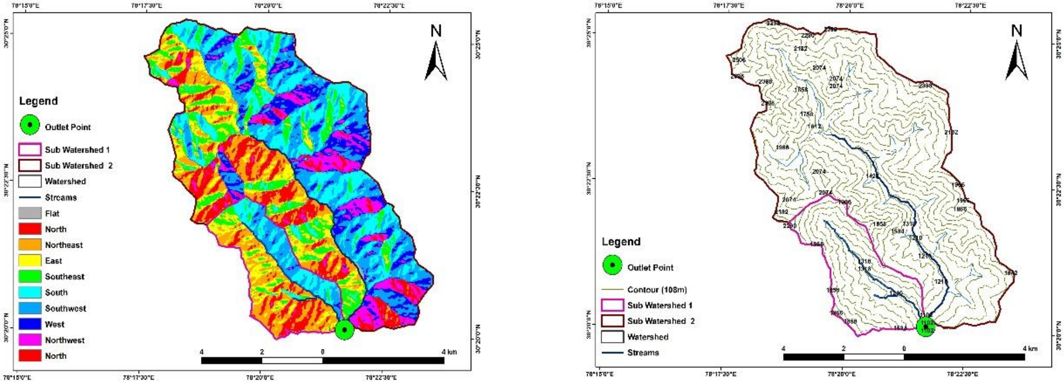


Aspect Contour

Fig. 4.6. Topographic maps of Henval catchment derived from CartoSat DEM (30 m).



DEM Slope



Aspect Contour

Fig. 4.7. Topographic maps of Henval catchment derived from SRTM DEM (90 m).

The SWAT model uses the Curve Number (CN) method for estimating surface runoff (Q_{surf}) (SCS 1972). The water balance of a given watershed is given by:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (4.1)$$

Where, SW_t = final soil water content (mm); SW_0 = the initial soil water content on day *i* (mm); t = time in days; R_{day} = rainfall (mm); Q_{surf} = surface runoff (mm); E_a = evapotranspiration (mm); W_{seep} = percolation (mm); and Q_{gw} = return flow (mm).

It has been extensively validated across the globe for streamflow and sediment loads including India (e.g., Santhi et al., 2001). The SWAT model has been applied in several studies in India for micro-watersheds (e.g., Kumar and Kumar, 2011; Tripathi and Gosain, 2013; Bhatt et al., 2016). Bhatt et al., 2016 applied SWAT for computing runoff in micro-watersheds (Choe watershed = 21 ha and W3B watershed = 70.45 ha) of the lower Himalayan region of India.

SWAT is chosen for the compatibility of available data and software and for its complex representation of fine spatial scales. The effects of spatial variations in topography, LULC, hydrologic soil types, and other watershed hydrology characteristics are incorporated by dividing the catchment into several sub-catchments based on drainage area. Further, the sub-catchments are divided into a number of hydrological response units (HRUs) within each sub-catchment based on LULC and hydrologic soil types. Each HRU is assumed spatially uniform in terms of land use, soil, topography, and climate. All model computations are performed at the HRUs level. The runoff is simulated separately for each HRU and routed to obtain the total runoff i.e., water availability at the outlet of a catchment.

4.2 Model Simulations

The initial parameter value in SWAT did not yield accurate streamflow simulations and required parameter calibration. However, the primary objective of this study was to evaluate the influence of DEM spatial resolution on estimates of surface runoff and water availability at the catchment outlet. It was assumed that there was no change in other input parameters, that all inputs provided a relatively accurate representation of field conditions, and that they were kept constant to evaluate the influence of spatial resolution on water availability at the catchment outlet in the Henval catchment. The independent simulation runs were conducted at monthly and annual time scales using different resolutions of DEMs in the SWAT model for the selected period, while keeping other input parameters unchanged. Average annual surface runoff was simulated using SWAT, and comparisons were made of hydrological water balance components (surface runoff, lateral flow, and groundwater flow) contributions to streamflow at varying DEM resolutions from different sources for the Henval Catchment.

4.4 Water Spread Area and Storage Capacity

The following equations (eqn. 4.3 to 4.6) were used to estimate the upstream water spread area and water storage volume of the RWH structure across multiple dam heights, using varying resolutions of multiple DEMs, to support the design of effective RWH strategies within the catchment. The detailed methodology for the estimation of upstream water spread area and storage volume across different RWH structure heights for each DEM's is shown in **Fig. 4.8**.

The water level above the dam outlet is estimated using equation 4.2:

$$Water\ level = Dam\ Elevation + h \tag{4.2}$$

Where,

h = dam height being evaluated (e.g., 1, 2, 3, 4, 5, 10, 15 m)

Dam Elevation = elevation at the dam outlet/sill from DEM

Further, the inundated pixels were calculated to estimate inundation areas using equation 4.3:

$$Water\ Surface\ = DEM < Water\ level \tag{4.3}$$

This provides a number of pixels below the water level within the catchment.

The depth at each inundated pixel were also estimated using water depth raster map (Eqn. 4.4):

$$Depth = Water\ level - DEM \tag{4.4}$$

4.4.1 Water Spread Area

Finally, total area covered by water was estimated using eqn. 4.5 and 4.6

$$Water\ Spread\ Area\ (m^2) = \sum(PixelArea \times Water\ Surface) \tag{4.5}$$

Then, converted to hectares:

$$Water\ Spread\ Area\ (ha) = Water\ Spread\ Area\ (m^2) \times 10^4 \tag{4.6}$$

4.4.2 Storage Volume (m³)

To estimate total water volume stored:

$$Storage\ Volume\ (m^3) = \sum(Depth \times Pixel\ Area)$$

or

$$Storage\ Volume\ (MCM) = Storage\ Volume\ (m^3) \times\ 10^6 \tag{4.7}$$

The above equations eqn.4.3 to 4.7, were used in the development of a general Google Earth Engine (GEE) framework which can be used for application to any area, enabling detailed analysis of the water spread area and corresponding storages in RWH structures using varying resolutions of DEMs [i.e., SRTM (90 m)-CGIR/SRTM90 V4; cop30-COPERNICUS GLO30, SRTM30-USGS SRTMGL1 003; ALOS30-AW3D30 V3.2; MERIT V1.0.3; CartoSAT (30 m), and ALOS PALSAR (12.5 m)] and different heights of check dams (i.e., 1, 2, 3, 4, 5, 10, 15 m), simply by providing either a probable outlet location or a catchment boundary.

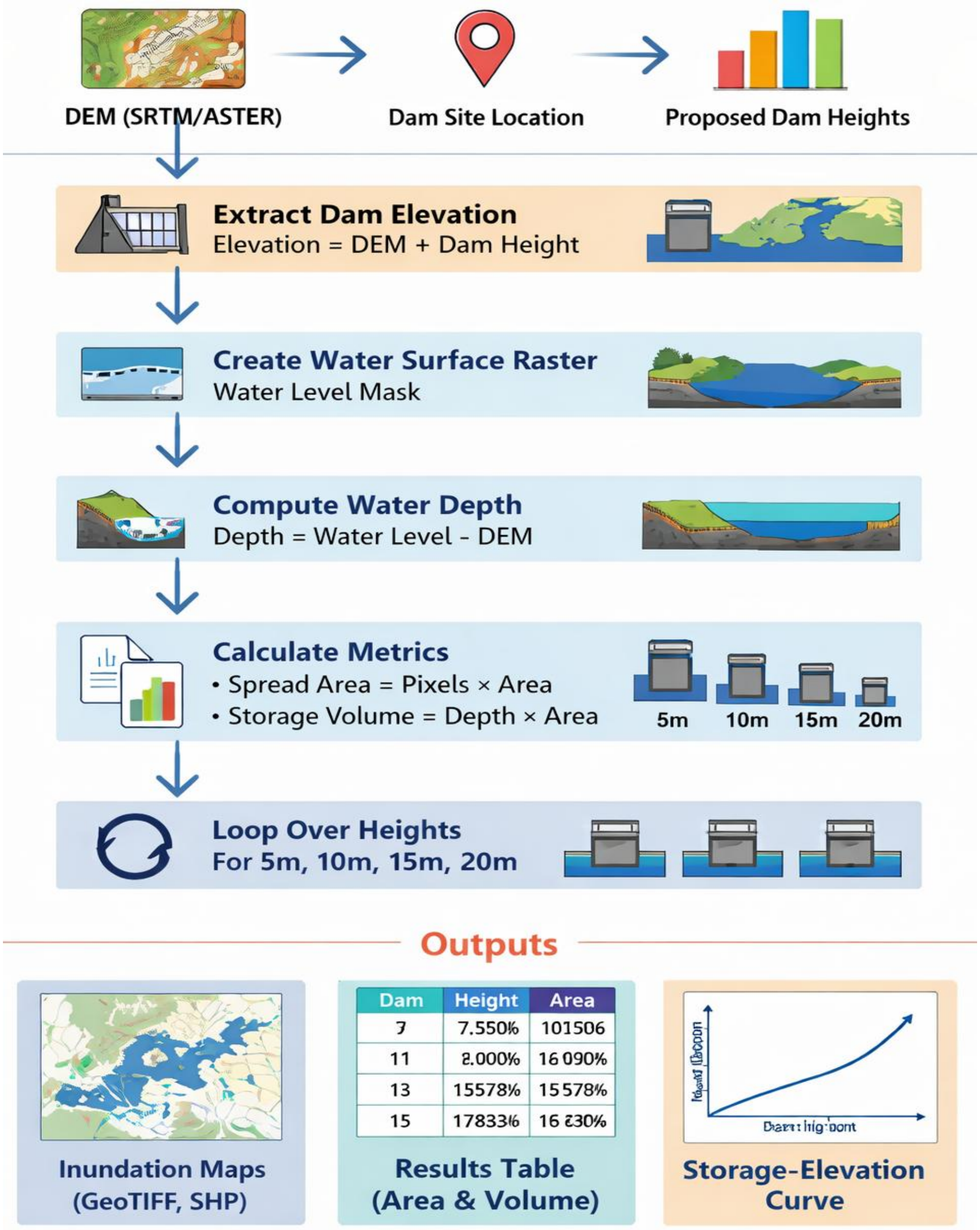


Fig. 4.8. Estimation of water spread area and storage using multiple DEMs for different dam heights.

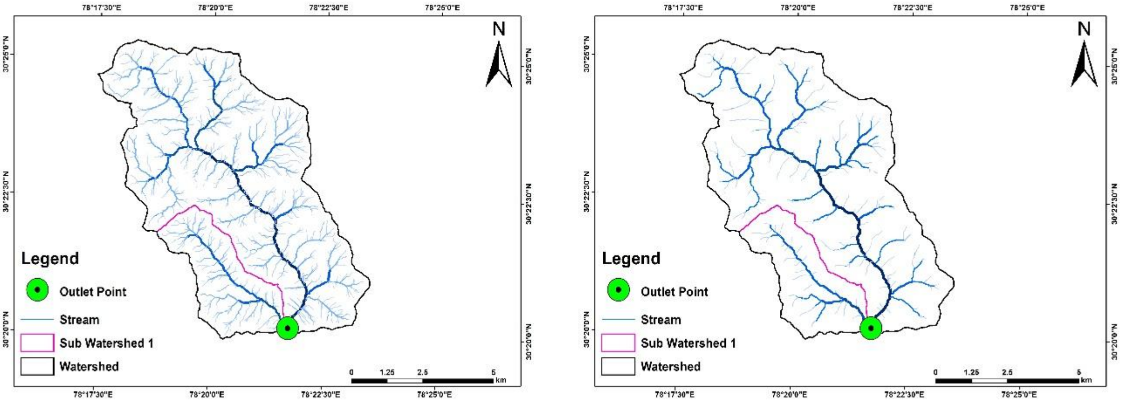
A demonstration study was carried out in the Henval catchment in Tehri-Garhwal District, Uttarakhand, as a case study.

5. RESULTS AND DISCUSSION

In this chapter, the influence of spatial resolution on morphometric attributes of the Henval catchment has been analyzed, and the impact of changing DEM resolution on water availability has been simulated using the SWAT model. Furthermore, the effects of varying DEM resolutions at different check dam heights on the water spread area and storage capacity of the rainwater harvesting (RWH) structures have been evaluated. The results are presented in the following sections and discussed thereafter.

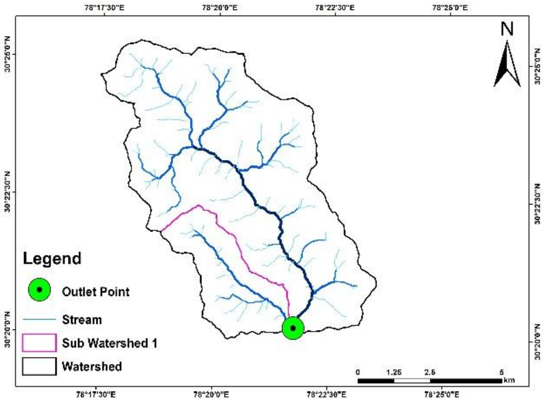
5.1 Morphometric analysis

The morphometric analysis of key parameters was conducted across multiple topographic datasets to evaluate the influence of spatial resolution on morphometric attributes in the Henval catchment. These key parameters include stream length, stream order, and number of streams using multiple sources of topographic data, namely SRTM 90 m, ASTER 30 m, CartoSAT 30 m, and ALOS PALSAR 12.5 m DEMs. Streams were extracted for the Henval catchment using different resolutions of DEMs separately by applying thresholds of 100, 500, and 1000 cells using ArcGIS (**Fig.5.1** to **Fig.5.3**).



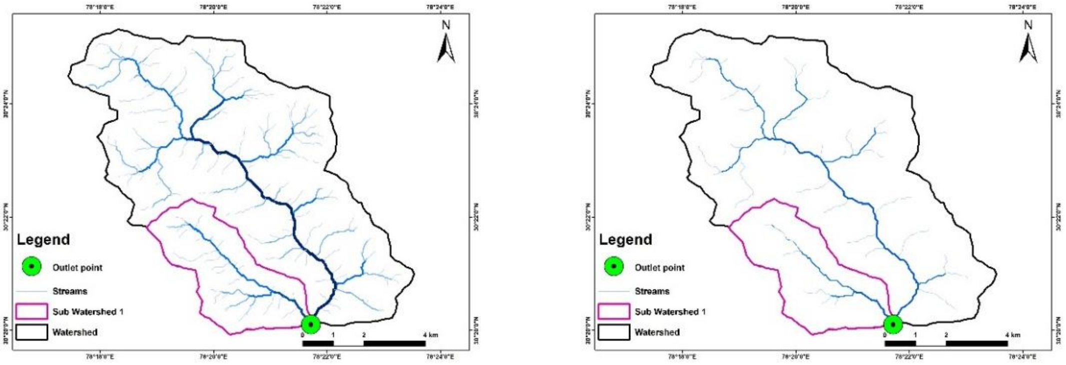
Threshold (100)

Threshold (500)

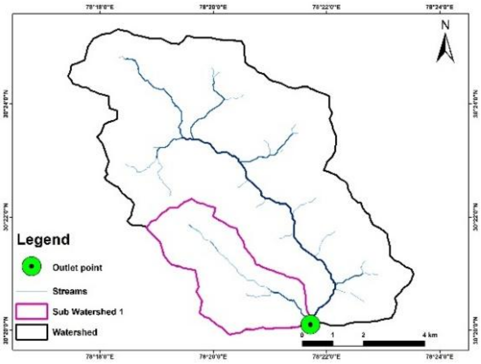


Threshold (1000*)

Fig. 5.1. Drainage maps of Henval catchment from ALOS PALSAR (12.5 m) DEM at different thresholds.

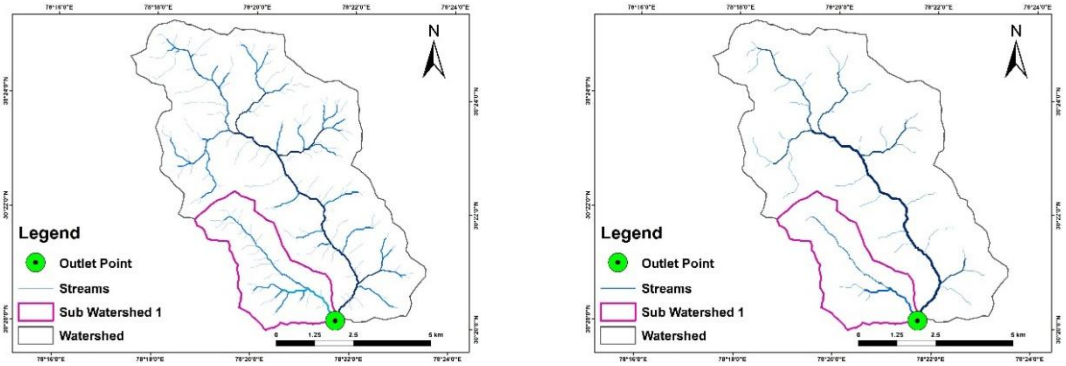


Threshold (100) Threshold (500)

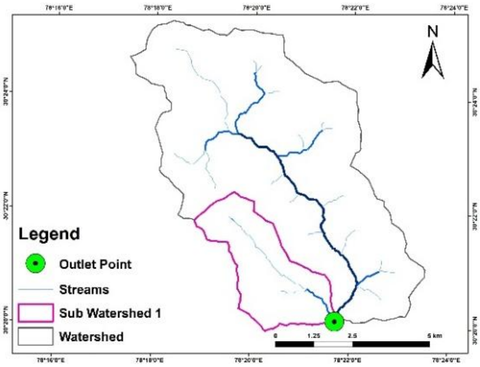


Threshold (1000)

Fig. 5.2. Drainage maps of Henval catchment from ASTER DEM (30 m) at different thresholds.



Threshold (100) Threshold (500)



Threshold (1000)

Fig. 5.3. Drainage maps of Henval catchment from SRTM (90 m) DEM at different thresholds.

The detailed statistics of the stream length, stream order, and number of streams are presented in **Tables 5.1** to **5.4**. The results reveals that higher the DEM resolution higher stream orders. Also, it was observed that small streams are ignored with decrease in resolution (**Table 5.1** to **5.4**). Results indicates that there is variation in stream orders with change in DEM resolution and area threshold (**Fig.5.4**).

Table 5.1. Morphometric parameters of the Henval catchment based on SRTM (90 m) DEM at varying thresholds.

Threshold (number of cells)		**100**	**500**	**1000**
Stream Length	Minimum	26.70 m	46.21 m	46.21 m
	Maximum	1728.73 m	3911.15 m	3658.64 m
	Average	330.29 m	701.60 m	911.78 m
	Total	112643.03 m	51946.72 m	35890.84 m
Stream Order	Order 1	172	36	20
	Order 2	86	21	9
	Order 3	33	14	10
	Order 4	12	0	0
	Order 5	37	0	0
Number of Streams		340	71	39

Table 5.2. Morphometric parameters of the Henval catchment based on ASTER (30 m) DEM at varying thresholds.

Threshold (number of cells)		**100**	**500**	**1000**
Stream Length	Minimum	26.71 m	46.21 m	66.75 m
	Maximum	1653.00 m	2214.66 m	3626.73 m
	Average	330.08 m	577.29 m	912.27 m
	Total	118556.38 m	52782.05 m	36791.31 m
Stream Order	Order 1	184	37	22
	Order 2	71	20	10
	Order 3	56	14	11
	Order 4	10	1	0
	Order 5	39	72	0
Number of Streams		360	37	43

Table 5.3. Morphometric parameters of the Henval catchment based on CartoSAT (30 m) DEM at varying thresholds.

Threshold (number of cells)		100	500	1000
Stream Length	Minimum	13.35 m	13.35 m	13.36 m
	Maximum	1463.71 m	2240.36 m	2385.01 m
	Average	291.14 m	533.62 m	527.09 m
	Total	112637.89 m	42245.52 m	24020.76 m
Stream Order	Order 1	193	48	30
	Order 2	100	28	11
	Order 3	59	0	0
	Order 4	5	0	0
Number of Streams		357	76	41

Table 5.4. Morphometric parameters of the Henval catchment based on ALOS PALSAR (12.5 m) DEM at varying thresholds.

Threshold (number of cells)		100	500	1000
Stream Length	Minimum	12.48 m	12.48 m	17.66 m
	Maximum	1682.55 m	1682.55 m	1621.03 m
	Average	288.90 m	288.90 m	409.91 m
	Total	113905.05 m	113905.05 m	84272.56 m
Stream Order	Order 1	1080	182	100
	Order 2	477	79	36
	Order 3	282	47	36
	Order 4	133	24	26
	Order 5	53	30	0
	Order 6	108	0	0
Number of Streams		2133	362	198

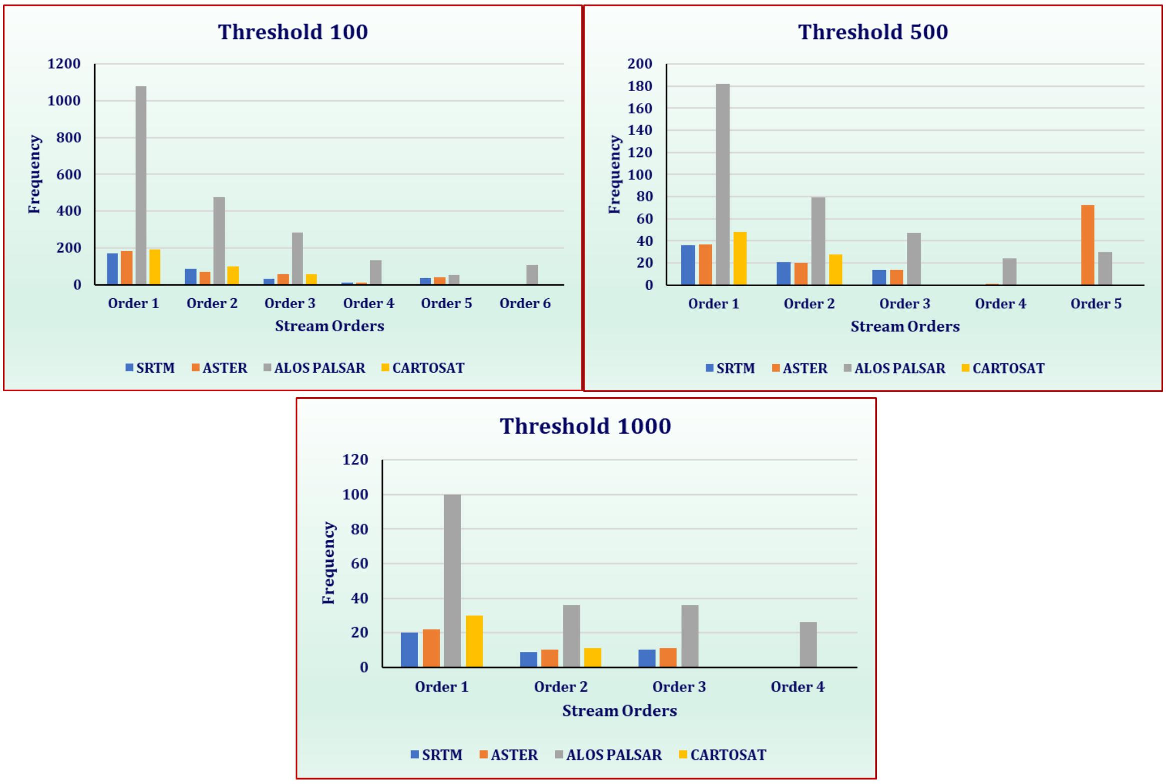


Fig. 5.4. Variation in stream orders with change in DEM resolution and area threshold.

5.2 Water Availability Estimates using different DEMs

As discussed in Chapter 4, an uncalibrated SWAT model was employed to estimate water availability at the outlet of the Henval Catchment using DEMs of varying spatial resolutions (SRTM 90 m, SRTM 30 m, ALOS PALSAR 12.5 m, and CartoSat 30 m). The impact of DEM resolution on monthly and annual water availability was simulated with the SWAT model (**Fig. 5.5 and Fig. 5.6**). Calibration and validation were not performed, as the primary objective was to assess the performance of DEMs with different spatial resolutions in estimating water availability. Other input parameters were assumed constant and representative of field conditions, ensuring that the influence of DEM resolution could be isolated. Hydrological components such as surface runoff, lateral flow, and groundwater flow were also simulated using different topographic datasets (**Fig. 5.7**).

Fig. 5.5 illustrates SWAT-simulated monthly cumulative streamflow derived from DEMs of varying resolutions. The results show that all four datasets produce nearly overlapping curves, demonstrating strong consistency in cumulative streamflow simulation over the 25-year period (1999–2024). The upward trend and minimal divergence among datasets indicate that DEM resolution has little effect on long-term cumulative streamflow estimates. This underscores the robustness of DEM-based hydrological modeling for cumulative measures, as terrain representation differences do not significantly alter aggregated water availability at the catchment outlet.

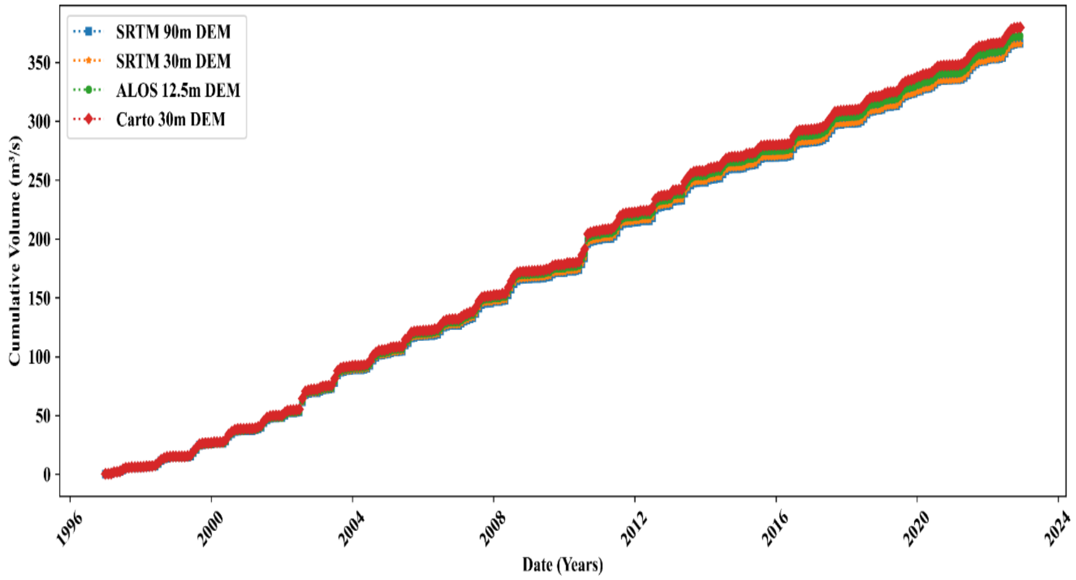


Fig. 5.5. SWAT-simulated streamflow for Henval Catchment.

Fig. 5.6 presents monthly simulated flows using different DEM resolutions. Unlike cumulative streamflow, these results reveal periodic fluctuations, with notable peaks around 2004, 2008, and 2012, likely linked to seasonal rainfall or extreme hydrological events. While the datasets generally follow similar patterns, slight differences in peak magnitudes and timings are evident. ALOS PALSAR and CartoSat datasets capture sharper peaks than SRTM datasets, suggesting that higher-resolution DEMs better represent localized terrain features that influence runoff and streamflow. This highlights the importance of DEM resolution in finer-scale flow simulations.

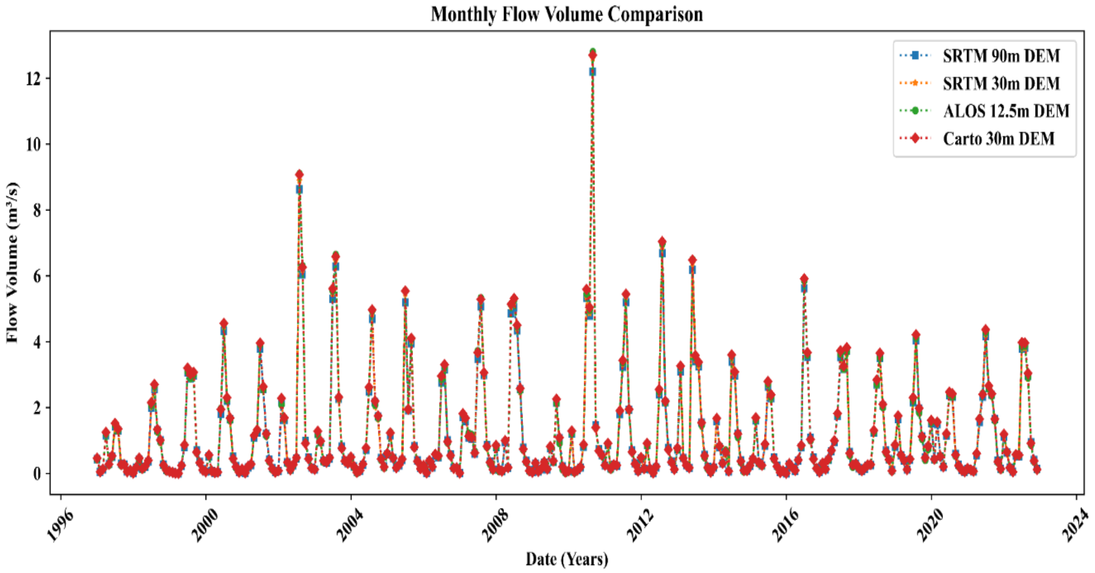
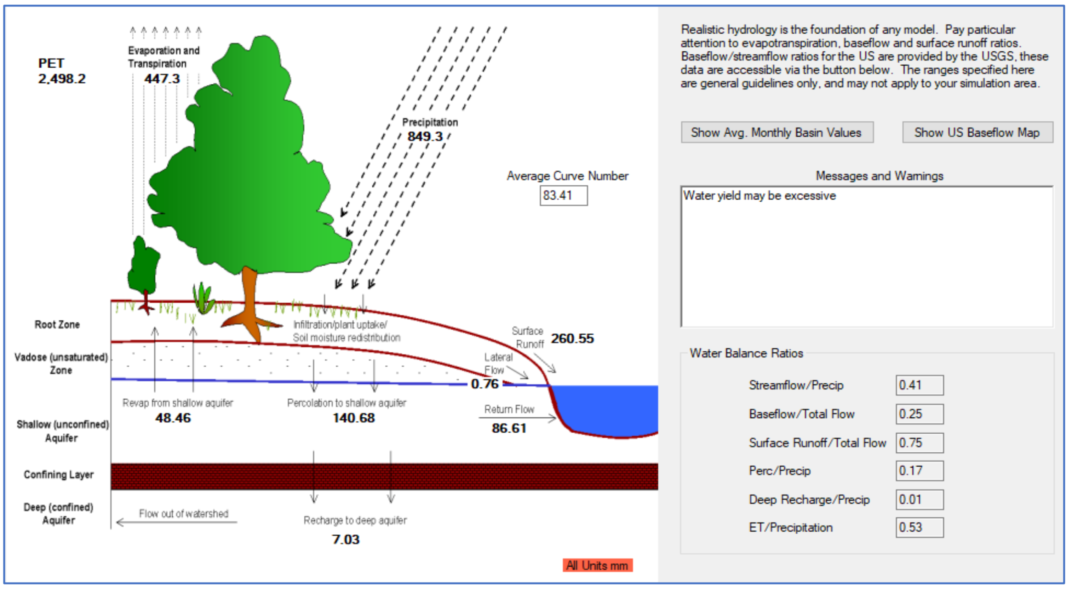


Fig. 5.6. Simulated monthly streamflow for Henval Catchment by different resolutions of DEMs.



Average Curve Number: 83.41

Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

Messages and Warnings

Water yield may be excessive

Water Balance Ratios

Streamflow/Precip	0.41
Baseflow/Total Flow	0.25
Surface Runoff/Total Flow	0.75
Perc/Precip	0.17
Deep Recharge/Precip	0.01
ET/Precipitation	0.53

Fig. 5.7. Annual Water balance components of Henval Catchment.

The findings of the study (**Fig. 5.5 & Fig. 5.6**) demonstrate that DEM choice has limited impact on long-term cumulative water availability but plays a critical role in capturing short-term variability and peak flow events. In conclusion, for water resource planning and long-term trend analysis, any of the DEMs can provide reliable results. However, higher-resolution DEMs offer distinct advantages for flood forecasting, event-based hydrological studies, and extreme flow management, as they more accurately capture the magnitude and timing of peak flows. Thus, DEM selection should be guided by the specific objectives of the study.

5.3 GEE-based Framework

In this study, a Google Earth Engine (GEE)-based program was successfully developed using the methodology outlined in Chapter 3. The developed GEE framework is versatile and can be applied to any region, enabling detailed analysis of water spread areas and corresponding water storage at rainwater harvesting (RWH) structures within a catchment. The framework supports evaluation using different DEMs [SRTM (90 m), Cop30, SRTM30, ALOS30, MERIT, CartoSAT (30 m), and ALOS PALSAR (12.5 m)] and varying check dam heights (1, 2, 3, 4, 5, 10, and 15 m), simply by providing either a probable outlet location or a catchment boundary.

The volumetric error analysis to account for differences among DEM sources has been carried out. These results are critical for developing design strategies that address key objectives such as enhancing storage, supporting groundwater recharge, managing floods, and meeting environmental flow requirements. Overall, the purpose of this study is to understand how DEM resolution and source influence water availability, water spread area and storage capacity estimation so that systematically these variations can be integrated into sustainable check dam planning.

5.4 Demonstration

As discussed in Section 5.2, four DEM datasets—SRTM (90 m), ASTER (30 m), CartoSAT (30 m), and ALOS (12.5 m)—were employed as topographic inputs to a SWAT model simulating flow conditions to assess water availability in the Henval catchment, Tehri-Garhwal District, Uttarakhand. Further, the developed GEE framework was demonstrated as a case study in the Henval Catchment. The detailed GEE-based framework and adapted methodology are presented in **Fig. 4.2.**

The water storage capacity of the RWH structure (hereafter referred to as a check dam) was estimated using topographic datasets of varying resolutions [SRTM 90 m, ASTER DEM 30 m, Copernicus30, ALOS30, MERIT 30 m, CartoSAT 30 m, and ALOS PALSAR 12.5 m]. The water spread area upstream of the check dam, along with the storage capacity within the dam, was assessed to support the development of effective RWH strategies, improve structural design, and better understand flood risk in the upstream areas of the Henval Catchment. These evaluations were carried out by varying check dam heights (1–15 m) and using seven DEMs from various open sources at different spatial resolutions (12.5 m, 30 m, and 90 m).

Fig. 5.8 and **Fig. 5.9** present the results for water spread area and water storage capacity, respectively, for different dam heights derived from the seven DEMs. The results clearly show that both the water-spread area and storage capacity vary with DEM resolution. Higher-resolution DEMs provide more accurate estimates, while coarser-resolution datasets introduce greater uncertainty and volumetric errors.

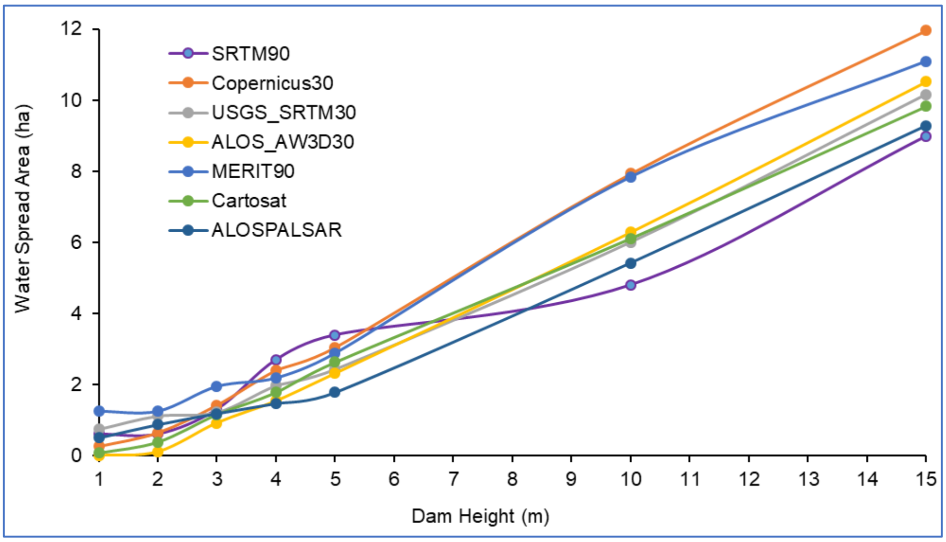


Fig. 5.8. Water spread area at the catchment outlet using multiple DEMs at different dam heights.

Fig. 5.8 to 5.10 illustrate how the water spread area and storage volume respond to increasing dam height across different DEMs. All datasets show a clear upward trend, confirming that both metrics increase with dam height. However, the magnitude of increase varies, affecting spatial estimates of water spread and storage capacity. This divergence highlights how DEM resolution and processing influence check dam capacity, with finer-resolution datasets capturing terrain depressions and basin contours more effectively.

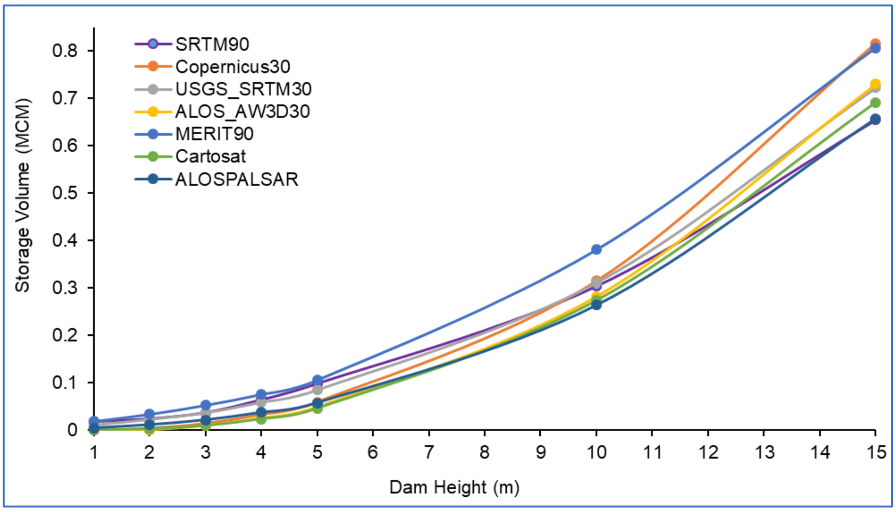


Fig. 5.9. Water storage at the catchment outlet using multiple DEMs at different dam heights.

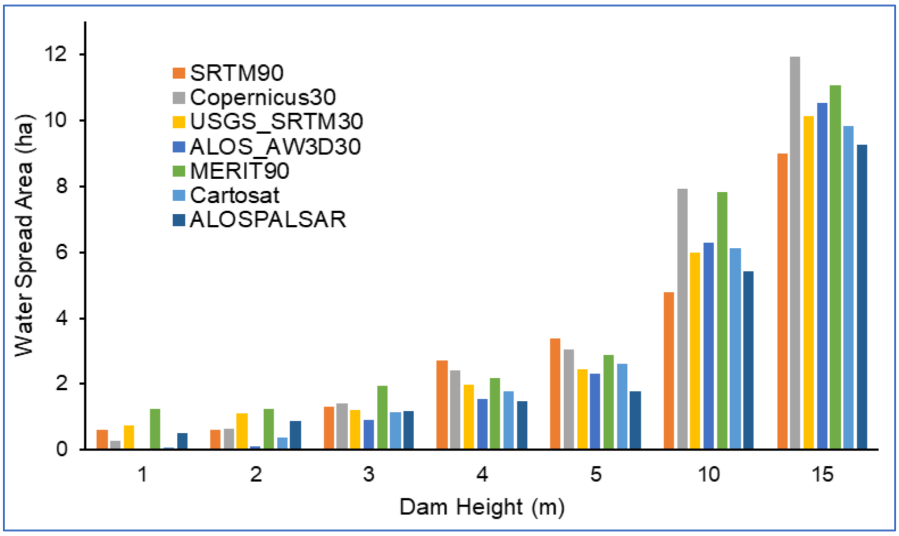
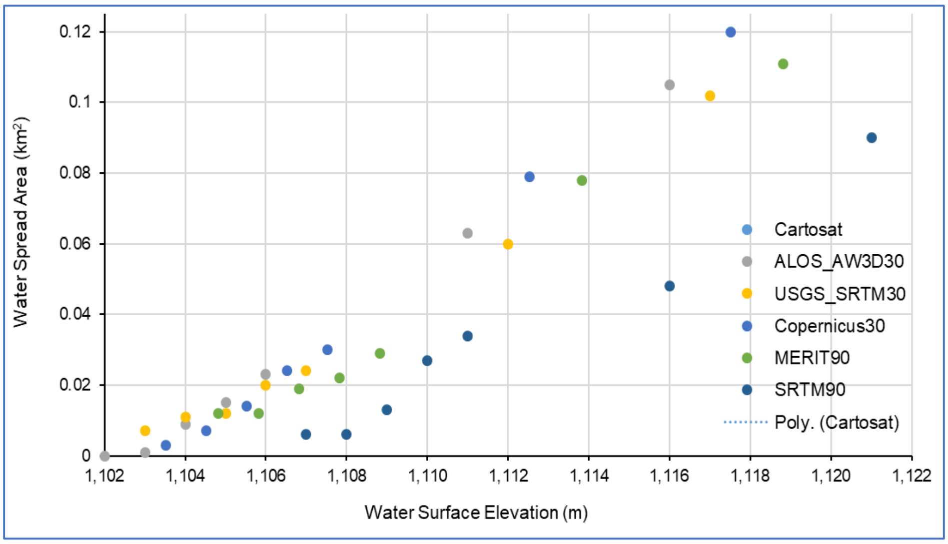
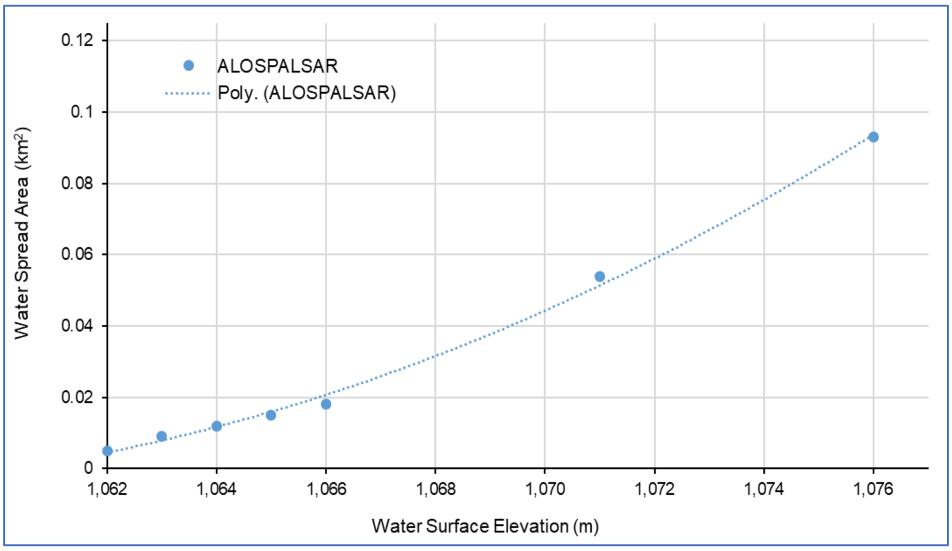


Fig. 5.10. Water spread area at the catchment outlet using multiple DEMs at different dam heights.

Elevation–area curves (**Fig. 5.11a&b**) show the surface area at a given check dam level, while elevation–storage curves (**Fig. 5.12a&b**) depict the volume stored at that level. These curves form the backbone of check-dam operations, planning, and water resource management.

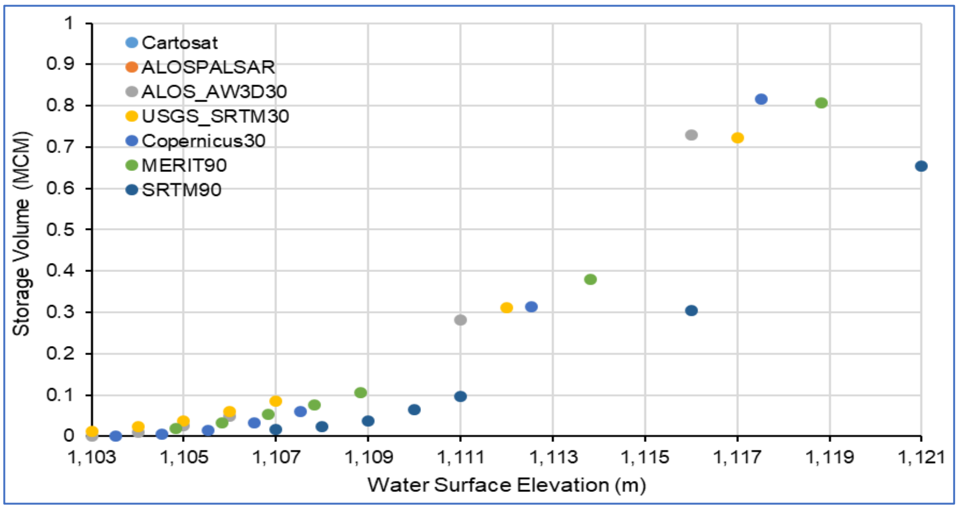


(a)

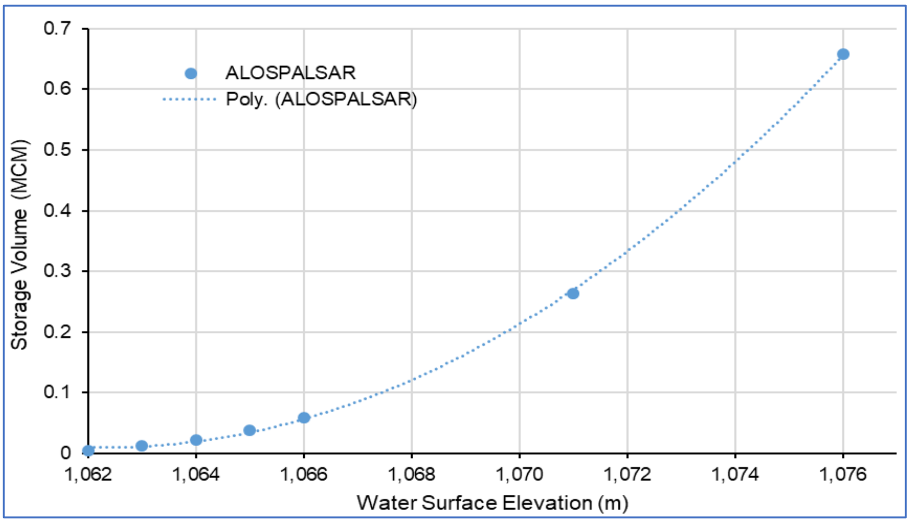


(b)

Fig. 5.11. a) Water spread area vs elevation at the catchment outlet using multiple DEMs at different dam heights.



(a)



(b)

Fig. 5.12. a) Water Storage vs Elevation at the catchment outlet using multiple DEMs at different dam heights.

Fig.5.13 demonstrates the nonlinear trend whereby incremental increases in surface area lead to disproportionately higher storage volumes. This has direct implications for check dam capacity planning, flood management, and dam safety assessments. Coarse-resolution datasets remain useful for broad regional assessments but must be applied cautiously in contexts requiring high precision.

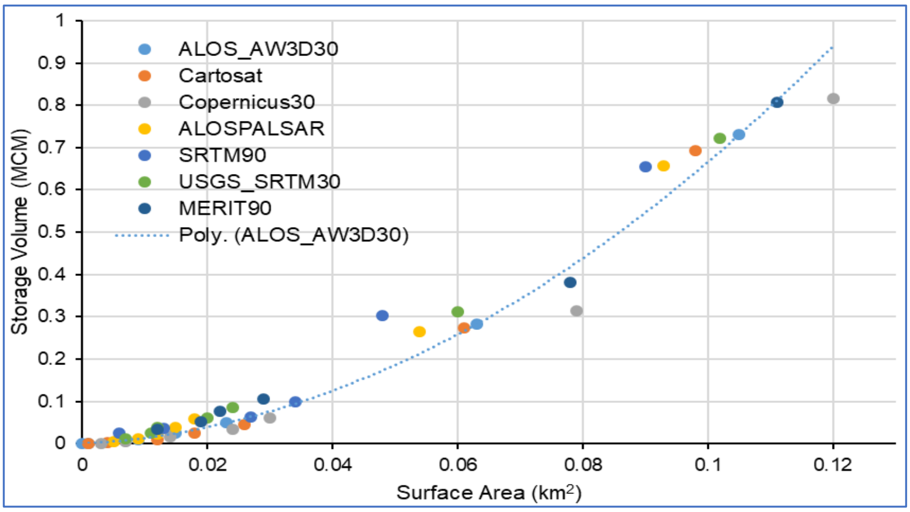


Fig. 5.13. Water Storage Volume vs. Surface area at the catchment outlet using multiple DEMs at different dam heights.

Fig. 5.14, a box plot reveal that at lower dam heights (1–2 m), both spread area and storage values are small and tightly clustered, indicating limited impoundment potential with relatively little disagreement among DEMs. At intermediate heights (3–5 m), the median spread area reaches 2–3 ha and storage capacity is about 0.1 MCM, with variability beginning to widen. At larger dam heights (10–15 m), both metrics increase sharply, with spread areas reaching 8–12 ha and storage approaching 0.6–0.8 MCM. DEMs diverge more strongly at these higher elevations:

MERIT90 and Copernicus30 consistently produce higher estimates, while ALOS_AW3D30 and CartoSAT yield lower or more variable values.

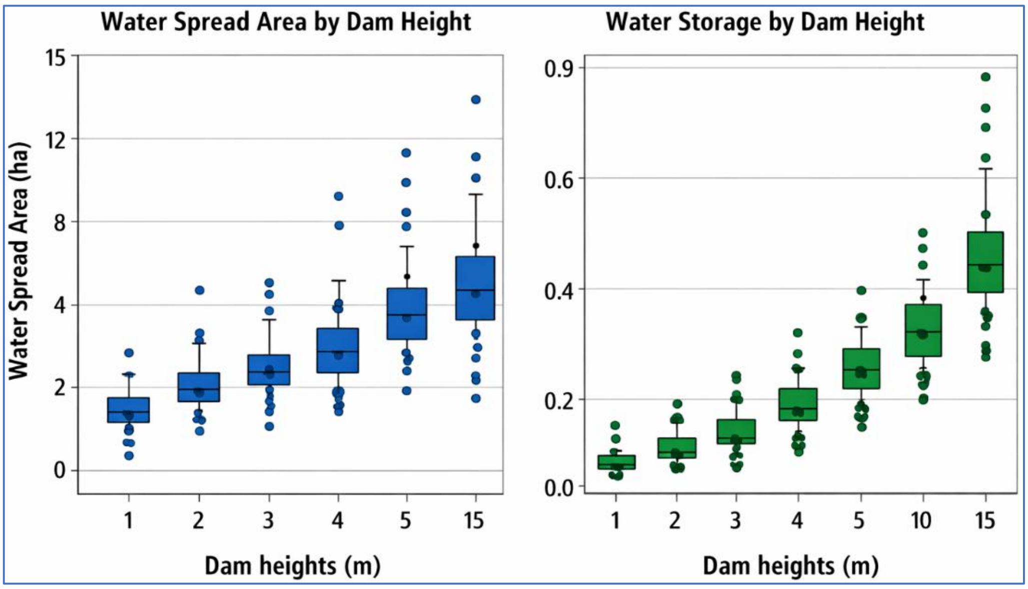


Fig. 5.14. Water spread area and water storage at the outlet of the catchment based on multiple DEMs at varying spatial resolutions & different dam heights.

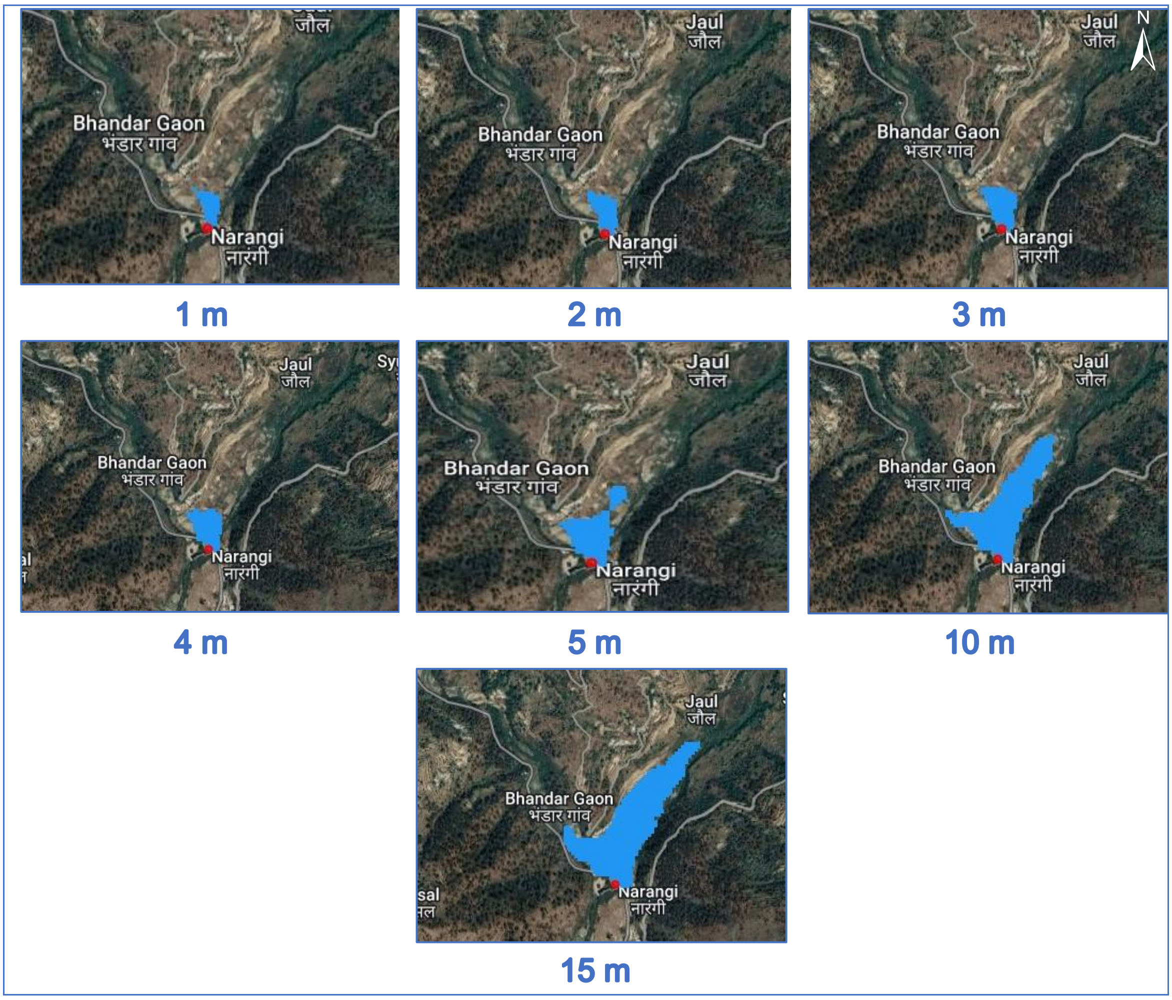
Table 5.5 provides detailed estimates of how dam height influences water spread area and storage, highlighting differences among DEM sources. At larger dam heights (10–15 m), spread areas reach 5–12 ha, and storage rises to 0.3–0.8 MCM. Copernicus30 and MERIT90 consistently report the largest values, while CartoSAT, ALOS PALSAR, and USGS SRTM30 provide slightly lower estimates. ALOS_AW3D30, which yielded very low values at low elevations, aligns more closely with other DEMs at higher elevations.

For example, spatial representations of the water-spread area at the Henval catchment outlet based on the ALOS PALSAR (12.5 m) DEM at different dam heights illustrate these differences (**Fig. 5.15**). Similarly, the GEE-based framework generates spatial representations of water-spread areas using other DEMs at varying resolutions for different dam heights, enabling comparative analysis and appropriate dataset selection.

Overall, the findings reveal that designing check dams or RWH structures using open-source topographic datasets requires careful consideration of DEM uncertainties and errors, which increase significantly with coarser resolution. Variability in storage estimates is more pronounced than in the spread area, especially at higher dam heights, reflecting the combined influence of horizontal extent and vertical depth on volumetric calculations. Reliance on a single dataset could lead to over- or underestimation of check dam potential, influencing management decisions.

Table 5.5. Water spread area and water storage at the outlet of the catchment based on multiple DEMs at varying spatial resolutions and different dam heights.

SN	Dam heights (m)	Water spread area (ha)							Water Storage (MCM)						
		SRTM90	Copernicus30	USGS_SRTM30	ALOS_AW3D30	MERIT90	Cartosat	ALOSPALSAR	SRTM90	Copernicus30	USGS_SRTM30	ALOS_AW3D30	MERIT90	Cartosat	ALOSPALSAR
1	1	0.615	0.267	0.745	0.004	1.248	0.077	0.509	0.018	0	0.012	0	0.019	0.001	0.005
2	2	0.615	0.654	1.119	0.112	1.248	0.387	0.882	0.024	0.005	0.024	0.001	0.034	0.003	0.012
3	3	1.312	1.428	1.221	0.923	1.944	1.161	1.192	0.037	0.015	0.038	0.01	0.053	0.01	0.022
4	4	2.705	2.404	1.97	1.542	2.183	1.781	1.476	0.064	0.034	0.06	0.026	0.076	0.024	0.038
5	5	3.402	3.049	2.434	2.316	2.879	2.632	1.785	0.098	0.06	0.086	0.049	0.106	0.046	0.058
6	10	4.807	7.931	6.007	6.286	7.834	6.116	5.424	0.304	0.315	0.312	0.282	0.381	0.274	0.264
7	15	8.988	11.957	10.157	10.525	11.086	9.832	9.276	0.655	0.816	0.723	0.73	0.807	0.692	0.658



1 m

2 m

3 m

4 m

5 m

10 m

15 m

Fig. 5.15. Water spread area at the outlet of the catchment based on ALOSPALSAR (12.5 m) DEM at different dam heights.

Therefore, these results underscore the critical role of DEM selection in hydrological modeling. A multi-DEM approach, supported by comparative analyses, is recommended to quantify uncertainty and enhance the robustness of hydrological simulations. This workflow can lead to more informed and resilient decisions about water infrastructure.

In summary, the study systematically quantifies the impact of varying DEM resolutions on water availability, spread area, and storage estimates to support effective check-dam design. Higher-resolution datasets provide more reliable estimates, while coarser datasets introduce significant uncertainty. These findings highlight the importance of fine-resolution data for sustainable rainwater-harvesting design and reliable hydrological modelling.

6. SUMMARY AND CONCLUSIONS

6.1 Summary

In the present study, a Google Earth Engine (GEE)-based program was developed for application to any region, enabling detailed analysis of water spread areas and corresponding storage at rainwater harvesting (RWH) structures using multiple Digital Elevation Models (DEMs) of varying spatial resolutions. The DEMs employed include SRTM (90 m) – CGIAR/SRTM90 V4, COP30 – Copernicus GLO30, SRTM30 – USGS SRTMGL1 003, ALOS30 – AW3D30 V3.2, MERIT V1.0.3, CartoSAT (30 m), and ALOS PALSAR (12.5 m). The program allows analysis by simply providing either a probable outlet location or a catchment boundary.

A demonstration was carried out in the Henval catchment, Tehri-Garhwal District, Uttarakhand, as a case study. Morphometric analysis of key parameters (e.g., stream length, stream order, and number of streams) was conducted across different DEMs to evaluate the influence of spatial resolution on morphometric attributes. Water availability in the Henval catchment was estimated using the SWAT model, with DEMs varied at different spatial resolutions while keeping other input parameters constant.

The water spread area and storage capacity were analyzed in upstream regions of potential storage structures, considering different check dam heights ranging from 1 m to 15 m and DEM inputs using the developed GEE program. Quantification and volumetric assessment of water availability, water spread area, and storage capacity were performed to support the development of effective RWH strategies in the catchment. Based on the findings, suitable recommendations were provided to guide RWH planning, particularly regarding the appropriate resolution of topographic data from different sources.

6.2 Conclusions

- DEM resolution significantly influences morphometric attributes such as stream length, stream order, and number of streams; higher-resolution DEMs capture finer stream networks, while coarser DEMs omit smaller streams.
- Long-term cumulative water availability estimates using SWAT are largely consistent across DEM resolutions, indicating robustness of DEM-based hydrological modeling for aggregated measures.
- Short-term variability and peak flows are better captured by higher-resolution DEMs, making them crucial for flood forecasting and event-based hydrological studies.
- The GEE-based framework effectively evaluates water spread area and storage capacity of check dams across varying DEMs and dam heights, enabling scalable and reproducible analysis.

- Higher-resolution DEMs provide more reliable estimates of water spread and storage capacity, while coarser datasets introduce greater uncertainty and volumetric errors, especially at larger dam heights.
- Variability in storage estimates is more pronounced than in the spread area, reflecting the combined influence of horizontal extent and vertical depth.
- Reliance on a single DEM dataset can lead to over- or underestimation of check dam potential, affecting water resource management decisions.

6.3 Recommendations

Based on the various findings of the study, the following recommendations are made:

- Employ multi-DEM approaches to quantify uncertainty and strengthen the robustness of hydrological simulations and check dam design.
- Use higher-resolution DEMs (e.g., ALOS PALSAR 12.5 m, CartoSAT 30 m) for applications requiring precision, such as flood forecasting, extreme flow management, and detailed RWH structure design.
- Apply coarse-resolution DEMs cautiously, restricting them to broad regional assessments rather than site-specific planning.
- Integrate volumetric error analysis into design strategies to improve storage estimation, groundwater recharge planning, and flood management.
- Leverage the GEE-based framework for scalable, comparative evaluation of DEMs, ensuring systematic integration of resolution-based variations into sustainable check dam planning.
- Align DEM selection with study objectives: cumulative water availability studies can rely on any DEM, while event-based hydrological analyses demand finer-resolution datasets.
- Leverage open-source DEMs as cost-effective tools, but supplement them with field validation and ground surveys for critical projects.
- Promote policy integration and stakeholder engagement to ensure that DEM-based hydrological insights translate into resilient water infrastructure decisions.

7. WAY FORWARD

The study recommended expanding research across diverse topographical regions to strengthen the findings and ensure the appropriate selection of datasets. Such datasets should account for varying constraints including data availability, cost, water resources, and acceptable margins of error to maximize the effectiveness of developing RWH strategies.

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The authors gratefully acknowledge the use of the topographic datasets in this study namely SRTM (90 m), ASTER DEM (30 m), and ALOS PALSAR (12.5 m) from NASA JPL, ASF DAAC and NRSC.

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SM Pingale
(Project Investigator)

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- Pingale SM., Patidar R., Rawat S.S., Khobragade S.D., Saini N., Qamar M.Z. (2024) *Investigating feasibility of open sources data for the estimation of catchment runoff, and water storage capacity of rainwater harvesting structures: A Review*. Proceeding of the 8th India Water Week 2024 (Partnership and cooperation for inclusive water development and management) organized by the Ministry of Jal Shakti, Government of India from 17 to 20 September, 2024. PN 70.

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SOFTWARE/DATA USED IN THE STUDY

1. ArcGIS
2. SWAT
3. DEM’s (SRTM 90; ASTER 30m; CartoSat (30 m), ALOS PALSAR 12.5 m)
4. LULC and Soil maps of the study area
5. Climatic data

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