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Contents

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NIPA PALM: THE MANGROVE JEWEL OF TROPICAL ESTUARIES

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The Nipa palm (*Nypa fruticans*) is a botanical marvel that has thrived for millions of years along the tidal estuaries and mangrove forests of Southeast Asia, India and the Pacific Islands. Unlike most palms, it grows horizontally with its trunk buried underground, giving rise to a lush canopy of feathery fronds that sway above the mudflats. This ancient species is not only ecologically vital but also culturally and economically significant, serving as a source of food, medicine, shelter and bioenergy for coastal communities.

Botanical Description

Nypa fruticans is the sole species in the subfamily Nypoideae of the palm family Arecaceae. It is a monocotyledonous plant with several distinctive features:

- **Growth Habit**: The trunk is subterranean and prostrate, branching underground to form dense clumps.
- **Leaves**: Pinnate leaves can reach up to 9 meters in length, emerging directly from the ground.
- **Flowers**: Inflorescences are unisexual; male flowers are borne on long spikes, while female flowers are globular and develop into fruit clusters.
- **Fruit**: The fruit is a large, woody, floating cluster of seeds that disperse via water currents, aiding in propagation.

This palm thrives in brackish water and muddy substrates, making it a keystone species in mangrove ecosystems.

Ecological Importance

The Nipa palm plays a crucial role in coastal ecology:

- **Soil Stabilization**: Its extensive root system binds soil, preventing erosion and protecting shorelines.
- **Habitat Creation**: Provides shelter and breeding grounds for fish, crustaceans and birds.
- **Carbon Sequestration**: Acts as a carbon sink, helping mitigate climate change.
- **Water Filtration**: Enhances water quality by trapping sediments and pollutants.

Its presence supports biodiversity and strengthens the resilience of mangrove ecosystems against rising sea levels and storm surges.

Medicinal Uses

Traditional medicine has long recognized the healing properties of the Nipa palm:

- **Antioxidant and Antibacterial**: Leaves and fruit contain phenolic compounds and flavonoids with antimicrobial activity.
- **Wound Healing**: Poultices made from young shoots are applied to cuts and skin infections.
- **Diabetes and Hypertension**: Fermented sap (vinegar) may help regulate blood sugar and blood pressure.
- **Anti-inflammatory**: Decoctions from leaves and fruit are used to treat joint pain and inflammation.

While these uses are promising, further pharmacological studies are needed to validate their efficacy and safety.

Ornamental Uses

Though not commonly cultivated for ornamental purposes, the Nipa palm offers aesthetic and ecological value:

- **Eco-landscaping**: Used in mangrove restoration and coastal beautification projects.
- **Botanical Gardens**: Featured in tropical exhibits for its unique morphology.
- **Cultural Symbolism**: Represents resilience and harmony with nature in coastal traditions.

Its dramatic fronds and ecological significance make it a visual and symbolic asset in sustainable landscaping.

Economic and Practical Uses

The Nipa palm is a multipurpose plant with wide-ranging applications:

- **Thatching and Weaving**: Leaves are durable and used for roofing, mats and baskets.
- **Food**: Immature seeds are sweet and gelatinous, consumed fresh or in desserts.
- **Alcohol and Vinegar Production**: Sap tapped from the inflorescence is fermented into vinegar or traditional alcoholic beverages like "tuba."
- **Construction Material**: Petioles and midribs are used in fencing and temporary structures.
- **Fuel and Bioenergy**: Dried leaves and fruit husks serve as biomass fuel; research is exploring its potential for bioethanol production.

These uses support rural economies and offer sustainable alternatives to synthetic materials and fossil fuels.

Cultural and Ethnobotanical Significance

The Nipa palm is deeply embedded in the cultural fabric of coastal communities:

- **Traditional Crafts**: Used in weaving, roofing and boat-making.
- **Festivals and Rituals**: Symbolizes fertility, protection and prosperity.
- **Folklore**: Featured in stories and songs that celebrate the harmony between humans and nature.

Its ethnobotanical relevance underscores the importance of preserving indigenous knowledge systems.

Environmental and Climate Resilience

As climate change intensifies, the Nipa palm offers hope for coastal resilience:

- **Salt Tolerance**: Thrives in saline and tidal conditions.
- **Flood Resistance**: Anchors soil and reduces flood impact.
- **Mangrove Rehabilitation**: Used in reforestation projects to restore degraded wetlands.

Its adaptability makes it a valuable ally in climate mitigation and ecosystem restoration.

Conservation and Sustainability

Despite its benefits, the Nipa palm faces threats:

- **Habitat Loss**: Urbanization and aquaculture encroach on mangrove zones.
- **Pollution**: Industrial waste and plastic debris affect its growth.
- **Overharvesting**: Unsustainable tapping and leaf collection can damage populations.

Conservation strategies include community-based management, sustainable harvesting practices and integration into agroforestry systems.

Research and Development

Ongoing studies are exploring the Nipa palm's potential in:

- **Phytochemistry**: Identifying bioactive compounds for pharmaceuticals.
- **Biofuel Production**: Evaluating sap and biomass for ethanol and biogas.
- **Ecological Impact**: Assessing its role in biodiversity and climate regulation.
- **Livelihood Programs**: Promoting its use in coastal development and poverty alleviation.

These efforts aim to unlock new applications while ensuring ecological balance.

Conclusion

The Nipa palm is more than a mangrove plant-it is a symbol of sustainability, resilience and cultural heritage. Its ecological role, medicinal potential and economic versatility make it a cornerstone of tropical estuarine ecosystems. As we face environmental challenges, conserving and cultivating the Nipa palm offers a pathway to harmonious coexistence with nature and a blueprint for sustainable development.

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HIDDEN ENGINES OF GROWTH: MICROBES FUELING PLANT NUTRITION

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Soil microorganisms, including bacteria, fungi, actinomycetes, and archaea, are fundamental to nutrient transformation and plant nutrition. Earlier research predominantly addressed single functions such as biological nitrogen fixation by *Rhizobium* or phosphate solubilization by *Pseudomonas*. Current studies emphasize the soil microbiome as an integrated system regulating nutrient cycling and plant-soil interactions. Metagenomic and high-throughput sequencing approaches have elucidated microbial diversity and functional networks. These insights support the development of biofertilizers and sustainable nutrient management strategies. Enhancing beneficial microbial consortia is therefore critical for advancing agricultural sustainability and global food security.

Introduction: Evolution of Soil Microorganisms in Plant Nutrition

The role of soil microorganisms in plant nutrition has advanced from basic observations to molecular-level insights (Adomako et al., 2020). Initially, studies focused on nitrogen-fixing bacteria such as *Rhizobium* in legumes, later extending to phosphorus-solubilizing bacteria and mycorrhizal fungi for nutrient mobilization and soil structure improvement (Pradhan et al., 2025). High-throughput sequencing has elucidated complex microbial networks regulating nutrient availability, pathogen suppression, and plant growth. Rhizosphere microbial diversity critically influences nutrient uptake efficiency, plant resilience, and ecosystem functioning (Pandey & Saharan, 2025). Harnessing these beneficial microbes as biofertilizers enhances crop productivity and nutrient use efficiency while reducing chemical fertilizer dependence, supporting sustainable agriculture (Shimada et al., 2024).

Nitrogen Fixation

Nitrogen is a vital nutrient for plants, required for proteins, nucleic acids, and chlorophyll. Although abundant in the atmosphere, N_2 is unavailable to plants until converted into ammonia by nitrogen-fixing microorganisms. Symbiotic bacteria like *Rhizobium* form nodules on legumes (Singh et al., 2023), while free-living diazotrophs such as *Azospirillum* enhance cereals (Bashan & de-Bashan, 2010). Cyanobacteria, including *Anabaena* and *Nostoc*, contribute significantly in paddy soils. Nitrogen fixation efficiency depends on microbial species, host plants, and soil conditions. Biofertilizers based on these microbes reduce chemical fertilizer dependence and promote sustainable agriculture.

Phosphorus Solubilization

Phosphorus (P) is a key macronutrient involved in energy transfer, root development, and overall plant growth. However, much of the soil P occurs in insoluble mineral forms, limiting its bioavailability. Phosphate-solubilizing microorganisms (PSMs) enhance P availability by secreting organic acids, chelators, or enzymes that release soluble P into the rhizosphere. Bacteria such as *Pseudomonas fluorescens* and *Bacillus megaterium* improve P uptake in crops like maize and tomato (Chen et al., 2006), while fungal PSMs, including *Aspergillus niger* and *Penicillium* spp., are particularly effective in acidic soils. The use of PSM-based biofertilizers improves crop productivity and reduces dependence on chemical P fertilizers, thereby supporting sustainable agriculture.

Potassium Mobilization

Potassium (K) is a vital macronutrient involved in enzyme activation, osmoregulation, stomatal regulation, and photosynthesis. Although soils contain large reserves of K, much of it is locked in insoluble minerals such as feldspars and micas. Potassium-solubilizing bacteria (KSB) release organic acids that mobilize K^+, making it plant-available (Siddiqui et al., 2008). Strains like *Bacillus mucilaginosus* and *Frateuria aurantia* enhance crop growth by improving K uptake in crops such as tomato and maize.

Micronutrient Availability

Soil microorganisms also play a pivotal role in mobilizing essential micronutrients such as iron (Fe), zinc (Zn), and manganese (Mn), which, although required in trace amounts, are critical for plant metabolism. Siderophore-producing bacteria like *Pseudomonas* spp. enhance

Fe solubility and uptake, thereby supporting chlorophyll biosynthesis and plant growth. Zinc-solubilizing bacteria, such as *Bacillus subtilis*, improve Zn availability in crops like wheat and rice, promoting enzymatic activities vital for growth and development (Yadav et al., 2023). Similarly, Mn-mobilizing bacteria facilitate Mn uptake, contributing to seedling vigor, stress tolerance, and photosynthetic efficiency.

Rhizosphere Interactions

The rhizosphere, the narrow zone of soil around plant roots, is a hotspot of plant–microbe interactions. Root exudates such as sugars, amino acids, and organic acids provide energy for microorganisms, which in turn release enzymes and metabolites that decompose organic matter and mobilize nutrients like nitrogen, phosphorus, and micronutrients (Berendsen et al., 2012). These interactions enhance nutrient cycling, root development, and plant health. For example, co-inoculation of *Azospirillum* and *Pseudomonas* in maize improves nutrient uptake, stimulates root growth, and increases disease resistance, highlighting the vital role of rhizosphere microbes in crop productivity.

Mycorrhizal Associations

Arbuscular mycorrhizal fungi (AMF) establish symbiosis with plant roots, extending hyphae into the soil to enhance nutrient uptake, particularly phosphorus and micronutrients. In maize, AMF inoculation can improve phosphorus acquisition by up to 40% under low-P conditions (Al-Karaki, 2006). They also strengthen plant tolerance to drought and abiotic stresses while improving soil aggregation. By reducing fertilizer dependence, AMF contribute significantly to sustainable agriculture and soil health.

Impact on Soil Fertility

Soil microorganisms enhance fertility by driving humus formation, soil aggregation, and nutrient cycling. Decomposition of organic matter produces stable humus that improves soil structure, aeration, and water retention (Lal, 2015). They also regulate the availability of nitrogen, phosphorus, potassium, and micronutrients. Synergistic interactions, such as AMF with nitrogen-fixing bacteria, enrich soil organic matter and boost crop productivity.

Challenges and Future Directions

The use of microbial inoculants enhances plant nutrition and soil health but faces challenges like environmental variability, soil differences, and competition with native microbes. Developing multi-strain consortia can improve nutrient mobilization (Vessey, 2003). Genomic and metagenomic tools help predict microbial function and resilience, enabling more effective biofertilizers. Integrating inoculants with precision agriculture ensures targeted application, promoting sustainable farming and reducing chemical fertilizer reliance (Bhattacharyya & Jha, 2012).

Conclusion

Soil microorganisms are vital for agroecosystems, enhancing plant nutrition, nutrient cycling, and soil structure while reducing dependence on chemical fertilizers. Biofertilizers, microbial consortia, and integrated soil management can sustainably improve crop productivity and soil fertility. To fully exploit their potential, further research is needed on microbial community dynamics, optimized inoculant formulations, and site-specific applications. Harnessing these interactions is key to advancing sustainable, productive, and environmentally friendly agriculture.

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RAINFALL RUNOFF MODELLING USING ArcSWAT

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Water is a very precious natural resource and at the same time very complex to manage. Therefore, this one-line objective is a mammoth task if this very precious resource has to be managed judiciously. A watershed is a hydrologic unit which produces water as an end product by interaction of precipitation and the land surface. The quantity and quality of water produced by the watershed are an index of amount and intensity of precipitation and the nature of watershed management. As fresh water resources are increasingly strained by agricultural and industrial usage, water conservation has become more and more important. As water demand increases, issues on water availability and demand become critical. This makes the management of water resources (assessing, managing and planning of water resources for sustainable use) a complex task. It has become more critical in places where rainfall is very low and erratic (Sowmiya & Arul, 2017). Land and Water are two important natural resources, as the entire life system depends on it. Effective management of these natural is very much important. The natural resources are mostly managed on the basis of watershed as natural unit. Watershed is a natural hydro geological entity bounded by a ridge line having single outlet. (Gavit et al., 2017)

The hydrological cycle has many interconnected components, with runoff connecting precipitation to bodies of water. Surface runoff is precipitation that does not infiltrate into the soil and runs across the land surface into surface waters (streams, rivers, lakes or other reservoirs). Surface runoff varies by time and location, with about one-third of the precipitation that falls on land turning into runoff; the other two-thirds is evaporated, transpired, or infiltrated into the soil. By returning excess precipitation to the oceans and controlling how much water flows into stream systems, runoff is important in balancing the hydrological cycle. The water balance equation governs the hydrological cycle by describing the flow of water into and out of a system for a specific period of time.(Knightes, 2017)

$$Q_S = P - ET - \Delta SM - \Delta GW$$

Where,

Q_S=surface runoff, P=precipitation, ET=evapotranspiration, ΔSM=change in soil moisture ΔGW=change in groundwater storage

Over the last few decades, a great stride is made on developing physically-based and distributed-parameter hydrological models (e.g., SWAT, SHE, AGNPS, etc.), which are capable of generating area-wise and hydrologic process-wise outputs over a watershed.

ArcSWAT 2012, a physical-based semi-distributed hydrological model having an interface with ArcView GIS software, Among the different kinds of models, semi-distributed models are the most efficient model for hydrological simulation as it exceeds the difficulties normally faced with fully distributed model and lumped model

Out of these models, the Soil and Water Assessment Tool (SWAT) is a continuous daily step, long period, physically based parameter, and distributed hydrologic model has been used widely to simulate agricultural watersheds management practices.

Model Input

ArcSWAT version 1.0.7 was used to prepare the input database for SWAT run.

Inputs:

1) Digital elevation model (DEM)
2) soils
3) land use land cover (LULC)
4) weather data of the study area (precipitation in daily details, solar radiation, maximum and minimum air temperature, wind speed, and relative humidity).

Sensitivity analysis of model: (Khayyun et al., 2019)

For Sensitivity analysis of model 7 to 8 parameters are considered for runoff estimation. They are given below:

i) ALPHA_BF: Base flow alpha factor (days),

ii) CH_K2: Effective hydraulic conductivity in main channel alluvium

iii) CH_N: Manning's roughness coefficient for the main channel,

iv) CN2: Initial SCS runoff curve number for moisture condition II,

v) ESCO: Soil evaporation compensation factor,

vi) GW_DELAY: Groundwater delay time (days).

vii) GWQMN: Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O),

Performance Evaluation of The Model

Following is used to evaluate the performance of the SWAT model simulation

1) Nash–Sutcliffe efficiency (ENS)
2) ratio of root-mean-square error (RMSE) to the standard deviation of observed data (STDEVobs), (RSR)
3) percent bias (Pbias)
4) coefficient of determination (R^2) was used for performance evaluation of the model

Nash-Sutcliffe Efficiency (N-S)

- Nash–Sutcliffe efficiency quantifies the variance of observed versus simulated data
- N-S values range between $-\infty$ and 1, where any ENS value greater or equal to zero indicated that the simulated value estimated the constituent of concern better than the mean observed value and an ENS value of one is a perfect simulation. The ENS values were calculated using the following equation:

$$E_{\mathrm{NS}} = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

Ratio of Root-Mean-Square Error (RMSE) To the Standard Deviation (RSR)

The ratio of root-mean-square error to the standard deviation is an error index statistic. Where, a perfect simulation will get if the values of RSR equal to zero and any RSR value less than 0.50 indicated an acceptable simulation. The RSR values were calculated using the following equation:

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV_{obs}}} = \frac{\sqrt{\sum_{i=1}^{n} (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2}}$$

Percent Bias Test

Percent bias test gives an indication about the average tendency of the simulated data to be greater than or less than the observed data.

Where any negative Pbias value indicates that the simulated data are greater than the observed data on average.

any positive Pbias value indicates that the simulated data is less than the observed data on average.

A perfect simulation will get if the Pbias is equal to zero. The Pbias values were calculated using the following equation:

$$P_{\mathrm{bias}} = \frac{\sum_{i=1}^{n} (O_i - S_i)}{\sum_{i=1}^{n} O_i} \times 100$$

Coefficient of Determination R^2

The R^2 describes the proportion of the variance between the measured data and that explained by the model.

Ranges of R^2 extend between 0 and 1, with higher values indicating an improved accuracy of the simulation, and typically values greater than 0.5 are considered acceptable.

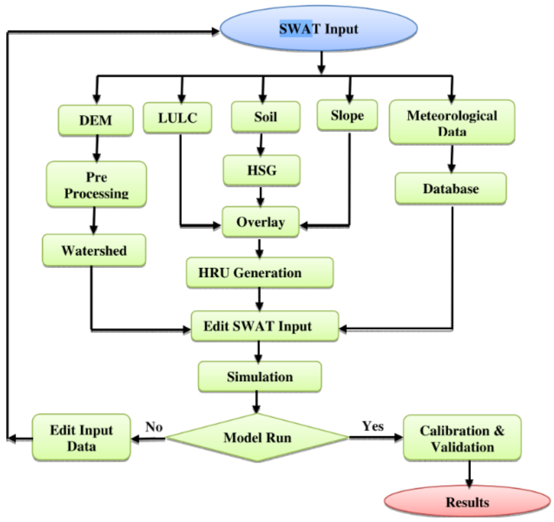
The R^2 values were calculated using the following equation:

$$R^2 = \frac{\left[\sum_{i=1}^{n} (O_i - \bar{O})(S_i - \bar{S})\right]^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sum_{i=1}^{n} (S_i - \bar{S})^2}$$

General performance ratings for recommended statistics in arc swat (Khayyun et al., 2019)

Performance rating	E_{NS}	RSR	P_{bias} (%)
Very good	$0.75 < E_{NS} \leq 1.00$	$0.00 \leq \mathrm{RSR} \leq 0.50$	$P_{\mathrm{bias}} < \pm 10$
Good	$0.65 < E_{NS} \leq 0.75$	$0.50 < \mathrm{RSR} \leq 0.60$	$\pm 10 \leq P_{\mathrm{bias}} < \pm 15$
Satisfactory	$0.50 < E_{NS} \leq 0.65$	$0.60 < \mathrm{RSR} \leq 0.70$	$\pm 15 \leq P_{\mathrm{bias}} < \pm 25$
Unsatisfactory	$E_{NS} \leq 0.\ 50$	$\mathrm{RSR} > 70$	$P_{\mathrm{bias}} \geq \pm 25$

Methodology flow chart (Gavit *et al.*, 2017)



Conclusion

ArcSWAT is a robust and scientifically sound tool for rainfall–runoff modelling and watershed-scale hydrological assessment. The model effectively represents key hydrological processes and demonstrates strong capability in simulating runoff responses under varying land use, soil, and climatic conditions. When appropriately parameterized, calibrated, and validated using standard statistical performance indicators, ArcSWAT can reliably support watershed management planning, evaluation of water conservation measures, and formulation of sustainable land and water resource management strategies. Its applicability is particularly significant in regions experiencing high rainfall variability and increasing stress on available water resources.

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OPEN-SOURCE GEOSPATIAL PLATFORMS FOR ECOSYSTEM SERVICE ASSESSMENT: TOOLS, FRAMEWORKS, AND APPLICATIONS IN NATURAL RESOURCE MANAGEMENT

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The world is undergoing rapid environmental change due to climate variability, land-use change, population growth, and increasing pressure on natural resources. Forests, agricultural lands, wetlands, and coastal ecosystems are being altered at an unprecedented pace, reducing their ability to provide essential benefits such as food, clean water, climate regulation, and protection from natural hazards. These benefits, known as ecosystem services, are fundamental to human well-being and sustainable development, yet they are increasingly under threat. The ecosystem services concept gained global recognition through initiatives such as the Millennium Ecosystem Assessment and was later strengthened by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. This framework helps explain how changes in ecosystems directly affect livelihoods, economies, and social stability. However, many ecosystem service assessments have traditionally relied on field surveys, expert opinion, or static maps, which often fail to capture spatial variation and long-term changes across large landscapes.

In the current era of global change, there is a growing need for clear, timely, and spatially detailed information on ecosystem services. Decision-makers require tools that can monitor ecosystem condition over time, identify areas of service loss or improvement, and support informed planning and management. This need has driven a shift toward modern, data-driven approaches that can assess ecosystem services consistently across regions and time, highlighting the importance of open-source geospatial platforms in natural resource management.

Conceptual Framework of Ecosystem Service Assessment

The concept of ecosystem services provides a structured way to understand how nature supports human societies. It was formally introduced through the Millennium Ecosystem Assessment and later refined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. At its core, the framework recognises that ecosystems do not only have ecological value, but also deliver a wide range of benefits that contribute directly and indirectly to human well-being.

Ecosystem services are commonly grouped into four broad categories. Provisioning services include tangible goods such as food, freshwater, fuelwood, and fibre. Regulating services refer to the regulation of ecological processes, including climate regulation, flood control, carbon sequestration, and water purification. Cultural services capture non-material benefits such as recreation, aesthetic values, spiritual significance, and cultural heritage. Supporting services, such as soil formation, nutrient cycling, and primary productivity, underpin the functioning of all other services. A key principle of ecosystem service assessment is the need for spatial and temporal explicitness. Ecosystem services vary across landscapes and change over time in response to land-use change, management practices, and climate variability. Modern conceptual frameworks therefore emphasise linkages between ecosystem structure, ecological processes, service flows, and human benefits. This integrated perspective is essential for identifying trade-offs and synergies among services and for translating scientific knowledge into practical guidance for natural resource management and policy planning.

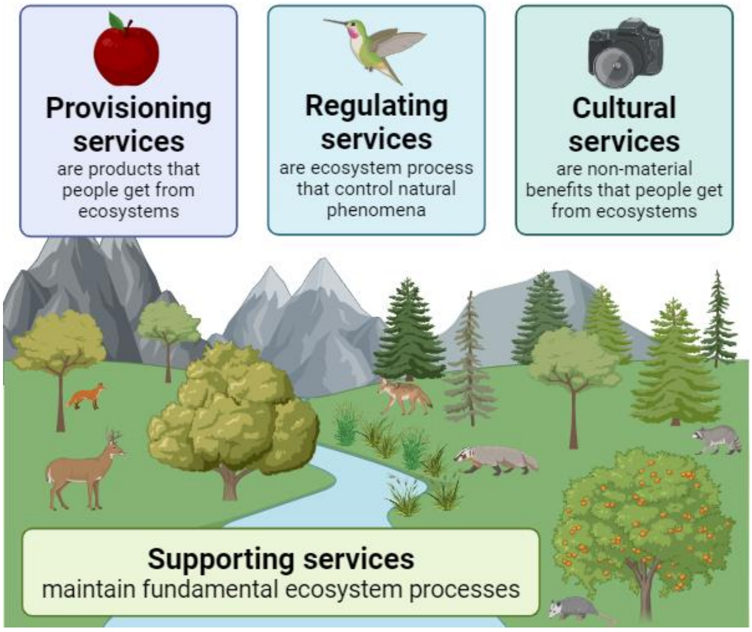

Fig. 1: Different type of ecosystem services

Open-Source Geospatial Big Data: A Paradigm Shift

Advances in Earth observation and digital technologies have led to an unprecedented increase in the volume, variety, and availability of geospatial data. This transformation, often described as geospatial big data, has fundamentally changed how ecosystems are observed, analysed, and managed. Open-access satellite archives, climate reanalysis products, and global environmental datasets now provide continuous, long-term records of land, water, and atmospheric processes, enabling ecosystem service assessment at scales that were previously impossible.

Open-source geospatial big data is characterised by large spatial coverage, high temporal frequency, and methodological transparency. Freely available satellite missions such as Landsat and Sentinel offer consistent multi-decadal observations of land-use and land-cover dynamics, vegetation condition, surface water extent, and coastal change. When combined with open climate and environmental datasets, these data allow researchers to link ecosystem structure and function with service provision across regions and time periods.

This shift represents a clear departure from traditional ecosystem service assessments that relied heavily on local field measurements, static maps, or costly proprietary datasets. Open-source geospatial big data enables scalable, repeatable, and cost-effective analyses, making ecosystem service science more inclusive and accessible, particularly in data-limited regions. Importantly, it supports comparative assessments across landscapes, monitoring of long-term trends, and rapid evaluation of management interventions. As a result, geospatial big data has become a cornerstone of modern ecosystem service assessment and a critical enabler of evidence-based natural resource management.

Core Open-Source Platforms for Ecosystem Service Assessment

The assessment of ecosystem services at landscape to regional scales increasingly relies on open-source geospatial platforms that integrate large data repositories, advanced analytics, and reproducible workflows. These platforms operate at different levels—cloud computing, desktop spatial analysis, and scientific programming—but together form a cohesive analytical ecosystem for modern natural resource management. More recently, the integration of GeoAI (geospatial artificial intelligence) has further enhanced the ability to extract meaningful ecosystem service information from complex and high-volume datasets.

Google Earth Engine

Google Earth Engine is a cloud-based geospatial analysis environment that provides direct access to multi-petabyte archives of satellite imagery and global environmental datasets. Its key strength lies in the ability to perform large-scale, multi-temporal analyses without the need for local data storage or high-end computing infrastructure. In ecosystem service assessment, Google Earth Engine is widely used for land use and land cover mapping, vegetation condition monitoring, surface water dynamics, coastal change analysis, and estimation of proxies related to carbon storage and climate regulation. The platform supports machine learning algorithms such as random forests and gradient boosting, enabling rapid and consistent mapping of ecosystem service indicators across large regions.

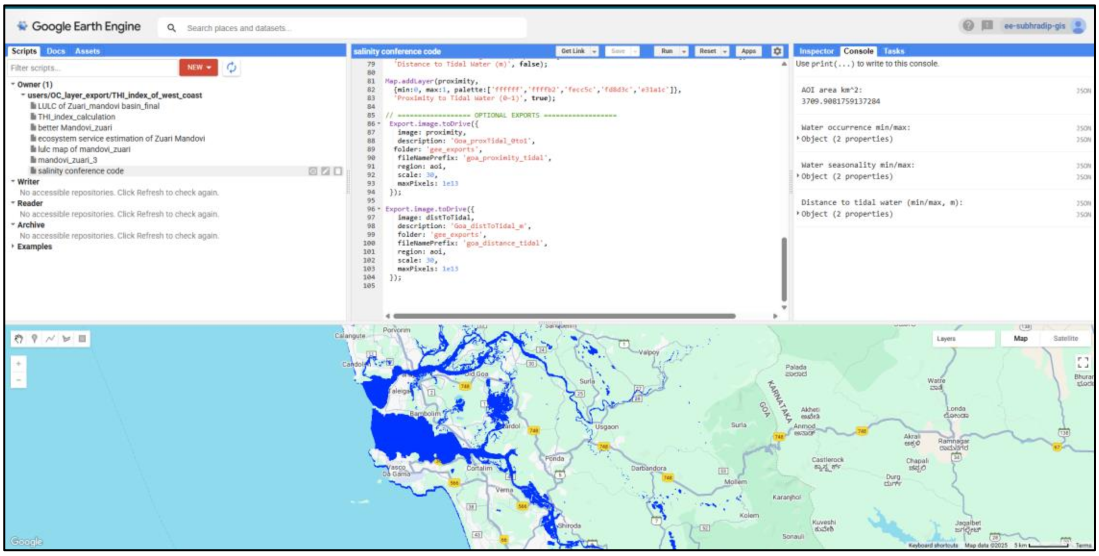

Fig. 2: Google Earth Engine Code Editor

QGIS

QGIS plays a critical complementary role by providing robust tools for spatial analysis, visualization, and decision-oriented mapping. While cloud platforms excel at data processing, QGIS is often used for refining outputs, conducting spatial overlays, generating zonal statistics, and integrating local datasets such as administrative boundaries or field observations. Its interoperability with GRASS GIS and SAGA allows for advanced terrain, hydrological, and landscape analyses that are essential for understanding ecosystem service distribution and spatial trade-offs at finer scales.

Python, GeoAI, and Scientific Computing Ecosystems

Python has become central to ecosystem service assessment due to its powerful open-source geospatial and scientific libraries. Tools such as xarray, rasterio, geopandas, and scikit-learn enable efficient handling of large spatio-temporal datasets, advanced statistical modelling, and automation of complex analytical workflows. The emergence of GeoAI, which applies artificial intelligence and machine learning to geospatial data, has further expanded analytical capabilities. Deep learning and ensemble models are increasingly used to improve land cover classification, detect ecosystem changes, and model relationships between environmental drivers and ecosystem service supply. Together, Python-based tools and GeoAI approaches support more accurate, scalable, and reproducible ecosystem service assessments suited to contemporary natural resource management challenges.

Methodological Framework for Ecosystem Service Assessment

A robust ecosystem service assessment requires a clear, transparent, and reproducible methodological framework that links geospatial data, ecological understanding, and decision-making needs. Open-source geospatial platforms enable such a framework by supporting systematic analysis across spatial scales and time periods. Although specific methods may vary by ecosystem and service type, most ecosystem service assessments follow a common sequence of analytical steps.

The first step involves defining the spatial boundary of the assessment. This may include administrative units, watersheds, landscapes, coastal belts, or agro-ecological regions, depending on the management objective. Clearly defined boundaries ensure consistency in data extraction, analysis, and interpretation. This is followed by land use and land cover (LULC) characterisation, which provides the structural basis for ecosystem service assessment. LULC maps derived from satellite imagery serve as a primary input for identifying ecosystem types and tracking changes over time. The next step focuses on the derivation of biophysical indicators that act as proxies for ecosystem services. These indicators may include vegetation indices, productivity metrics, surface water extent, soil moisture, or temperature-based variables, depending on the service being assessed. Open-source platforms allow these indicators to be generated consistently across large areas and multiple years, supporting temporal trend analysis and comparison across regions. Subsequently, spatial analysis and aggregation are conducted to identify ecosystem service hotspots, areas of decline, and spatial patterns of service provision. This stage often includes zonal statistics, landscape metrics, and multi-criteria analysis. Where relevant, trade-offs and synergies among ecosystem services are examined to understand how changes in land use or management affect multiple services simultaneously.

Finally, validation using field data, secondary datasets, or expert knowledge is essential to ensure credibility and applicability of results. Together, these steps form a flexible yet structured methodological framework that supports evidence-based ecosystem service assessment and informs sustainable natural resource management.

Spatially Explicit Valuation of Ecosystem Services

While biophysical assessment helps quantify the supply and distribution of ecosystem services, valuation adds an additional layer by linking ecosystem services to human benefits and decision-making processes. Spatially explicit valuation integrates ecological indicators with economic, social, or policy-relevant metrics, allowing ecosystem services to be compared, prioritised, and communicated in a form that is meaningful to planners and resource managers.

Ecosystem service valuation can be broadly categorised into monetary and non-monetary approaches. Monetary valuation translates ecosystem service flows into economic terms using methods such as market pricing, avoided cost, replacement cost, or benefit transfer. In geospatial frameworks, this is often achieved by linking spatially derived ecosystem service indicators—such as carbon storage, water regulation, or biomass productivity—with location-specific valuation coefficients. This spatial integration enables the identification of high-value ecosystem service hotspots and supports scenario analysis under alternative land-use or management options. Non-monetary valuation approaches, including indices, scoring systems, and participatory assessments, are equally important, particularly where monetary valuation is inappropriate or ethically contested. Spatial mapping of service importance, vulnerability, or demand provides insights into social and ecological priorities without reducing ecosystem values to purely economic terms. Open-source geospatial platforms facilitate such approaches by enabling the overlay of ecological indicators with socio-economic and demographic data.

A critical consideration in spatial valuation is the management of uncertainty and scale effects. Proxy-based indicators, transfer coefficients, and data resolution can influence valuation outcomes, necessitating transparency and sensitivity analysis. Spatially explicit valuation should therefore be viewed as a decision-support tool rather than an exact measure of ecosystem worth, helping to balance development objectives with long-term ecosystem sustainability in natural resource management.

Applications in Natural Resource Management

The integration of open-source geospatial platforms into ecosystem service assessment has significantly expanded their practical application in natural resource management. By providing spatially explicit and temporally consistent information, these approaches support informed decision-making across a wide range of ecosystems and management contexts. In agricultural landscapes, ecosystem service assessments are increasingly used to evaluate productivity, soil health, water regulation, and carbon sequestration. Spatial analysis of vegetation dynamics, evapotranspiration, and land-use change helps identify areas of declining soil and water services, assess the impacts of management practices, and support climate-smart agriculture planning. Such applications are particularly valuable for balancing food production with long-term ecosystem sustainability.

In forest and plantation systems, geospatial ecosystem service assessments contribute to monitoring biomass, carbon storage, habitat integrity, and regulating services such as climate and hydrological regulation. Time-series analysis enables the detection of deforestation, degradation, and regeneration trends, supporting sustainable forest management and restoration planning. These insights are increasingly used in climate mitigation strategies and biodiversity conservation initiatives.

Coastal and estuarine ecosystems benefit from spatially explicit assessment of services such as shoreline protection, fisheries support, and blue carbon storage. Open-source satellite data and geospatial tools allow for regular monitoring of mangroves, wetlands, and shoreline dynamics, helping to identify vulnerable areas and evaluate the impacts of development and climate-driven hazards. This information is critical for coastal zone management and adaptation planning.

In urban and peri-urban areas, ecosystem service assessment supports the evaluation of regulating and cultural services provided by green spaces, urban forests, and water bodies. Spatial mapping of heat mitigation, air quality regulation, and recreational services informs urban planning aimed at enhancing livability and resilience. Collectively, these applications demonstrate how open-source geospatial ecosystem service assessments can bridge science and practice, supporting sustainable and resilient natural resource management.

Advantages and Limitations of Open-Source Approaches

Open-source geospatial platforms offer several advantages that have made them central to contemporary ecosystem service assessment. One of the most significant strengths is cost-effectiveness, as freely available data and software reduce financial barriers for researchers and institutions, particularly in developing and data-scarce regions. Open-source tools also promote transparency and reproducibility, allowing methods and results to be verified, improved, and reused by the wider scientific community. The availability of long-term, globally consistent datasets enables comparative analyses across regions and time, supporting robust monitoring of ecosystem service dynamics. In addition, open-source platforms facilitate capacity building by encouraging skill development and interdisciplinary collaboration among ecologists, geographers, economists, and data scientists.

Despite these advantages, open-source approaches also face important limitations. Many ecosystem service assessments rely on proxy indicators, which may not fully capture complex ecological processes or local conditions. Limited availability of high-quality field data can constrain validation and introduce uncertainty into spatial analyses. Differences in data resolution, classification accuracy, and methodological choices can influence results, highlighting the need for careful interpretation. Furthermore, effective use of open-source geospatial platforms often requires technical expertise in programming, spatial analysis, and ecological modelling, which may limit adoption among practitioners without adequate training.

Recognising both strengths and limitations is essential for responsible application of open-source approaches. When combined with field observations, stakeholder knowledge, and sound ecological understanding, open-source geospatial platforms provide a powerful and credible foundation for ecosystem service assessment and natural resource management.

Future Directions and Research Priorities

As ecosystem service science continues to evolve, open-source geospatial approaches are expected to play an increasingly strategic role in natural resource management. One key research priority is the deeper integration of field-based observations with remote sensing and geospatial analytics, enabling more accurate calibration and validation of ecosystem service indicators. Strengthening these linkages will help reduce uncertainty associated with proxy-based assessments and improve confidence in spatial valuation outputs.

The application of GeoAI and advanced machine learning represents another important frontier. Artificial intelligence can enhance land-use classification accuracy, detect subtle ecosystem changes, and model complex, non-linear relationships between environmental drivers and ecosystem service supply. Coupling GeoAI with near-real-time satellite data offers opportunities for early warning systems and adaptive ecosystem management.

Future research should also focus on developing region- and ecosystem-specific valuation coefficients that reflect local ecological conditions and socio-economic contexts, rather than relying solely on global averages. In addition, stronger science–policy interfaces are needed to ensure that ecosystem service assessments are translated into actionable guidance for planners and decision-makers. Addressing these priorities will help position open-source geospatial ecosystem service assessment as a core component of sustainable and resilient natural resource governance.

Conclusion

Open-source geospatial platforms have transformed ecosystem service assessment by enabling spatially explicit, transparent, and scalable analysis across diverse ecosystems and management contexts. By integrating Earth observation data, advanced analytics, and reproducible workflows, these approaches allow ecosystem services to be monitored and evaluated in ways that are directly relevant to contemporary natural resource challenges. More importantly, they support a shift from descriptive assessments toward evidence-based, data-driven ecosystem governance**.**

As pressures from climate change and land-use intensification continue to grow, informed decision-making will depend on timely and reliable information on ecosystem condition and service provision. Open-source geospatial tools provide a practical pathway to bridge science and policy, empowering institutions and practitioners to design resilient, sustainable, and equitable natural resource management strategies. Their effective adoption, supported by capacity building and interdisciplinary collaboration, will be critical for safeguarding ecosystem services and ensuring long-term environmental sustainability.

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SPRINGSHED MANAGEMENT FOR REVIVING MOUNTAIN SPRINGS: A NATURE-BASED PATHWAY TO WATER SECURITY

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Springs constitute the most critical and dependable freshwater sources in India's mountainous and hill regions. In the Himalayas, Western Ghats, Eastern Ghats and associated hill systems, springs serve as the primary source of drinking water, support subsistence agriculture, sustain livestock, and maintain ecological flows in rivers during the lean season. Recognising their strategic importance, the Ministry of Jal Shakti has identified spring revival as a national priority, noting that nearly half of India's perennial springs have either dried up or become seasonal due to a combination of climatic, geological, and anthropogenic factors. The Ministry's document *"Springshed Management in the Mountainous Regions of India"* marks a paradigm shift in water management by formally recognising that springs are not isolated discharge points but manifestations of complex groundwater systems governed by recharge areas, subsurface geology, land use, and ecological health. Springshed management, therefore, focuses on restoring the natural processes that sustain spring flow rather than relying on extraction-based or outlet-centric interventions.

***Fig. 3**: Different components of Spring System*

Concept of Springshed: A Shift from Surface Watershed Thinking

A spring is the visible expression of groundwater emerging at the surface when subsurface flow paths intersect the land surface. The area that contributes recharge to this groundwater system is referred to as the springshed. Unlike surface watersheds, which are defined by topographic divides, springsheds are governed by subsurface geological controls such as fractures, faults, lithological contacts, and weathered zones.

Springsheds often extend across multiple surface watersheds and administrative boundaries. As a result, conventional watershed development programmes frequently fail to revive springs because they do not adequately address the actual recharge zones. Springshed management therefore requires a hydrogeology-driven approach that integrates geology, geomorphology, land use, vegetation, and community institutions.

Free-flowing Springs and Seep Springs

Springs in mountainous regions commonly occur as either free-flowing springs or seep springs, each reflecting distinct hydrogeological condition. Free-flowing springs discharge water at a well-defined point, often with a continuous and visible flow. These springs are typically controlled by fractures, joints, or contacts between permeable and impermeable rock formations. Because of their concentrated discharge, free-flowing springs are frequently developed for piped water supply systems but are also more vulnerable to disruption if recharge pathways are disturbed. In contrast, seep springs emerge diffusely over slopes as slow oozing or damp zones rather than a single outlet. They are associated with shallow aquifers, weathered rock layers, and soil–rock interfaces. Although individual discharge rates are low, seep springs play a crucial role in maintaining soil moisture, supporting vegetation, stabilising slopes, and sustaining baseflow to streams. The Ministry's framework recognises that seep springs are often overlooked but are hydrologically and ecologically significant, particularly in forested and grassland landscapes.

Fig. 2: (A) Free Flow Spring & (B) Seep Spring

Classification of Springs Based on Geo-hydrological Conditions

Springs in mountainous regions can be classified according to the geological and hydrological mechanisms controlling groundwater movement and also correct identification of spring type and aquifer conditions is fundamental for designing effective rejuvenation strategies, as recharge mechanisms and response times vary significantly among different spring classes.

1. **Depression springs:** These springs discharge where the ground surface intersects the water table, representing the upper surface of the aquifer (Fig. 3). Such springs are generally found in undulating topography where slopes change abruptly and the water table tends to intersect the topography in depressions.

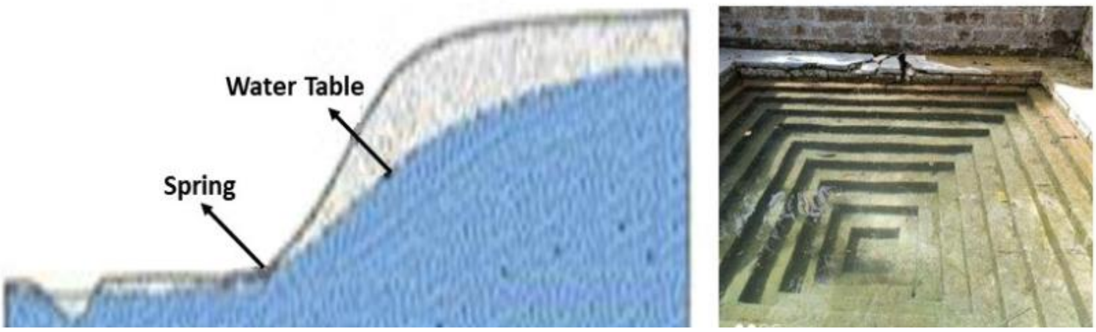

Fig. 3: Conceptual diagram of Depression Spring

2. **Contact springs:** These springs where a permeable water bearing formation overlies a less permeable or impermeable formation intersects the ground surface (Fig. 4). Occurrence of a number of springs in a horizontal line pattern indicate the existence of contact springs in the area.

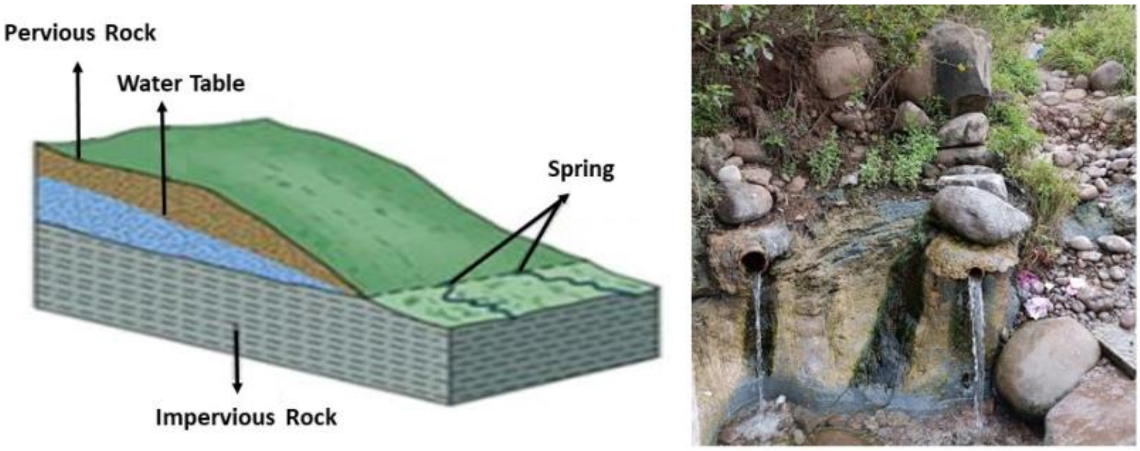

Fig. 4: Conceptual diagram of Contact Spring

3. **Fracture/fault spring**: These springs originate from water-bearing fractures or faults in the Earth's crust that intersect the topography along specific areas. In these springs, water seeps into the ground, navigating through geological fractures or faults, and eventually emerges as a spring on the Earth's surface (Fig. 5). Genesis of number of springs along a vertical line pattern are the indication of fracture or fault springs in the area.

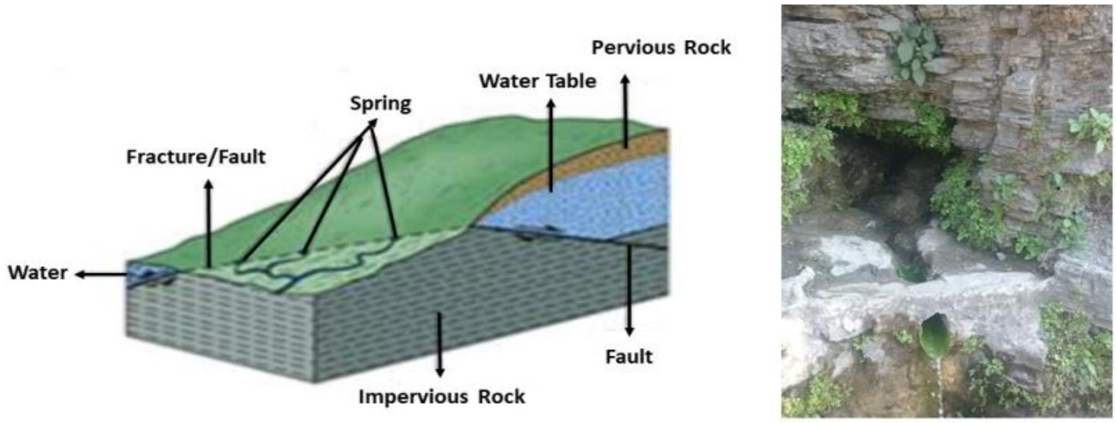

Fig.e 5: Conceptual diagram of Fracture/fault Spring

4. **Karst springs:** These springs are the typical example of springs originating from limestone or dolomite lithology. In Karst springs, water flow within sinkholes or cavities formed in carbonate rocks due to the dissolution of rock material by chemical action (Fig. 6). Over time, these cavities get enlarged due to continuous dissolution, forming caves from which groundwater emerges.

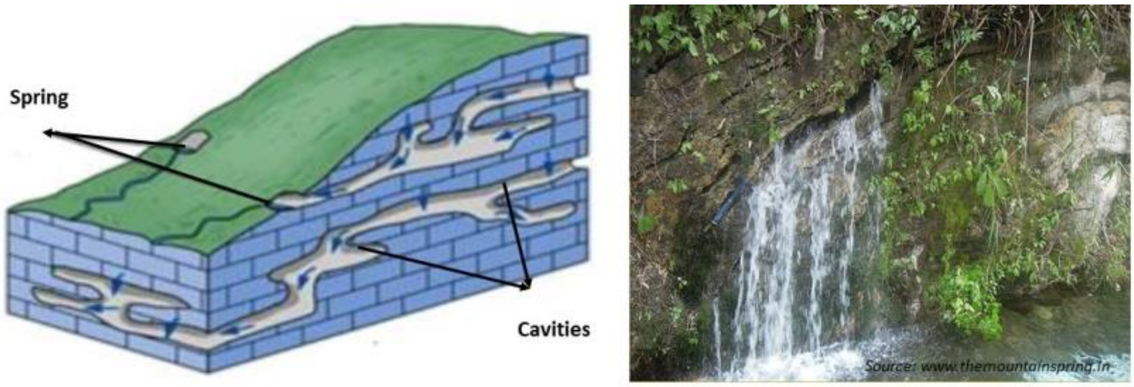

Fig. 6: Conceptual diagram of Karst Spring

Causes of Spring Degradation in Mountainous Regions

Spring discharge decline is primarily attributed to changes in recharge dynamics rather than reduced rainfall alone. Increasing rainfall intensity combined with shorter duration leads to higher surface runoff and reduced infiltration. Deforestation, loss of forest litter, road cutting, construction activities, and unregulated tourism disrupt natural recharge pathways. Climate change further compounds these issues by altering precipitation patterns, reducing winter snowfall, and increasing evapotranspiration. Springs act as early indicators of groundwater stress, and their drying reflects broader degradation of mountain aquifers. Addressing spring decline therefore contributes not only to drinking water security but also to long-term groundwater sustainability.

Springshed management is conceptualised as a phased and systematic process. It begins with spring inventory and mapping, followed by hydrogeological assessment to delineate recharge zones. Treatment measures are then implemented primarily in recharge areas rather than at the spring outlet. These measures aim to enhance infiltration, increase subsurface storage, and protect recharge pathways. Structural interventions such as contour trenches, staggered trenches, percolation pits, recharge shafts, and small check dams are combined with eco-hydrological measures including afforestation with native species, grass bunding, mulching, and protection of forest litter layers. The emphasis is on low-cost, decentralised, and nature-based solutions that work with the terrain rather than against it.

Spring outlets are protected through spring chambers, fencing, and diversion drains to prevent contamination. The Ministry also underscores the importance of water quality protection by regulating sanitation, waste disposal, and land-use practices within recharge zones.

Institutional Framework and Community Participation

Springshed management, as articulated by the Ministry of Jal Shakti, is inherently community-centric. Since recharge areas often extend beyond village or administrative boundaries, collective governance mechanisms are essential. Village water committees, Panchayati Raj Institutions, and local user groups are encouraged to take ownership of monitoring, maintenance, and regulation of spring use. The framework also promotes convergence with national programmes such as the Jal Jeevan Mission, MGNREGA, and watershed development projects like PMKSY to ensure financial sustainability and institutional support. Continuous monitoring of discharge, rainfall, and water quality is integral to adaptive management and long-term success.

Outcomes and Significance for Water Security

Evidence documented by the Ministry shows that scientifically planned springshed interventions can significantly enhance spring discharge, improve dry-season water availability, and reduce dependence on tanker water and deep borewells. Beyond drinking water security, revived springs contribute to improved agricultural productivity, enhanced ecosystem services, and sustained baseflows in rivers.

Springshed management thus represents a transition from extraction-driven water supply models to recharge-oriented, ecosystem-based groundwater governance, aligning with climate adaptation and sustainable development goals.

Conclusion

Springshed management framework provides a robust scientific and institutional foundation for reviving India's drying springs. By recognising springs as integral components of groundwater systems and addressing their recharge areas through hydrogeological understanding, ecological restoration, and community stewardship, springshed management offers a resilient pathway to water security in mountainous regions.

As climate variability intensifies and groundwater stress deepens, the revival of free-flowing and seep springs through springshed management will be indispensable for sustaining rural livelihoods, protecting fragile ecosystems, and securing India's water future.

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