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Fluvio-Structural Evolution and Geospatial Delineation of Groundwater Potential Zones in a Proterozoic Sedimentary Basin: The Ton River Basin, Central India

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***Abstract*— This study presents a multi-parametric quantitative assessment of the fluvio-structural controls, drainage morphometry, and hydro-geomorphological zonation of the Ton River Basin (~1,850 km² area) located within the Proterozoic Vindhyan Supergroup of Madhya Pradesh, Central India. Utilizing an integrated framework of Remote Sensing (RS), and Geographic Information Systems (GIS), we analysed the structural boundaries guiding the basin's landscape evolution. Morphometric analysis reveals that the catchment represents a well-developed, 5th-order drainage system characterized by a predominantly dendritic to sub-dendritic pattern. However, notable rectilinear stream deflections align with major structural lineaments trending NE–SW and NW–SE. A moderate drainage density (1.3 km/km²) and stream frequency (0.95 streams/km²) reflect a semi-permeable landscape with a balanced runoff-infiltration mechanism. Hypsometric analysis yields an integral (HI = 0.38) coupled with a smooth, concave profile, demonstrating that the basin has reached a geomorphically mature stage of denudational evolution in a state of dynamic landscape equilibrium.**

To delineate groundwater resource prospective zones, multi-criteria decision analysis (MCDA) via the Analytic Hierarchy Process (AHP) was performed to integrate seven reclassified thematic layers: lithology, slope, lineament density, drainage density, land use/land cover (LULC), soil texture, and geomorphic landforms. The derived Groundwater Potential Zonation (GWPZ) map demarcates three primary hydrogeological zones: High Potential (~18% spatial extent), restricted to porous Quaternary alluvial floodplains and dense, fracture-controlled sandstone lineament zones; Moderate Potential (~52%), spanning weathered, interbedded sandstone-shale plateaus; and Low Potential (~30%), corresponding to compact structural plateaus and impermeable Archean basement highs. The spatial reliability of the geospatial index was cross-verified against an in-situ field well inventory of 42 sample stations, achieving an overall validation accuracy of ~85%. These outcomes deliver a scientifically robust decision-support database for artificial recharge structures, soil conservation prioritization, and sustainable watershed development planning across semi-arid cratonic landscapes.

***Keywords*— Morphometric Analysis; Hypsometric Integral; Lineament Extraction; Hydrogeomorphology; Analytic Hierarchy Process (AHP); Vindhyan Supergroup.**

I. INTRODUCTION

Rivers function as highly sensitive and dynamic agents that modify terrestrial landscapes via continuous cycles of erosion, mass transport, and sediment deposition. In semi-arid regions under changing climatic and intensive anthropogenic stresses, understanding the geomorphic structures and hydrological parameters of drainage catchments is critical for environmental sustainability, soil preservation, and water resource management [1,2]. The structural templates of catchments, controlled by bedrock properties, guide the expansion of drainage networks, slope geometries, and fluid circulation [3,4]. Throughout human history, river basins have served as the cradles of civilization, providing fertile soils, water for irrigation, and pathways for transportation and settlement [5]. Even today, river systems play an essential role in sustaining agriculture, industries, and urban development, especially in developing regions like central India, where livelihoods remain heavily dependent on water availability and land productivity [6,7].

The Ton River Basin, situated in the Maihar region of the Satna District within Madhya Pradesh state, of Central India, represents a classic example of a structurally controlled, semi-arid fluvial environment influenced by structural, lithological, and climatic controls. Underlain by the Proterozoic Vindhyan Supergroup, which rests unconformably over the older crystalline basement of the Archean Bundelkhand Craton, this landscape is characterized by flat-lying sandstones, shales, and carbonate successions [8,9]. These rock sequences produce specific landscape geomorphic features including flat-topped plateaus, escarpments, cuestas, and low-gradient alluvial lowlands [10].

Despite its structural layout and regional hydrogeological importance, the basin is suffering from environmental degradation, marked by progressive declines in groundwater tables due to unregulated abstraction, intense monsoonal sheet-wash erosion, and accelerated gully development along soft shale outcrops (Central Ground Water Board [11] [CGWB], 2020).

Historically, regional water conservation plans in this terrain have been limited by a lack of integrated databases, treating geological features, surface forms, and hydrologic budgets as independent variables instead of interdependent components of a single Earth system. Advanced geospatial techniques, utilizing digital terrain datasets alongside multi-spectral satellite sensors, provide an alternative approach to map basin properties with high resolution and spatial coverage [12,13]. Quantitative morphometric computations permit structural interpretation of drainage metrics, basin shape indices, and landscape denudation stages [3,14,41]. Concurrently, multi-criteria evaluation of hydrogeomorphic variables enables spatial mapping of groundwater aquifers and areas prone to sediment loss [15,16,17]. Such integrated approaches have proven effective in various Indian basins—such as the Chambal, Son, and Ken systems—where lithological and structural variations play dominant roles in controlling hydrological behaviour [18].

This study addresses these regional constraints through an integrated remote sensing, and GIS workflow. By bridging the gap between geomorphological theory, hydrological practice, and spatial decision-support, this study enhances the regional understanding of Proterozoic basin geomorphology and hydrology within the Vindhyan terrain of central India. The specific objective is to implement a comprehensive RS-GIS-based multi-parametric framework to quantify basin morphometry, and isolate neotectonic controls on stream alignments, groundwater potential layout to inform local resource policy.

II. STUDY AREA

The Ton River Catchment encompasses a well-defined physical setting within the Maihar sector of Satna District, located in northern Madhya Pradesh, India, forming part of the northern Vindhyan Plateau. Geographically, the catchment is bounded by latitudes 24°10' N to 24°35' N and longitudes 80°35' E to 81°05' E, covering a total physical area of approximately 1,850 km². The basin forms an integral hydrological unit of the Ganga River System through its confluence with the Son River, one of the most prominent right-bank tributaries of the Ganga [19].

The trunk stream originates from the elevated terrains of the Kaimur Hills, flowing in a general northeastward direction across the Vindhyan Plateau before descending towards its confluence with the Son River system.

Climatically, the basin is situated within a tropical monsoonal zone with seasonal extremes [20]. The mean annual temperature ranges from minimums below 8°C during winter up to peak maximums exceeding 45°C in late summer, causing high evaporative water losses from surface soils. The mean annual rainfall varies between 900 and 1,150 mm, with over 85% occurring during the short southwest monsoon window (July–September) as short-duration storm events (India Meteorological Department [IMD] records). This high temporal concentration produces high runoff velocities, flash floods along headwater channels, and intense topsoil erosion. During the remaining dry months, the minor tributaries remain mostly dry, while the main trunk stream relies on baseflow inputs from deep fracture networks.

Physiographically, the landscape shows a clear structural transition from elevated sandstone plateaus and step-like escarpments in the south and southwest (~650 m above mean sea level) down to low-lying, flat alluvial lowlands in the northeast (~210 m amsl). This elevation variation exposes a sequence of resistant and erodible lithologies that control regional drainage networks, soil production, and moisture availability [10,21].

III. DATA SOURCE AND METHODOLOGY

3.1 Geospatial Dataset Acquisition and Standardization

To construct a spatial database, datasets were compiled from verified agencies and standardized to a uniform spatial reference system: Universal Transverse Mercator (UTM) Zone 44 North, keyed to the World Geodetic System 1984 (WGS 84) datum. Cartographic basemaps were prepared by georeferencing, and mosaicking Survey of India (SOI) topographical sheets (63K/1, 63K/2, 63K/5, and 63K/6) at a scale of 1:50,000.

Digital terrain elevation data were obtained from the 30-meter resolution NASA Shuttle Radar Topography Mission (SRTM) and METI/NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM registries [22]. Initial voids and anomalous data points along steep cliffs were resolved via localized spatial interpolation algorithms and checked against topographic contours [23]. Optical mapping used cloud-free multispectral imagery from Landsat-8 Operational Land Imager (OLI) and Sentinel-2A MultiSpectral Instrument (MSI) datasets.

Atmospheric corrections were implemented using Dark Object Subtraction (DOS) methods [24] (Chavez, 1996). Baseline lithological limits and fault zones were compiled from 1:250,000 scale geological series maps provided by the Geological Survey of India [25] (GSI, 2001). Long-term climate metrics (1990–2020) were sourced from India Meteorological Department (IMD) observation stations at Satna and Rewa.

3.2 Drainage Network Extraction and Structural Processing

Digital stream lines were extracted from the hydrologically corrected 30m terrain model [12]. Erroneous topographic hollows were resolved via automated sink-filling sequences [26]. Continuous flow orientation paths were calculated using the Deterministic Eight-direction (D8) routing matrix, assigning pixel paths to the steepest downward slope [27]. Cells with flow accumulation counts exceeding a calibrated 500-pixel index threshold were defined as drainage lines. The digital stream vectors were cross-verified against historical SOI drainage layers and updated to match satellite imagery. Hierarchical channel classification was executed using Strahler's stream ordering criteria [28,14].

Structural lineaments (fault traces, joints, fracture sets) were identified through directional relief shading of the DEM using four illumination azimuth orientations (45°, 135°, 225°, and 315°) to minimize sun-angle illumination bias. High-pass directional convolution filtering (Sobel filters) was applied to the multispectral bands of Landsat and Sentinel datasets to isolate tonal lineaments and fracture zones [13]. Identified structural arrays were checked against GSI maps and confirmed through field measurements of structural orientation trends [29].

3.3 Multi-Criteria AHP Modeling for Groundwater Mapping

Spatial mapping of Groundwater Potential Zones (GWPZs) was performed using an Analytic Hierarchy Process (AHP) multi-criteria evaluation scheme [30]. Seven thematic layers were generated: lithology, terrain slope gradient, lineament density, drainage density, land use/land cover (LULC), soil texture, and geomorphic landform features. Continuous raster maps for drainage density (Dd) and lineament density (Ld) were computed across the basin area using kernel spatial analytical equations in an ArcGIS environment [31].

The individual thematic parameters were reclassified into five suitability ranks based on hydrogeological importance: 5 (Very High), 4 (High), 3 (Moderate), 2 (Low), and 1 (Very Low).

Relative weight distributions among the variables were determined via a pairwise comparison matrix using Saaty's analytical hierarchy framework [30] (Saaty, 1980). The relative weights assigned based on hydrological contribution are: Lithology (0.25), Lineament Density (0.20), Slope Gradient (0.15), Drainage Density (0.15), Land Use/Land Cover (0.10), Geomorphic Landform (0.10), and Soil Profile Texture (0.05). The consistency index calculation yielded an acceptable value below the standard 0.10 threshold. The integrated Groundwater Potential Index (GWPI) was derived by running a spatial weighted overlay equation:

$$GWPI = \Sigma (Wi \times Xi)$$

Where Wi is the percentage weight allocation for thematic variable i, and Xi is the reclassified rank assignment for pixel cell values within that layer [32,17].

IV. RESULTS

4.1 Quantitative Basin Geomorphometry

The spatial analytics classify the Ton Catchment as a well-developed, 5th-order drainage system shown in fig.1. The total drainage count comprises 2,250 distinct stream channels with a cumulative network length of 1,186.90 km. First-order fingertip tributaries account for 51.5% of the absolute stream population (Nu = 1,160) and span a total distance of 577.01 km (Lu = 577.01 km), indicating strong headward erosion and stream dissection in the elevated headwaters [3].

The channel populations decrease geometrically as stream ordering increases, conforming to Horton's Law of Stream Numbers [3]. The mean stream length (Lsm) values increase systematically from 0.50 km for 1st-order up to 0.93 km for the 5th-order network channel, as lower-order networks coalesce into lower-gradient depositional valleys [14].

Table 4.1: Stream Hierarchy Dynamics and Geometric Distribution Metrics:

Stream Order (U)	Channel Count	Combined Length (Lu, km)	Mean Segment Length (Lsm, km)	Bifurcation Ratio (Rb)
1st	1160	577.01	0.50	1.75
2nd	661	293.11	0.44	2.55
3rd	259	155.40	0.60	3.01
4th	86	83.50	0.97	1.02
5th	84	77.88	0.93	—
Total / Mean	2250	1186.9	—	2.08

The bifurcation ratio (Rb) shows variation across stream transitions: it is lowest (1.75) between the 1st and 2nd orders, indicating uniform lithology and fewer structural interruptions, and peaks at 3.01 between the 3rd and 4th orders. This peak reveals structural control, where drainage segments adjust along regional fracture lineaments [33,34]. The mean bifurcation index (Rb = 2.08) indicates a structurally modified drainage network developed over a stable cratonic base.

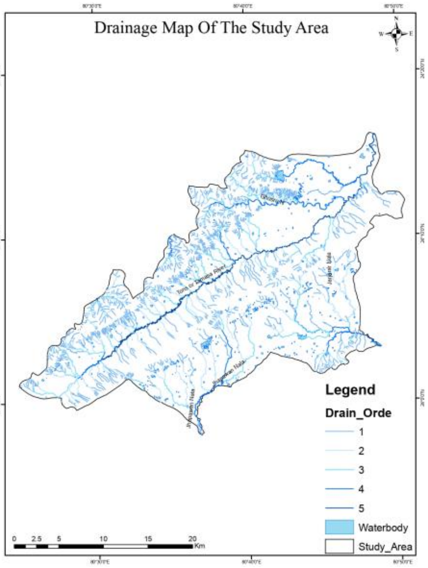

Fig. 4.1 – Fluvial network hierarchy and drainage map of the Ton River Basin study area. The layout illustrates the geometric branching density of channels extracted via the D8 routing matrix, highlighting the main trunk (5th-order Tamasa River) along with major seasonal sub-catchment feeding zones (Ghusru, Jhapan, and Jarjarar Nalas) tied to precise UTM Zone 44N coordinates.

4.2 Geological Mapping and Lineament Configuration

The geological framework is defined by Proterozoic sedimentary strata of the Vindhyan Supergroup resting on the Archean Bundelkhand Craton basement [35,36]. GSI maps and field checks establish five distinct local stratigraphic units across the basin: (1) Quaternary Alluvium (unconsolidated sand, silt, and clay distributions along river valleys), (2) Bhander Group (alternating sandstones, shales, and dolomites), (3) Rewa Group (Govindgarh Sandstone and Jhiri Shale arrays), (4) Kaimur Group (thicker quartzitic sandstones and intercalated shales), and (5) Semri Group (Lower Vindhyan limestones and compact shales) shows as fig.2.

Lineament analysis extracted prominent fracture corridors oriented along regional NE–SW and NW–SE tectonic trends [29].

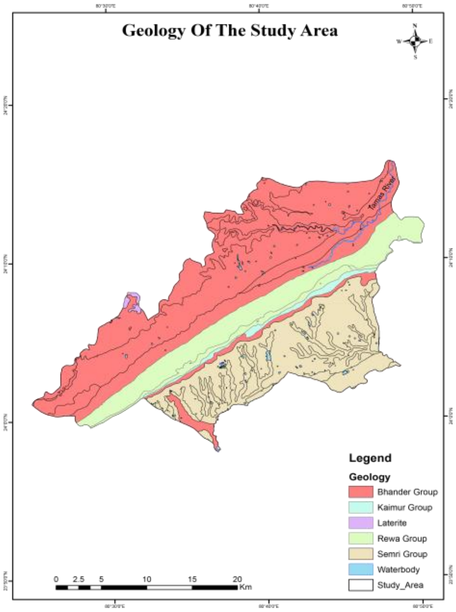

Fig. 4.2 – Geological map and structural trace network architecture across the study area. The spatial orientation map outlines the distribution of foundational lithostratigraphic divisions (Semri, Kaimur, Rewa, and Bhander Groups) intersecting the dominant NE–SW trend of the primary deep-seated Ton Lineament. The synchronized structural orientation rose diagram confirms neotectonic dominance controlling modern channel geometry.

4.3 Hydro-geomorphological Unit Characterization

The integrated remote sensing and digital mapping differentiated six distinct hydrogeomorphic units (HUs) within the catchment area [37,40] (National Remote Sensing Centre [NRSC], 2008; Indian Space Research Organisation [ISRO], 2011): HU1 (Structural Plateaus), HU2 (Dissected Plateaus), HU3 (Alluvial Floodplains), HU4 (Shallow Valleys), HU5 (Lineament-Controlled Zones), and HU6 (Inselbergs and Granite Hills).

4.4 Geospatial Groundwater Potential Mapping

Integrating the reclassified layers via AHP-weighted calculations produced the continuous Groundwater Potential Zonation (GWPZ) framework for the basin [32,17].

Table 4.2: Spatial Allocation and Hydrogeological Properties of Mapped GWPZ Classes:

Potential Class	Index Range	Area Contribution	Dominant Hydrogeomorphic Features	Measured Aquifer Parameters
High	> 3.5	~18%	Alluvial floodplains (HU3), lineament-controlled sandstone belts (HU5).	Shallow water tables (8–15 m bgl); high yields (5–10 L/s).
Moderate	2.5 – 3.5	~52%	Dissected plateaus (HU2), interbedded sandstone–shale zones.	Intermediate water table depths; seasonal recharge retention.
Low	< 2.5	~30%	Granite hills, structural plateaus, and steep slopes (HU1, HU6).	Deep water tables or dry rock sections; low well yields (<2 L/s).

V. DISCUSSION

The quantitative geomorphometric profile of the Ton Catchment indicates a landscape governed by structural templates rather than purely climatic forcing. The mean bifurcation ratio (Rb = 2.08) confirms that the structural framework of the Vindhyan Supergroup sedimentary bedding regulates drainage patterns [3,4]. The structural peak in Rb (3.01) across intermediate channel stream scales reflects drainage adjustments along regional lineaments, where joints and fracture planes cause straight channel courses and right-angled stream deflections [33, 16].

Table 5.1: Comparative Geomorphometric Metrics across Regional Vindhyan River Basins:

Morphometric Parameter	Ton Catchment (Current Study)	Betwa Catchment	Ken Catchment	Son Catchment
Catchment Area (A, km²)	1,850	7,000	4,200	9,500
Stream Ordering Hierarchy (U)	5th	6th	5th	7th
Drainage Density (Dd, km/km²)	1.30	1.50	1.40	1.60
Elongation Shape Index (Re)	0.56	0.63	0.59	0.65
Hypsometric Integral Metric (HI)	0.38	0.40	0.39	0.42
Ruggedness Number (Rn)	0.62	0.78	0.70	0.82

The validation of the GWPZ index model (85% accuracy) against in-situ well data confirms the utility of integrating remote sensing datasets with multi-criteria AHP matrices for hydrogeological mapping in data-scarce terrains [32,18]. Implementing site-specific interventions can improve water availability and landscape stability in accordance with national watershed programs like the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and the National Aquifer Mapping and Management Programme (NAQUIM) guidelines [38,39] (CGWB, 2017; Ministry of Agriculture & Farmers Welfare [MoA&FW], 2015).

VI. CONCLUSION

- The catchment contains a mature, 5th-order drainage network with a sub-dendritic configuration modified by structural adjustments along regional lineaments.
- Basin shape metrics (Re = 0.56, Ff = 0.37) define an elongated catchment geometry that reduces downstream peak discharges and extends water retention times.
- Hypsometric metrics (HI = 0.38) confirm that the landscape has reached a mature stage of denudational evolution under stable cratonic equilibrium conditions.
- Lineament configurations indicate that structural fractures trending NE–SW and NW–SE function as pathways for vertical fluid transmission, feeding deep structural aquifers.
- Multi-criteria AHP modeling mapped three distinct groundwater potential zones (GWPZs): High Potential (18%), Moderate Potential (52%), and Low Potential (30%), which were verified with 85% accuracy against field well inventories.

VII. DECLARATION

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Conflict of Interest Statement: The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement: The primary spatial maps, terrain matrices, georeferenced topographical sheets, and field monitoring data tables used during the current study are available from the corresponding author upon reasonable academic request.

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