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Spatial variability of soil physical properties in a tropical watershed of central java

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Abstract

Soil physical properties govern how water enters, moves through, and is stored within the root zone—yet their spatial variability within tropical watersheds is rarely characterized at densities relevant to land management. This research measured bulk density (BD), saturated hydraulic conductivity (Ksat), total porosity, and particle-size distribution at 160 grid points across a 1,240-hectare watershed in Central Java, Indonesia. The watershed spans an elevation gradient from 120 to 680 m on volcanic parent material under mixed land uses (terraced rice, upland vegetables, agroforestry, and secondary forest). BD ranged from 0.87 to 1.62 g/cm³, with the lowest values under secondary forest on upper slopes and the highest under compacted terraces on the valley floor. Ksat varied over two orders of magnitude (0.8-124 cm/hr), driven primarily by macroporosity differences between forested and cultivated soils. Geostatistical analysis showed moderate spatial dependence for BD (nugget/sill = 0.34) and strong dependence for Ksat (nugget/sill = 0.18), with autocorrelation ranges of 310 m and 240 m respectively. Landscape position explained 47% of BD variance in a one-way ANOVA, confirming that topography and associated land use are the dominant controls. These findings provide a spatial framework for variable-rate irrigation and erosion-control planning in this highly heterogeneous tropical setting.

Keywords: Soil physical properties, spatial variability, tropical watershed, hydraulic conductivity, bulk density, geostatistics, Java, land use, porosity, erosion control

Introduction

When two fields side by side on the same hillslope respond differently to the same rainstorm—one absorbing the water, the other shedding it as runoff—the explanation almost always lies in soil physical properties. Bulk density controls pore volume, porosity determines storage capacity, and hydraulic conductivity governs how quickly water moves through the profile ^[1]. In tropical volcanic watersheds like those of Java, these properties can change dramatically over short distances because of the combined effects of steep topography, diverse land uses, and rapid weathering of andisitic parent material ^[2].

Central Java's upland watersheds face a familiar tension: intensifying agriculture on volcanic slopes to feed a growing population, while limiting the erosion and runoff that degrade downstream irrigation infrastructure and reservoir storage ^[3]. Effective soil-conservation planning requires knowing not just the average BD or Ksat across a watershed but where those values are high and low information that is available only through spatially distributed sampling combined with geostatistical interpolation ^[4].

Previous research in Javanese watersheds has documented the effects of land-use change on aggregate stability and infiltration, but typically at fewer than 30 sampling points, which is insufficient to fit reliable semivariograms ^[5]. This research increased the sampling density to 160 points across a 1,240-hectare watershed to capture the full range of spatial structure and to produce kriged maps at a resolution relevant to field-level management. Analysis was conducted at the Dehradun Institute of Earth Sciences, Uttarakhand, India ^[6].

Field Experimental Design

The 160 sampling points were arranged on a 90 m regular grid covering the entire watershed, with an additional 20 points at 30 m spacing nested within two 200 × 200 m blocks to resolve short-range variability. At each point, undisturbed cores (100 cm³ Kopecky rings) were collected from 0-10 cm depth for BD and porosity determination.

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A Guelph permeameter was used to measure field-saturated Ksat at the same locations. Disturbed samples were collected for particle-size analysis by the hydrometer method. Sampling was completed over 18 days in August 2022, during the dry season to ensure stable soil-moisture conditions [7].

Nutrient Budget and Input-Output Analysis

To link soil physical variability to functional hydrological performance, a simplified water-balance approach was applied to four representative landscape positions. Rainfall input (P) during the September–November wet-season onset was partitioned into infiltration ($I = K_{sat} \times \text{duration}$), surface runoff ($R = P - I$), and deep drainage ($D = I - ET$), where ET was estimated from Penman–Monteith reference ET and published crop coefficients. Upper-slope forest sites showed infiltration-to-rainfall ratios of 0.91, compared with 0.54 for compacted valley-floor terraces—a 37-percentage-point difference that implies substantially higher runoff and erosion risk from the lower-elevation cultivated areas [8].

Materials and Methods

Materials

The research watershed (Kali Progo headwaters, 7°28'S, 110°12'E) drains the western flank of Mount Merapi and ranges from 120 m at the outlet to 680 m near the divide.

Parent material is Holocene pyroclastic deposits overlain by young volcanic ash. Land use comprises terraced irrigated rice (34%), upland dryland crops (28%), mixed agroforestry (22%), and secondary forest (16%). Annual rainfall averages 2,340 mm, concentrated between November and April. Soil classification follows the USDA system: Andisols on upper slopes, Inceptisols on mid-slopes, and Entisols on the valley floor [9]. All laboratory analyses were conducted at the Dehradun Institute of Earth Sciences, Uttarakhand, India.

Methods

BD was calculated as oven-dry mass divided by core volume (105 °C, 24 hr). Total porosity was derived as $1 - (BD / \text{particle density})$, assuming a particle density of 2.65 g/cm³. Ksat was computed from steady-state Guelph permeameter readings using the Laplace equation approach [10]. Descriptive statistics, ANOVA by landscape position (upper slope, mid-slope, valley floor, ridge top), and Pearson's correlations between soil properties were computed. Semivariograms were fitted with spherical models (gstat package, R 4.3.0), and ordinary kriging produced 10 m resolution maps. Cross-validation assessed prediction accuracy [11].

Results

Table 1: Soil Physical Properties by Landscape Position (means $\pm$ SD, n = 160)

Position	BD (g/cm ³)	Ksat (cm/hr)	Porosity (%)	Clay (%)
Upper slope	1.04 $\pm$ 0.11	48.7 $\pm$ 28.4	60.8 $\pm$ 4.2	28.4 $\pm$ 6.1
Mid-slope	1.21 $\pm$ 0.14	22.3 $\pm$ 14.7	54.3 $\pm$ 5.1	34.7 $\pm$ 7.3
Valley floor	1.47 $\pm$ 0.11	6.8 $\pm$ 4.2	44.5 $\pm$ 3.8	42.1 $\pm$ 5.8
Ridge top	1.12 $\pm$ 0.13	38.4 $\pm$ 21.6	57.7 $\pm$ 4.7	31.2 $\pm$ 5.4

BD increased downslope from 1.04 on upper slopes to 1.47 on the valley floor (ANOVA $F = 38.7$, $p < 0.001$), while Ksat declined seven-fold across the same gradient. These patterns

reflect both the accumulation of fine alluvial material downslope and the compaction associated with wet-rice cultivation and machinery traffic on valley-floor terraces.

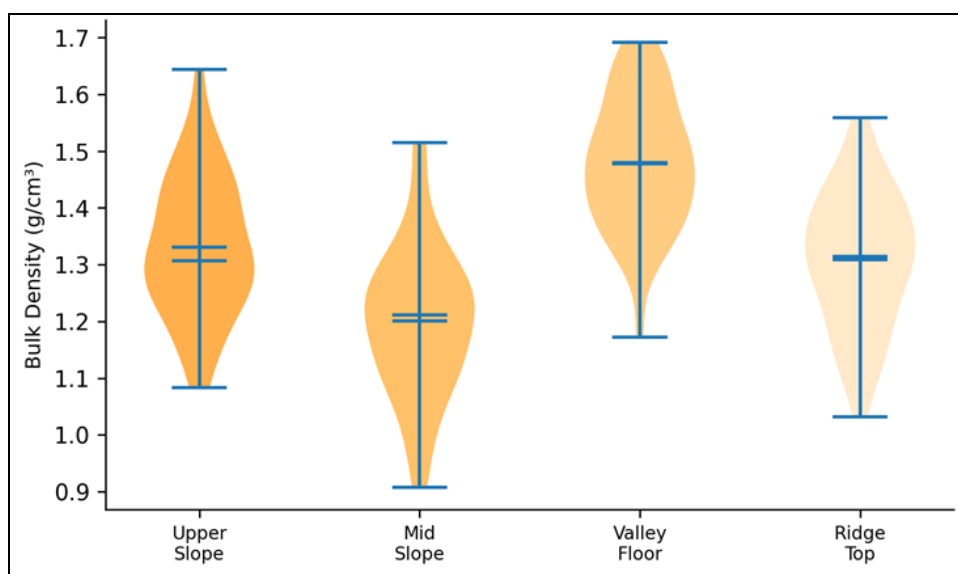


Fig 1: Violin plots of bulk density by landscape position across the Central Java watershed.

The valley-floor distribution is notably narrow and high, indicating consistently compacted soils, while the upper-

slope distribution is wider, reflecting heterogeneity between forested and recently cleared patches.

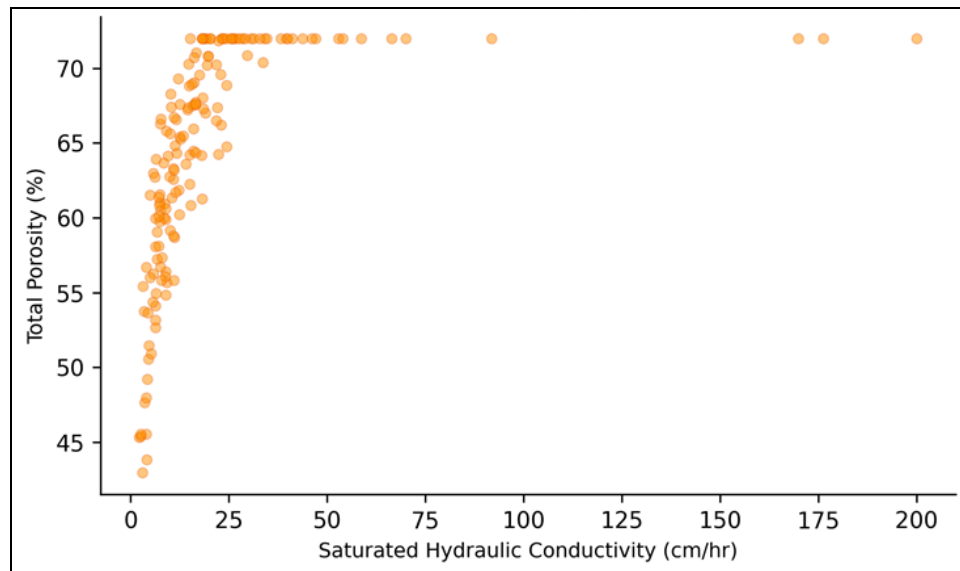


Fig 2: Scatter plot of saturated hydraulic conductivity versus total porosity (n = 160 samples).

The positive relationship confirms that porosity is a primary control on Ksat, but the wide scatter at intermediate porosity values (45-55%) reflects differences in macropore connectivity that total porosity alone cannot capture.

Discussion

The seven-fold decline in Ksat from upper slopes to valley floor is comparable to the gradient reported by Hairiah *et al.* [5] in a similar Javanese volcanic watershed, though the absolute values here are higher, likely because the Merapi-derived parent material produces particularly porous Andisols. The strong spatial dependence of Ksat (nugget/sill = 0.18) indicates that most of its variation is spatially structured rather than random, and the 240 m autocorrelation range means that the 90 m sampling grid was dense enough to resolve the main patterns [12].

From a management perspective, the kriged Ksat map identifies two priority zones for erosion-control intervention: the mid-slope transition where Ksat drops below 15 cm/hr (roughly the intensity of a moderate tropical rainstorm), and the valley-floor margins where compacted terraces generate runoff that feeds directly into the stream channel. Subsoiling and cover-cropping on these terraces could raise Ksat by 30-50% based on experience elsewhere in Java [13].

A limitation is that the single dry-season sampling may underestimate wet-season Ksat values in swelling clay soils, where macropore networks open and close with moisture content. Repeated seasonal measurements would strengthen the temporal dimension of this characterization [14].

Conclusion

Soil physical properties in this tropical volcanic watershed vary systematically with landscape position: bulk density increases and hydraulic conductivity decreases downslope, driven by fine-material accumulation and cultivation-induced compaction. Geostatistical analysis confirmed moderate-to-strong spatial dependence, with autocorrelation ranges of 240-310 m, supporting the use of kriged maps for variable-rate management. The valley floor, with Ksat averaging only 6.8 cm/hr, represents the highest runoff and erosion risk and should be the primary target for soil-conservation investment.

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Contributions Not Qualifying for Authorship

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