Geodesic Location–Allocation for Liquefaction Investigation Coverage in Uttarakhand, India

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Abstract

Site-scale liquefaction investigations in Uttarakhand are concentrated in the Roorkee–Haridwar and Rudrapur–Khatima corridors. This article asks a narrower, operational question: where should a limited reconnaissance programme investigate next to reduce geographic gaps in that evidence? Fifteen settlement-centred nodes were represented as a complete weighted graph, with four literature-supported investigation centres fixed as anchors. Exact enumeration evaluated one to five additions using p-median, p-center and equally weighted, within-budget normalised objectives. Existing anchors produced a mean nearest-centre distance of 27.15 km and a maximum of 69.29 km. For two additions, Dehradun–Kashipur and Vikasnagar–Kashipur were exactly co-optimal under the balanced and p-median objectives, reducing the mean to 15.61 km and the maximum to 41.04 km; all nodes then lay within an illustrative 50 km planning radius. A WGS 84 ellipsoidal ablation preserved all principal selections and changed the two-site balanced mean by only −0.003 km. In 2,000 seeded coordinate-perturbation trials, a western node was effectively invariant, while Kashipur and Bazpur divided most central-eastern selections. The result is a reproducible coverage design, not a liquefaction-hazard map. Complete tie reporting, coordinate provenance, deterministic rules, pinned software versions, convergence checks and file hashes make the analysis independently auditable.

Keywords: *geodesic distance; location–allocation; liquefaction investigation; p-median; p-center; reproducible cartography; Uttarakhand*

Introduction

Regional hazard maps can appear spatially complete even when the observations beneath them are geographically sparse. This distinction matters for soil liquefaction because triggering requires the joint occurrence of earthquake demand, saturation and contractive soil behaviour. Geomorphology, groundwater proxies, geology and shaking scenarios can identify areas worth investigating, but confirmation still depends on site information such as corrected penetration resistance, shear-wave velocity, groundwater depth, grading and cyclic response (Boulanger & Idriss, 2014; Youd et al., 2001). A continuous susceptibility surface is therefore not equivalent to a geographically representative field-evidence network.

Uttarakhand is an instructive case. Its steep Himalayan terrain grades southward into the Doon Valley, piedmont deposits and the Terai–Bhabar plains. Regional screening has identified lowland and foothill zones where liquefaction investigation is relevant, whereas site-scale dynamic-soil work is clustered around a smaller set of accessible corridors (Kirar & Maheshwari, 2018; Muley et al., 2015; Naik et al., 2022; Pudi et al., 2019). The available studies demonstrate that potentially liquefiable layers occur in parts of the state. They do not establish that every settlement between the studied corridors has the same soil, groundwater or seismic demand.

The practical gap is thus not a missing statewide prediction alone. It is the absence of a transparent rule for choosing the next reconnaissance locations. If a programme can add only one, two or three investigation centres, should it reduce average separation from existing evidence, protect the most remote settlement, or balance both goals? These questions are naturally expressed as location–allocation problems. The p-median objective minimises average demand-to-facility distance; the p-center objective minimises the maximum distance (Hakimi, 1964; Daskin, 1995). Both have clear interpretations for monitoring and service networks, *provided that the meaning of distance and the demand set are declared.*

This article builds directly on the graph-semantics argument of Sheode (2026). That paper proposed that geohazard graphs should be judged first by what their nodes and edges mean. The present work operationalises that principle in a new research design. Nodes are potential settlement-centred reconnaissance bases. Edges contain geodesic separation only. They do not represent subsurface continuity, road travel, hydrologic connection, stress transfer or seismic-wave propagation. Consequently, the output is geographic investigation coverage; not liquefaction probability or risk.

The cartographic contribution is equally important. A map is not used merely to display an answer found elsewhere. The spatial representation, node selection, distance model, boundary context and symbolisation together define the optimisation problem and its interpretation. Exact enumeration is feasible because the pilot network is small. The complete search space can therefore be inspected without a heuristic optimiser, and equal-valued solutions can be reported rather than hidden by software ordering.

The study addresses five questions:

1. How well do four literature-supported evidence anchors cover a declared set of southern Uttarakhand reconnaissance nodes?
2. Which additions minimise mean separation, maximum separation, or a balanced combination of both?
3. Are there multiple exactly co-optimal designs, and what decision freedom do those ties create?
4. Do the selections depend materially on a spherical rather than WGS 84 ellipsoidal distance model?
5. Are the main priorities stable to plausible uncertainty in settlement-centre coordinates and to omission of individual anchors?

The novelty lies in converting a literature-derived evidence gap into an exact, tie-aware and reproducible geodesic sampling design. The study does not claim to optimise a final drilling campaign. It provides an auditable first-stage geometry that can later be replaced by road, terrain, cost, population or deposit-specific weights when those data are assembled.

1. Study context and analytical scope

1.1 Evidence geography

The literature available for Uttarakhand combines regional screening with detailed local investigations. Pudi et al. (2019) integrated thematic geospatial layers through an analytical hierarchy process to map regional liquefaction susceptibility in the Himalayas. Such screening is useful for recognising broad alluvial and valley-floor domains, but the result remains sensitive to input scale, groundwater representation, shaking assumptions and expert weights. It identifies where field verification is justified rather than replacing that verification.

The Roorkee–Haridwar corridor contains the densest cluster of direct work. Muley et al. (2015) evaluated liquefaction potential around Roorkee using field and laboratory information. Kirar and Maheshwari (2018) examined large-strain dynamic soil properties in the same wider region. Earlier testing at Dhanauri, Roshnabad and the Solani River corridor showed that soil resistance, density, fines and groundwater conditions vary even over modest distances (Maheshwari et al., 2008; Maheshwari & Patel, 2010). In the eastern Terai, Naik et al. (2022) analysed soils from Rudrapur and Khatima using field- and laboratory-derived dynamic properties and Himalayan earthquake motions. These western and eastern clusters provide defensible evidence anchors for a pilot coverage analysis.

Other geophysical observations inform regional seismic behaviour but were not automatically classified as liquefaction investigations. For example, accelerogram-based estimates of source, attenuation and site characteristics have broader scientific value (Sharma et al., 2014), yet a recording station is not interchangeable with an SPT, CPT, borehole or cyclic soil test. The anchor rule therefore required literature explicitly associated with settlement-scale dynamic-soil or liquefaction work.

1.2 Purpose-driven node frame

The 15 nodes were selected before optimisation to form a bounded reconnaissance frame across the southern alluvial, piedmont and major intermontane-valley corridor. A node had to satisfy three practical criteria: it represented an identifiable settlement or service centre; it lay in, or provided access to, the lowland, foothill or valley-floor domains motivating the evidence synthesis; and it improved west-to-east geographic representation. High-elevation settlements dominated by different access and deposit conditions were outside the pilot frame. The resulting nodes are not a census of Uttarakhand municipalities, and they are not weighted by population.

Settlement centres are used because the decision being modelled is where to base reconnaissance, not where a particular borehole already exists. They offer unambiguous labels and can support logistics, but their coordinates should not be interpreted as proposed test points. A field phase would relocate each selected centre to accessible Quaternary deposits after desk study and local reconnaissance.

The four anchors—Roorkee, Haridwar, Rudrapur and Khatima—represent two documented investigation clusters. The other eleven nodes are eligible additions. The equal node weight means that every settlement contributes one observation to the coverage objective. This assumption deliberately avoids inventing population, asset or exposure weights. It also makes the result easy to audit: a different policy priority can be implemented later by publishing a new weight vector.

1.3 Claim boundary

Geodesic closeness is an operational measure of spatial coverage. It is not evidence that two sites share stratigraphy, groundwater or cyclic resistance. The analysis therefore supports statements such as “this addition reduces the longest geographic gap in the declared node set.” It does not support statements such as “this settlement has the greatest liquefaction hazard.” Maintaining that boundary is central to both the research design and the map legend.

2. Materials and methods

2.1 Nodes, roles and coordinate provenance

Table 1 gives the complete analysis input. Coordinates are approximate public-gazetteer settlement centres, rounded to four decimal places. The values were compiled on 12 September 2026; Appendix C records the source for every node. Different public gazetteers may place a nominal town centre at a municipal centroid, commercial centre or labelled map point. That uncertainty is addressed through the perturbation analysis rather than concealed as survey-grade precision.

Table 1. Settlement-centred nodes and analysis roles.

Node	Latitude (°N)	Longitude (°E)	Role
Dehradun	30.3244	78.0339	Candidate
Vikasnagar	30.4694	77.7728	Candidate
Rishikesh	30.1083	78.2972	Candidate
Roorkee	29.8543	77.8880	Fixed evidence anchor
Haridwar	29.9457	78.1642	Fixed evidence anchor
Laksar	29.7587	78.0415	Candidate
Kotdwar	29.7460	78.5220	Candidate
Haldwani	29.2183	79.5130	Candidate
Ramnagar	29.3948	79.1265	Candidate
Kashipur	29.2104	78.9618	Candidate
Rudrapur	28.9783	79.3996	Fixed evidence anchor
Khatima	28.9197	79.9698	Fixed evidence anchor
Sitarganj	28.9279	79.7025	Candidate

Node	Latitude (°N)	Longitude (°E)	Role
Tanakpur	29.0800	80.1200	Candidate
Bazpur	29.1580	79.1476	Candidate

2.2 Graph definition

Let the node set be $V = \{1, \ldots, 15\}$. The model uses a complete undirected graph $G = (V, E)$ because a pairwise separation is defined for every pair of settlement centres. Four nodes form the fixed anchor set A. For a budget of p additions, a subset S_p is chosen from the eleven eligible nodes, with $|S_p| = p$. The active facility set is $F_p = A \cup S_p$.

The graph is complete computationally, but its edges are not drawn on the map. Displaying 105 pairwise lines would obscure the nodes and could imply physical connectivity. Figure 1 therefore shows the spatial inputs and design symbols, while the edge weights remain in the calculation.

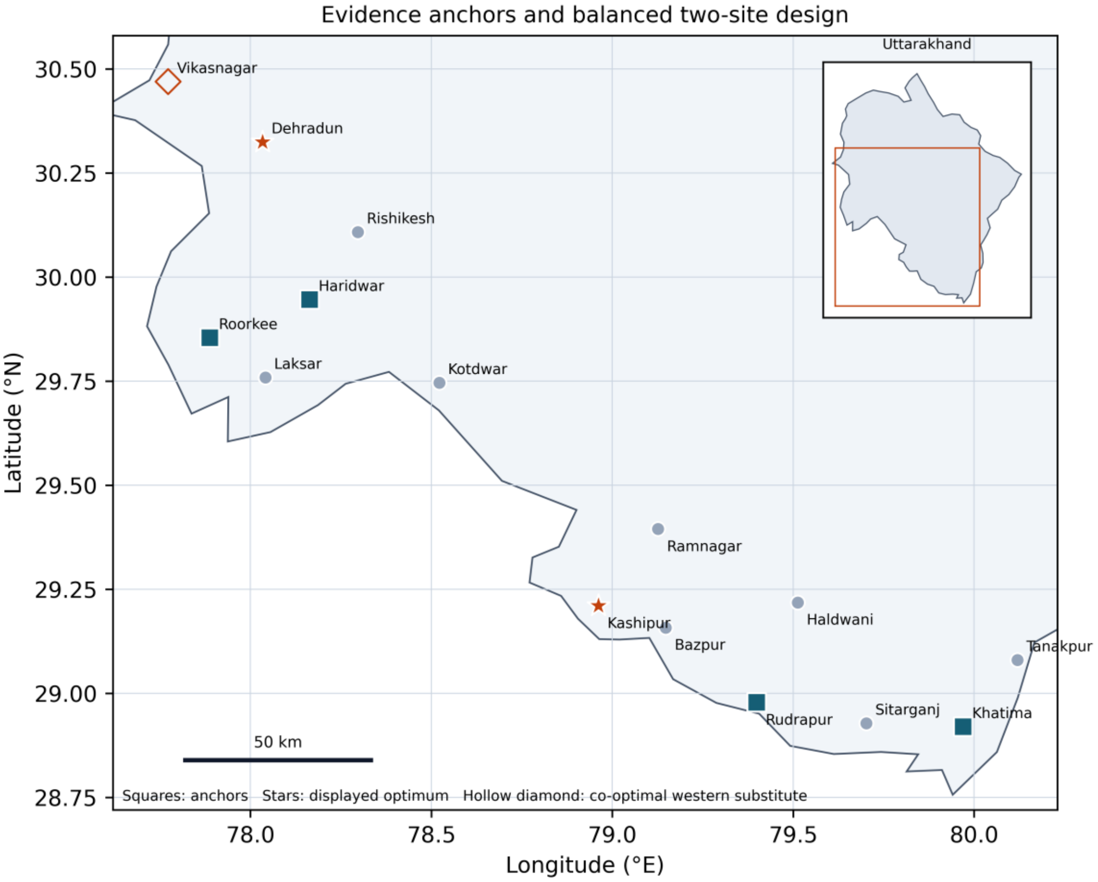

Figure 1 Spatial inputs and design symbols

2.3 Spherical geodesic distance

The primary edge weight is great-circle distance on a sphere of mean radius $R = 6371.0088$ km. For geodetic coordinates (ϕ_i, λ_i) and (ϕ_j, λ_j) in radians,

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$$a = \sin^2\left(\frac{\phi_j - \phi_i}{2}\right) + \cos\phi_i \cos\phi_j \sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right),$$

$$d_{ij} = 2R\arcsin\left(\sqrt{a}\right).$$

The formula is transparent and adequate for the scale and coordinate precision of the pilot. Nevertheless, "adequate" was tested rather than assumed. Section 2.7 describes an ellipsoidal ablation.

2.4 Coverage metrics

For node i, the distance to its nearest active centre is

$$\delta_i(F_p) = \min_{j \in F_p} d_{ij}.$$

Overall efficiency is measured by the mean nearest-centre distance,

$$\bar{d}(F_p) = \frac{1}{|V|} \sum_{i \in V} \delta_i\left(F_p\right),$$

and peripheral service by the maximum,

$$d_{\max}(F_p) = \max_{i \in V} \delta_i(F_p).$$

For communication, threshold coverage is also reported:

$$C_r(F_p) = \frac{100}{|V|} \sum_{i \in V} I\left\{\delta_i(F_p) \le r\right\},$$

for $r = 25$, 50 and 75 km. These radii are illustrative descriptors, not regulatory criteria and not assumed limits of geotechnical transferability.

2.5 Exact objectives and balanced normalisation

The p-median design minimises $\bar{d}(F_p)$, and the p-center design minimises $d_{\max}(F_p)$. To express a compromise, both quantities are normalised separately among all feasible configurations for each fixed value of p:

$$z_m = \frac{\bar{d} - \min_p(\bar{d})}{\max_p(\bar{d}) - \min_p(\bar{d})}, \qquad z_c = \frac{d_{\max} - \min_p(d_{\max})}{\max_p(d_{\max}) - \min_p(d_{\max})}.$$

The subscript on the extrema denotes the set of configurations evaluated at that same budget, not a normalisation pooled across $p = 1, \ldots, 5$. The balanced score is

$$B = 0.5 z_m + 0.5 z_c.$$

Equal weighting was chosen before examining results. It does not assert universal equivalence between efficiency and peripheral coverage; it supplies a readable compromise for the pilot.

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All combinations were enumerated. The numbers of feasible designs for $p = 1$ to 5 were 11, 55, 165, 330 and 462, respectively, totalling 1,023 configurations. Exact enumeration guarantees the optimum within the stated model and permits complete reporting of ties.

2.6 Co-optimality and deterministic display rule

An earlier draft allowed the first array minimum to stand in for the solution. That behaviour can hide substantively useful ties. The revised workflow sorts eligible nodes lexicographically, identifies every configuration whose objective equals the minimum within an absolute tolerance of 10^{-9} and zero relative tolerance, and reports the entire co-optimal set. The lexicographically first configuration is used only as a representative in figures and row ordering. It is not treated as scientifically superior. The same rule resolves the rare numerical ties that may arise in coordinate-perturbation trials.

2.7 WGS 84 ellipsoidal ablation

To test geodetic-model dependence, every pairwise separation and every balanced optimisation was recomputed on the WGS 84 reference ellipsoid, with semi-major axis $a = 6378.137$ km and flattening $f = 1/298.257223563$. The inverse solution follows the iterative nested-equation method of Vincenty (1975), with a convergence threshold of 10^{-12} radians and at most 200 iterations. All pairs in this regional network converged normally. This ablation isolates the effect of Earth geometry while leaving nodes, anchors, objectives and weights unchanged.

2.8 Coordinate-perturbation sensitivity and convergence

Gazetteer uncertainty was tested with 2,000 Monte Carlo trials. In each trial, all 15 coordinates were displaced by a radius drawn uniformly from 0 to 5 km and an independent bearing drawn uniformly from 0 to 2π. The implementation uses NumPy Generator(PCG64) with seed 84294. The exact draw order is fixed: an array of 15 radii is drawn first, followed by an array of 15 bearings. Latitude increments use 111.32 km per degree; longitude increments include the cosine of latitude. The complete spherical distance matrix and balanced two-site enumeration are then recalculated.

Selection frequencies were inspected after 250, 500, 1,000 and 2,000 trials. For a reported frequency $\hat{q}$, Monte Carlo standard error was estimated as

$$\mathrm{MCSE}(\hat{q}) = 100\sqrt{\frac{\hat{q}(1-\hat{q})}{N}}$$

in percentage points, where $\hat{q}$ is expressed as a proportion and $N = 2000$. This diagnostic distinguishes genuine instability in site choice from noise caused by a finite simulation count.

2.9 Anchor-omission sensitivity

Each fixed anchor was removed in turn. The omitted settlement then became eligible, and the balanced two-site problem was rerun with the other three anchors retained. This experiment tests the structural importance of each anchor to the coverage geometry. It is not predictive cross-validation because the model does not predict soil behaviour.

2.10 Software, files and reproducibility controls

The analysis was executed with Python 3.12.14, NumPy 2.3.5 and Matplotlib 3.10.8. The deterministic workflow writes the node table, full design summary, ellipsoid ablation, nested JSON results, three 600 dpi figures, exact environment pins, licences, a README and a SHA-256 manifest. *The code is MIT-licensed; the compiled node table is released under CC BY 4.0 with attribution to the listed sources. Numeric values are stored at full precision and rounded only in the manuscript.*

The analysis package as Supplementary Material S1 is sufficient to rerun the study without proprietary software.

3. Results

3.1 Existing coverage

With Roorkee, Haridwar, Rudrapur and Khatima fixed, the mean nearest-anchor distance was 27.1546 km and the maximum was 69.2870 km. Seven of 15 nodes (46.67%) were within 25 km, 13 (86.67%) were within 50 km and all were within 75 km. Thus, a generous 75 km radius creates an impression of completeness that is not supported at closer operational ranges. The greatest gap lies in the western/northern part of the frame, away from both evidence clusters.

3.2 One- and two-site designs

With one addition, Kashipur was the unique p-median solution, reducing the mean to 21.1691 km but leaving the 69.2870 km maximum unchanged. The p-center and balanced objectives instead had two exactly co-optimal solutions: Dehradun or Vikasnagar. Either produced a mean of 21.5921 km and maximum of 53.3642 km. Their identical node-level metrics arise because both serve the same previously remote western subset while the fixed anchors remain nearest for the other settlements.

With two additions, the p-median and balanced objectives again had two co-optimal configurations: Dehradun–Kashipur and Vikasnagar–Kashipur. The displayed Dehradun–Kashipur representative reduced the mean to 15.6066 km and the maximum to 41.0358 km. Ten nodes (66.67%) were within 25 km and all were within 50 km. Relative to the existing anchors, those changes equal reductions of 42.53% in the mean and 40.77% in the maximum.

The two-site p-center objective had six co-optimal designs because several central-eastern choices shared the same worst-served distance when paired with either western alternative. Their maximum was 41.0358 km; their mean distances differed. This distinction is important: equality under the p-center objective does not imply equality on every secondary measure.

Table 2. Representative exact solutions; the representative is lexicographic when ties occur.

Added sites	Objective	Representative additions	Co-optimal count	Mean (km)	Maximum (km)	≤25 km (%)	≤50 km (%)
0	Existing anchors	—	1	27.15	69.29	46.67	86.67
1	p-median	Kashipur	1	21.17	69.29	60.00	93.33
1	p-center	Dehradun	2	21.59	53.36	53.33	93.33
1	Balanced	Dehradun	2	21.59	53.36	53.33	93.33
2	p-median	Dehradun; Kashipur	2	15.61	41.04	66.67	100.00
2	p-center	Bazpur; Dehradun	6	15.63	41.04	66.67	100.00
2	Balanced	Dehradun; Kashipur	2	15.61	41.04	66.67	100.00
3	Balanced	Dehradun; Kashipur; Kotdwar	2	12.87	29.78	73.33	100.00
4	Balanced	Dehradun; Kashipur; Kotdwar; Vikasnagar	1	10.89	28.87	80.00	100.00
5	Balanced	Dehradun; Haldwani; Kashipur; Kotdwar; Vikasnagar	1	8.96	26.03	86.67	100.00

3.3 Complete tie structure

Table 3 makes the non-uniqueness explicit. At budgets one to three, the balanced and p-median results allow Dehradun and Vikasnagar to substitute for one another without changing the objective. The p-center criterion admits additional central alternatives because it ignores improvements that do not reduce the current worst distance. At $p = 4$, the p-median and balanced objectives select both western nodes, ending that substitution. At $p = 5$, all three objectives converge on the same unique set.

Table 3. Complete co-optimal sets for objectives with multiple solutions.

p	Objective	All co-optimal additions
1	p-center; balanced	Dehradun **or** Vikasnagar
2	p-median; balanced	Dehradun + Kashipur **or** Vikasnagar + Kashipur
2	p-center	Bazpur + Dehradun; Bazpur + Vikasnagar; Dehradun + Kashipur; Dehradun + Ramnagar; Kashipur + Vikasnagar; Ramnagar + Vikasnagar
3	p-median; balanced	Dehradun + Kashipur + Kotdwar **or** Vikasnagar + Kashipur + Kotdwar
3	p-center	Bazpur + Dehradun + Kotdwar; Bazpur + Vikasnagar + Kotdwar; Dehradun + Kashipur + Kotdwar; Dehradun + Ramnagar + Kotdwar; Kashipur + Vikasnagar + Kotdwar; Ramnagar + Vikasnagar + Kotdwar
4	p-center	Bazpur + Dehradun + Kotdwar + Vikasnagar; Dehradun + Kashipur + Kotdwar + Vikasnagar; Dehradun + Kotdwar + Ramnagar + Vikasnagar

The ties are not a computational defect. They identify genuine discretion within the stated geometry. A planner may choose between Dehradun and Vikasnagar using deposit access, road logistics, local institutional capacity or expected drilling cost without sacrificing the exact balanced coverage score.

3.4 Diminishing returns

For three additions, either western alternative combined with Kashipur and Kotdwar was balanced-optimal. Mean distance fell to 12.8708 km and the maximum to 29.7837 km. The unique balanced four-site design included both Dehradun and Vikasnagar with Kashipur and Kotdwar; the mean fell to 10.8853 km, but the maximum declined by less than 1 km, to 28.8718 km. A fifth site, Haldwani, reduced the mean to 8.9605 km and the maximum to 26.0309 km.

Figure 2 shows that the first three additions generate the largest reductions in the worst-served distance. The mean continues to improve with each addition, but the marginal gain becomes progressively smaller. This is not a universal cost–benefit threshold because no monetary cost was modelled. It is a geometric statement that can inform later budgeting.

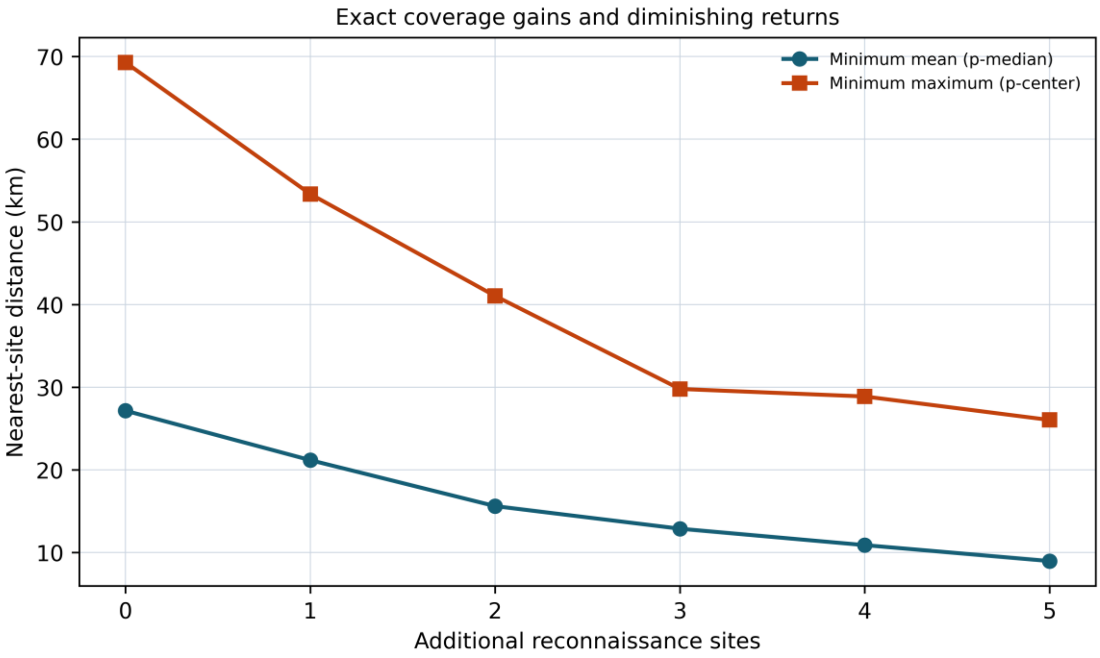

Figure 2 Diminishing returns

3.5 WGS 84 ablation

The ellipsoidal model preserved every principal selection and every balanced tie set. Under WGS 84, baseline mean and maximum distances were 27.1242 and 69.0841 km (Table 4). For the balanced two-site representative, they were 15.6035 and 41.0552 km. Relative to the spherical calculation, the changes were −0.0031 km in the mean and +0.0194 km in the maximum. These differences are orders of magnitude smaller than the 5 km coordinate perturbations and have no planning consequence at the stated precision.

Table 4. Spherical and WGS 84 balanced-design ablation.

Added sites	Balanced representative	Sphere mean (km)	WGS 84 mean (km)	Sphere maximum (km)	WGS 84 maximum (km)
0	Existing anchors	27.1546	27.1242	69.2870	69.0841
1	Dehradun	21.5921	21.5840	53.3642	53.2608
2	Dehradun; Kashipur	15.6066	15.6035	41.0358	41.0552
3	Dehradun; Kashipur; Kotdwar	12.8708	12.8665	29.7837	29.7991
4	Dehradun; Kashipur; Kotdwar; Vikasnagar	10.8853	10.8799	28.8718	28.8006
5	Dehradun; Haldwani; Kashipur; Kotdwar; Vikasnagar	8.9605	8.9598	26.0309	26.0803

The ablation supports continued use of the transparent spherical equation for this pilot while documenting that the result is not an artefact of that choice. It does not imply that spherical distance is always sufficient for longer baselines or higher-precision geodetic applications.

3.6 Coordinate robustness and Monte Carlo precision

Across 2,000 perturbation trials, Dehradun appeared in 99.95% of balanced two-site solutions and Vikasnagar in 0.05%. The deterministic unperturbed problem treats them as exactly co-optimal, but small independent movements usually favour Dehradun. The second position divided mainly between Kashipur (53.40%) and Bazpur (46.20%), with Ramnagar appearing in 0.40%. Frequencies sum to 200% because each trial selects two nodes.

The estimated MCSE was 0.05 percentage points for Dehradun and Vikasnagar, 1.12 for Kashipur, 1.11 for Bazpur and 0.14 for Ramnagar. At 250 trials, Kashipur and Bazpur frequencies were 53.2% and 46.8%; at 2,000 they were 53.4% and 46.2%. This stability shows that the central-eastern split is structural under the perturbation model rather than a short-run simulation fluctuation.

The 2.5th, median and 97.5th percentiles of the optimal mean distance were 14.53, 15.59 and 16.63 km. Corresponding maximum-distance quantiles were 35.57, 41.13 and 46.84 km. Coordinate uncertainty therefore affects achieved distances more than the principal west-plus-central/east spatial pattern.

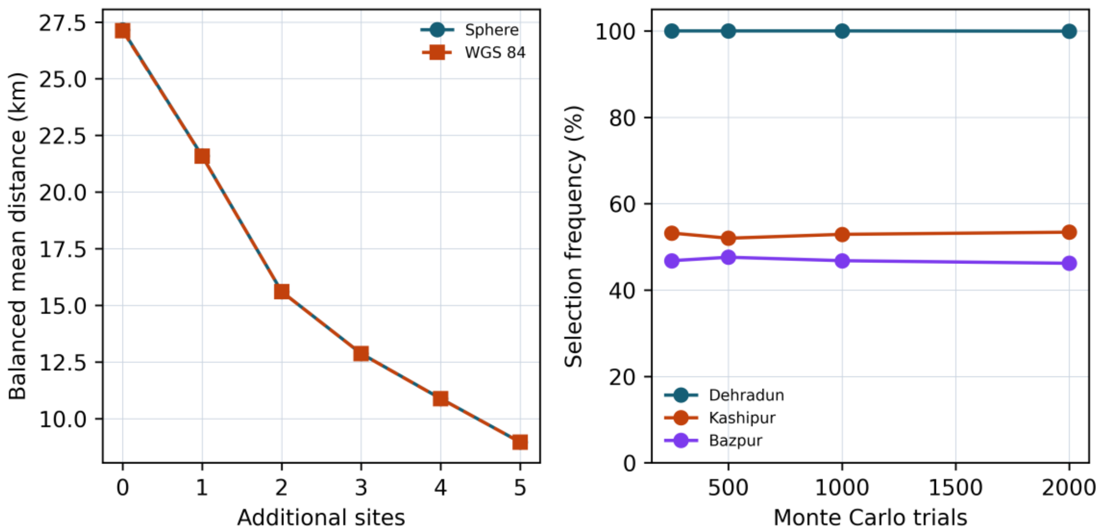

Figure 3 (a) Mean Distance (b) Monte Carlo precision

3.7 Anchor-omission sensitivity

Removing Roorkee retained the Dehradun/Vikasnagar plus Kashipur pattern, although the mean rose to 17.89 km. Removing Rudrapur shifted the central-eastern choice to Bazpur. When Haridwar or Khatima was removed, the omitted anchor itself was reselected alongside a western node. In every case, Dehradun and Vikasnagar remained interchangeable in the unperturbed geometry.

Table 5. Balanced two-site results after omitting one fixed anchor.

Omitted anchor	Representative additions	Co-optimal alternative	Mean (km)	Maximum (km)
Roorkee	Dehradun; Kashipur	Vikasnagar; Kashipur	17.89	41.04
Haridwar	Dehradun; Haridwar	Vikasnagar; Haridwar	21.59	53.36
Rudrapur	Bazpur; Dehradun	Bazpur; Vikasnagar	18.22	41.04
Khatima	Dehradun; Khatima	Vikasnagar; Khatima	21.59	53.36

The re-selection of Haridwar and Khatima supports their structural importance within this node frame. Roorkee has greater geographic redundancy with neighbouring western anchors and candidates, while Rudrapur's omission transfers coverage responsibility toward Bazpur.

4. Discussion

4.1 A field-priority result, not a hazard ranking

The strongest conclusion is that the existing evidence geography has a western gap and a central-eastern gap. A two-centre reconnaissance expansion should occupy one position in each. In the exact balanced geometry, Dehradun and Vikasnagar are interchangeable western bases, while Kashipur is the central-eastern partner. Under small coordinate perturbations, the western position remains nearly invariant but Dehradun usually has the lower score; Kashipur and Bazpur share the other position. This is a practical finding because it separates a robust regional pattern from fragile town-level ordering.

No part of this result ranks liquefaction susceptibility. Dehradun's frequent selection does not mean that it is more liquefaction-prone than Haridwar, Kashipur or any other node. It means that, among declared settlement centres, a western investigation base closes a geographic gap left by the existing anchors. Field-site selection within that area must still screen deposits, groundwater, land access and expected shaking.

4.2 Why complete tie reporting improves the science

Optimisation software often returns one minimiser even when many exist. In a policy or field-planning setting, that behaviour can turn arbitrary ordering into apparent scientific certainty. The corrected tie analysis changes the interpretation of the manuscript. Dehradun is not the sole exact western optimum in the unperturbed graph; Vikasnagar has identical one-site and paired balanced metrics. Likewise, the p-center objective admits several central choices because it only protects the worst-served node.

Reporting all co-optimal solutions creates a useful decision space. Once exact geographic performance is held constant, planners can use criteria not represented in the graph: access to suitable deposits, travel time, permissions, laboratory support, seasonal groundwater conditions or the availability of prior logs. The tie is therefore an invitation to collect discriminating information, not a reason to suppress the model.

4.3 Geodetic and cartographic contribution

For a journal concerned with geodesy and cartography, the study's contribution is the disciplined connection between spatial representation and inference. First, it declares the coordinate source and precision of every node. Second, it tests the sphere against WGS 84 rather than relying on convention. Third, it uses a state boundary and study-frame inset to locate the network without allowing the boundary to enter the optimisation. Fourth, its symbol hierarchy distinguishes existing anchors, a representative optimum, a co-optimal substitute and other candidates.

The WGS 84 ablation shows that reference-surface choice is not driving the result at this scale. That negative finding is scientifically useful: it identifies coordinate definition and network specification as more consequential than sub-kilometre distance refinements. The 5 km perturbation is intentionally much larger than the sphere–ellipsoid difference and more closely matches uncertainty about where a reconnaissance base or eventual test site would lie within a settlement.

4.4 Objective choice, service equity and field cost

The p-median and p-center criteria encode different planning ethics. Minimising mean distance rewards aggregate efficiency. Minimising maximum distance protects the most remote node. The balanced score gives both equal influence after within-budget normalisation. The two-site result is unusually convenient because the balanced and p-median optima also attain the p-center minimum. At other budgets, the objectives need not agree.

Equal settlement weights are transparent but not neutral. A population-weighted model could favour urban centres; an exposure-weighted model could emphasise critical infrastructure; a deposit-area model could emphasise spatially extensive young sediments. A road-time model might move selections toward transport junctions, while a cost-constrained field design might cluster tests. These are appropriate extensions only when their data and policy meanings are declared.

4.5 From reconnaissance base to sampling campaign

A selected settlement should be treated as a search area. A defensible field programme would proceed in stages. First, geological and geomorphological screening would identify young, potentially saturated deposits and exclude bedrock-dominated or steep sites. Second, local data would refine groundwater seasonality and access. Third, reconnaissance geophysics, CPT, SPT or boreholes would be located within the relevant deposits. Finally, triggering analysis would apply an accepted framework and a clearly specified earthquake demand.

The graph can be updated after each stage. Newly investigated sites can replace settlement centroids as anchors. Candidate weights can reflect mapped deposit extent or exposed assets. Edges can become road-network time or campaign cost. That sequential use preserves the logic of Sheode (2026): change the graph only when the meaning of the relationship changes, and change the claim with it.

4.6 Relation to the literature synthesis

The preceding evidence synthesis identified an imbalance between broad regional susceptibility mapping and geographically clustered site-scale studies. The present paper does not recycle that synthesis as a review article. It uses the synthesis to define the anchor set, then asks and answers an independent optimisation question. The result is thus "clubbed with" the conceptual graph paper through a declared methodological lineage, while remaining a distinct empirical-computational article with new inputs, algorithms, results and sensitivity tests.

This separation also protects originality. The earlier graph paper supplies a general modelling principle. The present manuscript supplies a specific network, exact enumeration, co-optimality analysis, WGS 84 ablation, Monte Carlo experiment and cartographic output. The evidence-review document remains a source-development record and is not overwritten or resubmitted as this article.

4.7 Reproducibility as an inspectable chain

Reproducibility here is more than posting source code. A reproducer needs the node coordinates, role assignments, selection rule, equations, numerical tolerance, software versions, random-number generator, seed, draw order, output schema and verification targets. *The supplementary package contains each element and hashes the generated files. Appendix A gives a compact execution test; Appendix B states what each output can and cannot mean.*

Supplementary Material S1 remains the complete package.

5. Limitations

The study has six main limitations. First, the node frame is purpose-driven and small. It represents selected settlements across the relevant southern and valley-floor corridor but does not exhaust all towns, deposits or infrastructure. A different node universe can change the optimum.

Second, settlement-centre coordinates are planning proxies, not surveyed geotechnical sites. The perturbation experiment quantifies one aspect of that uncertainty but cannot guarantee that suitable deposits lie near the nominal centre.

Third, geodesic distance omits roads, terrain, travel time, river crossings, land access and field cost. Those omissions matter in Himalayan logistics. *The present distance is appropriate only for a first-stage geographic coverage claim.*

Fourth, equal node weights omit population, critical assets and mapped deposit extent. *The result should not be used as a statutory investment ranking without stakeholder-defined weights.*

Fifth, anchor assignment is *literature-derived and settlement-scale. It* does not imply that every part of an anchor municipality has been characterised, and an undiscovered or unpublished borehole could change the evidence geography.

Sixth, coordinate perturbation is not model-completeness analysis. It tests small shifts in the declared nodes, not missing nodes, uncertain evidence classification, future earthquakes or soil heterogeneity. *The reported robustness is therefore conditional on the graph definition.*

These limitations bound the result but do not negate it. The analysis answers a deliberately narrow question exactly and exposes the assumptions needed to ask a richer one.

Journal-status statement: It is not under-review at any journal. Subsequent versions may contain substantial revisions arising from community feedback / submission to journal(s). Co-author(s) may be included in future versions. Feedback is welcome. Please feel free to contact the author (via email only). PRE-PRINT VERSION (I): 20.09.2026

Conclusions

This study converts a literature-derived gap in Uttarakhand liquefaction investigations into an exact geodesic location–allocation problem. Four documented investigation centres leave the 15-node frame with a mean nearest-anchor distance of 27.15 km and a maximum of 69.29 km. Two additional centres reduce those values to 15.61 and 41.04 km and bring every node within an illustrative 50 km radius.

The corrected conclusion is set-valued: Dehradun–Kashipur and Vikasnagar–Kashipur are exactly co-optimal under the balanced and p-median objectives. The p-center objective admits six two-site configurations. Complete reporting turns those ties into planning flexibility rather than arbitrary certainty. A WGS 84 ellipsoidal calculation preserves all principal selections, and seeded coordinate perturbation confirms the robust need for one western and one central-eastern reconnaissance position.

The recommended next step is not to declare these settlements hazardous. It is to treat the co-optimal western alternatives and the Kashipur–Bazpur central corridor as first investigation priorities, then choose actual sites using deposit, groundwater, access and exposure information. The reproducible package makes that conclusion auditable and provides a clear base for road-network, terrain-aware and weighted extensions.

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Author contribution

Mohit Sheode: conceptualisation, literature synthesis, methodology, software specification, formal analysis, visualisation, writing—original draft, and writing—review and editing.

Disclosure statement

The author declares no competing financial or personal interests.

Data and code availability

The complete analysis package is available as Supplementary Material S1. It contains geodesic_evidence_network_v2.py, nodes.csv, design_summary.csv, ellipsoid_ablation.csv, results.json, figures, requirements.txt, licences, a README and manifest_sha256.json. Code is released under the MIT License and the compiled node table under CC BY 4.0. Link: https://github.com/mhtsht-cyber/Geodesic-Location-Allocation-for-Liquefaction-?tab=MIT-1-ov-file

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Appendix A. Reproduction protocol

1. Place geodesic_evidence_network_v2.py in a clean working directory.
2. Create a Python 3.12.14 environment and install numpy==2.3.5 and matplotlib==3.10.8 from requirements.txt.
3. Run python geodesic_evidence_network_v2.py once.
4. Confirm that geodesic_network_outputs_v2 contains the files listed in the data-availability statement.
5. Compare SHA-256 digests against manifest_sha256.json. Numeric CSV and JSON files should be identical in the pinned environment; raster metadata can be platform-dependent.
6. In results.json, confirm baseline mean 27.1546204102 km and maximum 69.2869901065 km.
7. Confirm two balanced co-optima for $p = 2$: Dehradun–Kashipur and Vikasnagar–Kashipur, with mean 15.6065705633 km and maximum 41.0358463831 km.
8. Confirm WGS 84 two-site balanced mean 15.6035033132 km and maximum 41.0552313767 km.
9. Confirm PCG64 seed 84294, 2,000 trials, 5 km maximum displacement, and radius-before-bearing draw order.
10. Treat any change to nodes, coordinates, anchors, weights, distance rule or tolerance as a new analysis version and archive a new manifest.

Appendix B. Claim-to-evidence boundary

Output	Supported interpretation	Unsupported interpretation
Nearest-centre distance	Geographic separation from an evidence or proposed reconnaissance centre	Similarity of soil profile, groundwater or shaking
p-median selection	Best average coverage under equal node weights	Highest population risk
p-center selection	Best worst-case geographic coverage	Highest liquefaction probability
Balanced selection	Equal-weight compromise after normalisation within fixed p	Statutory priority without local review
Co-optimal set	Configurations with identical objective performance at stated tolerance	Proof that locations are interchangeable in cost or geology
WGS 84 ablation	Sensitivity to reference-surface geometry	Validation of road or terrain accessibility
Coordinate perturbation	Stability to small shifts in settlement-centre coordinates	Robustness to missing nodes, deposits or boreholes
Anchor omission	Structural importance within the declared graph	Validation of the underlying geotechnical studies

Appendix C. Coordinate provenance

All coordinate pages were accessed 12 September 2026. Values are rounded public settlement centres, not surveyed sites. The machine-readable node table preserves the values used in analysis.

Node	Source used for nominal centre	Source locator or note
Dehradun	LatitudeLongitude.org	"Dehradun, India latitude longitude"
Vikasnagar	GeoCountries	"Vikasnagar Satellite Map & GPS Coordinates 2026"
Rishikesh	Wikipedia	"Rishikesh", coordinate listing
Roorkee	LatLong.net	"Where is Roorkee, Uttarakhand, India"
Haridwar	LatLong.net	"Where is Haridwar, Uttarakhand, India"
Laksar	Latitude.to	"GPS coordinates of Laksar, India"
Kotdwar	FindLatitudeAndLongitude.com	Kotdwar/Kotdwara, Pauri Garhwal search result; rounded nominal centre
Haldwani	LatLong.net	"Where is Haldwani, Uttarakhand, India"
Ramnagar	GeoCords	Ramnagar coordinate listing
Kashipur	LatLong.net	"Where is Kashipur, Uttarakhand, India"
Rudrapur	LatLong.net	"Where is Rudrapur, Uttarakhand, India"
Khatima	LatLong.net	"Where is Khatima, Uttarakhand, India"
Sitarganj	Geloky	"Sitarganj India map lat long coordinates"
Tanakpur	Wolfram Knowledgebase	Tanakpur city entity position
Bazpur	Geloky	"Bazpur India map lat long coordinates"

The boundary inset uses a decimated plotting copy of the Wolfram Knowledgebase administrative-division polygon for Uttarakhand (entity labelled "Uttaranchal, India"), retrieved 13 September 2026. It is used only for orientation.