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Abstract

Public groundwater programmes increasingly use rapid geophysical surveys to site deep irrigation tubewells, on the implicit assumption that deeper target formations also yield better water. We tested this assumption in the Tarai alluvial aquifer of Uttarakhand, India, by linking multi-frequency natural electric field (MNEF) siting records with the chemistry of 15 deep community tubewells and 15 nearby shallow sources. The MNEF sections indicated a multilayered sequence, with shallow water-bearing strata at 20–40 m, deeper strata at 50–100 m and recommended drilling depths of 90–150 m. Mean electrical conductivity was lower in deep groundwater (1.59 ± 0.49 dS m^{-1}) than in shallow groundwater (2.07 ± 0.79 dS m^{-1}), but the difference was not significant (p = 0.058). pH, bicarbonate, calcium, Cu, Zn, Fe, Mn and Pb also did not differ significantly between depth categories. Cadmium exceeded the FAO irrigation guideline (0.01 mg L^{-1}) in both groups (mean contamination factor 1.6), and elevated Mn was confined to a few shallow wells. Exploratory multivariate analyses showed heterogeneous trace-metal covariation rather than a depth-controlled pattern. Hydrogeophysical siting can locate productive formations, but it is not a proxy for water

quality; baseline and periodic chemical testing, particularly for Cd, should accompany programme-scale tubewell development.

Keywords: groundwater exploration; hydrogeophysics; hydrochemistry; irrigation water quality; trace metals; Tarai aquifer

1. Introduction

Groundwater is the largest accessible store of fresh water and underpins agricultural production, domestic supply and ecosystem services worldwide.[1,2] Irrigation accounts for most groundwater abstraction, particularly in monsoon-dependent regions where rainfall is highly variable. India is the largest groundwater user in the world, accounting for nearly one-quarter of global abstraction, and more than 60% of its irrigated agriculture depends on groundwater.[3,4] Rising dependence has increased production but has also intensified pressure on aquifers, making sustainable groundwater development a national priority.[5]

Sustainable irrigation depends on the chemical quality as well as the quantity of groundwater.[6] Water containing excessive salts or toxic trace elements can degrade soil properties, crop growth and irrigation infrastructure.[7,8] Groundwater chemistry reflects mineral weathering, dissolution, ion exchange, residence time and redox reactions,[9,10] and is further modified by agriculture, industry, urban growth and waste disposal.[5] Elevated Fe, Mn, Cd, Pb, fluoride and arsenic have been reported from several Indian aquifers, where long-term irrigation with poor-quality water can lead to accumulation of potentially toxic elements in soils and reduced productivity.[11–13] Groundwater development should therefore evaluate quality alongside availability.[11,14]

Conventional exploration relies on drilling guided by local knowledge or limited hydrogeological information,[15] which leads to failed boreholes and uncertain yield and quality.[16] Hydrogeophysical techniques provide rapid, non-invasive characterisation of subsurface formations,[17–20] and natural-field and multi-frequency electromagnetic methods are increasingly used to delineate aquifer geometry and estimate drilling depths.[21–23] These methods, however, provide only indirect information about groundwater occurrence and cannot establish whether the water is suitable for irrigation. Hydrochemical characterisation remains essential because it integrates the effects of lithology, flow paths and geochemical evolution.[24–27]

The Tarai belt along the southern Himalayan foothills hosts one of the most productive alluvial aquifer systems of northern India.[28,29] Its thick Quaternary deposits of interbedded sand, gravel,

63 silt and clay form multilayered aquifers that sustain intensive irrigated agriculture,[30] and both
64 shallow and deep groundwater in the north-western alluvial aquifers show geogenic and
65 anthropogenic contamination.[31] Under the Pradhan Mantri Krishi Sinchayee Yojana–Har Khet
66 Ko Pani–Ground Water (PMKSY-HKKP-GW) programme, the Government of India funds
67 community deep tubewells whose locations and depths are selected by hydrogeophysical
68 survey.[32,33] Whether these deeper, geophysically targeted formations actually deliver better
69 irrigation water than the shallow sources farmers already use has not been tested, and studies
70 that combine geophysical siting records with hydrochemistry in the multilayered Indo-
71 Gangetic aquifers remain scarce.[34]

72 This study addresses that gap with the first field comparison, to our knowledge, between MNEF
73 siting records and the hydrochemistry of the community tubewells subsequently drilled under
74 a public groundwater programme. Rather than validating the geophysical method itself, we ask
75 a practical question: does selecting a deeper water-bearing formation through a rapid
76 geophysical survey correspond to measurably better irrigation-water chemistry? We
77 hypothesised that groundwater from deep, geophysically targeted tubewells would have lower
78 electrical conductivity (EC) and lower trace-metal concentrations than nearby shallow
79 groundwater. The objectives were to (i) describe the water-bearing strata interpreted from
80 MNEF surveys at the sampled sites; (ii) compare pH, EC, bicarbonate, calcium and six trace
81 metals in deep and shallow groundwater; (iii) screen these against FAO irrigation guidelines;
82 and (iv) explore hydrochemical associations relevant to monitoring community irrigation
83 sources.

84 ## 2. Materials and Methods

85 ### 2.1 Study area

86 The study was conducted in the Udham Singh Nagar and Haridwar districts of Uttarakhand,
87 India, in the Tarai belt along the southern Himalayan foothills (approximately 28°43′–30°15′
88 N, 77°42′–80°10′ E; Fig. 1). The area forms part of the Indo-Gangetic alluvial plain. The
89 climate is humid subtropical, with mean annual rainfall of about 1,644 mm, nearly 80% of
90 which falls during the south-west monsoon (June–September), and mean air temperatures
91 ranging from about −1.2 °C in winter to 41 °C in summer.[35] Agriculture is dominated by rice–
92 wheat and sugarcane systems irrigated mainly from shallow and deep tubewells.[36,37] The stage
93 of groundwater development is about 65% in Haridwar[38] and 79% in Udham Singh Nagar.[39]
94 Between 2020 and 2022, the HKKP-GW component of PMKSY established 206 community

irrigation tubewells in the two districts (188 solar photovoltaic-powered and 18 grid-powered), all sited after hydrogeophysical survey.[35]

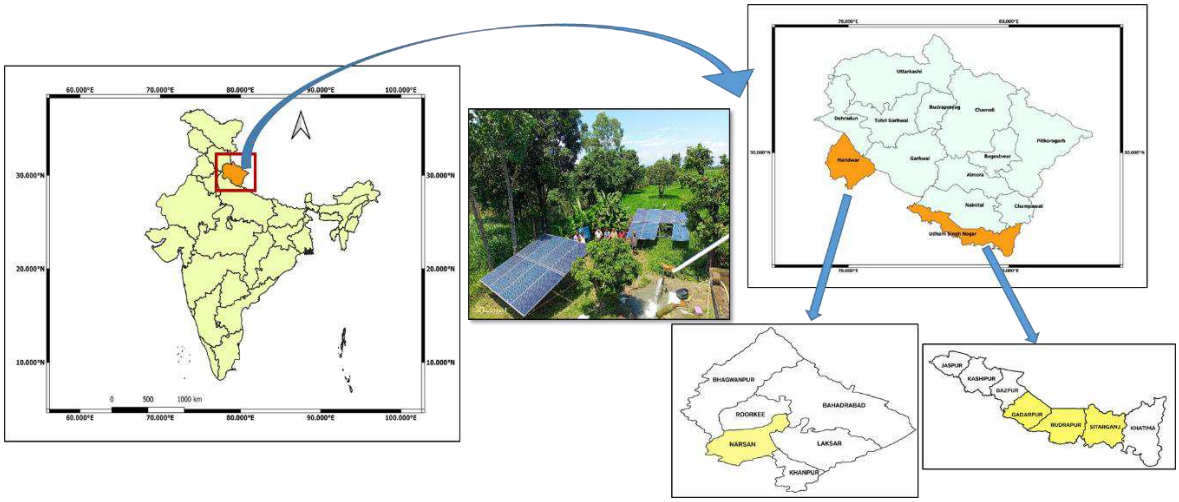


Fig. 1. Location of the study area: Udham Singh Nagar and Haridwar districts of Uttarakhand, India, and the development blocks in which PMKSY-HKKP-GW community tubewells were installed. The photograph shows a typical solar-powered community tubewell. Matched sampling sites are mapped in Supplementary Fig. S1.

2.2 Hydrogeophysical investigation

Surveys were carried out between September 2020 and September 2021, before borehole construction, using a PQWT-S300 multi-frequency natural electric field instrument (Hunan Puqi Geologic Exploration Equipment Institute, China). The instrument records variations in natural geo-electric field signals associated with changes in subsurface lithology and groundwater occurrence.[17,19] At each proposed site, measurements were acquired along predetermined traverses following the manufacturer's operating procedure and processed with the manufacturer's software to produce two-dimensional sections of relative electrical variation. The sections were interpreted together with regional geological information and field observations to identify likely lithological boundaries, water-bearing intervals and recommended drilling depths. Because the method is indirect, the interpreted zones are treated as target formations, not as measurements of hydraulic conductivity, yield or chemistry; no independent geophysical method or borehole logging was available for validation.

Boreholes were constructed by rotary drilling, cased and developed, and static water level and completed depth were recorded during field verification. Survey records were matched to the sampled deep wells using beneficiary records, village names and geographic coordinates

(Supplementary Table S1). These operational records provide context for the sampled wells but do not establish a causal link between the geophysical interpretation and water chemistry.

2.3 Groundwater sampling

Thirty groundwater samples were collected during a single pre-monsoon campaign (May 2022): 15 from deep community tubewells and 15 from nearby shallow sources in the Rudrapur, Sitarganj and Gadarpur blocks of Udham Singh Nagar, where deep-well survey records could be linked to the sampling location (Supplementary Fig. S1). Sites were selected for access and record availability, not by probability sampling, and no formal power-based sample-size calculation was made. Shallow sources were chosen near the deep wells where access permitted, but unique pair identifiers were not recorded consistently, so proximity was treated as site context rather than a pairing variable. Wells were pumped before sampling, and samples were collected in acid-washed polyethylene bottles and stored at about 4 °C until analysis following standard methods.[40]

2.4 Physicochemical and trace-metal analysis

pH and EC were measured with calibrated portable meters, and bicarbonate (HCO_3^-) and calcium (Ca^{2+}) were determined by titration.[40] Fe, Mn, Cu, Zn, Pb and Cd were determined by atomic absorption spectrophotometry, with calibration against certified standards. Calibration was checked with standards and quality-control samples throughout the analytical run.

2.5 Evaluation of groundwater suitability for irrigation

Measured values were compared with the FAO irrigation-water guidelines of Ayers and Westcot[41] (Supplementary Table S2): pH and EC as indicators of water reaction and salinity, HCO_3^- and Ca^{2+} against their usual ranges, and Cu, Zn, Fe, Mn, Pb and Cd against maximum recommended concentrations for long-term irrigation. These comparisons are screening indicators: sodium adsorption ratio, residual sodium carbonate and crop- and soil-specific factors were not evaluated. Differences between deep and shallow groups are interpreted as associations with depth category, not as proof that depth or geophysical siting caused the observed chemistry.

2.6 Contamination factor assessment

For each metal, a contamination factor (CF) was calculated following Håkanson[42] (Eq. 1):

$$CF_i = \frac{C_i}{C_{ref}} \quad (1)$$

where C_i is the measured concentration of metal i (mg L^{-1}) and C_{ref} is the corresponding FAO maximum recommended concentration for irrigation water.[41] Following Håkanson's classes, CF < 1 indicates low, 1 ≤ CF < 3 moderate, 3 ≤ CF < 6 considerable and CF ≥ 6 very high contamination. Because the reference is an irrigation guideline rather than a geochemical background, CF is used here as a normalised exceedance ratio, not as a source-apportionment metric.

2.7 Statistical analysis

Descriptive statistics (minimum, maximum, mean, standard deviation and coefficient of variation) were calculated for all parameters. Deep and shallow groups were compared with Welch's *t*-test for pH, EC, HCO_3^-, Ca^{2+} and Cu, and with the Mann–Whitney *U* test for the right-skewed Zn, Mn, Fe, Pb and Cd distributions. Groups were treated as independent because unique pair identifiers were not available for all wells. Pearson correlation coefficients were calculated among the ten variables. Principal component analysis (PCA) was performed on the correlation matrix of the standardised variables; components with eigenvalues above 1 were retained, and unrotated eigenvector coefficients are reported. Hierarchical cluster analysis (HCA) used Ward's linkage and Euclidean distance on standardised variables. Given 30 samples and ten variables, the multivariate analyses were treated as exploratory. Analyses were run in Python in a Jupyter Notebook environment, with significance at $p < 0.05$.

3. Results

3.1 Hydrogeophysical characterization of groundwater-bearing formations

The MNEF sections indicated a multilayered alluvial sequence of alternating sand, gravel, silt and clay, with deeper water-bearing intervals beneath shallower strata. At the 15 matched sites, shallow intervals were interpreted at approximately 20–40 m and deeper intervals at 50–100 m (Supplementary Table S1). Recommended drilling depths were generally 90–120 m, reaching 150 m at Sakeniya (Gadarpur block). Static water levels recorded during field verification were 3–17 m below ground level, and completed borehole depths were 67–92 m (Supplementary Table S1). These depths are survey interpretations and construction records, not independently validated aquifer boundaries.

3.2 Physicochemical characteristics of groundwater for irrigation

Both groups were neutral to slightly alkaline (Table 1, Fig. 2). Mean pH was 7.62 ± 0.21 in deep and 7.57 ± 0.24 in shallow groundwater ($p = 0.563$), and all values lay within the FAO

normal range of 6.5–8.4. Mean EC was lower in deep (1.59 ± 0.49 dS m^{-1}) than in shallow groundwater (2.07 ± 0.79 dS m^{-1}), but the difference was not significant (p = 0.058). Both means fell in the 0.7–3.0 dS m^{-1} class of slight-to-moderate restriction; the upper range of the shallow samples extended above 3.0 dS m^{-1} (severe restriction), whereas all deep samples remained below it (Fig. 2b). HCO_3^- was identical in the two groups (1.18 me L^{-1}; p = 0.971), with a minority of samples in each group above 1.5 me L^{-1}, the threshold relevant only to overhead sprinkler irrigation. Ca^{2+} was somewhat lower in deep (3.13 ± 0.78 me L^{-1}) than in shallow groundwater (3.47 ± 0.94 me L^{-1}; p = 0.290) and within the usual range for irrigation water.

Table 1. Physicochemical parameters of deep and shallow groundwater (mean ± SD, n = 15 per group) and FAO irrigation guideline values.

Parameter	Deep groundwater	Shallow groundwater	p-value (Welch t)	FAO guideline[a]
pH	7.62 ± 0.21	7.57 ± 0.24	0.563	6.5–8.4 (normal range)
EC (dS m^{-1})	1.59 ± 0.49	2.07 ± 0.79	0.058	<0.7 none; 0.7–3.0 slight to moderate; >3.0 severe restriction
HCO_3^- (me L^{-1})	1.18 ± 0.32	1.18 ± 0.35	0.971	<1.5 no restriction (overhead sprinkling only)
Ca^{2+} (me L^{-1})	3.13 ± 0.78	3.47 ± 0.94	0.290	0–20 (usual range)

[a]Ayers and Westcot[41]; full guideline values in Supplementary Table S2.

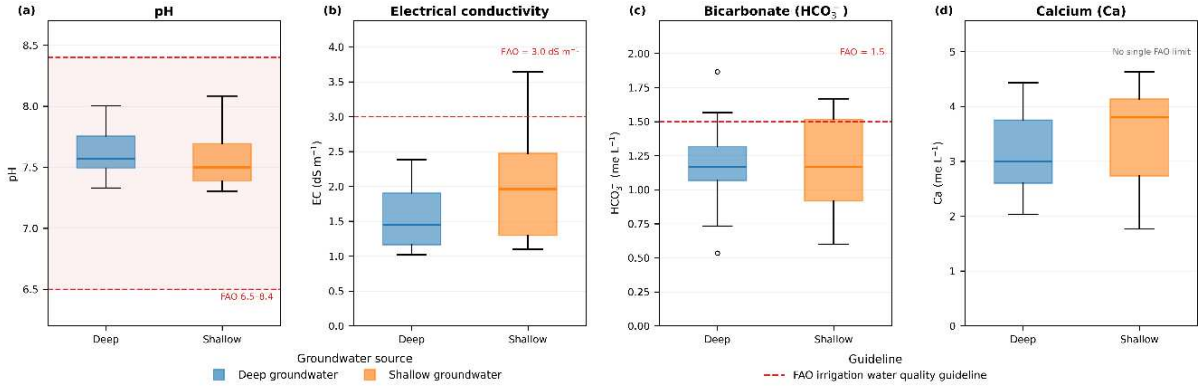


Fig. 2. Box plots of (a) pH, (b) electrical conductivity (EC), (c) bicarbonate (HCO_3^-) and (d) calcium (Ca^{2+}) in deep and shallow groundwater (n = 15 per group). Boxes show the interquartile range and median, whiskers extend to 1.5 × the interquartile range and circles are outliers. Dashed red lines are FAO irrigation guideline values;[41] no single guideline applies to calcium.

3.3 Trace-metal concentrations and irrigation-water screening

Copper and zinc were low in both groups and well below FAO guidelines (Table 2, Fig. 3). Mean Cu was 0.0417 ± 0.0037 mg L^{-1} (deep) and 0.0425 ± 0.0047 mg L^{-1} (shallow; $p = 0.637$), and mean Zn 0.0114 ± 0.0043 and 0.0155 ± 0.0078 mg L^{-1} ($p = 0.081$). Mean Fe was 0.281 ± 0.050 mg L^{-1} in deep and 0.428 ± 0.327 mg L^{-1} in shallow groundwater ($p = 0.125$), far below the 5.0 mg L^{-1} guideline. Mean Mn was 0.0138 ± 0.0123 mg L^{-1} in deep and 0.2109 ± 0.5107 mg L^{-1} in shallow groundwater ($p = 0.290$). No deep sample exceeded the Mn guideline of 0.20 mg L^{-1}, whereas three shallow samples did (up to 1.943 mg L^{-1}; Fig. 3d); the shallow mean therefore marginally exceeded the guideline because of these few wells rather than a general depth contrast.

Lead was below the FAO irrigation guideline in every sample, with means of 0.0977 ± 0.0803 (deep) and 0.0719 ± 0.0714 mg L^{-1} (shallow; $p = 0.340$). Cadmium was the clearest concern: its means were almost identical in deep (0.0164 ± 0.0056 mg L^{-1}) and shallow groundwater (0.0163 ± 0.0081 mg L^{-1}; $p = 0.740$), both exceeding the 0.01 mg L^{-1} guideline, and the interquartile range of both groups lay above the guideline (Fig. 3f). Deeper abstraction therefore did not remove the Cd concern.

Table 2. Trace-metal concentrations (mg L^{-1}; mean ± SD, $n = 15$ per group) in deep and shallow groundwater and FAO irrigation guideline values.

Metal	Deep groundwater	Shallow groundwater	Test	*p*-value	FAO guideline[a]
Cu	0.0417 ± 0.0037	0.0425 ± 0.0047	Welch *t*	0.637	0.20
Zn	0.0114 ± 0.0043	0.0155 ± 0.0078	Mann–Whitney *U*	0.081	2.0
Mn	0.0138 ± 0.0123	0.2109 ± 0.5107	Mann–Whitney *U*	0.290	0.20
Fe	0.281 ± 0.050	0.428 ± 0.327	Mann–Whitney *U*	0.125	5.0
Pb	0.0977 ± 0.0803	0.0719 ± 0.0714	Mann–Whitney *U*	0.340	5.0
Cd	0.0164 ± 0.0056	0.0163 ± 0.0081	Mann–Whitney *U*	0.740	0.01

[a]Maximum recommended concentration for long-term irrigation.[41]

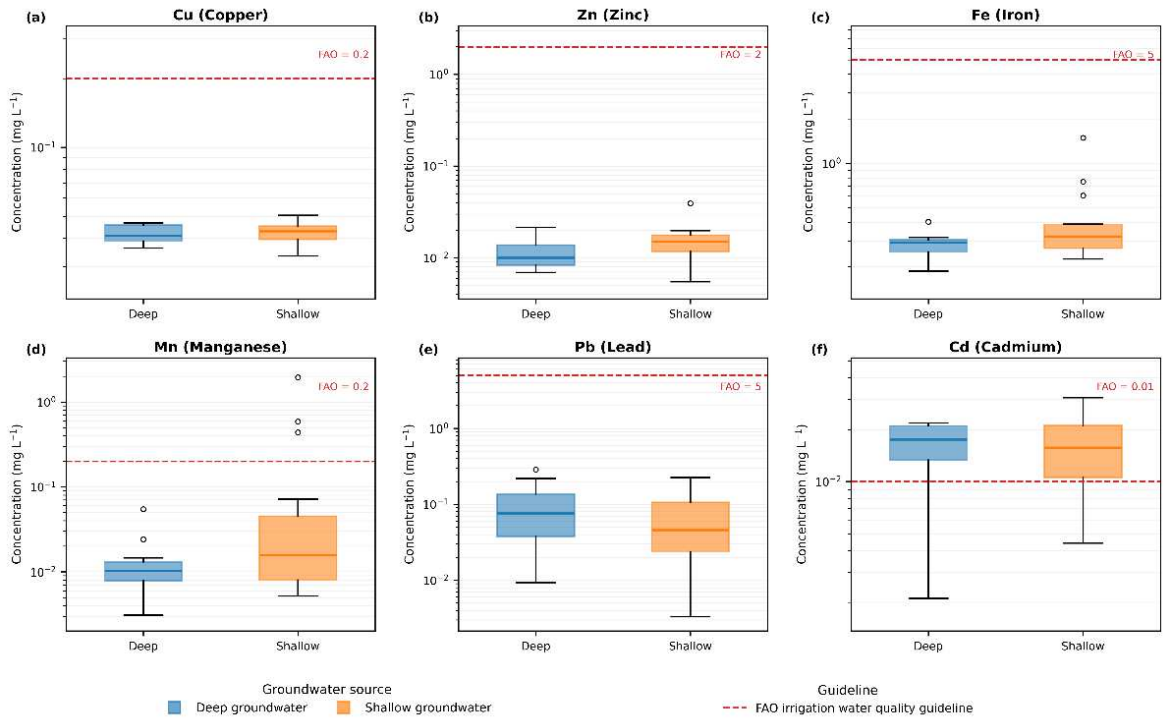


Fig. 3. Box plots of trace-metal concentrations in deep and shallow groundwater: (a) Cu, (b) Zn, (c) Fe, (d) Mn, (e) Pb and (f) Cd, on logarithmic axes (n = 15 per group; box-plot conventions as in Fig. 2). Dashed red lines are FAO maximum recommended concentrations for irrigation water.[41]

3.4 Contamination factor analysis

Mean CF values for Cu, Zn, Fe and Pb were below 1 in both groups (Supplementary Table S3), indicating low contamination relative to the irrigation benchmark. The mean CF for Mn was 0.07 in deep groundwater but 1.05 in shallow groundwater, reflecting the few elevated wells. Cadmium had the highest CF in both groups (1.64 ± 0.56 deep; 1.63 ± 0.81 shallow), corresponding to moderate contamination, with mean concentrations about 1.6 times the benchmark. CF ranks exceedance relative to the selected guideline and does not by itself identify the source of a metal.

3.5 Correlation analysis of groundwater quality parameters

The correlation matrix (Fig. 4) showed weak-to-moderate associations; with n = 30, $|r| \geq 0.36$ is significant at $p < 0.05$. HCO_3^- and Ca^{2+} were positively correlated (r = 0.53), consistent with a contribution from carbonate mineral dissolution, and pH was negatively correlated with both HCO_3^- (r = −0.60) and Ca^{2+} (r = −0.67). EC correlated most strongly with Cu (r = 0.60), and Fe with Cu (r = 0.40), whereas the EC–Mn association was weak (r = 0.33). Cd was positively

associated with HCO_3^- ($r = 0.48$) and negatively with pH ($r = -0.48$), with a similar but weaker pattern for Pb ($r = 0.38$ and -0.38). These patterns indicate that some trace metals covary with general water chemistry, but correlation alone cannot separate geogenic mobilisation from local inputs.

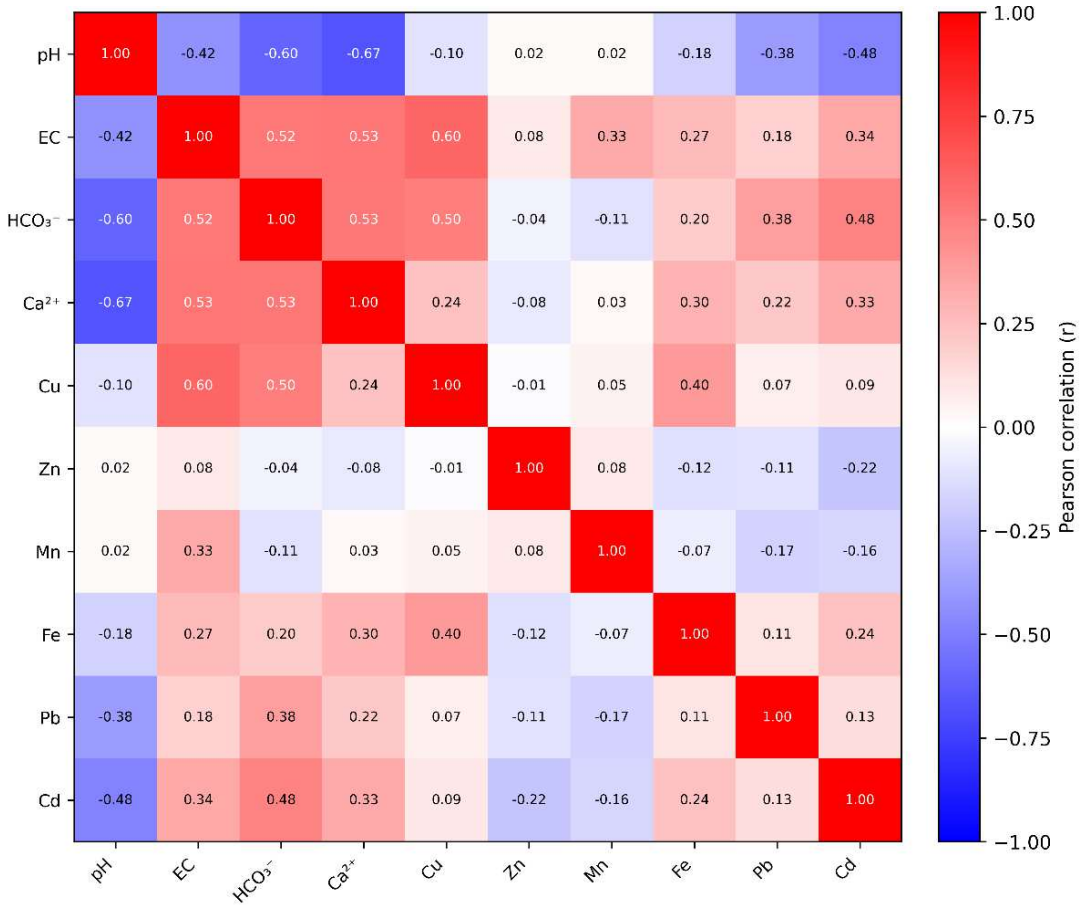


Fig. 4. Pearson correlation matrix of physicochemical parameters and trace metals in groundwater ($n = 30$); $|r| \geq 0.36$ is significant at $p < 0.05$.

3.6 Principal component analysis

Three components had eigenvalues above 1 (3.51, 1.50 and 1.16) and together explained 61.7% of the variance (Fig. 5, Supplementary Table S4). PC1 (35.1%) had high positive coefficients for HCO_3^- (0.44), Ca^{2+} (0.41), EC (0.40) and Cd (0.32) and a negative coefficient for pH (−0.41), describing a mineralisation gradient along which Cd increases as pH decreases. PC2 (15.0%) was dominated by Mn (0.58), EC (0.41) and Cu (0.39), and PC3 (11.6%) by Fe (0.57) and Cu (0.44), with a negative coefficient for Zn (−0.44) (Supplementary Table S5). The spread of trace metals across all three components indicates that they do not follow one common pattern across the sampled wells. With 30 samples and ten variables, the component structure is exploratory and should guide future sampling rather than serve as source apportionment.

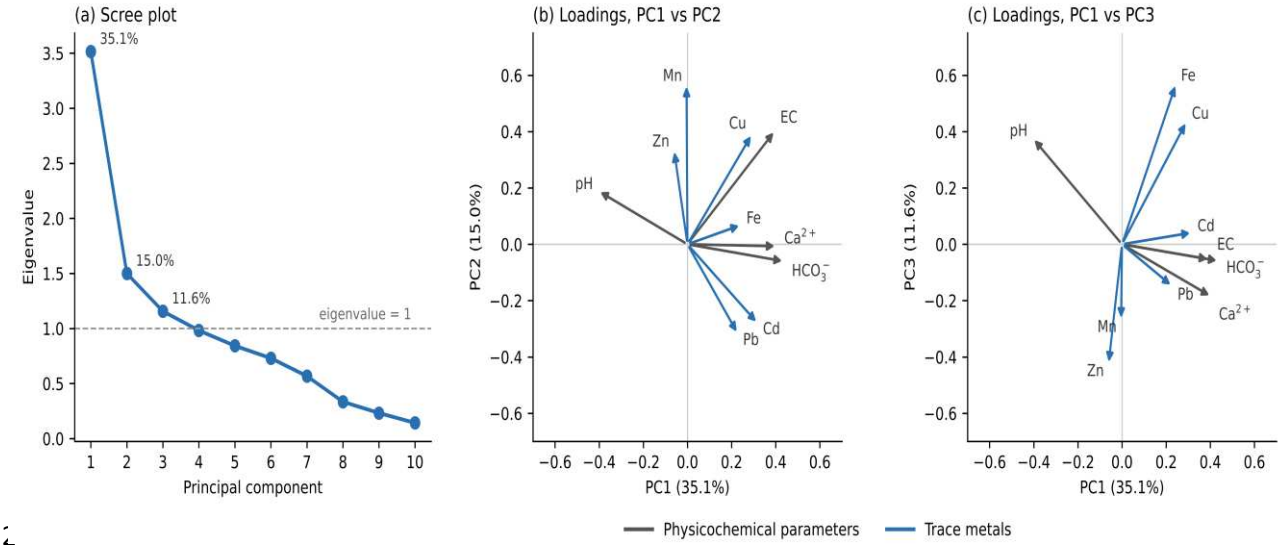


Fig. 5. Principal component analysis of ten standardised hydrochemical variables (n = 30): (a) scree plot of eigenvalues, with the dashed line marking the eigenvalue-one (Kaiser) criterion and labels giving the variance explained by PC1–PC3; (b, c) unrotated loading vectors on PC1–PC2 and PC1–PC3 (grey, physicochemical parameters; blue, trace metals).

3.7 Hierarchical cluster analysis

Ward-linkage clustering separated the 30 samples into three groups (Fig. 6). Cluster I (14 samples) had higher mean EC (2.37 dS m^{-1}) and Fe (0.456 mg L^{-1}); Cluster II (15 samples) had lower mean EC (1.28 dS m^{-1}), Fe (0.268 mg L^{-1}) and Mn (0.013 mg L^{-1}); and the third group was a single sample (T5) with Mn of 1.943 mg L^{-1}, an outlier rather than a hydrochemical facies. The clusters show that water quality varies between individual wells and that a few samples strongly influence group means, particularly for Mn; they describe similarity within this dataset and are not independently confirmed aquifer types.

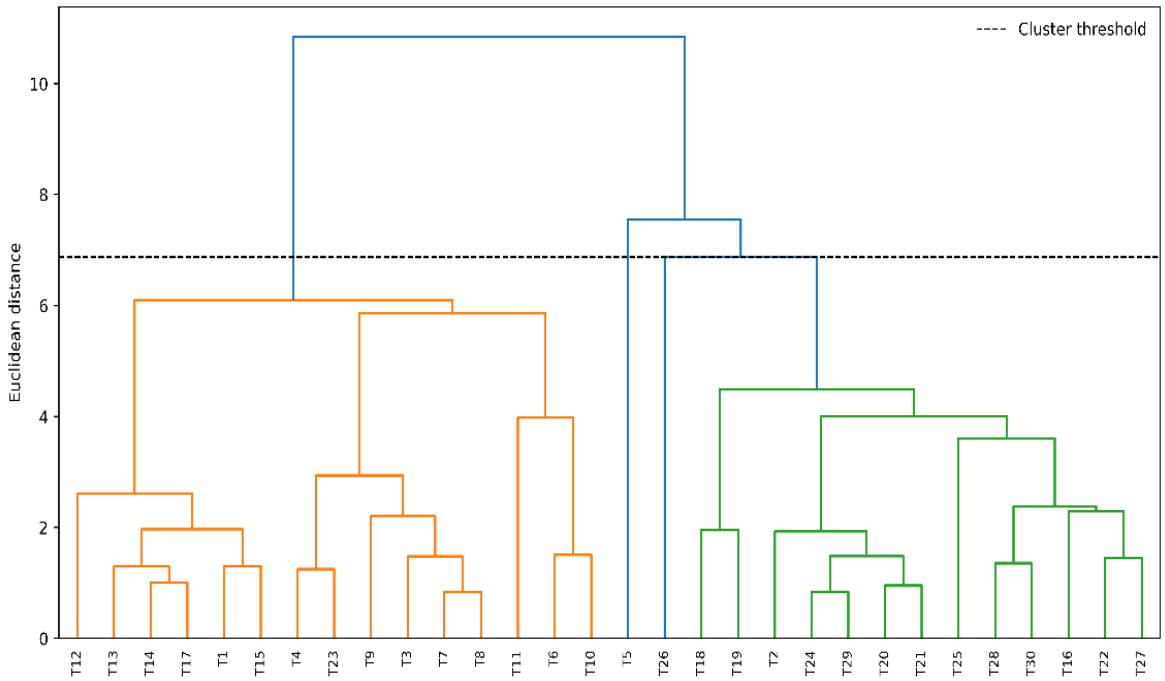


Fig. 6. Hierarchical cluster dendrogram of the 30 groundwater samples (Ward linkage, Euclidean distance). The dashed line marks the cut height (distance ≈ 6.9) defining Cluster I (green branches and T26; n = 14), Cluster II (orange branches; n = 15) and the single-sample group T5.

4. Discussion

The central finding is that hydrogeophysically targeted deep tubewells did not deliver uniformly better irrigation water. The deep samples had lower mean EC and were free of the extreme salinity and Mn values seen in a few shallow wells, but none of the ten measured parameters differed significantly between depth categories, and Cd exceeded the FAO guideline in both. This negative result matters for programme design: geophysical siting is often presented as a quality safeguard, yet our data show that it answers a different question (where a productive formation lies) from the one that matters for irrigation (what is in the water).

The lower mean EC of deep groundwater (p = 0.058) is consistent with less mineralised water in the deeper formations of multilayered Tarai alluvium, where clay-rich layers can limit the downward movement of recharge from intensively irrigated fields.[28,31] With 15 wells per group, however, this is a trend rather than an established depth effect, and because wells were not assigned to depth at random, differences may also reflect local lithology, recharge, pumping history or land use. Earlier irrigation-water assessments in Udham Singh Nagar and the

adjacent Upper Doab also reported marked spatial variation in groundwater quality,[34,37] consistent with the well-to-well differences captured by our cluster analysis.

Fe and Mn were more variable in shallow groundwater, and all Mn exceedances occurred in shallow wells. Reducing conditions in shallow, organic-rich alluvial aquifers commonly mobilise Fe and Mn by dissolution of oxyhydroxide coatings,[43] and heterogeneous redox conditions between nearby wells would explain why only a few shallow wells were affected. Dissolved oxygen, redox potential and Fe–Mn speciation were not measured, so this mechanism remains plausible rather than demonstrated; operationally, Mn should be checked at individual wells rather than inferred from depth.

Cadmium was the only metal whose mean exceeded its irrigation guideline in both groups, at virtually identical concentrations. Its association with HCO_3^- and lower pH on PC1 suggests co-variation with the mineralisation gradient. Phosphate fertilisers are a recognised diffuse Cd source in intensively cropped soils,[44] and corrosion of well fittings or geogenic release are other possible contributors; the present data cannot distinguish these sources. The practical implication is nonetheless clear: long-term irrigation with water at about 0.016 mg L^{-1} Cd may lead to gradual accumulation in soils and crops, which is the basis of the FAO guideline.[41] Although Pb was well below the irrigation guideline, the Pb (0.07–0.10 mg L^{-1}) and Cd (0.016 mg L^{-1}) means in both groups exceed the Indian and WHO drinking-water limits of 0.01 and 0.003 mg L^{-1}, respectively.[45,46] Where community irrigation tubewells are also used for domestic supply, they should not be assumed safe to drink without testing.

For groundwater-development programmes, hydrogeophysical surveys and water-quality testing are complementary, not interchangeable. MNEF interpretation can help select target intervals and improve drilling success, but it cannot certify that the abstracted water meets irrigation-quality criteria. A defensible approach is to pair geophysical siting with baseline chemical analysis at commissioning (salinity, sodicity indices and trace metals including Cd and Mn), followed by periodic monitoring; such testing can be written into the operating procedures of programmes such as PMKSY-HKKP-GW.[32]

4.1 Limitations and future research

The dataset comprises 30 samples from a single pre-monsoon campaign in three blocks, selected purposively from programme sites with traceable survey records, without a power calculation or spatial sampling grid; it therefore cannot represent the full heterogeneity of the Tarai aquifer or seasonal variation. Deep and shallow sources were close to each other, but

unique pair identifiers were not available for all wells, so the tests treated the groups as independent. The MNEF interpretations were not validated with borehole logs or a second geophysical method. The chemical suite excluded Na^{+}, Mg^{2+}, major anions, sodium adsorption ratio, residual sodium carbonate, arsenic, fluoride and redox indicators, and the multivariate analyses are exploratory given the sample-to-variable ratio. Future work should use a spatially balanced, multi-season design with a sample size justified in advance, borehole lithological logs, a full major-ion suite with charge-balance checks, redox measurements and, where possible, isotopic and land-use data, to test the mechanisms suggested here and to determine whether the Cd exceedance persists across seasons and aquifer settings.

5. Conclusions

In the sampled Tarai community wells, MNEF survey records identified a multilayered alluvial sequence and guided drilling to 90–150 m, but deeper abstraction did not produce statistically better irrigation-water chemistry. Deep groundwater showed a non-significant trend towards lower salinity and lacked the Mn outliers found in shallow wells, while Cd exceeded the FAO irrigation guideline equally at both depths. Hydrogeophysical siting should therefore be treated as a tool for locating productive formations, not as a proxy for water quality, and programme-scale tubewell development should include baseline and periodic chemical testing. These conclusions apply to the sampled locations and require confirmation through broader spatial and seasonal sampling.

Declarations

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Author contributions

V.P.C.: conceptualisation, methodology, formal analysis, investigation, visualisation, writing – original draft, supervision and project administration. V.K.S.: resources, investigation, data curation and writing – review and editing. P.R.: conceptualisation, methodology, validation, writing – review and editing and supervision. A.G.: investigation, formal analysis, data curation and writing – review and editing. C.P.S.: investigation, formal analysis and writing – review and editing. All authors read and approved the final manuscript.

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Competing interests

V.K.S. is employed by the Minor Irrigation Department, Government of Uttarakhand, which implemented the PMKSY-HKKP-GW tubewells studied here, and P.R. is employed by the Central Ground Water Board. The authors declare no other financial or non-financial competing interests.

Data availability

The anonymised sample-level data supporting this study are provided as Supplementary Data 1. Programme field records used to interpret the MNEF surveys are available from the corresponding author on reasonable request, subject to permission from the implementing authority.

Ethics and Consent to Participate declarations

Ethics and Consent to Participate declarations: not applicable. This study did not involve human participants, human data or tissue, or animals. Groundwater samples were collected from community tubewells with the cooperation of beneficiary farmers and the implementing authority; beneficiary identities are not reported.

Consent to Publish declaration

Consent to Publish declaration: not applicable. The manuscript does not contain any individual person's data in any form, including personal details, images or videos.

Clinical trial number

Clinical trial number: not applicable. This study is not a clinical trial.

Use of generative AI

A generative AI tool was used for language editing, formatting and consistency checking, and to redraw Fig. 5 and Supplementary Fig. S1 from the authors' data. The authors reviewed all outputs and take full responsibility for the content.

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