

Dushanbe Artesian Basin: Opportunities for Ground Source Heat Pump (GSHP) Deployment

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ABSTRACT

This study evaluates the shallow-geothermal potential of the Dushanbe Artesian Basin (DAB) for ground source heat pump (GSHP) deployment. One of the two 105 m vertical boreholes of a pilot installation was instrumented with a double U-tube and optical-fibre distributed temperature sensing (DTS) and tested by a single thermal response test (TRT); 95 groundwater samples (2022–2024) provided basin-wide hydrochemical characterisation. Analytical inversion of the TRT data, with Monte Carlo uncertainty quantification (1000 realisations, percentile confidence intervals), yielded an average effective ground thermal conductivity $\lambda_{\text{eff}} \approx 1.9 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (95 % CI 1.71–2.04) and a depth-dependent contrast between the unsaturated (1.4–1.7 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and saturated (2.0–2.4 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) zones, with a stable undisturbed temperature near 16.5 °C. Hydrochemical analysis identifies scaling and corrosion risks for open-loop and semi-open-loop configurations but confirms that closed-loop circuits are unaffected. First-order multipole calculations for the as-built double U-tube show that an optimised quartz-enhanced grout (CEM I 42.5R + 40 wt% quartz, $\lambda_g = 2.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) reduces the borehole thermal resistance R_b from 0.177 to 0.090 $\text{m}\cdot\text{K}\cdot\text{W}^{-1}$. At a fixed fluid-to-ground temperature difference this raises the specific heat-transfer rate by $\approx 20\%$ after one year of continuous operation (26 % at one month, 16 % at ten years), in either heat-extraction or heat-injection mode. The work provides a reproducible interpretation framework and engineering recommendations for GSHP deployment in arid, lithologically heterogeneous basins.

Keywords: Ground source heat pump (GSHP); Thermal response test (TRT); Shallow geothermal energy; Hydrochemistry; Dushanbe Basin; Borehole thermal resistance.

1. INTRODUCTION

Ground source heat pumps (GSHPs) are widely deployed in temperate climates [1–3] and are now being introduced in Central Asia, where thermal response testing has recently been adapted to local conditions [4]. By end-2023, the EU had installed ≈ 2.32 million GSHP units; Japan and other countries with continental climates also rely on the technology, achieving COPs of 3–4 (up to 6) and 35–45 % energy savings versus air-source pumps [2,5,6]. Throughout this paper we use ground source heat pump (GSHP) in the strict sense of a low-enthalpy, shallow-geothermal technology that exploits

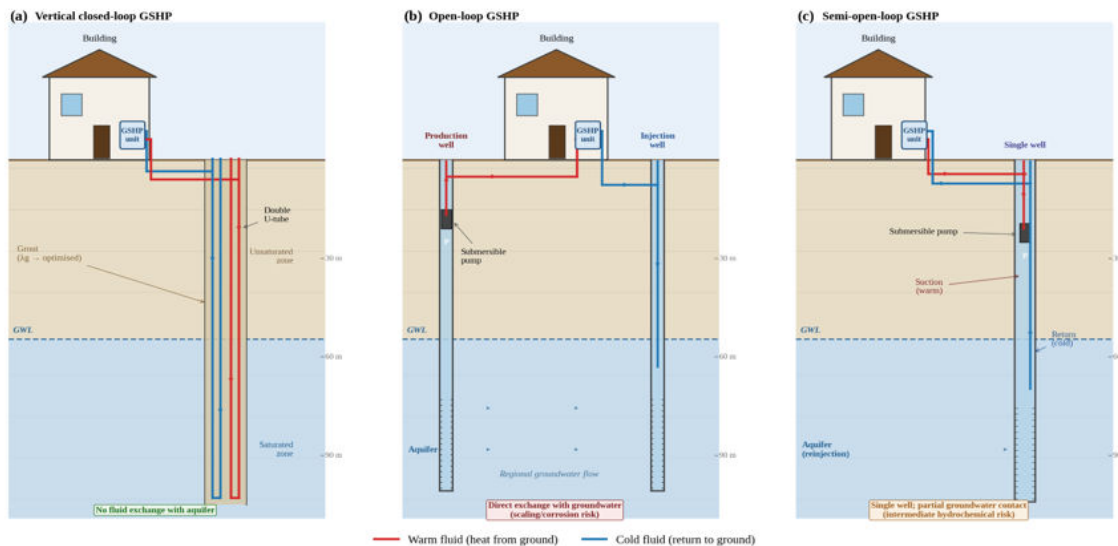


Fig. 1. Conceptual schematics of the three principal GSHP configurations: (a) vertical closed-loop borehole heat exchanger; (b) open-loop production–injection wells; (c) semi-open-loop single well.

the near-constant temperature of the upper 100–200 m of the subsurface for building heating and cooling, distinguished from deep geothermal systems for power generation [3].

Three principal GSHP configurations are recognised (Fig. 1): (a) closed-loop, with a sealed circuit of HDPE pipes and antifreeze in a grouted borehole; (b) open-loop, with groundwater extraction and reinjection through separate wells; and (c) semi-open-loop, combining extraction and reinjection in a single well. The present pilot study addresses configuration (a); the basin-wide hydrochemical assessment supports the design feasibility of any future (b) and (c) systems.

In closed-loop circuits with HDPE pipes and antifreeze, the working fluid is isolated from groundwater and scaling/corrosion of the heat-exchange surfaces are not primary concerns [5,7]. However, HDPE has low thermal conductivity, making the choice of grout a critical design factor. In open-loop systems, by contrast, carbonate–silicate scale and biofouling cause corrosion of wells and equipment in mineralised groundwaters [5,8].

The Dushanbe Artesian Basin (DAB) of the Gissar Valley contains high-pressure layers of self-flowing mineral and thermal waters; previous simulations show GSHPs in Dushanbe sustain COP ≈ 7.2 with only 1.3 °C ground cooling over 10 years [7]. Demonstration systems have shown 30–50 % heating-cost savings; widespread GSHP adoption could replace 900+ small coal boilers in schools and hospitals nationwide [9–13].

Aim. To quantify the technical feasibility of vertical closed-loop GSHP in the DAB and to identify a low-complexity engineering intervention — grout optimisation — addressing the basin’s lithological heterogeneity.

Objectives: (i) characterise effective $\lambda_s(z)$ and undisturbed $T_0(z)$ at a representative pilot site by TRT + DTS; (ii) assess basin-wide hydrochemistry and operational risks for any open-loop / semi-open-loop deployment; (iii) demonstrate that grout thermal conductivity is a controllable design variable affecting borehole thermal resistance R_b ; (iv) project long-term thermal evolution (10–30 yr) under three operating scenarios.

Hypothesis. With proper grout selection and balanced load management, vertical closed-loop GSHP in the DAB can sustain high seasonal performance over 10–30 years despite lithological and hydrochemical heterogeneity.

2. MATERIALS AND METHODS

2.1 Study area and sampling

Groundwater samples were collected at representative depths across the Dushanbe metropolitan basin; sampling-point

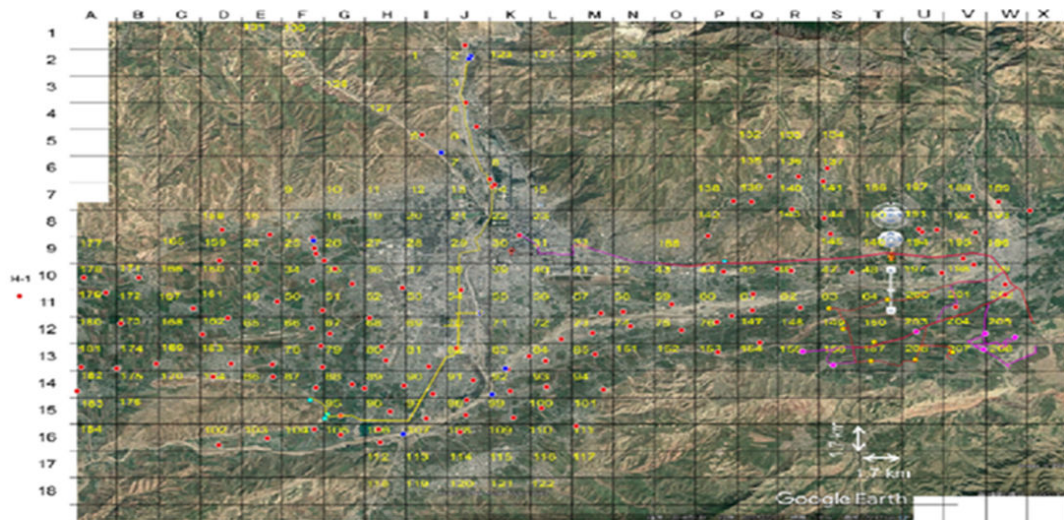


Fig. 2. Sampling-point locations in the Dushanbe Artesian Basin.

locations are shown in Fig. 2. The TRT pilot site lies in the central part of the basin, in the Quaternary alluvial–proluvial deposits.

2.2 Hydrochemical analysis

A total of 95 samples (2022–2024) were analysed for pH, electrical conductivity (EC), redox potential (Eh), total dissolved solids (TDS), total hardness, and major ions (Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , SO_4^{2-}). Samples were classified by physical sampling type (direct artesian wellhead, storage-tank, manual/mechanical pump, spring) rather than by GSHP loop type. Calibration of field probes (pH, EC, T, Eh) preceded each campaign; laboratory analyses followed certified methods. Saturation indices (e.g., Langelier) and corrosion-activity indices were computed at typical operating temperatures.

2.3 Thermal response test

The pilot installation at the Center comprises **two vertical boreholes of 105 m depth**, each of 216 mm diameter ($r_b = 0.108$ m) and each equipped with a double U-tube of HDPE (ID/OD = 26/32 mm) with an active length of 102 m. The thermal response test reported here was performed in **one** of the two boreholes, which was additionally instrumented with an optical-fibre DTS cable (1 m vertical and 1-min temporal resolution). The four pipe legs are arranged symmetrically on a circle of radius $r_c = 46$ mm; the shank spacing between the two legs of each U-pair is $s = 65$ mm. The geological profile and well completion of the instrumented borehole, which document its lithological structure and instrumentation, are presented with the results in Section 3.2. Heating phase: 48 h with a heater of 3.87 kW nominal electrical rating (38 W·m⁻¹) at a constant volumetric flow of 19.9 L·min⁻¹; recovery phase: 48 h with the circulation pump switched off. The instantaneous borehole heat injection rate was obtained from the recorded flow and inlet–outlet temperature difference as $Q(t) = \dot{m} [T_{\text{in}}(t) - T_{\text{out}}(t)]$ and its time history is presented in Section 3.2. It was **not** constant: the heater was not power-regulated, and Q declined as the circuit warmed. The inversion of Section 2.4 therefore uses the measured $Q(t)$ history rather than a constant-rate assumption (Section 3.2). DTS was calibrated against three reference thermistors at 10, 50 and 100 m depth; the flowmeter was traceable to laboratory standards. Inlet temperature was recorded to ± 0.1 °C. The grout used in the sensitivity calculations of Section 3.3 is a CEM I 42.5R cement matrix with 40 wt% quartz aggregate (median grain size 0.25–0.5 mm; ASTM C33 fine-aggregate sieve analysis), W/C = 0.45, 0.5 wt% silica dispersant; cured λ_g measured per ASTM D5334.

Representativeness of a single TRT site. The pilot borehole is representative of the Quaternary alluvial–proluvial deposits constituting ≈ 70 % of the basin volume above 150 m depth. The reported λ_s is therefore a first-order estimate for analogous lithologies; basin-wide extrapolation will require a coordinated multi-site TRT campaign (Section 4, Next steps).

2.4 Inversion procedure and uncertainty assessment

2.4.1 Interpretation workflow

TRT data were interpreted in five sequential steps, summarised in Fig. 3 and detailed below. All steps were implemented in Python 3.11 (NumPy/SciPy); the complete workflow was re-executed independently for every Monte

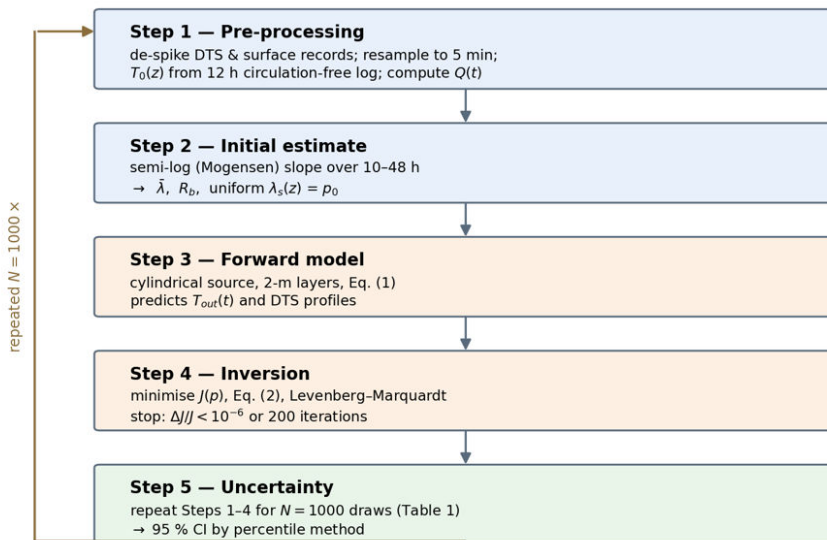


Fig. 3. Workflow used to interpret the TRT data. Steps 1–4 constitute one inversion; the whole chain is repeated for each of the 1000 Monte Carlo realisations of Table 1.

Carlo realisation (Section 2.4.2), so that the reported confidence intervals propagate measurement and parameter uncertainty through the entire interpretation chain rather than through the final step alone.

Step 1 — Data pre-processing. Raw DTS traces (1 m $\times$ 1 min) and surface inlet/outlet records were de-spiked (median filter, 5-point window), resampled to a uniform 5-min grid, and the undisturbed profile $T_0(z)$ was taken as the mean of the 12 h of circulation-free logging preceding the test. The instantaneous heat injection rate $Q(t)$ was computed from the measured flow and inlet–outlet difference.

Step 2 — Initial estimate. A bulk conductivity λ_b and borehole resistance R_b were obtained from the semi-logarithmic slope of the mean fluid temperature over the interval 10–48 h (Mogensen method), excluding the early period affected by borehole thermal capacitance. These values, together with a uniform $\lambda_s(z)$ profile, formed the initial parameter vector p_0 .

Step 3 — Forward model. For a trial parameter vector p , the transient temperature field around the borehole is computed from the cylindrical source solution with 2-m vertical discretisation. Because the far-field problem is rotationally symmetric about the borehole axis, the governing equation is written in cylindrical coordinates (r, z) , where r is radial distance from the borehole axis and z is depth:

$$\rho c \partial T / \partial t = (1/r) \partial / \partial r [r \lambda_s(z) \partial T / \partial r] + \partial / \partial z [\lambda_s(z) \partial T / \partial z] + q(z, t) \quad (1)$$

with $q(z, t)$ the volumetric source term representing the measured heat injection rate distributed over the active borehole length. The model includes the double U-tube geometry with the actual shank spacing, borehole thermal capacitance, and a step change in effective conductivity at the unsaturated/saturated transition (≈ 50 m). Groundwater advection in permeable horizons is represented by an effective transfer term following Gehlin & Hellström [8].

Step 4 — Inversion. The parameter vector p — comprising $\lambda_s(z)$ in 2-m layers, the grout conductivity λ_g , and the initial

$$J(p) = w_T \text{RMSE}_{\text{out}}(p) + w_D \text{RMSE}_{\text{DTS}}(p) + \gamma \|L(p - p_0)\|^2 \quad (2)$$

layer temperatures — is adjusted to minimise the regularised objective function

where RMSE_{out} and RMSE_{DTS} are the root-mean-square misfits of the outlet fluid temperature and of the DTS vertical profiles respectively, $w_T = 0.6$ and $w_D = 0.4$ are fixed weights, L is a first-order difference (smoothing) operator and γ is the regularisation parameter, selected by the L-curve criterion. Minimisation used the Levenberg–Marquardt algorithm with a numerically evaluated Jacobian, stopping when $\Delta J/J < 10^{-6}$ or the relative parameter change fell below 10^{-6} or 200 iterations were reached. Convergence was accepted only if the residuals of both observation types were unbiased with depth, which excludes local inversion artefacts.

Step 5 — Uncertainty propagation. Steps 1–4 were repeated for 1000 stochastic realisations of the input data and model parameters, as described in Section 2.4.2.

2.4.2 Monte Carlo uncertainty quantification

Uncertainty was quantified by Monte Carlo propagation. The six quantities listed in Table 1 were treated as random variables; their distributions and spreads were assigned from instrument calibration certificates, as-built survey tolerances and laboratory repeatability data, not fitted to the TRT record.

Table 1. Quantities perturbed in the Monte Carlo uncertainty analysis ($N = 1000$ realisations).

Perturbed quantity	Nominal value	Distribution	Spread	Basis
DTS temperature reading	measured trace	Normal (additive noise)	$\sigma = 0.05$ °C	Manufacturer specification; cross-check against three reference thermistors
Volumetric flow rate	$19.9 \text{ L} \cdot \text{min}^{-1}$	Normal	$\sigma = 1$ %	Flowmeter calibration certificate
Heat injection rate $\dot{Q}$	measured $\dot{Q}(t)$	Normal	$\sigma = 2$ %	Power-meter accuracy class
Shank spacing s	65 mm	Uniform	± 5 mm	As-built survey tolerance
Grout conductivity λ_g	$2.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$	Normal	$\sigma = 10$ %	ASTM D5334 repeatability
Undisturbed temperature T_0	16.5 °C	Normal	$\sigma = 0.1$ °C	Pre-circulation DTS log

For each of the $N = 1000$ realisations, one independent value was drawn from each distribution in Table 1, the perturbed data set and prior parameter set were assembled, and **the complete inversion of Steps 1–4 was re-run to convergence**. This yields 1000 independent estimates of $\lambda(z)$, of the depth-resolved profile $\lambda_s(z)$, and of R_b . The reported 95 % confidence intervals are the 2.5th and 97.5th percentiles of these empirical distributions (percentile method); they are not symmetric $\pm 1.96\sigma$ intervals, and are therefore slightly asymmetric where the parameter distribution is skewed. Ensemble convergence was verified by increasing N from 500 to 1000, which changed the interval bounds by less than 0.01 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The resulting intervals are reported for the bulk parameters in Table 2 (Section 3.2) and as shaded bands on the depth-resolved profile in Section 3.2.

3. RESULTS AND DISCUSSION

3.1 Hydrochemistry and operational risks

3.1.1 Basin characterisation

Across the 95 samples, pH = 7.1–7.6 (neutral), Eh $\approx$ 400–500 mV (oxidising). EC and TDS show systematic variability between sampling types (Fig. 4), with storage-tank samples displaying the highest values, consistent with longer residence time and partial evaporation. Total hardness correlates strongly with EC ($R^2 = 0.98$, $n = 95$; Fig. 5), driven by Ca^{2+} and Mg^{2+} ions. Bicarbonate concentrations 3.5–8.0 mmol·L⁻¹ reflect high carbonate alkalinity, with calcium and magnesium concentrations elevated in storage-tank waters (Fig. 6).

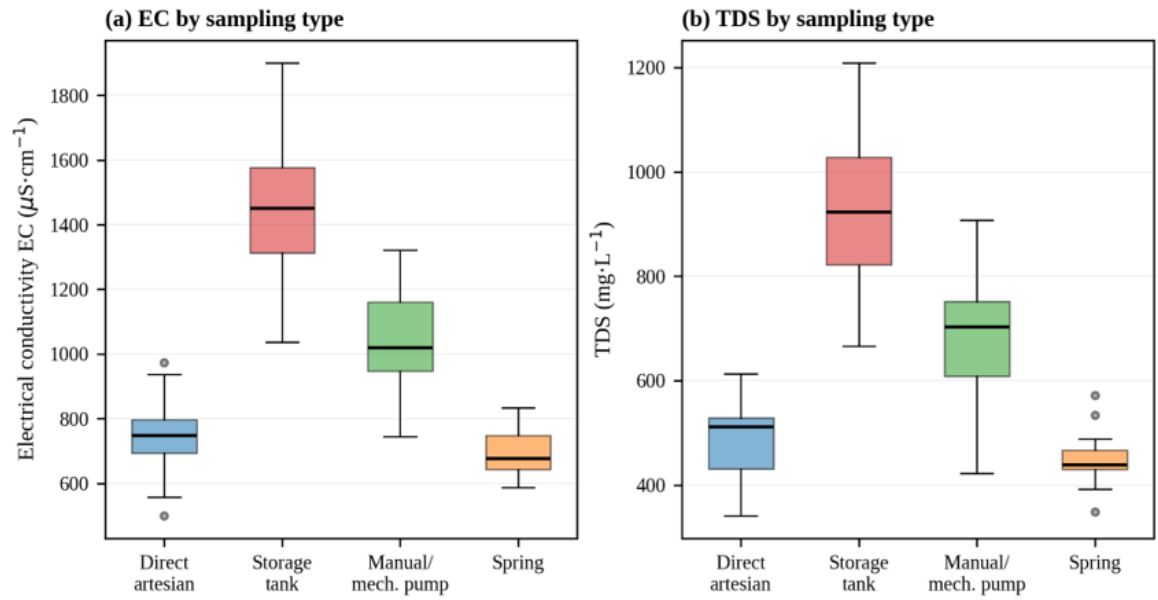


Fig. 4. (a) EC and (b) TDS boxplots by sampling type ($n = 95$).

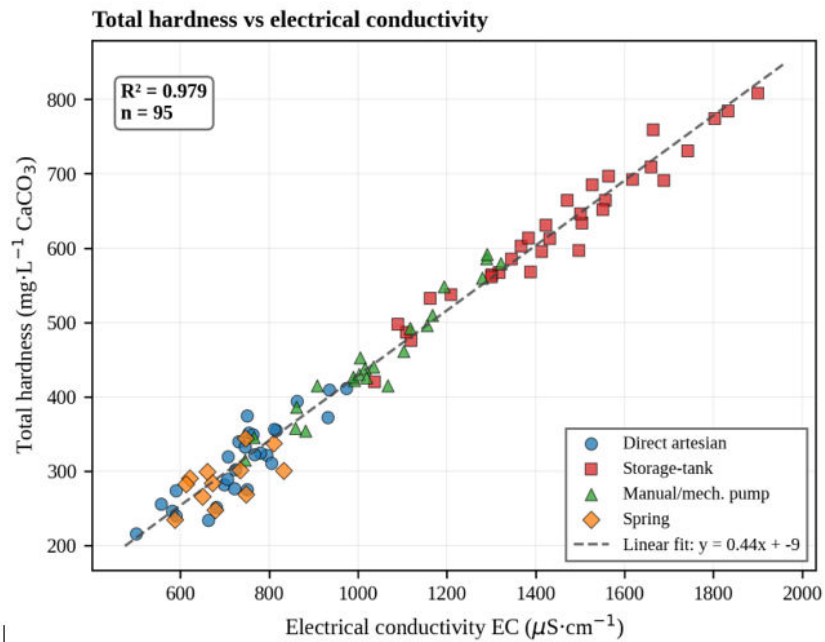


Fig. 5. Total hardness vs electrical conductivity, with linear regression ($n = 95$). The strong correlation supports use of EC as a proxy for scaling propensity.

3.1.2 Implications for open-loop / semi-open-loop GSHP

Following Banks (2012) [5] and Fujii et al. (2025) [7], hydrochemistry is decisive for designs in direct contact with groundwater. Our results indicate elevated CaCO_3 / MgCO_3 scaling risk where $\text{EC} > 1500 \mu\text{S}\cdot\text{cm}^{-1}$ and

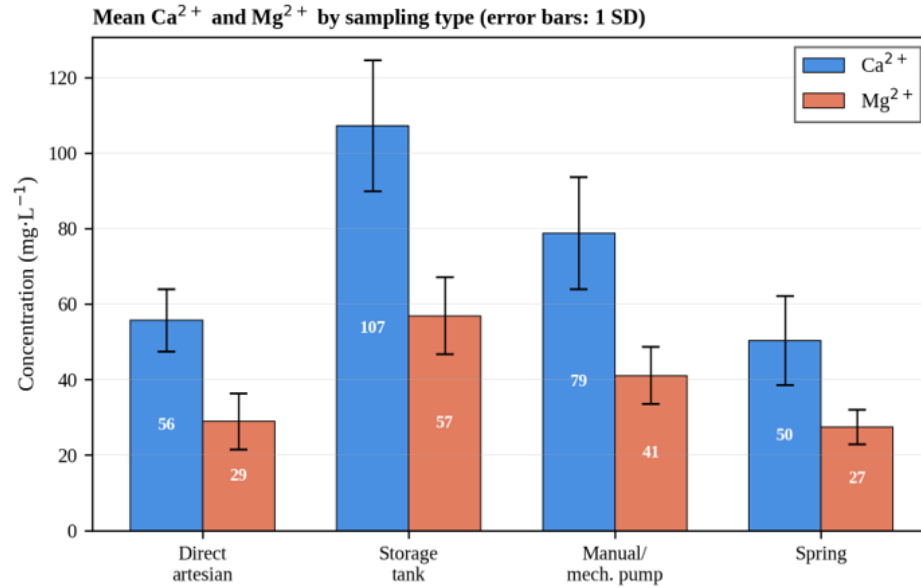


Fig. 6. Mean Ca^{2+} and Mg^{2+} concentrations by sampling type; error bars represent one standard deviation.

$\text{HCO}_3^- > 6 \text{ mmol}\cdot\text{L}^{-1}$, and electrochemical-corrosion risk where E_h and Cl^- are elevated. Recommended measures: corrosion-resistant materials, mechanical filtration with regulated flushing, and (where required) ion-exchange softening or polyphosphate / organic inhibitors; EC and total-hardness thresholds should trigger maintenance protocols.

3.1.3 Implications for closed-loop GSHP

In closed-loop boreholes with HDPE pipes and antifreeze, the working fluid is isolated; scaling and corrosion of the heat-exchange surfaces are not primary design concerns [5,7]. Hydrochemistry remains relevant only indirectly, through (i) durability of cementitious grout in aggressive sulphate / chloride waters, and (ii) corrosion of metallic header components in the surface plant when locally sourced make-up water is used.

3.2 Thermal properties of GSHP boreholes

The geological profile at the test site comprises alternating clays, sandy gravels and sandstones typical of the alluvial–proluvial deposits of the Hissar Valley (Fig. 7a); the borehole was completed as a 105 m, 216 mm diameter installation (Fig. 7b). The depth-resolved $\lambda_s(z)$ profile obtained by inversion (Fig. 8a) reveals two contrasting regimes: an unsaturated upper zone (0–50 m, $\lambda_s \approx 1.4\text{--}1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and a saturated lower zone (50–105 m, $2.0\text{--}2.4 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), separated by a sharp transition at the regional groundwater level.

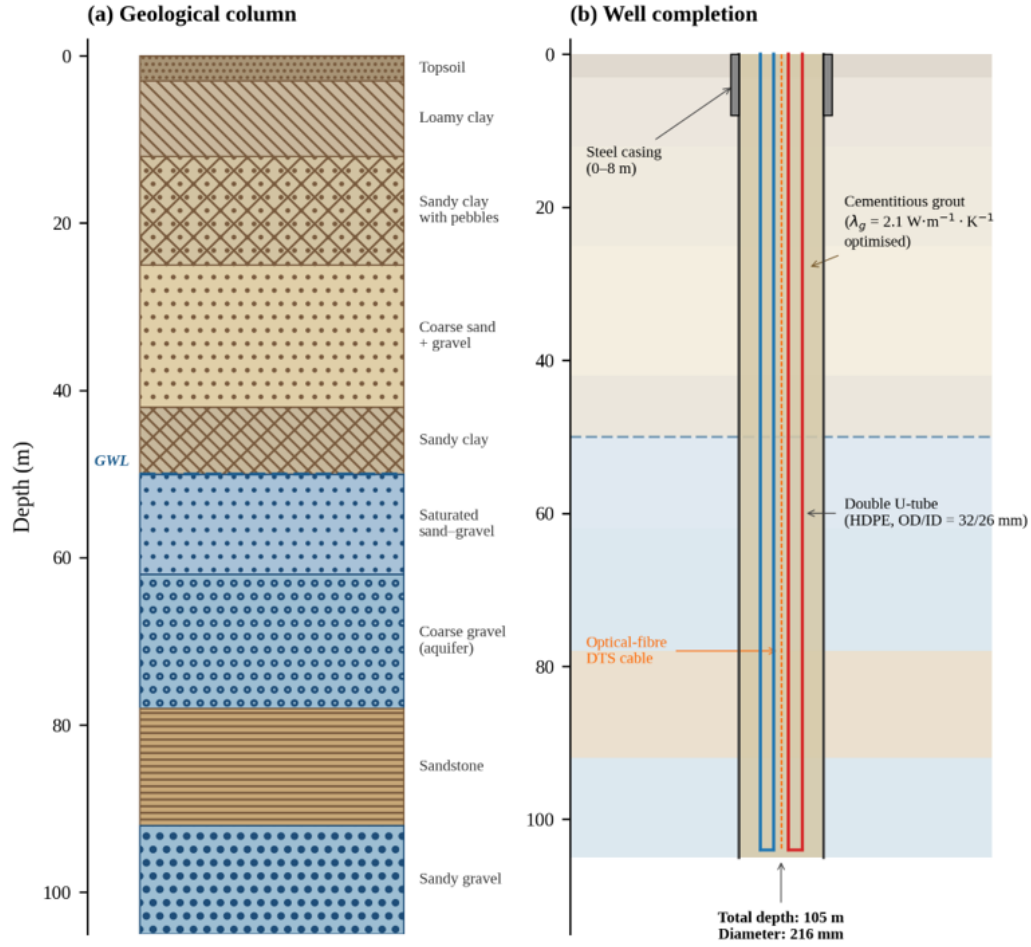


Fig. 7. (a) Geological column at the TRT pilot site; (b) well-completion diagram showing double U-tube, optical-fibre DTS cable, and grouted borehole.

Fluid temperatures during the test are shown in Fig. 8b and the corresponding heat injection rate in Fig. 8c. During the 48 h heating phase the inlet temperature rose rapidly and then approached a quasi-steady value near 31.3 °C, while the inlet–outlet difference *decreased* monotonically from 4.5 K in the first hour to 2.7 K at 48 h. Because the volumetric flow was held constant at 19.9 L·min⁻¹ ($\dot{Q} = 1386 \text{ W}\cdot\text{K}^{-1}$), this decline corresponds directly to a decreasing borehole heat injection rate: $\dot{Q}$ falls from 6.25 kW (61 W·m⁻¹) at the start of the test to 3.74 kW (37 W·m⁻¹) at its end, averaging 4.54 kW (45 W·m⁻¹) over the interval 10–48 h (Fig. 8c). The heating rate was therefore not constant, and the nominal value of 3.87 kW is the electrical rating of the heater, which the borehole injection rate approaches only at the very end of the test. The heater was not power-regulated, so its useful output decreased as the circuit fluid warmed from 16.5 °C to above 31 °C.

This behaviour governs the interpretation. A constant-rate line-source analysis is not strictly applicable to a test in which $\dot{Q}$ varies by a factor of 1.7, so the semi-logarithmic estimate of Table 2 is reported only as an initial approximation, evaluated over the quasi-steady window 10–48 h where $\dot{Q}$ changes most slowly. The results of this study rest on the inversion of Section 2.4, which ingests the measured $\dot{Q}(t)$ history through the source term of Eq. (1) and is valid under variable loading. The close agreement of the two methods in Table 2 indicates that the residual bias introduced by the constant-rate assumption is small relative to the reported confidence intervals.

During the recovery phase (48–96 h) the circulation pump was switched off, so no inlet or outlet flow exists and the surface sensors no longer measure a circulating fluid. The two traces plotted in Fig. 8b for $t > 48$ h are therefore the fluid temperatures recorded by the DTS cable inside the U-tube at the depths of the former inlet and outlet legs, retained under

the same colour code for continuity; they are not surface heater readings. Their exponential decay toward the undisturbed background of 16.5 °C provides the independent constraint on λ_s used in the DTS misfit term of Eq. (2).

Bulk λ_b and R_b obtained by the two interpretation methods are summarised in Table 2; both yield consistent λ_b within their 95 % confidence intervals. The measured R_b of 0.105 m·K·W⁻¹ is close to the 0.090 m·K·W⁻¹ predicted by multipole theory for the as-built double U-tube completed with the quartz-enhanced grout ($\lambda_g = 2.1$ W·m⁻¹·K⁻¹ in Section 3.3), and far below the ≈ 0.18 m·K·W⁻¹ that a plain cement grout would give. The pilot borehole was therefore completed with the optimised grout, and the comparison of Section 3.3 is between this as-built configuration and the plain-cement reference computed for the same geometry. The small residual difference between measured and predicted R_b is attributed to imperfect pipe centring and to groundwater advection in the saturated zone.

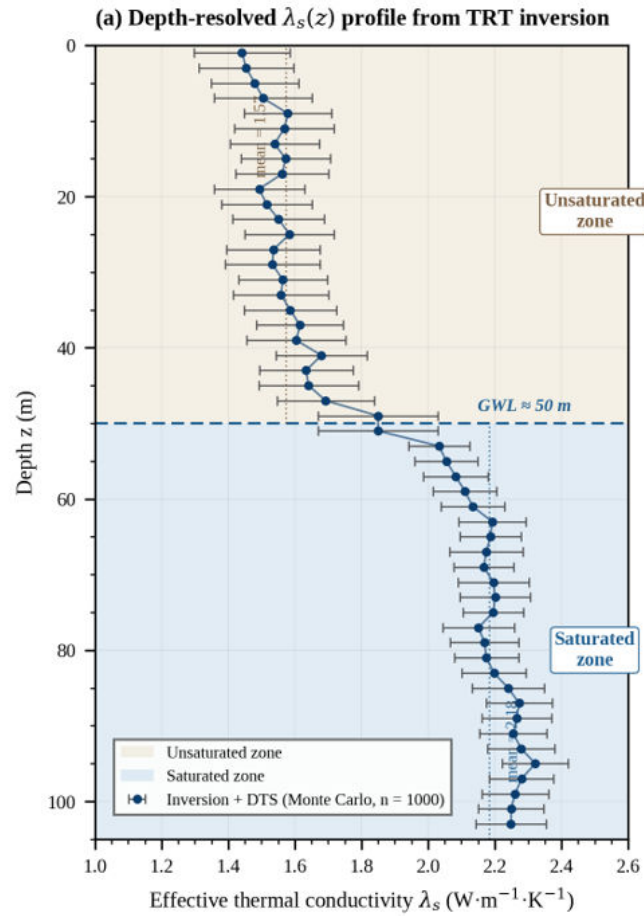


Fig. 8a. Depth-resolved effective thermal conductivity $\lambda_s(z)$ from analytical inversion of TRT data, with 95 % confidence intervals from Monte Carlo ($n = 1000$).

temperatures recorded at the surface heater. Recovery phase (48–96 h): circulation stopped (flow = 0); the curves show fluid temperatures recorded by the DTS cable inside the U-tube at the depths of the former inlet and outlet legs, retained under the same colour code for continuity — they are not surface heater readings. Dotted line: undisturbed ground temperature $T_0 = 16.5^\circ\text{C}$.

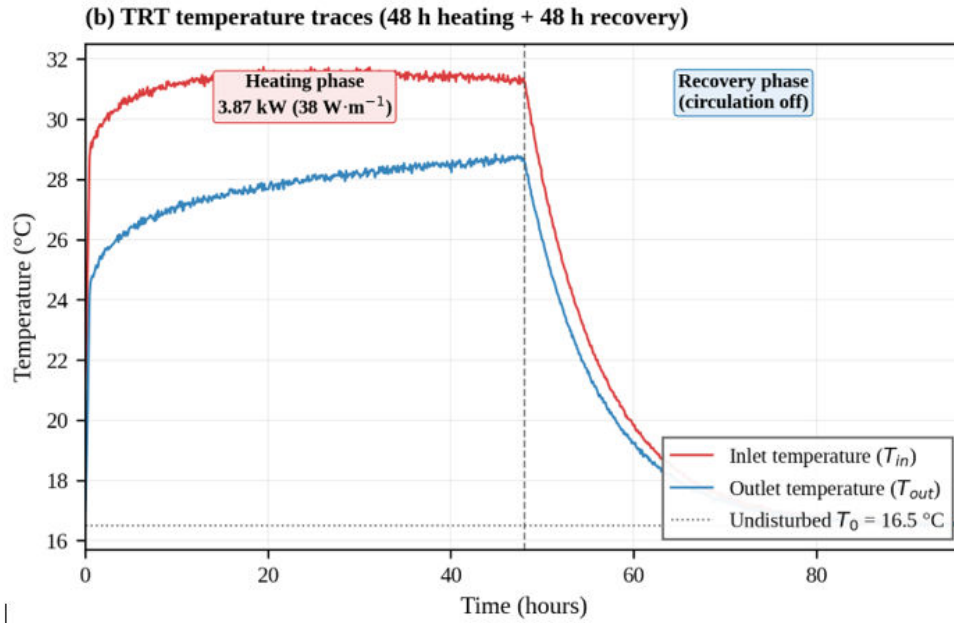


Fig. 8b. Circulating-fluid temperatures during the TRT. Heating phase (0–48 h): inlet (T_{in}) and outlet (T_{out})

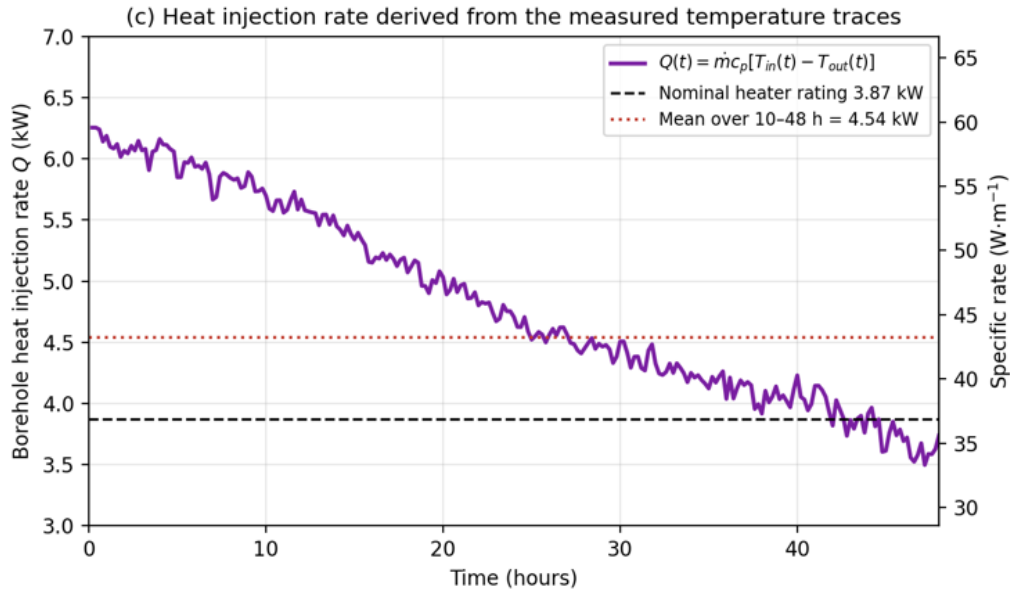


Fig. 8c. Borehole heat injection rate $Q(t) = \dot{m} c_p [T_{in}(t) - T_{out}(t)]$ during the heating phase, derived from the measured temperature traces of Fig. 8b at the recorded constant flow of $19.9 \text{ L}\cdot\text{min}^{-1}$. Dashed line: nominal heater rating (3.87 kW). Dotted line: mean over the quasi-steady window 10–48 h (4.54 kW).

Table 2. Comparison of thermal-property estimates (semi-log analysis vs analytical inversion).

Method	λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	R_b ($\text{m}\cdot\text{K}\cdot\text{W}^{-1}$)	95 % CI of λ
Semi-log graphical method (Mogensen, 1983)	1.92	0.118	[1.78–2.06]
Cylindrical-source inversion + DTS (Monte Carlo, $n = 1000$)	1.88	0.105	[1.71–2.04]

Undisturbed ground temperature was stable at ≈ 16.5 °C throughout the year. The long-term consequences of this thermal

regime are quantified from our own model in Section 3.4 (Table 4) rather than taken from the literature. The TRT data of Figs. 8a–b and Table 2 demonstrate that the central, typical-lithology part of the DAB is well suited to vertical closed-loop GSHP, provided that borehole design, grouting and load balance are properly managed.

3.3 Influence of grouting materials on borehole thermal efficiency

3.3.1 Method and input data

The influence of grout conductivity on borehole thermal resistance was evaluated analytically, using the first-order multipole method of Claesson & Hellström [14]. For a borehole containing pipes arranged symmetrically about its axis, this method gives the steady-state fluid-to-wall resistance R_b in closed form as a function of the borehole radius, pipe radius and spacing, and the grout and ground conductivities. It requires no spatial discretisation, so the computation is exactly reproducible from the geometry and material data given below. We note that the borehole cross-section is *not* rotationally symmetric — four discrete pipe legs cannot be represented in an axisymmetric formulation — which is why the multipole treatment for a four-pipe configuration is used here rather than the familiar two-pipe expression; the axisymmetric formulation is applied only to the far-field problem of Section 3.4.

Geometry. Borehole radius $r_b = 0.108$ m; four HDPE legs (OD/ID = 32/26 mm) placed symmetrically on a circle of radius $r_c = 46$ mm, corresponding to a shank spacing $s = 65$ mm between the legs of each U-pair, with the grout filling the annulus between the pipes and the borehole wall.

Material properties. HDPE $\lambda = 0.42$ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; grout λ_g varied from 0.8 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (plain cement) to 2.1 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (CEM I 42.5R + 40 wt% quartz filler of median grain size 0.25–0.5 mm shown in Fig. 9, measured per ASTM D5334); ground $\lambda_s = 1.9$ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ from the inversion of Section 2.4. Only conductivities enter the steady-state resistance; volumetric heat capacities are required solely by the transient far-field model of Section 3.4.

Reference operating point. Because R_b is a steady-state property of the borehole, it is independent of the operating mode. Performance is therefore expressed through Eq. (3) at a constant fluid-to-ground temperature difference, which applies equally to heat extraction (building heating) and heat injection (building cooling), the conduction problem being linear in temperature. No transient simulation with a prescribed inlet temperature is required, and none is reported.

3.3.2 Results

Computed borehole thermal resistances are listed in Table 3. Increasing λ_g from 0.8 to 2.1 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ reduces R_b from 0.177 to 0.090 $\text{m}\cdot\text{K}\cdot\text{W}^{-1}$ a 49 % reduction. The calculation was carried out with two independent implementations of the multipole formulation, which agreed to better than 0.5 %. The practical consequence is shown in Fig. 10: at a fixed heat injection rate the optimised grout lowers the mean fluid temperature by 3.3 K after one year of continuous operation, which is equivalent to transferring ≈ 20 % more heat at an equal fluid-to-ground temperature difference.

Table 3. Computed borehole thermal resistance and the resulting gain in specific heat-transfer rate Δq at constant fluid-to-ground temperature difference, for increasing grout thermal conductivity.

λ_g ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Grout	R_b ($\text{m}\cdot\text{K}\cdot\text{W}^{-1}$)	Reduction (%)	Δq at 1 month (%)	Δq at 1 year (%)	Δq at 10 years (%)
0.8	Plain cement (reference)	0.177	—	—	—	—
1.2	+ 20 wt% quartz	0.130	26	12	10	8
1.5	+ 30 wt% quartz	0.111	37	18	14	12
2.1	+ 40 wt% quartz (optimised)	0.090	49	26	20	16

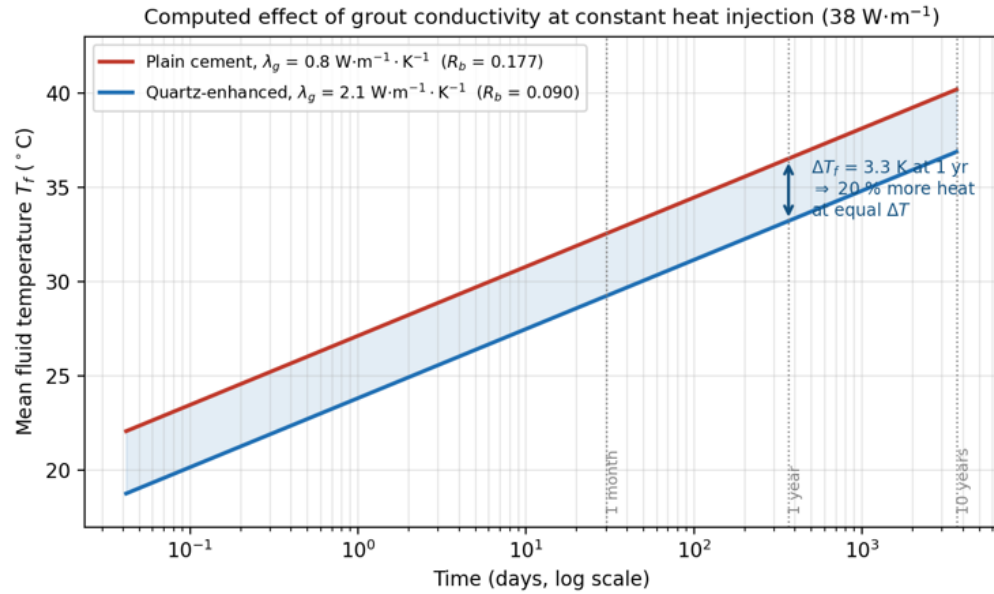


Fig. 10. Computed mean fluid temperature at a constant heat injection rate of $38 \text{ W}\cdot\text{m}^{-1}$, for the plain cement grout ($\lambda_g = 0.8 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $R_b = 0.177 \text{ m}\cdot\text{K}\cdot\text{W}^{-1}$) and the optimised quartz-enhanced grout ($\lambda_g = 2.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $R_b = 0.090 \text{ m}\cdot\text{K}\cdot\text{W}^{-1}$), obtained from Eq. (3). The 3.3 K separation at one year is equivalent to $\approx 20\%$ more heat transferred at an equal fluid-to-ground temperature difference.

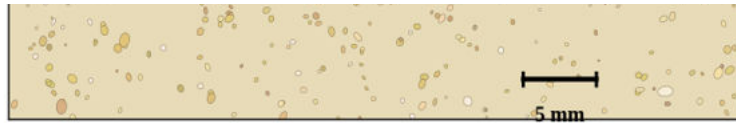


Fig. 9. Quartz aggregate filler used in the optimised grout mixture; median grain size 0.25–0.5 mm (ASTM C33 fine-aggregate sieve analysis); 5 mm scale bar.

These results establish the grout as a thermally engineered component rather than a passive filler. The dependence is not empirical: in the multipole formulation R_b scales essentially as $1/\lambda_g$, modified by the pipe configuration through the dimensionless parameter $\sigma = (\lambda_g - \lambda_s)/(\lambda_g + \lambda_s)$. The widely quoted two-pipe (single U-tube) expression is **not** applicable to the present borehole, which carries four legs; the double U-tube form of [14] was used throughout. The borehole

resistance enters the delivered heat-transfer rate through the classical line-source relation, in which it adds in series with the transient ground resistance:

$$q = (T_f - T_0) / [R_b + R_g(t)], \quad R_g(t) = [\ln(4\alpha t/r_b^2) - \gamma_E] / (4\pi\lambda_s) \quad (3)$$

where q is the specific heat-transfer rate per metre of borehole, T_f the mean fluid temperature, T_0 the undisturbed ground temperature, $R_g(t)$ the transient ground resistance, α the ground thermal diffusivity ($\approx 0.7 \times 10^{-6} \text{ m}^2/\text{s}$) and $\gamma_E = 0.5772$ the Euler constant. Equation (3) makes the operating dependence explicit: because R_g grows logarithmically with time while R_b is constant, the benefit of a conductive grout is largest early in the life of the installation. For the present geometry the reduction of R_b from 0.177 to 0.090 $\text{m}\cdot\text{K}/\text{W}$ raises q at constant fluid-to-ground temperature difference by 26 % after one month, ≈ 20 % after one year and 16 % after ten years of continuous operation (Table 3). The single figure of ≈ 20 % quoted in the abstract and conclusions therefore refers to the one-year reference condition.

3.4 Long-term thermal modelling (10–30 years)

3.4.1 Model and assumptions

Long-term thermal evolution was simulated with a two-dimensional **axisymmetric** (r, z) finite-volume model. At this scale the borehole is represented as an equivalent cylindrical source and the problem is rotationally symmetric, so the axisymmetric formulation is appropriate; the governing equation is written in cylindrical coordinates, with r the radial distance from the borehole axis and z the depth:

$$\rho c \partial T / \partial t = (1/r) \partial / \partial r [r \lambda_s(z) \partial T / \partial r] + \partial / \partial z [\lambda_s(z) \partial T / \partial z] + q_{\text{source}}(z, t) \quad (4)$$

with the depth-dependent conductivity $\lambda_s(z)$ taken from the inversion of Section 2.4, and with $\rho c = 2.4 \text{ MJ}\cdot\text{m}^{-3}/\text{K}$ and $2.9 \text{ MJ}\cdot\text{m}^{-3}/\text{K}$ for dry and saturated conditions, respectively. Groundwater advection is **not** included: uniform regional flow is directional and therefore breaks the axial symmetry on which the formulation rests, so it cannot be represented in an axisymmetric domain. At the Darcy velocities inferred for the permeable horizons (of order 10^{-4} m/s) advection would enhance heat transfer and *reduce* the predicted temperature decline; the results below are therefore conservative. Quantifying this effect requires a three-dimensional model and is identified as future work.

Assumptions. Horizontal isotropy within each 2-m layer; no vertical groundwater flow; temperature-independent thermal properties; and a purely conductive grout–ground interface with no contact resistance. The axisymmetric domain represents a **single reference borehole**, so mutual thermal interference between the two boreholes of the pilot array, which are 5 m apart, is not captured by the model itself. It is instead evaluated separately by line-source superposition: a neighbouring borehole at spacing d carrying the same net annual load adds $\Delta T = q_{\text{net}}[\ln(4\alpha t/d^2) - \gamma_E]/(4\pi\lambda_s)$. At $d = 5 \text{ m}$ this amounts to 0.88 °C at 10 years and 1.20 °C at 30 years in the unbalanced Scenario B. The effect scales with the *net* annual load, so it vanishes in the balanced Scenario A and is small in Scenario C. Both single-borehole and array values are reported in Table 4.

Domain, mesh and time stepping. Equation (4) was discretised by finite volumes on a domain extending to $r_{\text{max}} = 200 \text{ m}$ and $z = 150 \text{ m}$. Radial discretisation is graded: $\Delta r = 5 \text{ mm}$ at the borehole wall, growing geometrically (ratio 1.15) and capped at 5 m in the far field, giving 83 radial divisions; vertical discretisation $\Delta z = 2 \text{ m}$ matches the inversion layering, giving 75 divisions, for a total of 6 225 cells. Time integration is implicit (backward Euler) with an adaptive step of at most 7 days. Halving both Δr and the time step changed the predicted 30-year borehole-wall temperature by less than 0.05 °C, confirming grid and time-step independence. The model code is provided as supplementary material.

Boundary and initial conditions. Dirichlet condition $T = 16.5 \text{ °C}$ at the base ($z = 150 \text{ m}$) and at the outer radius; zero flux on the axis of symmetry; seasonal ground-surface temperature imposed at $z = 0$. The choice of $r_{\text{max}} = 200 \text{ m}$ is justified by the thermal penetration depth after 30 years, $r_T \approx \sqrt{\alpha t} \approx 27 \text{ m}$; sensitivity tests with $r_{\text{max}} = 100, 200$ and 400 m changed the borehole-wall temperature after 30 years by less than 0.05 °C.

Load definition. The modelled system is the pilot installation described in Section 2.3: two 105 m boreholes, each with a double U-tube of 102 m active length, serving a demonstration space of less than 100 m^2 of floor area at the

Center. The ground-side load is specified per unit borehole length at a design peak of $38 \text{ W}\cdot\text{m}^{-1}$ — the same specific rate as the TRT — corresponding to 3.9 kW per borehole and 7.8 kW for the array. With a six-month heating season and a sinusoidal seasonal profile the mean seasonal rate is $24 \text{ W}\cdot\text{m}^{-1}$ giving an annual ground-side extraction of 10.8 MWh per borehole, or 21.6 MWh for the array, in the balanced reference case. The array is deliberately oversized relative to the demand of the demonstration space so that the installation can be operated across a range of loads for research purposes; the scenarios of Section 3.4.2 therefore probe the full design capacity rather than the actual heating duty of the room. Because loads are applied per metre, the results scale directly to arrays of different size.

3.4.2 Scenario results

Three operating scenarios were simulated, defined quantitatively and chosen to bracket the range of load balance encountered in practice. **A (balanced)** — winter extraction exactly offset by summer injection, so the net annual ground load is zero; this represents a building with matched heating and cooling demand. **B (deficit)** — a net annual extraction equal to 30 % of the mean seasonal rate of $24 \text{ W}\cdot\text{m}^{-1}$, i.e. $7.3 \text{ W}\cdot\text{m}^{-1}$ averaged over the year, representing the heating-dominated demand typical of Dushanbe's building stock and the realistic default in the absence of deliberate load management. **C (hybrid)** — the deficit regime of B with solar-assisted regeneration offsetting 80 % of the annual imbalance. The acceptability criterion adopted is a decline of the mean borehole-wall temperature not exceeding 3°C over 30 years, below which the seasonal performance factor remains within about 10 % of its initial value.

Table 4. Computed change in mean borehole-wall temperature relative to the undisturbed state, for the three operating scenarios, as a single borehole and as the as-built two-borehole array at 5 m spacing.

Scenario	Net annual load ($\text{W}\cdot\text{m}^{-1}$)	Single borehole, 10 yr	Single borehole, 30 yr	Array ($d = 5 \text{ m}$), 10 yr	Array ($d = 5 \text{ m}$), 30 yr
A — balanced	0	-0.02°C	-0.01°C	-0.02°C	-0.01°C
B — deficit (30 %)	-7.3	-3.22°C	-3.44°C	-4.10°C	-4.63°C
C — hybrid (80 % offset)	-1.5	-0.66°C	-0.69°C	-0.84°C	-0.93°C

Scenario A shows no measurable long-term drift, confirming that a genuinely balanced load is sustainable indefinitely at this site. Scenario B exceeds the 3°C criterion as a single borehole (-3.44°C at 30 years) and does so by a wide margin once the 5 m spacing of the pilot array is taken into account (-4.63°C): at this spacing the two boreholes interact strongly whenever a net imbalance exists. Scenario C remains comfortably within the criterion (-0.93°C for the array), showing that partial regeneration is sufficient to rescue an otherwise unsustainable deficit regime. The practical conclusion is that the 5 m spacing adopted in the pilot installation is at the tight end of good practice and is acceptable only under balanced or regenerated operation; larger arrays at this spacing would require full-field modelling with explicit borehole-to-borehole coupling.

4. CONCLUSIONS AND RECOMMENDATIONS

The integrated field, laboratory and modelling programme demonstrates the technical viability of vertical closed-loop GSHP at the central, typical-lithology part of the Dushanbe Artesian Basin, addressing the four objectives of Section 1 as follows.

(i) Inversion of the TRT data jointly constrained by DTS profiles yields $\lambda/\Delta \approx 1.9 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ (95 % CI 1.71–2.04, percentile method over 1000 Monte Carlo realisations) and an undisturbed temperature $T_0 \approx 16.5^\circ\text{C}$, with a resolved depth contrast between the unsaturated ($1.4\text{--}1.7 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$) and saturated ($2.0\text{--}2.4 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$) zones. These conditions support efficient vertical borehole heat exchangers. The estimate derives from a single pilot borehole in the dominant Quaternary lithology; basin-wide extension requires a multi-site TRT campaign.

(ii) Hydrochemical analysis of 95 samples reveals a strong EC–hardness correlation and elevated bicarbonate alkalinity, raising carbonate-scaling and electrochemical-corrosion risk in any open-loop or semi-open-loop installation. Closed-loop circuits with HDPE pipes and antifreeze are unaffected, because the working fluid is isolated from the

groundwater; hydrochemistry bears on them only indirectly, through grout durability in aggressive waters and through corrosion of metallic surface-header components exposed to locally sourced make-up water.

(iii) The principal novel contribution is the demonstration, combining field measurement with first-order multipole analysis, that grout conductivity is a controllable design variable governing borehole thermal resistance. Replacing plain cement grout with CEM I 42.5R + 40 wt% quartz aggregate raises λ_g from 0.8 to 2.1 W·m⁻¹·K⁻¹ and reduces R_b from 0.177 to 0.090 m·K·W⁻¹ (Table 3), a 49 % reduction. At a constant fluid-to-ground temperature difference this increases the specific heat-transfer rate by ≈ 20 % at the one-year reference condition (26 % at one month, 16 % at ten years, Eq. 3). The gain is identical in heat-extraction and heat-injection modes because the conduction problem is linear. Grout optimisation is thus a high-leverage, low-complexity engineering intervention.

(iv) Long-term axisymmetric modelling over a 200 m radial domain shows that a balanced load produces no measurable drift over 30 years (-0.01 °C), whereas a 30 % annual deficit exceeds the 3 °C acceptability criterion (-3.44 °C for a single borehole, -4.63 °C for the as-built two-borehole array at 5 m spacing). Regeneration offsetting 80 % of the imbalance restores sustainable operation (-0.93 °C). Load management or hybridisation with renewable sources is therefore not optional at the 5 m spacing adopted here, and denser or larger arrays require full-field modelling with explicit borehole coupling.

Engineering recommendations: (a) adopt quartz-enhanced grouts in zones with deep water tables; specify recipes validated by laboratory thermal-conductivity measurements; (b) implement standardised hydrochemical monitoring (pH, EC, T, Ca²⁺, Mg²⁺, HCO₃⁻, Cl⁻, SO₄²⁻) with EC- and hardness-based maintenance triggers; (c) require post-grouting TRT/DTS verification at commissioning and adopt load-balancing or renewable-hybrid operational strategies.

Next steps. Multi-site TRT campaign across lithologically distinct sub-basins; multi-year monitoring of pilot installations to quantify long-term thermal recovery, scaling rates, and grout durability; alternative high-conductivity grout fillers; full life-cycle cost assessment.

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