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Production-Reinjection Regulation and Risk Management of a Deep Sandstone Geothermal Reservoir under Reinjection-Capacity Constraints: A Planning Analysis for the Geothermal Project of the University Student Entrepreneurship Park in Binzhou High-Tech Zone

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Abstract

In the development of deep sandstone geothermal reservoirs, target reinjection ratios are often set without verifying the reinjection capacity, and volumetric balance is frequently taken as evidence of pressure recovery. Taking the geothermal project of the University Student Entrepreneurship Park in Binzhou High-tech Zone as an example, this paper establishes an operating window jointly constrained by the reference production rate, the target reinjection ratio and the sustainable reinjection capacity. Because the reinjection well of the project is still at the planning stage, the production-side inputs are taken from the project report, whereas the reinjection capacity is represented by assumed scenarios; the quantitative results are therefore scenario-based and illustrate the planning logic rather than predict site performance. From the production volume, the heating-season duration and the daily operating hours, the reinjection capacity required to reach different target reinjection ratios at a specified production rate is determined, and the limiting production rate that keeps the reinjection ratio unchanged when the reinjection capacity declines is also examined. An idealized analysis based on the superposition of Theis well-flow solutions shows that volumetric balance between production

and reinjection alone is not sufficient to establish hydraulic head recovery at every evaluation location. A management procedure of capacity verification, plan matching and operational review is therefore proposed, centered on the reinjection capacity margin, the specific injectivity (the reinjection rate per unit increase in hydraulic head) and the separate assessment of hydraulic head, water temperature and water quality. The corresponding supervision checkpoints are also identified. The results provide a reference for reviewing operating plans and for designing reinjection tests and monitoring programs in similar projects.

Keywords

Deep Sandstone Geothermal Reservoir, Reinjection Capacity, Reinjection Ratio, Production-Reinjection Regulation, Hydraulic Head Response, Supervision Checkpoints

1. Introduction

The development of geothermal water from deep sandstone reservoirs has to satisfy the heating demand, the reinjection requirements and the requirements for protecting the geological environment at the same time. In engineering management, the reinjection ratio (the ratio of the reinjected volume to the produced volume) is convenient to meter and to audit, but whether it can be achieved depends on the flow rate and the pressure that the reinjection well and the surface system can sustain over the long term. If a reinjection-ratio target is set without verifying the reinjection capacity, production and reinjection may still be mismatched at the peak of the heating season; conversely, even when the total produced and reinjected volumes are nearly balanced, this does not mean that the hydraulic head, the temperature and the formation deformation between the production and reinjection wells and in the surrounding area have recovered [1].

Reinjection tests already carried out in sandstone reservoirs provide a basis for engineering design. The test at Yucheng, Shandong Province, recorded a long-term stepwise reinjection process, and work in the Northwest Shandong Depression shows that the reinjection capacity and the reservoir parameters may change under different test conditions [2] [3]. Reviews further point out that the pore-throat structure, the pressure loss during seepage and water-rock interaction jointly affect reinjection performance, that a decline in reinjection capacity is usually the combined result of physical, chemical and biological clogging, and that cooling of the reinjected water itself also lowers the reinjection capacity [4] [5]; the flow rate, the well spacing and the reinjection temperature further influence thermal breakthrough as the temperature field evolves [6]. International experience likewise shows that in-field reinjection can support reservoir pressure and mitigate drawdown and subsidence, but that a reinjection scheme should be drawn up early and adjusted as operation proceeds [7]. These studies indicate that reinjection plan-

ning has to extend from water-volume targets to capacity verification and dynamic monitoring; test results obtained elsewhere, however, cannot be substituted directly for the parameters of the present project.

Taking the geothermal project of the University Student Entrepreneurship Park in Binzhou High-tech Zone as an example, this paper establishes an operating window jointly constrained by the reference production rate, the target reinjection ratio and the sustainable reinjection capacity, and examines the production rate that a given reinjection capacity can support at a specified target reinjection ratio. It also considers how to avoid mistaking an improved volume budget for the removal of local pressure and subsidence risks. On this basis, a management procedure of capacity verification, plan matching and operational review is proposed, centered on the reinjection capacity margin, the specific injectivity (the reinjection rate per unit increase in hydraulic head) and the separate interpretation of hydraulic head, water temperature and water quality, together with the corresponding supervision checkpoints. Because the reinjection well of this project is still at the planning stage, site-specific reinjection test curves, transmissivity, storativity and historical drawdown records are not yet available. The analysis therefore combines the production-side data of the project with assumed reinjection-capacity scenarios and is intended as a pre-commissioning planning analysis: its quantitative results show how the decision rules operate and how sensitive the operating plan is to the reinjection capacity, and are not validated predictions of site performance. The results provide a reference for reviewing operating plans and for designing reinjection tests and monitoring programs in similar projects.

2. Project Conditions

The geothermal mining area of the University Student Entrepreneurship Park in Binzhou High-tech Industrial Development Zone covers 0.68 km^2 and contains one production well with a completion depth of 1655.13 m (the stratigraphic description refers to a drilled depth of 1670.0 m). The production interval is 1374.40 - 1638.40 m, the wellhead water temperature is 63˚C, the hydrochemical type is Cl-Na and the total dissolved solids are about 13.5 g/L; the geothermal fluid is strongly corrosive and has a marked scaling tendency. The stratigraphic record of the well, whose main target is the deep sandstone reservoir of the Dongying Formation, places the base of the Guantao Formation at about 1398.7 m, with the Dongying Formation below it; the top of the production interval lies about 24 m above this boundary and the cumulative thickness of the utilized reservoir is 96.5 m. Without reinjection, the allowable production rate of the project is 1859.14 m^3/d, equivalent to 2.231×10^5 m^3 over a 120-d heating season; this value is taken as the baseline for comparing operating schemes. The key parameters are listed in Table 1. The Yucheng case is a test in a mixed Guantao-Dongying reservoir, in which the measured maximum reinjection rate was 58.6 m^3/h; the 70 m^3/h quoted in that paper is a fitted value [2]. Well Tanguan-1 in the Dongying area targets the Guantao Formation of the Zhanhua Sag, and after perforated completion its

reinjection rate reached 90 - 105 m^3/h, giving full reinjection [8]. Numerical simulation of a sandstone reservoir in the Jiyang Depression shows that, at a single-well reinjection rate of 40 m^3/h, a decrease in formation permeability from 800 mD to 200 mD raises the pressure increase at the reinjection well from about 0.08 MPa to about 0.24 MPa [9]. Single-well reinjection capacity therefore varies widely with the target interval, the completion technique and the reservoir permeability even within the same region, and the reinjection pressure has to be checked separately. The capacity scenarios of 48 - 80 m^3/h used here are of the same order of magnitude as these data and serve only for sensitivity analysis; the design capacity of the reinjection well of this project must be established by site-specific tests.

Table 1. Key data and sources.

No.	Parameter	Value or content	No.	Parameter	Value or content
1	Mining area; completion (drilled) depth	0.68 km^2; 1655.13 (1670.0) m	7	Reference production rate	77.46 m^3/h (equivalent hourly value at 24 h/d)
2	Production interval; wellhead temperature	1374.40 - 1638.40 m; 63˚C	8	Reinjection-capacity scenarios	80, 64, 48 m^3/h
3	Daily production; heating season	1859.14 m^3/d; 120 d	9	Reinjection-ratio scenarios	80%, 90%, 100%
4	Required reinjection ratio	Not less than 80% (project required)	10	Well-influence coefficient β	0.25, 0.50, 1.00
5	Commissioning and reinjection status	Well completed and put into use in 2012; reinjection well planned	11	Regional reinjection capacity for reference [2] [8]	58.6 m^3/h; 90 - 105 m^3/h
6	Automatic monitoring frequency	Once per 30 min in the heating season; once per day outside it (project requirement for the production well; proposed for the reinjection well)			

Note: Items 1 - 6 and the reinjection-temperature limit of 30˚C used in Section 5.1 are from the requirement of the project supervisor; they are adopted here as project conditions and are checked against the current standards [11]-[13] in the supervision review. The monitoring frequencies in item 6 are those specified in the report for the existing production well; for the planned reinjection well, they are proposed values, to be confirmed in its dedicated monitoring design. Item 7 is derived from item 3 (Section 4.1), items 8 - 10 are assumed values for the sensitivity analysis, and item 11 is taken from the literature.

3. Analytical Methods

3.1. Volume Budget and Operating Window

The comparison uses a single volume-metering basis and neglects the density differences caused by temperature. Within the same accounting period, the produced volume and the reinjected volume are denoted V_p and V_i; the reinjection ratio r and the net withdrawal D are defined by Equation (1):

$$r = \frac{V_i}{V_p}, D = V_p - V_i = (1-r)V_p \tag{1}$$

Under the simplified condition of constant rates, with production and reinjection running simultaneously for the same duration τ, $V_p = Q_p\tau$ and $V_i = Q_i\tau$. For non-synchronous operation, the two volumes should be integrated separately before the ratio is calculated; if a strict mass balance is required, the rates should be converted to a common state or expressed as mass flow rates. Let C_i denote the reinjection capacity that has been confirmed by testing and can be sustained under the allowable pressure and water-quality conditions, r_t the target reinjection ratio and Q_{ref} the reference production rate. When all other conditions are satisfied, the capacity-constrained upper limit of the production rate, Q_{lim}, is:

$$Q_{lim} = \min\left(Q_{ref}, \frac{C_i}{r_t}\right) \tag{2}$$

Equation (2) gives the feasible upper limit set by the reinjection capacity and the reference production rate. Valid permits, the water-abstraction plan, the wellhead pressure, the head change, thermal breakthrough and water-quality requirements impose further constraints that the actual production rate must also satisfy, so Q_{lim} cannot be used directly as a design value. It should also be noted that Q_{ref} is an equivalent hourly reference obtained by spreading the allowable daily volume Q_d over 24 h of continuous operation (Section 4.1), not an instantaneous rating of the well. If the system operates for $t_d < 24$ h per day, the daily allowance corresponds to an average rate of Q_d/t_d during operation, which is higher than Q_{ref}; such a rate is admissible only if it also respects the applicable instantaneous limits, such as the permitted maximum instantaneous abstraction, the ratings of the pump and pipelines and the allowable drawdown in the production well, and Q_{ref} in Equation (2) should then be replaced by the smaller of Q_d/t_d and these limits. In the calculations for Table 2, $Q_p = Q_{lim}$ and $Q_i = r_tQ_p$, so that the target reinjection ratio is met exactly; where the safe reinjection capacity on site is larger, a higher reinjection ratio may be chosen. To judge whether the planned production rate matches the available capacity, the reinjection capacity margin M is defined as:

$$M = \frac{C_i}{r_tQ_p} \tag{3}$$

$M \geq 1$ means that the reinjection-ratio target can be met at the planned flow rate, whereas $M < 1$ calls for a lower production rate or for the reinjection capacity to be restored. M reflects the capacity constraint alone and not the overall geo-environmental risk. Setting $C_i = \lambda C_{i0}$, where λ is the fraction of reinjection capacity retained, allows operating schemes to be compared as λ changes. The baseline capacity adopted here is $C_{i0} = 80$ m^3/h, and λ takes the values 1.0, 0.8 and 0.6 so that the sensitivity across discrete scenarios can be examined. Equations (2) and (3) inherit the assumption of Section 3.1 that production and reinjection run at constant rates for the same duration within the accounting period. When the durations differ, for example when tail water is buffered and reinjected over different

hours, or when a monthly or peak-period plan includes shutdowns of only one of the wells, the check should be made on volumes rather than rates: the required reinjected volume $r_t Q_p \tau_p$ is compared with the deliverable volume $C_i \tau_i$, where τ_p and τ_i are the production hours and the available reinjection hours in the period. The margin then becomes $M = C_i \tau_i / (r_t Q_p \tau_p)$ and the capacity-constrained production limit becomes $C_i \tau_i / (r_t \tau_p)$; Equations. (2) and (3) are recovered when $\tau_i = \tau_p$.

3.2. Difference between Volumetric Balance and the Local Head Response

The Theis solution for well flow in a confined aquifer and linear superposition [10] are used to examine how the production well and the reinjection well act differently at a given evaluation location. The aquifer is assumed to be homogeneous, isotropic, of uniform thickness and infinite in extent; both wells fully penetrate the aquifer; production and reinjection start at the same time and at constant rates; the transmissivity T and the storativity S remain constant; and boundaries, well losses, water-rock reactions and temperature changes are neglected. Taking drawdown as positive,

$$s(x,t) = \frac{Q_p W(u_p) - Q_i W(u_i)}{4\pi T} \tag{4}$$

$$u_k = \frac{R_k^2 S}{4Tt} (k = \mathrm{p,i}), W(u) = \int_u^\infty \frac{\mathrm{e}^{-\xi}}{\xi} \mathrm{d}\xi \tag{5}$$

where R_p and R_i are the distances from the evaluation location to the production well and to the reinjection well, t is the time since production and reinjection began, and W is the well function. The flow rate, the time and T are expressed in a consistent system of units. For the same production rate, taking the drawdown without reinjection, s_0, as the reference and defining $\beta = W(u_i)/W(u_p)$ gives

$$\frac{s}{s_0} = 1 - r\beta, \beta = \frac{W(u_i)}{W(u_p)} \tag{6}$$

β reflects the relative influence of the two wells at a given location and time; under the constant-rate, synchronous operation assumed above, r is also equal to the ratio of the flow rates. When $r = 1$ and $\beta \neq 1$, the head response at the evaluation location is in general not zero: a net drawdown remains where the location is closer to the production well ($\beta < 1$), whereas a head rise ($s/s_0 < 0$) occurs where it is closer to the reinjection well ($\beta > 1$). Balance of total volumes and balance of pressure in space are therefore not the same criterion.

3.3. Operational Monitoring and Anomaly Identification

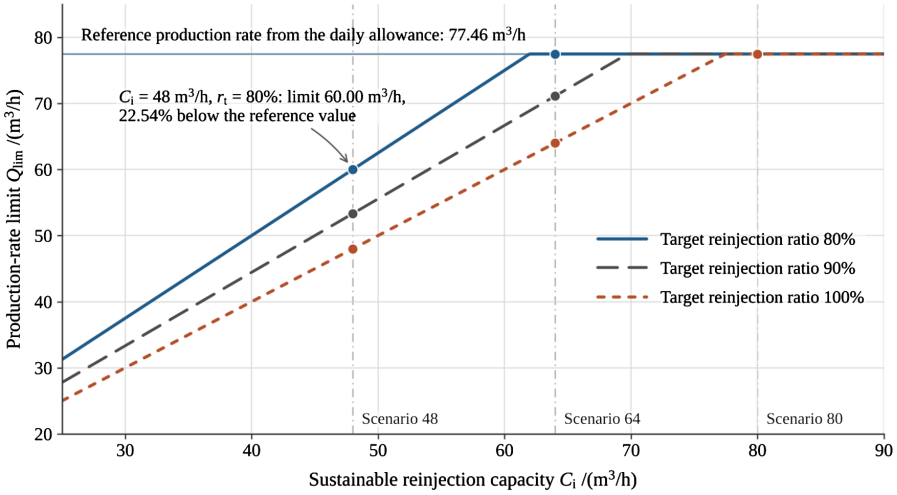
To distinguish an insufficient reinjection rate from deteriorating hydraulic conditions, the specific injectivity J and its relative value K are introduced:

$$J = \frac{Q_i}{\Delta h_i}, K = \frac{J}{J_0} \tag{7}$$

where Δh_i is the effective head increase under reinjection relative to the contemporaneous static-head baseline, referred to the same elevation datum; the reinjection head is determined at the reinjection wellhead from the pressure gauge installed downstream of the filter and the control valve (or from a downhole gauge at the top of the reinjection interval, where one is available). For pressurized reinjection, the wellhead pressure converted to head is added to the wellhead elevation, and only the friction loss in the wellbore between the measuring point and the reinjection interval is deducted; losses in the surface pipelines, the filter and the valves upstream of the measuring point lie outside the measurement boundary of J, so that filter resistance is excluded from this indicator and is monitored separately through the filter pressure drop. In addition, the viscosity change caused by the difference in water temperature should be taken into account in any comparison; J_0 is the baseline value obtained under comparable test conditions, and J has units of m^2/h. Because the static head at the reinjection well is affected by the operation of the production well and by regional trends, the contemporaneous baseline cannot be measured directly while reinjection is underway; it is proposed to be estimated as follows. The initial static head is measured before the reinjection well enters service; during operation the baseline is updated from the heads recorded during planned reinjection shutdowns once the rate of head recovery has fallen below a criterion specified in the test design, and between such measurements it is interpolated, with the interference of the production well estimated from its metered rate (by Equation (4) with parameters derived from the reinjection tests, or empirically from the shutdown records) and the regional trend taken from an observation well outside the zone of influence, where one is available. Values of J should be compared with J_0 only at the same elapsed time since the start of the reinjection step (for example, at the end of steps of equal duration), because under transient conditions Δh_i continues to rise with time even when the well and the formation are unchanged, and only after comparable prior operation, that is, a similar duration of the preceding shutdown or recovery period, a similar residual head and a similar rate and temperature history; otherwise a difference in J may reflect the test conditions rather than a change in the well. When J or K falls, the cause should be examined together with the filter pressure drop, the quality and temperature of the reinjected water and the operating history. Because J is measured downstream of the filter, a falling reinjection rate accompanied by a rising filter pressure drop and an essentially unchanged J points to increased resistance in the surface system; if J falls at the same time, the possibility that particles are passing the filter should also be checked, whereas a continued rise in the reinjection head in the well under comparable conditions calls for further inspection of the wellbore and the near-well formation. No single indicator is sufficient to identify a clogging mechanism on its own, and the anomaly thresholds, whether absolute or expressed as percentages, should be set jointly from stepwise reinjection tests, the equipment conditions and the engineering design.

4. Calculated Results

The calculations in this section combine site-specific production-side data from the project report (allowable daily production and heating-season length) with assumed reinjection capacities (Table 2) and assumed well-influence coefficients (Figure 1). They are scenario calculations that show how the decision rules of Section 3 operate and how sensitive the operating plan is to the reinjection capacity; they are not predictions of site performance, which will require the reinjection tests described in Section 5.1.



Note: The curves are calculated from Equation (2) and the dots are the values for the three capacity scenarios in Table 2. The reference daily production is taken from the project report and the horizontal axis gives assumed capacities; on-site limits on head, pressure and temperature are not considered.

Figure 1. Relationship between the reinjection capacity and the capacity-constrained upper limit on the production rate.

4.1. Capacity Required at Different Reinjection Ratios

For 1859.14 m³/d over 120 d with continuous operation 24 h per day, τ = 2880 h and Q_{ref} = 77.4642 m³/h (77.46 m³/h hereafter), and the production volume for the heating season is 223 096.8 m³. If this production rate is maintained, the reinjection capacities required for target reinjection ratios of 80%, 90% and 100% are 61.97, 69.72 and 77.46 m³/h, respectively. Raising the target ratio therefore requires the sustainable reinjection capacity to be increased accordingly, or the production rate to be reduced. With the reference production rate unchanged and each ratio met exactly, the net withdrawal over the heating season is 44619.36, 22309.68 and 0 m³, respectively. These values are the metered differences between the produced and the reinjected volumes; the actual change in aquifer storage is also affected by lateral recharge, leakage, boundary conditions and abstraction from other wells. The project supplies conventional heating for about 44,500 m² and low-temperature workshop heating for about 100,000 m², and the actual load varies with air temperature; constant-rate operation over 24 h is only a basis for comparison, and the instanta-

neous flow rate has to be recalculated when the daily operating hours change. Q_{ref} is therefore an equivalent hourly reference rather than an instantaneous production limit. If, for example, the system operated for 16 h per day, the same daily allowance would correspond to 116.20 m^3/h during operation; this rate could be adopted only if it did not exceed the instantaneous limits noted in Section 3.1, and, with reinjection running over the same hours, the capacity required for an 80% reinjection ratio would rise in the same proportion to 92.96 m^3/h.

4.2. Production Adjustment When the Reinjection Capacity Declines

Table 2 lists the combinations of the three capacity scenarios and the three reinjection-ratio targets. At a reinjection capacity of 80 m^3/h, all three ratios can be achieved at the reference production rate. When the capacity falls to 64 m^3/h, the 80% target can still be met, whereas 90% requires the production rate to fall to 71.11 m^3/h and 100% requires 64.00 m^3/h. When the capacity falls to 48 m^3/h, all three targets require a lower production rate, the reductions being 22.54%, 31.15% and 38.04%, respectively. The operating cost of raising the reinjection-ratio target thus depends on the reinjection capacity available. Where the capacity is sufficient, the ratio can be raised without reducing production; where it is not, the heating load, the backup heat sources and the production-reinjection plan have to be adjusted together. Writing a reinjection-ratio target into the management rules cannot by itself replace restoration of the capacity of the reinjection well, maintenance of the system and arrangements on the demand side.

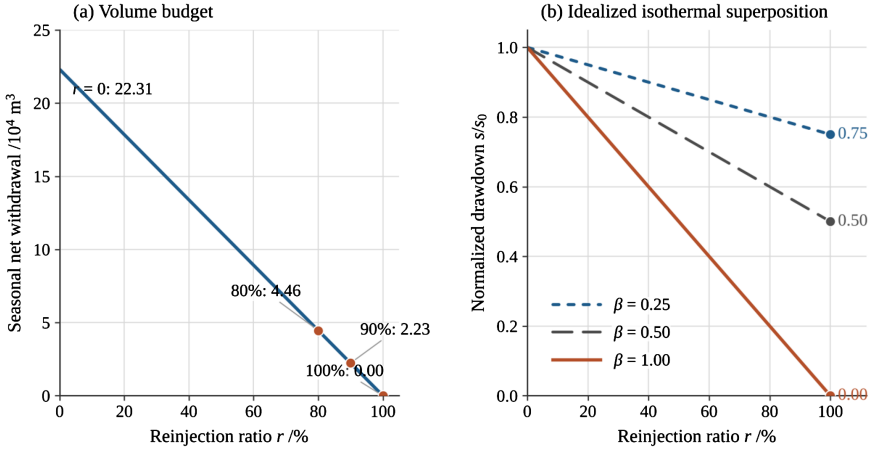
Table 2. Operating results for combinations of assumed reinjection capacity and target reinjection ratio.

Reinjection capacity C_i/(m^3/h)	Target reinjection ratio/%	Production rate/(m^3/h)	Reinjection rate/(m^3/h)	Seasonal net withdrawal/10^4 m^3	Production reduction/%
80	80	77.46	61.97	4.462	0.00
80	90	77.46	69.72	2.231	0.00
80	100	77.46	77.46	0.000	0.00
64	80	77.46	61.97	4.462	0.00
64	90	71.11	64.00	2.048	8.20
64	100	64.00	64.00	0.000	17.38
48	80	60.00	48.00	3.456	22.54
48	90	53.33	48.00	1.536	31.15
48	100	48.00	48.00	0.000	38.04

Note: All values are calculated for 120 d and 24 h/d, with the reinjection rate just meeting the target ratio. The reductions are relative to 77.4642 m^3/h and are calculated from unrounded values. The capacities of 80, 64 and 48 m^3/h are assumed values for the sensitivity analysis. The reference rate of 77.46 m^3/h is the equivalent hourly value of the daily allowance, and equal production and reinjection hours are assumed.

4.3. Improvement in the Volume Budget and Verification of the Head

Figure 2 compares the volume budget with the idealized local head response. At a fixed production rate, the net withdrawn volume falls linearly as the reinjection ratio rises, whereas the normalized drawdown depends on the product $r\beta$. For $\beta = 0.50$ and $r = 1$, s/s_0 is still 0.50; for $\beta = 1.00$, $r = 1$ corresponds to zero net drawdown at that location in the same simplified model. Because the site values of T and S and the position of the reinjection well are not yet known, β is varied over assumed values. Once β is given, $s/s_0 = 1 - r\beta$ does not depend on T and S; the qualitative finding that $r = 1$ does not imply zero drawdown wherever $\beta \neq 1$ therefore holds irrespective of the site parameters, whereas the specific values of s/s_0 are illustrative. The difference may arise from the spatial distribution of the influence of the production and reinjection wells. Formation deformation further depends on the change in confined head, the distribution of the compressible layers, the stress history and the hydraulic connections. Without such data, the subsidence cannot be converted from the reinjection ratio, and reaching a reinjection ratio of 80% or 100% is not sufficient to show that the subsidence risk has been removed; engineering verification requires the produced and reinjected volumes, the hydraulic head and the surface deformation to correspond in both time and space.



Note: (a) based on the reference production volume in the project report, the dots being the net withdrawal at reinjection ratios of 80%, 90% and 100%; (b) based on the idealized isothermal well-flow superposition model with assumed values of β, the dots being s/s_0 at $r = 100\%$.

Figure 2. Different criteria: volume budget and local head response.

5. Engineering Risk Control and Implementation Conditions

5.1. A Capacity Verification-Plan Matching-Operational Review Management Procedure

Before commissioning, or before the operating plan is revised, the production and reinjection intervals, the well completion structure, the water-abstraction require-

ments and the reinjection conditions should first be checked, and stepwise and sustained reinjection tests should be carried out to confirm C_i and J_0 under the allowable pressure and under comparable water-quality and water-temperature conditions. Q_{lim} and M are then calculated for the target reinjection ratio, and plans are drawn up for the heating season, for each month and for peak periods. Because Equations (2) and (3) assume equal production and reinjection durations, the planned production hours and the available reinjection hours should be stated explicitly in each monthly and peak-period plan; where they differ, the required reinjected volume $r_t Q_p \tau_p$ should be compared with $C_i \bar{\tau}_i$ as described in Section 3.1, instead of applying Equation (3) to the rates alone. Likewise, where the daily operating hours are shortened in a peak period, the resulting instantaneous production and reinjection rates should be checked against the applicable instantaneous limits. During operation, the plan is reviewed against the measured flow rates, cumulative volumes and heads; if a fall in C_i leads to $M < 1$, the production rate should first be brought back into line with the available capacity and the cause of the fall should then be investigated. From the point of view of supervision, the three stages correspond to witnessing of the reinjection tests, review of the operating plan and review of the operation records (in Figure 3 the solid boxes are the operation-management stages and the dashed boxes are the corresponding supervision checkpoints). The review concentrates on the test evidence for the adopted value of C_i and on whether the planned production rate satisfies $M \geq 1$, as shown in Table 3.

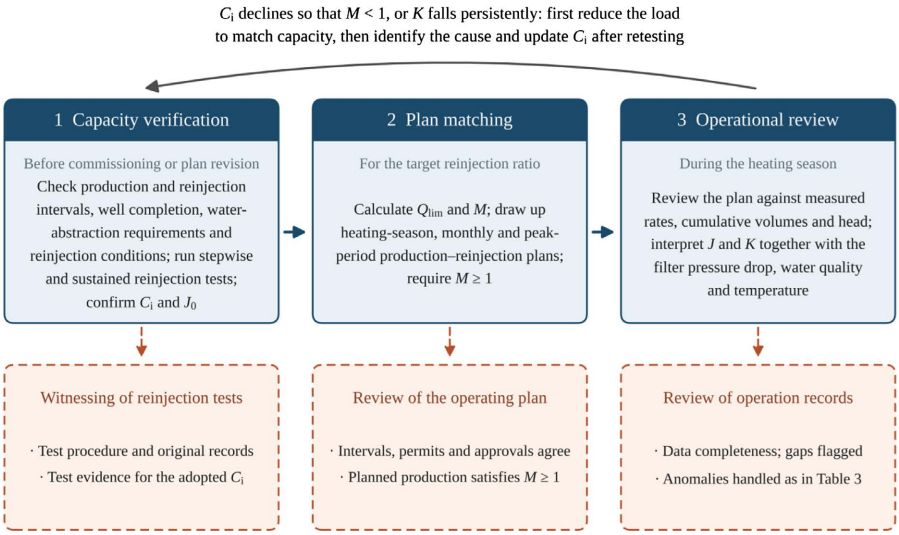


Figure 3. The capacity verification-plan matching-operational review procedure and the supervision checkpoints.

Water-quality anomalies, exceedance of pressure limits and problems of wellbore integrity should be dealt with separately, and compliance in one indicator must not be used to offset a failure in another: meeting the reinjection ratio does not compensate for a reinjection pressure above the design allowable value, and a

high reinjection rate does not replace verification of water-quality compatibility. The geothermal fluid of this project is highly mineralized and clearly prone to corrosion and scaling, and the project supervisor requires the reinjection temperature to be below 30˚C; both the higher viscosity of the cooled tail water and the change in the mineral dissolution-precipitation equilibrium may reduce the reinjection capacity [5]. Reinjection tests should therefore be carried out as close as practicable to the operating temperature and water quality, and in the supervision review the requirements for the reinjection ratio, the reinjection temperature and the sampling frequency should be checked against the current standards [11]-[13] and the project approval documents. The 80% minimum reinjection ratio, the 30˚C limit and the monitoring frequencies are listed in **Table 1**.

Table 3. Operating problems and the corresponding response logic.

Observation	Evidence to be checked	Management measure
$M < 1$: the available capacity cannot meet the planned reinjection ratio	Measured capacity; production plan; cumulative produced and reinjected volumes	Adjust the production plan to the verified capacity; check the equipment and the condition of the well, and update the capacity value after retesting
J (measured downstream of the filter) remains essentially unchanged while the reinjection rate falls and the filter pressure drop rises	Pressures upstream and downstream of the filter; flow rate; water quality; maintenance records	Inspect the surface filtration and the pipelines; retest under comparable conditions after treatment, rather than attributing the change directly to reservoir clogging; if J also falls, check the integrity of the filter and the particle content downstream of it
The reinjection ratio is met but the observed head keeps falling	Other wells in the region; static-head baseline; timing of production and reinjection; interlayer connections	Re-examine the regional water balance and head response; adjust operation and, where necessary, add monitoring and hydrogeological analysis
Anomalies in reinjection pressure, water quality or well integrity	Instrument calibration; design limits; water samples; wellbore inspection	Reduce the load or stop reinjection in accordance with the dedicated design and the emergency plan and establish the cause; do not raise the reinjection pressure in order to maintain the reinjection ratio
Anomalous change in surface deformation	Contemporaneous head; engineering loads; regional subsidence; monitoring accuracy	Verify the reliability and extent of the deformation and carry out a dedicated investigation; do not attribute it directly to a single geothermal well

5.2. Monitoring Configuration and Record Quality

The minimum monitoring set comprises the production and reinjection rates and cumulative volumes, the head (or the corrected pressure) in the production and reinjection wells, the water temperature, the key water-quality indicators and the filter pressure drop, together with records of shutdowns, maintenance, well flushing and similar events. Surface-deformation monitoring should have a stable datum and sufficient spatial control; leveling, GNSS or other methods may be deployed in accordance with a dedicated monitoring design. Regional remote-sensing deformation data may be used to establish background conditions, but their

time scale and spatial resolution should be checked for suitability before use. Before the supervisor checks the completeness of the data, a common baseline should be established from the approved heating season. Planned shutdowns and instrument failures should be flagged separately, and missing values must not be replaced by smoothed interpolation when thresholds are assessed. The initial static head and J_0 for the first reinjection heating season should be measured separately before the reinjection well enters service, to serve as the baseline for later assessment, and the measured data should then be used to test how well the theoretical upper limit matches the actual heating load.

5.3. Discussion of Applicability

The method described here follows established well-flow theory and converts the reinjection-ratio target into a testable reinjection-capacity requirement and an upper limit on production, so that management of the reinjection ratio is linked directly to the operating plan; at the same time, the volume budget, the local head and the surface deformation are checked separately at different levels of verification. The method is therefore suited to the review of operating plans for projects with limited data. This project lacks reinjection test curves, long-term observed heads, transmissivity, storativity, compressibility parameters and subsidence series, and the well-flow model neglects interlayer heterogeneity, boundaries, water temperature and water-rock interaction; the method consequently cannot be used to predict thermal breakthrough or the rate of subsidence, or to determine the optimum well spacing. Accordingly, the present work is positioned as a pre-commissioning planning analysis: once the reinjection well has been drilled and tested, the measured C_i, J_0, T and S and the observed heads should replace the assumed scenarios, and the analysis of Section 4 should be repeated and checked against the operating records. The main target interval of this project is the Dongying Formation, and the siting of reinjection wells in other areas still requires a dedicated assessment based on local parameters [14]. When the well layout is reviewed, the justification of the production-reinjection well spacing should be included among the items to be checked; before the operational review, the baseline values should be reconciled with the original approval and the field records, and the initial static head and the baseline specific injectivity should be measured before the reinjection well enters service. The time-varying load of the heating system, the permit conditions and the maintenance costs have not been included in a joint optimization, so the method and the conclusions are suited to the preliminary comparison of schemes and to the design of test tasks, and do not replace engineering design or a dedicated safety assessment.

6. Conclusions

(1) For an allowable production rate of 1859.14 m^3/d, a 120-d heating season and 24 h of operation per day, the equivalent hourly reference production rate is 77.46 m^3/h and the production for the heating season is 2.231×10^5 m^3. If this rate

is maintained, the reinjection capacities required to achieve reinjection ratios of 80%, 90% and 100% are 61.97, 69.72 and 77.46 m^3/h, respectively, so that the reinjection-ratio target and the verified reinjection capacity can be analyzed together.

(2) The capacity constraint can be converted into an explicit condition for adjusting operation. At an assumed reinjection capacity of 48 m^3/h and a target reinjection ratio of 80%, the upper limit on production is 60.00 m^3/h, 22.54% below the reference value.

(3) The idealized well-flow superposition analysis shows that a balance between produced and reinjected volumes cannot by itself prove that the head has recovered at every evaluation location. The operating plan should be matched to the reinjection capacity margin, the specific injectivity should be used to help identify anomalies, and the associated risks should be verified separately through monitoring of head, temperature, water quality and surface deformation; in supervision, control can be exercised in three stages: witnessing of the reinjection tests, review of the operating plan and review of the operation records.

Foundations

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Author Contributions

Shaofeng Yao: Conceptualization, methodology, investigation, data analysis, and writing—original draft. Guoqiang Fu: Supervision, and writing—review and editing. Jianxin Feng: Numerical simulation. Xiaobin Xu and Fengrui Wu: Experimental, data curation. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zou, P.F., Wang, C.H., Du, J.G., *et al.* (2023) Simulation and Optimization of Production-Reinjection Schemes for a Geothermal Water System: A Case Study of the Rural Clean-Energy Heating Demonstration Area in Northern Jiangsu. *Hydrogeology & Engineering Geology*, **50**, 59-72. (In Chinese)

[2] Wang, X.P., Liu, H., Jiang, S.J., *et al.* (2020) Reinjection Tests of Sandstone Geothermal Reservoirs in Sedimentary Basins: A Case Study of Yucheng City, Shandong Province. *Geological Review*, **66**, 485-492. (In Chinese)

[3] Feng, S.T., Wang, C.M., Yang, Y.B., *et al.* (2019) Evaluation of the Influence of Sandstone Geothermal Reservoir Reinjection on the Reservoir: A Case Study of the Geothermal Area in the Northwest Shandong Depression. *Acta Geologica Sinica*, **93**, 158-167. (In Chinese)

[4] Zhao, K., Shen, J., Cai, Y., *et al.* (2024) Identification of Reinjection DIFFICULTIES In Sandstone Geothermal Reservoirs and Countermeasures. *Earth Science Frontiers*, **31**, 196-203. (In Chinese)

[5] Luo, W., Kottsova, A., Vardon, P.J., *et al.* (2023) Mechanisms Causing Injectivity Decline and Enhancement in Geothermal Projects. *Renewable and Sustainable Energy Reviews*, **185**, Article ID: 113623. https://doi.org/10.1016/j.rser.2023.113623

[6] Li, J.L., Kang, F.X., Bai, T., *et al.* (2024) Response Mechanism and Regularities of the Temperature Field of Sandstone Geothermal Reservoirs to Reinjection Parameters. *Earth Science*, **49**, 3318-3333. (In Chinese)

[7] Kaya, E., Zarrouk, S.J. and O'Sullivan, M.J. (2011) Reinjection in Geothermal Fields: A Review of Worldwide Experience. *Renewable and Sustainable Energy Reviews*, **15**, 47-68. https://doi.org/10.1016/j.rser.2010.07.032

[8] Li, C.S. and Wang, Y.S. (2021) Research and Tests on Drilling and Completion Technology for Geothermal Reinjection Wells in the Dongying Area. *Petroleum Drilling Techniques*, **49**, 50-54. (In Chinese)

[9] Fan, Y.F., Duan, Z.F., Yang, Y.H., *et al.* (2024) Influence of Reservoir Characteristics on Production-Reinjection Well Spacing in Sandstone Geothermal Reservoirs: A Case Study of the Jiyang Depression. *Hydrogeology & Engineering Geology*, **51**, 215-223. (In Chinese)

[10] Theis, C.V. (1935) The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage. *Transactions*, *American Geophysical Union*, **16**, 519-524. https://doi.org/10.1029/TR016i002p00519

[11] Ministry of Natural Resources of the People's Republic of China (2024) Technical Requirements for Reinjection of Hydrothermal Geothermal Resources: DZ/T 0481—2024. (In Chinese)

[12] Ministry of Natural Resources of the People's Republic of China (2024) Specification for Monitoring of Development and Protection of Hydrothermal Geothermal Resources: DZ/T 0482—2024. (In Chinese)

[13] Shandong Administration for Market Regulation (2021) Technical Regulation for Reinjection of Geothermal Tail Water: DB37/T 4310—2021. (In Chinese)

[14] Duan, X.F., Kang, F.X., Wu, X.H., *et al.* (2024) A Method for Calculating Reasonable Production-Reinjection Well Spacing of Sandstone Geothermal Reservoirs Based on Production-Reinjection Balance Simulation. *Bulletin of Geological Science and Technology*, **43**, 170-180. (in Chinese)