Groundwater heat utilization potential of the Swiss unconsolidated aquifers

Emanuel Huber[1], Vincent Badoux[2], Pierre Christe[3]

[1] GEOTEST Ltd, Bernstrasse 165, 3052 Zollikofen, Switzerland

[2] b-geo llc, Delsbergerallee 50a, 4053 Basel, Switzerland

[3] Swiss Federal Office of Energy, Pulverstrasse 13, 3063 Ittigen, Switzerland

emanuel.huber@geotest.ch

Keywords: groundwater, heat potential, unconsolidated aquifers, thermal utilization, geodata.

ABSTRACT

Groundwater in unconsolidated sediments plays a crucial role in Switzerland, not only as a natural drinking water resource but also for various other uses, including heat extraction. The unconsolidated aquifers contain significant amounts of thermal energy, which can be harnessed for sustainable heating and storage systems. This potential offers a promising alternative to conventional fossil fuel-based heating systems, contributing significantly to climate protection and the energy transition. This study addresses a significant gap in national-scale assessments of shallow geothermal resources, developing and applying two complementary evaluation approaches (the Volume-Approach and the Thermal-Balance Approach) to quantify the recoverable heat energy and sustainable heat-extraction rate from Switzerland's unconsolidated aquifers. Primary outputs include: (1) a harmonized set of geodata of heat utilization potential per canton; (2) methodological advances refining existing approaches; (3) validation against numerical modelling and regional studies; and (4) concrete recommendations for future data collection and management. The results reveal a total stored heat-energy resource of approximately 17 TWh (for ΔT = 3 K) and a sustainably extractable power of ~4.2 GW, of which only ~11 % is currently exploited. The study underpins the strategic potential of groundwater-source heat pumps to contribute to Switzerland's Energy Strategy 2050+ targets, while highlighting the need for coordinated trans-cantonal groundwater thermal management.

1. INTRODUCTION

The Swiss Energy Strategy 2050+ sets ambitious targets for decarbonizing space heating, with near-surface geothermal systems—particularly groundwater-source heat pumps—identified as key renewable contributors. Unconsolidated (Quaternary) aquifers in Switzerland collectively hold over 10 km^3 of groundwater (Sinreich et al., 2012), representing a substantial thermal energy reservoir hitherto only partially characterized for heat utilization potential. While individual cantonal studies and small-scale assessments exist, there has been no consistent national geodata to guide policy, planning, and investment. In this context, the Swiss Federal Office of Energy commissioned GEOTEST Ltd to (1) compile existing hydrogeological data, (2) refine methodologies for quantifying heat utilization potential, (3) produce harmonized set of geodata, and (4) formulate recommendations to support sustainable groundwater thermal management across cantonal boundaries.

Understanding both the total theoretically recoverable heat in place (an "exhaustible" resource, Gringarten, 1978) and the rate at which heat can be replenished through natural processes ("sustainable yield", Stauffer et al. 2013) is essential. The former informs stored resource availability, while the latter determines feasible extraction rates without impairing groundwater temperatures or ecosystem services. By combining two analytical frameworks—the Volume-Approach (closed-system estimate of stored heat) and the Thermal-Balance Approach (open-system estimate of sustainable flux)—the study provides comprehensive insights for stakeholders ranging from federal agencies to municipal planners and geothermal practitioners.

2. OBJECTIVES AND SCOPE

The project's objectives were sixfold.

First, it aimed to compile data by inventorying and assessing the availability of hydrogeological geodata at the cantonal level through web screening and an online survey.

Second, it sought to test and enhance existing methodologies, refining both the Volume- and Thermal-Balance Approaches to make them suitable for application at a national scale.

Third, the project involved estimating potential: specifically, calculating (a) the total heat energy stored (in kWh) using the Volume-Approach, and (b) the sustainably extractable power (in kW) using the

Thermal-Balance Approach, each for a temperature change (ΔT) of 3 K.

Fourth, a set of geodata was created in accordance with the Swiss Geodata Model (MGDM) to represent heat utilization potential.

Fifth, validation efforts included cross-checking results with a 3D groundwater flow and heat transport model and comparing them with existing regional potential studies, such as the one conducted in the St. Gallen Rhine River Valley.

Finally, the project proposed recommendations to improve cantonal and national groundwater geodata practices, aiming to support ongoing monitoring and sustainable management.

The study's spatial focus includes all unconsolidated aquifer extents within cantonal boundaries, explicitly excluding karst and fracture-karst systems as well as deeper aquifers below approximately 100 meters due to data limitations.

3. METHODOLOGICAL FRAMEWORK

The concept of 'heat potential' is inherently ambiguous, as its interpretation depends on the definition of 'heat'—whether considered in terms of energy (J) or power (W)—and of 'potential,' which may refer to theoretical maxima, sustainable yields, technical feasibility, economic viability, or societal acceptability. Bayer et al. (2019) provide a comprehensive framework for navigating these various dimensions and clarifying the terminology.

This study quantifies the theoretical potential of unconsolidated shallow aquifers subject to the following conditions:

1. A maximum permissible temperature change of $\Delta T = 3$ K, as mandated by Swiss Waters Protection Ordinance.
2. Exclusive use of publicly available geodata sets.
3. No consideration of existing groundwater uses, anthropogenic influence (e.g., urban heat island effect; Allen and Milenic, 2003) and climate change.
4. Exclusion of cooling applications and aquifer thermal energy storage (ATES).
5. No incorporation of land-use regulations, economic feasibility, or technical limitations.
6. Average conditions (average groundwater recharge, groundwater heads, etc.).
7. By multilayer aquifers only the top aquifer is considered.

A quantification of the heat utilization potential based on analytical solutions is adopted, as these methods enable rapid computation with minimal overhead, making them well-suited for large-scale sensitivity analyses and theoretical potential assessments where the complexity and runtime of numerical models would be impractical.

3.1 Volume-Approach (Heat in place)

The Volume-Approach treats the aquifer as a closed reservoir of water with finite heat content. The total theoretically recoverable heat in place E (J) is given by (Gringarten, 1978):

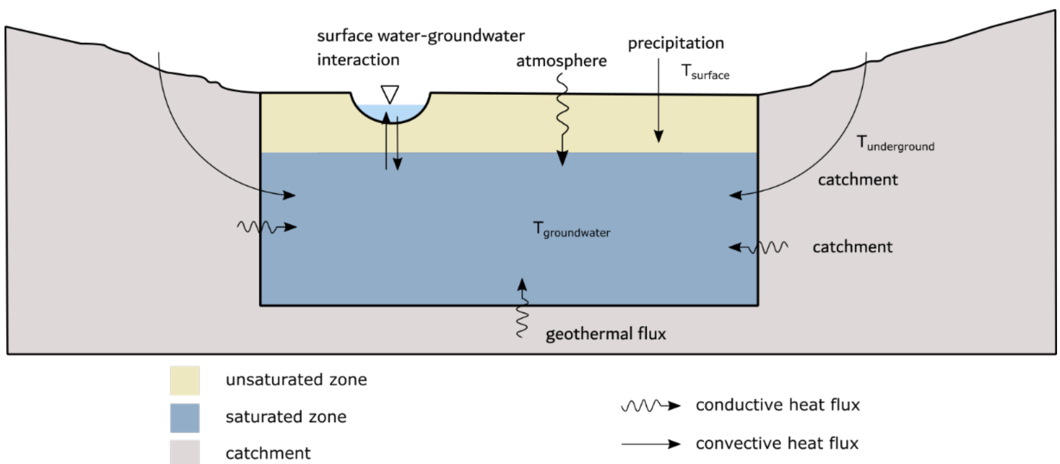
$$E = c_w \cdot \rho_w \cdot n \cdot V \cdot \Delta T \qquad [1]$$

where c_w (J/kg/K) is the water specific heat capacity, ρ_w (kg/m^3) the water density, n the porosity, V (m^3) the saturated aquifer volume, and ΔT (K) the permissible temperature drawdown (3 K). The volume V is approximated by the product of average saturated thickness a, and planimetric area of the groundwater unit F_{GW}. This approach yields a one-time energy resource, independent of temporal regeneration.

3.2 Thermal-Balance Approach

By contrast, the Thermal-Balance Approach (Stauffer 2013) regards the aquifer as an open system in dynamic thermal equilibrium with the atmosphere, hydrosphere, and lithosphere.

Figure 1: Illustration of the various heat fluxes on a vertical cross-section of an aquifer perpendicular to the groundwater flow direction.



Following Stauffer et a. (2013), it is assumed that the groundwater temperature is in perfect equilibrium with the atmosphere, hydrosphere, and lithosphere and that the temperature T_0 is constant everywhere. The groundwater is then cooled by ΔT (analogous to the volume approach, see Figure 1). This cooling of the groundwater creates an imbalance (i.e., a temperature gradient) between groundwater and its surroundings. The temperature gradient causes a heat flow towards the groundwater, which is ultimately available for heat utilization. These replenishing heat flows define the theoretical sustainable heat utilization potential.

There are two main types of heat flow: **convective** and **conductive** heat flow.

3.2.1 Convective heat fluxes

In **convective** (or **advective**) heat flow, heat is transported by groundwater recharge, which introduces water warmer than the ambient groundwater into the system (e.g., through infiltration of precipitation or lateral inflow from catchment areas). Convective heat flow is defined as follows:

$$J = q \cdot c_w \cdot \rho_w \cdot \Delta T \qquad [2]$$

J represents the heat flow in watts (W), and q is the recharge flow rate (m^3/s).

The following convective heat fluxes toward groundwater were defined as follows.

Convective heat flux from surface water bodies (J_{sw})

Because of the lack of comprehensive data (no spatially exhaustive information), heat flux resulting from the infiltration of surface water into groundwater was not considered in the present study. Similarly, groundwater exfiltration into surface waters was also discarded. As a result, the heat utilization potential is likely underestimated, since the thermal contribution from surface water infiltration is omitted.

Convective heat flux from precipitation (J_N)

$$J_N = (N - EP) \cdot f_N \cdot F_{GW} \cdot c_w \cdot \rho_w \cdot \Delta T \qquad [3]$$

With N the precipitation (m/s), EP the evapotranspiration (m/s), and f_N the infiltration coefficient.

Convective lateral heat flux from catchments (J_c)

The heat flux from lateral inflows is defined by:

$$J_c = q_c \cdot c_w \cdot \rho_w \cdot \Delta T \qquad [4]$$

Where q_c (m^3/s) is the flow rate from lateral catchments defined by:

$$q_c = (N - EP) \cdot f_c \cdot F_c - A_o \qquad [5]$$

with f_c the infiltration coefficient for the lateral catchments, and A_o (m^3/s) the rate of infiltrated water that exist the catchment as surface water runoff. The latter is not publicly available for Switzerland and is therefore ignored.

Groundwater inflow into and outflow out of the groundwater system.

When the thermal-heat balance is applied to subunits of the aquifers, groundwater flows from upstream to downstream subunits. Because it is assumed that groundwater is cooled by ΔT in every point of the aquifer, the groundwater inflow and outflow have a relative temperature of $-\Delta T$. That means that no heat can be extracted from groundwater inflow and no extractable heat exits the subunit.

3.2.2 Conductive heat fluxes

In **conductive** heat flow, the transfer of thermal energy occurs through direct contact between groundwater, the atmosphere, and the lithosphere. Conductive heat flow is defined according to Fourier's law:

$$J = \lambda \cdot F \cdot (\Delta T / L) \qquad [6]$$

with λ (W/m/K) the medium thermal conductivity, F (m^2) the medium contact area, L (m) the medium thickness, and ΔT (K) the temperature difference. $\Delta T/L$ is the temperature gradient (K/m).

The following conductive heat fluxes toward the groundwater system were defined as follows.

Conductive heat flux from the atmosphere (J_a)

Stauffer et al. (2013) propose calculating the conductive heat flux from the atmosphere as follows:

$$J_a = \lambda_{eq} \cdot F_{GW} \cdot (\Delta T / (a + m/2)) \qquad [7]$$

with λ_{eq} (W/m/K) the equivalent thermal conductivity of the unsaturated zone and half the saturated zone, a (m) the depth to the groundwater table, and m (m) the groundwater thickness.

Numerical 3D simulations of groundwater flow and heat transport, applied to a hypothetical scenario involving instantaneous heat extraction with a temperature change of $\Delta T = 3K$ at every point within the aquifer, indicate that long-term heat extraction exclusively occurs at the outer boundaries of the aquifer's saturated volume (see Section 3.4.1 Numerical Model Comparison).

Therefore, the groundwater thickness term can be removed from Equation [7], which simplifies to:

$$J_a = \lambda_u \cdot F_{GW} \cdot (\Delta T / a) \qquad [8]$$

with λ_{eq} (W/m/K) the thermal conductivity of the unsaturated zone,

This implies that the smaller the depth to the groundwater table, the greater the heat flux from the atmosphere. The groundwater thickness has no influence on the heat flux from the atmosphere.

Conductive lateral heat flux from catchments

Because of the geometry of the unconsolidated aquifers that are generally much wider than deep, it is assumed that the lateral heat flux is much lower than the geothermal heat flux. Estimating the lateral heat flux is challenging, as the lateral surface area of the aquifer is difficult to define, and the temperature gradient is unknown (a thermal numerical model would be required for this purpose). For these reasons, the lateral heat flux from adjacent areas was not considered.

Conductive heat flux from the Earth's interior (Geothermal heat flux, J_{geo})

The geothermal heat flux is defined as:

$$J_{geo} = q_{geo} \cdot F_{GW} \qquad [9]$$

with q_{geo} (W/m^2) the geothermal heat flux density.

3.2.3 Theoretical sustainable heat utilisation potential

The theoretical sustainable heat utilization potential J_{pot} (W) is the sum of the convective and conductive fluxes, and is approximated as follows:

$$J_{\mathrm{pot}} \approx J_N + J_{\mathrm{c}} + J_{\mathrm{a}} + J_{\mathrm{geo}} \qquad [10]$$

All heat fluxes, except for the geothermal heat flux, which is assumed to be constant, are proportional to ΔT.

Since the lateral conductive heat flux is not considered, the groundwater thickness is not included in the calculation. For future extensions of the heat balance approach, it should be examined how lateral heat fluxes could be integrated.

3.3 Implementation and workflow

Estimation of the heat flux relies on canton-wide geodata of precipitation, evapotranspiration, unsaturated-zone thickness, thermal conductivity, groundwater surface gradients, and geothermal heat-flux density (Table 2).

The following workflow (Figure 2) is implemented to compute the theoretical sustainable heat utilization potential for both approaches:

1. Geodata acquisition (vector and raster geodata, WFS) for key parameters: aquifer extents, saturated thickness, groundwater level contours, and average precipitation and evapotranspiration.
2. Attribute cleaning
3. Spatial computation and interpolation for continuous raster surfaces where needed.
4. Computation of specific heat flux terms on a per-polygon basis.
5. Aggregation by Swiss canton and mosaic for national coverage.
6. Export of final geodata in Swiss-Geodata-Model-compliant feature classes and styling rules for the federal GIS portal.

Steps 3 through 5 are performed automatically using GIS-based scripting.

3.3.1 Balance polygons

For both approaches, the computations were based on cantonal geodata of "groundwater occurrences in unconsolidated sediments". Connected polygons were aggregated, and if a cantonal geographical naming was available, they were aggregated according to their cantonal naming. Polygons that were too large were subdivided into smaller units, preferably along bedrock step features. The resulting polygons were then clipped to the cantonal boundaries, as many of the original geodata were not consistent across cantonal borders. In the following, we refer to these polygons—on which the heat utilization potential is calculated—as *balance polygons*.

Because of limited data availability, some parameters were assumed to be constant (Table 1). The remaining parameters were estimated based on publicly available geodata (Table 2). Further computational details are provided below.

The heat-in-place and the thermal balance are computed at the balance-polygon-scale using average or summed values (see Figure 2).

Table 1: Constant parameter.

Symbol	Description	Value
λ_{u}	Thermal conductivity unsaturated zone	2.6 W/(m·K)
c_w	Specific heat capacity of water	4’182 J/(kg·K)
ρ_w	Water density	999.96 kg/m^3
f_N, f_{c}	Infiltration coefficient aquifer and catchment	0.3
n	Aquifer porosity	0.2[(1)]

[(1)] Sinreich et al. (2012)

3.3.2 Depth to groundwater table

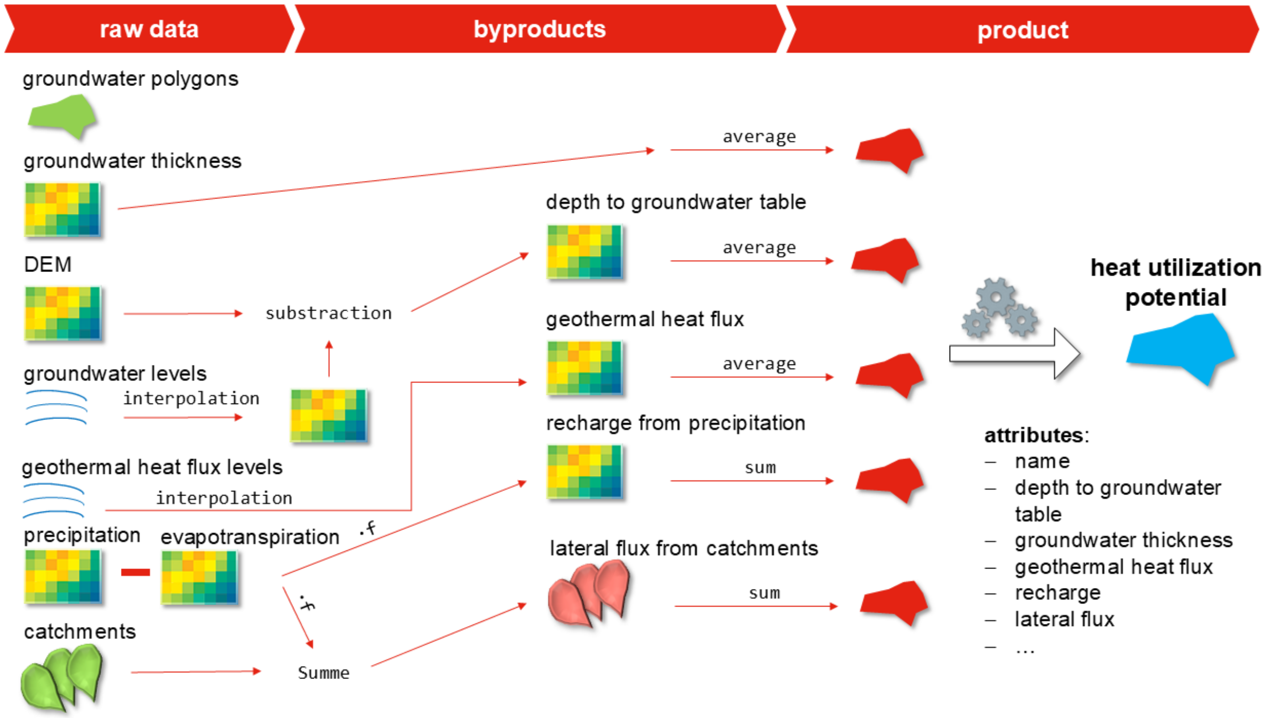
The average depth to groundwater table was calculated for each balance polygon. For cantons that do not have depth-to-groundwater-table-datasets, the depth to groundwater was derived from the groundwater levels. The latter were interpolated for each balance polygon and subtracted from the digital elevation model (Swisstopo DHM25). To minimize interpolation errors, the interpolation was restricted to 1 km around the available groundwater level contours. If this interpolation area covered only a small part of the balance polygon, the determined average depth to groundwater table is uncertain. Negative or zero values can occur in the determination of the depth to groundwater table due to poor data quality. To avoid overestimating the heat flux from the atmosphere or calculating unrealistic values, the depth to groundwater table smaller than 0.2 m is set equal to 0.2 m.

Where neither the depth to groundwater table data nor the groundwater level contours are available, it is assumed that the average depth to groundwater table is

Table 2: Spatial datasets used to compute the heat utilization potential.

Symbol	Description	Topology	Source
F_{GW}	Area of aquifer (m²)	Polygon	Cantonal datasets
F_c	Area of catchment (m²)	Polygon	Swisstopo: "partial catchment areas 2 km²"
P	Precipitation (m/s)	Raster	Hydrological Atlas of Switzerland: "average precipitation heights (1981-2010)"
EP	Evapotranspiration (m/s)	Raster	Hydrological Atlas of Switzerland: "average annual evaporation heights (1973–1992)"
q_{geo}	Heat flux density	Raster	Swisstopo: "heat flux density 500"
a	Depth to groundwater (m)	Polyline	Cantonal datasets (groundwater level contours)

Figure 2: General workflow for determining the heat utilization potential in the unconsolidated aquifers of Switzerland.



15 m (Sinreich et al., 2012). This allows an estimate of the heat flux from the atmosphere.

3.3.3 Lateral inflow from catchments

The heat flux from lateral inflows is simply related to the area of the topographical catchment areas adjacent to the balance polygon (aquifer), although the topographical catchment areas do not correspond one-to-one with the subsurface catchment areas. The catchment areas that have an outlet point within the considered balance polygon were assigned to it. In the calculation of the heat flux from lateral inflows, only the area F_c of the catchment that does not overlap with the balance polygon is considered. If no catchment drains into a balance polygon, the convective latera heat flux from catchments is set equal to 0 kW.

3.3.4 Groundwater thickness

The calculation of the heat flux from the atmosphere is based, among other things, on the groundwater thickness. In many cantons, the groundwater thickness is represented by multipolygons that divide the aquifer into thickness classes (e.g., thickness from 2 m to 10 m, from 10 m to 20 m, etc.). The volume of each part of the multipolygons is calculated based on the lower limit of the thickness class, and then, summed over the balance polygon. Where no cantonal data are available, the thickness was derived from the hydrological atlas of Switzerland (HADES) geodata "groundwater occurrences" (analogous to the cantonal datasets).

3.4 Validation

3.4.1 Numerical Model Comparison

To evaluate the heat balance approach, a three-dimensional groundwater flow and heat transport model is developed using FEFLOW (DHI, 2023). The model is designed to represent the conceptual framework of the heat balance approach. It simulates an aquifer embedded within its recharge area, positioned directly atop an aquitard to ensure that water from the catchment area flows laterally into the aquifer (Figure 3).

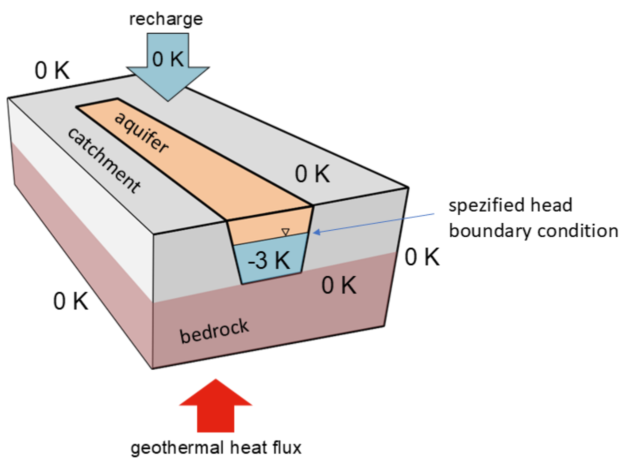
Groundwater recharge is applied at the top of the model, feeding the aquifer, while groundwater outflow is controlled by a fixed head boundary condition within the aquifer. Model parameters are provided in Table 3.

The relative temperature at the model boundaries is set to 0 K, except at the bottom boundary, where a heat flux boundary condition is applied. The groundwater recharge is also assigned a relative temperature of 0 K.

A steady-state simulation was conducted to obtain equilibrium temperature distribution. Subsequently, heat was extracted uniformly from the saturated zone of the aquifer such that the groundwater temperature decreased by $\Delta T = 3$ K. A homogeneous cooling effect across the entire groundwater volume is assumed.

The spatial heat flux towards groundwater is investigated and calculated for its top, bottom and lateral boundaries. The calculated heat fluxes are then compared with those derived from the heat balance approach.

Figure 3: Illustration of the various heat fluxes on a vertical cross-section perpendicular to the groundwater flow direction. The relative initial temperature is indicated in Kelvin.



3.4.2 Regional Study Benchmark

Additional validation was conducted by comparing the calculated heat utilization potential with existing potential assessments. The Rhine Valley aquifer was selected for this comparison. As part of the study *"Groundwater Management in the Canton of St. Gallen"*, an assessment of the thermal potential of the Rhine Valley aquifer was conducted (TK CONSULT Ltd, 2023). In that study, a specific extractable thermal power of 2 W/m² was estimated as being sustainably usable.

4. RESULTS

4.1 Validation

4.1.1 Numerical Model Comparison

The numerical model indicates that the heat extraction exclusively occurs at the outer boundaries of the aquifer's saturated volume (Figure 4). This justifies not taking the aquifer thickness into account in the computation of the heat flux from the atmosphere (Eq. 8).

The heat fluxes from the numerical model calculated at the groundwater boundaries (saturated zone) are compared with those derived from the heat balance approach (Table 4).

Table 3: Model parameters.

Aquifer	
Width	200 m
Length	1'200 m
Aquifer thickness	25 m
Groundwater thickness	20 m
Volumetric heat capacity	2 MJ/m³/K
Thermal conductivity	2.6 W/m/K
Hydraulic conductivity	$1 \cdot 10^{-3}$ m/s
Catchment (moraine)	
Width	200 m
Length	2000 m
Thickness	25 m
Volumetric heat capacity	2.1 MJ/m³/K
Thermal conductivity	2.6 W/m/K
Hydraulic conductivity	$1 \cdot 10^{-5}$ m/s
Aquitard (Molasse)	
Width	200 m
Length	2'000 m
Thickness	25 m
Volumetric heat capacity	2.1 MJ/m³/K
Thermal conductivity	2.6 W/m/K
Hydraulic conductivity	$1 \cdot 10^{-15}$ m/s
Additional Parameters	
Porosity	0.2
Longitudinal dispersion	5.0 m
Lateral dispersion	0.5 m
Groundwater recharge from precipitation	174 mm/a
Depth to groundwater at outflow (specified head potential)	2 m
Geothermal heat flux	0.065 W/m²

The largest deviation (69%) concerns the geothermal heat flux, which in the analytical heat balance approach flows vertically beneath the aquifer. In the thermal groundwater model, however, the heat flux converges from a larger area toward the aquifer bottom (Figure 4). Additionally, heat also flows into groundwater from the aquitard and the surrounding catchment area. A portion of the heat from the catchment area does not pass through the lateral boundaries of the aquifer, which may explain the lower heat flux compared to the heat

Figure 4: Top: Groundwater temperature at equilibrium (without groundwater heat utilization); Middle: Groundwater temperature with a 3 K cooling of the aquifer; Bottom: Temperature difference between the top and middle panels.

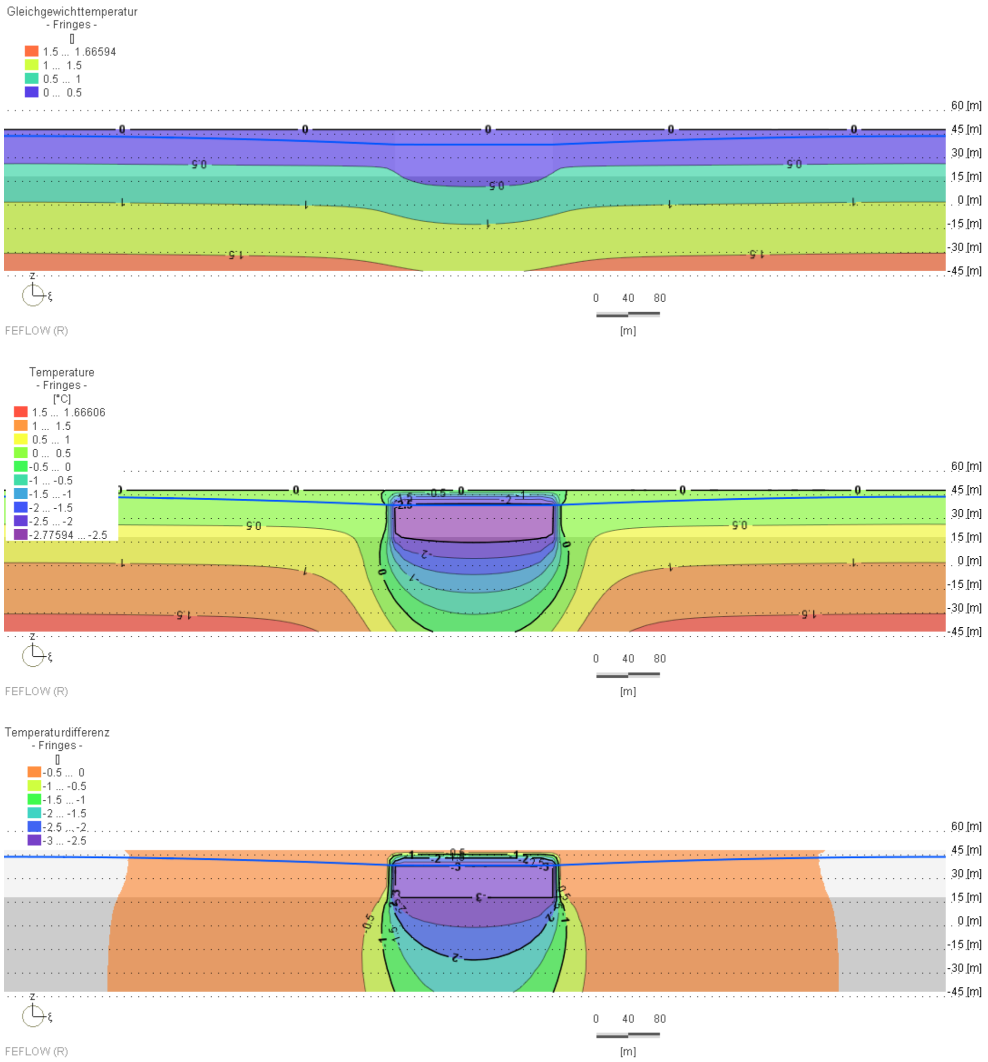


Table 4: Results from the comparison between the numerical groundwater flow and heat transport model, and the analytical thermal-balance approach.

	Numerical model		Analytical model	
	Heat flux (kW)	Heat flux proportion	Heat flux (kW)	Heat flux proportion
Top boundary (heat from atmosphere and precipitation)	287	60%	255	61%
Lateral boundaries (heat from catchment)	125	26%	145	35%
Bottom boundary (geothermal flux)	64	13%	19.5	5%
Heat utilization potential	476		420	

balance approach. The deviation between the calculated potentials is 12%.

This comparison indicates that the magnitudes of the heat fluxes are in good agreement. Therefore, the heat balance approach was considered suitable for estimating the thermal potential.

4.1.2 Regional Study Benchmark

In the present study, the calculated extractable power (or specific thermal potential) for the Rhine Valley aquifer, based on the heat balance approach, ranges from 1.4 W/m² to 1.9 W/m². These results are slightly lower than the 2 W/m² estimated with numerical modelling. Nevertheless, the results of the present study show a very good agreement with the findings of the St. Gallen study.

4.3 National geodata

As part of this project, a national dataset on the heat utilization potential in Switzerland's unconsolidated aquifers was developed in accordance with the Swiss Geodata Model (MGDM). This comprehensive geodata covers the majority of cantons and is published with its documentation on the federal GIS portal (https://map.geo.admin.ch, "groundwater heat utilisation potential").

4.2 Heat utilization potential for Switzerland

In the current heat utilization potential calculation based on the thermal-balance approach, the thickness of the aquifers plays no role. The specific heat fluxes (kW/m²) from precipitation and geothermal sources show little variation compared to the heat fluxes from the atmosphere and the catchment areas. When the depth to the groundwater table is small, the heat flux from the atmosphere dominates. If the catchment area is large relative to the aquifer, the heat flux from the catchment area dominates.

As an additional comparison, the thermal energy (in kWh) available from groundwater, as well as the heat utilization potential (in kW) for the whole of Switzerland, was calculated. The cantons of Jura, Valais, Vaud, Neuchâtel, and Appenzell Innerrhoden are not considered in the calculation because they have either no significant groundwater unit in unconsolidated aquifer or the groundwater related data are not publicly available.

The calculation based on the volume approach results in an estimated thermal energy from groundwater of approximately 17 TWh.

Using the heat balance approach, the sustainable heat utilization potential in Switzerland's unconsolidated aquifers amounts to approximately 4.2 GW. This corresponds to an average specific heat utilization potential of 1.36 W/m².

5. DISCUSSION

5.1 Methodology of the thermal-balance approach

5.1.1 Atmospheric heat flux

The computation of heat flux from the atmosphere (thermal-balance approach) as proposed by Stauffer et al. (2013) could be further improved by removing the dependency on the groundwater thickness. In the thermal balance approach the heat fluxes are captured at the boundaries of the saturated aquifer volume, as shown by numerical modelling.

This is a significant advantage over the computation by Stauffer et al. (2013), as data on groundwater thickness are often sparse or unavailable, whereas groundwater levels and depth to the water table are more commonly accessible.

In the current study, the depth to the groundwater table is averaged across each balance polygon, which leads to an underestimation of the atmospheric heat flux compared to calculations performed at a finer spatial resolution. The underestimation is larger for smaller depth to groundwater table. Therefore, a recommended next step is to adapt the analytical method to compute atmospheric heat flux at the raster pixel scale, enabling a more spatially detailed and accurate assessment of the groundwater heat utilisation potential.

5.1.2 Advective groundwater heat flux

The proposed thermal balance approach differs fundamentally from the volumetric Darcy flow approach described by Epting et al. (2018). In the latter, the specific advective groundwater heat flux J_{adv} is calculated based on the Darcy flow rate q_D and assumed to be equal to the heat potential:

$$J_{adv} = q_D \cdot c_w \cdot \rho_w \cdot \Delta T \qquad [11]$$

The Darcy flow rate is estimated at a fine spatial resolution using a numerical model.

In contrast, the thermal balance approach assumes that the groundwater temperature has already been reduced by ΔT, meaning that the thermal energy associated with advective groundwater flow has effectively been already extracted. As a result, no additional heat is available for extraction from the advective component under this approach.

5.1.3 Multilayered aquifer

Handling multilayered aquifers in the thermal balance approach is challenging and requires additional assumptions as well as extended computations. For simplicity, only the upper groundwater layer was considered in the calculation for multilayered aquifers. The next step in the development of methods is to account for the heat utilization potential of all the multilayered aquifers.

5.1.4 Significance of the heat utilisation potential

The computed heat potential based on the thermal balance approach most likely underestimate the theoretical sustainable heat utilisation potential for the following reasons. (1) Some heat fluxes are not considered (convective heat flux from surface water bodies; conductive lateral heat flux from catchment; anthropogenic heat fluxes, see Menberg et al., 2013); (2) the atmospheric heat flux is underestimated; (3) climate change and anthropogenic effects are not accounted for.

The theoretical sustainable heat utilisation potential represents the upper bound of the heat that can be technically, economically, and acceptably extracted when solely heat extraction is considered.

Although not considered in this study, Aquifer Thermal Energy Storage (ATES) is highly relevant, as it can significantly enhance theoretical sustainable heat utilisation potential by enabling seasonal storage and recovery of thermal energy, thereby optimizing the temperature differential for utilisation. Compared to passive systems, ATES allows for more efficient and sustained use of the aquifer, even in regions with limited natural thermal gradients. Moreover, it supports long-term sustainable operation by maintaining the thermal balance within the aquifer.

5.2 The effective heat utilisation in Switzerland

The results show that the total thermal energy content (heat in place) in unconsolidated aquifers amounts to approximately 17,360 GWh (17 TWh). In comparison, the geothermal energy extracted from shallow groundwater systems in 2023 was around 547.8 GWh (EnergieSchweiz, 2024). Assuming no natural regeneration, this implies a depletion timespan of roughly 31 years under current extraction rates. However, this estimate does not account for natural replenishment, which would extend the utilization period. The thermal balance approach indicates a sustainable national heat extraction potential of approximately 4.2 GW. Given that the installed capacity in 2023 was around 372.4 MW (EnergieSchweiz, 2024), this represents only 11% of the estimated national potential.

These findings demonstrate that the heat potential of Switzerland's unconsolidated aquifers remains largely untapped and could make a significant contribution toward achieving the goals of the Energy Strategy 2050+.

5.2 Recommendations for Groundwater-Related Geodata

The wide availability of publicly accessible groundwater geodata enables the implementation of a largely automated workflow to compute valuable information at the national scale. However, this study has identified several remaining needs and challenges related to geodata. Based on these findings, we recommend the following:

- Groundwater resources should be divided into hydrogeologically consistent accounting units that are practical for use in models or calculations. Assigning geographic names to these accounting units enables clearer reference to the respective units.
- Groundwater resources that extend across multiple cantons should be described in a consistent manner by all cantons.
- As information on deeper groundwater resources is often unavailable, the geodata remains incomplete and will need to be consolidated in the future.
- For groundwater level contours, it should be explicitly stated whether they represent groundwater heads or groundwater table levels. This distinction is particularly relevant for confined aquifers. The type of groundwater level should also be specified (e.g., lowest, average, or highest groundwater level).
- Currently, spatial groundwater data are primarily available in vector format (polygons and polylines), while raster data are largely lacking. However, advances in computing power and high-speed internet access now make it feasible to generate and use raster datasets, which would enable more efficient and advanced computational analyses.

6. CONCLUSIONS

This study assessed the heat utilisation potential in Switzerland's unconsolidated aquifers using two complementary approaches: the Volume-Approach and the Thermal-Balance Approach. The Volume-Approach estimates the finite thermal energy stored in groundwater, treating the aquifer as a closed system. In contrast, the Thermal-Balance Approach considers the aquifer as an open system and quantifies the sustainable, long-term usable heat based on simplified energy fluxes between the groundwater and its surrounding environment.

The results reveal a total stored heat-energy resource (heat in place) of approximately 17 TWh (for $\Delta T = 3$ K) and a sustainably extractable power of ~4.2 GW, of which only ~11% is currently exploited.

The study also highlights several methodological advancements, including the refinement of existing approaches and validation against numerical modeling and regional studies. The creation of a harmonized set of geodata of heat utilization potential per canton provides a valuable tool for policy, planning, and investment. Additionally, concrete recommendations for future data collection and management were formulated to support sustainable groundwater thermal management.

Despite the promising potential, the study identifies several areas for improvement. The thermal balance method could be further refined by including additional sources such as surface water infiltration and lateral conductive heat fluxes. Moreover, the atmospheric heat flux computation could be improved by adapting the analytical method for computation at a finer spatial resolution.

In conclusion, the strategic potential of groundwater-source heat pumps to contribute to Switzerland's Energy Strategy 2050+ targets is significant. However, realizing this potential requires coordinated efforts in data collection, methodological refinement, and trans-cantonal groundwater thermal management. The findings of this study provide a robust foundation for future research and policy development aimed at harnessing the thermal energy stored in Switzerland's unconsolidated aquifers for sustainable heating and storage systems.

REFERENCES

Allen A., Milenic D. (2003) Low-enthalpy geothermal energy resources from groundwater in fluvioglacial gravels of buried valleys. Applied Energy, 74(1–2):9-19. DOI: 10.1016/S0306-2619(02)00126-5

Bayer P., Attard G., Blum P., Menberg K. (2019) The geothermal potential of cities. Renewable and Sustainable Energy Reviews, 106:17–30. DOI: 10.1016/j.rser.2019.02.019.

Gringarten, A.C. (1978) Reservoir lifetime and heat recovery factor in geothermal aquifers used for urban heating. Pure and Applied Geophysics, 117: 297–308. DOI: 10.1007/BF00879755

EnergieSchweiz (2024) Statistik der geothermischen Nutzung in der Schweiz – Ausgabe 2023. Schlussbericht.

Epting J, Müller MH, Genske D, Huggenberger P. (2018) Relating groundwater heat-potential to city-scale heat-demand: a theoretical consideration for urban groundwater resource management. Appl Energy 2018;228:1499–505.

Menzel L., Lang H., Rohmann M. (1999): Mittlere jährliche aktuelle Verdunstungshöhen 1973–1992. In: BWG: Hydrologischer Atlas der Schweiz (Tafel 4.1), Bern.

Sinreich M., Kozel R., Lützenkirchen V., Matousek F., Jeannin P.-Y., Löw S. (2012) Grundwasserressourcen der Schweiz – Abschätzung von Kennwerten. Aqua & Gas, 9:15–19.

Stauffer, F., Bayer, P., Blum, P., Giraldo, N.M., & Kinzelbach, W. (2013). Thermal Use of Shallow Groundwater (1st ed.). CRC Press. DOI: 10.1201/b16239

TK CONSULT Ltd (2023) Thermische Grundwassernutzung des Lockergestein-Grundwasserleiters im St.Galler Rheintal – Hydrothermische 3D-Grundwassermodellierung. Technichal report TKC26.044 from 26th April 2023.

Acknowledgements

This study was funded by the Swiss Federal Office of Energy (SFOE). The authors gratefully acknowledge its support.

Emanuel Huber thanks GEOTEST Ltd for its financial support in the preparation and publication of this manuscript.