ThermoProVal: towards improved guidelines for the realisation of borehole heat pumps in alpine geological settings

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Project ThermoProVal aims at promoting the use of shallow geothermal energy in alpine areas with a particular emphasis on the correct execution of geothermal boreholes. This is not only important to ensure sound performance of the borehole heat pump (BHP) during its life-cycle but also mandatory, as laid down in the Swiss Federal Waters Protection Ordinance. The ski resort of Verbier in the Swiss Alps is used as a case example. The study systematically compares the dimensioning of BHP based on a priori *parameter values (deduced from knowledge of the local geology and the SIA 384/6 Swiss codes) with results from* a posteriori *values obtained from thermal response tests (TRT). First observation indicates that BHP designs are generally significantly oversized by about 30 per cent. This discrepancy is a direct result of groundwater flows at depths that are easily evidenced by mean of TRT but rarely taken into account in conventional design. Groundwater flows, despite improving the effective ground thermal conductivity, represent also a serious challenge for drilling operations, leading to overbreaks, injection washouts and increased risks due to potentially confined groundwater conditions. ThermoProVal recommends establishing a set of specific survey and drilling guidelines for the realisation of BHP in alpine geological settings with a strong focus on optimising cooperation between geologists, drilling companies, heating engineers and the authorities.*

Le Projet ThermoProVal a pour but de promouvoir, en région alpine, l'utilisation de l'énergie géothermique à faible profondeur en insistant particulièrement sur la bonne exécution de forages géothermiques. Cela est non seulement important pour garantir le bon fonctionnement de la sonde géothermique verticale (SGV) pendant son cycle de vie, mais également une obligation découlant de l'Ordonnance Fédérale sur la protection des eaux. La station de ski de Verbier dans les Alpes suisses sert de cas d'école. L'étude compare de façon systématique le dimensionnement de la SGV à partir de valeurs choisies a priori *(valeurs déduites des données géologiques locales et des codes suisses SIA 384/6), avec les résultats obtenus* a posteriori *à partir de tests de réponse thermique (TRT). Les premiers résultats indiquent un surdimensionnement des SGV est en général surdimensionnée d'un facteur de l'ordre de 30%. Cet écart est dû à des circulations d'eau souterraine en profondeur qui sont facilement mises en évidence par moyen de TRT, mais rarement pris en compte lors d'une conception conventionnelle. Si ces circulations améliorent de fait la conductivité thermique réelle, elles représentent un défi important lors des opérations de forage conduisant à des hors-profils, des affouillements et des risques accrus en cas de conditions artésiennes. ThermoProVal vise l'établissement d'une série de recommandations spécifiques pour les études et les forages destinées à l'implantation de SGV en milieux géologiques alpins ainsi que l'amélioration de la coopération entre les géologues, les compagnies de forage, les ingénieurs en géothermie et les autorités.*

El proyecto ThermoProVal tiene como objetivo promover el uso de energía geotérmica superficial en áreas alpinas con un énfasis particular en la ejecución correcta de los pozos geotérmicos. Esto no sólo es importante para garantizar el buen funcionamiento de la bomba de calor del pozo (BHP) durante su ciclo de vida, sino también obligatorio, tal como se establece en la Ordenanza Federal de Protección de Aguas Federales Suiza. La estación de esquí de Verbier en los Alpes suizos se utiliza como ejemplo. El estudio compara de manera sistemática el dimensionamiento de BHP basado en valores de parámetros a priori *(deducidos del conocimiento de la geología local y de los códigos suizos SIA 384/6) con los resultados de los valores* a posteriori *obtenidos de las pruebas de respuesta térmica (TRT). Una primera observación indica que los diseños BHP son, en general, significativamente sobredimensionados en alrededor del 30 por ciento. Esta discrepancia es un resultado directo de los flujos de agua subterránea que se evidencian fácilmente por la media de TRT, y que raravez se tienen en cuenta en el diseño convencional. Los flujos de aguas subterráneas, a pesar de mejorar la conductividad térmica efectiva del suelo, representan también un serio desafío para las operaciones de perforación, lo que genera sobrecargas, fracasos de inyección y mayores riesgos debido a condiciones de aguas subterráneas potencialmente confinadas. ThermoProVal recomienda establecer un conjunto de guías específicas de prospección y perforación para la realización de BHP en entornos geológicos alpinos con un fuerte enfoque en la optimización de la cooperación entre geólogos, empresas de perforación, ingenieros de calefacción y las autoridades.*

Requirements for geothermal boreholes in Switzerland - a short overview

In Switzerland, the trend of implementing individual geothermal heating solutions for domestic purposes (borehole heat pumps – BHP) has steadily increased since the 2000s. Accordingly, in 2009 the Swiss Federal Office of the Environment (FOEN) released general recommendations (FOEN, 2009) to ensure harmonious practice between cantons[1] and application

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1 The Swiss Confederation consists of 26 cantons that all have a permanent constitutional status and, in comparison with the situation in other countries, a high degree of independence. The individual cantons have very different locations – the Alps, the Swiss Plateau and the Jura mountains – and differ not only in topographical characteristics but also in population and degree of urbanisation. In terms of resource management, the Swiss cantons remain sovereign over their underground resources, which is also the case for geothermal energy.

of the legal requirements relevant to the authorisation procedure. These are briefly described as follows.

Land planning and construction requirements:

With respect to the Swiss Constitution, land owners have the right to freely use the underground space to the depth required to cover their needs. Some limitations are however introduced regarding how the public domain is defined, limiting accordingly the available depth, or if the used resource has economic value. To gain a construction permit, every project inquiry requires a public consultation phase where potentially affected citizens can make use of their right to oppose the project. If there is no opposition, the construction authority delivers a permit.

Environmental and water protection requirements:

The construction permit includes a set of general conditions that address overall quality prescriptions aimed at ensuring sound execution of the project and proper initial evaluation of environmental impacts. Implicitly, geothermal boreholes are to be executed by well-trained professionals applying the most recent technical standards. Specific conditions are moreover defined in the Swiss Federal Legislation on Water Protection (Water Protection Ordinance): the use of shallow geothermal heat, i.e. in Switzerland to a depth generally not exceeding a few hundred of meters, must not affect groundwater quality or its dynamics, and a local thermal equilibrium of aquifers is to be maintained.

Energy planning requirements:

The Swiss Energy Strategy calls for the promotion of indigenous renewable energies in the energy mix of Switzerland. With this regard, federal subsidies are allotted to support the development of individual heating solutions based on renewable energies, as well as for the replacement of electric or fossil-fuel based heating. This explains in part the interest in BHP in the last decade. In this context, it is the task of the cantons to develop a rational and efficient energy planning at the local and regional scale. How to realise these objectives in very disparate settings (urban vs. rural, lowland vs. highland areas) is left to the judgement of cantonal or in some cases local authorities. As such, they are implicitly responsible for adequately monitoring and anticipating the cumulative effect induced by the multiplication of BHP projects.

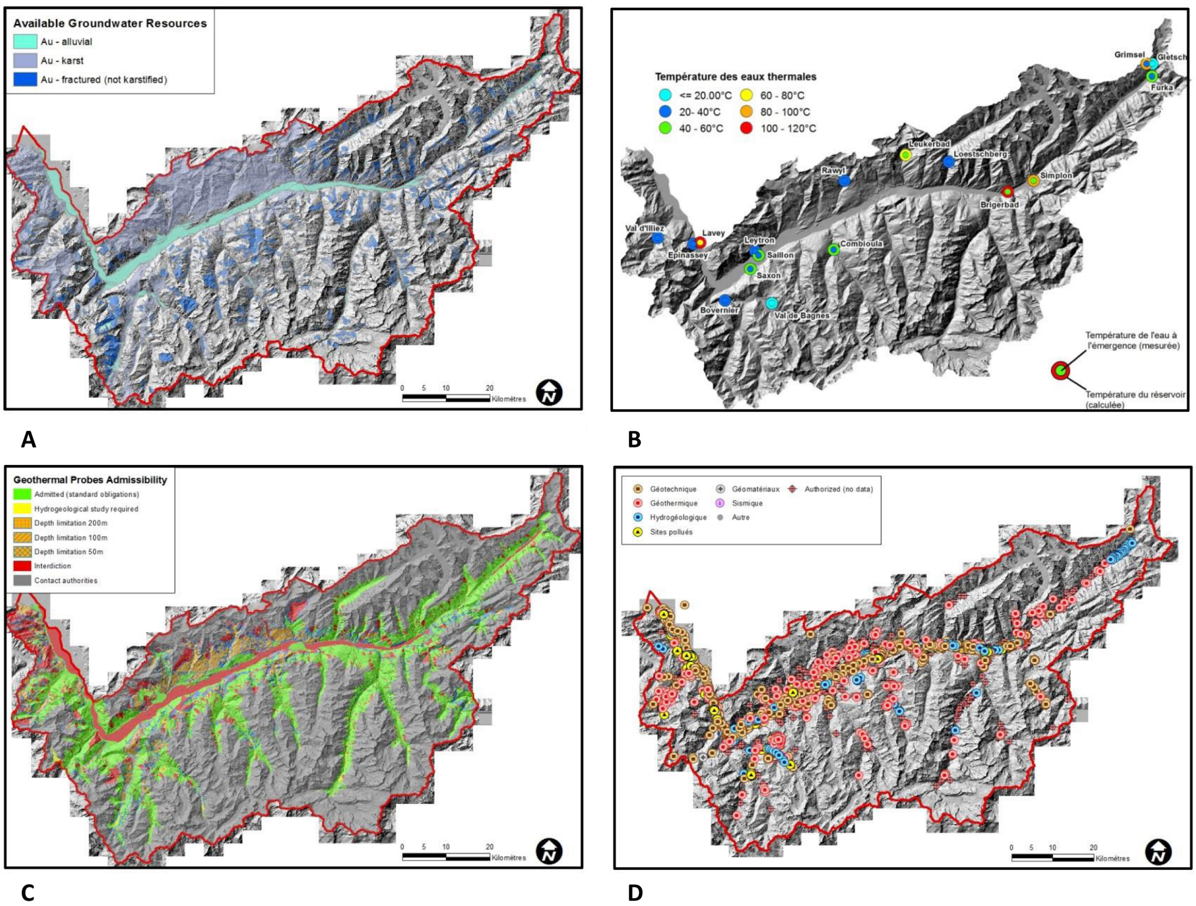


*Figure 1 : A) Spatial extent of the major hydrogeological reservoirs in Canton of Valais: alluvial (green), karst (pale blue) and fractured (blue). Currently, the extent of fractured rock type aquifers are affected by the biggest uncertainty in terms of structure and geometry. As such, potentially available groundwater ressources in these settings are still roughly estimated. B) Hot springs in Valais with indication of the measured spring temperature and the inferred temperature of the associated geothermal reservoir. Courtesy of CREALP. C) Availabilty map for geothermal boreholes (used to study the feasibility of a BHP project). Within the construction zone, a set of general and specific conditions apply for boreholes, as defined by the current geological knowledge. There is a general interdiction on geothermal probes in the Rhone Valley due to protection requirements of the Rhone aquifer. In the Rhone Valley, extensive use of open loop groundwater heat pumps is performed (not discussed in this paper). D) Borehole Database of Canton Valais (**https://geocadast.crealp.ch**). At the end of 2016, about 5,500 logs were publicly made available through the internet.*

To simplify the evaluation of projects, FOEN recommends the canton to develop "admissibility maps", which are land planning instruments aiming at reliably assisting land owners and contractors in the initial feasibility assessment of geothermal boreholes. Such instruments compile available information in a risk assessment and management perspective, defining "open" and "closed" zones for boreholes, as well as sectors where a maximum borehole depth has to be respected or where additional geological investigations are required. Layers of information that are generally compiled are water protection measures, maps of contaminated sites, interpreted geological data (i.e. derived from 1:25,000 geological maps & cross-sections, maps of geological hazards, past surveys, research …), and underground infrastructures such as tunnels, hydroelectric/gas pipes, etc.

To address the dimensioning and design requirements of BHP, in 2010 and 2015 the Swiss Society of Engineers and Architects (SIA) released two dedicated codes: 384/6 for geothermal probes (i.e. BHP) and 384/7 for groundwater heat pumps. They provide a set of standard technical recipes and introduce calculation schemes accounting for the thermal response of common geological ground materials. Specific recommendations for individual projects are given based on the predicted energy needs, broadly differentiating between "regular" and "complex" projects. For a complex design, the use of numerical computation is mandatory. However, a lack of accurate data about site condition and detailed underground structure challenges model parameterisation, often resulting in overestimation and the introduction of conservative security factors.

Recently, conflicts among neighbours related to interfering BHP are increasing in densely constructed areas, leading authorities and professionals to evaluate potential adjustments of the SIA codes and question long-term resource management issues. This problem is twofold: on one hand, improvement of the overall design of BHP is addressed. On the other hand, potential improvement in the execution of geothermal boreholes by the drilling companies is evaluated. Especially since 2015 a more holistic approach has been promoted to avoid the risk of a loss of confidence in the BHP technology. Case studies have been carried out in the city of Zürich (Wagner *et al.*, 2015). An evaluation of analysis techniques to document more accurately the correct implementation of geothermal boreholes has been moreover published under the support of the Swiss Federal Office of Energy (Energie Schweiz, 2015).

Confronted with the challenges of underground planning, several Swiss cantonal administrations are currently reinforcing their geological data recovery policies. A recent document from the Swiss Federal Office of Topography (swisstopo) provides a legal framework for a standardised geological data collection, management and processing for broad and effective public access (Kettiger, 2016). Such progress should make it easier in the future to constantly actualise admissibility maps for geothermal projects, minimising risk of potential conflicts, reducing uncertainties in geothermal resource assessment and management, and promoting more efficiently the use of both shallow and deep geothermal energy in a long-term perspective.

Geothermal potential of the canton of Valais

Despite a particularly contrasted geological setting hosting some of the most emblematic mountains across the country, a common quote inherited from the mining rush in the 19th century refers to the Canton of Valais as a land "rich in poor raw materials". However, from a 21st century perspective, generalised availability to water resources in Valais represents one of the major economic values of the Canton, with a strong contribution to national hydropower production and facilitated access to high standard drinking water. In the current energy debate in Switzerland, geothermal energy as a contributor to the indigenous production of renewable energy (heating + power) should gain attention very soon. Potential targets in Valais have been defined already since the early 1990s (Bianchetti *et al.*, 1992; Sonney and Vuataz, 2008).

For groundwater protection issues (but also geothermal resource assessment), three major typologies of reservoir are delimited on the hydrogeological map of the Canton of Valais (***Figure 1A***). Based on information from thermal springs, each of these reservoirs is potentially attractive for geothermal prospection (***Figure 1B***) and would benefit from exploration programmes as they are still poorly documented.

Geothermal heating in Valais is currently restricted to shallow potentials, mainly through vertical BHP but also open loop groundwater heat pumps. ***Figure 1C*** depicts the admissibility map for geothermal boreholes of Valais. Each year, information from newly realised boreholes assists the actualisation of the map. In recent years, the Canton of Valais has focussed on gathering information about groundwater flow paths at depth. A major contribution to geological knowledge and resource management is therefore borehole data. The Canton of Valais has been maintaining a borehole database since 2013, with about 5,500 logs made accessible online at the end of 2016 (***Figure 1D***).

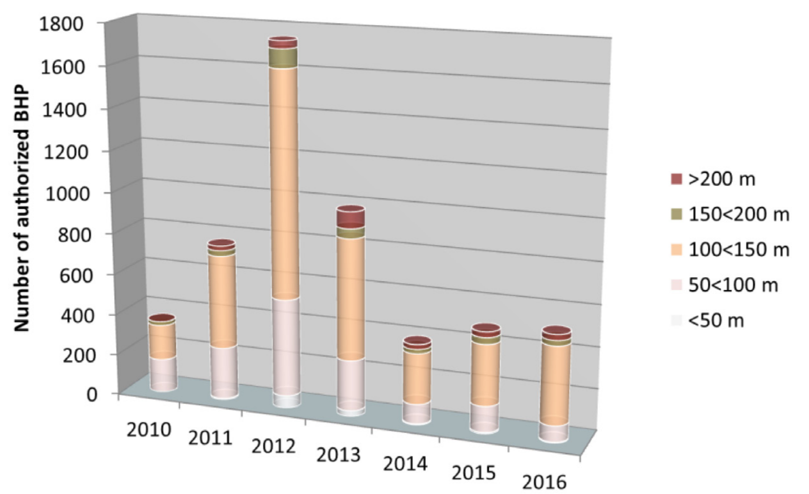


Figure 2: Changes in BHP demand in the Canton of Valais between the years 2010 and 2016 highlighting typical borehole depths. Data represents the total number of authorised boreholes. A peak in demand was observed in 2012, related to a 2011 modification in the land planning policy that introduced a limited construction quota for municipalities outside urbanised areas. Accordingly, an excess amount of BHP projects were submitted to the cantonal authority to be delivered a permit before these new rules became effective. Note that the majority of BHP projects are realised at a depth between 50 and 150 m. Data do not differentiate between individual BHP and BHP fields.

It is expected that the continuous documentation of underground resources will strongly benefit and assist the economic development of Canton Valais in the 21st century and facilitate project planning through high-level risk assessment and thorough evaluation of environmental impacts.

BHP in Valais: Trend and challenges

On average, 400 borehole authorisations are issued every year in Canton Valais by the Service of Environmental Protection. More than 50% are BHP (open loop groundwater heat pumps included). In this context, individual projects often need multiple boreholes (BHP fields), assuming sometimes very complex design with up to 30 boreholes per project. Over time, improper (i.e. inaccurate) design increases the risk of resource overuse and damage to the system, potentially leading to groundwater contamination issues. The evolution of BHP in Valais between the year 2010 and 2016 is illustrated in ***Figure 2***, highlighting typical drilling depths.

Despite fairly harmonised authorisation conditions, among which is the obligation to transmit to the authorities a documented borehole report including geological log, transmission of geological information unfortunately still occurs in less than 20% of the cases.

The Service of Environmental Protection of Canton Valais is currently working on the release of a practical guideline for professionals and construction authorities, informing them about BHP standards and communicating about related hazards. ***Figure 3*** summarises possibly affected objects with BHP and depicts principles for more sustainable resource management at the local and regional scale, used to proactively limit neighbourhood conflicts and damage to existing construction and infrastructures.

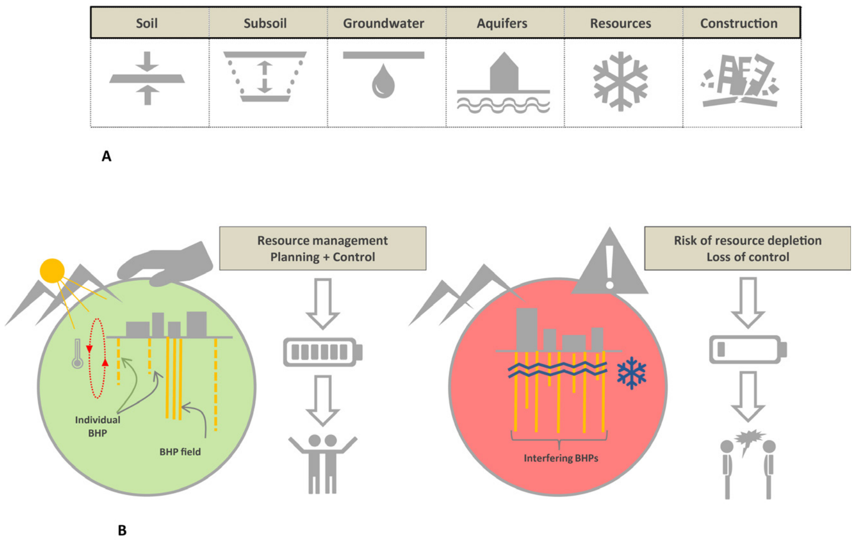


Figure 3: A) Depiction of common risks and impact patterns associated with the realisation of BHP in alpine geological settings and generally taken into account to compile "admissibility maps". To assess the effect of a new BHP project on the local geothermal resource, knowledge about existing projects in the neighborhood is of paramount importance. The pictograms were developped by the Service of Environmental Protection as a mean to stimulate communication and understanding of the problems inherent to BHP in Valais. Practical Guidelines for practitioners and authorities are in preparation. B) "Good" and "bad" behaviours in the use of shallow geothermal energy in alpine geological settings. The lack of planning and an uncoordinated realisation of individual projects seiously increase the risk of interference between nearby BHPs, resulting in faster depletion of the available geothermal heat and increasing the occurrence of neighbourhood conflicts. Coupling BHP with solar energy, surrounding or exhaust air, can be used to ensure an active regeneration of geothermal heat and might provide a viable practice to solve existing conflicts, especially in alluvium. See Wagner et al. *(2015) for a complete discussion.*

Project ThermoProVal - A case study in the Swiss Alps

Project ThermoProVal aims at promoting the use of shallow geothermal energy in alpine areas with a particular emphasis on the correct execution of geothermal boreholes. A key aspect of the project is therefore to help improving project design based on an initial approval of ground thermal response and more careful consideration of both geology and hydrogeology at the local scale.

According to the SIA 384/6 Swiss codes, the design of BHP is mainly influenced by the thermal properties of soils, especially their thermal conductivity (i.e. their property to conduct heat). Thermal parameters of soils are mainly determined by laboratory tests on homogeneous samples, though they are strongly influenced by their water content. In rocks, water content depends essentially on the degree of disturbance of the rock mass, i.e. fracture network development. There is therefore a strong scale effect to take into account when extrapolating those values to real project conditions.

Several mathematical relationships make it possible to correct the laboratory value of thermal conductivity using various parameters characterising, for instance, the mineralogical composition of the soil or its water content (Reiffsteck *et al.*, 2013). Nevertheless, due to the number of required parameters and the difficulty of assessing them, tabulated values – like those proposed by the SIA 384/6 codes – are commonly used for designing BHP projects. This approach has proved to be suitable for fairly homogeneous geological conditions, but is challenged in the presence of complex ground conditions, especially where groundwater flow patterns are inferred or overlooked. Water circulation at depth not only strongly increases thermal ground response, but requires particular care during drilling operations to secure clean borehole execution and ensure the level of groundwater protection required by the Swiss Water Protection Ordinance.

Based on an analysis of current practice, three steps have therefore been defined in the framework of the project, using the densely constructed ski resort of Verbier (Bagnes municipality) as a case example.

Critical analysis of a priori BHP design

SIA Code 384/6 code requires ensuring a life cycle for BHP of at least 50 years. A mapping of known projects across the Val de Bagnes territory has therefore been conducted (***Figure 4***). Based on available data, typical expected lithological columns were defined to help characterise geological heterogeneity within three main sectors assumed to have contrasting ground thermal response (***Figures 4 and 5***).

Thermal parameters are assessed according to the values tabulated in the SIA 384/6

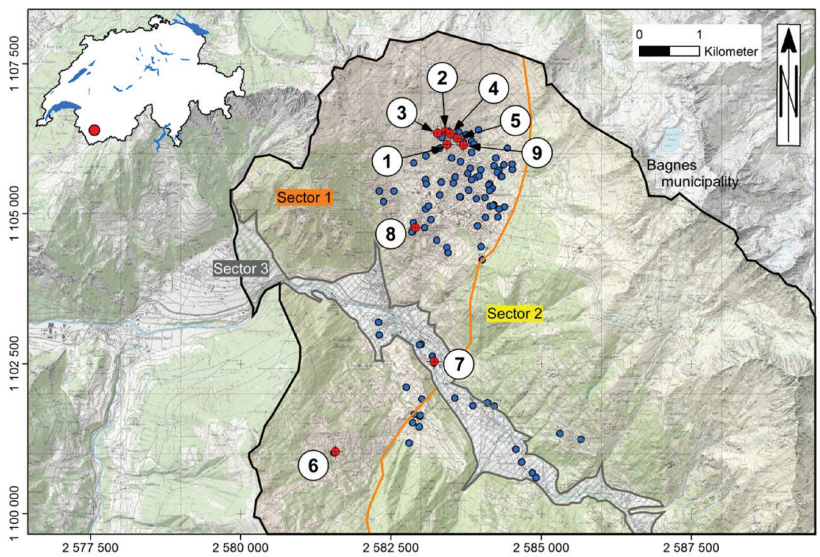
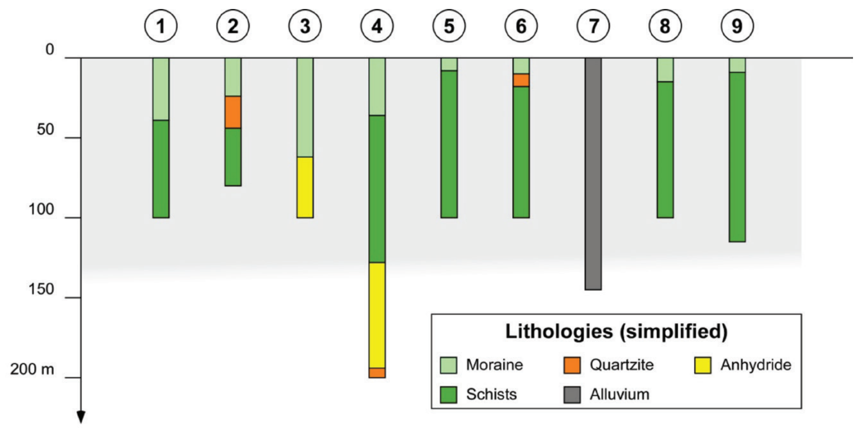


Figure 4: Bagnes municipality (reproduced with authorisation of swisstopo nr. JA100035): localisation of known BHPs (blue dots) and subdivision of the territory based on geological characteristics. Sector 1: predominance of shale (flysch, carbonaceous shale), partially covered by Quaternary deposits; Sector 2: crystalline rocks (mainly quartzite or gneiss), partially covered by Quaternary deposits; Sector 3: Quaternary glacial and fluviatile deposits (alluvium). BHP projects where a TRT could be performed in the framework of project ThermoProVal are highlighted in red. Indicative numbers refer to selected projects for which a simplified lithological columns and thermal conductivities are given in ***Figure 5.*** *The majority of BHP data are clustered around the village of Verbier in the northern part of sector 1. Please note that currently no TRT data is available for sector 2.*



Thermal conductivity (W/mK)

	1	2	3	4	5	6	7	8	9
Calculated	1.9	2.7	1.7	1.8	1.9	1.9	1.9	1.9	1.9
Measured	4.2	3.0	2.3	3.6	4.2	3.8	3.0	3.3	4.0

Figure 5: Simplified lithological columns for 9 BHPs realised on the territory of the municipality of Bagnes as depicted in ***Figure 4.*** *For each project, the* a priori *calculated thermal conductivity (derived from SIA 384/6 codes) is compared with the a posteriori calculated thermal conductivity (based on TRT results). This synthesis for various BHP analysed within the ThermoProVal project indicates a discrepancy of about 30% between theoretical and real ground thermal parameters.*

codes. Based on single values, a theoretical thermal conductivity along the entire borehole can be calculated. As can be seen in *Figure 4*, the density of available geological data in the case of Bagnes is quite disparate. This makes it currently difficult to assess the thermal potential of each geological sector with the same level of accuracy. The ski resort of Verbier (Northern part of sector 1 in *Figure 4*) can be predicted with better confidence.

Confronting a priori design with real ground conditions

In situ thermal response tests (TRT) (Gehlin, 2002; Energie Schweiz, 2015) on selected BHP projects under construction provide a mean to *a posteriori* compare BHP designs with in situ measured thermal conductivity along the entire borehole length. In the ThermoProVal project, TRT are performed about 10 days after the installation of the BHP by the drilling company; the delay is in order to avoid effects of exothermal reaction induced by grouting. TRT duration is about 3 days.

To help assess groundwater flow paths and conflicting situations along the borehole length, thermal profiles are made before and after the completion of a TRT (***Figure 6***). Such information is pivotal to assess the quality of the drilling execution and the quality of the grouting operations. Volumes of injected bentonite-cement mixtures have to be cautiously documented by the drilling company to allow for a critical comparison with the TRT interpretation by the geologist.

Case by case interpretation of BHP performance

The comparison of *a priori* (theoretical) parameters with *a posteriori* (measured) parameters allows better anticipation of the expected short and long-term behaviour of BHPs. Any data provided by the drilling company and – if available – by the geologist supervising the project are essential in this context, and should be collected and analysed properly by those responsible for any BHP project.

With a multiplication of individual projects on an already densely constructed area, neighbouring BHPs can negatively interact over time. With heterogeneous geological conditions that can significantly affect ground thermal response, performance bias can very easily be introduced, increasing the risk of conflicts with concurrent BHP or accelerating depletion of the geothermal resource (***Figure 3B***).

Surprisingly, it has proven difficult to convince architects and engineers responsible for individual BHP projects to engage in critical design analysis – even in the framework of Project ThermoProVal, which gave them an opportunity to carry out a TRT without additional costs.

This challenge would have therefore to be directly addressed by the different authorities in charge (construction, energy and environmental protection). Within the

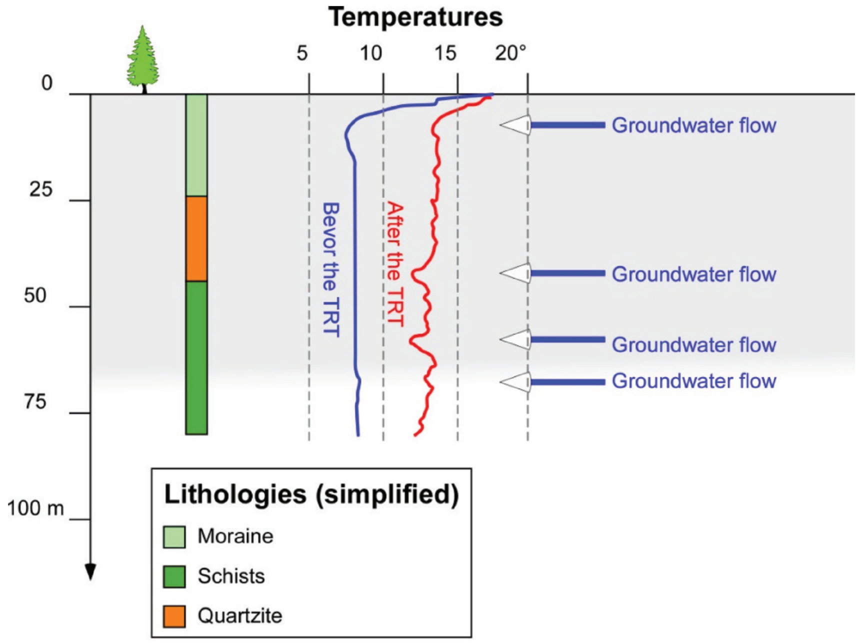


*Figure 6: Example of thermal profiles realised as part of TRT, illustrating the presence of groundwater flows (case no. 2 in **Figures 4 and 5**). Based on the available borehole report, data are sparse in terms of groundwater characterisation (flow rate, temperature, chemistry, etc.). The geological information system of Canton Valais should be dedicated in the future to allow access to such information at an early stage of the feasibility assessment for new BHP projects.*

ThermoProVal project, it is accordingly proposed to monitor a set of selected BHP projects representative of the geological sectors depicted on ***Figure 4*** in order to progressively gain knowledge on the seasonal variation in ground thermal response and to help promote and optimise resource management at the local to regional scale through effective and binding recommendations.

Application of geological knowledge: recommendations for BHP in alpine geological settings

Project ThermoProVal is conducted on the Bagnes territory of Canton Valais and takes the ski resort of Verbier as a case example to perform a critical analysis of the development of BHP in alpine geological settings. The observations made in this context are representative of other Swiss alpine municipalities facing similar development trends, both in terms of construction and shallow geothermal energy consumption. They confirm that there is a high level of uncertainty prevailing during the design of BHP projects. In the case of Verbier, ground thermal parameters based on Swiss codes and used for the design of BHPs are generally significantly underestimated by about 30 per cent (***Figure 5***). As a consequence, the length and/or number of BHPs – and therefore the costs of installation – are overestimated by the same amount.

This discrepancy is a direct result of (sub)-horizontal groundwater flows that are easily evidenced by means of the thermal profiles carried out as part of TRT, but rarely taken into account by the geologists during the design stage – and surprisingly rarely pointed out by the drilling companies, likely because they are subject to severe financial and time constraints. The existence of these localised groundwater flows, part of the hydrogeological systems supplementing drinking water resources, often go together with abnormal high grout consumption reported by the drilling companies, and signal the likely presence of overbreaks and grout washouts. In such cases, optimal thermal contact between the BHP and the soil is difficult to ensure, especially in the long run. Some thermal profiles even demonstrate the existence of vertical groundwater flows, indicating a real risk of interconnecting superimposed aquifers. This situation might lead at depth to progressive contamination of drinking water resources and clearly contravenes the Swiss Federal Water Protection Ordinance.

Facing suboptimal practices, one of the main motivations to initiate Project ThermoProVal was therefore to demonstrate that the sound, performance-oriented planning of BHP could be relatively easily addressed if closer collaboration between geologists (evaluation and projection of in situ conditions), engineers (BHP design and requirements) and drilling companies (correct execution of BHP boreholes) could be ensured.

In the case of BHP, local but also regional hydrogeological conditions largely control thermal ground parameters but short- and long-term effects are often difficult to anticipate, because the influence of groundwater flow paths on the effective performance of the geothermal installation is unknown. Long-term monitoring – for instance as suggested in ThermoProVal by equipping selected boreholes with fibre optics and making regular thermal profiles – could provide an interesting mean with this respect. Unnoticed groundwater flows represent also a huge challenge for drilling companies, because of the aforementioned problems of grouting, instability or interconnecting aquifers. Here again, access to better initial geological input can massively help reduce potential risks and define protective measures for drilling operations. For instance, the systematic use of a geotextile wrap in order to avoid grout washouts could be a simple and low-price solution, if washout is anticipated.

Based on these considerations, availability maps for geothermal boreholes can be improved by adding information accounting for groundwater occurrence at depth in order to lower the level of uncertainty. In the case of Bagnes, zones of *"possible groundwater flows"* (for highly fractured and permeable rocks), *"probable groundwater flows"* (near boreholes that show the presence of water) and *"confirmed groundwater flows"* (in or close to groundwater protection zones) are currently being discussed. Because feasibility studies in alpine geological settings are still very often confronted with a substantial lack of initial information about geological and hydrogeological conditions, authorities have a key role to play in order to promote a geological information system that would be accessible to professionals and where integrated data from previous BHP projects could be consulted. This is relevant not only for heating engineers but also for drilling companies.

With this in mind, Project ThermoProVal wishes to establish applicable guidelines for drilling operations in regions with a partly unknown and highly heterogeneous geology. In order to ensure resource management in the long-term, one of the biggest challenges remaining is the need to facilitate communication between the different protagonists involved at the administrative and practical levels. It still seems therefore quite fair to remind all those involved that correctly executed projects not only lead to longer-term efficiency of BHP but also to improved protection of public resources, both from an energetic and environmental perspective.

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