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Geothermal Potential of Shallow Aquifers: Decision-Aid Tool for Heat-Pump Installation

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ABSTRACT

The BRGM aims to give valid data about the geothermal potential to the entrepreneurs, engineers and the individuals to help them in their energetic choice to invest in the execution of a geothermal project involving geothermal heat pumps.

Thus, the BRGM carried out regional inventories based on the available data on the characteristics of the shallow aquifers (depth, thickness, transmissivity, chemical quality). Then, the maps of the geothermal productivity of these aquifers have been drawn using a G.I.S..

So, it is possible for everybody to obtain the characteristics of each of the aquifers placed in every point of the territory covered by the regional G.I.S.: projected flow rate, depth of drilling, temperature.

These maps are currently available for five regions and two departments and the different actors of the geothermal network have access to them through the internet website Geothermie-Perspective.

Different methods have been used for the first three inventories due to the highly scattered data available for the aquifer on site. None of these methods have been a priori chosen as nobody knew which one would have been the best one.

These methods will be presented within the framework of the WGC2010 and the choice of the finally selected method, which depends on the quality and on the quantity of data which we can arrange in tired databases of the BRGM, will be discussed.

1. INTRODUCTION

Within the context of developing renewable energies in France, BRGM is offering a decision-aid tool for evaluating the very low geothermal energy exploitability¹ of aquifers; one talks about the geothermal potential of shallow aquifers.

The tool is based on an atlas of groundwater resources suitable for the development of very low geothermal energy between the surface and 100 m depth. The atlas is an on-line Geographic Information System (SIG) accessible via the ADEME and BRGM Internet site specific to geothermics: www.geothermie-perspectives.fr ;

The aim is to provide access to the geothermal potential maps for the general public, contractors (consulting firms, architects), contracting authorities, etc., so that they can consider a geothermal solution among their energy options.

The creation of this tool is on a region by region basis because the disparity of the data available in each region does not enable the adoption of a single approach to mapping the geothermal potential. A methodological harmonization is, however, proposed so that the final documents are comparable at the national level.

2. CURRENT PROGRESS

Currently, five regional atlases have been completed and are available on line, five are in preparation and ten will be produced in 2010-2011, before regional geothermal development schemes are set up in each of France's regions.

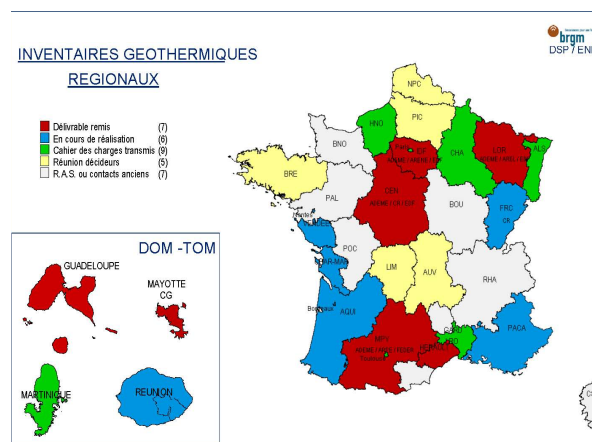


Figure 1: Progress of the regional geothermal atlases of France on 31 October 2009

The completed atlases are accessible on line via the site <http://www.geothermie-perspectives.fr/>

This consultation tool enables one to obtain information that is useful for analysing the feasibility of projects for producing very low geothermal energy from an aquifer:

- local geology: typical geological sections;
- data relative to local aquifer development (depth of access to the groundwater resource, exploitable yield);
- quality of the water resource (temperature, chloride content, salinity, corrosive or encrusting character, iron content, etc.).

The provided information is of an indicative nature, which should be sufficient for orienting a heat-pump project, but the exact determination of the resource characteristics requires a specific study.

¹ Energy solution based on heat pump

The maps, at a scale of 1:50,000, are based on a regionalization of the characteristic parameters and their degree of accuracy is acceptable at the regional scale, but not at project scale which requires a detailed analysis of the local aquifer potential.

The information for each region can be accessed from a map or from the name of the commune of interest to the end-user.

The following screenshots (in French) give examples of the information provided.

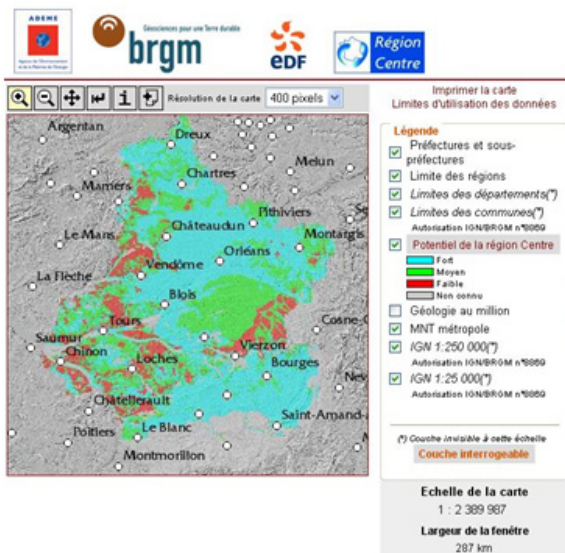


Figure 2: Window for queries from the regional map

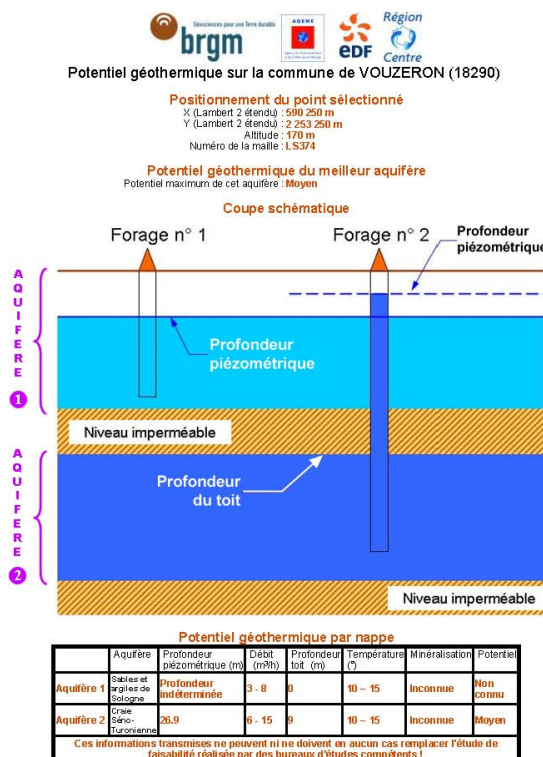


Figure 3: Information sheet provided for a given sector (standard hydrogeological section below the selected point and characteristic discharge-depth of the resource)

3. ATLAS DESIGN: PRINCIPLE AND METHODS

3.1 General Design Principle

3.1.1 General Methodology

The general design principle of the atlas is built on a method of index mapping with criterion weighting. The method is based on a combination of various parameter (or criterion) maps used for assessing a regional property (here, the geothermal potential of the aquifers) by assigning a numerical index (or note) to each parameter. Combining the maps is done by means of multicriteria processing software (GIS); it enables the relative consideration of each criterion influencing the general potential of an aquifer.

The difficulty in implementing such a method lies primarily in the choice of criteria, their notation and their assigned weighting.

3.1.2 Geothermal Potentiality Criteria

Four criteria are proposed for considering the very low geothermal energy potential of France's shallow aquifers:

- Productivity of the aquifer or exploitable yield;
- Temperature of the resource;
- Depth of access to the resource;
- Quality of the resource.

The first two are representative of the aquifer's production yield for a geothermal use; the other two are known as "economic" because they directly impact a project's capital and running costs.

Their simultaneous analysis allows one to determine the interest of a geothermal operation.

3.1.3 Mapping the Geothermal Potential

The atlas of geothermal potential is made up of set of thematic maps and a synoptic map of each shallow aquifer of regional interest, as well as a general synthetic map of the regional geothermal potential which corresponds to a compilation of the best potentialities per aquifer.

Its construction involves various steps:

- Collection of data relative to each criterion:

This step includes the collection of both printed data from the literature and digital data from different databases;

- Criterion classification and indexing —Valorization in the form of single criterion maps:

Gathering of the data into classes and indexing the classes: the spatial variability of the geothermal potential is characterized by dividing the criteria into classes. Each class is then assigned an index representative of the associated geothermal potential (low note for the poorest potential, high note for the best potential). The indices vary from 1 to 5 from the geothermally least favorable to most favorable situation; these are given in Table 1.

Mapping each criterion: so-called "single criterion" maps are produced to account for the aquifer's potential with respect to each criterion; they show the criterion's classification and indexing.

- Depth of access to the groundwater resource map;
- Aquifer productivity map (exploitable yield map);
- Groundwater temperature map;
- Groundwater quality map.

Table 1. Classification and Indexing of the Geothermal Potential Criteria: Evaluation of the "Aquifer."

Geothermal potential criterion	Criterion classification	Indexing
Aquifer productivity (Q)	< 5 m ³ /h	1
	5 - 10 m ³ /h	2
	10 - 50 m ³ /h	3
	50 - 100 m ³ /h	4
	Q > 100 m ³ /h	5
Resource temperature (T)	< 10 C	2
	10 - 15 C	5
	> 15°C	3
Depth of access to the resource (D)	< 5 m	1
	5 - 15 m	2
	15 m - 30 m	3
	30 m -100 m	4
	> 100 m	5

- **Multicriteria analysis and calculation of the geothermal potential of each aquifer:**

- Weighting the criteria: some criteria have a stronger influence than others on the geothermal potential of the aquifer. To account for this irrefutable fact, each criterion is weighted according to its importance in terms of the geothermal potential (high order for the most sensitive criteria, low order for the less significant criteria);

The attribution of each criterion's weighting takes into consideration a ranking of the criteria and the abundance and precision of the source data.

- Mapping the geothermal potential by aquifer: this map is obtained by the weighted combination of the single-criterion maps. An index of geothermal potential is calculated by weighted addition of the single criterion potentiality notes assigned to each mesh of the calculation grid. A potentiality index distribution map is then drawn up; this corresponds to the geothermal potential map of the aquifer.

- **Compilation of the regional geothermal potential map showing the areas favourable for installing groundwater heat pumps.**

The compiled maps are all georeferenced and gathered into a GIS.

The diagram of Figure 4 summarizes the proposed mapping methodology for the regional geothermal potential.

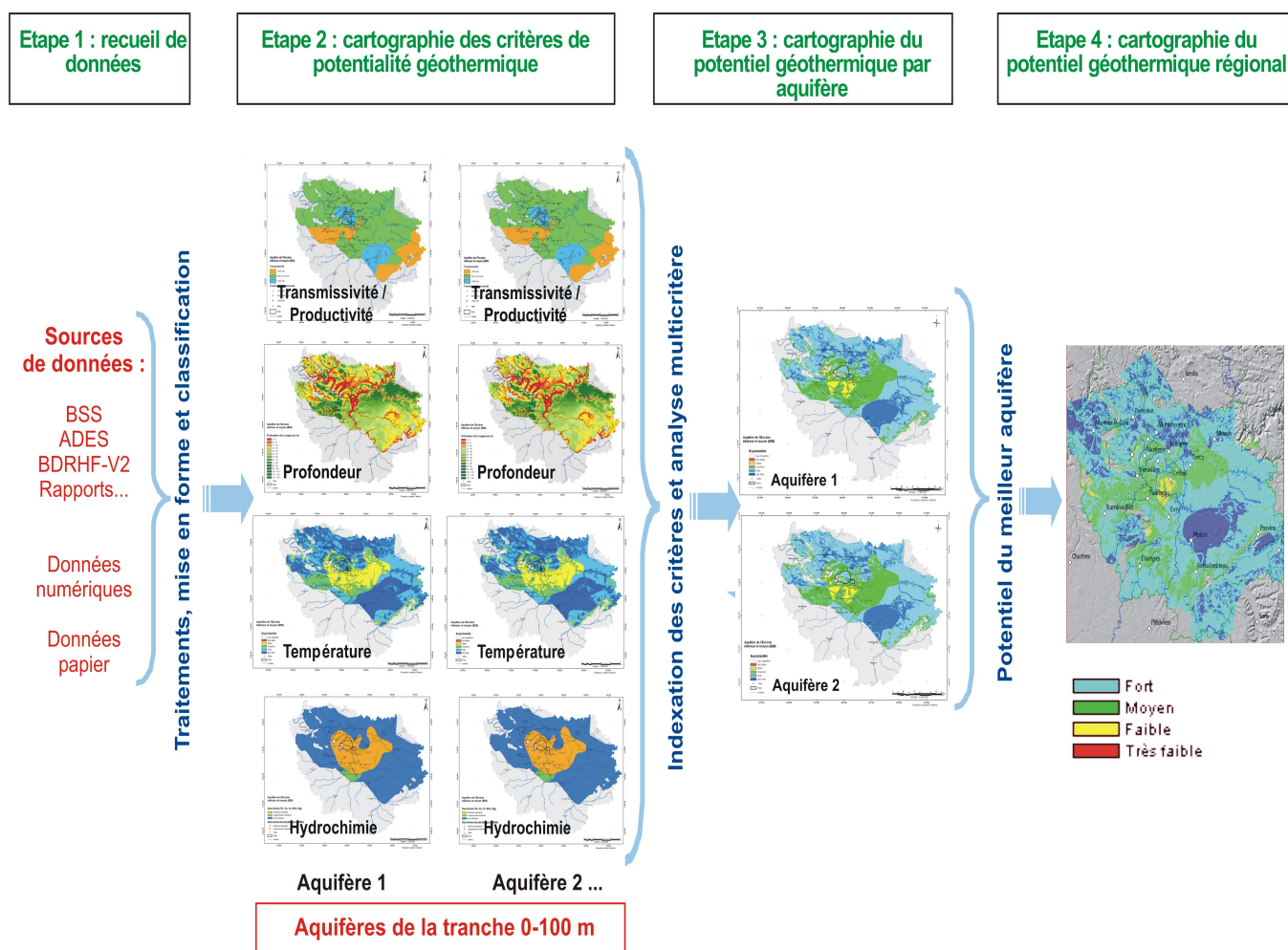


Figure 4: Preparation of regional geothermal potential maps

It is important to note that drawing up the atlas is based above all on the data collection and that the quality of the final map is directly related to the quality and density of the available data. This first data-collection step is thus very important; it enables one to decide the cartographic options to be implemented during the following steps.

The data sources generally used are:

- BSS: the Subsurface Data Bank which provides data on the geometry and nature of the geological formations, on the aquifer piezometry and productivity, and on the groundwater's physical chemistry;
- ADES: the national Groundwater Data Access Bank which provides additional physical chemistry and piezometric data;
- BD-RHFV2: the French Hydrogeological Reference Frame Database which provides the contours of France's hydrogeological units to 3 scales of precision (N1: national, N2: regional, and N3: local);
- Geological map at 1:50,000 scale;

- Regional hydrogeological atlases;
- Data derived from hydrodynamic models;
- Archived reports.

3.2 Criteria of Geothermal Potential, Data Sources, and Classification and Indexing

3.2.1 Aquifer Productivity

Various methods of evaluating and representing the "aquifer productivity" criterion (Q) were developed during the compilation of the first atlases. Three of these are shown in Figure 5 to 7.

They have their advantages and disadvantages and the advisability of using one or the other of the methods cannot a priori be defined; they must be analysed on a regional level. It depends primarily on the nature and availability (quantity and regional distribution) of the source data. However, recommendations can be made, which is the subject of the following paragraphs.

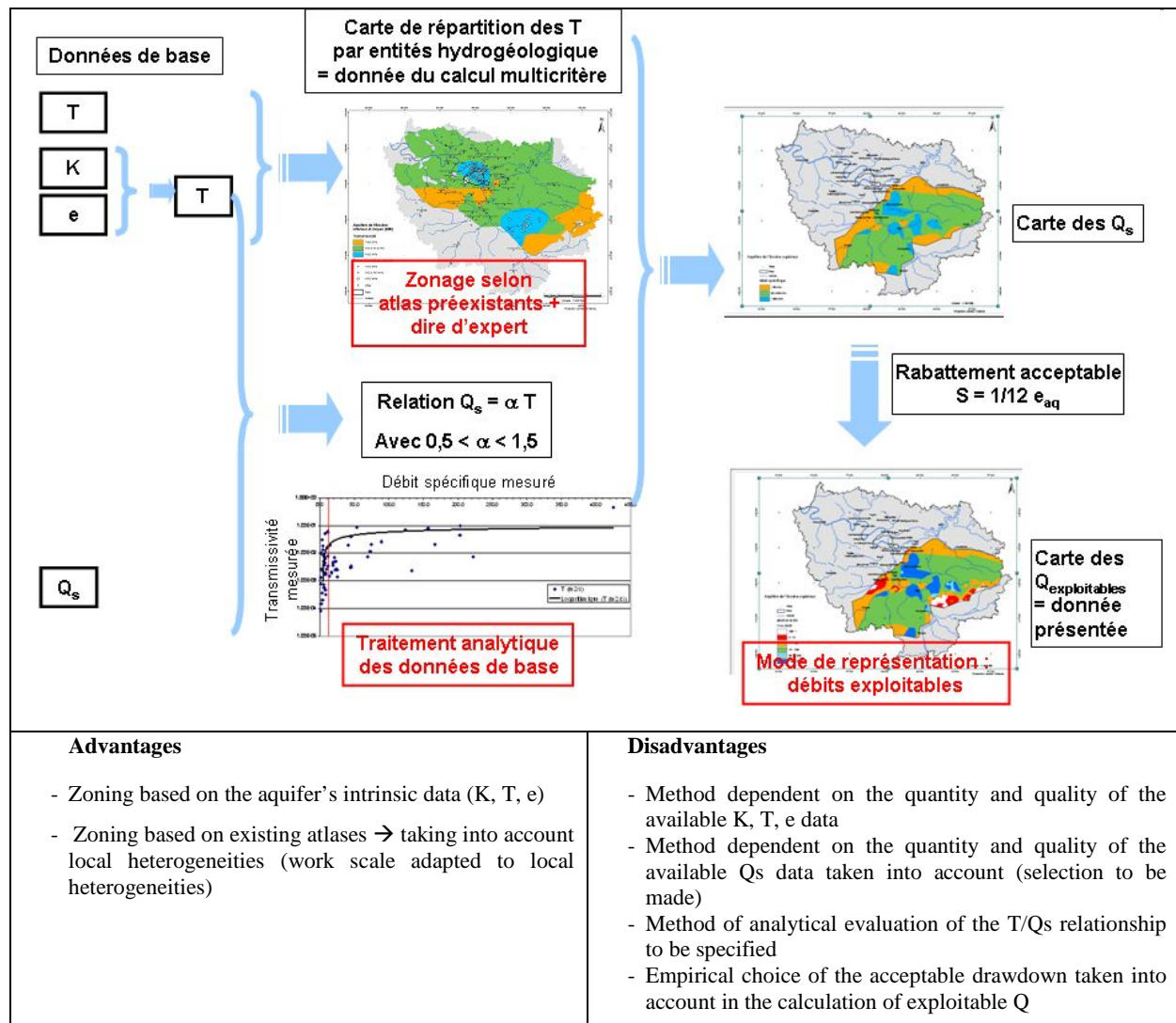


Figure 5: Preparation of regional geothermal potential maps

a - Data sources

The aquifer productivity corresponds to the evaluation of the extractable water resource of the aquifer reservoir. The source data used to evaluate this are:

- **Transmissivity** (noted T) and permeability (noted K): parameters intrinsic to the aquifer (representing its potential yield), and very representative of the resource.

The permeability data must be coupled with aquifer thickness data (e) to reconstruct the transmissivity data ($T = K \times e$).

- **Specific capacity** (noted QS - this is the ratio of the pumped discharge in a well over the level of the groundwater drawdown caused by the pumping).

This parameter is representative of the aquifer properties, and also of the technical properties of the catchworks. It is thus less representative of the resource than the transmissivity, but the data making it possible to map it are generally more numerous.

The source data are all the local discharge/drawdown measurements available in the BSS and not necessarily associated with complete pumping tests.

- **Well yield:** this parameter corresponds to the exploitable yield, but is above all representative of the technical properties of the catchworks and the needs associated with the use of the resource. It is not very representative of the actual production capacity of the resource.

It is recommended that:

- priority is given to taking the aquifer's intrinsic data (T, K, e) into account.

- using the specific capacity data used in the event that intrinsic data are unavailable; these data must be sorted so as to select the most representative of the aquifers.

- as a last resort, should both intrinsic data and Q_S be unavailable, taking the production yield data into account if there is a very large number of them and if they are regionally well distributed. The source data come from test-pumping reports (commonly archived in the BSS).

The density of these intrinsic data is commonly low, which makes it difficult to exploit them for regional mapping.

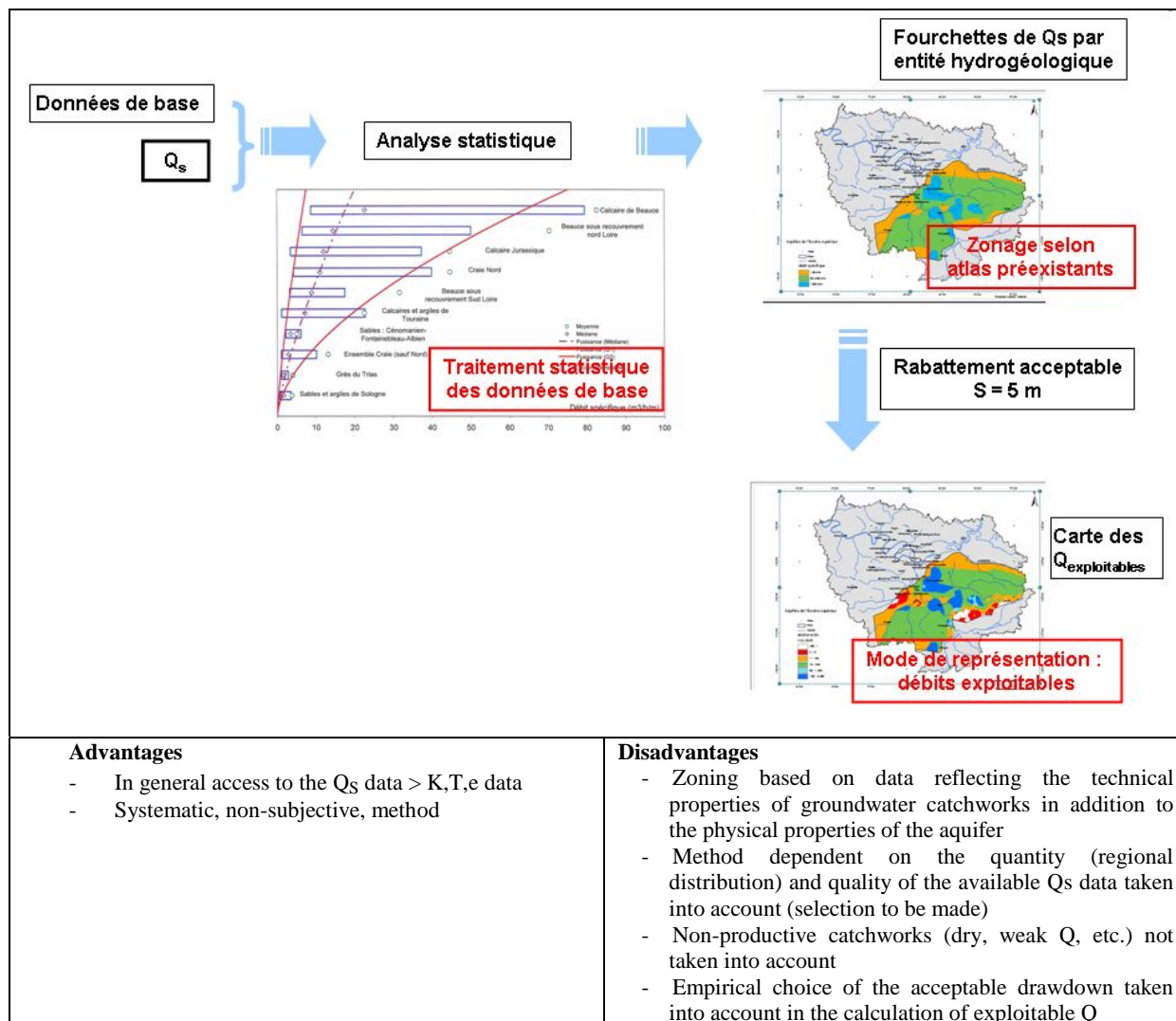


Figure 6: Evaluation of the "aquifer productivity" criterion based on statistical analysis of specific capacities and a pre-existing zoning

b - Mode of representation: transition from source data to exploitable yields

As a general rule, the project partners and future users of the regional geothermal potential atlases would like for the aquifer productivity, regardless of the source data used for its evaluation, to be represented as exploitable yields.

A distribution map of the potentially exploitable yields must thus be included in the regional atlases.

Its preparation involves processing productivity data and interpreting them in terms of potentially exploitable yields. Various approaches can be adopted depending on source data taken into account:

- **Transmissivity**, which can be translated into exploitable yields by looking for a link of the type $Q_S = \Delta T$ and by the equation $Q_{\text{exploit}} = Q_S \times s_{\text{acceptable}}$ for the aquifer (s = drawdown).

- **Specific capacities**, which can be translated into exploitable yields by the equation $Q_{\text{exploit}} = Q_S \times s_{\text{acceptable}}$ for the aquifer.

- **Well production yields** which can be used directly to represent the distribution of an aquifer's exploitation.

The first two methods of interpreting the source data involve defining the acceptable drawdown for the aquifers in order to standardize the method of evaluating aquifer productivity and avoid the regional disparities on this subject.

It is proposed to limit this to 1/3 of the aquifer's saturated thickness and up to a maximum of 5 m.

In addition, a method of translating the intrinsic parameters of the aquifer into exploitable yields should be developed (by the end of 2009) on the basis of what was initiated in Ile-de-France (relation $Q_S = \Delta T$ and $Q_{\text{exploit}} = Q_S \times s_{\text{acceptable}}$).

The first method is based on the aquifer's intrinsic data but breaks down into two phases during each of which approximations are introduced.

The second is based on data that are not always very representative of the aquifer characteristics, but the approximations introduced for evaluating the exploitable yields are limited.

It is thus recommended that the first method be used only if the input data are very abundant (which is rare) and well distributed, otherwise to favour the second method.

c - Zoning method

Different methods of zoning the regional productivity of aquifers have been developed on a regional level: kriging, statistical zoning, expert zoning, zoning based on existing reference frames (geological units, hydrogeological units).

As before, the choice of one or other of the methods depends primarily on the nature and availability of the source data which themselves condition the precision of the zoning and its representativeness of the regional heterogeneities.

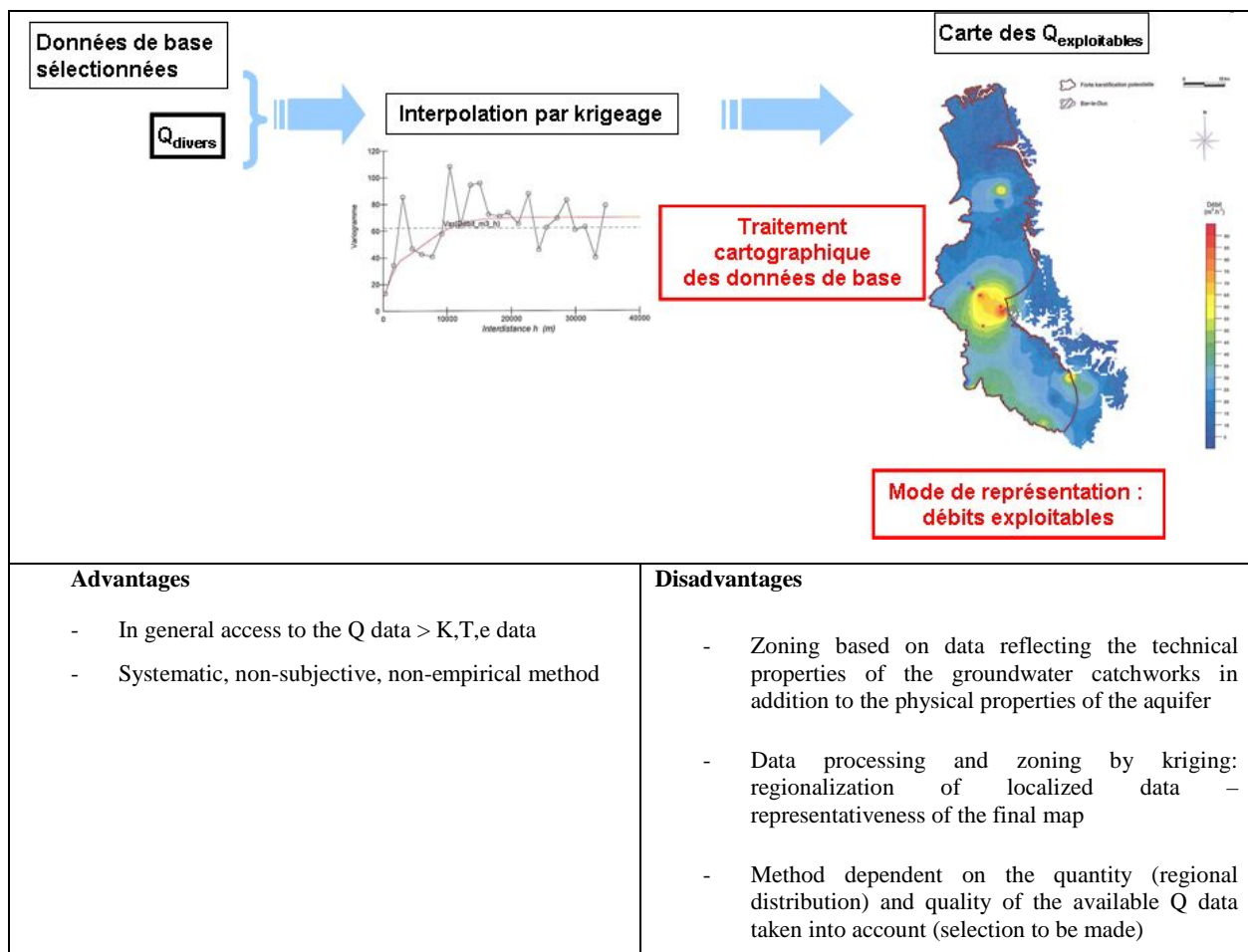


Figure 7: Evaluation of the "aquifer productivity" criterion based on interpolation by kriging the operating flow data

The following remarks are however called for:

- Zoning from pre-existing atlases allows one to take local heterogeneities into account (adapted working scale) and should always be favoured.
- The method of zoning by cartographic interpolation of specific data (kriging) does not seem the most suited for representing aquifer exploitability. However, a study of the method's sensitivity is to be carried out in 2009 which will make it possible to better determine the method's possibilities.

In every case, it is important in reports to always specify the nature of the source data used and to provide a location map of the data measurement points.

d - Mode of representation: transition from exploitable yield data to extractable capacity data

It is noted that many users would like to have maps of geothermal exploitability translated into terms of extractable capacity. This implies translating the aquifer productivity map into extractable heating-capacity maps and extractable cooling-capacity maps through the following relations:

- Heating capacity: $P = Q_{\text{exploit}} \times \Delta T \times 1.16 / (1 - 1 / \text{COP}_{\text{heat}})$
- Cooling capacity: $P = Q_{\text{exploit}} \times \Delta T \times 1.16 / (1 + 1 / \text{COP}_{\text{cold}})$

These calculations involve fixing the parameters ΔT , COP_{heat} and COP_{cold} to be taken into account.

However, there is a risk of seeing these maps used under conditions where the parameters ΔT , COP_{heat} and COP_{cold} would be very different from those used for the calculations. This would amount to misleading the users and so it is not desirable to offer such maps.

e - Classification

The following classification is proposed for the aquifer productivity criterion (Q):

- $Q < 5 \text{ m}^3/\text{h}$: high risk of production failure. The resource is regarded as feeble;
- $Q = 5 - 10 \text{ m}^3/\text{h}$: possible to consider heating individual houses;
- $Q = 10 - 50 \text{ m}^3/\text{h}$: possible to consider heating buildings of 1000 to 5000 m^2 ;
- $Q = 50 - 100 \text{ m}^3/\text{h}$: possible to consider heating buildings of 5000 to 10,000 m^2 ;
- $Q > 100 \text{ m}^3/\text{h}$: possible to consider heating large buildings.

3.2.2 Resource Temperature

a - Data sources

- Specific well measurements. Attention to the quality of the data; errors linked to the mode of temperature acquisition are possible (equilibrium between the well water and atmospheric temperature).
- Estimation according to the depth to the aquifer based on the local geothermal gradient;
- Estimation according to the altitude of the water point.

b - Classification

A classification of the resource temperature criterion (T) is proposed that is based on the evolution of the degree of efficiency of a heat pump used in heating mode according to the temperature of the resource.

- $T < 10^\circ\text{C}$: difficult to operate a heat pump in heating mode;
- $T = 10^\circ - 15^\circ\text{C}$: very favourable for operating a heat pump in heating and air-conditioning mode and for free-cooling;
- $T > 15^\circ\text{C}$: difficult to operate a heat pump in air-conditioning mode.

3.2.3 Depth of Access to the Resource

The depth of access to the resource (D) corresponds to the groundwater piezometry for a free aquifer, and to the depth of the roof of the considered aquifer for a confined aquifer.

This criterion takes into account two aspects of an aquifer's geothermal potential:

- The cost of the operation: drilling costs (directly related to well depth), equipment (pump type and power related to the discharge head) and operating costs (electricity consumption of the pump);
- The risk of piezometric overestimation caused by injecting the extracted water back into the same aquifer, which is unfavourable to the project.

a - Data sources

- Local piezometric data available in BSS, ADES, and various reports;
- Existing piezometric maps;
- Geometry of the geological formations: BSS, geological models, BDRHF-V2

b - Proposed classifications

The following classification is proposed for the depth of access to the resource criterion (D):

- $D < 5 \text{ m}$: risk of piezometric overestimation on injection unfavourable for the project;
- $D = 5 - 15 \text{ m}$: lowest cost well enabling an economic groundwater heat-pump project for an individual house;
- $D = 15 - 30 \text{ m}$: drilling costs weigh heavily on the economics of a groundwater heat-pump project for an individual house;
- $D = 30 - 100 \text{ m}$: the drilling cost can only be amortized by a high surface consumption (small apartment building or several individual houses);
- $D > 100 \text{ m}$: deep geothermal energy beyond the scope of the atlas.

3.2.4 Resource Quality

Within the context of evaluating geothermal potential, the resource quality criterion takes into account the corrosive, encrusting or plugging character of a groundwater. It plays a role in the economic assessment of a project because the typology of the materials used must be adapted to the water chemistry.

The phenomena involved are complex (chemical precipitation and solution reactions) and implicate a large range of environmental parameters that are not always available for all the aquifers (data availability is very heterogeneous from one aquifer to another and from one region to another is concerned).

The data used are the groundwater analysis data available in BSS, ADES and various reports.

A range of exploitation-constraint evaluation parameters related to the water's quality and classification is defined in the *SEQ-Eaux souterraines*² (the suggested thresholds are expert opinions based on the thermodynamics of the electrochemical equilibria and/or the literature considered as being a reference in this domain). It is proposed to retain them (when the data are available) for evaluating the constraints related to the groundwater geochemistry and likely to weigh on very low geothermal energy exploitation projects.

The parameters characterizing groundwater's capacities are: Good, mediocre, poor or unsuitable for the use by Health Pump.

a - Parameters characterizing groundwater's corrosive capacity

- Dissolved CO₂

[Dissolved CO₂] < 50 mg/l: good;
[Dissolved CO₂] = 50 - 120 mg/l: mediocre;
[Dissolved CO₂] = 120 - 200 mg/l: poor;
[Dissolved CO₂] > 200 mg/l: unsuitable

- Dissolved O₂

[Dissolved O₂] = 0 mg/l : very good;
[Dissolved O₂] < 0.1 mg/l: good;
[Dissolved O₂] = 0.1 - 4 mg/l: poor;
[Dissolved O₂] = 4 - 8 mg/l: unsuitable.

- Salinity

[NaCl] < 0.6 g/l : good;
[NaCl] = 0.6 - 1.5 g/l: mediocre use;
[NaCl] = 1.5 - 3 g/l: poor;
[NaCl] > 3 g/l: unsuitable.

- Conductivity

C < 1300 mS/cm: good;
C = 1300 - 3000 mS/cm: mediocre;
C = 3000 - 6000 mS/cm: poor;
C > 6000 mS/cm: unsuitable.

- pH

pH > 9.8: very good;
pH = 7 - 9.8: good;

pH = 6 - 7: mediocre;

pH < 6: unsuitable.

- Chlorides

[Cl⁻] < 150 mg/l: good;
[Cl⁻] = 150 - 400 mg/l: mediocre;
[Cl⁻] = 400 - 1000 mg/l: poor;
[Cl⁻] > 1000 mg/l: unsuitable.

- Sulphates

[SO₄⁻] < 250 mg/l: good;
[SO₄⁻] = 250 - 500 mg/l: mediocre;
[SO₄⁻] = 500 - 1500 mg/l: poor;
[SO₄⁻] > 1500 mg/l: unsuitable.

- Ferrobacteria

Absence: very good;

Presence: unsuitable.

- Sulphate-reducing bacteria (SRB)

Absence: very good;
SRB < 10 N/ml: good;
SRB = 10 - 100 N/ml: poor;
SRB > 100 N/ml: unsuitable.

- Sulphides

[HS⁻] < 0.1 mg/l: good;
[HS⁻] = 0.1 - 8 mg/l: acceptable;
[HS⁻] = 8 - 50 mg/l: poor;
[HS⁻] > 50 mg/l: unsuitable.

- Eh (index of the presence of iron ions and precipitates)

Eh = > -600 mV: very good;
Eh = -600 - -500 mV: mediocre;
Eh = -500 - -400 mV: poor;
Eh = < -400 mV: unsuitable.

b - Parameters characterizing groundwater's encrusting and plugging capacity

- pH

pH < 5: very good;
pH > 5: mediocre.

- Eh (index of the presence of iron ions and precipitates)

Regardless of the Eh value, if pH ≤ 3.5: very good;
If pH = 3.5 - 9.6 and Eh = > -0.166pH+1.333: very good;
If pH = 3.5 - 9.6 and Eh = < -0.166pH+1.333: mediocre;
pH > 9.6 and Eh = -750 - -250 mV: mediocre;

- Dissolved O₂

[Dissolved O₂] < 0.1mg/l: very good;
[Dissolved O₂] 0.10 - 5.5 mg/l: mediocre;
[Dissolved O₂] > 5.5 mg/l: unsuitable.

- Ferrobacteria

Absence: very goo;

² *SEQ-Eaux souterraines*: evaluation grid of groundwater suitability for various uses and functions established within the framework of an inter-water agency study with collaboration between Water Agencies, MATE and BRGM in 2001.

Presence: mediocre.

- Saturation index (depending on the complete alkalinity titration (CAT) value)

CAT < 10°f and Langelier index < 0.2: very good;

CAT < 10°f and Langelier index = 0.2 - 2: mediocre;

CAT < 10°f and Langelier index > 2: unsuitable;

CAT < 10°f and Langelier index < 0.2: very good;

CAT > 10°f and Langelier index = 0.2 - 1: mediocre;

CAT > 10°f and Langelier index > 1: unsuitable.

3.2.5 Review of the Criteria Classification and Indexing

Finally, the proposed classification for the various criteria of geothermal potentiality as well as their indexing could be based on the one hand on index about aquifer productivity, resource temperature and depth of access to the resource, characteristic that could be quantified and on the other hand on resource quality (chemical, physical, corrosive, encrusting, ...), which signify that it is possible or no to use the resource.

3.3 Evaluation of the Geothermal Potential: Choice of Multicriteria Calculation Code

After having collected the source data and compiled single criterion maps for each aquifer, a simultaneous analysis of these maps is done by automatic multicriteria computation under the GIS. This computation results in a geothermal potential map for each aquifer.

The different studies carried out in the regions shows that a significant disparity exists at the level of the method of drawing up the geothermal potential maps for the aquifers. The disparities concern the criteria taken into consideration and the multicriteria calculation code that is used (i.e. on the weighting given to the criteria).

In order to homogenize the content of the regional atlases, a single method is proposed that could be generalized.

This method comes down to evaluating the geothermal potential merely on the basis of the productivity, temperature and access depth criteria and supplementing this with a map of constraints associated with the quality criterion and providing it, as an indication only, wherever these constraints exist and where the data are sufficiently dense to be characterized.

The multicriteria calculation code to be applied is:

Geothermal potential = 2x Aquifer productivity + 1x Temperature + 1x Access depth

3.4 Representation: Choice of Map Compilation Scale

The grid for the criteria mapping and multicriteria calculation is 500 m (which corresponds to a 1:50,000-scale precision).

Despite that, and because of the various approximations involved (approximations associated with the criteria zoning and productivity calculations), the information map scale for the end-users should be no larger than 1:100,000 and should possibly be limited to commune scale.

CONCLUSION

A methodology is proposed for evaluating the very low geothermal energy potential of shallow aquifers in the 0–100 m depth interval. Its field of application concerns the energy development of aquifers associated with the use of heat pumps for heating purposes.

It is based on index mapping with a weighting of geothermal potential criteria.

The selected criteria are aquifer productivity, resource temperature, access depth to the resource and resource quality.

Recommendations are given concerning the classification to adopt for each criterion and the calculation code to be used for the geothermal potential per aquifer.

The resource quality criterion is not integrated into the calculation because of the frequent unavailability of data enabling one to qualify it. It is recommended to provide only characteristic elements (a list of guide parameters is given) of the constraints related to the groundwater geochemistry when the existence of these constraints is proven, because they are likely to weigh on geothermal development projects.

The proposed method is still very theoretical and local adaptations should be retained in response to particular problems.

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