# Development of a Decision Support System for the geothermal reservoir of the North Alpine Foreland Basin (NAFB) in Bavaria, Germany

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## ABSTRACT

Especially in hot spot areas with coinciding high heat demand and geothermal potential, such as the greater Munich area, the installation of many more geothermal plants is planned to maximise the utilization of the hydrothermal reservoir and decarbonise the heating sector. This increases the need for sustainable reservoir management and for an improved and standardised assessment of the potentials and risks.

In order to meet these needs, the Bavarian State Ministry of Economic Affairs funds the development of a tool for the holistic assessment of the deep geothermal reservoir of the North Alpine Foreland Basin (NAFB) use via the project "BeM-TG".

This project aims to implement a decision support system (DSS), providing the best possible information for evaluating potential geothermal projects in Bavaria by providing valid statements specifically adapted to different stakeholder needs. It will support the decision-making process of authorities for permits, provide planners with all available relevant data and point out potentials and risks to all interested parties.

The aim is to provide the relevant parameters for planning together with an uncertainty evaluation for sustainable reservoir management, including seismic risks, drilling risks, interference risks, hydrochemistry, as well as production and temperature prognosis at all locations in the NAFB. To reach these assessment goals, we developed a concept for the DSS and created a data matrix identifying which specific data is needed and available to support decision-making. Further work is necessary to determine the uncertainty of the database; this includes evaluating the uncertainty of the base parameters by quality and the uncertainties of all the following processing steps, as well as the spatial uncertainty in the NAFB caused by limited data availability.

This uncertainty assessment is included in the conceptualisation of each prognosis module of the DSS. The concepts show possible processing steps to create the needed output data and determine in which cases existing data can provide sufficient information or if further concepts need to be developed to fill data gaps. The present study focuses on the DSS modules regarding production prognosis and the prognosis of the interference between geothermal plants, while further assessment objectives are evaluated by our project partners.

It is shown that despite the currently limited database in the NAFB, a valid prognosis of interference and production including uncertainty estimation can still be made based on the available data or regional models.

## 1. INTRODUCTION

Energy consumption for heating and cooling accounts with a share of 56% for most of total final energy consumption in Germany, with space heating and hot water accounting for 33.5% of heat and cooling demand across all sectors (Bracke et al. 2022; UBA 2024). The most important heat sources are still mineral oil and natural gases (Bracke et al. 2022; Keim et al. 2020). The utilization of deep geothermal energy for heating is one of the most environmentally friendly forms of renewable energy, with the potential to significantly reduce CO2 emissions.

In the southern region of Bavaria, there are particularly favourable conditions for the deployment of deep geothermal energy. Over the past 25 years, 26 geothermal systems have been successfully implemented in this area. The calculated technical potential for deep geothermal energy corresponds to 40% (7655 MWth) of Bavaria's heat requirements (Keim et al. 2020). In order to fully utilize this potential, it would be necessary to construct about 500 production and injection wells (Keim et al. 2020).

As part of the heat transition, Bavaria continues to expand its use of deep geothermal energy, aiming to utilize the full potential of the hydrothermal reservoir. The need to assess the potential and risks, as well as the uncertainties associated with them, increases as deep geothermal exploration progresses. As well, there is also an increase in the efforts for the permitting process for the authorities and an increase in the need for the supply of geological data as a basis for planning. The geothermal reservoir will be explored to a greater extent in the future, increasing the chance of geothermal systems interacting with each other. Furthermore, it is crucial for production and operational safety of deep geothermal plants to ensure the sustainable management of the whole hydrothermal reservoir.

The “BeM-TG” project (assessment model deep geothermal energy in Bavaria) aims to develop a decision support system (DSS) for the Bavarian part of the Northern Alpine Foreland Basin (NAFB) to make valid prognoses about:

- the production of a deep geothermal well,
- the interference between geothermal plants,
- the drilling risk
- and the risk of microseismicity.

The tool is intended to standardize and simplify the authorities' approval practices, to provide planners with all available and relevant information, and to inform interested municipalities about potentials and risks. The focus of this paper is thereby the overall conceptual development of the DSS and the production and interference prognosis.

## 2. DATABASE FOR GEOTHERMAL EXPLORATION IN THE STUDY AREA

The project area is the Bavarian part of the NAFB (Figure 1). The available data for geothermal project planning in the NAFB is unevenly distributed in the area. Nevertheless, a lot of geothermal projects are planned in future all over the NAFB, also in the less explored areas, so it is necessary to provide best knowledge about opportunities and risks especially for this projects. While there are a lot of geothermal wells in the greater area of Munich, in all the other regions, there are very few or no wells drilled from which to gain information. Furthermore, even when data exists for all drilled wells, it is not yet available to everyone. The merging and evaluation of all available base data in the area provides the basis for a regional geological and numerical model. The data quality will be checked as well as the data will be analysed with respect to the addressed fields and developed concepts. Hence pre-analysed data will be available and the DSS aims to connect these data and its uncertainties to the most probable prognosis.

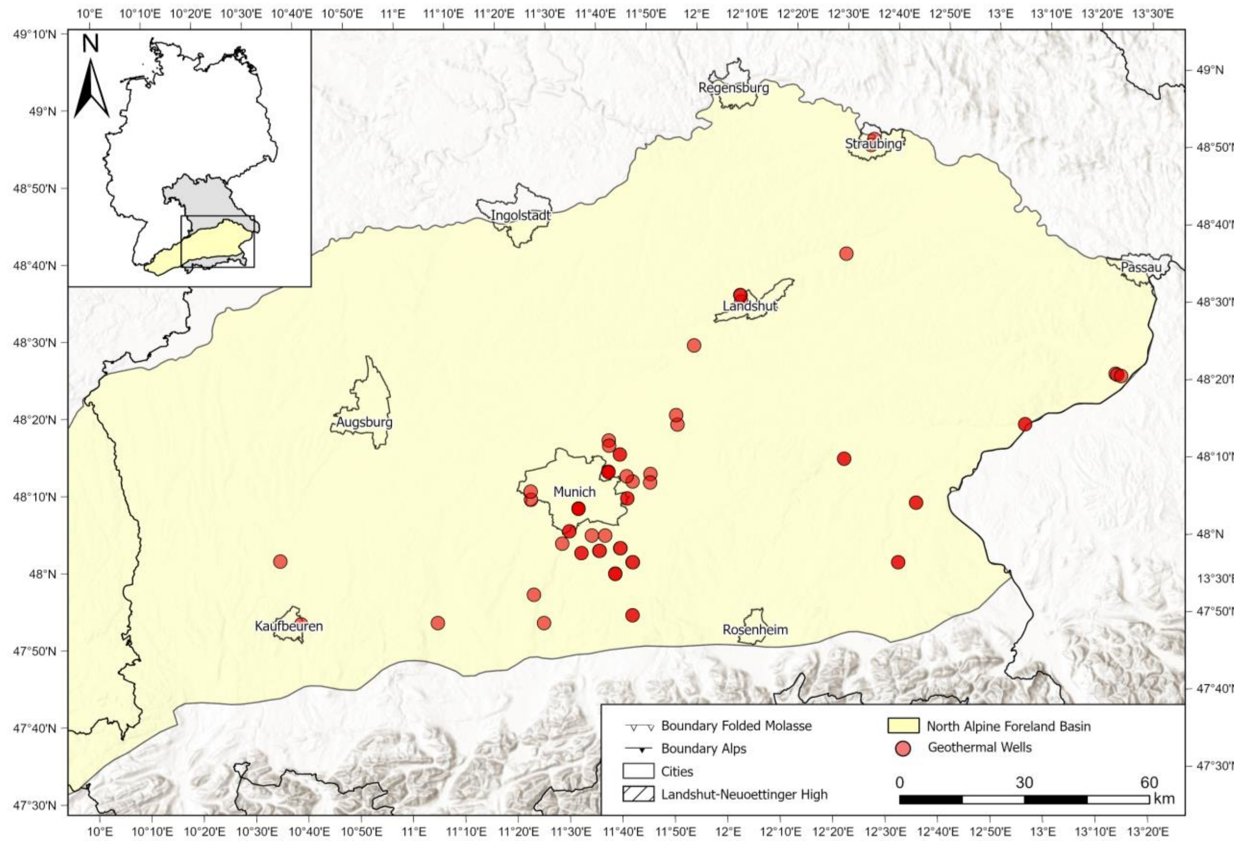


**Figure 1: Project area of the DSS in the NAFB in Bavaria with geothermal well locations.**

### 2.1 Database Production Prognosis

As commonly known, the thermal output of a deep hydrothermal well depends on the quality of the hydrothermal reservoir, mainly characterized by the quantity of the reservoir, which depends on the productive flow rate and the temperature of the produced water (Schulz and Thomas 2007), and the chemical composition of the thermal water (Stober and Bucher 2012). The thermal output (*P*) of a hydrothermal doublet can be calculated with the following equation (Stober and Bucher 2012):

$$P = Q*(T_P - T_I) * \rho_F * c_F \qquad [1]$$

The key parameters for the estimation of the thermal output are production rate (Q), production temperature ($T_P$) and injection temperature ($T_I$). The production temperature ($T_P$) thereby depends crucially on the temperature of the reservoir ($T_{Res}$), which depends on the depth of the reservoir ($D_{Res}$) and as well on the depth of the actual flow zones (hydraulic active zones) in the reservoir ($D_{Flow}$). The production rate (Q) depends on various interconnected reservoir parameters. The Porosity (φ) of the aquifer, Reservoir permeability (K) (matrix, fault and karst permeability), Reservoir Thickness (M), Transmissibility (Tr), Reservoir Pressure ($P_{Res}$), Fault surfaces. Fluid density ($\rho_F$) and specific heat capacity ($c_F$) are pressure and temperature-dependent variables, which also depend on the total solution content and gas content of the thermal water. All relevant input data for production prognosis which must be assessed and evaluated in the DSS are listed in Table 1, showing the interconnection of the Parameters. or tables on certain pages or at the end of the paper.

**Table 1: Relevant input data for production prognosis derived from equation (1). Thermal or electrical output from direct measurements (yellow), production rate (direct measurements and related parameters) (red), production temperature (direct measurements and related parameters) (blue), geological parameters (orange), hydro chemical parameters (green) (Ernst et al. in prep.).**

| Objective | Needed output | Information input | |
|---|---|---|---|
| Production prognosis | Thermal output (Q ~ Φ, M, K, Tr, $P_{res}$) (K ~ faults, $D_{Res}$) ($T_P$ ~ $T_{Res}$, $D_{Res}$, $D_{Flow}$, Q) | **Pth/el direct** | |
| | | **Production rate Q** | |
| | | **Production temperature $T_P$** | |
| | | $T_P$ | Reservoir temperature $T_{Res}$ (undisturbed natural T field) |
| | | | Injection temperature $T_I$ |
| | | | Depth of hydraulic active zones $D_{Flow}$ |
| | | | Depth top reservoir $D_{Res}$ (Horizon surfaces) |
| | | Q | Porosity Φ |
| | | | Formation thickness **M** |
| | | | Reservoir pressure $P_{res}$ |
| | | | Reservoir permeability **K** (Matrix + fault + karst permeability) |
| | | | Transmissibility **Tr** (Thickness aquifer * permeability) |
| | | | Fault surfaces |
| | | **Thermal capacity fluid c** | |
| | | **Density of thermal fluid ρ** | |

### 2.2 Database Interference Prognosis

For the interference between geothermal sites or geothermal permitting areas the change of temperature and variation of pressure are relevant, which are controlled by the thermal and hydraulic characteristics of the reservoir. This means they are highly dependent on the level of knowledge of the geometry of the subsurface and the quantity and quality of measured, calculated or collected hydraulic, thermal, hydro chemical and mechanical parameters (Stober and Bucher 2012).

The reservoir temperature ($T_{Res}$) in the undisturbed natural temperature field and the injection temperature ($T_I$) thereby define the change of temperature ($\Delta T$). For the change of temperature, it is important to understand the formation of a cold plume at the injection well. The key thermophysical parameter necessary to determine heat flow is the thermal diffusivity ($\alpha$) (Labus et al. 2023).

The change of pressure is defined by the production rate (Q) as well as by the injection rate ($Q_I$). Furthermore, the flow in the surrounding underground can be determined by information about the flow well regime and permeability (K). Geological factors influencing the change of pressure are the depth of the hydraulic flows as well as information about faults. In Table 2 all relevant input data for production prognosis are listed, showing the interconnection of the Parameters

**Table 2: Relevant input data for interference prognosis. Temperature related data (blue), production and injection rate related parameters (red), geological parameters (orange), pressure related parameters (purple), hydro chemical parameters (green) (Ernst et al. in prep.).**

| Objective | Needed Output | Information Input |
|---|---|---|
| **Interference between geothermal sites** | **Change of temperature $\Delta T$** | Reservoir Temperature $\mathbf{T_{Res}}$ (Undisturbed natural T field) |
| | | Thermal diffusivity $\boldsymbol{\alpha}$ |
| | | Injection temperature $\mathbf{T_I}$ |
| | | Temperature plume |
| | **Change of pressure $\Delta P$** | Production rate **Q** |
| | | Injection rate $\mathbf{Q_I}$ |
| | | Depth of hydraulically active zones $\mathbf{D_{Flow}}$ |
| | | Flow well regime |
| | | Pressure buildup/drop |
| | | Horizontal influence of pressure |
| | | Permeability **K** |
| | | Faults |
| | **Change of hydrochemistry** | pH |
| | | Total dissolved solids (TDS) |
| | | Density of thermal fluid $\boldsymbol{\rho}$ |

## 2.3 Data Matrix

The first step is to create a holistic data model as a basis for assessing the utilisation of the hydrothermal geothermal resource in cooperation with the relevant stakeholders.

The objectives of the assessment model are defined as the prognosis of production and the risk of hydraulic and thermal interference between geothermal projects. The required output and information input is defined for each of these individual modules. The matrix structure starts with the prognosis aims of the assessment model and then splits down further into the parameters required for quantitative assessment in each particular prognosis aim (Table 1, Table 2).

Based on the different application scenarios, a data model is created that lists all relevant data, documents the data origin and data paths, and specifies the quality of the data in terms of its uncertainties. Furthermore, the spatial availability of the data is checked. The data model (matrix) is meant to show which interpreted data (e.g. static, numerical, analytical, statistical…) and raw data (e.g. well logging data, well test data, operational data…) are already available, as well as which data still needs to be analysed or generated for an assessment model. The matrix is a prerequisite for this.

## 3 DSS FOR THE GEOTHERMAL EXPLORATION OF THE NAFB

The DSS will be customised to the different user groups and to provide user-specific decision support. A distinction is made between the approving authorities, specialist planners and non-technical groups such as local authorities. The approving authorities are the focus of the DSS. Depending on the needs of the stakeholders, different levels of detailed information, raw data and processed data as well as further information on missing data or next steps are provided. In order to be able to make valid decisions, it is important that the decision-maker knows which data and information are important for their decision, whether these data and information are fully available in the specific case and what uncertainties exist in the existing data basis for their assessment. In order to adapt the DSS to the various needs, application scenarios were first created based on literature research and the internal experience of the project participants.

In the specific case of the DSS for the deep geothermal exploration of the NAFB, the database sets the approach for the decision-support. There are two scenarios to distinct: 'hot spot' regions with a detailed and dense database and less explored regions with very little data.

In the 'hot spot' regions, a large number of geothermal projects have already been carried out so that offset well data and information from well reports, geophysical logs, hydraulic tests, and 3D seismic measurements are extensively available and therefore, the knowledge on the reservoir is comprehensive there. The information relevant to the prognosis aims can be extracted from the available data, analysed and its uncertainty assessed. Because of the data density, this database can be interpolated in the greater Munich area so that an estimate of the reservoir characterisation can be made at each location. This data base in turn provides the basis for applying high quality analysis methods such as numerical models in the DSS and using them to assess the interference between geothermal sites to make the most precise, quantitative statements possible.

This contrasts with the less explored areas where there are generally very few, often widely spaced, offset wells available. Furthermore, no or only 2D seismic data are available. The spatial heterogeneity of the reservoir can only be poorly described and there is a high degree of uncertainty. Quantitative assessments are difficult to make and the data base for the decision support is not sufficient. Numerical models for hydraulic-thermal simulation cannot be used effectively. Nevertheless, the DSS attempts to provide all available information on other assessment mechanisms and analyses for decision support. The expert assessment of the database for a particular prognosis aim is therefore an important step in the DSS. This involves identifying the relevant existing data and defining their role in the assessment process. A simple assessment with likely relatively high uncertainties should be carried out and its uncertainty quantified. In addition, the uncertainties of the data base should be communicated and what data would still be needed to carry out a complete, high quality (quantitative) assessment.

In summary, the DSS should include the bundled compilation of relevant data, a standardised and valid potential and risk assessment and support for regulatory decisions. The decision support for the prognosis aims, therefore, varies according to the data availability and is adapted to the user group.

The DSS will accelerate and improve planning and regulatory practices in the future. While the technical processes of geothermal borehole development cannot be significantly speeded up, planning aspects can be addressed to accelerate the development of geothermal energy. Issues that the DSS can deal with include the bundled compilation of relevant data, a uniform and valid assessment of potentials and risks, and obtaining permits. In addition, current practice tends to look at wells individually within a claim and does not consider potential interference with other geothermal wells at the earliest planning stage. In the future, the focus will be not only on individual wells but more on the reservoir as a whole.

## 4. CONCEPT DEVELOPMENT AND FEASIBILITY

The DSS will be built up in a modular way in which each prognosis aim is first achieved separately to develop a conceptual model for each module. This means, that for production prognosis and interference prognosis, separate concepts are created with separate data analysis and separate integration and interpretation of the analysis. The results will only be joined in the very last step of the decision support process when the decision support knowledge is provided in the output. In the decision process, it must be analysed whether the output information is sufficient for all stakeholders to make a decision or whether more information is needed.

### 4.1 DSS Concept Production Prognosis

A flowchart was created with a detailed concept for the prognosis modules to connect the available input data with the defined output data by possible processing steps (Figure 2). Thereby, possible data utilisation scenarios are outlined. These data utilisation flows show in which cases existing data can provide sufficient output and in which scenarios concepts need to be developed to fill data gaps.

The production prognosis can be divided into production rate prognosis and production temperature prognosis. These two prognosis parts can be derived by different methods and data bases, which also include different uncertainties. In the developed concept, two different options are considered. In option 1 offset wells are available that have a similar geological setting so that actual production rate and production temperature data can be used to estimate a prognosis. Nevertheless, it is necessary to examine how the data quality of these off-set boreholes is evaluated and at what distance from the assessment location this information is available. Where offset wells are not available or are very distant, option 2 is that a prognosis must be made using proxies for empirical correlation or regional parameter models using already defined regional trends and dependencies. A concept is needed to decide between these two options. The approach needs to evaluate in which cases the use of option 2 leads to a better prognosis than the use of the offset well data. Therefore, the input location needs to be analysed in context with the available offset wells by factors such as distance, quantity, data quality, regional geology and others. For each option, an uncertainty assessment is required, evaluating the input data quality and quantity of the data used. Existing numerical models that can simulate the parameters volume flow and temperature would be another option for the forecast if the data basis allows a numerical model to be created and if the current data basis is considered.

The final part of the concept is an outline of how the output generated in this way will be presented to the different stakeholders. The different stakeholder groups are therefore defined as the citizens, who receive the most basic information, followed by the municipalities and the planners, who need more detailed information about the availability of data and also the next steps for action, and the authorities, who need all the information in the most detailed way, e.g. also sensible data.

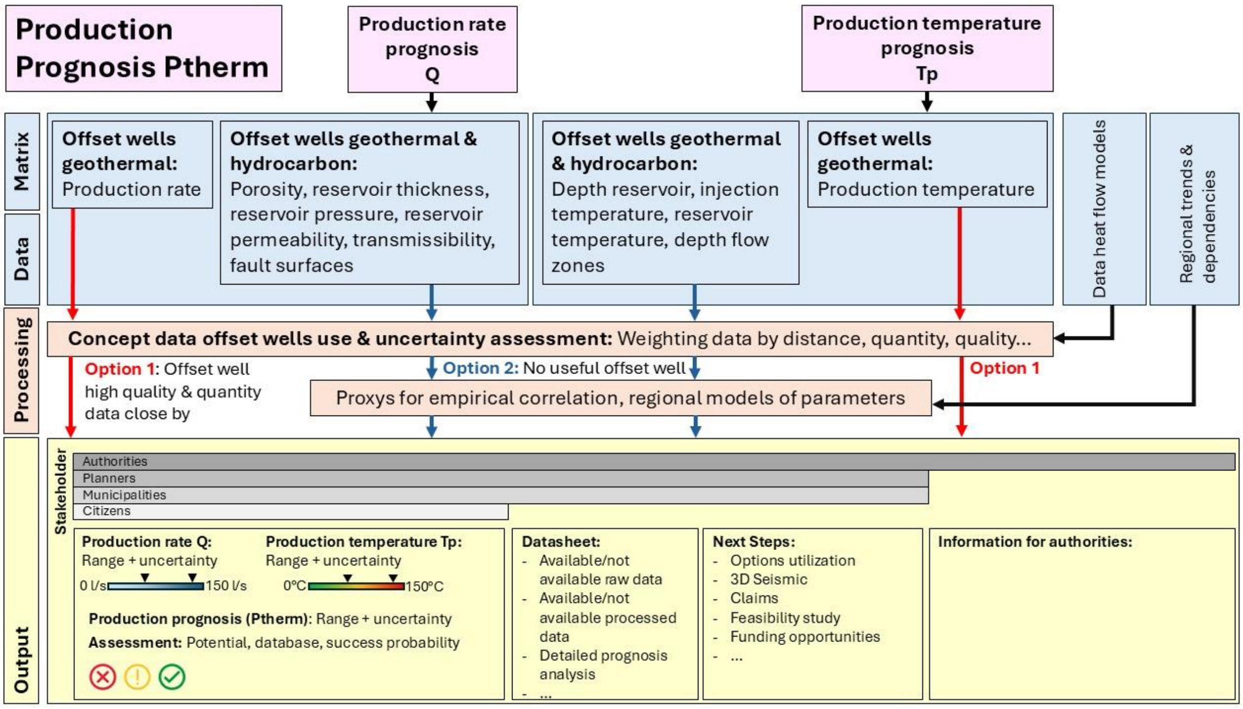


**Figure 2: Preliminary draft of the production prognosis concept (Ernst et al. in prep.).**

## 4.2 DSS Concept Interference Prognosis

Unlike in production prognosis, there are no methods for interference prognosis that can be transferred from local to large-scale application. Therefore, new approaches will have to be developed to meet the predicted target, and it is not yet clear whether and how these can be implemented.

For the DSS module interference prognosis, there was also a flowchart created (Figure 3). Therefore, interference between geothermal sites can be divided into temperature change and pressure change at a location. Firstly, clear thresholds for judging if an interference takes place between geothermal plants must be defined. Hence, evaluation criteria like temperature and pressure change values at nearby plants or claim borders must be defined. The interference prediction is based on the geological static model, which is parameterised and then hydraulically coupled in a first step, and then hydraulically and thermally coupled. For further processing there are different possibilities depending on the quantity and quality of data available in certain regions. In option 1, a numerical thermal hydraulic model could be developed for regions with high data quality and quantity. Depending on the result, it may be possible to derive interference prognosis from this in real time, but if this is not possible due to long computation times, an option could be a pre-simulation of several locations which can then be used in a simulation repository to make a prognosis. The feasibility of both approaches must be critically examined. For option 2 an analytical model may serve as a preliminary approach to estimate prognosis of thermal and hydraulic interference in areas with lower data quality and quantity. Although the precision of analytical models is generally lower than that of numerical simulations, this uncertainty can only play a minor role with a generalised data basis. Option 3 could be the use of AI methods or simple analytical methods. These could offer significantly better performance with high accuracy at the same time. The workflow here is more variable and depends on the progress during the project timeframe. Here, as well, for each option, there is an uncertainty assessment required evaluating the input data quality and quantity of the data used. Similar to the concept of production forecasts, the output is then outlined with different levels of information detail depending on the needs of the different stakeholders.

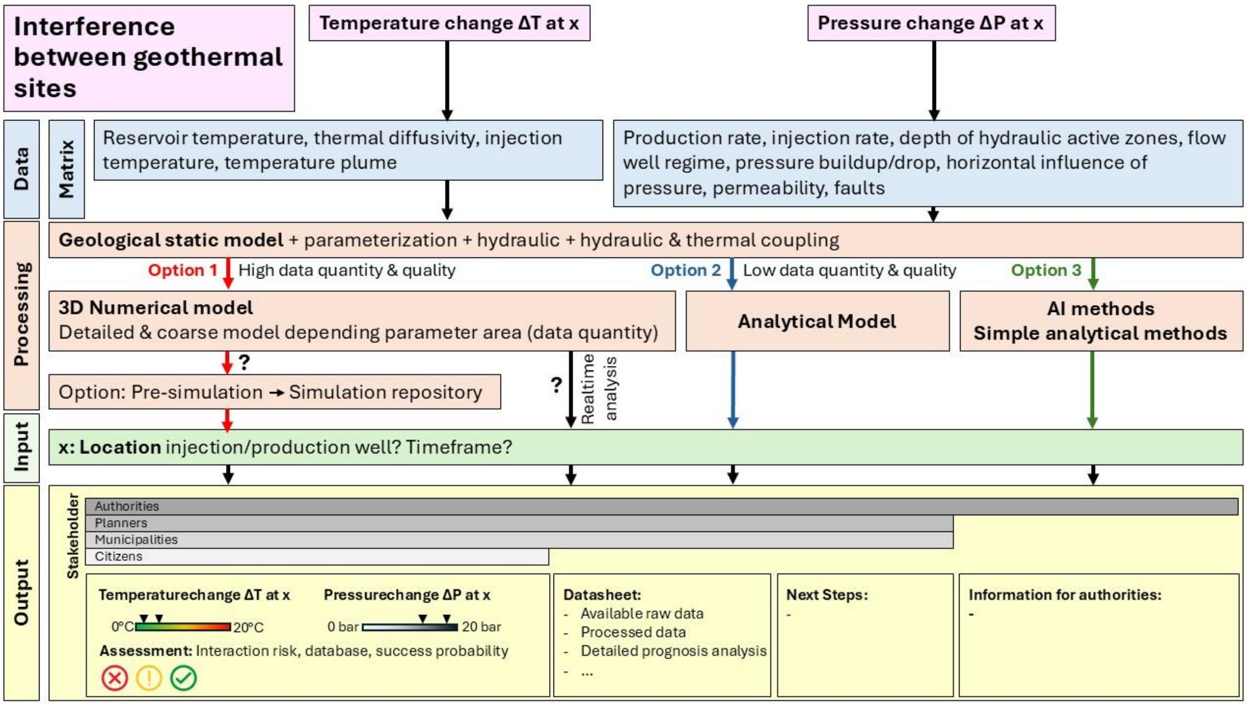


**Figure 3: Preliminary draft of the interference prognosis concept (Ernst et al. in prep.).**

## 5. CONCLUSIONS

The development of a decision support system (DSS) within the "BeM-TG" project represents a significant step toward sustainable and efficient utilization of deep geothermal energy in Bavaria's North Alpine Foreland Basin. By integrating diverse data sources and addressing key risk and uncertainty factors, the DSS enhances transparency and supports informed decision-making for all stakeholders involved in geothermal project development. The conceptual work presented demonstrates that, even with current data limitations, meaningful prognoses for production and interference are achievable.

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