EVALUATED GUIDELINES ON HARMONIZED WORKFLOWS AND METHODS FOR URBAN AND NON-URBAN AREAS

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Table of contents

1. Introduction

The GeoPLASMA-CE project produced a transnational web information system presenting the geothermal potential as well as risk factors and land-use conflicts for the shallow geothermal use in six pilot areas in Austria, Czech Republic, Germany, Poland, Slovakia and Slovenia. We modelled the 3D geological structure of the subsurface for each pilot area, calculated the geothermal potential for open and closed loop geothermal systems and produced thematic maps visualizing land use risks and conflicts and the general suitability for open and closed loop geothermal systems.

Since the data, the classification schemes, the scale and level of detail, the legal regulations and the modelling software varied among the project partners, comparable modelling results could only be obtained since as many work steps of data interpretation, processing and modelling as possible were standardized. Therefore, the project partners agreed on using harmonized workflows.

This report is the guideline for mapping the geothermal potential, risk and conflict factors for shallow geothermal uses in urban and non-urban areas for open loop and closed loop geothermal installations. It is based on the harmonized workflows designed for the GeoPLASMA-CE project tested in the pilot areas. After using the workflows, the partners gave their feedback in order to modify and improve them. This deliverable presents the harmonized and evaluated workflow in order to place our experiences to public disposal. It is addressed to geoscientists who want to calculate the potential of shallow geothermal installations. The workflow is presented in various chapters referring to different topics such that a user can identify most relevant part for himself easily.

The separation of the workflow in “urban” and “non-urban”, which was choosen for the deliverables D.T2.3.2 “Harmonized workflow for urban areas” and D.T2.3.3 “Harmonized workflow for non-urban areas” was not used in this deliverable, since it turned out, that there are no major differences in the application of the workflows.

2. Outputs elaborated by the workflows

Table 1 presents an overview of the outputs which have been designed for the GeoPLASMA-CE project. The base for the decision to produce these outputs was the stakeholder survey of D.T2.1.1 “Template of a harmonized questionnaire” which was performed in order to investigate which information and products stakeholders working in the field of shallow geothermal energy are interested in. Most important stakeholder groups, licensing authorities, political stakeholders, designers/consultants of geothermal plants, drilling companies, equipment producers and others, were asked to participate. A set of 65 parameters concerning different aspects of the use of geothermal energy was registered. The results are presented in the catalogue of requirements (D.T2.1.2 “Catalogue of requirements”, https://portal.geoplasma-ce.eu/). The GeoPLASMA-CE partners generated a list of 32 output parameters produced in the project and discussed the best suitable physical properties or categories to represent one output. For qualitative variables, we decided to use a combination of binary and categorial classification, in order to meet the needs of the various pilot areas. After the list with the output parameters had been established, all partners selected a subset which was relevant for the specific pilot area. This means that not all outputs were produced by all partners. Additionally, we deleted some outputs from the parameter list, since we had not sufficient data to produce them or because we got unreasonable results. These outputs are **not** represented in **Table 1**, but they will be discussed in chapter 4 “Evaluation of the harmonized workflows”.

Table 1: Overview of the output parameters produced in the GeoPLASMA-CE project.

Output parameter	Unit	Explanation
General information		
Virtual borehole	m above sea level	In the GeoPLASMA-CE web information system one can click at any location in the pilot areas to get a virtual (non-existing) borehole that provides information about the geological conditions. It is based on a 3D geological model and specifies the upper boundary of a geological unit.
Suitability – closed loop systems	1- shallow geothermal applications are generally possible 2-attention/additional information needed 3- shallow geothermal applications are generally prohibited	Qualitative map with information on the applicability of a closed loop shallow geothermal system.
Suitability – open loop systems	1- shallow geothermal applications are generally possible 2-attention/additional information needed 3- shallow geothermal applications are generally prohibited	Qualitative map with information on the applicability of an open loop shallow geothermal system
Potential for closed loop systems		
Surface temperature	degC	Mean annual groundsurface temperature. In GeoPLASMA-CE it represents the mean annual average soil temperature at the surface of the earth. It can be derived from the mean air temperatures at the surface (SAT), by satellite observation (LST) or by direct soil temperature measurements in shallow depths (<5 meter below surface).
Average thermal conductivity	W/m·K	The thermal conductivity is the ability of the rock to transport thermal energy in the form of heat. The values show the average thermal conductivity for a specific depth interval (including the unsaturated zone) and does not account for advective effects.

Output parameter	Unit	Explanation
Subsurface temperature	degC	Estimated average subsurface temperature at the midpoint of a closed loop system (borehole heat exchanger).
Potential for open loop systems		
Groundwater bodies suitable for open loop systems	0-not present 1-present	Location of aquifers suitable for open loop systems. Outline of a groundwater body suitable for open loop systems.
Hydraulic productivity at peak load	$l/d/m^2$	Amount of utilizable groundwater at peak load. Maximum yield available at a specific location for an open loop system defined for a given period (peak load, day or year). At peak load, the pumping rate is significantly higher during a short period of time than at average supply level.
Specific thermal power at peak load	W/m^2	Specific thermal power per well doublet derived from the hydraulic and thermal productivity.
Thermal productivity	°C	Groundwater temperatures at a representative day. The groundwater temperature and quantity determine the energy content available for heating and cooling with open loop systems.
Energy content	$MWh/a/m^2$	The annual amount of thermal energy per surface unit which can be extracted or injected into an aquifer for heating and/or cooling.
Conflict maps		
Flood risk	0-not present 1-present	Location of regions which might be flooded seasonally.
Karst areas and caves	0-not present 1-present	Cavities in the subsurface caused by dissolution of carbonate or sulfate rocks by groundwater. Karst areas may cover vulnerable aquifer systems (high hydraulic conductivity) and may cause technical problems during the drilling process (mud loss).
Boreholes	0-not present 1-present 2-water production and monitoring 3-geological engineering database boreholes 4-central geological database boreholes	Location of existing boreholes containing geological data.
Mining areas	0- not present 1 - present unspecified 2-inactive open pit 3- active open pit 4-inactive underground mine 5-active underground mine 6-protected mineral resources 7-mining heap	Hollow spaces in the subsurface, which may cause problems with grouting material for closed loop systems. Drilling may be prohibited in such areas.
Natural protection areas	0-not present, 1-present unspecified 2-natural reserve where drilling is forbidden 3- natural reserve where the user has to check whether drilling is forbidden	Protected area of importance for wildlife, flora or fauna, or features of geological interest, which are indicated for conservation. Shallow geothermal energy might be limited in natural reserves, such as landscape protection areas, Natura 2000 protection areas and the Nationalpark Donau-Auen e.g. due to prohibitation of excavation. In such areas drilling may be not allowed or permitted, therefore further information is required.

Output parameter	Unit	Explanation
Water protection areas	individual categorization in each country	Area dedicated to drinking water or curative water supply. Geothermal installations might be restricted in these areas. Water protection areas prevent groundwater used as drinking water from negative influences. Decrees outline each water protection area and define protective measures. This might include prohibition of excavation or obligatory permits, which could influence the use of shallow geothermal energy.
Natural gas emission	0- not present 1-unspecified 2-CO_2 3-methane 4-radon	Near surface gas zones, which may cause blow outs during drilling and leads to risk of explosions (methane), intoxication and erosion of the subsurface around the drilling. Gas-bearing fissures may be encountered in isolated cases.
Contaminated areas and earthworks	0-not present 1-present unspecified, 2-landfills or road/railway embankment 3-polluted sites	Site for the disposal of waste materials by burial (landfills) or polluted underground due to activities with materials hazardous to the environment. The sites could harm shallow geothermal installations close by and on the other hand, further unintended dissemination of hazardous material through drilling and operating wells has to be prevented
Tectonics/faults	0-not present 1-present unspecified 2-minor fault, 3-major fault	Zone, where rocks have been broken and displaced, may cause geotechnical problems while drilling or problems at cementation jobs for closed loop systems.
Landslides	0-not present 1-landslide risk zone 2-landslide deposit	Ground movement occurring if a slope changes from a stable to an unstable condition. They may cause damage to shallow geothermal applications.
Supply lines	0-not present 1-present unspecified 2-tunnel (underground road or railway) 3-electric 4-gas 5-district heating 6-water 7-sewage 8-telecommunication	Location of subsurface infrastructure, which may restrict shallow geothermal systems.
Local/regional development plan	0-not present 1-drilling forbidden	Region which is affect by a regional development plan.
Shallow geothermal energy systems	0-not present 1-ground-source heat pump installed	Location of existing geothermal uses, which may lead to limitations of use.
Confined or artesian groundwater	0-not present 1-present	Aquifer with a confining layer on top which may offer protection but also may cause an increased pressure of the groundwater. If a well is drilled into it, the water rises in the well and the pressure field is disturbed. Confined or artesian groundwater might be present, due to specific hydrogeological conditions. Category "artesian well close by" means that artesian groundwater wells with a depth between 100 and 200 m are located at a distance of 200 m.

Output parameter	Unit	Explanation
Hydraulically separated aquifers	0-not present 1-present	Two aquifers divided by at least one aquitard. Drilling into hydraulically separated aquifers may shortcut them and influence the hydraulic system (e.g. salinity increase of low mineralized aquifers).
Underground infrastructure	0-not present 1-present unspecified 2-parking site 3-storage 4-underground cities	Anthropogenic underground objects which must not be drilled into.
Problematic groundwater chemistry	0- not present 1-unspecified 2-Manganese and iron 3- Carbonate 4-metal corrosion 5-concrete corrosion	Outline of regions with problematic chemistry (e.g. low oxygen content). Due to the groundwater chemisty scaling of iron, manganese and carbonate in wells and metal corrosion of heat exchangers or wells casings is possible.

3. Urban and non-urban aspects

Rural areas have a much smaller density of population than cities. In Central Europe, most rural areas are agricultural sites, which may include small industrial plants, forests and natural protection zones. People live in small towns or villages or even in isolated farms. Since a connection of small villages or farms with district heating is either complicated or not possible, geothermal installations may provide an important source for heating and warm water supply in family and green houses.

Due to a small population density, the ground surface is mainly unsealed. Additionally thermal emission from heated buildings and the density of pipelines and tunnels is much smaller than in cities as well. Natural factors control the temperature of the shallow subsurface, like the solar radiation including aspects of slopes and vegetation. Therefore, temperatures of rock and groundwater follow the natural annual cycle with a temperature shift depending on the depth. The geothermal gradient of the shallowest parts of the subsurface is also following a natural cycle down to a neutral zone. Below this zone, the geothermal gradient is controlled by geological factors. The geothermal regime in rural areas can therefore be considered to be undisturbed and to be controlled by the rock composition and groundwater flow.

Therefore, mainly natural factors have to be considered by a workflow specifying the geothermal potential and their conflict and risk factors of a non-urban region.

Rural regions often are several 100 km^2 large. Therefore, a structural model describing the subsurface has to comprise many modelled objects (40-60 geological units).

Input parameters controlling the shallow geothermal potential are:

- Mean annual ground surface temperature,
- Geothermal gradient,
- Thermal conductivity of the rocks.

Anthropogenic activities like heating of buildings or existing thermal installations can be mainly neglected. However, drainage of agricultural areas and the use of groundwater for agricultural farms may influence the depth of the groundwater table and result in reduced thermal conductivities and heat extraction capacities of the rocks.

Rural regions provide specific risk and conflict factors for shallow geothermal usage:

- Protection zones like natural reserves or water protection zones are important national goods and must not be influenced by geothermal installations,
- Specific geological structures may provide risk factors, e.g. karst, fault zones, swellable rocks, quicksands or steep slopes,
- Shallow gas leakage may cause eruptions while drilling or health damage (e.g. radon),
- Old mines or cavities may cause instabilities of the boreholes and bad conditions for heat conduction (if they are filled with air).

Shallow geothermal conditions of urban areas in Central Europe are usually characterized by large aquifers, since towns were built and developed near big rivers where groundwater is available as well. Additionally, anthropogenic activities strongly influence the temperature regime of the underground:

- Surface sealing,
- Thermal emission from heated buildings and industrial plants founded in the aquifer or the unsaturated zone,
- High density usage of groundwater and re-injection of heated/cooled groundwater to the aquifer due to cooling/heating processes (open loop systems),
- Effects of tunnel systems, e.g. for underground traffic, and of pipelines, e.g. for water supply and sewage.

Within these actions, the thermal effects of heating outweigh the effects of cooling and lead to the development of “urban heat islands”. This term is commonly used to explain higher temperatures in cities compared to rural areas. However, it is often neglected to emphasize that this also affects the underground, where a general increase of rock and groundwater temperatures below cities can be determined. One consequence is a negative or missing geothermal gradient in the uppermost subsurface of a city. Higher groundwater temperatures implicate a larger potential for heating and a smaller potential for cooling.

A high potential for shallow geothermal energy provides the opportunity to overcome certain challenges in cities. Many cities have problems with air pollution caused by heating with fossil energy sources, such that the usage of the emission-free geothermal energy provides an important alternative, which has to be taken into account for modern city development strategies (e.g. in Krakow and Ljubljana). However, if geothermal energy is used extensively in a city, the existing geothermal installations around a future installation have to be considered in the planning phase. Resulting thermal- and hydraulic summation effects may reduce the heat extraction capacity as well as the energy content at a specific site. On the other hand, they can also positively influence each other if a heating and a cooling system are situated consecutively. In order to ensure sustainable and maximum exploitation of shallow geothermal energy, an integrative management of the groundwater for heating and cooling purposes is crucial.

Following aspects have been identified as important and will be included in the harmonized workflows of urban areas:

- Anthropogenic activities have to be considered by a workflow specifying the geothermal potential of an urban area,
- Special attention has to be paid to input parameters: The ground surface temperature of a city is different from its environment due to sealing and heating,
- The rock and groundwater temperature has to be examined carefully in order to identify heat islands, which affect the shallow geothermal potential,

- The neutral zone with zero geothermal gradient beneath a city is thicker than in a rural area,
- Existing geothermal usages in populous districts may influence the thermal extraction capacity and the energy content, e.g. in areas with groundwater flow, and have to be quantified.

Mapping of conflict and risk factors is also specific for urban areas. In addition to the natural conflict potential, which also exists in rural areas, urban areas comprise many anthropogenic conflict potentials:

- The subsurface infrastructure, like a dense net of subsurface pipelines and electric lines, provides a conflict potential, as well as an underground network,
- In industrial areas polluted sites exist, which provide a risk factor for the contamination of the groundwater,
- Anthropogenic influence on the hydrochemical conditions in near surface groundwater bodies like enhanced chloride contents or changes in the oxygen level,
- The conflicting and concurrent use of groundwater for industry and drinking water has to be taken into consideration.

It was possible to include those aspects in the workflow, without preparing separate workflows for urban and non-urban areas. In that way, we could manage to make the workflows better readable and to avoid very similar versions for both two scenarios.

4. Evaluation of the harmonized workflows

The project partners tested the workflows in the pilot areas during the testing phase of GeoPLASMA-CE and afterwards provided feedbacks to the coordinator of the joint workflows. If necessary, the workflow was corrected or adapted basing on the feedback.

Some of the initial versions of the workflows were presented as click-by-click guidelines for particular software packages. During the realization phase of GeoPLASMA-CE, it turned out that these very particular and software depending guidelines have a limited transferability and might confuse users applying slightly different software solutions. Therefore, the updated workflows will be presented in a more generic way. Detailed processing guidelines are shown in the appendix of this document.

In the following chapters, the evaluation for individual workflows are presented in the context of the main parameters needed to characterize resources and limitations of use linked to shallow geothermal use.

5. Data management

5.1. Purpose/ use of the workflow

In GeoPLASMA-CE, joint data management concepts needed to be developed for the following reasons:

- Six different countries participated in the project and three of six pilot areas were covered by more than one country,
- The cooperation aimed at a joint web information system showing harmonized thematic contents in six different languages,
- Processing input data from partly public and partly restricted access sources requires a clear documentation of the data background and should ensure to protect data privacy rules,

- Simple and resource efficient electronic interfaces and procedures are needed for the exchange and publishing of data,
- The data flow needs to be fully documented in order to produce adaptable and sustainable datasets.

The developed data management concept was addressing the following issues:

- *Harmonization of technical language* to produce clearly formulated, unambiguous output datasets describing resources and limitations of use related to shallow geothermal. Literature studies in the beginning of GeoPLASMA-CE revealed that uniform technical definitions of resources and limitations of use are missing in Europe. Moreover, a harmonized technical language is the prerequisite of a multilingual web information system,
- *Harmonized documentation of produced output datasets* linked to explanatory notes and annotations published at the web information systems,
- *Handling and documentation of input data* regarding limitations of access, documentation of data sources and operators as well as the currentness of each produced dataset,
- *Data exchange inside the team and to the service provider* of the joint web information system.

The joint data management concept bases on the following data domains and levels of cooperation, which are outlined in **Figure 1**:

- *Source and raw data*, which are not shared or included in the joint data management concept. Managing these data stays at the sole responsibility of the respective partner,
- *Input data* comprise processed and harmonized raw data, which feed into the preparation of joint output datasets. Joint data management guidelines need to be applied to these data and a metadata documentation needs to be executed. We decided not to publish the metadata documentation of input data but keep it on record for documentation purposes at each involved partner,
- *Harmonized output data* need to be in line with the harmonized output parameter list of the deliverable D.T2.3.1 "Set-up of harmonized data management infrastructure", Annex 1, https://portal.geoplasma-ce.eu/ and have a defined data format. We created a joint metadata documentation of these datasets, which is published at the web information system. Furthermore, all input data processed to create a certain output dataset needed to be included in link-table for documentation purpose by all involved partners. The link-tables themselves were not published at the web information system. Managing output dataset was under the responsibility of the project coordinator and the project partner responsible for the web information system. However, partners who were delivering ready to publish datasets to the web information system manager needed to follow joint data delivery rules, which were part of the GeoPLASMA-CE data management guideline. The data- and web manager just performed conformity checks of the delivered data formats and metadata documentation. All content related quality checks of the delivered data were under the responsibility of the respective partner,
- *Web data* just cover the information published at the web information system and comprise (1) displayed output datasets, (2) the related metadata documentation and (3) linked explanatory notes.

The elaborated data management concept is summarized in a harmonized data management infrastructure (project deliverable "D.T2.3.1 Set-up of harmonized data management infrastructure", https://portal.geoplasma-ce.eu/. The joint data management also comprises several annexes providing guidelines for the partners how to name and specify data sets and output files.

Figure 1: Competences and responsibilities of the project partners of the harmonized geodata management.

5.2. Evaluation of the workflow and lessons learned

The initial data management guideline was applied in the six GeoPLASMA-CE pilot areas and was slightly adapted during the data preparation process. In the following section covers the most relevant adaptions and lessons learned.

Data management concepts addressing input data:

The partners were very happy with this data management concept, since it allowed the most possible flexibility for all partners. Partners in international pilot areas made bilateral agreements on data management which were tuned to their specific needs.

Data management concepts addressing output data:

The harmonized output parameters were specified in the first year of the project on the basis of a stakeholder query in all partner countries. The final decision on the output parameters produced in each pilot area was made by the project partners, e.g. if the stakeholders wished information about karst, if no carbonate rocks are present in the pilot area. The partners had long discussion about the units and categories used for the output parameters. A good compromise was the combination of binary variables "not present –present" with categorial variables specifying characteristics of the outputs. This classification satisfied the data situation and legal regulations of all partners.

The explanatory notes were organized in one table comprising the explanation of all output parameters in 6 languages. Changes in this table were problematic, because no partner was able to correct the notes in all six languages.

The workflow for conflict mapping was developed in two versions, one for vector data and one for raster data. This has proved to be a very serviceable solution, since the partners had a long discussion whether vector or raster data should be delivered for the web information system.

The metadata and data description consisted of too many too big tables which made the data documentation confusing and error-prone.Therefore, the partners gave the feedback, that data delivery or data management in must be a lot simpler and more intuitive. Two different platforms were used for data exchange: the own cloud for the exchange of documents and for the exchange of data among partners within the same pilot area. The HiDrive was used for final data upload for the web information system. In a perfect scenario, one platform for all project data would replace the own Cloud and HiDrive exchange platforms. Data management and upload (concerning geo data) with web forms and metadata was read automatically from the file and can be edited any time. A basic web viewer for geo data might simplify the internal handling of the data. Documents and geo data could be combined for a better overview.

Data transfer to the joint web information system and web presentation:

In GeoPLASMA-CE, we established an MS Excel spreadsheet based interface for managing the web presentation of prepared output datasets. The spreadsheet covered required formats of file headers and datasets as well as information on the graphical presentation of data (e.g. data ranges, data classes and colour schemes) and supported an automated presentation of datasets at the web information system. It turned out that the automated data import using an MS Excel spreadsheet was not very suitable as it could not prevent misleading entries by the partners, which prohibited the correct display of datasets. In many cases, the web manager needed to manually correct the entries given by the partners in the management tool for web presentation. We therefore recommend applying online input masks linked to databases with strict rules to fill-out control files for the display of web data.

5.3. Adapted workflow

The initial was only slightly adapted during the testing phase in the pilot areas. The updated joint data management guidelines can be downloaded from the GeoPLASMA-CE website "D.T2.3.1 Set-up of harmonized data management infrastructure", https://portal.geoplasma-ce.eu/.

6. 3D-modelling workflow

6.1. Purpose/ use of the workflow

This workflow helps to set-up the structure of the geological subsurface. The 3D model provides information on the location, thickness as well as neighbourhood relations of geologic units. Basis of the 3D modelling is a conceptual model, which is used to interpret the geologic data available in the region. The 3D model provides a consistent, unambiguous compilation of this geologic data. It forms important input data for the calculation of the geothermal potential and for the evaluation of some risk factors like the occurrence of swellable rocks or karst.

6.2. Evaluation of the workflow

The 3D modelling workflow was evaluated by four 3D modellers inside GeoPLASMA-CE. In general, the workflow was clear and understandable.

During the realization phase of GeoPLASMA-CE, two approaches were added to the initial workflow concerning **fault planes**:

- One partner used the localization of thousands of hypocenters of earthquake swarms to constrain dip angles and strike direction of the most important groups of faults in the model as these data points were nicely distributed along several active fault planes at 6-10 km depth,
- We additionally added the recommendation to conventionally model faults as vertical planes in case no information about their dip angle is available.

For **modelling of metamorphic rocks** the information should be added, that the lithological boundaries are usually modelled parallel to the general orientation of the dominant foliation measured in surrounding outcrops, where the boundary is not defined by younger intrusions or faults.

Modelling of units consisting of small volumes or **small thickness** consumed too much time (ca ¼ to 1/3 of total data processing and modelling time) in GeoPLASMA-CE. Therefore, we conclude to model only significant accumulations of sedimentary rocks and to omit small irregular bodies.

Modelling the tops of geological bodies was not seen as the best approach for modelling Quarternary units, since geological bodies have often consistently and well defined basis developed during a single geological event, but their tops are more complex regarding geometry and genesis, especially in erosive environments. In reality, it was often necessary to first model the bottom of a body and then to perform its fragmentation to create appropriate outlines of underlying units, because creating the tops directly was not possible for overlapping lenses. However, modelling of the unit bases is not reasonable for the metamorphic units and other deep reaching rock units if their bases were neither reached in the boreholes nor are part of the modelling domain. However, the thermal properties of these units had to be specified for the potential modelling. In order to provide explicit information about the deep parts of the model, specifying the tops was necessary. Therefore, the workflow should be extended in such a way, that both unit representations are considered.

6.3. Adapted workflow

The workflow for generation of the 3D model comprises steps of data preparation, the geometry modelling and the post-processing of the model (**Figure 2**).

a) **Defining the spatial resolution of the model**: During the data preparation step, all data have to be transformed into the same spatial georeference system. The data have to be interpreted according to the desired later use of the geometrical model and the associated level of detail. In order to identify the required level of spatial resolution, we recommend to perform parameter- and sensitivity studies on the expected impact on the quality of the aimed resource- and conflict of use indicators. The modelling domain needs to be specified accordingly to such pre-modelling data analyses.

b) **Defining the geological resolution of the model**: Rules for the delimitation of special lithological bodies have to be specified. A standard geologic column has to be worked out comprising all lithological objects to be included in the model. Once again, the simplification of the geological standard column should consider its impact on the aimed resource- and conflict of use parameters. During this step, those simplifications should focus on avoiding mapping and/ or model unnecessarily small geological units. In addition, the contact relationship between the lithological units (erosional, intrusive) specified in the standard geologic column has to be determined. The standard geologic column and the contact relationships are combined to the scheme of lithological units, which represent the conceptual model forming the logical basis of the 3D modelling.

c) **A harmonized fault network** has to be constructed. It is a set of fault data with the same level of detail or resolution. Deformation zones have to be included into the model if they displace or cut off important lithological units and if they are hydraulically active. The level of detail of the modelled fault zone has to be specified according to the scale of the model and to the hydraulic properties of the deformation zone. Lateral offsets along the map edges have to be corrected. The harmonized fault network needs to be kinematically reasonable.

d) In a next step, the geologic **raw data have to be interpreted**, respecting the scheme of lithological units and the harmonized fault network as well as the rules for delimitation. The input data have to be digitized from raster data sources and processed, such that a harmonized input data set is produced which has to be imported to the 3D modelling software. After the data import, a consistency check is necessary.

e) **The top boundary** of the 3D model is represented by a digital elevation model. A suitable digital elevation model (DEM) has to be selected, after the spatial and geological resolution of the standardized output model has been specified. The resolution of the DEM used for 3D modelling should be a bit finer than that of the output model, but not too fine, since DEM with a high resolution need more storage and contain more non-geological objects. Some locations in the DEM might represent non-geological objects like a water table, a bridge. Therefore, they have to be processed in order to show the correct geologic boundary, which is the bottom of the water body or of the bridge. **We suggest correcting lakes bigger than one hectare**. The outline of the lakes can be taken from a topographic map. The depth of the lake can be either provided by the state surveys or has to be guessed. The elevation of the DEM has to be subtracted by the depth of the lake.

f) **The model base** forms the lower limit of the 3D model. Since the GeoPLASMA-CE project refers to shallow geothermal use, a vertical extent of the models of 200 m was specified by the partners. In order to avoid too large a variation in the modelling depth in regions with topographic changes and to obtain a smooth model base, the minimum topographic envelope is used for specifying the model base. This can be calculated from the DEM by performing the morphological operation of erosion which is smoothing the shape of the DEM such that steep peaks or valleys disappear. Alternatively, the DEM can be resampled to a 1000 m x 1000 m resolution and the average elevation minus 200 m be used to represent a smooth model base parallel to the topography.

g) **Modelling of lithological boundaries** comprises fault and horizon modelling as well as modelling of the boundaries of metamorphic rocks. The location of the boundaries can be specified by borehole profiles, maps or cross-sections. The orientation of the boundaries can be specified by field measurements of bedding planes or foliation (for metamorphic units). The interpolation algorithms are specific to the software and cannot be harmonized. The fault network has to be modelled first, because it displaces lithological bodies.

h) If the **fault** dip is not known, the faults can be either modelled as vertical surfaces or data from seismic hypocentres can be used for the description of the fault location. Modelling top downward is strongly recommended since most data is available near the ground surface. Therefore, most details will also be modelled near the ground surface. For deeper units, fewer details are known, such that these units can respect geometric constraints set by the upper units without getting inconsistent with the data. This is often not the case, when upward modelling is performed. Then, inconsistencies are produced.

Depending on the structure of the subsurface in the modelling domain, the user has to decide, whether to model the tops or the bases of a unit. Geological bodies have often consistently and well-defined base developed during a single geological event. Then, the bases have to be modelled first and then to be combined as tops of the units underneath. If the base of a unit is not known or if the geological body is an intrusion or vertically shifted, it can be reasonable to model the unit tops. In GeoPLASMA-CE, all models had to be transferred into representations of the unit tops, since this was necessary for the generation of virtual boreholes in the web information system and for the calculation of the closed loop geothermal potential.

Additionally, this approach makes sure that all parts of the model are “known” or specified.

A standardized final 3D model output has to be produced. This model represents its geologic units by their top boundaries in a 2D raster vertex structure. The grid points are specified by a mandatory master grid. The parameters of the master grid are presented in deliverable “D.T2.3.1 Set-up of harmonized data management infrastructure”, https://portal.geoplasma-ce.eu/.

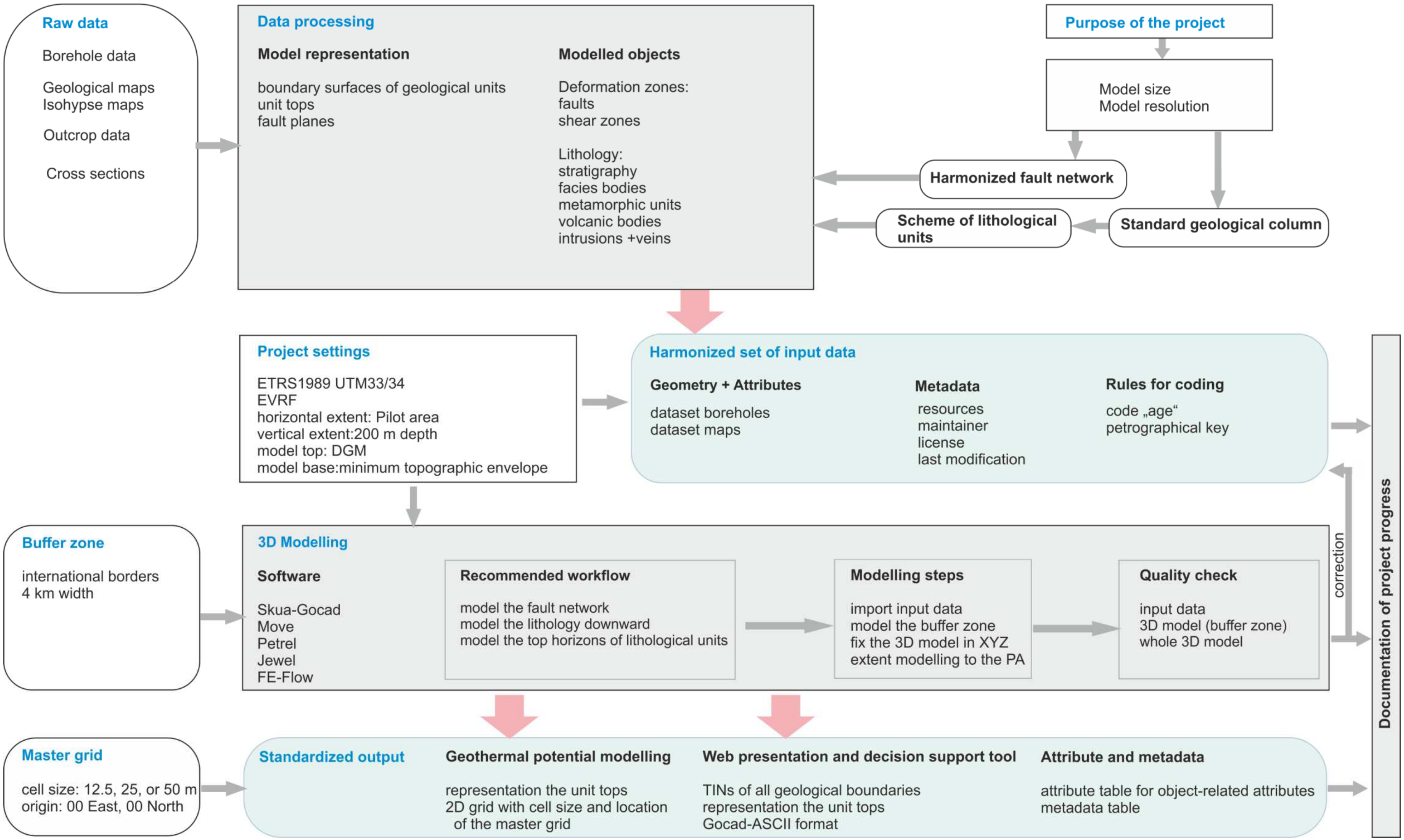


Figure 2: GeoPLASMA-CE workflow for 3D modelling.

6.4. Overview of harmonized rules, specifications and workflow steps for 3D modelling

1. **Specifications for the modelling domain**

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters
Elevation reference system	EVRF2007
Horizontal extent	Pilot areas
Vertical extent	200 m
Model top	digital elevation model
Model base	minimum topographic envelope
No data domain	is possible inside of the model
Model scale	1:10 000 for urban pilot areas
	1:50 000 for regional pilot areas
Buffer zones for transnational pilot areas	4 km width

2. **Specification of the modelled objects**

Sedimentary units	Stratigraphy
Facies bodies	
Metamorphic units	
Magmatic bodies	Intrusions
	Veins
	Extrusive bodies

3. **Specification of the model representation**

Boundary surfaces

Horizon top surfaces

Fault surfaces

4. **Input**

Rules and Concepts:

Standard geologic column

Structure and depositional relationship

Scheme of lithological units

Harmonized fault network

Raw data and raw data processing:

Outcrop data

Borehole data

Geologic maps

Cross sections

Isohypse maps

5. **3D modelling**

Generate a harmonized set of input data

Model the fault network

Model the lithological units

Check quality

6. **Standardized output**

3D Web viewer: Triangulated network (TIN) in Gocad-ASCII format (.ts)

Workflow for mapping of the geothermal potential: 2D Grids of the tops of geologic bodies

Metadata table: complete one line for every .ts file

Add petkey and age code to the metadata table

7. Workflow for conflict and traffic-light maps

7.1. Purpose and use of the derived workflows

The created workflows aim to:

- Map possible land-use conflicts and limitations of shallow geothermal use, i.e. hazards and legal restrictions applicable to the implementation of a shallow geothermal energy system,
- Process the data in order to achieve a well-arranged user-friendly web-presentation,
- Create maps, which indicate the suitability for open loop and closed loop installations in an easy-to-understand traffic light system.

The workflows apply to both, open loop as well as closed loop systems and are relevant for urban and non-urban areas. Access to a suitable geoinformation system (e.g. ArcGIS, QGIS) is required, as well as access and publication rights to comprehensive geoscientific and spatial planning data.

The workflow produces the following outputs:

- A suitability map for open loop systems,
- A suitability map for closed loop systems,
- A series of associated land-use conflict and limitation of use maps.

The deliverable “D.T2.3.1 Set-up of harmonized data management infrastructure”, https://portal.geoplasma-ce.eu/ is highly relevant for this workflow as this document contains the specifications relating to the conflict categories, file properties and metadata. Strict compliance with these specifications is necessary in order to publish the outputs on the GeoPLASMA-CE web information system.

The workflow is divided in two parts: One flowchart represents working with raster data and the other flowchart applies to the utilization of vector data.

7.2. Evaluation of the workflow

User feedback indicated that there were no major problems in the application of the conflict mapping workflow itself. Issues with conflict maps or suitability maps were mainly observed in relation to the data management workflow.

The main issue was non-compliance with specifications such as the NoData value, correct file format, file naming conventions, etc. As a consequence, the specifications listed at the start of the workflow were supplemented by checklists at the end of the workflow, and further references to the relevant annexes of the data management workflow were also added.

Other issues concerned the definitions of the conflict categories and the raster resolution. The root cause of this was inadequate identification of user requirements in the preparation phase. Although again primarily a data management issue, both the data management workflow and the conflict mapping workflow were adapted several times in order to satisfy user demand. A major departure from the initial draft version of the conflict mapping workflow, where all workflow outputs were to be presented as raster data, was the incorporation of conflict maps in vector format. In order to prevent inconsistencies, the suitability maps had to follow suit; appropriate steps were added to the workflow. At first limited to polygon data, a further workflow amendment allowed the creation of layers with line- and point data and implemented the necessary steps to make these data accessible to location queries and suitability maps.

Although the motivation for the inclusion of vector data outputs was a single partner’s request and driven by the wish to display very detailed information in an urban setting (namely, every single supply line at property scale), all partners decided to switch to vector data. Apart from initial data deliveries in the GeoPLASMA-CE pilot area Vogtland (Germany) to the Web-GIS portal for testing and demonstration purposes, the raster data workflow was not utilized.

Based on the partner feedbacks, a topology check was introduced for vector data. The main goals were to ensure that mutually exclusive conflict categories do not overlap, and that each conflict map completely covers the pilot area without leaving any gaps.

Lessons learned:

- The identification of requirements, in particular the necessary resolution, should be performed very carefully. Changes at a later stage are very time-consuming and may be difficult to implement,
- Following the vector data workflow is very time-consuming compared to the raster data workflow, as there are much higher demands on data quality (e.g. topology checks).

7.3. Adapted workflow

7.3.1 Overview

Geothermal energy is clean, emission-free and sustainable. However, in some areas drilling is prohibited or subject to conditions – for example to protect groundwater bodies, which supply drinking water, or to prevent interference with mining infrastructure. Other areas may be free of legal restrictions regarding drilling or groundwater interventions, but are exposed to hazards that might threaten the drilling process. Examples for such hazards are water-reactive formations or the existence of natural cavities. It is important to know about these hazards in order to take appropriate precautions and ensure a safe operation.

This workflow applies to both open loop and closed loop systems and is relevant for urban and non-urban areas. Not all data layers ("conflicts") are of the same relevance for all applications. For example, the existence of deep underground mining may be very important for deep closed loop installations, but not so relevant to open loop systems placed within the top 10 m of the subsurface.

Access to a suitable geoinformation system (e.g. ArcGIS, QGIS) is required, as are access and publication rights to comprehensive geoscientific and spatial planning data.

The workflow produces the following outputs:

- one suitability map for open loop systems,
- one suitability map for closed loop systems,
- a user-specified number of land-use conflict maps.

The deliverable "D.T2.3.1 Set-up of harmonized data management infrastructure", https://portal.geoplasma-ce.eu/ is highly relevant for this workflow as this document contains the specifications relating to the conflict categories, file properties and metadata. Strict compliance with these specifications is necessary in order to publish the outputs on the GeoPLASMA-CE web information system.

Within the workflow, the following main steps can be distinguished (**Figure 3**):

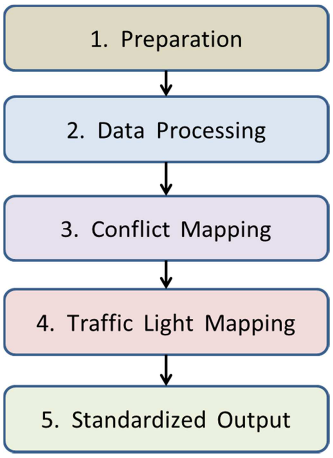


Figure 3: Main elements of conflict mapping workflow.

G.1 Specification of requirements
Identify relevant hazards and land-use conflicts. Define target group and specify required outputs.

G.2 Collection of input data
Compile existing data and create new data sets if required.

G.3 Analysis of input data
Evaluate data quality, data density, extent and formats. Determine suitability and supplement with new data if necessary.

V.1 Data conversion / vectorization
Conversion of analog data into vector data if required.

V.2 Conflict Layer
Classify data according to the data classes defined in DT2.3.1 Annex 8.

V.3 Corresponding polygon layer
Buffer point/line data to obtain polygons.

V.4 Extent layer
Identification of locations with data available (value = 0) and no data available (value = -9999). One extent layer for each conflict required.

V.5 Conflict Layer
Create an integer field named "conflict". Classify data according to the data classes defined in DT2.3.1 Annex 8. Enter conflict category for each polygon in the field "conflict".

V.6 Conflict Map
Combine extent layer and conflict layer by merging the two layers.

V.7 Topology check
Delete empty geometries. Fill gaps between polygons. Ensure that mutually exclusive conflict categories do not overlap.

V.8 Interpretation
Assign a traffic light value 1, 2 or 3 (representing green, yellow and red) to each conflict category.

V.9 Assignment of traffic light values
Create an integer field named "traffic_va". Assign each polygon the correct traffic light value based on the field "conflict".

V.10 Traffic light map
Merge all relevant conflict maps. Retain only the polygon with the highest traffic light value for each location (e.g. use "erase" tool or "clip and discard" feature of the editor if using ArcGIS). Dissolve.

V.11 File properties
Refer to DT2.3.1 and annexes for correct reference system, file format and file name.

V.12 Metadata
Complete link tables and metadata table correctly to enable data transfer to webGIS.

V.13 Attributes
Delete all attributes except for the field "conflict" for conflict maps and the field "traffic_va" for traffic light maps. Ensure correct spelling (case sensitive!) of field names.

G.4 webGIS
Submit data to webGIS host for verification and publication.

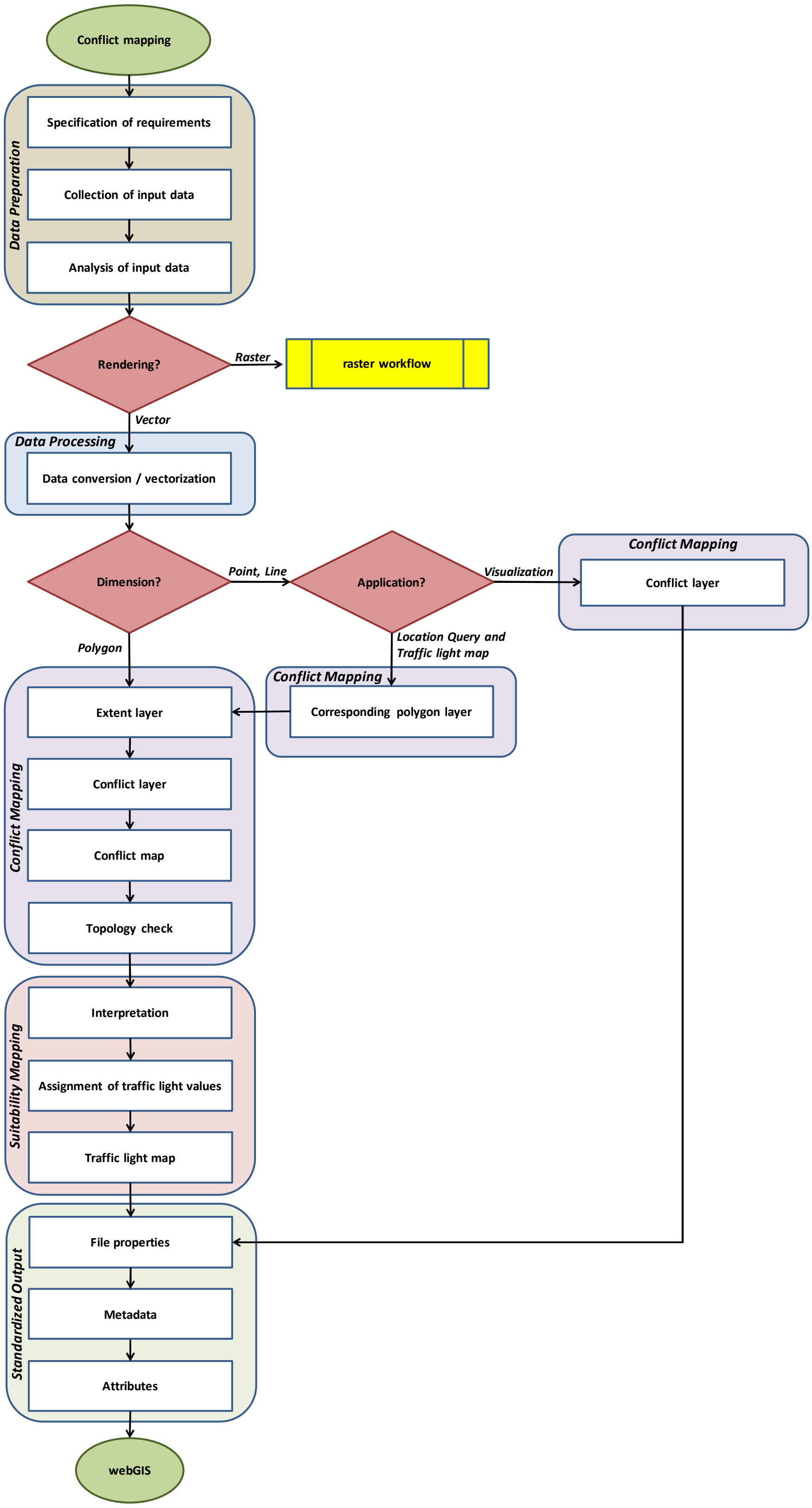


Figure 4: Workflow applicable to vector data.

G.1 Specification of requirements
Identify relevant hazards and land-use conflicts. Define target group and specify required outputs.

G.2 Collection of input data
Compile existing data.

G.3 Analysis of input data
Evaluate data quality, data density, extent and formats. Determine suitability. Acquire new or additional data if necessary.

R.1 Master Grid
Select suitable resolution (raster cell size) common to all outputs. Create master grid (snap raster) to ensure cell alignment of all raster data.

R.2 Data Conversion / Rastering
Conversion of vector data into raster data if required. Resampling of raster data with required resolution.

R.3 Extent Layer
Identification of locations with data available (value = 0) and no data available (value = -9999). One extent layer for each conflict required.

R.4 Conflict Layer
Classify conflict data according to the data classes defined in DT2.3.1 Annex 8. Cell values are the conflict categories.

R.5 Conflict Map
Combine extent layer and conflict layer by selecting max. cell value for each location.

R.6 Interpretation
Assign a traffic light value 1, 2 or 3 (representing green, yellow and red) to each conflict category.

R.7 Assignment of traffic light values
Reclassify the value (conflict category) of each conflict map with the respective traffic light values.

R.8 Traffic light map
Combine all reclassified conflict maps by selecting the max. cell value for each location.

R.9 File properties
Refer to DT2.3.1 and annexes for correct reference system, NoData-value, file name and file format.

R.10 Metadata
Complete link tables and metadata table correctly to enable data transfer to webGIS.

G.4 webGIS
Submit data to webGIS host for verification and publication.

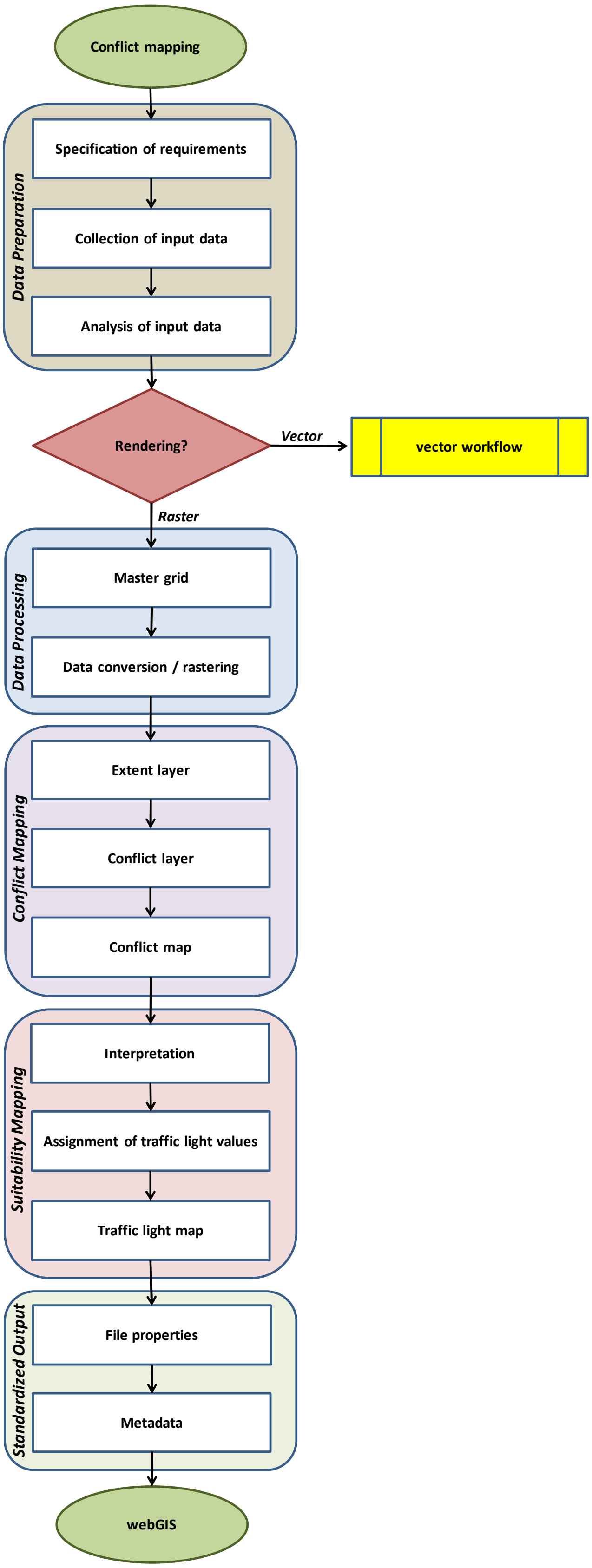


Figure 5: Workflow applicable to raster data.

During the first step, Preparation, the requirements are specified. It is necessary to identify the target group and their needs and their requirements regarding the content (conflict parameters) and the spatial resolution. This step forms the base of all further activities and should be performed with due care. All available input data are compiled and analysed with respect to their suitability for these requirements, e.g. data extent, data density, and data quality. If necessary, additional data has to be acquired.

During the second step, Data Processing, the data is processed to obtain consistent input.

During the third step, Conflict Mapping, maps depicting land-use conflicts are created: An extent layer is created for each data layer (referred to as a “conflict”). The extent layer distinguishes only between areas for which data are available and areas for which no data are available, without further describing the data itself. A second layer, the conflict layer, categorizes information about those areas for which data is available and conflicts are present (e.g. which water protection zone) or known to be absent (e.g. there is no water protection zone). Combination of these two layers results in a map with full coverage which distinguishes between areas where

- there is no data available relating to this conflict, i.e. it is not known whether the conflict exists or not,
- it is certain that there are no conflicts,
- conflicts are present and categorized.

During the fourth step, Traffic Light Mapping, the conflict maps are interpreted with respect to their impact on the feasibility of a) an open loop and b) a closed loop geothermal installation. Each conflict category is evaluated and rated on a scale of 1 – 3. The value one (“green”) indicates no conflict, i.e. the conflict category does not impact on SGE and installing an SGE system is generally possible. The value two (“yellow”) is assigned to conflict categories where

- further information is required (i.e. no data is available, or a case-by-case decision has to be taken),
- stipulations restrict the use of shallow geothermal energy or specify details of the geothermal plant (e.g. limitation of drilling depth or usage of specific grouting material),
- hazards are present and have to be mitigated during the implementation of an SGE system.

The value three (“red”) is assigned to conflict categories, which usually prevent the installation of a SGES.

All conflict maps are evaluated as above. All interpreted conflict maps relating to closed- and open loop systems are combined to individual traffic light maps. The value shown in the traffic-light map is the maximum value which is specified for each location by all relevant conflicts.

During the last step, **Standardized Output**, the created outputs are converted to the properties required by the Web-GIS, e.g. file format, reference system and file name. All relevant metadata has to be provided in the correct form.

7.3.2 Preparation

A conflict is a disagreement of aims. In the context of shallow geothermal use, it means a land-use conflict, which may arise when one portion of land or of the subsurface is exposed to more than one uses.

A hazard describes conditions that may negatively impact the safe installation or operation of a shallow geothermal system.

In order to plan a shallow geothermal installation, the hazards and land-use conflicts have to be known by the user, planning office, drilling company and authority.

The first step of mapping land-use conflicts and hazard risk is to develop an inventory of possible hazards and conflicts. **Table 2** lists examples which may serve as a starting point.

After the relevant conflicts and hazards have been identified, existing data has to be collected and evaluated. The following aspects should be considered:

- Data quality,
- Extent and coverage (gaps),
- Data density.

If necessary, additional data has to be acquired to improve data density, obtain full coverage, or verify data points.

Once sufficient input data of suitable quality has been collected, each data set has to be analysed with respect to its structure:

- Is the data model raster or vector?
- Is the relevant attribute binary, categorial, sequential, discrete or continuous?
- What is the dimension – is it point, line or polygon data?

A table helps sorting the input data according to these properties, because the processing steps are the same for objects of the same data structure, irrespective of the various contents described by the data sets.

A major decision has to be taken at this time: Should the output be presented as raster or vector data? The answer to this question is of significant impact and should not be taken lightly. Reversing the decision later means that all work completed beyond this point will be going to waste.

The workflow for the generation of conflict maps and traffic light maps separates here into its two main parts. All data have to be converted to the same data model. If the workflow for raster data is used, inaccuracies due to the raster size will occur. Therefore, if the input data are mainly available in vector data models, it is recommended to use the workflow for vector data. If the input data are mainly available as raster data, the inaccuracies exist from the very beginning and the workflow for raster data can be used, which saves the data transformation steps.

Table 2: Risk and conflict factors for shallow geothermal use.

Group	Factor	Effect/impact
Protection zones	Drinking water protection zone	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Curative water protection zone	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Drinking/curative water well	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Industrial water well (mineral water, breweries, chemical and textile industries)	Ground water could be contaminated by drilling activity or by fluids emitted by the geothermal plant
	Floodplain	Area restricted for settlement
	Natural reserve	Region which should develop independently of human influence of any kind
Geology	Mineral formation and transformation, e.g. swellable rocks (anhydrite, clay)	Water injected by a geothermal plant could initiate mineral transformation and lead to damage of houses and infrastructure
	Aquifer is existing (minimum thickness and yield)	Installation of an open loop system is possible
	Significant change of groundwater table	Could initiate ground motions due to hydrostatic changes caused by open loop systems, which might cause damages in the surroundings of the geothermal plant
	Confined or artesian aquifer	Could cause water eruption in the drilling hole, leading to difficulties in sealing the borehole heat exchanger properly
	Hydraulically separated aquifers	Drilling into hydraulically separated aquifers could connect them and change the hydraulic system and could cause salinization of fresh water aquifers
	Groundwater mineralization like sulfate containing groundwater	Mineralization can obstruct and destroy open loop systems, grouting material may be altered or destroyed by the mineralized water, efficiency of the heating system decreases
	Karst	Problems for closed loop systems if grouting cannot be conducted properly and cavities remain, impeding heat and fluid exchange of the geothermal plant
	Shallow gas leakage, CO_2, radon, methane	For gas saturated water: While drilling, blow out might occur and cause water or sediment eruptions Radon and CO_2: Health damage possible while drilling and the well bore might create migration paths for the gas Methane: Danger of explosion
	Fault and fracture zones in crystalline rocks	Geotechnical problems could occur while drilling, problems with grouting material are possible
	Quick sand	Well bore is not stable
	Slope of the ground surface	Geotechnical problems possible (the sequence of geological strata, e.g. the existence of clay layers and the dip direction are also important)
Anthropogenic intervention	Existing shallow geothermal use in the neighborhood	This might reduce the efficiency of a heat plant
	Distance to borders (property, protection zone)	Legal restrictions Probably not important for the GeoPLASMA-CE raster size
	Requirement to use district heating	No geothermal plants are allowed by regulation
	Pipelines	Pipelines could be destroyed by drilling activity
	Subway lines	Disturbance of traffic possible, problems with grouting may occur
	Public property	Geothermal use could be prohibited
	Mining concession or licenses	Geothermal use could be prohibited
	Past mining activities and artificial cavities	Problems during grouting are possible
	Contaminated sites	Migration of the contamination possible, surrounding subsurface and groundwater may be contaminated by drilling activity, the well bore might create migration paths
	Old deposits	Migration of the contamination possible, surrounding subsurface and groundwater may be contaminated by drilling activity, the well bore might create migration paths
	Governmental requirements	E.g. limitation of the drilling depth for specific geologic units

Table 3: Raster vs. Vector data

	Raster	Vector
Advantages	• Lower demands on input data quality • Data processing less extensive • Suitable for continuous data such as satellite pictures, scans of analog data • Less comprehensive license or less extensions required for some GIS	• Precise location • High and variable resolution (loss-free zoom) • Overlapping polygons / several conflict categories possible for each location and layer • Attribution possible • Smaller data volume • Faster processing • Selection and editing of individual features possible
Disadvantages	• Fixed resolution • Only one attribute per cell and layer	• Requires topology check (time, license) • High demands on input data quality

7.3.3 Vector data workflow - Data Processing

The vector data workflow is schematically illustrated in **Figure 4**. Vector data can be obtained by converting a raster into point data, i.e. each raster cell is represented by a point (located in the cell center) with a single attribute, the raster value.

Analog data can be scanned and automatically converted to point, line, or polygon data. Automated conversion usually requires comprehensive verification and manual correction.

Analog data can be digitized manually which is usually very time consuming. When digitizing data, it is advisable to assign attributes to each feature as it is created.

For all of the above, further attribution is necessary.

Attribute data is that part of geodata, which contain thematic information about a spatial object, such as a property or category. Attribute data provides characteristics about spatial data. Attribute data is usually appended in tabular format to spatial features.

The attribute table has to include an integer field “conflict” which contains the conflict category as defined in the “D.T2.3.1 Set-up of harmonized data management infrastructure”, Annex 8, https://portal.geoplasma-ce.eu/. This field is required for the creation of conflict maps and for executing a location query via the web information system. Important: The field name is case-sentisive and the inclusion of additional characters (such as blanks or underscores) will prevent automatic import into the webGIS. In order to minimize access time to the outputs via the internet and to reduce data storage requirements for the webGIS host, data layers submitted to the webGIS should not contain any other attributes.

For all conflict layers, a conflict category of 0 signifies absence of conflict, and a conflict category of 1 signifies the presence of a conflict which is not further categorized. Most conflict layers allow further categorization, e.g. for the conflict “anthropogenic lines”, there are – in addition to the categories 0 and 1 – separate categories for electric lines, gas lines, water pipes etc.

The conflict category 0 – known absence of conflict – is treated exactly like the other conflict categories.

Each feature (whether point, line or polygon) has to have a value for the field “conflict”; this field may never be blank or contain values other than those specified in “D.T2.3.1 Set-up of harmonized data management infrastructure”, Annex 8, https://portal.geoplasma-ce.eu/.

Line- and point data can only be considered in the location query or contribute to the traffic light map if

- a corresponding polygon layer has been created,
- a conflict map has been generated by combining this corresponding polygon layer with an extent layer.

The resulting conflict map has to be made available to the web portal in addition to the point- or line data to be visualized, and the metadata table has to be filled in correctly for both layers referring to this conflict. Otherwise, the point- or line data will be visualized only without further impact, and location queries are not possible for this conflict.

Figure 6 shows the conversion of line- and point data to polygon features. This can be done by constructing the convex hull around all features, which might be reasonable for a mine with many mining galleries, because unknown galleries might exist. Or it can be done by calculating a buffer, which provides a safety distance for each feature present in the conflict layers. This might be reasonable e.g. for wells, such that you construct a safety distance around each well rather than specifying an outline around the full area where wells exist.

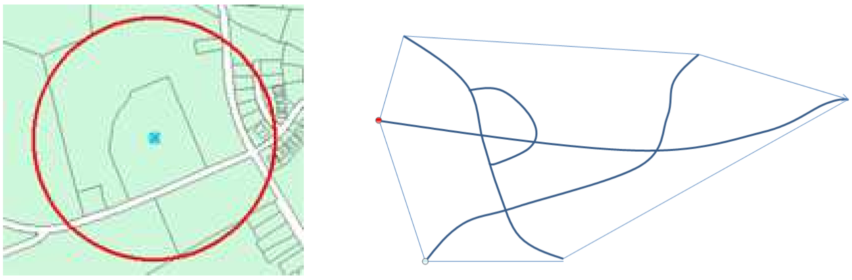


Figure 6: Conversion of point and line data to polygons.

The person responsible for the creation of the conflict maps in each pilot area has to take a decision regarding the size of the buffers surrounding point or line data. If you e.g. generate a buffer around a drinking water well where geothermal use is forbidden, you have to respect regulations as well as the groundwater flux. If you generate a buffer around abandoned mines, you should take into consideration knowledge of the inaccuracy of the old mine maps.

The conflict layer is the polygon layer in which all input features for a particular topic (conflict) are compiled. It contains the geometry and category of conflicts, including areas where conflicts are known to be absent (i.e. conflict category 0). In case of point or line data, a corresponding polygon layer is required if the data is to contribute to the traffic light map and the location query.

The only exception to this rule concerns point or line data that need to be displayed without having any impact on the traffic light maps and without inclusion in the location query report. In this specific case, proceed to chapter 7.3.4. Note that correct attribution of the conflict categories is required for visualization in the webGIS.

The extent layer is a map showing where the data describing one land-use risk or conflict factor are ***not*** available. This information is very important. If it is absent, the impression might be generated that no risk is present when, in fact, it is simply not known whether a risk is present or not. Since the extent layer shows only polygons for which data is ***not*** available and the conflict layer shows only polygons for which data ***is*** available (including those belonging to category 0, i.e. known absence of conflict), the two layers complement each other to cover the entire pilot area without any gaps.

Areas with known absence of conflict are indicated in the conflict layer.

If the conflict layer contains point- or line data, a corresponding polygon conflict layer has to be created first. This corresponding polygon layer has to be utilized to generate the extent layer.

Two cases for specifying the extent layer can be distinguished:

*Case 1: The data set is valid for the whole pilot area (**Figure 4**, left).*

In this case, an extent layer is not required.

Case 2: The data set is only valid for part of the pilot area (**Figure 4**, right).

In this case, an extent layer is required. Proceed with this chapter.

One extent layer has to be created for each conflict. In order to create an extent layer, perform the following steps:

- Create a new data layer,
- Copy the pilot area polygon into the new layer,
- Create a field “conflict” as integer,
- Assign the NoData value -9999 to the entire pilot area,
- Erase the part of the new layer which is covered by data related to the respective conflict.

The result is a map (**Figure 7**) which shows polygons with the “conflict” value -9999 in those areas for which data is absent. Areas for which data is available are not covered by any polygons.

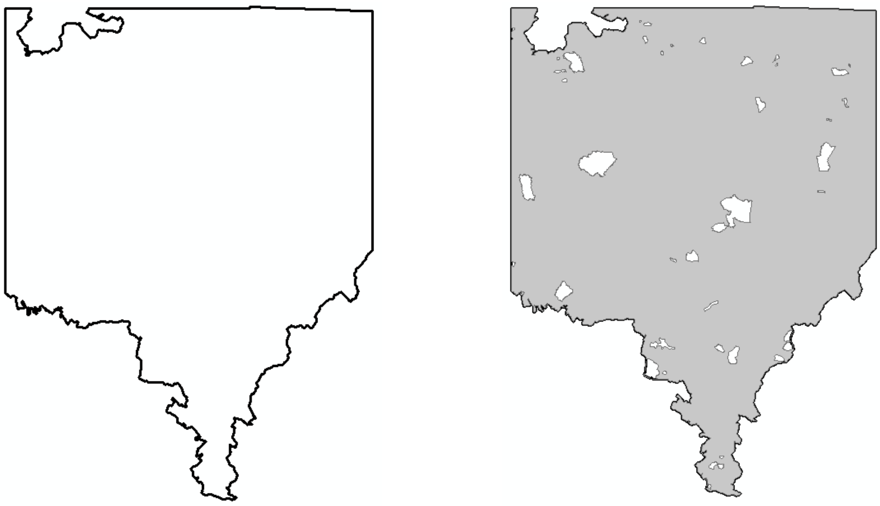


Figure 7: Examples for extent layers. Black: pilot area outline; white: areas for which conflict data is available; grey: areas for which no conflict data is available.

The extent layer and the conflict layer (in case of line- or point data, the corresponding polygon layer) are joined to create a conflict map. In the conflict map, there are no gaps within the pilot area. The “conflict” field of the attribute table contains either the NoData-value -9999 or the conflict category 0, 1, … for each polygon. There may not be any blank lines or invalid data entries in the “conflict” field of the attribute table.

This is a prerequisite for both traffic light maps and location queries via the web information system.

In order to create a conflict map, merge the conflict layer and extent layer. Ensure that the “conflict” fields are merged correctly. If for some reason this is not the case, they have to be manually joined, e.g. in the “field map” section of the ArcGIS merge dialogue, or by copying values into the correct field.

All conflict maps which are to be included in the location query have to undergo a topology check in order to ensure that

- there are no gaps within the pilot area polygon,
- polygons bearing the NoData-value and polygons representing one of the conflict categories 0,1, 2, … do not overlap at any location,
- polygons bearing the value 0 (not conflict present) do not overlap with polygons of the conflict categories -9999, 1, 2, … at any location,
- artefacts which may have been created during data processing are removed.

Conflict maps may contain overlapping polygons, and the location query will return each conflict category as a search result. However, in order to ensure that polygons of higher interest are visible in the conflict map and not covered by polygons of lesser interest, a ranking of conflict categories has to be performed for conflict maps containing more than one conflict category. The ranking has to be entered in the corresponding link table and will be applied by the web services provider. The ranking is *not* part of the attribute table and symbology settings will not be imported by the webGIS.

In order to assign ranks to each conflict category, open the link table (Excel file) associated with the conflict map. In the column "priority" enter the appropriate value 1, 2, …, n for the rank:

- Rank = 1: The least important ("bottom") conflict category,
- Rank = 2: The second least important conflict category,
- Rank = n: The most important ("top") conflict category.

7.3.4 Vector data workflow - Traffic light maps

The suitability of a location for open loop or closed loop installations is indicated by a simple traffic light system. This step requires the evaluation of the impact of the conflicts and hazards shown in the conflict maps. The interpretation cannot be harmonized across the partner countries - a conflict may have very different impact depending on national regulations, technical standards etc. However, since transnational pilot areas deliver joint maps, the countries involved in a transnational pilot area have to agree on a joint interpretation.

One of the colours green, yellow and red is assigned to every single conflict category contributing towards the suitability map. The evaluation of a particular conflict category may be different for open loop systems and closed loop systems. Polygons of the same conflict category and installation type have to be evaluated the same for reasons of consistency and transparency. The colours are stored in the attribute table in form of the values one, two or three with the following definitions:

1 ("green"): Shallow geothermal installations are generally possible

No conflicts and hazards known.

2 ("yellow"): Attention - more information required

At least one conflict is present. Shallow geothermal use is allowed with special obligations such as limitations of drilling depth, special drilling equipment or grouting material. Or: Information is missing, it is not possible to decide whether shallow geothermal installations are allowed or prohibited. Or: A case-by-case evaluation is required.

3 ("red"): Shallow geothermal installations are generally prohibited

At least one conflict is present that forbids shallow geothermal installations.

In order to assign the traffic light values to each polygon, perform the following steps:

- Prepare a table which contains all relevant conflict categories and their traffic light values,
- In each conflict map, add a new integer field “traffic_va” (ensure correct lower case spelling!),
- Select all polygons belonging to the same conflict category,
- Assign the correct traffic light value,
- Repeat for the remaining conflict categories until every single polygon has been reclassified.

Note that the field “traffic_va” may not be left blank and may contain only the values 1, 2 or 3.

The traffic light map is compiled directly from the reclassed conflict maps without the need for further processing steps. All conflict maps are merged into one shape file. It is not necessary to remove overlapping polygons or to dissolve polygons, but it is strongly recommended to reduce file size and prevent artefacts.

If data quality of one or more conflict maps makes it inadvisable to submit traffic light maps as vector data, a raster map may be submitted instead. However, submitting a mixture of raster and vector data will lead to inconsistencies in the location query close to polygon borders, due to the inevitable loss of precision when rastering, and is not recommended (**Figure 8**).

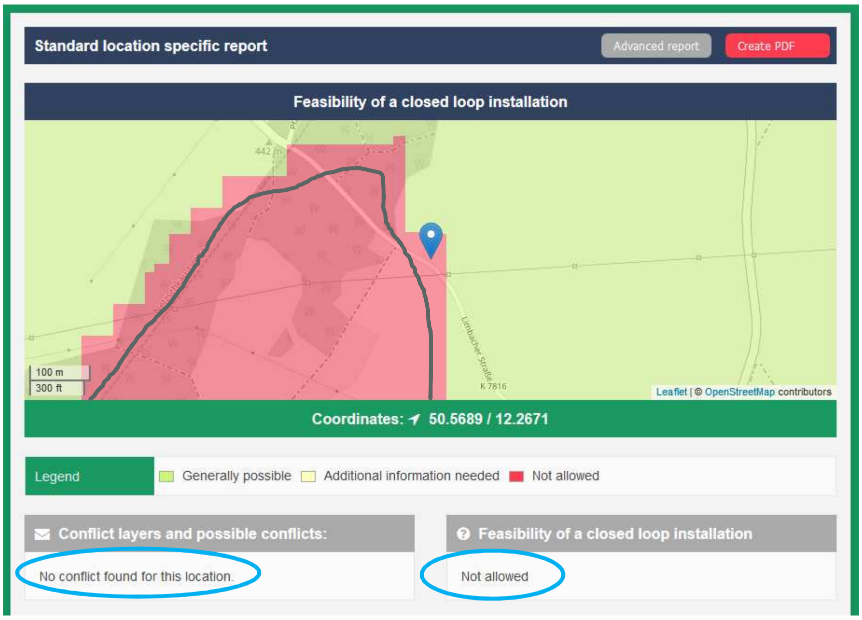


Figure 8: Inconsistent information caused by mixing vector data and raster data.

In order to compile the traffic light maps, perform the following steps:

- Merge all reclassified conflict maps relating to open loop systems and ensure that the field “traffic_va” is merged correctly,
- Combine all polygons of the same traffic light value into one polygon (dissolve), i.e. obtain max. 3 polygons in total,
- Select the polygon with the traffic_va = 3, then clip and erase all intersecting polygons,
- Select the polygon with the traffic_va = 2, then and clip and erase all intersecting polygons.

This procedure has to be repeated with all conflict maps relating to closed loop systems.

7.3.5 Vector data workflow - Standardized output

Before submitting the conflict map, ensure that all relevant specifications are adhered to. Refer to DT2.3.1 Set-up of Harmonized Data Structure including annexes for detailed information and examples of file name convention, link tables etc. Non-compliance with the specifications will lead to rejection of the data by the webGIS host. The checklist below can be used to ensure that all specifications are met:

- Ensure that reference system and datum are correct,
- Output format is ESRI .shp of one of the following dimensions: point, line, polygon (preferably without Z or M values),
- Point- and line data has to be accompanied by a corresponding polygon conflict map if it is to be used for location queries/part of traffic light map,
- The conflict maps contain only one attribute field “conflict” (integer). Permitted values of the “conflict” field are either the NoData value -9999 or the conflict category 0, 1, … whereas blank fields are not allowed,
- Polygons bearing the NoData value -9999 may not overlap with any other polygons within the same conflict map,
- Polygons bearing the category value 0 (known absence of conflict) may not overlap with any other polygons within the same conflict map;
- The traffic light maps contain only one attribute field “traffic_va” (integer). Permitted values of the field are 1, 2 and 3 whereas other values or blanks are not allowed,
- No gaps are allowed within the pilot area outline; this applies to conflict maps and traffic light maps,
- Ensure a link table is filled in for each conflict map. In case of line- or point data, the link table has to be completed for the corresponding polygon layer,
- Ensure the metadata table is filled in correctly for all layers, including those with point or line data,
- Verify that all file names adhere to the naming convention.

7.3.6 Raster data workflow

The raster data workflow is schematically illustrated in **Figure 5**. The logical steps of data preparation are the same as in the vector data workflow. Input data in the vector model have to be converted into raster models. Only one numerical attribute can be specified for a raster data set. For each conflict, a conflict layer and an extent layer have to be produced. Both layers can be combined by an if–then command, specifying, that the attribute values of the conflict layer have to be used, if the extent layer has the attribute representing that data are available.

As preparation for the production of the traffic-light maps, a reclassification has to be performed assigning all attribute values of one conflict layer to the attributes 1… shallow geothermal installations are generally possible (green); 2… attention: more information required (yellow); 3... shallow geothermal installations are generally prohibited (red). All reclassified conflict maps have to be combined to one single traffic-light map by calculation of the cell maximum (local cell statistics).

Export all maps in a data format using the specifications given in “D.T2.3.1 Set-up of harmonized data management infrastructure”, https://portal.geoplasma-ce.eu/.

7.4. Important harmonized rules, specifications and workflow steps for thematic maps on land-use conflicts and risk factors

1. **Specifications for the modelling domain**

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters
Mastergrid	specify raster extent and resolution
List of harmonized outputs	specification of parameters, units and categories

2. **Data preparation**

   Preparation of a list with relevant factors of land-use conflict and risk

   Collection of input data

   Analysis of the data structure of the input data

   Decision for either the vector or the raster data workflow

3. **Generation of conflict maps**

   Transformation of all input data sets to one data model (vector or raster)

   Specification of a data-extent layer for each conflict layer

   Assignment of attributes describing the conflict

   Combination of conflict and extent layers

   Setting the Geoprocessing environment to the master grid coordinates, extent and resolution

   Standardization of output for each conflict or risk factor

   Complete the metadata table

4. **Generation of traffic light maps**

   Interpretation of the conflict data concerning the three suitability categories due to their impact on the use of shallow geothermal energy

   Assignment of the attributes of the three traffic-light categories to all conflict layers

   Combination of all conflict and extent layers such that the maximum value of all layers is displayed for each location

5. **Standardized output**

   Setting the Geoprocessing environment to the master grid coordinates, extent and resolution

   Standardization of output in raster format

   Complete the metadata table

8. Problematic groundwater bodies

8.1. Purpose and use of the workflow

Specific groundwater chemistry conditions might lead to operational problems of shallow geothermal use and hence an increase of operational costs, if they are not already known in the planning phase. This workflow provides a guideline to identify and characterize groundwater zones affected by potential operational risks of shallow geothermal use due to scaling or corrosion. It contains proposed working steps, methodological approaches and joint minimum standards to be fulfilled. The description of individual working steps follows a chronological order from the assessment of archive data and operator's experiences to the compilation of output data layers for the web presentation.

8.2. Evaluation of the workflow

After compiling the initial catalogue of workflows, some partners reported the need of information about the groundwater chemistry in their pilot areas due to known cases of areas with problematic groundwater chemistry, which led to complications of shallow geothermal applications. Therefore, we decided to include a workflow for problematic groundwater bodies. Three partners provided feedback on the first version of this workflow, which was implemented in this following final version of the workflow.

8.3. Adapted workflow

8.3.1 Overview

The workflow addresses natural chemical conditions in shallow groundwater bodies, which may lead to scaling or corrosion in groundwater wells or corrosion in borehole heat exchangers. We aimed at simplified methods allowing giving an indication of such zones based on analysis of groundwater samples. Complex numerical calculations using standard software like PHREEQ-C are not part of this general workflow but may be used upon case to case decision for validation purposes. **Table 4** shows operational problems related to chemical groundwater properties included in this workflow.

In this evaluation we do not consider scaling effects related to microbiological activity (fouling) due to its complexity of occurrence that need to be studied in more detail.

The risk factors are related to critical thresholds, which can be expressed by saturation indices or critical values of one or several groundwater characteristics. The indices or critical values are valid for present groundwater conditions and the thresholds values cannot be simply applied to groundwater with different chemical or temperature conditions. The updated workflows provide a simplified joint approach to determine these thresholds related to the before mentioned detailed risk scenarios. The updated workflows will also provide joint minimum standards and recommendations (**Table 5**).

Table 4: Risk scenarios and associated risk factors.

Risk scenario	Risk factor
A.1 Scaling of Iron (Fe) and Manganese (Mn)	• High concentrations of iron or manganese dissolved in groundwater • High content of present oxygen and neutral to alkaline conditions • Organic acids present in groundwater related to anthropogenic contamination can cause the enrichment of dissolved Fe, Mn.
A.2 Scaling of carbonates	• High content of hydrogen carbonates (HCO^{-}_3) • High content of CO_2 in groundwater • Significant temperature changes in the groundwater used in the open loop circle (only valid for temperature changes far above 6K)[1] • Significant changes of pH value of groundwater to alkaline conditions can lead to carbonate precipitation.
B.1 Corrosion of casings / heat exchangers	• High content of chlorine (Cl^-) or sulphates (SO_4^{-2}) in the groundwater • Oxygen content > 2 mg/l or 20 % • High content of H_2S in the groundwater • Low pH
C.1 Corrosion of grouting / cementation of borehole heat exchangers	• High content of sulphates (SO_4), carbonate dissolving carbonic acid CO_2, ammonium (NH_4^+), Ammonium ($NH_{4\ aq.}$), magnesium (Mg) in the groundwater • Low pH

Table 5: The general workflow and recommendations and standards proposed by GeoPLASMA-CE.

Task	Recommendation / minimum standard related to the harmonized workflows
Assessment of existing archive data and experiences of operators: hydro chemical analyses and in-situ measurements at wells or springs	• Parameters to be assessed • Plausibility and quality checks
Data processing of literature and archive data based on single datum points and interpretation	• Calculation of saturation indices based on Langelier Index (corrosion and scaling related to carbonates) • Identification of critical thresholds for precipitation of iron and manganese • Identification of detailed risk scenarios based on a joint characterization scheme
Additional field measurements in wells and springs	• Parameters to be assessed • Quality standards on measuring the oxygen content
Integrative characterization of groundwater bodies	• Joint rules for assigning attributes to groundwater bodies (e.g. ISO_5667-11-1993).
Data compilation for web presentation	• Creation of data layer • Applying the joint legend related to risk scenarios • Joint annotation notes related to the risk scenarios

[1] Referring to the German guideline VDI 4640, Blatt 2 (2001a) temperature changes at a moderate level (<6 K) do not lead to scaling of carbonates in groundwater wells.

8.3.2 Assessment of existing archive data and experiences of operators

In a first step assess the following input data for the aquifers, which you want to investigate. If you are interested in risk scenarios for open loop systems, prepare the outline of aquifers suitable for open loop systems according to the workflow in chapter 11 – open loop systems. If there are multiple groundwater stories above each other, prepare the following steps separately for each one.

Input data:

- Existing groundwater observation wells,
- Existing chemical analyses or publications related to the chemical composition of groundwater bodies existing in your pilot area,
- Existing open loop systems including contact details of operators,
- Operational problems indicating scaling/corrosion reported by operators.

Please note that relevant chemical components and physical attributes needed for the evaluation of risks are listed in Table 7.

In a next step, create an **internal database** showing the location and type of object (observation well, spring or open loop system utilization) as well as the availability of the parameters listed in **Table 4**.

Then digitize and compile the latest available datasets and perform a **preliminary plausibility check** based on the ion-balance. You may use the "accuracy-calculator" provided by Lenntech (2019, **Table 6**).

Table 6: Thresholds proposed by the calculator of Lenntech.

Concentration (Σ_{anions})	Acceptable residuals
0 - 3.0	±0.2%
3.0 -10.0	±2%
10.0 - 800	±5%

Do not use analyses having ion misbalance greater than shown above.

If archive data of single wells are available for a time series, it is necessary to prepare the data before elaborating the risk parameters as described in the next step. Instead of using maximum or minimum values within a data series, please use percentile 10 (representing the minimum) and percentile 90 (representing the maximum). In this way, the effect of outliers can be minimized. In Microsoft Excel the functions PERCENTILE or QUARTILE are suitable to calculate the percentiles.

Apart of literature and archive data, also **assess existing experiences of open loop system operators and experts from authorities or installers as well as geo-engineers at planned location**. Ask them if any operational problems have been observed at their related installation or if zones of operational problems are known to experts. Operational risks may cover:

- Reduction of yield at wells or enhanced electricity consumptions,
- Blocking of heat exchangers by scaling or observed coating,
- Need of well cleaning or frequently cleaning of filters necessary.

If operational problems have been observed, please ask for the possibilities of local inspections and sampling, if possible. Mark operating open loop systems in maps and your internal database.

Table 7: Parameters and physical attributes needed to evaluate the risk of scaling and corrosion.

Parameter	Unit	Relevant for risks shown in Table 3
O_2	% saturation (mg/l)	A.1 Scaling of Iron (Fe) and Manganese (Mn) B.1 Corrosion of casings / heat exchangers
pH	--	A.1 Scaling of Iron (Fe) and Manganese (Mn) A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
O_2	mg/l	A.1 Scaling of Iron (Fe) and Manganese (Mn) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
Electric conductivity	µS/cm	A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
Eh	mV	A.1 Scaling of Iron (Fe) and Manganese (Mn)
Temperature	degC	A.1 Scaling of Iron (Fe) and Manganese (Mn) A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
TDS	mg/l	A.1 Scaling of Iron (Fe) and Manganese (Mn) A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
Fe^{2+}	mg/l	A.1 Scaling of Iron (Fe) and Manganese (Mn)
Mn^{2+}	mg/l	A.1 Scaling of Iron (Fe) and Manganese (Mn)
Ca^{2+}	mg/l	A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
HCO_3^-	mg/l	A.2 Scaling of carbonates ($CaCO_3$) B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
Cl^-	mg/l	B.1 Corrosion of casings / heat exchangers
$SO4^{2-}$	mg/l	B.1 Corrosion of casings / heat exchangers C.1 Corrosion of grouting / cementation of borehole heat exchangers
Mg^{2+}	mg/l	C.1 Corrosion of grouting / cementation of borehole heat exchangers
NH_4^+	mg/l	C.1 Corrosion of grouting / cementation of borehole heat exchangers
H_2S	mg/l (smell test)	B.1 Corrosion of casings / heat exchangers

8.3.3 Data processing and interpretation

Find below evaluations of each risk factor and a formula, which can be used in MS Excel to check automatically, whether a risk is present at a single well, or not. Perform the evaluation of groundwater bodies based on single observation points (e.g. well or spring). If a critical parameter falls below a determined value, please use percentile 10 to perform this check. If a critical parameter exceeds a determined value, please use percentile 90 to perform this check. The result of these checks lead to a binary evaluation scheme (e.g. “1” indicates at least one potential risk and “0” stands for no risks identified at a specific well). Create a list of observation points linked to the likelihood of risks mentioned in **Table 7**.

We have chosen low threshold values in order to apply a precautionary approach in identifying likely risks. That means we have chosen the lowest level of thresholds, which might lead to operational problems of shallow geothermal energy use. In addition, make additional comments inside the MS Excel template or at any other documents on any observations apart of the estimated critical values, especially if reports from operators have been received. Information from the operators can either be included in the database as well or as annotations regarding the output data layer.

8.3.4 Evaluating the risk of Iron (Fe^{2+}) precipitation (risk A.1)

There is a risk of Iron precipitation if the following critical values have been reached **in whole**:

- pH <7.5,
- O_2 content <20%; <2 mg/l ,
- Fe^{2+} content >0.2 mg/l.

Excel formula: IF(AND(ph_p10<7.5 ; Fe_p90>0.2 ; O2_p10<2);1;0)

8.3.5 Evaluating the risk of Manganese (Mn^{2+}) precipitation (risk A.1)

There is a risk of Manganese precipitation if the following critical values have been reached **in whole**:

- O_2 content <20%; <2 mg/l,
- Mn^{2+} content >0.1 mg/l.

Excel formula: IF(AND(Mn_p90>0.1 ; O2_p10<0.2);1;0)

8.3.6 Evaluating the risk of carbonate scaling (risk A.2)

For evaluating the risk of carbonate ($CaCO_3$) precipitation, we use the Ryznar Stability Index (RSI) based on the indication scheme improved by Carrier (1965). The index can directly be calculated at the following online calculator (Lenntech, 2019):

https://www.lenntech.com/calculators/ryznar/index/ryznar.htm

Use either the online calculator, or if you have many wells, it might be more comfortable to use a calculation template.

- Scaling is likely when RSI < 6.0.

Excel Formula: IF(RSI_p10<6;1;0)

8.3.7 Evaluating the risk of metal corrosion (risk B.1)

A risk may occur, if **at least two** of the below listed critical values are met:

- Cl^- content >100 mg/l,
- $SO4^-$ content > 250 mg/l,
- Electric conductivity > 2500 µS/cm,
- TDS > 1000 mg/l,
- RSI indicator >7.5,
- O_2 content >20% (or > 2 mg/l),
- H_2S^- present (> 1mg/l, "rotten-egg odour").

Excel Formula:

IF((Cl_p90>100)+(SO4_p90>250)+(LF_p90>2500)+(TDS_p90>1000)+(RSI_p90>7,5)+(O2_p90>2)+(H2S_p90>1)> 1;1;0)

8.3.8 Evaluating the risk of concrete corrosion (risk C.1)

For evaluating the risk of corrosion related to carbonates, we use the Ryznar Stability Index (RI) based on the indication scheme improved by Carrier (1965). The index can directly be calculated at the following online calculator, or if you have many wells, it might be more comfortable to use the calculation template in the Excel sheet in Annex 4.

Corrosion is likely when RSI > 7.5

In addition, please check the below listed critical values for concrete corrosion with regard to the German norm DIN 030-1:2008-06 (2001).

- pH < 6.5,
- NH_4^+ (Ammonium) > 15 mg/l,
- Mg > 300 mg/l,
- Sulfate (SO_4) > 300 mg/l,
- Carbonate dissolving carbonic acid (CO_2) > 15 mg/l.

Corrosion is likely, when **at least two** of the above mentioned critical values have been reached.

Excel Formula:

IF((RSI_p90>7,5)+(pH_p10<6,5)+(NH4_p90>15)+(Mg_p90>300)+(SO4_p90>300)+(CO2_p90>1)>1;1;0)

8.3.9 Additional field measurements in wells and springs

Additional field measurements in groundwater wells, springs / natural outflows and open loop system wells should be performed if one or more of the below listed cases arise:

- Archive and literature data indicate operational risks, but not all parameters needed for interpretation are available or further consolidation of data needed,
- Problems observed at operating open loop systems,
- Wells close to groundwater bodies closely connected to surface water bodies.

Concerning the sampling and in-situ measurements, the following minimum standards have to be applied:

- Do not sample water from taps,
- Always use pumps for sampling,
- Do not use air lift (Mammut-) pumps,
- *Exchange the volume of the well 1.5 times at least to get representative samples of the ground water*. Take the sample when the parameters pH, T, electric conductivity, O_2-content and redox potential are constant during pumping,
- *Wells*: Take the water sample at least 1.5 meter below the groundwater table and use pumps for extracting the water. If the observed water column is less than 1.5 meters do not use the well for sampling. Pump continuously and slowly not to stir present mud or sediments in the borehole,
- Use sampling containers for in-situ measurements. Supply the sampling container with water for at least 5 minutes before taking samples or performing in-situ measurements,
- Take samples from the bottom of the container and avoid contamination by oxygen,
- Continue in-situ measurements until pH and oxygen values are stable.

How to calculate the required minimum pumped water volume and / or pumping time:

$$V_{min} = 1.5 \cdot \frac{\pi}{4} d^2 \cdot l \qquad (1)$$

d… well diameter (m), l… screen length (m)

If the pumping rate Q (l/s) is known, the required minimum pumping period t_{min} (s) can be calculated by:

$$t_{min} = \frac{V_{min}}{Q} \quad (2)$$

The measurement of the water volume and pumping rate will be done via the sampling container and a watch. Try to use containers with a known volume.

Try to perform repeated sampling at different times of the year to investigate possible variations between wet and dry seasons.

8.3.10 Integrative characterization of groundwater bodies

After you have evaluated all available data reflecting single wells, perform the upscaled interpretation of potentially problematics groundwater zones inside your groundwater body/bodies based on the following principles and working steps:

- Insert the evaluated wells for each risk according to the joint legend as classed post map using hydrogeological maps as base maps. Treat observations reported from operators equal to evaluated wells based on measured values,
- Now try to conceptually define clusters of problematic groundwater zones for each risk. If one single well indicates a problem, define the cluster as problematic. If several risks were identified, create additional categories stating the risks, which occur at the same location,
- If you are not sure to outline the problematic zone due to insufficient number of wells, then try to interpret the zone based on hydrogeological assumptions like recharge mechanisms, groundwater age, groundwater depths and possible interchange with surface waters (rivers, lakes connected to groundwater bodies). Try to seek analogues to regions with a sufficient number of evaluated wells,

- Create the outline of your problematic zones based on conceptual considerations and try to apply a conservative approach. Be aware, we only provide indications of potential risks to raise awareness of investors, planners and installers,
- Document your considerations and concepts for outlining problematic groundwater zones. The documentation will be included in the explanatory notes of the data layer.

8.3.11 Data compilation for web presentation

The map of problematic groundwater zones will be included in the location specific query of the GeoPLASMA-CE web information system. Each pilot area can decide for themselves, if the map of problematic groundwater zones will be shown on the GeoPLASMA-CE map viewer as separate conflict layer or not.

At the web information system, the output parameter will be presented as a **categorical data layer** related to the identified detailed risk scenarios. The raster or vector data will include the following categories (representing the risks specified in Table 4):

- "No risks anticipated",
- "No data available",
- "Risk for scaling of Iron (Fe) / Manganese (Mn)",
- "Risk for scaling of carbonates",
- "Risk for corrosion of casings / heat exchangers",
- "Risk for corrosion of grouting / cementation of borehole heat exchangers",
- If several risks were identified, create additional categories stating the risks, which occur at the same location.

9. Potential of closed loop systems

9.1. Purpose and use of the workflow

This workflow helps to produce thematic maps which show how well suitable one location is for a closed loop system. All calculations of the closed loop potential neglect the flow of groundwater. Therefore, the heat transfer between the borehole heat exchanger and the subsurface is mainly controlled by heat conduction and can be described by Fourier's law. The most important parameters and boundary conditions controlling the heat conduction are the ground surface temperature, the geothermal gradient and the mean thermal conductivity. Additionally, the heat transfer rate in W/m can give an idea about the efficiency of a closed loop system. These parameters are interesting for energy planners as well as for public users.

9.2. Heat extraction rate in W/m

9.2.1 Evaluation

In our first harmonized workflow, the empirical formula used in the "Geothermieatlas" of Saxony (Geothermieatlas Sachsen, 2019), the "Saxon formula" was suggested for calculation of the heat extraction rate. This formula specifies the heat transfer rate in W/m. It is an empirical formula which was determined with simulation software for a standard single-family house with an annual heat production time of 2,400 h/a:

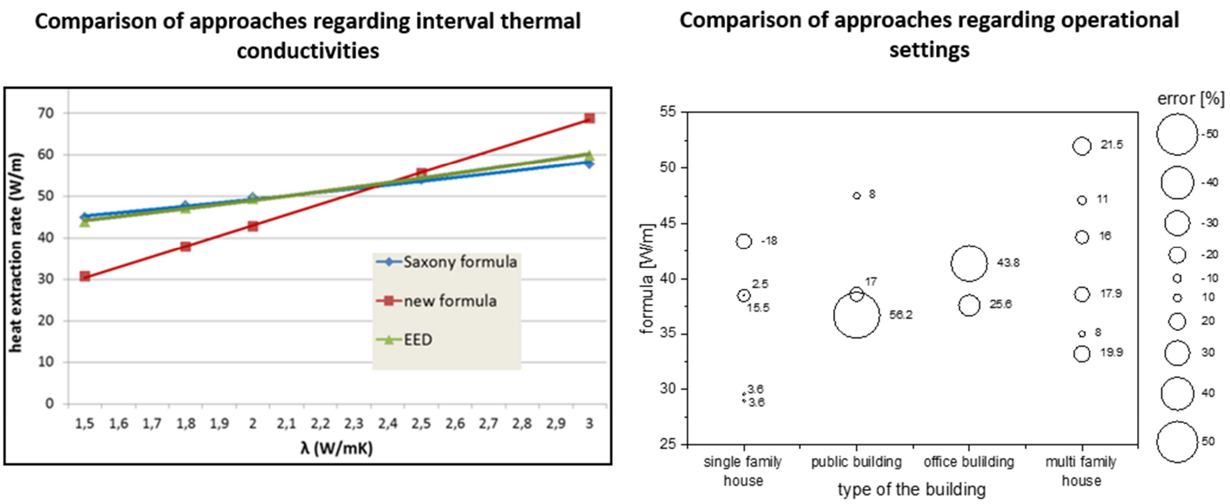
$$HEC = -0.85 \cdot \lambda^2 + 12.39 \cdot \lambda + 26.26 \quad (3)$$

where HEC is the specific heat extraction capacity in W/m and λ is the specific thermal conductivity in W/(m·K).Many assumptions, standardized settings and boundary conditions have to be specified like the undisturbed ground temperature and periods of heating, which vary among the pilot areas, technical parameters of the geothermal plant (borehole diameter, life time), the size of the house (single family standard house) and others. Therefore, the partners decided that this formula is not well suitable as harmonized output for the GeoPLASMA-CE project.

In a next step, we applied the infinite line source approach (Reuss, 2015), which considers the ambient temperature of a subsurface interval and the duration of the heat transfer apart of the thermal conductivity of the surrounding rock.

$$q = \frac{(T - T_0) \cdot 4\pi\lambda}{\ln\left(\frac{4\kappa t}{r_b^2}\right) - \gamma} \quad (4)$$

Where q is the heat extraction capacity in W/m, r_b is the borehole radius κ is the thermal diffusivity in m^2/s, γ Euler's constant, T_0 the undisturbed ground temperature, T the temperature after heat extraction, t the operation time, λ the specific thermal conductivity. The major limitation of the infinite line source method is caused by assuming steady state conditions at the heat transfer. The infinite line source method was tested in the project region Zwickau Altenburg in Germany by comparing it with (1) an empiric formula created by the Saxon State Office for Environment, Agriculture and Geology as well as with (2) the standard software EED (Hellström and Sanner, 2000) for designing borehole heat exchangers. The benchmark test considered the variation of interval bulk thermal conductivities in the test region and different operational settings (single homes, multifamily homes as well as service buildings).



Created by K. Hofmann (Saxony State Office) in the framework of GeoPLASMA-CE).

Created by K. Zschoke (geoENERGIE Konzept GmbH) in the framework of GeoPLASMA-CE).

Figure 9: Comparison of the infinite line source method with an empiric formula and the standard software EED for estimating the heat transfer rate of a borehole heat exchanger.

As shown in **Figure 9,** applying the infinite line source method led to lower heat transfer rates at interval thermal conductivities below 2.35 W/m·K and to an overestimation above the before mentioned threshold value. Referring to different operational settings (operational hours per year and amount of heat transferred between the borehole heat exchanger and the surrounding underground), the best fitting between the line source method and the software EED was observed for single family homes, which still represent the major user of ground source heat pumps. The largest differences of up to ±50% of the estimated heat transfer rates were observed for service buildings, which are affected by special operational settings, which consist of lower number of annual operational hours and different annual energy balances due to combined heating and cooling.

Figure 10 illustrates the results for the calculation of the heat extraction rate for the both formula, the Saxon formula is visualized in red, the line source formula in green. This illustration show, that the line source formula underestimates the heat extraction rate in rocks with specific thermal capacity of < 3 W/m·K, which is relevant for most natural rocks (**Figure 11**).

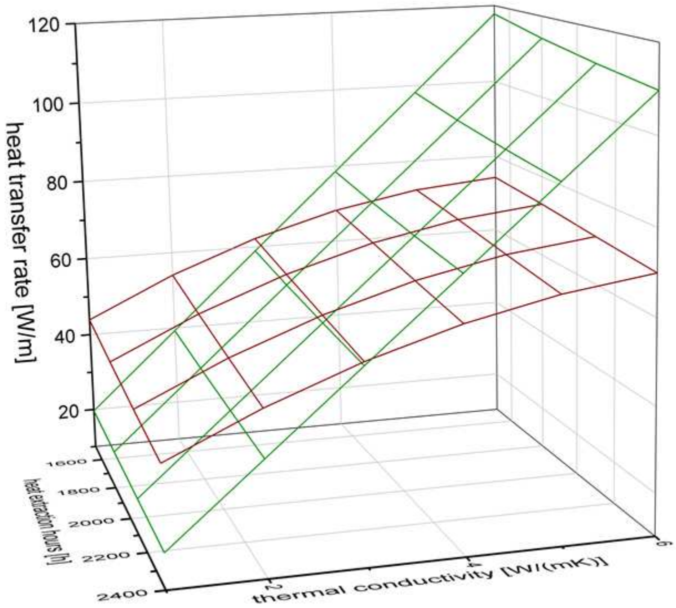


Figure 10: Comparison of the calculated heat extraction rates for the Saxon formula (red) and the line source formula (green).

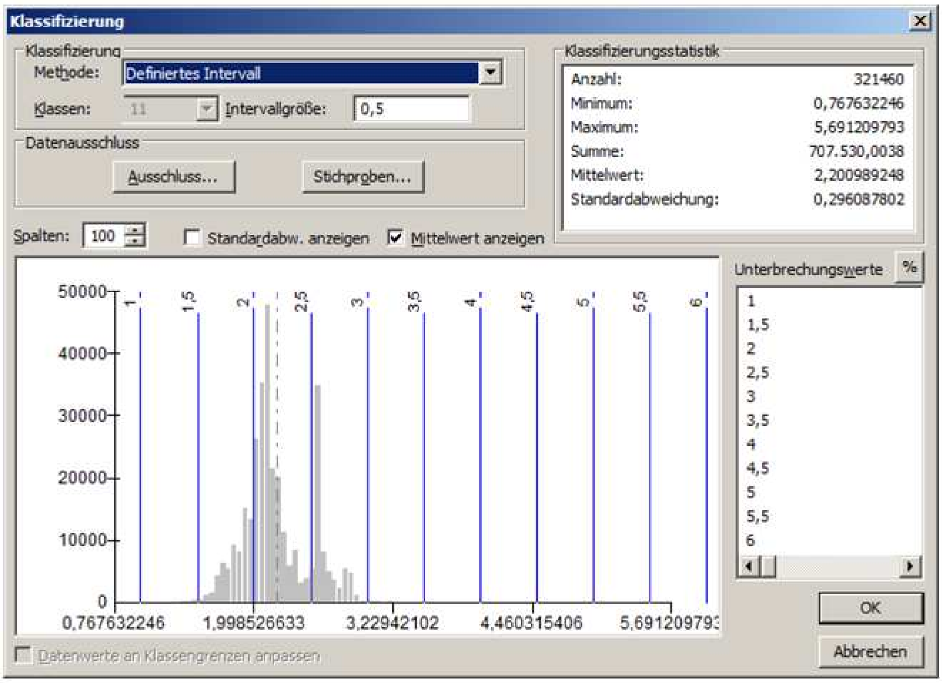


Figure 11: Specific thermal conductivity of rocks for a pilot area in Saxony. The average value is 2.2 W/m·K. the calculated heat extraction rate will be strongly underestimated by the line source formula.

9.2.2 Adapted workflow

The specific heat transfer rate does not solely depend on the subsurface conditions but also needs to account for operational setting and therefore represents a dynamic parameter. Giving an appropriate estimation of the heat transfer rate requires an interactive input of operational settings in web information systems. As such an interface would have exceeded the scope of GeoPLASMA-CE, the project team decided not to include the heat transfer rate in the resource mapping for closed loop systems.

9.3. Average Thermal Conductivity

9.3.1 Evaluation

The workflow or the calculation of the average thermal conductivity uses the 3D model, measurements of the specific thermal conductivity of rocks and the level of the groundwater below the surface as input data. In a first step, the average thermal conductivity for each geological is calculated for dry and wet rock properties. In a second step, the average thermal conductivity per depth level is calculated. This calculation was performed with an ArcGIS add-in which must be delivered for a specific version of ArcGIS. Therefore, all partners had to use the same GIS version. Although a tutorial was delivered with the add-in, some partners had problems to install it and some partners had problems to use the add-in, since they did specify the parameters in a wrong way, used wrong units or filenames.

9.3.2 Adapted workflow

A schematic illustration of the workflow is given in **Figure 13**.The standardized output of the 3D modelling workflow describing the structure of the modelling domain will be used as input in this workflow. A set of geometry 2D grids representing the lithological top surfaces with a resolution of 12.5, 25, 50 m has to be loaded to the ArcGIS software. Additionally, a grid specifying the depth below surface of the groundwater table is required. The software automatically takes the value of the shallowest geological unit as ground surface, such that no digital elevation model has to be loaded.

During the data preparation step, the laboratory and literature data for specific thermal conductivities (wet/dry) collected in the thematic work package (TWP) have to be assigned to the drilling data. In each lithological unit, several petrographic subunits are recorded in the drilling profiles. These subunits describe the variability of the specific thermal conductivity within one stratigraphic unit represented in the model (**Figure 12**). In order to obtain the representative thermal conductivity for each unit, the thickness-weighted arithmetic mean is calculated for each unit as well as both the dry rock and wet rock properties, prior to loading the drilling data into ArcGIS.

The spatial distribution of the representative thermal conductivity of each unit is interpolated in ArcGIS from the weighted mean values for wet and dry rocks with the Inverse-Distance Method. The results are two raster data sets (wet, dry) describing the thermal conductivity at the top of one unit with the same coordinates, resolution and extent as the raster describing the geometry of the unit. If the density of data points is too small to obtain feasible interpolation results, additional artificial nodes have to be added, a mean value assigned to these newly added data points, and the interpolation has to be repeated.

The ArcGIS extension “IE Geothermie”, provided by PP04 (LfULG) can be used to calculate the average thermal conductivity for an interval from the ground surface to a given depth level. The ArcGIS extension provides the possibility to calculate the thermal conductivities in 10 m intervals. The calculation of 10 m intervals is necessary for the location query tool on the GeoPLASMA-CE web tool (for a map visualization of these parameters, a few representative levels may be selected as not all 10 m intervals have to be shown). The raster data set describing the geometry of the geologic units, the thermal conductivity for dry rocks, the thermal conductivity for saturated/wet rocks and the raster specifying the depth of the groundwater table below the ground surface are necessary as input data. The ArcGIS extension calculates the average thermal conductivity down to the depth level. For all units above the groundwater table, the dry thermal conductivity is used as input. For all vertices below the ground water table, the wet thermal conductivity is used.

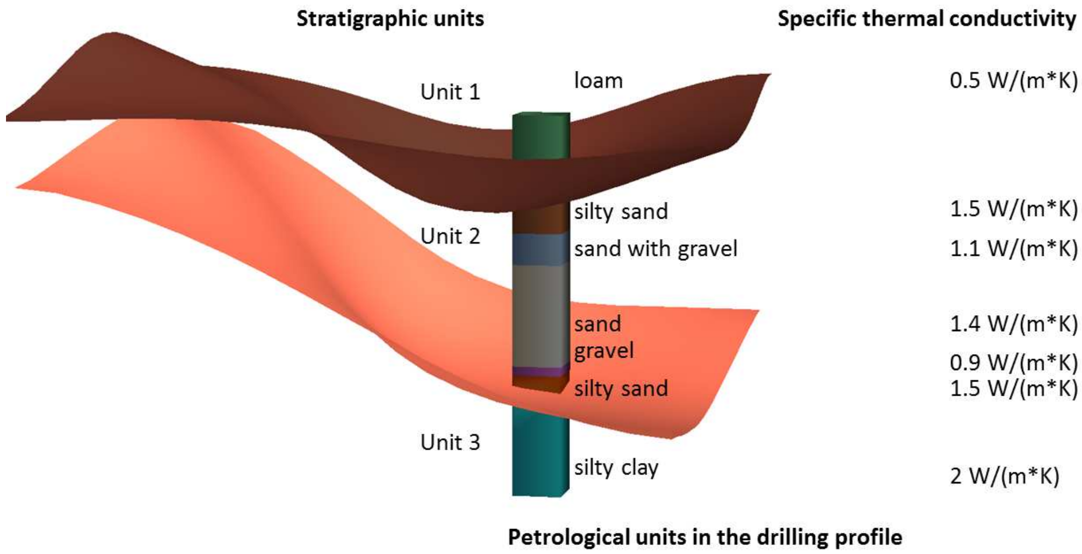


Figure 12: Connection of stratigraphic and petrographic information: A 3D model comprises three units (unit 1, unit 2, unit 3). Each unit has a variable petrography documented in the borehole profiles (unit 2 consists of silty sand, sand with gravel, sand, gravel, silty sand). For each petrography, physical parameters can be specified. A thickness averaged parameter will be assigned to the unit.

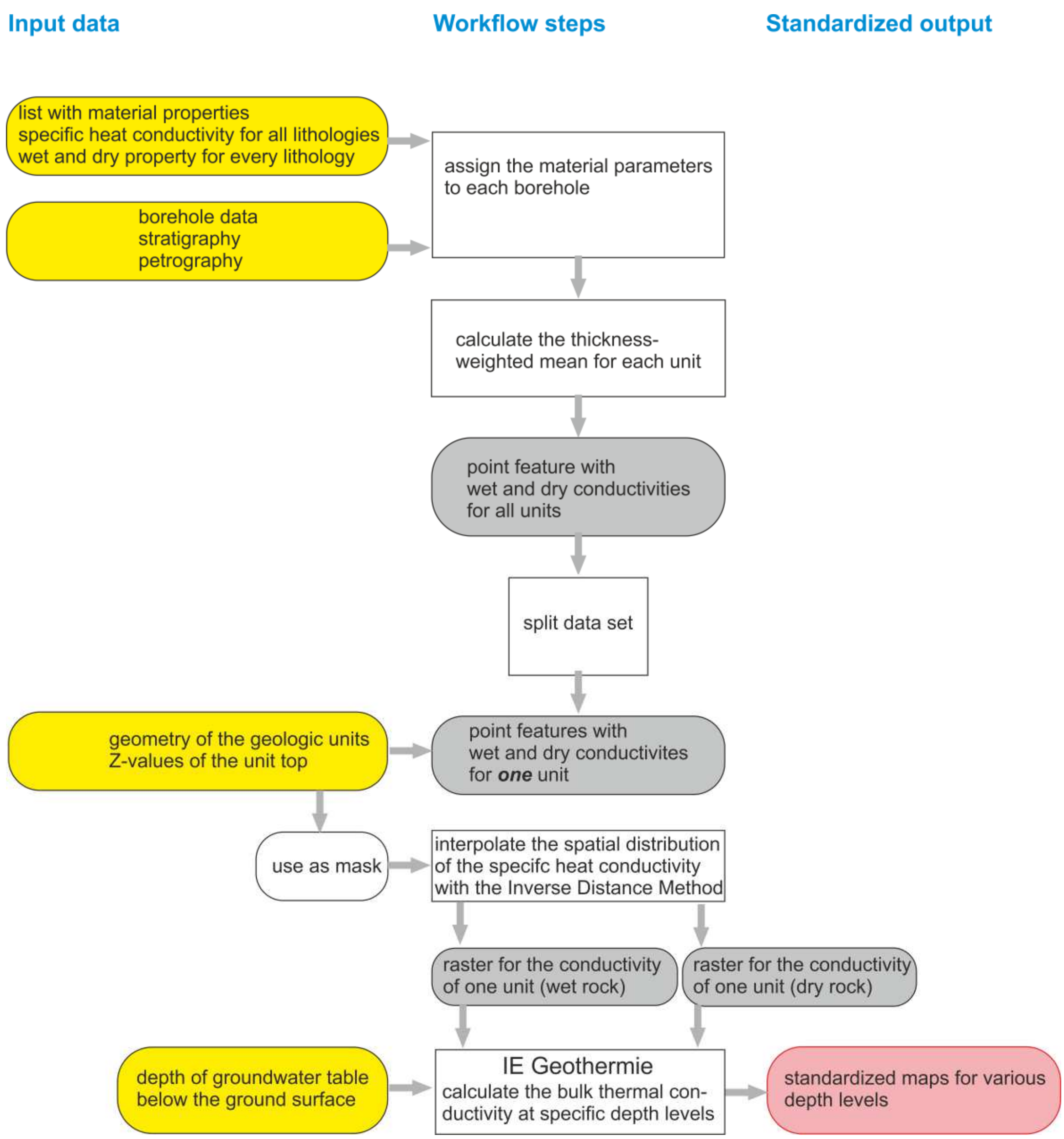


Figure 13: Workflow for the calculation of the potential for closed-loop systems.

9.3.3 Overview over the important harmonized rules, specifications and workflow steps for thematic maps on average thermal conductivity

1. **Input data**

   Geometry data for geologic units

   Depth of the groundwater table below the ground surface

   Borehole data – model units, petrography

   List with rock parameters of the specific thermal conductivity for wet and dry rocks with petrographic description

2. **Processing of the input data**

   Assign the rock parameters to each petrographic layer of the boreholes

   Calculate the thickness weighted mean of the material parameters for each model unit at the boreholes

   Split the data set into one separate point feature per model unit

3. **Quality check the input data**

   Are all borehole data and the geometry data for this unit coincident?

   Are the rock parameters feasible?

4. **Interpolation of the material parameters for the whole geologic unit**

   Interpolate one raster data set per unit for the wet specific thermal conductivities with the Inverse Distance Method

   Interpolate one raster data set per unit for the dry specific thermal conductivities with the Inverse Distance Method

   Use the geometry data from the model unit as mask and snap raster

5. **Quality check of the interpolation result**

   Check whether the interpolation was extended to the whole model unit

   If necessary, digitize additional artificial data points

   Assign the mean rock properties (conductivity dry/wet) to the artificial data points

   Repeat the interpolation

6. **Calculations**

   Calculate the thermal conductivity for various depth levels respecting the location of the groundwater table

   Reclassify the map of the thermal conductivity for the depth level of 200 m as categorial map representing geothermal rock properties

7. **Standardized output**

   One standardized raster data set for each map with the attributes as specified in the deliverable D.T2.3.1 “data management infrastructure”, Annex 1, https://portal.geoplasma-ce.eu/

   Complete the metadata table

   Add object-related attributes to the metadata table

10. Surface temperature, thermal gradient and subsurface temperatures

10.1. Purpose and use of the workflow

For designing a borehole heat exchanger, the average ambient subsurface temperature for its entire borehole length needs to be estimated. One can directly measure the subsurface temperature in new constructed borehole heat exchangers (BHE) ahead of a Thermal Response Test (TRT) or estimate it before constructing a BHE based on the average surface temperature and subsurface interval geothermal gradients.

In an ideal environment, the increase of temperature is controlled by the surface temperature, a seasonal zone influenced by it and a mostly conductive thermal regime, expressed by the geothermal gradient (degC/m). Advective heat transport processes in the presence of groundwater of a significant Darcy flow velocity might also superpose the pure conductive regime. Standard designing software programs like EED (Hellström & Sanner, 2000) follow this approach.

In practice, climate change as well as anthropogenic influences, especially in urban settlements (also known as urban heat island effect) introduces excess heat into the subsurface, which leads to a strong transient temperature signals with wavelengths of up to 10s of metres. **Figure 14** shows a temperature signal measured in a borehole heat exchanger located in the city of Vienna, which is also influenced by an anthropogenic heated groundwater body in depths at about 10 to20 metres. Repeated measurements have been conducted between 2017 and 2018 at a borehole heat exchanger, which was not in use. The measured temperature profile indicates a transient temperature signal caused by a heat wave propagating from the surface to a depth of more than 80 metres. Hence, a workflow has been developed, which determines the geothermal gradient from temperature profiles and enhances the basic linear model in three steps by adding temperature information at the surface and, if available, also within the transient zone.

The output parameters of the workflow developed in GeoPLASMA-CE are able to deliver the following parameters, which are shown at the project related web information system:

- Mean annual surface temperature (degC),
- Average subsurface temperature for a defined depth interval (degC),
- Effective thermal gradient for a defined depth interval (degC/m).

The subsurface temperature was calculated for different depth intervals between 50 and 200 meters below surface, which were defined by the project partners. These parameters can be used as input values for designing borehole heat exchangers with standard software programs like EED for an additional consideration of long-term transient temperature signals.

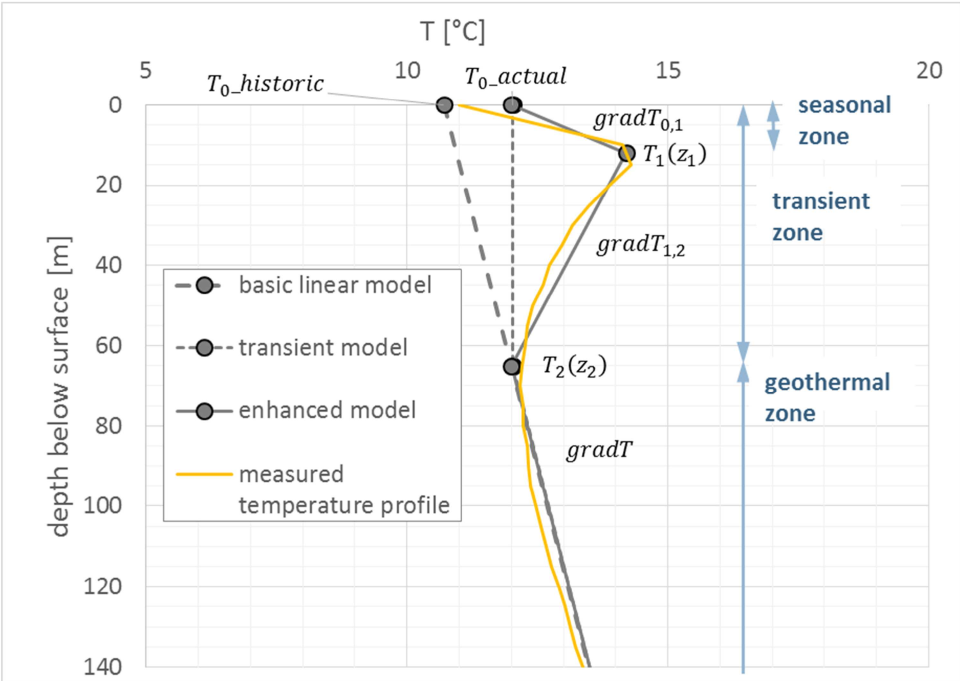


Figure 14: Linear approximation of a transient temperature signal (yellow line) in three steps: "basic linear model" from geothermal gradient extrapolation, "transient model" with actual surface temperature and "enhanced model" with additional temperature information within the transient zone. The transient signal caused by long-term raise of the surface temperature by climate change superposed by urban heat island effects reaches depths of more than 80 meters below surface.

10.2. Evaluation

The initial version of the GeoPLASMA-CE workflows just considered the parameter "surface temperature" to indicate resources of closed loop systems. During the parameter studies and sensitivity studies, we learned that a good estimation of the subsurface temperature is vital for evaluating the capacity of a borehole heat exchanger, expressed by the specific heat transfer rate (W/m). According to the line-source theory, the average subsurface temperature for a defined depth interval shows the same sensitivity as the thermal conductivity of the ambient rocks.

In GeoPLASMA-CE, we elaborated an analytic as well as empiric approach to approximate the transient zone by a **linearization approach**, which consists of the following consecutive thermal zones:

- *Seasonal zone*: Depth interval with variable temperature conditions according to the seasonal change of the surface temperature. The seasonal zone is part of the transient zone,
- *Transient zone*: Depth interval influenced by propagating long term temperature changes at the surface, by changes of the mean annual surface temperature of the last decades. This zone is dominated by transient heat conduction and often shows zero or negative temperature gradients,
- *Geothermal zone*: Depth interval, which is not yet affected by the transient zone and which reflects steady state conductive heat transport caused by the geothermal regime.

10.3. Adapted workflow for the mean annual surface temperature

10.3.1 Input data

The mean annual surface temperature can be derived from the following data sources:

- *Satellite infrared (IR) measurements*: In GeoPLASMA-CE, this was the main data source to create the surface temperature maps. We used MODIS LST data[2] for the period 2000 until 2013. The raster dataset obtains a spatial resolution of 250 metres and a sensitivity of 0.1 degC. The data are free as long as our derived products remain also free (Open Database License). The main advantage of using satellite data is given by the easy access and low processing effort to create temperature maps. The main disadvantage is given by neglecting thermal coupling between the surface and the subsurface and by masking effects in urban areas by IR reflection of sealed surfaces and building roofs,
- *Soil temperature measurements*: In some pilot areas, scattered soil temperature time series are available. These surveys cover the uppermost 1 to 2 metres of the subsurface at selected earth observation stations. The main advantage of such datasets is given by the capability to implicitly consider thermal coupling effects between the atmosphere and the solid subsurface. In contrast, earth observation stations are located at areas, which are not affected by local influences such as sealed surface (urban heat island effect) or strong reliefs (effective solar radiation balance). Moreover, the number of soil temperature observation stations is too small in most regions to directly create maps by interpolations of nodes. In GeoPLASMA-CE, some partners used soil temperature time series to calibrate the surface temperature maps derived from satellite data,
- *Air temperature measurements*: Air temperature observations are mostly operated by meteorological survey organizations and are generally affected by a higher density of stations than for soil temperature observation points. However, air temperature data need to be corrected for the thermal coupling effect between the atmosphere and the solid subsurface. In a first approach, a range between 1 to 2 degC needs to be added to mean annual air temperatures to obtain the mean annual surface temperature. As for soil temperature observation points, it has to be considered that phenomena like urban heat island effects or the annual thermal radiation budgets of the relief orientation may not be considered in these datasets. In GeoPLASMA-CE, some partners used air temperature observations, which were corrected for the thermal coupling effect, to calibrate satellite IR data.

Please note that temperature profiles derived from pre-Thermal Response Test measurements or borehole temperature measurements are not suitable to derive the surface temperature as these data are affected by seasonal variations of the surface temperature and moreover, thermal coupling between the uppermost metre of the brine column in the borehole heat exchanger and the ambient air temperature.

10.3.2 Recommended workflow

Based on the experiences gained in GeoPLASMA-CE we recommend the following processing steps (**Figure 15**):

- *Processing of satellite data*: Download the MODIS LST dataset and choose the mean annual temperature (dataset "BIO1"). Only minor format adaptions (change the dataset from integer to float by dividing through the number "10") needs to be applied. We recommend neglecting datasets

[2] Source: http://www.geodati.fmach.it/eurolst.html

older than 20 years in order to consider climate change effects. Old data might lead to an underestimation of the actual mean annual surface temperature,

- *Processing of soil temperature data:* To avoid filtering effects and thermal balance of the solid subsurface the uppermost vertical observation point, normally in depths up to 50 cm below the surface, should be applied. In a next step, the mean value needs to be calculated for the selected period. We recommend using the latest 10 years of observation. You may approximate the mean annual surface temperature by the soil temperature if the above-mentioned depth limits are given. If datasets from different elevation levels are available, you may calculate an elevation dependent linear regression to project the soil temperature to the entire pilot area by correlating the function with a DHM. For this you need at least 3 soil temperature observation stations in your project area,
- *Processing of air temperature data:* Apply the same routines as for the soil temperature data in case no ready to use datasets of the mean annual air temperature are available. In addition, approximate the thermal coupling between the atmosphere and the solid subsurface by adding a value of 1degC to 2degC to the mean annual air temperature,

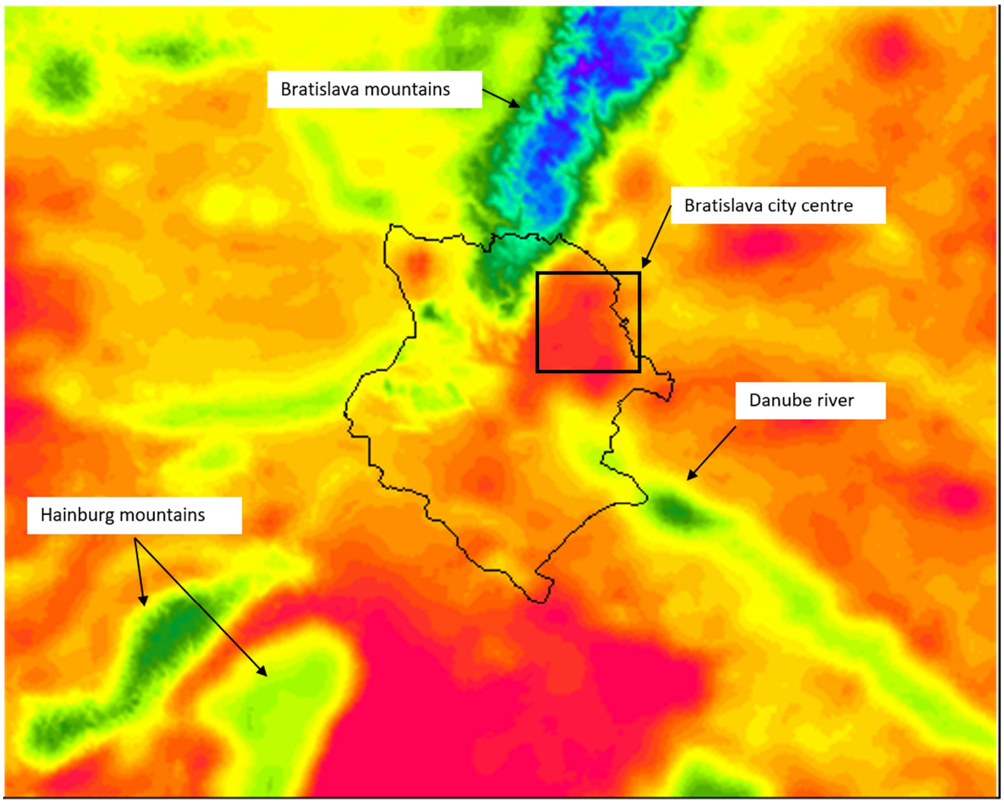


Figure 15: Example of the MODIS LT dataset for the pilot area Bratislava – Hainburg.

- *Validation and calibration of satellite mean annual temperature maps*: Compare the satellite data with observed mean annual soil- or air temperature data at the single locations of observation stations and determine the remaining residual temperatures. If available, calculate the residual temperature distribution as well between mean annual surface temperature amps derived from satellite data and direct observations (e.g. based on interpolation with the elevation of the available observation station). The calculated residual map can be used to evaluate areas strongly influenced by local to regional phenomena like urban heat island effects. Finally, you may add the resulting mean temperature residual to the mean annual temperature dataset derived from satellite data – normally, this should be in the range of up to ± 2degC.

In GeoPLASMA-CE, we did not apply a uniform correction value to the MODIS LST satellite datasets for the mean annual temperature, as the validation step revealed different results. In the pilot area Vienna, no correction needed to be applied while a constant value of +1degC was added to the satellite data in the pilot area Ljubljana.

10.4. Adapted workflow for the subsurface interval temperatures and interval thermal gradients

During GeoPLASMA-CE, we developed an analytic – empiric approach based on available data background in the pilot area Vienna. The so called "standard workflow" was applied for the pilot areas Vienna, Hainburg – Bratislava and Walbrzych – Broumov.

In the pilot area Ljubljana, a slightly adapted workflow needed to be developed as the subsurface temperature regime was strongly influenced by a thick aquifer of high Darcy velocities in some parts of the pilot area. In this area, the depth of the transient zone was set to the depth level of the aquifer, at which no variation of the groundwater temperature was observed. Outside the zones of significant convective heat transport the standard workflow was applied in Ljubljana.

For the pilot area Krakow, two numerical heat transport models (software Petrel) were created for (1) the surface to the base of the seasonal zone, (2) for the transient thermal zone and (3) the geothermal zone beneath the transient zone. The average subsurface temperatures for defined depth intervals were directly extracted from the numerical heat transport model.

10.4.1 Standard workflow (case study Vienna)

This workflow requires data to evaluate the geothermal gradient, at least at one point, and the availability of surface temperature maps as a prerequisite. It may not be applied in case of strong vertical hydrothermal groundwater movement. The workflow might be applied in areas with mainly horizontal groundwater flow, if the groundwater mean temperature is available, as a (interpolated) map, and also for areas with scattered observation data by applying synthetic mathematical models. The measured temperature profiles are used to determine the geothermal gradient, which is usually stable for a large area. Therefore, the workflow gets along with a very poor data density of temperature profiles also. The transient zone, which is usually very dependent on local geology and surface temperature, can change quickly in a lateral small distance. This information is gathered mainly from surface temperature and optional additional temperature information within the transient zone.

Input data for the gradient zone:

- Temperature profile measurements ahead of thermal response tests (TRT) represent the most important data source for estimating the thermal gradients. The highest quality of input data can be achieved by temperature logging in the water or brine filled inner tubes of a borehole heat exchanger (BHE). The temperature profile has to be measured, before the TRT is performed and after a waiting period of at least one week after drilling and BHE completion. If direct measurements in BHEs ahead of thermal response tests are not possible, the temperature profile can be approximated by fluid circulation test without the introduction of heat by the TRT device. By logging the fluid temperature (degC), the flow volume (m^3/s) as well as the flow time (s) during the circulation test you may derive an approximated temperature profile with depth. In both cases, it is very important, that the water colums in the tubes of the BHE is not disturbed, e.g. by filling up the TRT tubes before profile measurement. Please note that the above-mentioned minimum requirements concerning the waiting time after drilling the BHE must be achieved,

- *Temperature logs in drillings:* Scientific- or exploration drillings (e.g. mining, deep groundwater exploration or hydrocarbon exploration) might obtain temperature profile measurements, which could be used as data nodes. However, please be aware that in most of such cases assessing the subsurface temperature conditions was not the primary exploration target. Furthermore, drillings executed in previous periods of more than 20 years should not be considered to estimate the transient thermal zone, as later changes in the mean annual surface temperature may have introduced an additional thermal signal. If conserved scientific or explorational drillings are available in your area of investigations, we recommend performing additional highly precise temperature profile measurements,
- *Temperature and heat flow density datasets:* Local to regional temperature and heat flow density maps can be used to determine the geothermal gradient. Please note that first you need to estimate or assess the average depth of the transient zone's depth level before interpreting geothermal maps. Do not use maps for depth levels inside the transient zone.

Input data for the transient zone:

- *Mean annual surface temperature maps* are necessary to have actual surface temperature and further to determine the base of the transient zone,
- *Groundwater observation wells* can be used to measure the mean annual groundwater temperature, which might act as an important input for the temperature models.

The workflow proposes the following processing steps (**Figure 16**):

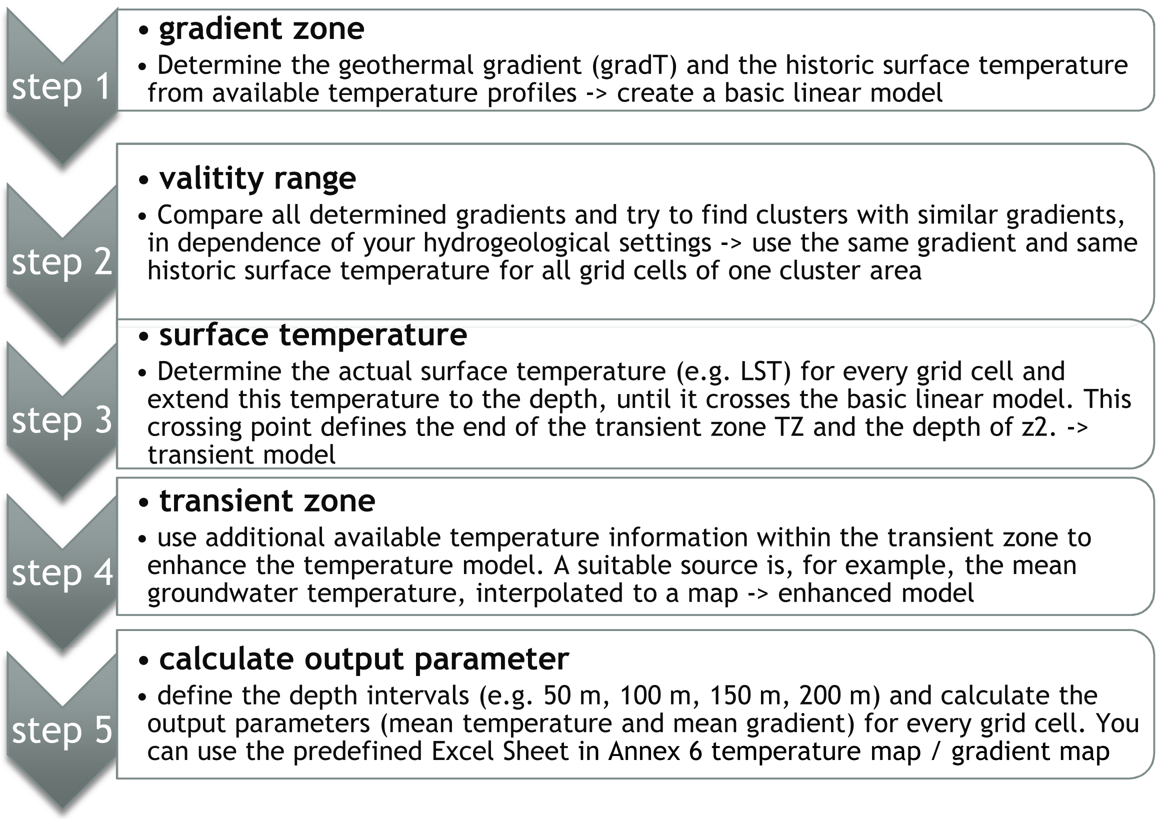


Figure 16: Adapted workflow for calculating the average interval subsurface temperature in the pilot area Vienna.

The enhancement of the linear temperature models are visualized at the example in **Figure 17**. The linear model is gathered from a measured temperature profile. With the actual surface temperature from satellite data of 12.2 °C, the transient model with can be achieved and the depth of the transient zone (z_2 = 46 m) can be calculated. The temperature profile at this location is obviously influenced by an additional heat source (e.g. heat island effect, horizontal groundwater movement). By adding the annual mean temperature information in the shallow groundwater (13.2 °C, 15 m) the enhanced model can be created. The enhanced model can be different in the direct surrounding of the measured profile, if the surface temperature or the groundwater temperature changes, while the gradient remains uniform. The Gaussian model can explain the measured profile best, by adding a temperature change of 2.5 °C for the last 50 years to the surface, originated from the linear model with the historic T_0 of 10.4 °C. At the location a surface temperature change of 1.7 °C in the last 60 years is known. The remaining warming can be explained by urban heat island effects. The Gaussian model can be calculated with the Excel sheet in Annex 6b. This simple analytic heat flow model can be used additionally in areas without temperature measurements and without significant groundwater movement to estimate a geothermal gradient by giving the historic surface temperature and the earth properties.

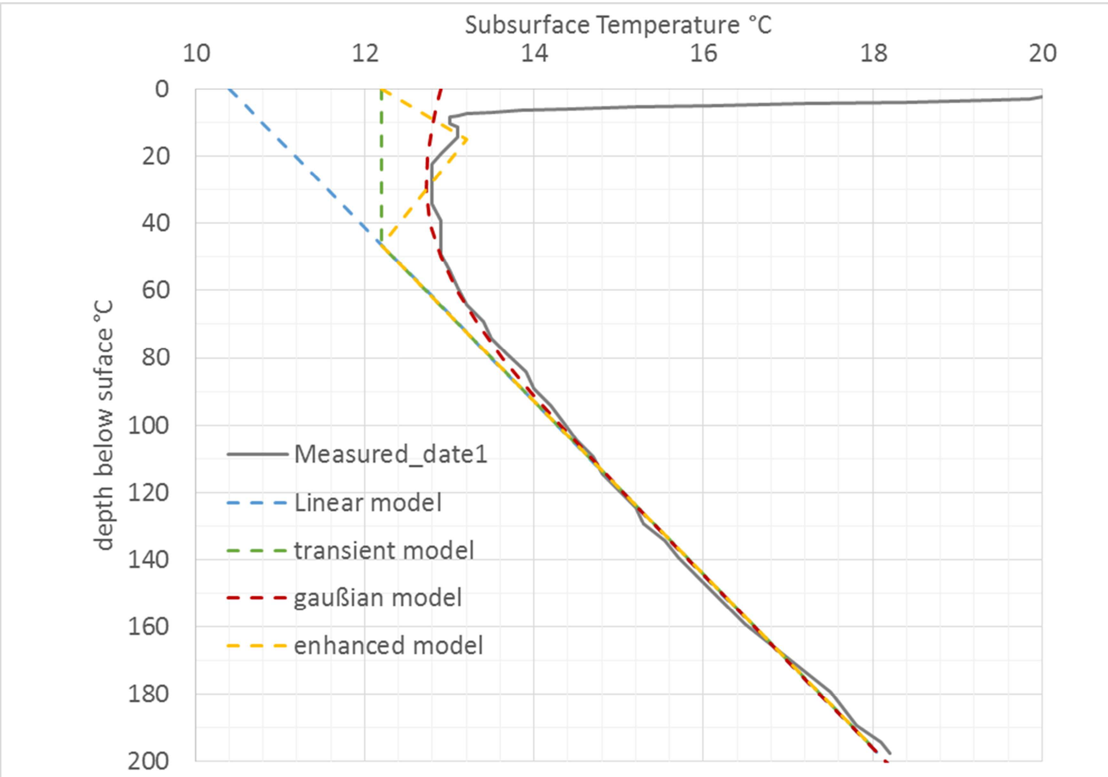


Figure 17: Comparison of the linearized models and the Gaussian model with a measured temperature profile in Vienna. The grey colored line represents the measured temperature profile; the blue line shows the basic linear model by setting a historic surface temperature of 10.4 °C, a heat conductivity of 1.6 W/m/K, a heat flow of 62 mW/m² (results a gradient of 0.039 K/m). With an additional surface temperature change of 2.5 K for the last 50 years, the measured profile can be approximated well by the Gaussian model. By setting the actual surface temperature from satellite data (T0_actual = 12.2 °C) the transient model is determined by extrapolation to the basic linear model. By adding the annual mean temperature of the groundwater the enhanced model (yellow) is ready.

Ad step 1:

The thermal gradient is equal to the pure conductive geothermal gradient and can be either determined from measured temperature profiles (linear regression of measured values) or estimated from thermal conductivity and heat flow density models. Attention needs to be paid for zones with expected great contrasts in the thermal conductivity of the prevailing geological units, which leads to changes of the interval geothermal gradient. In GeoPLASMA-CE, we applied a quality criteria of R^2>0.95 for applying a linear regression on measured subsurface temperatures for estimating the geothermal gradient.

Ad step 2:

There are different approaches for determining the validity area of the gradients:

- *Case 1 – no direct measurements of subsurface profiles are available*: without qualified measurements the gradient has to be estimated. This can be done by applying simple analytical models as the Gaussian model – you can use the Excel tool in the Annex 5. The challenge is to find the correct historic surface temperature, which is very sensitive to the virtual temperature profile. Also the thermal underground parameters have to be estimated. Numerical heat transport models can handle detailed underground parameters but have the same challenge as the analytic Gaussian approach.,
- *Case 2 – only one or a low number of temperature profile measurements are available*: We recommend performing spatial cluster analyses and define zones with similar gradient and historic surface temperature, by considering hydrogeological information,
- *Case 3 – high number of temperature profile measurements (ratio between number of grid cells and observation point is less than 1,000)*: A gradient map can be created and directly be upscaled from single observation points by raster interpolation.

Ad step 3 & 4 - Upscaling of data:

In GeoPLASMA-CE, we applied different ways to create maps for the different interval subsurface temperatures and thermal gradients. In a first step, all partners defined the depth interval for which the data will be calculated. We defined a minimum depth interval from 0 to 50 meters for subsurface temperature- and effective thermal gradient maps to be published. The appropriate way to upscale single observation points to datasets or maps covering the entire area of investigation strongly depends on the availability of nodes (number and spatial distribution of subsurface temperature profiles) as well as on the chosen approach (analytic-empiric standard workflow versus modelling approach). The following input data might be available in terms of raster datasets:

- Surface temperature (derived from satellite data),
- Depth and mean temperature of groundwater bodies (in case of the presence of a relevant groundwater body),
- Geothermal gradient derived from thermal conductivity and heat flow density models.

Ad step 5:

In GeoPLASMA-CE team decided to calculate the mean temperature and mean gradients of defined depth intervals as output parameter. Please note, that not the temperature distribution at a certain depth level but the average temperature over the entire defined depth interval, beginning from surface, needs to be calculated by weighted averaging referring to the thickness of all involved sub-intervals. Another possibility would be, to output the linearized temperature profiles of step 4 with 3 to 5 parameters directly. $T_{0\_historic}$, T_{0_actual} and grad T are necessary. z_1 and T_1 are optionally, defining the enhanced model. T_2 is set to $T_{0\text{-}acutal}$ by definition and z_2 can be calculated. The calculation of the output parameters can be done with the aid of the predefined Excel sheet in Annex 5, by giving at least the main input data ($T_{0\_historic}$, grad T, T_{0_actual}). When the columns for the optionally input data (T_1, z_1,) are empty, the transient model is considered for the grid cell, otherwise the enhanced model is considered automatically.

The following formula gives the weighted average of the subsurface temperature and the temperature gradient for depths (d) greater than z_2:

$$T_{mean}(d) = \frac{1}{d} \cdot \left[\frac{T_0+T_1}{2} \cdot z_1 + \frac{T_1+T_2}{2} \cdot (z_2 - z_1) + T_2 \cdot (d - z_2) + grad\ T \cdot \frac{(d-z_2)^2}{2}\right] \quad (5)$$

$$gradT_{mean}(d) = \frac{1}{d} \cdot \left[gradT_{0,1} \cdot z_1 + gradT_{1,2} \cdot (z_2 - z_1) + grad\ T \cdot (d - z_1)\right] \quad (6)$$

Indices: 0… surface; 1… data point in transient zone, 2…begin of geothermal zone

grad T… geothermal gradient, gradients having indices according to the temperature points of the linearized model (e.g. $gradT_{1,2}$ represents the thermal gradient between T_1 and T_2)

Note that in this approach T_2 can be set to the same value as the surface temperature T_0

Error estimation: We recommend using the direct temperature profile measurements in boreholes for error estimation by comparing the predicted and measured interval temperatures and gradients. We recommend to adapt the subsurface temperature and thermal gradient models in case the remaining error between measured and predicted subsurface interval temperatures and thermal gradient is larger than ±10 %. Of course, the error for grid cells without measurements can only be estimated.

Conclusion and final remark: The linearization approach of the non-linear transient temperature zone can just be considered as a simple approximation affected by prediction errors. We recommend performing subsurface temperature surveys linked to thermal response test measurements in order to amend the empiric background of this approach. For that reason, periodic updates of subsurface interval temperature and thermal gradient models are strongly recommended in case new observation points (direct temperature profile measurements in boreholes) are available in a certain area of investigation.

10.4.2 Applied approach (case study Ljubljana)

Due to the presence of a strong groundwater body (high thickness and Darcy velocity), the pilot area Ljubljana needed to be divided into 3 zones. The Ljubljansko polje area is dominated by the groundwater body, which is controlling the subsurface temperature of the uppermost 10s of metres below surface. The mean annual groundwater temperature for the depth intervals (50, 100, 150 and 200 meters) needed to be derived from numerical thermal-hydraulic model (software FEFLOW), which was calibrated by wellhead- and temperature times series in groundwater observation wells. At the Ljubljansko barje area, we observed subsurface temperature are higher that on the rest of the pilot area, which might be caused by convective heat transport phenomena at a carbonate aquifer below the quaternary sediments, which bears natural thermal water. The average interval temperatures for the different zones were empirically derived from temperature profiles in 17 boreholes in the area. Due to lack of geological knowledge about the bedrock units below the Quaternary sediments it was not possible to extrapolate the temperature to a greater depth then the measured depth of these boreholes. Outside the known coverage of the thermal water convection zones, the geothermal gradient was estimated according to the standard workflow mentioned above. For the remaining part of the pilot area Ljubljana, the above-mentioned standard approach was applied using uniform estimations of the different interval depths (e.g. depth of transient zone was set to 50 meters below surface) and uniform thermal gradients or each interval, as only one borehole temperature profile was available.

10.4.3 Applied approach (case study Krakow)

The Krakow pilot area extends along the Vistula valley, which strongly influences hydrogeological conditions along the axial, west-east part of the city. Furthermore, two main hydrogeological bodies are in the northern (Jurassic/carbonate aquifer) and southern (Tertiary/sandstone aquifer) extent of Krakow administrative boundaries. The limited time in the GeoPLASMA-CE project allowed us to only create a steady state hydrogeological model (without heat transport modelling), what is not enough to evaluate how much these aquifers influence the shallow subsurface temperature regime. Thus, only the heat transport by conduction was taken into consideration, which is unlikely to be fully representing the overall subsurface temperature regime. For the purpose of subsurface temperature model preparation, we have created the database consisting of: 10 thermal logs (continuous curves), a regional models of heat flow as well as temperature gradient distribution - derived from archive deep geothermal atlas. Nine from the available temperature logs came from TRT, whilst one was derived from deep hydrocarbon exploration borehole, performed in 1966. The density of boreholes providing temperature logs in Kraków pilot area is relatively low and equal to 0.03 wells/km^2.

For the top temperature model boundary condition, expressing the mean annual surface temperature, the dataset of the satellite MODIS LST (BIO1) have been used. Due to the fact that the surface temperature amplitude within the Krakow pilot area, based on MODIS LST, doesn't exceed 1.7degC, none validation and calibration of satellite data were introduced. Despite the fact that measurements of the basic aquifer parameters, including the first water table and temperatures were performed in 42 observation wells, they were not used for the purpose of subsurface temperature model calibration. The reason was that they were made only once within the framework of GeoPLASMA-CE project, and are not representative. No additional suitable data, concerning temperatures were present in the Kraków pilot area.

The construction of the 3D subsurface thermal model using Petrel software considered the qualitative and quantitative analysis of available temperature records in individual wells. The executed processing steps included data quality checks on consistency and plausibility concerning the depth of the seasonal zone (z1) and transient zone (z2), as well as linear trend analysis (on plot) for estimation of temperature gradient in z3 (gradT) bottom part of the profile. All available boreholes temperature datasets passed the quality standards with threshold of the aimed maximum accuracy of the temperature gradient equal to 0.0005 degC/m. Coefficient of determination (R^2) for the linear approximation of the temperature profile in the geothermal zone derived from the borehole logging data ranged within the limits of 97.055% to 99.934%.

The subsurface temperature model in Kraków pilot area was divided into 3 intervals: (1) surface to the base of the seasonal zone, (2) below seasonal zone down to base of the transient zone and (3) beneath seasonal zone (geothermal zone) affected by steady state conductive heat transport form the earth's interior. The results of 2D temperature logs data interpretation shows that depth of the seasonal zone z1 is between ca. 1.5 to almost 28 m, furthermore no correlation of seasonal zone z1 depth with depth of the top or the base of groundwater bodies has been recognized. Considering the above-mentioned depth of seasonal zone z1 was set up arbitrarily to 20 m below the surface. Consequently, a constant value of temperature, equal to mean annual surface temperature, was assigned through the entire interval, which means that the geothermal gradient within the uppermost 20 m was set up to "0".

The depth of transient zone (z2) was derived from analysis of particular temperature well logs on plot diagrams, assuming intersection of the measured temperature profile (raw data) with the extrapolation of the geothermal gradient to the surface. The obtained data set has been mapped through the entire Kraków area. The depth of transient zone (z2) the adequate temperatures derived from logs were assigned. The depth variability of transient zone resulting from the analysis of raw data (thermal curves) in Krakow ranges from 13 to 95.2 m (with average 55.0 m) and such obtained from the 3D model ranges within the limits 15-70 m, with a maximum counts values (75.5%) in between 45-55 m. The 3D model of transient zone (z2) was created based on polynomial approximation of raw data, as shown in the drawing below on **Figure 18**.

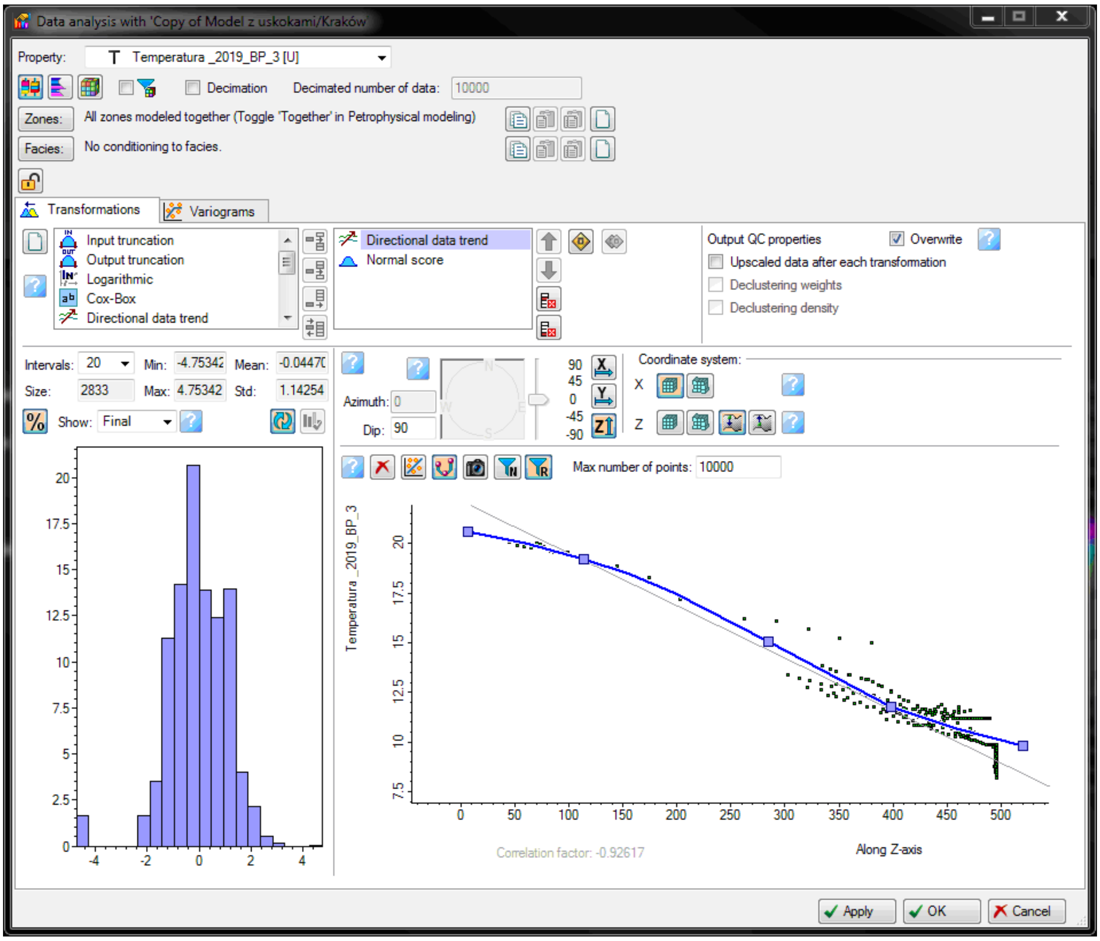


Figure 18: Example of subsurface temperature data analysis for calibrating the overall prediction model of the transient zone (z2) in the pilot area Krakow.

Theoretically, the bottom part of thermal model is described by the pure conductive geothermal gradient which was determined on the basis of measured temperature profiles by linear approximation (regression). The obtained gradient distribution map was validated by the results of the geothermal gradient estimation obtained through combined thermal conductivity and available archival regional heat flow density models.

Finally, all the obtained models of z1, z2 and z3 zones have been merged in the software Petrel and presented in a terms of a 3D parametric model. Such model was used for estimation of subsurface intervals temperatures and preparation the geothermal potential assessment layers.

11. Potential of open loop systems

11.1. Purpose and use of the open loop workflow

The purpose of the open loop workflow is to show the energy content and the hydraulic and thermal productivity. As no appropriate guideline was available, a new method has been developed during GeoPLASMA-CE to create the output parameters specified in **Table 8**. The energy content is given in Kilowatt hour per year and per square meter and is separated in three categories: Heating, cooling and balanced use. Hydraulic productivity is given for peak load in litres per day and per square meter and the thermal productivity in Watts per square meter. Please note that spatial reference is given to the surface consumed by an individual open loop system. Inside the consumed space, no additional system can be installed.

The output values are calculated in dependence of the geometric, hydraulic and thermal properties of the groundwater body (aquifer). Therefore, at first, the geometric extent of the groundwater body, suitable for thermal use, has to be specified. Further the net aquifer thickness, the depth of the groundwater level and the hydraulic conductivity of the aquifer is necessary as main input parameter, see Table 9. For the thermal productivity also the minimum groundwater temperature in the heating season and the maximum groundwater temperature in the cooling season are necessary. These input parameters are usually dependent on the geographic location and should be given as maps.

The challenge to calculate the available potential for an open loop system is, that is not known, if other installations will be installed or removed in the surrounding. Hence, it has to be assumed that every landowner can use the aquifer equally according to the extent of the property. This is in contradiction to the authorisation process in many countries, where the “first come - first served” principle is applied. The advantage of this principle is, that the aquifer can more easily be used for larger open loop systems, with the disadvantage that some users in the surrounding cannot fully use the aquifer anymore. The developed potential maps show resources independently of existing and future open loop installations. This means, that a possible mutual influence between different installations are not considered explicitly. Land use planners can give priority to some landowners by summing up the energy content of neighbouring land parcels, with the consequence, that neighbours might not be able to use their aquifer energy. This strategy can be useful for public buildings.

Table 8: Main output parameters of open loop workflow.

class	description of output parameter	symbol	unit
Energy content	Specific energy content available for balanced heating and cooling	E_{BAL}	$\frac{kWh}{m^2 \cdot yr}$
	Specific energy content available for heating	E_{HEAT}	$\frac{kWh}{m^2 \cdot yr}$
	Specific energy content available for cooling	E_{COOL}	$\frac{kWh}{m^2 \cdot yr}$
Thermal capacity and hydraulic productivity	Specific hydraulic productivity at peak load	$Q_{PEAK,specific}$	$\frac{l}{d \cdot m^2}$
	Available thermal capacity for open loop system at peak load	$P_{PEAK,specific}$	$\frac{W}{m^2}$

The energy content is designed for the purpose that every installation can use the stored thermal energy beneath its land area without changing the groundwater to a critical temperature for a specific operational life time (recommended period > 20 years). The calculation considers the stored energy in the aquifer and in case of unbalanced use the recharge from surface or from the aquitard below.

11.2. Development and evaluation of the open loop workflow

A first draft of the open loop workflow refers to a study for the municipality of Vienna. The study was designed for geothermal energy mapping for an urban development area, where the energy contents for balanced and unbalanced use were calculated for each construction field. The peak load was calculated as the maximum possible yield of the aquifer, considering a maximum drawdown of the water table to 1/3 of the saturated zone. The analytic calculations were calibrated with a numerical simulation by introducing a recovery factor. This study showed the general feasibility of the method, but for specific hydrogeological situations, especially for very thick groundwater bodies or groundwater bodies with a high Darcy velocity, the calculation led to clearly over exaggerated values. Hence, the workflow was completely revised and updated.

The updated workflow shows the main improvement to provide potential values which are independent from the grid size or site area. Therefore, the values for energy potential and peak load was changed in units like energy per square meter (kWh/m^2), flow rate per square meter ($l/d/m^2$) or power per square meter (W/m^2). Also, the peak load calculation was improved. The maximum hydraulic yield was limited by fixing the hydraulic radius and not by limiting the maximum drawdown of the groundwater table to 1/3 of the net aquifer thickness. By setting a constant hydraulic radius of one well, also the area, needed for one well doublet, can be estimated and therefore the peak load values can be calculated per square meter.

The updated workflow was applied by the GeoPLASMA-CE partners with the following feedback:

- A graphical overview to the workflow steps was requested. Improvement: the workflow steps were simplified and a simple graphical workflow added,
- The well radius of 1 m seems to be too high. Improvement: The well radius can now be set as a constant input parameter with the default value of 1 m, which can be adapted by the user of the workflow as the hydraulic radius is much more sensitive and decisive to the result. The adaption of the well radius can be done iteratively during the calibration process (workflow step 3),
- The peak potential values are very high for very thick aquifers, like in the pilot area Ljubljana (thickness 50 to 100m). Improvement: The maximum applicable aquifer thickness was limited to 20 m per well, since this is the maximum size of a doublette in a well.

11.3. Adapted workflow

The workflow steps are visualised in **Figure 19**, followed by a brief description of the workflow steps. The necessary input parameters and the resulting output parameters are summarized in **Table 9** and **Table 10.**

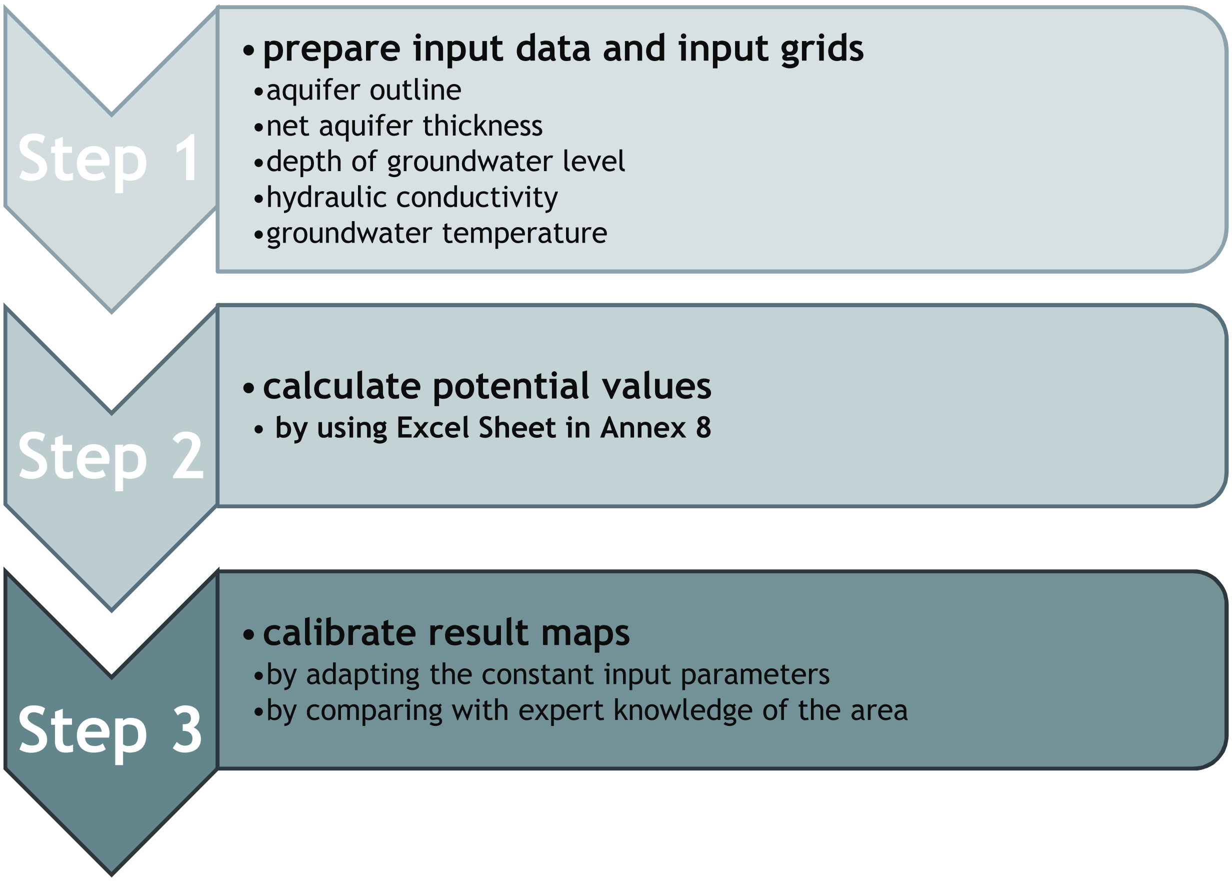


Figure 19: Workflow steps for open loop potential calculation.

11.3.1 Step 1 - prepare input data grids

- **Aquifer outline**

  The aquifer outline has to be available on the master grid for further processing, which means, every master grid cell, where a near-surface aquifer can be used for open loop systems, should have value 1. Every other grid cell should have value "0" (no aquifer available) or "-9999" (no data). It is recommended to exclude surface water areas, like lakes or rivers, by assigning value "0".

- **Net aquifer thickness**

  The net aquifer thickness is calculated from two grids: "mean groundwater level" and "aquifer base" by subtraction. The resulting grid should show the fully saturated zone of the aquifer, which can be uses for open loop systems.

  The grid "mean groundwater level" can be gathered in three ways:

  - per Interpolation of all observation wells in the aquifer,
  - per numerical simulation (static 2D simulation is in most cases sufficient) with the observation wells as calibration points,
  - using existing groundwater isohypse maps.

  The grid "aquifer base" can be interpolated from drilling log information. Also stratigraphic information might be useful as an input. The "net aquifer thickness" grid is one of the most sensible parameter for energy potential calculation. The better the quality of this layer, the better also the results.

- **Depth of groundwater level:**

  The "depth of groundwater level" grid is calculated from the two grids "DEM" (digital elevation model) and "mean groundwater level" and shows the partly, or unsaturated zone above the aquifer up to the surface. This information is needed to estimate the influence of the surface temperature to the groundwater or, more explicitly, to calculate the heat flow from surface for unbalanced use.

- **Hydraulic conductivity:**

  The hydraulic conductivity can be derived best from hydraulic pumping tests or sieving grain analyses. Both provide local information in the aquifer. The hydraulic conductivity often varies in a porous aquifer due to the sedimentation of materials with different hydraulic properties. Therefore, it is important to gather a representative amount of data to estimate the hydraulic conductivity correctly. If an aquifer is known for its homogeneity, it is accepted to take the mean value for the calculations.

- **Groundwater temperature:**

  The information of the groundwater temperature can be gathered from groundwater temperature monitoring stations. Two grids have to be generated (per interpolation or numerical modelling):

  - winter minimum of the mean groundwater temperature in the saturated zone $T_{OBS-LOW}$,
  - summer maximum of the mean groundwater temperature in the saturated zone $T_{OBSHIGH}$.

  One grid cell should contain the annual minimum or maximum of the mean temperature along the thickness of the saturated zone. If monitoring data for interpolation or modelling are not available in a sufficient number, the minimum and maximum temperature must be estimated for the whole pilot area as a constant values. Please consider the influence of the seasonal zone and its phase shift with depth.

Table 9: Input parameter maps to calculate the open loop output parameters

class	description of input maps	symbol	unit	sensibility to energy content	sensibility to productivity
Aquifer parameter	Aquifer outline – suitable groundwater body	-	-	+++++	+++++
	Net aquifer thickness – fully saturated zone	SZ	m	++++	++++
	Depth of groundwater level	GWD	m	++	o
	Hydraulic conductivity	kf	$\frac{m}{s}$	o	++++
Thermal productivity	minimum observed groundwater temperature at heating period (winter)	$T_{OBS-HIGH}$	°C	++	++
	maximum observed groundwater temperature at cooling period (summer)	$T_{OBS-COOL}$	°C	++	++

Table 10: Constant input parameter, necessary to calculate the open loop potential outputs.

	symbol	Default value	unit	sensibility to results
Life time	LT	20	yr	++
Maximum allowed temperature difference between extraction and injection	ΔT	5	K	+
hydraulic radius	R	50	m	+++++
well radius	r_0	1	m	++
Recovery factor	rf	0.75	-	+++
minimum allowed injection temperature, overall	$T_{LOWBOUND}$	5	°C	+++
maximum allowed injection temperature, overall	$T_{HIGHBOUND}$	18	°C	+++
volumetric heat capacity of the saturated aquifer	c_{VA}	2.4	$MJ/m^3/K$	+
thermal conductivity of overburden	λ_{OB}	1.2	W/m/K	+
thermal conductivity of aquitard	λ_{Bott}	2	W/m/K	+
volumetric heat capacity of aquitard	c_{VB}	2	$MJ/m^3/K$	+

11.3.2 Step 2 – calculate open loop potential

To calculate the open loop potential, you can use the programmed MS Excel sheets of Annex 8: Use the line-based calculations of the sheet "raster_calc", import the input data grids from column A-G and get your results in column H-K of Annex 8. Use the default values for the constant input parameters at this step.

Alternatively, you can manually calculate the potential values by following the formulas of the theoretical background in Annex 8.

11.3.3 Step 3 – calibrate result maps

Quality of the results depends primarily on the quality of the input grids. Secondarily, they also depend on some constant values and limitations, given in **Table 10**. The hydraulic radius R and ΔT can be used to calibrate the peak load values, as they are very sensible to the results. The recovery factor rf can also be used to influence all result values equally. $T_{LOWBOUND}$ and $T_{HIGHBOUND}$ are the minimum and maximum allowed temperature and have also some impact on the results.

It is recommended to validate the results by discussing them with experts in the specific area. When the results are not reasonable, it is possible to change the constant input parameters.

If feasible, use the default values stated in **Table 10**, as the results are then comparable between different areas.

12. Conclusions

The presented guideline provided the basis for the work in the GeoPLASMA-CE project whose results are presented on the web information system.

The elaborated workflows comprise extensive set of characteristic parameters describing the potential of shallow geothermal plants.

After intensive discussions among the partners, the geogen potential for closed-loop geothermal systems has been specified by the surface temperature and the average thermal conductivity for a specific depth interval and the mean subsurface temperature for a specific depth interval. The partners produced conductivity maps for various depth intervals; such the user can read the potential for the required drilling depth. These parameters provide an overview for non-expert users of the web information system, how "rich" one location is in geothermal energy. In addition, it is a physical parameter which can be used by energy planners. The presentation of the surface temperature and the subsurface temperature is also addressed to energy planners, who can use it as boundary condition for their calculations of the design of a geothermal plant.

The issue of calculating the heat extraction rate has not been satisfactory during the project time. One reason is, that this output combines technical and natural parameters. Since the project team wanted to produce standardized or at least comparable outputs, many assumptions for variable parameters like borehole diameter, heating demand of a building or subsurface temperature would have been necessary. However, these parameters vary widely among the pilot areas, such that the calculation results would become unrealistic. Therefore, the heat extraction rate has not been produced as output for GeoPLASMA-CE.

The potential maps for open-loop geothermal systems show the occurrence of groundwater bodies, the hydraulic productivity and thermal capacity at peak load and the thermal productivity. As no appropriate workflow was available, a new method has been developed during GeoPLASMA-CE to create the output parameters. In addition to the other parameters, the energy content in $kWh/a/m^2$ has been estimated for heating, cooling and balanced use.

The GeoPLASMA-CE project resulted in a comprehensive collection of risk and conflict factors referring to the use of shallow geothermal energy. The list comprises a categorial classification for each parameter, which meets the needs of all project partners. The risk and conflict factors were validated with respect to their effect on the construction and operation of shallow geothermal plants and compiled in the traffic-light maps illustrating the suitability of a location for closed and open-loop systems in three colours. These traffic-light maps very clearly present information on whether a shallow geothermal plant is in general possible or not. If a user has found out, that a location of interest is suited for a shallow geothermal plant, he can use the potential maps to get information on how good the location is.

The new approaches and lessons learned during the testing at the pilot areas feed into this evaluated guidelines. This guideline gives a summary of all workflow steps to achieve harmonized standards of mapping shallow geothermal potential and land use conflicts to follow up users and stakeholders in Central Europe.

All maps visualizing the characteristic parameters for our pilot areas can be found on our web information portal https://portal.geoplasma-ce.eu/.

13. References

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14. Annexes

All digital annexes are available at https://portal.geoplasma-ce.eu/.

Annex 1	Problematic groundwater bodies: Theoretical background: Summary of literature study
Annex 2	Subsurface temperature estimation; EXCEL sheet for the data documentation
Annex 3	Subsurface temperature estimation; EXCEL sheet "documentation approach"
Annex 4	Subsurface temperature estimation; EXCEL sheet for calculation of the output parameters
Annex 5	Subsurface temperature estimation; EXCEL sheet for the calculation of the error function for the transient model
Annex 6	Subsurface temperature estimation; EXCEL sheet for the calculation of the error function for the linear model
Annex 7	Background information and application of the subsurface temperature workflow
Annex 8	Open loop potential; EXCEL sheet for the calculation of the potential