Harmonized workflows for urban areas

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A. Purpose of the workflow

The GeoPLASMA-CE project will produce a transnational web-based platform presenting geothermal risk and potential maps for six pilot areas in Austria, Czech Republic, Germany, Poland, Slovakia and Slovenia. **Figure 1** and **Table 1** provide an overview of the pilot areas.

Figure 1: The pilot areas of the GeoPLASMA-CE project.

Table 1: Brief characteristics of the pilot areas.

Pilot area	Urban/ non-urban	Thematic focus	Scale
Vogtland/ W-Bohemia	non-urban	Land-use conflict with thermal and curative water protection	1: 50 000
Wałbrzych/ Broumov	non-urban	Improvement of air quality by using emission-free shallow geothermal energy	1: 50 000
Krakow	urban	Improvement of air quality by using emission-free shallow geothermal energy	1: 10 000
Bratislava/ Hainburg	urban	Evaluate energy market, regulation, support and consumer behaviour in an international region	1: 50 000
Vienna	urban	Use of open loop systems in an aquifer with many shallow geothermal applications	1: 20 000
Ljubljana	urban	Development of energy management strategies for the city	1: 10 000

Some pilot areas cover rural areas with decentralized heating, some pilot areas comprise urban areas with an intensive usage of the subsurface which may be in conflict with the production of shallow geothermal energy. Some pilot areas are well suitable for the use of open loop systems because they host aquifers. Closed systems can be installed everywhere, also if no aquifer is present. Therefore, some pilot areas without large aquifers, e.g. situated on crystalline rocks, are especially suitable for closed loop systems. Some pilot areas are already advanced in the usage of shallow geothermal energy and have to deal with conflicting usage; other pilot areas are following with plans to emission-less energy and have to collect information on their geothermal potential.

During the work in the pilot areas, the partners will use harmonized workflows for developing geological 3D models as a basis for geothermal potential and conflict maps. Since the data, the classification schemes, the scale and level of detail, the legal regulations and the modelling software may vary among the project partners, comparable modelling results can only be obtained if as many work steps of data interpretation, processing and modelling as possible are standardized. Therefore, the project partners agreed on mandatory specifications and rules. Since not all work steps can be standardized, the workflow also contains recommendations and flexible parts which are performed by the partners according to their specific requirements.

This report is the guideline for mapping the geothermal potential, risk and conflict factors for shallow geothermal use in non-urban areas. Two pilot areas, Vogtland/W-Bohemia and Wałbrzych/Broumov are located in rural areas and will follow this workflow. It includes general harmonization rules as well as detailed descriptions of workflow steps. The deliverable also specifies the standardized final outputs that have to be produced by the project partners.

First of all, the project partners specified the outputs they will produce on the basis of a stakeholder query of D.T2.1.1, such that the provided workflow can meet the needs of each pilot area.

B. Aspects of shallow geothermal use in urban areas

The 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, the temperature regime of the underground below urban areas is strongly influenced by anthropogenic activities like:

- surface sealing,
- thermal emission from heated buildings and industrial plants founded in the aquifer or the unsaturated zone,
- 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 (Bsp. Krakow und 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. They may influence each other and decrease the heat extraction capacity and the energy content at one site. Additionally, 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. This integrative approach will be implemented in the workflows for potential mapping and furthermore in the strategies (A.T4.2). Together they will provide a useful tool for energy planners and local authorities to foster a sustainable use of shallow geothermal energy in the pilot areas.

The 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.

The 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.
- The conflicting and concurrent use of groundwater for industry and drinking water has to be taken into consideration.

C. Action plan for the implementation of methodical workflows in urban pilot areas

C.1 Purpose of the action plan

The action plan was developed in order to provide an overview of the outputs which have to be produced for each pilot area. The base for this decision was the stakeholder survey of D.T2.1.1, which was performed in order to investigate which information and products (maps, online-platforms) the stakeholders working in the field of shallow geothermal energy are interested in. The 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) and provide the basis for deciding which outputs should be produced during the project. The desired outputs, the data and software as well as the workflows needed to produce these outputs are presented in the following chapters.

C.2 Pilot Area Kraków

C.2.1. Specification of the pilot area

The city of Krakow announced a resolution on the adoption of a "Low Emission Reduction Program for the City of Krakow". One way to reduce emission is the use of heat pumps. However, the market of shallow geothermal energy in the City of Krakow is still poorly recognized. Krakow City is located within the extent of several underground aquifers providing an important source of tap water. Unfortunately, a possible increasing number of applications may cause conflicts of land-use and thermal overload of the shallow groundwater bodies. The objectives of the project in the Krakow pilot area is to support the city of Krakow with information on possible use of shallow geothermal energy and on conflicts arising from multiple use of the subsurface and groundwater.

C.2.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T2.1.2) showed that stakeholders are interested in the following information on the geothermal potential as well as the land-use and risk potential:

- suitability of forms of geothermal energy,
- risk and land-use-conflict maps,
- geology,
- geothermal potential maps,
- temperature,
- heat extraction capacity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- curative water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use,
- cavities,
- faults,
- karst,
- pipelines,
- limitation of drilling depth.

The suitability of geothermal systems will be presented by traffic light maps for open and closed loop systems. In order to determine the geothermal potential of the city of Krakow, all outputs for open and closed loop systems will be produced. In addition to the stakeholder requirements, the project partners agreed on describing the geothermal potential for closed loop systems by the heat extraction capacity, which provides a brief overview on the potential of a location for public users like house-owners. In order to provide important information for the expert platform produced by the GeoPLASMA-CE project, the partners agreed on modelling or/and displaying the ground surface temperature and the geothermal gradient as well as the thermal conductivity at different depth intervals. The geothermal potential for open loop systems will comprise the thermal capacity, the energy content, the hydraulic productivity and the thermal productivity.

In contrast to the stakeholder requirements, limitations of drilling depth will not be modelled, because they are not necessary. In addition to the stakeholder requirements, the location of natural reserves and protection areas will be modelled as well as sites of landfill and contaminated areas, because this knowledge is necessary for the protection of the environment and of the aquifer.

C.2.3. Geological 3D modelling

The 3D model will be generated with the software Petrel. Input data are geologic maps and drilling data provided by the Polish geological survey. The model will comprise the boundaries of geological bodies as a 2D grid. In addition, the geologic bodies are modelled by a stratigraphic grid.

Within the Krakow area there are three variously developed regional tectonic units. First, in the Northern part there is the Silesian-Cracow Monocline, developed mainly as limestones and dolomites, partly sandstones, aged from Carboniferous to Jurassic. The second unit is the Carpathian Foredeep, consisting of Neogene and Paleogene claystones, mudstones, and fine sandstones with interlayers of evaporates, mainly gypsum. The smallest, Southern unit is Carpathian Flysch, made out of folded sandstone and claystone layers aged Craterous-Neogene.

Numerous tectonic faults are related to folding of the Carpathian Mountains, most probably they are still active, although in a very limited range of tension.

Units are going to be modelled simultaneously, with common boundaries. Similarly, layers will be modelled simultaneously, with common footwall/top boundaries, whilst internal variety of layers will be provided by automatic zoning process.

C.2.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview of the systems of geothermal plants which are suitable for one location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview of locations where the use of a geothermal system is possible or not.

Table 2 gives a general overview of the input data that are needed to generate the suitability maps.

Table 2: Input data necessary for the calculation of the suitability maps.

pilot area			suitability maps	
			traffic light map closed loop system	traffic light map open loop system
Krakow	catalogue of requirements Krakow		x	x
	presentation Krakow (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	geological maps	map	x	x
	Water level (normal water table)	m sub sl		x
	Water level (high water table)	m sub sl		x
	Water level (low water table)	m sub sl		x
	Maximum pumping rate	l/s		x
	Maximum daily pumping rate	m³/d		x
	Maximum annual pumping rate	m³/yr		x
	Grain size distribution	%		x
	Hydraulic conductivity (derived from grain size distribution)	m/s		x
	Effective porosity of aquifer derived from pumping test	%		x
	Hydraulic conductivity derived from pumping tests	m/s		x
	Gross aquifer thickness	m		x
	Net aquifer thickness (related to normal water level)	m		x
	groundwater: Total dissolved solids (TDS)	mg/l		x
	groundwater: Content of NaCl	mg/l		x
	groundwater: Content of NO3-	mg/l		x
	groundwater: Content of SO42-	mg/l		x
	groundwater: Content of Fe2+	mg/l		x
	groundwater: Content of Fe (total)	mg/l		x
	groundwater: Content of Mg2+	mg/l		x
	groundwater: Content of K+	mg/l		x
	groundwater: Content of Ca2+	mg/l		x
	groundwater: Content of Mn	mg/l		x
	groundwater: Content of HCO3-	mg/l		x
	groundwater: pH value			x
	groundwater: Content of O2	mg/l		x
	groundwater: Electical conductivity of water sample	µS/cm		x
	water protection areas (curative, drinking water)	map	x	x
	natural reserves / protection areas	map	x	x
	confined/artesian groundwater areas	map	x	x
	Tectonics / faults	map	x	x
	cavity, mining maps	map	x	x
	landslides map	map	x	x
	karst maps	map	x	x
	anthropogenic lines (electricity, gas,…)	map	x	x
	landfills, contaminated area map	map	x	x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
	Outline of groundwater bodies with problematic chemistry (scaling, corosion, anthropogenic contamination)	map	x	x
	necessary calculation software		ArcGIS	ArcGIS
	necessary workflow		conflict potential	conflict potential

C.2.5. Land-use conflict and risk factors of geothermal use

Groundwater protection is one of the major aspects of land-use conflict management in Kraków. Since the groundwater is also used as drinking water, its contamination by drilling on contaminated industrial sites or by using it in open loop systems has to be avoided. Artesian and confined groundwater needs to be taken into consideration. In addition to anthropogenic risk factors like electric lines and water pipes, geologic risk factors are also relevant for Kraków and will be shown on conflict maps.

Table 3: Factors of land-use conflict and risk for the use of shallow geothermal energy in the pilot area Kraków.

pilot area			water protection areas (curative, drinking water)	natural reserves / protection areas	confined/ artesian groundwater	tectonics/ faults	cavity/ mining areas	land-slides	karst areas	anthropogenic lines (electricity, gas,...)	landfills, contaminated areas
			maps of conflict and risk factors								
Krakow	catalogue of requirements Krakow		x		x	x	x		x	x	
	presentation Krakow (X = yes)		x	x	x	x	x	x	x	x	x
	necessary INPUT DATA										
	parameter	unit									
	boreholes: Coding of bore holes (geological codes - LUT)				x				x		x
	boreholes: Location (harmonized coordinate system including elevation)				x				x		x
	boreholes: Final depth (TVD)	m			x				x		x
	boreholes: Final depth (MD)	m			x				x		
	boreholes: Lithological borehole profile								x		x
	boreholes: Stratigraphic borehole profile								x		x
	Petrographical rock descriptions (LUT)								x		x
	Standardized, harmonized lithological profile								x		x
	Standardized, harmonized stratigraphic profile								x		x
	Full geological 3D-model				x	x	x		x		x
	geological maps	map			x	x	x		x		x
	Water level (normal water table)	m sub sl			x						
	Water level (high water table)	m sub sl			x						
	Water level (low water table)	m sub sl			x						
	Effective porosity of aquifer derived from pumping test	%			x						
	Hydraulic conductivity derived from pumping tests	m/s			x						

	Gross aquifer thickness	m			x						
	Net aquifer thickness (related to normal water level)	m			x						
	water protection areas (curative, drinking water)	map	x								
	natural reserves / protection areas	map		x							
	drilling limitation layer	map			x						
	swellable rock map	map									
	confined/artesic groundwater areas	map			x						
	tectonics/ faults	map				x					
	cavity, mining maps	map					x				x
	landslides map	map						x			
	shallow gas leackage data	map									
	karst maps	map							x		
	anthropogenic lines (electricity, gas,…)	map								x	
	landfills, contaminated area map	map									x
	Outline of groundwater bodies with problematic chemistry (scaling, corosion, anthropogenic contamination)	map									x
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts

C.2.6. Calculation of the geothermal potential for closed loop systems

In a city like Kraków, the conflicting use of groundwater for several purposes like industry or geothermal energy production may limit the possible use of open loop systems, although a large productive aquifer is available. For this reason, the potential of closed loop systems which do not use ground water is modelled by all output parameters.

Table 4: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Kraków.

pilot area			closed loop systems thermal conductivity maps (W/m·K)	heat extraction maps (W/m)	surface temperature maps (°C)	temperature gradient maps (K/100 m)
Krakow	catalogue of requirements Krakow		x	x	not recorded	not recorded
	presentation Krakow (X = yes)		x	x	x	x
	necessary INPUT DATA					
	parameter	unit				
	boreholes: Coding of bore holes (geological codes - LUT)		x	x		
	boreholes: Location (harmonized coordinate system including elevation)		x	x		x
	boreholes: Final depth (TVD)	m	x	x		x
	boreholes: Final depth (MD)	m	x	x		x
	boreholes: Lithological borehole profile		x	x		
	boreholes: Stratigraphic borehole profile		x	x		
	Petrographical rock descriptions (LUT)		x	x		
	Standardized, harmonized lithological profile		x	x		
	Standardized, harmonized stratigraphic profile		x	x		
	Full geological 3D-model		x	x		
	Geothermal gradient	K/m				x
	Bulk thermal conductivity (single, average value)	(W/m·K)	x	x		
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	x		
	Thermal conductivity of dry rock sample	(W/m·K)	x	x		
	Thermal conductivity of saturated rock sample	(W/m·K)	x	x		
	Bulk thermal conductivity map	map/grid		x		
	Mean annual surface temperature	°C			x	x
	Groundwater temperature (series, single depth point)	°C				x
	Groundwater temperature (series, multiple depth points)	°C				x
	temperature profiles derived from TRT	°C	x	x		x
	Water level (normal water table)	m sub sl	x	x		x
	necessary calculation software		Petrel ArcGIS	Petrel ArcGIs	ArcGIS	Petrel ArcGIS
	necessary workflow		3D modelling closed loop	3D modelling closed loop	closed loop	closed loop

C.2.7. Calculation of the geothermal potential for open loop systems

Kraków City is located within the extent of several underground aquifers which provide a source for geothermal energy. As basis for the development of a concept for emission less energy production, the capacity, energy content and productivity of the aquifers will be quantified.

Table 5: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of open loop systems in the pilot area Kraków.

pilot area			open loop systems				
			aquifer outline map	thermal capacity (kW)	energy content (MWh/yr/ha)	hydraulic productivity (l/s, m³/d)	thermal productivity (°C)
Krakow	catalogue of requirements Krakow		not recorded	not recorded	not recorded	not recorded	not recorded
	presentation Krakow (X = yes)		x	x	x	x	x
	necessary INPUT DATA						
	parameter	unit					
	Full geological 3D-model				x	x	
	geological maps	map		x	x	x	
	Bulk thermal conductivity (single, average value)	(W/m·K)			x		
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)			x		
	Thermal conductivity of dry rock sample	(W/m·K)			x		
	Thermal conductivity of saturated rock sample	(W/m·K)			x		
	Bulk thermal conductivity map	map/grid			x		
	Mean annual surface temperature	°C			x		
	Groundwater temperature (series, single depth point)	°C					x
	Groundwater temperature (series, multiple depth points)	°C					x
	Water level (normal water table)	m sub sl			x	x	
	Water level (high water table)	m sub sl				x	
	Water level (low water table)	m sub sl				x	
	Maximum pumping rate	l/s				x	
	Maximum daily pumping rate	m³/d			x	x	
	Maximum annual pumping rate	m³/yr			x	x	
	Grain size distribution	%				x	
	Hydraulic conductivity (derived from grain size distribution)	m/s				x	
	Effective porosity of aquifer derived from pumping test	%				x	
	Hydraulic conductivity derived from pumping tests	m/s				x	
	Gross aquifer thickness	m			x	x	
	Net aquifer thickness (related to normal water level)	m			x	x	
	Location of existing geothermal utilizations				x		
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map	x	x	x	x	x
	necessary calculation software		ArcGIS	ArcGIS	Petrel ArcGIS	Petrel ArcGIS	ArcGIS
	necessary workflow		open loop	open loop	3D modelling open loop	3D modelling open loop	open loop

C.3 Pilot Area Bratislava - Hainburg

C.3.1. Specification of the pilot area

Pilot area Bratislava (Slovakia, Austria) includes Bratislava city and the transboundary part of Austria in the vicinity, including town Hainburg with the total evaluated area of 603 km^2 (Slovak part - 367 km^2 and Austrian part 236 km^2). From geological point of view pilot area is diverse including hard rocks (granites, limestones, dolomites) and non-consolidated sediments (gravels, sands, clays). Estimated population in the pilot area is around 450,000 inhabitants (434,000 in Slovakia and 16,000 in Austria) including urban and rural areas resulting in different population density and different energy needs. The energy market, regulation, support and consumer behavior is different in both countries and so having its own specifics that will be evaluated within the project. At the end this will lead to proper further recommendations delivered to policy makers and stakeholders.

C.3.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T2.1.2) showed, that stakeholders are interested in the following information:

- suitability of forms of geothermal energy,
- risk and land-use-conflict maps,
- geology,
- geothermal potential maps,
- temperature,
- thermal conductivity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use.

The suitability of forms will be presented by traffic-light maps for open and closed loop systems. The other user requirements will be met by the production of conflict maps. Although natural reserves were not required, they will be mapped, since open loop system will be located in sediments and groundwater which have to be utilized in first place for drinking water supply. That’s why it is important to respect protection zones and natural reserves

C.3.3. Geological 3D modelling

The geometry of the geological units and structures will be modelled with the software Paradigm Skua/Gocad. The data about the lithological content from the boreholes will be evaluated by project partners and will be assessed by harmonized and unified legend. The processed data will be input for the geological model. Based on information about geology from boreholes 7 cross-sections covering all area will be compiled. Proposed horizontal scale will be 1:50 000, vertical scale is depending on the borehole data (proposed scale is 1:7500). The hydrogeological model will include delineation of the aquifers and aquitards of the Danube basin and adjacent hills and mountains. The model will comprise the boundaries of geological bodies as triangulated surfaces. Proposed modeled horizons for the 3D geological model are defined based on geological setup and needs for hydraulic and geothermal modeling in regional level:

Quaternary (holocene Danube sediments)

- Interglacial quarternary gravel deposits
- Neogene
- Mesozoic (carbonates)
- Mesozoic (non-carbonates)
- Crystalline base rock

If needed other layers will be added to the modelled horizons (more precise Quaternary partition, weathered zone for hard rock – upper layer 10 m – 25 m).

Faults – will be added to the model based on geological maps and cross-sections.

C.3.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview over the systems of geothermal plants which are suitable for one location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview on where the use of one geothermal system is possible or not. Table 6 gives a generally overview over the input data that are needed to generate the suitability maps.

Table 6: Input data necessary for the calculation of the suitability maps.

pilot area			suitability maps	
			traffic light map closed loop system	traffic light map open loop system
Bratislava	catalogue of requirements Bratislava		x	x
	catalogue of requirements Hainburg		x	x
	presentation Bratislava (X = yes)		x	x
	presentation Hainburg (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	Full geological 3D-model		x	x
	geological maps	map	x	x
	Water level (normal water table)	m sub sl		x
	Water level (high water table)	m sub sl		x
	Water level (low water table)	m sub sl		x
	Maximum pumping rate	l/s		x
	Maximum daily pumping rate	m³/d		x
	Maximum annual pumping rate	m³/yr		x
	Grain size distribution	%		x
	Hydraulic conductivity (derived from grain size distribution)	m/s		x
	Effective porosity of aquifer derived from pumping test	%		x
	Hydraulic conductivity derived from pumping tests	m/s		x
	Gross aquifer thickness	m		x
	Net aquifer thickness (related to normal water level)	m		x
	groundwater: Total dissolved solids (TDS)	mg/l		x
	groundwater: Content of NaCl	mg/l		x
	groundwater: Content of NO3-	mg/l		x
	groundwater: Content of SO42-	mg/l		x

	groundwater: Content of Fe2+	mg/l		x
	groundwater: Content of Fe (total)	mg/l		x
	groundwater: Content of Mg2+	mg/l		x
	groundwater: Content of K+	mg/l		x
	groundwater: Content of Ca2+	mg/l		x
	groundwater: Content of Mn	mg/l		x
	groundwater: Content of HCO3-	mg/l		x
	groundwater: pH value			x
	groundwater: Content of O2	mg/l		x
	groundwater: Electical conductivity of water sample	µS/cm		x
	water protection areas (curative, drinking water)	map	x	x
	natural reserves / protection areas	map	x	x
	confined/artesic groundwater areas	map	x	x
	cavity, mining maps	map	x	x
	landslides map	map	x	x
	karst maps	map	x	x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
	Outline of groundwater bodies with problematic chemistry (scaling, corossion, anthropogenic contamination)	map	x	x
	necessary calculation software		ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts

C.3.5. Land-use conflict and risk factors of geothermal use

In the Danube basin, all kinds of aquifer are present. There are fissured crystalline hard rocks, karstified Mesozoic aquifers and porous aquifers of different stratigraphy and permeability value. Therefore geologic conflict potentials of karst, landslides, artesic and confined groundwater have to be mapped. The protection of the groundwater is also an import factor conflicting with shallow geothermal use. Therefore, groundwater protection zones industrial contaminated sites will be mapped, too. A natural reserve is important for the ecosystem of the city and does also conflict with the shallow geothermal use.

Table 7: Factors of land-use conflict and risk for the use of shallow geothermal energy in the pilot area Bratislava - Hainburg.

pilot area			maps of conflict and risk factors						
			water protection areas (curative, drinking water)	natural reserves / protection areas	confined/ artesic groundwater	landslides	karst areas	hydraulically separated aquifers	existing geothermal use
Bratislava	catalogue of requirements Bratislava		x		x				not recorded
	catalogue of requirements Hainburg		x		x				not recorded
	presentation Bratislava (X = yes)		x	x		x	x	x	x
	presentation Hainburg (X = yes)		x	x	x		x	x	x
	necessary INPUT DATA								
	parameter	unit							
	boreholes: Coding of bore holes (geological codes - LUT)				x		x		
	boreholes: Location (harmonized coordinate system including elevation)				x		x		
	boreholes: Final depth (TVD)	m			x		x		
	boreholes: Final depth (MD)	m			x		x		
	boreholes: Lithological borehole profile						x		
	boreholes: Stratigraphic borehole profile						x		
	Petrographical rock descriptions (LUT)						x		
	Standardized, harmonized lithological profile						x		
	Standardized, harmonized stratigraphic profile						x		
	Full geological 3D-model				x		x		
	geological maps	map			x		x		
	Water level (normal water table)	m sub sl			x				
	Water level (high water table)	m sub sl			x				
	Water level (low water table)	m sub sl			x				
	Effective porosity of aquifer derived from pumping test	%			x				
	Hydraulic conductivity derived from pumping tests	m/s			x				
	Gross aquifer thickness	m			x				
	Net aquifer thickness (related to normal water level)	m			x				
	water protection areas (curative, drinking water)	map	x						
	natural reserves / protection areas	map		x					
	drilling limitation layer	map			x				
	swellable rock map	map							
	confined/artesic groundwater areas	map			x				
	landslides map	map				x			
	shallow gas leackage data	map							
	karst maps	map					x		
	hydraulically separated aquifers by aquitards							x	
	Location of existing geothermal utilizations								x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map							x
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts	conflicts	conflicts

C.3.6. Calculation of the geothermal potential for closed loop systems

Part of Bratislava – Hainburg pilot area has geological conditions that are not suitable for implementation of the open loop systems. These are mainly mountain and hilly areas and areas with limited water circulation. Other part of the area is under water protection regulations. In these areas calculation of the geothermal potential for closed loop systems will be performed.

Table 8: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Bratislava - Hainburg.

pilot area			closed loop systems			
			thermal conductivity maps (W/m·K)	heat extraction maps (W/m)	surface temperature maps (°C)	temperature gradient maps (K/100 m)
Bratislava	catalogue of requirements Bratislava		x	x	not recorded	not recorded
	catalogue of requirements Hainburg		x	x	not recorded	not recorded
	presentation Bratislava (X = yes)		x	x	x	
	presentation Hainburg (X = yes)		x	x	x	
	necessary INPUT DATA					
	parameter	unit				
	boreholes: Coding of bore holes (geological codes - LUT)		x	x		
	boreholes: Location (harmonized coordinate system including elevation)		x	x		x
	boreholes: Final depth (TVD)	m	x	x		x
	boreholes: Final depth (MD)	m	x	x		x
	boreholes: Lithological borehole profile		x	x		
	boreholes: Stratigraphic borehole profile		x	x		
	Petrographical rock descriptions (LUT)		x	x		
	Standardized, harmonized lithological profile		x	x		
	Standardized, harmonized stratigraphic profile		x	x		
	Full geological 3D-model		x	x		
	Geothermal gradient	K/m				x
	Bulk thermal conductivity (single, average value)	(W/m·K)	x	x		
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	x		
	Thermal conductivity of dry rock sample	(W/m·K)	x	x		
	Thermal conductivity of saturated rock sample	(W/m·K)	x	x		
	Bulk thermal conductivity map	map/grid		x		
	Mean annual surface temperature	°C			x	x
	Groundwater temperature (series, single depth point)	°C				x
	Groundwater temperature (series, multiple depth points)	°C				x
	temperature profiles derived from TRT	°C				x
	Water level (normal water table)	m sub sl	x	x		
	necessary calculation software		Skua ArcGIS extension	Skua ArcGIS extension	ArcGIS	ArcGIS
	necessary workflow		3D modelling closed loop	3D modelling closed loop	closed loop	closed loop

C.3.7. Calculation of the geothermal potential for open loop systems

Bratislava – Hainburg pilot area has significant groundwater resources in the lowland area. The main aquifer is connected to the Danube river quaternary deposits. Part of urban area (on SVK side) and on rural area (on AT side) is placed above the aquifer. For sustainable use of this great shallow geothermal energy potential its quantification as well as awareness of constraints for its utilisation is needed.

Table 9: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of open loop systems in the pilot area Bratislava - Hainburg.

pilot area			open loop systems				
			aquifer outline map	thermal capacity (kW)	energy content (MWh/yr/ha)	hydraulic productivity (l/s, m³/d)	thermal productivity (°C)
Krakow	catalogue of requirements Krakow		not recorded	not recorded	not recorded	not recorded	not recorded
	presentation Krakow (X = yes)		x	x	x	x	x
	necessary INPUT DATA						
	parameter	unit					
	Full geological 3D-model				x		
	geological maps	map		x	x	x	
	Bulk thermal conductivity (single, average value)	(W/m·K)			x		
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)			x		
	Thermal conductivity of dry rock sample	(W/m·K)			x		
	Thermal conductivity of saturated rock sample	(W/m·K)			x		
	Bulk thermal conductivity map	map/grid			x		
	Mean annual surface temperature	°C			x		
	Groundwater temperature (series, single depth point)	°C					x
	Groundwater temperature (series, multiple depth points)	°C					x
	Water level (normal water table)	m sub sl			x	x	
	Water level (high water table)	m sub sl				x	
	Water level (low water table)	m sub sl				x	
	Maximum pumping rate	l/s				x	
	Maximum daily pumping rate	m³/d			x	x	
	Maximum annual pumping rate	m³/yr			x	x	
	Grain size distribution	%				x	
	Hydraulic conductivity (derived from grain size distribution)	m/s				x	
	Effective porosity of aquifer derived from pumping test	%				x	
	Hydraulic conductivity derived from pumping tests	m/s				x	
	Gross aquifer thickness	m			x	x	
	Net aquifer thickness (related to normal water level)	m			x	x	
	Location of existing geothermal utilizations				x		
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map	x	x	x	x	x
	necessary calculation software		ArcGIS	ArcGIs	Skua/ ArcGIs	Skua/ ArcGIS	ArcGIS
	necessary workflow		open loop	open loop	3D modelling open loop	3D modelling open loop	open loop

C.4 Pilot Area Vienna

C.4.1. Specification of the pilot area

GeoPLASMA-CE in Vienna (Austria) focuses on the challenges of geothermal use of groundwater in the city districts 21 and 22 and adjacent communities in Lower Austria. The pilot area covers parts of the groundwater body Marchfeld, which already host many shallow geothermal applications. Growing numbers of single installations will influence each other and prevent a sustainable use of groundwater for heating and cooling. GeoPLASMA-Ce wants to provide concepts to overcome this challenge.

C.4.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T2.1.2) showed, that stakeholders are interested in the following information:

- suitability of forms of geothermal energy,
- risk and land-use-conflict maps,
- geology,
- geothermal potential maps,
- thermal conductivity,
- heat extraction capacity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use.

The suitability of forms will be presented by traffic-light maps for open and closed loop systems. The pilot actions clearly focus on open loop systems. Therefore, for closed loop systems only crucial information is provided. Heat extraction maps, which are limited to a certain mode of operation, are disregarded. Confined groundwater areas are also disregarded, because there are no known confined areas in the shallow Quaternary aquifer. Instead, natural reserves and landfills will be included in conflict mapping, although this was not required by the stakeholders, because they might limit the use of shallow geothermal energy.

C.4.3. Geological 3D modelling

The geometry of the geological units and structures will be modelled with the software Paradigm Skua/Gocad. In this pilot area also 3D modelling focuses on open loop systems. Therefore the model will contain the following three layers, which are important for potential mapping of open loop systems. The top layer consists of the geologic and anthropogenic units covering the aquifer (backfill, sand, loess and haugh) and overlies the Marchfeld aquifer. Neogene sediments of the Vienna basin represent the underlying aquitard. The model will comprise the boundaries of these hydrogeological bodies as triangulated surfaces. LP-GBA will establish the 3D model combining existing and new 2D hydrogeological maps.

C.4.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview over the systems of geothermal plants which are suitable for one location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview on where the use of one geothermal system is possible or not. Table 10 gives a general overview over the input data that are needed to generate the suitability maps.

Table 10: Input data necessary for the calculation of the suitability maps.

pilot area			suitability maps	
			traffic light map closed loop system	traffic light map open loop system
Vienna	catalogue of requirements Vienna		x	x
	presentation Vienna (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	Full geological 3D-model		x	x
	geological maps	map	x	x
	Water level (normal water table)	m sub sl		x
	Water level (high water table)	m sub sl		x
	Water level (low water table)	m sub sl		x
	Maximum pumping rate	l/s		x
	Maximum daily pumping rate	m³/d		x
	Maximum annual pumping rate	m³/yr		x
	Grain size distribution	%		x
	Hydraulic conductivity (derived from grain size distribution)	m/s		x
	Effective porosity of aquifer derived from pumping test	%		x
	Hydraulic conductivity derived from pumping tests	m/s		x
	Gross aquifer thickness	m		x
	Net aquifer thickness (related to normal water level)	m		x
	groundwater: Total dissolved solids (TDS)	mg/l		x
	groundwater: Content of NaCl	mg/l		x
	groundwater: Content of NO3-	mg/l		x
	groundwater: Content of SO42-	mg/l		x
	groundwater: Content of Fe2+	mg/l		x
	groundwater: Content of Fe (total)	mg/l		x
	groundwater: Content of Mg2+	mg/l		x
	groundwater: Content of K+	mg/l		x
	groundwater: Content of Ca2+	mg/l		x
	groundwater: Content of Mn	mg/l		x
	groundwater: Content of HCO3-	mg/l		x
	groundwater: pH value			x
	groundwater: Content of O2	mg/l		x
	groundwater: Electical conductivity of water sample	µS/cm		x
	water protection areas (curative, drinking water)	map	x	x

	natural reserves / protection areas	map	x	x
	confined/artesic groundwater areas	map	x	x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
	Outline of groundwater bodies with problematic chemistry (scaling, corossion, anthropogenic contamination)	map	x	x
	necessary calculation software		ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts

C.4.5. Land-use conflict and risk factors of geothermal use

Since the geological situation is convenient in Vienna, no geologic risk potentials have to be mapped. The most important factor of land-use conflict is the geothermal use of groundwater. Due to the increasing numbers of applications, a thermal overload of the shallow groundwater bodies has to be expected. In addition, the environmental protection of the nature and groundwater are important factors of conflict.

Table 11: Factors of land-use conflict and risk for the use of shallow geothermal energy in the pilot area Vienna.

pilot area			maps of conflict and risk factors				
			water protection areas (curative, drinking water)	natural reserves / protection areas	confined/ artesic groundwater	existing geothermal use	landfills, contaminated areas
Vienna	catalogue of requirements Vienna		x		x	not recorded	
	presentation Vienna (X = yes)			x		x	x
	necessary INPUT DATA						
	parameter	unit					
	boreholes: Coding of bore holes (geological codes - LUT)				x		x
	boreholes: Location (harmonized coordinate system including elevation)				x		x
	boreholes: Final depth (TVD)	m			x		x
	boreholes: Final depth (MD)	m			x		
	boreholes: Lithological borehole profile						x
	boreholes: Stratigraphic borehole profile						x
	Petrographical rock descriptions (LUT)						x
	Standardized, harmonized lithological profile						x
	Standardized, harmonized stratigraphic profile						x
	Full geological 3D-model				x		x
	geological maps	map			x		x
	Water level (normal water table)	m sub sl			x		
	Water level (high water table)	m sub sl			x		
	Water level (low water table)	m sub sl			x		

	Effective porosity of aquifer derived from pumping test	%			x		
	Hydraulic conductivity derived from pumping tests	m/s			x		
	Gross aquifer thickness	m			x		
	Net aquifer thickness (related to normal water level)	m			x		
	water protection areas (curative, drinking water)	map	x				
	natural reserves / protection areas	map		x			
	drilling limitation layer	map			x		
	confined/artesic groundwater areas	map			x		
	cavity, mining maps	map					x
	Location of existing geothermal utilizations					x	
	landfills, contaminated area map	map					x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map				x	
	Outline of groundwater bodies with problematic chemistry (scaling, corossion, anthropogenic contamination)	map					x
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts

C.4.6. Calculation of the geothermal potential for closed loop systems

The pilot actions in Vienna clearly focus on open loop systems, therefore maps showing the thermal conductivity and the underground temperature combined will be produced. Together, both parameters indicate the geological potential of closed loop systems independent from the operational mode of the application and legal requirements.

Table 12: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Vienna.

pilot area			closed loop systems thermal conductivity maps (W/m·K)	closed loop systems surface temperature maps (°C)
Vienna	catalogue of requirements Vienna		x	not recorded
	presentation Vienna (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	boreholes: Coding of bore holes (geological codes - LUT)		x	
	boreholes: Location (harmonized coordinate system including elevation)		x	
	boreholes: Final depth (TVD)	m	x	
	boreholes: Final depth (MD)	m	x	
	boreholes: Lithological borehole profile		x	
	boreholes: Stratigraphic borehole profile		x	
	Petrographical rock descriptions (LUT)		x	
	Standardized, harmonized lithological profile		x	
	Standardized, harmonized stratigraphic profile		x	
	Full geological 3D-model		x	
	Bulk thermal conductivity (single, average value)	(W/m·K)	x	
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	
	Thermal conductivity of dry rock sample	(W/m·K)	x	
	Thermal conductivity of saturated rock sample	(W/m·K)	x	
	Mean annual surface temperature	°C		x
	Water level (normal water table)	m sub sl	x	
	necessary calculation software		Skua ArcGIS extension	ArcGIS
	necessary workflow		3D modelling closed loop	closed loop

C.4.7. Calculation of the geothermal potential for open loop systems

Since the city of Vienna is situated on a productive aquifer well suitable for open loop systems, all aspects characterizing the potential for geothermal wells will be included in the project.

Table 13: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of open loop systems in the pilot area Vienna.

pilot area			open loop systems				
			aquifer outline map	thermal capacity (kW)	energy content (MWh/yr/ha)	hydraulic productivity (l/s, m³/d)	thermal productivity (°C)
Vienna	catalogue of requirements Vienna		not recorded	not recorded	not recorded	not recorded	not recorded
	presentation Vienna (X = yes)		x	x	x	x	x
	Thermal conductivity of dry rock sample	(W/m·K)			x		
	Thermal conductivity of saturated rock sample	(W/m·K)			x		
	Bulk thermal conductivity map	map/grid			x		
	Mean annual surface temperature	°C			x		
	Groundwater temperature (series, single depth point)	°C					x
	Groundwater temperature (series, multiple depth points)	°C					x
	Water level (normal water table)	m sub sl			x	x	
	Water level (high water table)	m sub sl				x	
	Water level (low water table)	m sub sl				x	
	Maximum pumping rate	l/s				x	
	Maximum daily pumping rate	m³/d			x	x	
	Maximum annual pumping rate	m³/yr			x	x	
	Grain size distribution	%				x	
	Hydraulic conductivity (derived from grain size distribution)	m/s				x	
	Effective porosity of aquifer derived from pumping test	%				x	
	Hydraulic conductivity derived from pumping tests	m/s				x	
	Gross aquifer thickness	m			x	x	
	Net aquifer thickness (related to normal water level)	m			x	x	
	Location of existing geothermal utilizations				x		
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map	x	x	x	x	x
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS ArcGIS	ArcGIS ArcGIS	ArcGIS
	necessary workflow		open loop	open loop	3D modelling open loop	3D modelling open loop	open loop

C.5 Pilot Area Ljubljana

C.5.1. Specification of the pilot area

The objective of the project activities in Ljubljana pilot area (Slovenia) is to quantify spatial distribution of shallow geothermal potential for utilization with ground source heat pumps and integrate this information into development and management strategies of the city with a goal to meet environmental objectives set in the Ljubljana city Sustainable Energy Action Plan 2010 - 2020. The region of Ljubljana city comprises two aquifers containing significant quantities of groundwater which form the main resource exploited for the public water supply of the city. One of the aquifers is unconfined, the other is confined or semi-confined with artesian to subartesian conditions.

C.5.2. Stakeholder requirements and aimed outputs

The stakeholder query (D.T2.1.2) showed, that stakeholders are interested in the following information:

- suitability of forms of geothermal energy,
- risk and land-use-conflict maps,
- geology,
- geothermal potential maps,
- thermal conductivity,
- heat extraction capacity,
- local map scale,
- detailed information on groundwater and aquifers,
- drinking water protection zones,
- curative water protection zones,
- hydraulically separated aquifers,
- confined aquifers,
- existing use,
- cavities,
- floodplains,
- pipelines,
- limitations of drilling depth.

The suitability of forms will be presented by traffic-light maps for open and closed loop systems. Anthropogenic lines for electricity and water are very important conflict factors in the city and will be included in the conflict mapping.

C.5.3. Geological 3D modelling

The geometry of the geological units and structures will be modelled with the software JewelSuite. The model will comprise the two aquifers (Ljubljansko polje – unconfined aquifer and Ljubljansko barje – confined aquifer). At Ljubljansko polje aquifer one layer will be used. Ljubljansko barje artesian aquifer will be distinguished into two layers; lower aquifer and upper aquitard. Basement of the aquifers and surrounding hills will be represented by one layer. Spatial distribution of geological units of hilly area will be based on geological map. Input data for geological 3D model is provided by Geological survey of Slovenia. The model will comprise the boundaries of geological bodies as triangulated surfaces.

C.5.4. Suitability maps

Suitability maps will be produced for all pilot areas. The suitability maps give an overview over the systems of geothermal plants which are suitable for one location. The maps will be produced separately for open and closed loop systems. They will be provided as traffic-light maps giving an overview on where the use of one geothermal system is possible or not. Table 14 gives a generally overview over the input data that are needed to generate the suitability maps.

Table 14: Input data necessary for the calculation of the suitability maps.

pilot area			suitability maps	
			traffic light map closed loop system	traffic light map open loop system
Ljubljana	catalogue of requirements Ljubljana		x	x
	presentation Ljubljana (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	Full geological 3D-model		x	x
	geological maps	map	x	x
	Water level (normal water table)	m sub sl		x
	Water level (high water table)	m sub sl		x
	Water level (low water table)	m sub sl		x
	Maximum pumping rate	l/s		x
	Maximum daily pumping rate	m^3/d		x
	Maximum annual pumping rate	m^3/yr		x
	Grain size distribution	%		x
	Hydraulic conductivity (derived from grain size distribution)	m/s		x
	Effective porosity of aquifer derived from pumping test	%		x
	Hydraulic conductivity derived from pumping tests	m/s		x
	Gross aquifer thickness	m		x
	Net aquifer thickness (related to normal water level)	m		x
	groundwater: Total dissolved solids (TDS)	mg/l		x
	groundwater: Content of NaCl	mg/l		x
	groundwater: Content of NO3-	mg/l		x
	groundwater: Content of SO42-	mg/l		x
	groundwater: Content of Fe2+	mg/l		x
	groundwater: Content of Fe (total)	mg/l		x
	groundwater: Content of Mg2+	mg/l		x
	groundwater: Content of K+	mg/l		x
	groundwater: Content of Ca2+	mg/l		x
	groundwater: Content of Mn	mg/l		x
	groundwater: Content of HCO3-	mg/l		x
	groundwater: pH value			x
	groundwater: Content of O2	mg/l		x
	groundwater: Electical conductivity of water sample	µS/cm		x
	water protection areas (curative, drinking water)	map	x	x

	natural reserves / protection areas	map	x	x
	drilling limitation layer	map	x	x
	swellable rock map	map	x	x
	confined/artesic groundwater areas	map	x	x
	cavity, mining maps	map	x	x
	anthropogenic lines (electricity, gas,…)	map	x	x
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map		x
	Outline of groundwater bodies with problematic chemistry (scaling, corossion, anthropogenic contamination)	map	x	x
	necessary calculation software		ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts

C.5.5. Land-use conflict and risk factors of geothermal use

Risk factor arises mainly from the confined aquifer, which requires protection and limitations of drilling depth. Underground lines for electricity, telephone and water supply play also an important role for the evaluation of the risk potential. In addition, existing geothermal use plays an important role in a densely-settled city.

Table 15: Factors of land-use conflict and risk for the use of shallow geothermal energy in the pilot area Ljubljana.

pilot area			maps of conflict and risk factors					
			water protection areas (curative, drinking water)	drilling limitation layer	confined/ artesic groundwater	cavity/ mining areas	existing geothermal use	anthropogenic lines (electricity, gas,…)
Ljubljana	catalogue of requirements Ljubljana		x	x	x	x	not recorded	x
	presentation Ljubljana (X = yes)		x	x	x		x	x
	necessary INPUT DATA							
	parameter	unit						
	boreholes: Coding of bore holes (geological codes - LUT)			x	x			
	boreholes: Location (harmonized coordinate system including elevation)			x	x			
	boreholes: Final depth (TVD)	m		x	x			
	boreholes: Final depth (MD)	m		x	x			
	boreholes: Lithological borehole profile			x				
	boreholes: Stratigraphic borehole profile			x				
	Petrographical rock descriptions (LUT)			x				
	Standardized, harmonized lithological profile			x				
	Standardized, harmonized stratigraphic profile			x				
	Full geological 3D-model			x	x	x		
	geological maps	map		x	x	x		
	Water level (normal water table)	m sub sl		x	x			

	Water level (high water table)	m sub sl		x	x			
	Water level (low water table)	m sub sl		x	x			
	Effective porosity of aquifer derived from pumping test	%			x			
	Hydraulic conductivity derived from pumping tests	m/s			x			
	Gross aquifer thickness	m			x			
	Net aquifer thickness (related to normal water level)	m			x			
	water protection areas (curative, drinking water)	map	x					
	natural reserves / protection areas	map						
	drilling limitation layer	map		x	x			
	swellable rock map	map		x				
	confined/artesic groundwater areas	map		x	x			
	tectonics/ faults	map		x				
	cavity, mining maps	map		x		x		
	karst maps	map		x				
	hydraulically separated aquifers by aquitards			x				
	Location of existing geothermal utilizations						x	
	anthropogenic lines (electricity, gas,…)	map						x
	landfills, contaminated area map	map		x				
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map					x	
	Outline of groundwater bodies with problematic chemistry (scaling, corossion, anthropogenic contamination)	map		x				
	necessary calculation software		ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS	ArcGIS
	necessary workflow		conflicts	conflicts	conflicts	conflicts	conflicts	conflicts

C.5.6. Calculation of the geothermal potential for closed loop systems

Part of Ljubljana pilot has limitation for implementation of open loop systems (limited groundwater availability, water protection regulations). In these areas calculation of the geothermal potential for closed loop systems will be performed.

Table 16: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of closed loop systems in the pilot area Ljubljana.

pilot area			closed loop systems	
			thermal conductivity maps (W/m·K)	heat extraction maps (W/m)
Ljubljana	catalogue of requirements Ljubljana		x	x
	presentation Ljubljana (X = yes)		x	x
	necessary INPUT DATA			
	parameter	unit		
	boreholes: Coding of bore holes (geological codes - LUT)		x	x
	boreholes: Location (harmonized coordinate system including elevation)		x	x
	boreholes: Final depth (TVD)	m	x	x
	boreholes: Final depth (MD)	m	x	x
	boreholes: Lithological borehole profile		x	x
	boreholes: Stratigraphic borehole profile		x	x
	Petrographical rock descriptions (LUT)		x	x
	Standardized, harmonized lithological profile		x	x
	Standardized, harmonized stratigraphic profile		x	x
	Full geological 3D-model		x	x
	Bulk thermal conductivity (single, average value)	(W/m·K)	x	x
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)	x	x
	Thermal conductivity of dry rock sample	(W/m·K)	x	x
	Thermal conductivity of saturated rock sample	(W/m·K)	x	x
	Bulk thermal conductivity map	map/grid		x
	Water level (normal water table)	m sub sl	x	x
	necessary calculation software		Jewel Suite ArcGIS extension	Jewel Suite ArcGIS extension
	necessary workflow		3D modelling closed loop	3D modelling closed loop

C.5.7. Calculation of the geothermal potential for open loop systems

Ljubljansko polje aquifer is one of the biggest and most productive aquifers in Slovenia. Majority of urban area is placed above the aquifer. For sustainable use of this great shallow geothermal energy potential its quantification as well as awareness of constraints for its utilisation is needed.

Table 17: Desired outputs, necessary software, input data and harmonized workflows for describing the geothermal potential of open loop systems in the pilot area Ljubljana.

pilot area			open loop systems: aquifer outline map	thermal capacity (kW)	energy content (MWh/yr/ha)	hydraulic productivity (l/s, m³/d)	thermal productivity (°C)
Ljubljana	catalogue of requirements Ljubljana		not recorded	not recorded	not recorded	not recorded	not recorded
	presentation Ljubljana (X = yes)		x	x	x	x	x
	necessary INPUT DATA						
	parameter	unit					
	Full geological 3D-model				x		
	geological maps	map		x	x	x	
	Bulk thermal conductivity (single, average value)	(W/m·K)			x		
	Bulk thermal conductivity (distributed TC profile)	(W/m·K)			x		
	Thermal conductivity of dry rock sample	(W/m·K)			x		
	Thermal conductivity of saturated rock sample	(W/m·K)			x		
	Bulk thermal conductivity map	map/grid			x		
	Mean annual surface temperature	°C			x		
	Groundwater temperature (series, single depth point)	°C					x
	Groundwater temperature (series, multiple depth points)	°C					x
	Water level (normal water table)	m sub sl			x	x	
	Water level (high water table)	m sub sl				x	
	Water level (low water table)	m sub sl				x	
	Maximum pumping rate	l/s				x	
	Maximum daily pumping rate	m³/d			x	x	
	Maximum annual pumping rate	m³/yr			x	x	
	Grain size distribution	%				x	
	Hydraulic conductivity (derived from grain size distribution)	m/s				x	
	Effective porosity of aquifer derived from pumping test	%				x	
	Hydraulic conductivity derived from pumping tests	m/s				x	
	Gross aquifer thickness	m			x	x	
	Net aquifer thickness (related to normal water level)	m			x	x	
	Location of existing geothermal utilizations				x		
	Outline of relevant groundwater bodies suitable for shallow geothermal use (combined output with conflict of use maps)	map	x	x	x	x	x
	necessary calculation software		ArcGIS	ArcGIS	Jewel Suite ArcGIS	Jewel Suite ArcGIS	ArcGIS
	necessary workflow		open loop	open loop	3D modelling open loop	3D modelling open loop	open loop

D. Harmonized workflow for 3D modelling

D.1 The workflow – a brief description

The 3D structural model is a representation of the subsurface geometry in 3D dimensions. The 3D models provide information on the location, thickness, and structure as well as neighbourhood relations of geologic units. The 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.

Since the data, the rock classification schemes, the scale and level of detail, the geologic interpretation and the modelling software may vary among the project partners, a comparable modelling result can only be obtained if as many modelling steps as possible are harmonized or standardized. In subsequent steps, the 3D model will be used for the calculation of the geothermal potential. The results of the potential and conflict potential mapping in the pilot areas can only be comparable when the steps of data interpretation, processing and modelling are harmonized.

The presented workflow provides the base for the production of a standardized 3D model for GeoPLASMA-CE. 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**).

During the data preparation step, all data have to be transformed into the same georeference system. The data have to be interpreted according to the project aim and the desired level of detail. Due to these criteria, a modelling domain has to be specified. For details of this specification see D.3.2. Rules for the delimitation of special lithological bodies have to be specified. A standard geologic column comprising all lithological objects to be included in the object has to be worked out. In addition, the contact relationship between the lithological units 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 is the conceptual model forming the logical basis of the 3D modelling. A harmonized fault network has to be constructed. For details of these specifications see chapter 5. Then 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 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 (detailed steps are given in D.3.8).

The 3D model is created by interpolation between the input data. First, the fault network has to be modelled. Then, the lithology inside of the fault blocks can be modelled. Since all GeoPLASMA-CE partners use different modelling software, the interpolation algorithm cannot be standardized, but has to be performed as predefined by the 3D modelling software. A top-downward modelling workflow is recommended, since the data density is usually highest near the surface and inconsistencies might arise if units with few input data are modelled prior to units described by many data. Modelling of the unit tops is also recommended, since an approach specifying tops always makes sure that all parts of the model are “known” or specified.

If the pilot area contains an international border, a buffer zone has to be specified, which has to be a minimum of 2 km wide on each side of the border since discontinuities in the model will occur otherwise. The data in the buffer zone have to be exchanged among the partners, and the geologic units are modelled collectively. After a consistency check and finalization of the 3D model in the buffer zone, this model has to be fixed and modelling has to be extended to the whole pilot area. A final consistency check is necessary. The accuracy of the model depends on the density of the input data, on the conceptual expert knowledge about the modelled geology and on the complexity of geologic situation.

A standardized final 3D model output has to be produced. This model represents the geologic units by their top boundaries in a 2D raster data 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 (harmonized data management infrastructure). The standardized 3D model will be stored in the GeoPLASMA-CE database.

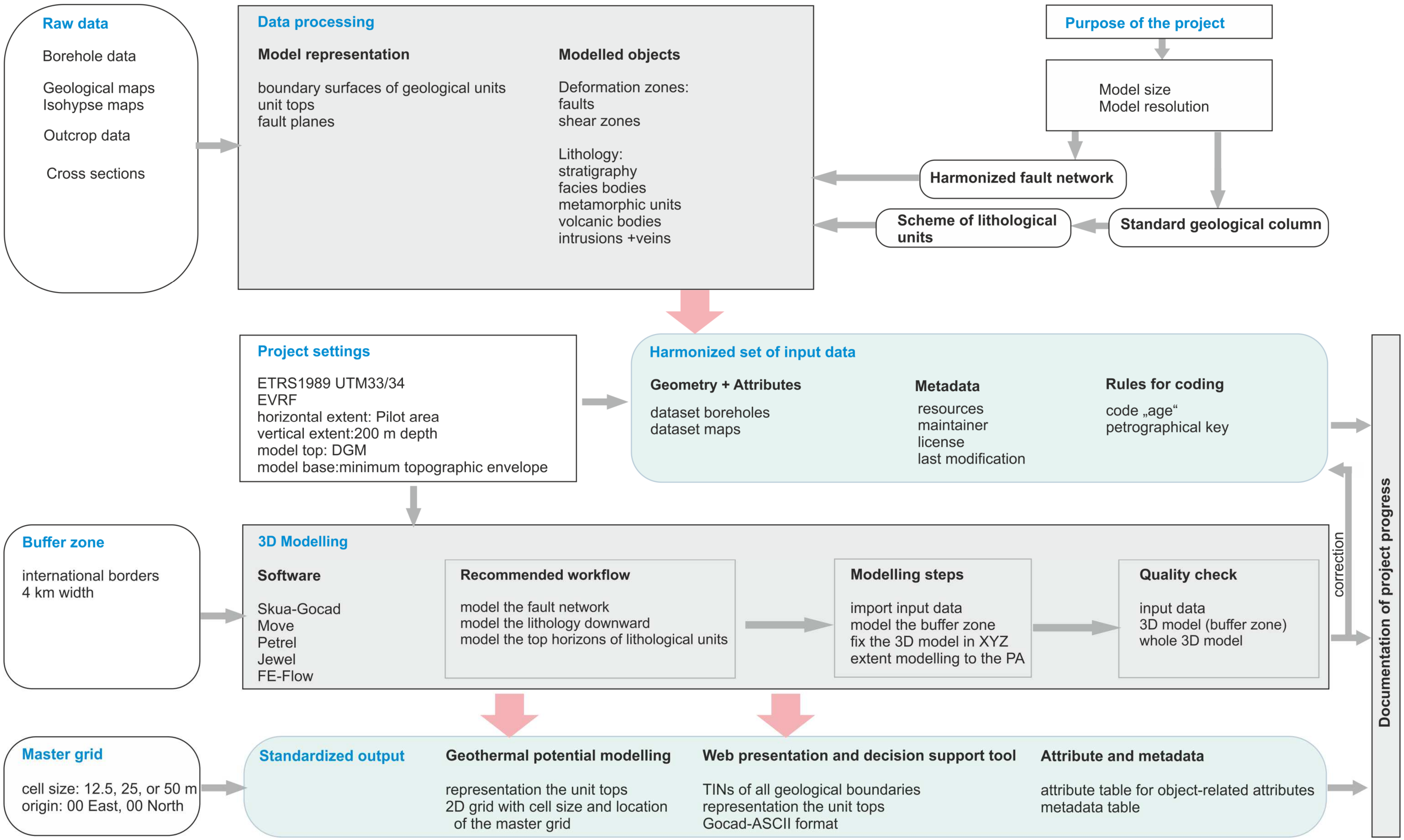


Figure 2: GeoPLASMA-CE workflow for 3D modelling.

The following list provides an overview over the important rules, specifications and workflow steps for 3D modelling. The toolkit in chapter D.3 gives a detailed description of each step.

1. Documentation of the project

2. Model specification

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

Specification of the modelled objects

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

Specification of the model representation

Boundary surfaces

Horizon top surfaces

Fault surfaces

3. Model 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

Quality check

Outcrop data

Borehole data

Geologic maps

Cross sections

Isohypse maps

Harmonized set of input data

4. 3D modelling

3D Modelling workflow

Quality check

5. Standardized 3D model output

3D Web viewer: Triangulated network (TIN)

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

Attribute table with age and petrography codes per unit

Metadata table for the whole 3D model

D.2 Rules and mandatory specifications - a checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters → See D.T2.3.1 for specification
Elevation reference system	EVRF2007 → See D.T2.3.1 for specification
Project documentation	template for the documentation of the project progress → See D.T2.3.1 for specification
Vertical extent	≥200 m
Model base	minimum topographic envelope
Buffer zones for transnational pilot areas	4 km width
Model representation	boundary surfaces tops of lithological units fault surfaces
Harmonized set of input data	Stay in line with the joint list of attributes → See D.T2.3.1 for specification Specify code for “age” and “petrography” Fill the metadata table for each data set
3D structural modelling	The buffer zone has to be modelled first along political borders (2 km on each side of the border). After a quality check and correction, this model is kept fixed and extended to both sides of the pilot areas.
Harmonized 3D model output data	2D Grids of the geologic boundary surfaces Metadata table for the whole model Attribute table with age and petrography codes → See D.T2.3.1 for specification

D.3 Tool kit for 3D modelling – detailed description of the workflow steps

Project documentation

D.3.1. Project documentation

General remarks

The documentation contains information which is important for the use of the model at any time after the project end by any person. The project documentation has to give an overview of the modelling steps, the input data, the modelling steps, and the project agents. Since the documentation is necessary to validate the model, it should also contain information on the interpretation and correction of the primary data.

Description of workflow steps

The project documentation template is given as an EXCEL spread sheet in deliverable D.T2.3.1 (harmonized data management infrastructure) as processdocu.xlsx (**Figure 3**Fehler! Verweisquelle konnte nicht gefunden werden.).

Project Title	**GeoPLASMA-CE**									
Project area	Pilot area 1 Vogtland- W-Bohemia									
last modification	20.05.2017									
by	Ines Görz									
status	data preparation									
	in progress									
Project type	**shallow geothermal**									
Geological 3D model	structure of lithological units									
Parameterized 3D model	permeabilty									
	specific heat capacity									
Geothermal potential model	specific heat extraction capacity									
	temperature gradient									
land-use conflicht maps	swellable rocks									
	karst units									
Project settings										
spatial reference system	ETRS1989 UTM 33 N									
elevation reference system	EVRF 2007									
coordinates lower left corner	X: 28658 m	Y: 5548730 m								
coordinates lower right corner	X:322651 m	Y: 5548730 m								
coordinates upper left corner	X: 28658 m	Y: 5609540 m								
coordinates upper right corner	X:322651 m	Y: 5609540 m								
depth	200 m beneath ground surface									
Processing										
work step	data category	objects	processing	software	source	maintainer	processed by	Date	comments	status
Data preparation	well data	B31, B32, B41, B42, B43, B51; B52, B53, B54, B61, B62, B63, B64, B65, B66, B67, B68, B69, B71, B72, B74, B75, B76, B77	conversion into ETRS1989 UTM 33	ArcGIS 10.4	Saxon drilling and outcrop database	LfLUG (Tobias Duteloff)	Ines Görz	17.05.2017	transformation on the fly	ready

Figure 3: Screenshot of the processdocu.xlsx template.

D.3.2. Modelling domain

D.3.2.1. Six pilot areas

General remarks

A pilot area is a region that was chosen to participate in the project because of its special geologic or geothermal characteristics or because of its great interest in developing concepts for the use of geothermal energy. The GeoPLASMA-CE project comprises 6 pilot areas which are defined as polygon shapes. **Figure** 4 gives an overview of the GeoPLASMA-CE pilot areas.

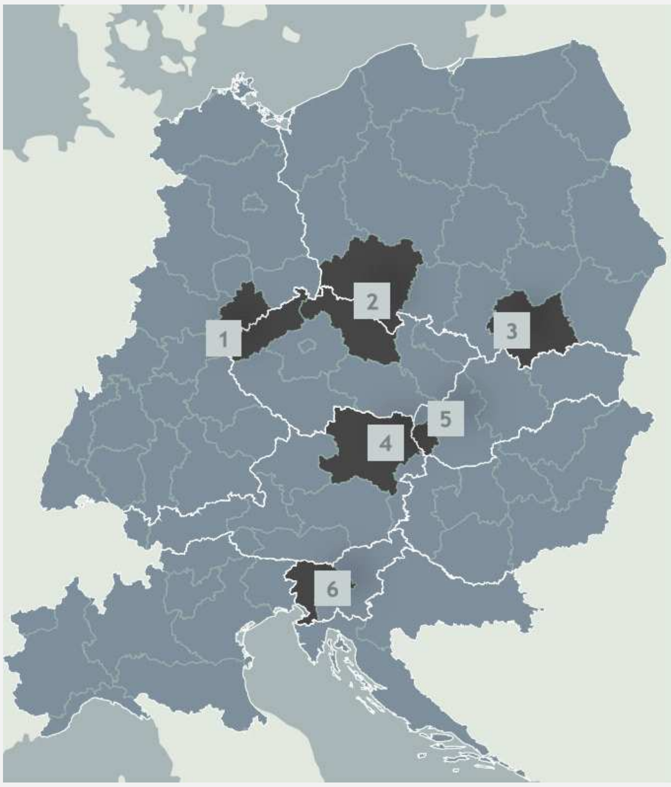


Figure 4: Overview of the GeoPLASMA-CE pilot areas.

Specification of project settings

D.3.2.2. Buffer zones at international borders

Description of workflow steps

The buffer zone of 4 km width is modelled first by both partners working in the transnational pilot area. A harmonized lithological legend and a harmonized fault network have to be specified prior to data processing. Geologic data sets are exchanged among the partners.

After finalization of the 3D model in the buffer zone, the units are kept unchanged and the 3D model is extended to both sides through the whole pilot area.

D.3.2.3. Model base 200 m below ground surface

General remarks

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 (**Figure 5**).

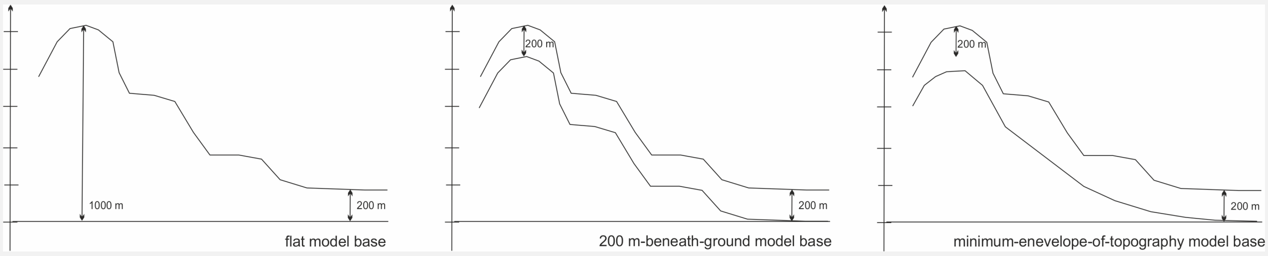


Figure 5: Possibilities for specifying the model base.

Description of workflow steps

Determination of the minimum topographic envelope

Morphological operations are a collection of non-linear operations related to the shape or morphology of objects in a raster image. In ArcGIS, the Focal Statistics tool performs morphological operations that compute an output raster where the value for each output cell is a function of the values of all the input cells that are in a specified neighbourhood around that location. The structural elements specify the cells that are included in the morphological operation. Calculate the minimum envelope by performing an erosion. The size of the structural element specifies how smooth the envelope is.

Spatial analyst tools→Neighborhood →Focal statistics →circle, 3 cells →minimum

Alternative

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.

D.3.2.4. Model top: Digital elevation model of the desired output resolution

General remarks

A digital elevation model is a 3D representation of the terrain surface. It forms the upper boundary of all geologic units and is therefore the top unit that has to be included in the 3D subsurface models. DEMS can be represented by raster or vector surface data structures.

DEMs are commonly built using data collected using remote sensing techniques, where two satellites emit radar waves and register the reflected signal. Since the radar waves also reflected by non-geologic objects like houses, roads, dams, the digital elevation model has to be processed prior to its usage in geologic 3D modelling.

Description of workflow steps

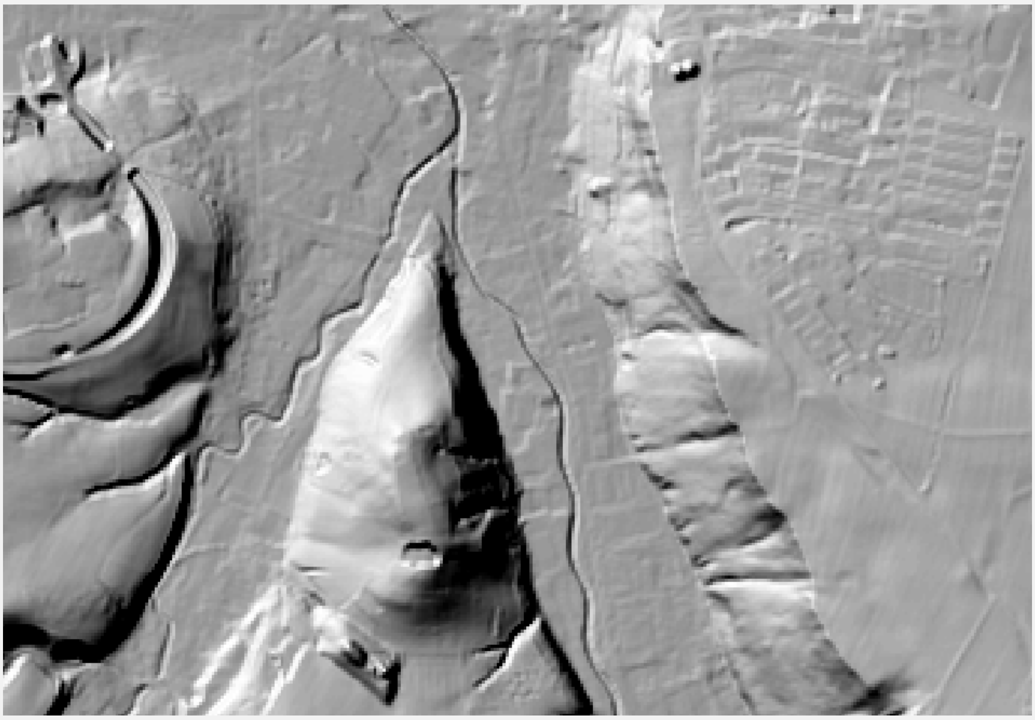


Figure 6: Digital elevation model with anthropogenic objects: Waste deposit in the South, roads in the North-East.

Resolution of the DEM

Digital elevation models are available with various resolutions (2m, 5m, 10m, 30m, 50m,…). A suitable DEM has to be selected, after the 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-geologic objects.

Processing of the DEM

Each DEM contains objects which are non-geologic, such as bridges, dams or water surfaces (**Figure** 6). If drilling data are linked to a DEM representing one of these objects, the depth of the geologic boundaries represented by the drilling may be wrong. Therefore, the DEM has to be correct prior to loading the drilling data.

Correction of water surfaces

Water bodies are represented in the DEM by the water table. Therefore, they have to be processed in order to show the correct geologic boundary, which is the bottom of the water body. We suggest to correct lakes bigger than 1 ha. 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 estimated. The elevation of the DEM has to be subtracted by the depth of the lake.

Rivers should not be corrected, as long as they are narrower than 2 raster cells.

> *Create a polygon shapefile "lake" with an attribute "ground_elevation"→ load the shapefile to ArcGIS (+ add data)*

Specify the area that has to be corrected:

> *Right-click on the layer "lake" → edit feature → digitize the outline of the deposit*

Generate several buffer rings inside of the polygon and assign realistic value for the elevation of the lake ground:

> *ArcToolboxes → Analysis Tools → Proximity → Buffer → create buffers inside of the lake polygon with increasing distance → specify the values for the lake ground elevation in the attribute table*

> *ArcToolbox → conversion tools → to raster → polygon to raster → value field "ground_elevation" → specify the cell size of the DEM*

> *ArcToolbox → Spatial analyst tools → map algebra → raster calculator → Con("lake"<Maximumdepth, ground_elevation, DEM)*

Correction of technical and infrastructural objects

Technical and infrastructural objects have to be identified and specified by polygons. NULL values can be assigned to the parts of the DEM inside of the polygons. The holes can be filled using morphological operations like closure (an erosion followed by a dilation).

> *Create a polygon shapefile "deposit" → load the shapefile to ArcGIS (+ add data)*

Specify the area that has to be corrected:

Right-click on the layer "deposit" → edit feature → digitize the outline of the deposit

Convert into a raster:

ArcToolbox → conversion tools → to raster → polygon to raster → specify the cell size of the DEM

Reclassify the raster:

ArcToolbox → Spatial analyst tools → Reclass → Reclassify

Give the same value (e.g. 1) to all polygons, i.e. to the entire range of values, and assign the value 0 to "no data" cells. Note: In the following step, the raster calculator will not work in areas where one or more layers contain "no data" cells, therefore the numerical value 0 is required to preserve the full extent of the layer.

Correct the elevation of the DEM in the region of the deposit:

ArcToolbox → Spatial analyst tools → map algebra → raster calculator → SetNull("deposit","DEM","VALUE =1")

This will cut "holes" into the DEM since the elevation of the digitized features will be set to "no data".

Fill the "holes" with data interpolated from surrounding cells by chosing an appropriate value for the diameter of the neighbourhood (100 cells in this example):

ArcToolbox → Spatial analyst tools → map algebra → raster calculator → Con(IsNull("DEM"), FocalStatistics("DEM", NbrCircle(100, "CELL"), "MEAN"), "DEM")

Note: In later ArcGIS versions, the

ArcToolbox → Spatial analyst tools → surface functions → elevation void fill

function may be utilized instead.

D.3.3. Model scale

Description of workflow steps

The model scale determines the level of detail of the model, which is specified in the harmonized legend, the harmonized fault network and the minimum areal extent and thickness of geologic units reproduced in the 3D model.

Scale for the GeoPLASMA-CE pilot areas:

Vogtland / W-Bohemia	1 : 50 000
Wałbrzych / Broumov	1 : 50 000
Krakow	1 : 50 000
Bratislava /Hainburg	1 : 50 000
Vienna	1 : 25 000 1 : 10 0000
Ljubljana	1 : 10 000

D.3.4. Geologic bodies presented in the 3D-model

D.3.4.1. Lithological units

General remarks

Units that should be modelled, if they are present in the modelling domain:

- Hydrogeological units,
- Sedimentary units:
- Stratigraphy,
- Facies bodies,
- Metamorphic units,
- Magmatic bodies:
- Intrusions,
- Volcanic units,
- Veins.

A **standard geologic column** specifies which units are modelled in each pilot area. Small units or units with similar geothermal properties can be merged.

Specification recommended for 1: 50 000 regional models

A unit is included in the model if its horizontal extent is larger than 10 000 m^2 and if they are thicker than 2 m. Exception: Thermally highly relevant units like quartzite veins or clay layers controlling the dynamics of an aquifer.

Description of workflow steps

An interpretation of the geologic data with respect to the modelled process or potential is necessary. For GeoPLASMA-CE, this means that rock units with varying geothermal potential have to be represented in the model. Structures like folds in a rock with similar thermal properties can be neglected.

In addition to representing the geothermal-hydrological units, it is recommended to model important marker horizons or units if these can be easily determined in the geologic data set and aid in setting up the 3D structure of the modelling domain.

D.3.4.2. Wet and dry lithological units

General remarks

Rocks with high water content have a different specific thermal conductivity than dry rocks. The water can be related to pores or fractures. If a dense rock is strongly fractured or decomposed, it can be wet and this decomposed or fractured portion of the rock then has different thermal properties than the dry rock. Therefore, dense and decomposed or fractured rocks have to be modelled as separate rock units, such that varying thermal parameters can be assigned to the units.

Description of workflow steps

For modelling the potential of closed loop systems, it is necessary to delimit porous, fractured and weathered rock units from dense rocks, when interpreting the well data and generating the standardized geologic column. The reason for this is that the thermal conductivity in each geologic unit will be averaged. If a weathered and a fresh rock are not modelled separately, the whole rock unit will be represented by the average of the thermal conductivities. If the weathered zone with small thermal conductivity shall be represented in the model, it has to be delimited as a separate unit. In addition, the thermal conductivity for water saturated and dry rocks will be assigned to the model. If a porous rock is not delimited from a dense rock, this differentiation is not possible in the model.

D.3.5. Geologic surfaces presented in the 3D-model

D.3.5.1. Deformation zones

General remarks

- Fault planes;
- Fault zones;
- Detachment zones;
- Shear zones.

Description of workflow steps

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 fault surface and the horizon top have to be combined to the boundary of one geologic body.

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 (**Figure 7**).

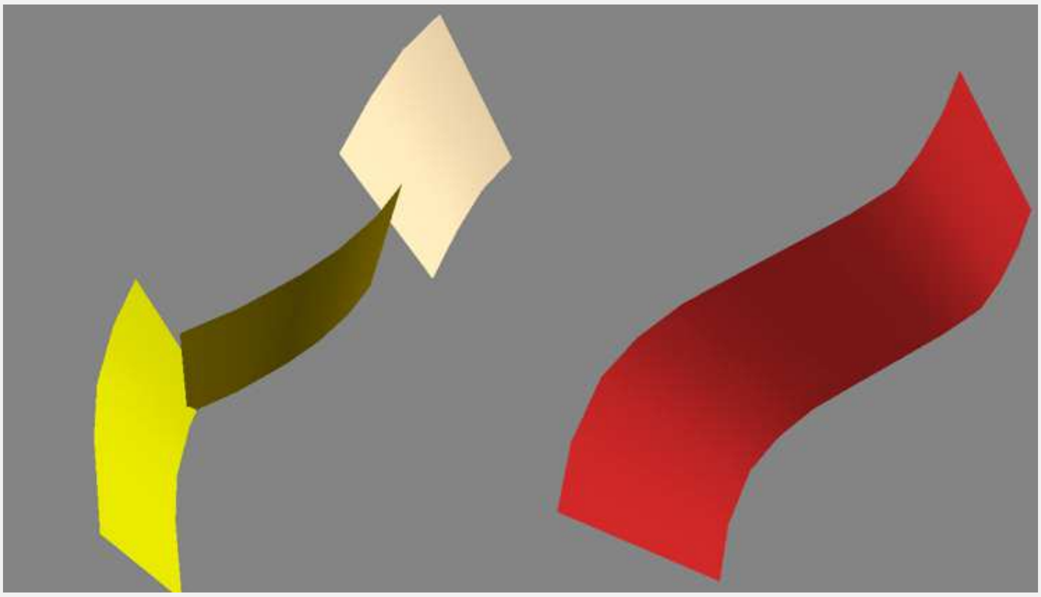


Figure 7: Different levels of detail of a fault model.

D.3.5.2. Lithological units: Horizon top surfaces

General remarks

Lithological bodies can be represented in the model either by their volumes or by their boundary surfaces. All GeoPLASMA-CE partners use software working with boundary surfaces. This representation has the advantage that it is storage-efficient. Lithological units can be represented by their top surfaces, base surfaces or by their envelopes (**Figure 8**). In order to generate comparable modelling results, one uniform representation of objects is mandatory for the GeoPLASMA-CE project.

Modelling approaches modelling the tops are realized in Skua and in Petrel. This modelling approach is especially well suitable, since a model specified by top horizons is completely known and can be modelled from top downward. Since most data are available near the surface, atop down modelling approach avoids inconsistencies in the model.

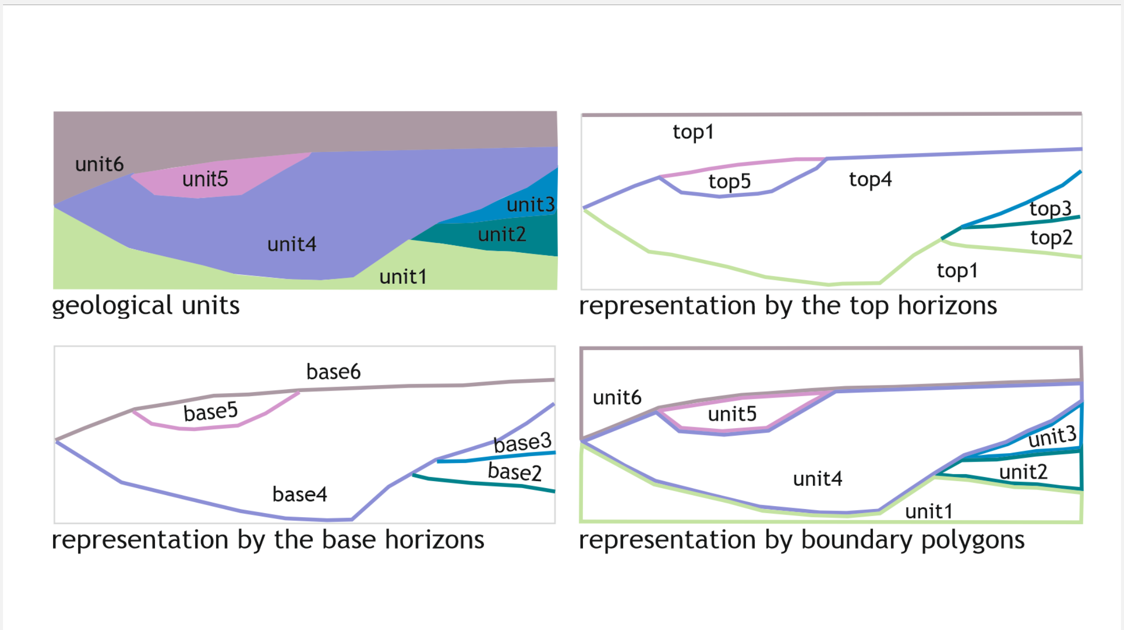


Figure 8: Various representations of lithological units by boundary surfaces.

Description of workflow steps

As final representation, a model of the horizon tops is required. The modelling workflow itself cannot be specified, since the GeoPLASMA-CE partners work with various data sets and software systems. However, it has to be pointed out that modelling top or base horizons requires different processing of the input data, such that the data set becomes consistent with the modelling approach used.

D.3.6. Harmonization rules

D.3.6.1. Standard geologic column

General remarks

The standard geologic column is a composite diagram showing, in vertical sequence, geologic strata underlying a given area down to the model base, with the names of the various rock formations indicated in the column. The standard geologic column comprises information on the petrology and stratigraphy of the pilot area. Since continuously varying lithologies in nature have to be delimited as homogeneous lithological bodies in the model, the standard geologic column provides the guideline for the assignment of a rock to one specific modelled rock body. It is a theoretical classification scheme which combines rocks with similar lithology, geothermal and hydrogeological properties to one geologic unit. Each rock unit represents one row in the column.

Description of workflow steps

How to generate the standard geologic column

Usually, the geologic maps of a pilot area provide a good starting point for developing a standard geologic column, because the map units are already classified and stratified, while drilling data are usually documented in a more continuous and detailed way with less interpretation.

However, depending on the author, geologic maps display different petrological classification schemes and levels of detail and may apply different classification criteria. These different interpretations give an impression about the variability of rock types mapped and have to be harmonized.

1. *Which rocks do exist?*

First, the lithological units of the pilot area have to be registered.

2. *Which rock groups do exist?*

I.e., in the standard column of the TransGeoTherm project, various descriptions of low moor sediments had to be registered and harmonized (**Table 18**):

Table 18: Different names for similar geological units in Saxony.

Rock group	unit code	Map Pleistocene	Map Niesky	Map Görlitz
Low moor sediments		Peat, low-moor	Muck	Limnic formation (low moor)

For the geothermal mapping, also criteria like hydrogeologic or geothermal properties have to be considered for the classification. Therefore, a 50 cm thin clay layer with an areal extent of some kilometers needs to be modelled, since it controls the flow of the groundwater, while a large 500 m thick “porphyric” granite and “coarse-grained” granodiorite can be classified in the same group.

3. *Shall the rocks of one petrological group be represented in the model / in the column?*

This is a subjective decision of the project agents and depends on the modelling purpose and on the desired level of detail.

- *Importance criterion*

  This is the criterion with the highest priority. If one rock has specific properties controlling the whole system, it has to be included into the column. This may be the hydraulic property of a thin large clay layer or the large specific thermal conductivity of salt rocks.

- *Areal criterion*

  The resolution of a model is the size of the raster cells of the output model. Smaller objects cannot be represented.

  Make a decision, which minimum number of raster cells has to belong to one geologic unit. I.e., in the TransGeoTherm project, the minimum lateral extend of modelled units was set to 10,000 m^2. This corresponded to 16 raster cells, since a 25 x 25 m raster was used.

- *Thickness criterion*

  In general, a minimum modelled thickness of 2m is used for 3D modelling in regional models in Saxony. However, do not forget to check the importance criterion!

- *Are enough data available to describe the geometry in 3D?*

  Not just the geometry, but also the contact of one body to the next has to be modelled. A minimum of 3 data points is needed for 3D modelling of undeformed sedimentary rocks with constant thickness and dip. However, since variability in thickness and dip is typical for geologic units, use as many data as possible! For complicated structures like a salt diapir, two intersecting pairs of seismic section are needed at minimum.

Check small geologic bodies like lenses or intrusions with irregular geometries and contacts, whether you can construct their 3D geometry to get a feeling how many data are needed.
If a rock unit will ***not*** be represented in the 3D model, it has to be accumulated by its surrounding rocks. Take care that no inconsistencies form at borders of geologic maps or political districts, when you merge rock units.

4. *In which sequence do the rock units occur?*

The neighborhood relationship and the sequence of the rock groups and, in case of sedimentary units, the relative age are described by the order of the units in the standard geologic column. After you have decided which rock units are included into the standardized stratigraphic column, you have to bring them in the sequence of their relative age. The oldest unit is displayed in the bottom row of the column.

5. *Assign the code "age" to each rock unit in the standard geologic column.*

Later, during processing of the input data, this code will be assigned to all well, map and outcrop data to indicate, that they belong to the same model body. The coding is explained in the next tool kit.

D.3.6.2. Structure and contact relationships

General remarks

The structure in 3D modelling specifies the geometry and topology of the boundary surfaces which subdivide the volume of the modelling domain. The general geologic structural style should be represented by the model (undeformed sediments, fold-and-thrust-belt, graben structure,…). The model has to consist of consistent bodies. The structure specifies the boundaries between rock units – depositional contacts, intrusive contacts and tectonic contacts- as well as deformational geometries like fault blocks, folds or nappes. Internal structures like foliation are usually neglected in geometrical 3D models.

Description of workflow steps

The structure of a pilot area has to be determined by delimiting various rock types in the 3D data set. Geologic concepts and expert knowledge about the region can aid in developing a structural concept which describes the data set in a consistent and unambiguous way.

"Layer cake" - conformable and unfaulted structure

This is the simplest structure that can be modelled (**Figure 9**). In this case, the geologic objects are bigger than the modelling domain and no body ends inside of the modelling domain. The boundary surfaces of the objects are only bordered by the modelling box. No boundary surfaces cut or intersect, although the thickness of the rock bodies may vary.

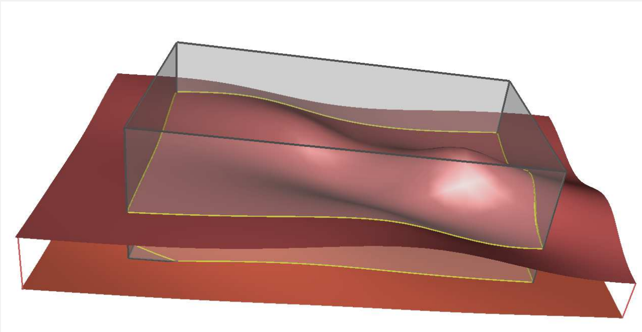


Figure 9: The two conformable boundary surfaces of a geologic unit have borders which are specified by the intersection lines with the model box (yellow). There are no internal borders.

Faults and unconformities and cross-cutting intrusive boundaries are either not known or ignored for simplification reasons. Examples for this structure are undisturbed marine sedimentary deposits or a metamorphic nappe structure. All data points used for 3D modelling are "picks". This means, that they describe that a boundary is present at the data point. However, it is known that the boundary is also present outside of the data points (in contrast to a deposition outline).

“Lens” or “Blob” – object boundary is completely inside of the modelling domain

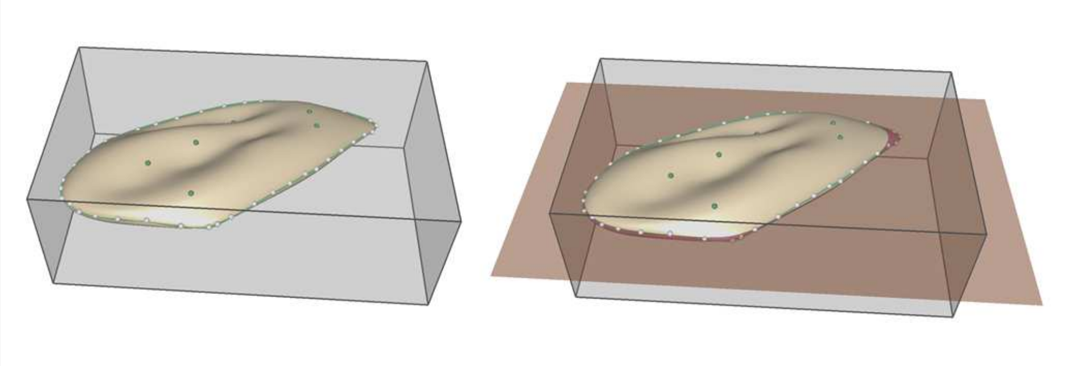


Figure 10: A geologic unit with a boundary surface completely located inside of the model box can be described by two types of data: Outlines specifying the end of the lateral extension of the body (green line-left), and picks specifying the location of the boundary surface (green points –left). If the boundary surface of a lens coincides with another unit boundary, it specifies an unconformity.

In this case (**Figure 10**), the boundary of a geologic object is completely located inside of the modelling domain. The geologic data referring to it may either represent an outline (like the green line with white dots in the left image: A deposition outline), indicating that the border is ending along the data points. Or they may be picks, just indicating that the object was traced at the data point (green points at the left image). If the border of an inner boundary surface ends at another boundary surface, this is called unconformity in sedimentary environments. The unconformity can be erosional – this means that the bottom surface of the geologic object is cut off by the top boundary surface. The unconformity can be baselap, this means that the top boundary surface is cut off by the bottom boundary surface. Whether a lens is described by baselap or erosion is the agent’s interpretation. However, the modelling results are different depending on the chosen interpretation. In cross-border pilot areas, a uniform interpretation has to be used in order to avoid inconsistencies along the border.

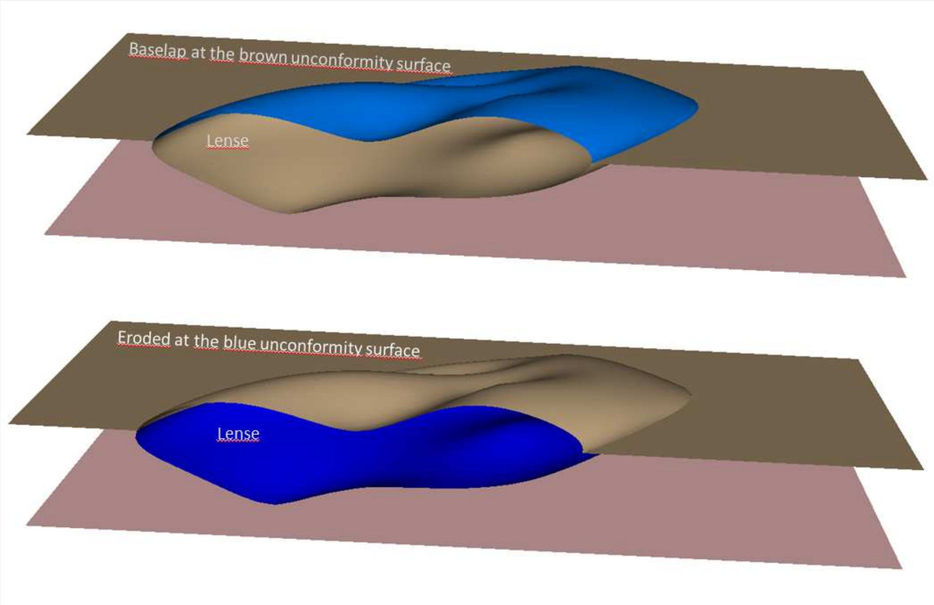


Figure 11: Baselap and erosional unconformities can be distinguished depending on whether the base surface of a body is cut off by its top surface or vice versa.

Object boundary is partially inside of the modelling domain

In this case (**Figure 11**), a boundary surface can be partially bordered by the model box and partially inside of the modelling domain. The contact relationships are the same as for "lenses".

Intrusive boundaries

Intrusive rocks cut through their host rock (**Figure 12**). The boundary surfaces of the youngest intrusive bodies are continuous; the boundary surfaces of older rocks are cut off successively by younger intrusions.

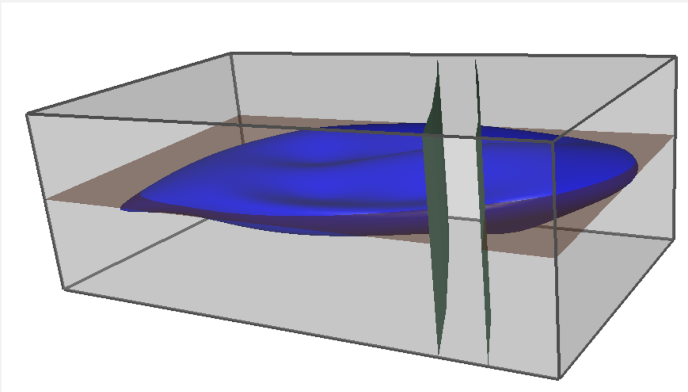


Figure 12: The boundary surfaces of intrusive bodies cut off the boundary surfaces of their host rock units. Older units are cut off by younger ones (brown by blue and green, blue by green).

Object boundaries displaced by fault or shear zones

Faults and shear zones are boundaries between rock units which accumulated a displacement. Faults are indicated in the 3D data set by sudden changes in the depth or thickness of rock boundaries and the local absence or duplication of rock units in wells. Shear zones may be broader than faults and can be delimited as separate rock units if necessary. Metamorphic rock units are usually bordered by faults or shear zones.

D.3.6.3. Scheme of lithological units

General remarks

The scheme of lithological units is a combination of the standard geologic column and the contact relationship between the units represented in the column. It specifies the relative position and the contact relations of all rocks to be modelled. **The scheme of lithological units provides the conceptual model and is therefore the basis for the structural modelling.** Additionally, it provides a correlation scheme between various lithologies of the same relative age. It is one of the most important tools in structural 3D modelling, since it can explain the varying sequence of units in borehole profiles which are all consistent with the same standard geologic column. The scheme of lithological units is important for the quality check of the borehole profiles (toolkit D.3.8.2) and for the quality check of the 3D model.

Description of workflow steps

A scheme of lithological units has to be produced for all pilot areas. It is a scheme which combines the standard geologic column with the structure and contact relationships and the spatial occurrence of the lithological units (**Figure 13**). The input data and the result of the 3D modelling have to be consistent with this scheme.

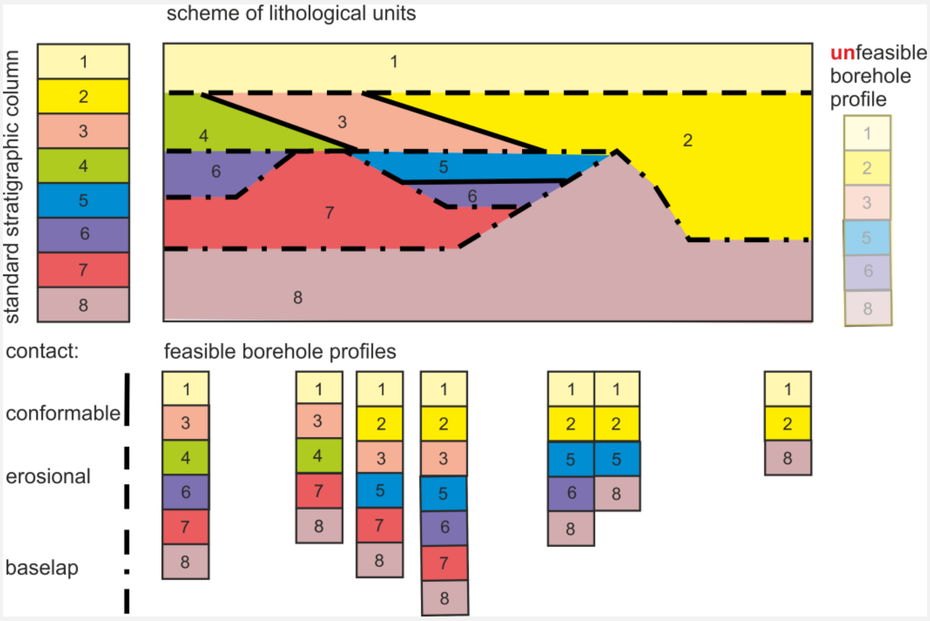


Figure 13: Scheme of lithological units in comparison to the standard stratigraphic column, feasible and unfeasible borehole profiles.

D.3.6.4. Harmonized fault network

General remarks

The harmonized fault network is a set of fault data with the same level of detail or resolution and is used for the combination of different geological maps. If a fault is extending to the edge of the map, it will only be part of the harmonized fault network if it is also traceable on the neighboring geologic map. Lateral offsets along the map edges have to be corrected.

Description of workflow steps

The harmonized fault network should include structurally and geothermally important faults on the simplest possible level of detail (**Figure 14**). It should be kinematically reasonable.

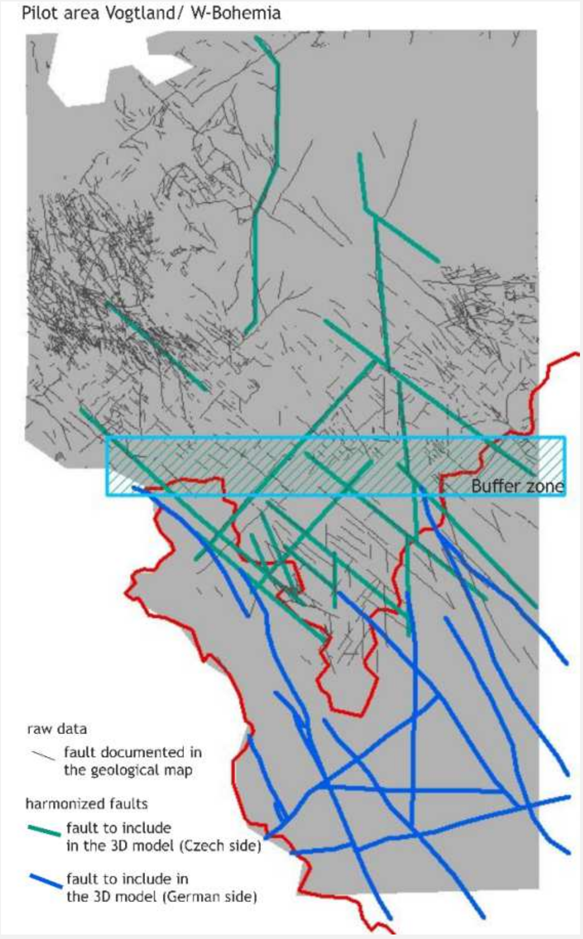


Figure 14: Harmonized fault network in the pilot area Vogtland/W-Bohemia.

D.3.7. Raw data and raw data processing

D.3.7.1. Outcrop data

General remarks

Outcrop data is geologic data directly determined by a geologist at the Earth's surface or in a mine. This may be point or line data.

Description of workflow steps

Outcrop data is the most reliable data in geology. In addition to petrography and stratigraphy, outcrop data may provide important structural data. **The structural concept of a 3D model usually is consistent with outcrop data in the model region.** However, the level of detail usually much higher that the level of detail of a regional 3D model.

Model input – raw data

D.3.7.2. Borehole profiles

General remarks

Well data comprise information on the location of the well head, on the well path and on the lithology documented along the well path. Usually, they comprise a detailed petrographic description. This has to be classified according to the rock groups of the standard column. Additionally, the rock groups have to be stratified, which means that the stratigraphic location of each rock group has to be qualified. After classification and stratification, petrographic data in the well receive a code which specifies to which unit in the scheme of lithological units a data point belongs to.

Description of workflow steps

Example

The example shows the lithological attributes of a well documentation from Saxony (**Table 19**). The well data are interpreted due to their hydrogeological properties. A general subdivision in aquifers and aquitards is used. If two aquifers are located directly on top of one another, they may be merged in one model body. This is the case for Cenomanian sandstone and conglomerate.

In case of model bodies 2 and 3 the two aquitards were kept as separate model bodies, because one is a continuous layer and the other a lens, both having a different function in the hydrogeological system.

The Cenomanian marlstone and its altered cap were merged to one model body, since both rock units act as aquitard (model body 6). In contrast, the gneiss and its altered cap have different hydrogeological properties: The sandy silt acts as aquifer in contrast to the dense gneiss which is impermeable. Therefore, the rocks are assigned to two different model bodies: The altered gneiss is model body 8, the dense gneiss is model body 9.

After the decision was made, which rocks are merged or kept separately, all wells have to be interpreted in a consistent way.

For the specification of the “groups” of the output model, only a subdivision in aquifer (01) and aquitard (02) was taken.

Table 19: Example for coding of a drilling data set.

Well	data	Processing			Assignment	to	model bodies
Petrology	Verbal description	Interpretation	Lithological group	Stratigraphy	Model body	Project-internal code	Age code
sand	strongly silty with gravel	slope wash	Loam lense aquifer	Holocene	Holocene-aquifer	1	001 01 01 01 01
silt	strongly sandy with clay	slope wash loam	loam lense aquitard	Holocene	Holocene-aquitard	2	001 01 01 01 02
silt	uniformly silty	loess	loam continuous aquitard	Holocene	Holocene-loess	3	001 01 01 01 02
sand	fine lamination of dark and yellow fine sand layers	basin fill	sand continuous aquifer	Pleistocene	Pleistocene-aquifer	4	001 01 02 02 04
sandstone	dense and hard banks	marine sediment	sandstone continuous aquifer	Cenomanian	Cenomanian-aquifer	5	002 01 01 32 01
gravel stone	fine gravel, sandy	marine sediment	conglomerate aquifer	Cenomanian	Cenomanian-aquifer	5	002 01 01 32 01
silt	decomposed marlstone	marine sediment, altered	lloam continuous aquitard	Cenomanian	Cenomanian-aquitard	6	002 01 01 32 02
marlstone	banked	marine sediment	marlstone continuous aquitard	Cenomanian	Cenomanian-aquitard	6	002 01 01 32 02
sandstone	banked with silt layers	marine sediment	sandstone aquifer	Cenomanian	Cenomanian-aquifer	7	002 01 01 32 01
silt	sandy l with fine feldspar gravel and biotite	altered gneiss	loam aquifer	Cambrian	Cambrian-aquifer	8	004 32 00 00 01
gneiss	biotite gneiss	gneiss	gneiss aquitard	Cambrian	Cambrian-aquitard	9	004 32 00 00 02

Model input – raw data

D.3.7.3. Geologic map

General remarks

Geologic maps are projections of the outcrop of geologic bodies to a horizontal plane. A geologic body is usually represented by a polygon describing its intersection surface with the Earth's surface. The polygon is specified by an outline delineating the border of the geologic body at the Earth's surface.

A line in a geologic map represents the intersection of a geologic surface with the Earth's surface. Line objects are usually used to represent geologic surfaces without their relation to a specific geologic body, like faults.

Points in geologic maps usually represent points of measurement of the orientation of a surface.

Description of workflow steps

Project the map data to the DEM

The geologic body was mapped by a geologist moving along the Earth's surface with its topography. The geologic map is a horizontal plane which is not describing the Z-values of the mapped boundary lines. In order to correct this and to bring the geologic boundaries in a correct position in 3D, all map data have to be projected in vertical direction onto the DEM surface.

Classification of polygon data

The feature most relevant for 3D modelling is the polygon, since it represents the outline of geologic bodies at the Earth's surface. However, care has to be taken since the geologic meaning of a polygon boundary may not be clear or may be different for different parts of the polygon:

If the boundary of a **geologic object is only partially inside of the modelling domain**, the polygon boundary consists of the intersection of the geologic boundary with the Earth's surface and of the map border. The map border has no geologic meaning. If the polygon part representing the map border is projected to the ground surface and used for 3D modelling, this produces errors, since the real position of the geologic boundary is in the subsurface (**Figure 15** map polygon unit 1). Therefore, each map polygon has to be split in parts representing the geologic boundaries and in parts representing the map boundaries.

In some cases, the polygon can represent the top and the base boundary of a stratigraphic unit and has to be split into parts which have to be assigned to the proper model boundary surfaces (**Figure 15** map polygon unit 2).

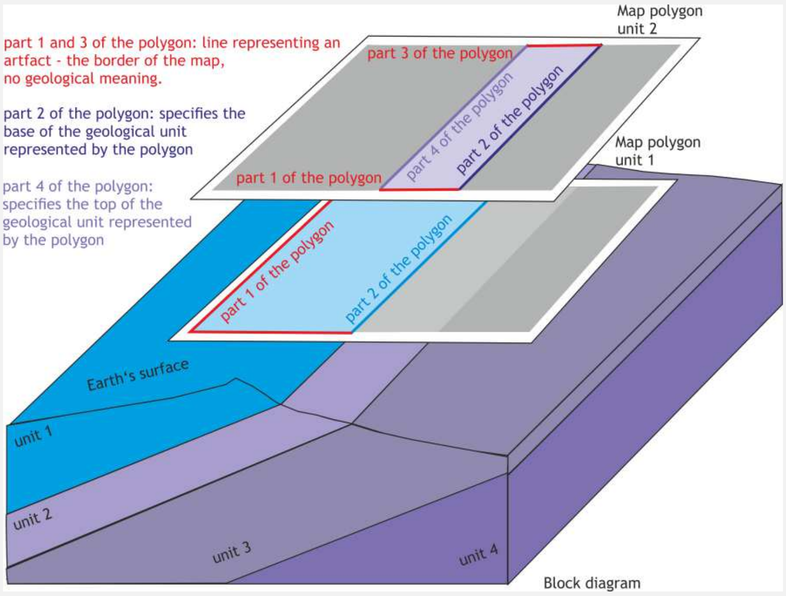


Figure 15: Relation of objects on a geological map to objects in a 3D model in conformable sedimentary rocks.

If a geologic boundary is completely inside of the map, erosion and deposition outlines have to be distinguished (**Figure 16**):

A deposition outline describes the top of a geologic unit. An erosion outline describes the base of a geologic unit. If horizon tops are modelled, the erosion outline in **Figure 16** has to be specified as top of unit 2 although, in the map, it is shown as outline of unit 1. So: Be careful with classifying map data to the proper model boundary surfaces!

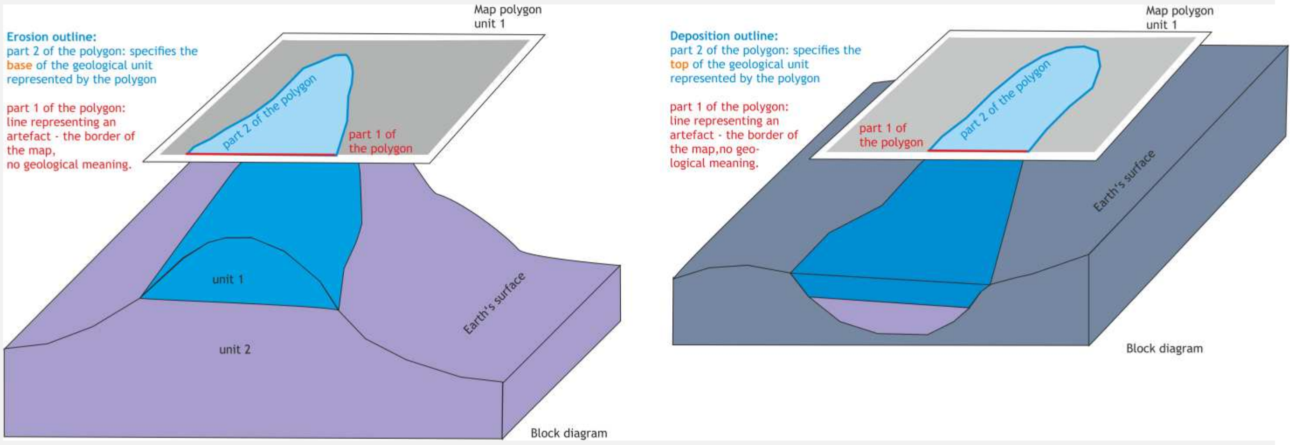


Figure 16: Relation of objects on a geological map to objects in a 3D model in sedimentary rocks with unconformities.

D.3.7.4. Cross sections

General remarks

Geologic cross sections are interpreted data providing a vertical model of the geologic structure along a line. The boundaries of geologic units and faults are represented as lines in the cross sections. Cross sections have to be used with care because they are usually inconsistent in 3D.

Description of workflow steps

Cross sections are useful tools for interpretation of the geologic raw data. They aid in developing an imagination, which data belong to a geologic body, which size and structure it has. The geologic data can be interpreted with various conceptual models, i.e. differences in the depth of one boundary may be explained by sedimentation, folding, faulting. The cross section has to explain all available data in a consistent way by checking the possible structural concepts.

Cross sections should be drawn perpendicular to the strike of the geologic units, since then the apparent dip is coincident with the real dip.

Model input – raw data

D.3.7.5. Isohypse maps

General remarks

An isohypse map is a map contouring constant depth levels of a geologic boundary surface (horizon or fault). It is interpreted data generated by interpolation. It provides picks where the position of one horizon is known, but not an outline.

Description of workflow steps

Isohypse maps have to be carefully checked against the borehole data set. If deviations to several wells are found, the isohypse data can either be neglected or shifted by a constant amount (difference to the well marker).

D.3.8. Quality check

D.3.8.1. Outcrop data

General remarks

This is a process reviewing the quality and correctness of all data used. The XYZ coordinates and the geologic information of the data has to be checked especially in the context of other data in order to obtain a consistent and geologic reasonable data set.

Description of workflow steps

Outcrop data have to be considered most reliable. However, different geologists may use different interpretations of field evidence. Therefore, outcrop data have to be validated in the sense of the geologic concept used for 3D modelling.

In addition, location errors like erroneous XYZ coordinates may occur.

D.3.8.2. Borehole profiles

General remarks

The quality check of the input data includes a check of proper import of the boreholes (location, missing information) as well as a consistency check of the imported geologic boundaries.

Description of workflow steps

Check of the drilling location

Errors may occur in the XY coordinates and in the Z-value. First, check whether digits are missing or duplicated in the X Y coordinates. Then, check the differences of the Z-values of the well heads against the DEM. Differences of <1 m can be neglected. Possible sources of errors:

- The well has an ellipsoid-referenced Z-value (GPS measurement). In this case, the deviation is 30-40 m and has to be corrected as described in D.T2.3.1.
- The DEM is erroneous (represents a spike / building) → correct the DEM as described in D.3.2.4.
- The DEM has changed due to an anthropogenic deposit or excavation → if the difference is feasible, keep the drilling head.
- The drilling head is erroneous → project it to the DEM and move the whole drilling path respectively.

Check for errors in stratigraphy

A wrong stratigraphic assignment can be detected by a shift of the Z-value of one well marker, by local changes in the unit thickness, by changes in the sequence of the units.

- Correct a wrong stratigraphy in the well documentation
- Refine the stratification, if necessary, in the well documentation
- Do **not** correct to fine stratigraphy in the well documentation. This is only done in the coding step of the well data processing in order to not lose information.

Check for missing well markers

If a well marker is missing, this can have various reasons:

- The unit exists, but was missed and not documented in the borehole.
- The unit exists, but the borehole is too short to reach it.

In both cases, the unit has to be modelled at the location of the borehole.

- The unit was faulted out along a normal fault. No unconformity exists, but the borehole is intersecting the “hole” in the unit produced by faulting.
- The unit is absent due to an unconformity. The modeler has to decide whether this is a baselap or an erosion.

Check for errors in petrography

Since well data are registered by various persons with various levels of knowledge and often by non-geologists, at different times, the description of the well data may be heterogeneous. Inconsistencies in the petrographic description may already occur in the field. Later, errors during the digital registration and classification may occur.

- Check original well documentation,
- Check the neighboring drillings and harmonize the inconsistent one, if reasonable.

D.3.8.3. Geologic maps

General remarks

The quality check of map data mainly includes a consistency check against borehole and outcrop data.

Description of workflow steps

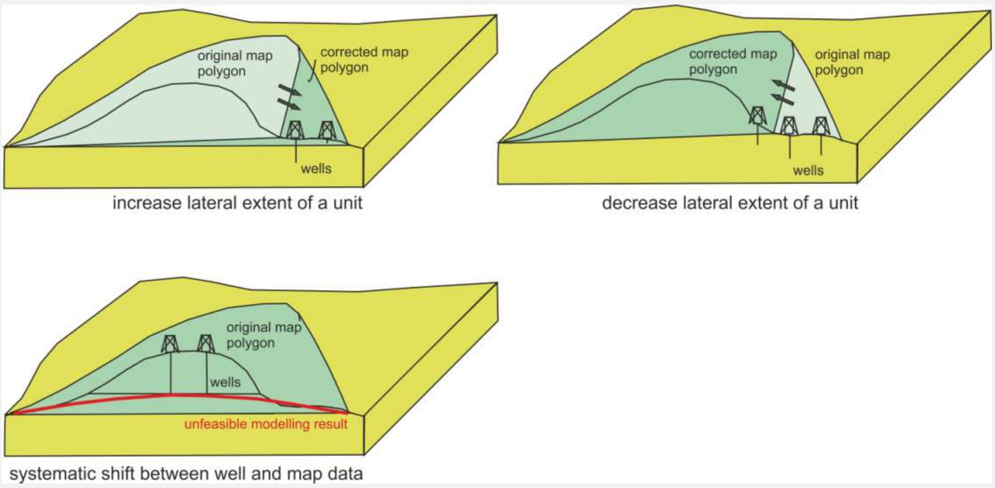


Figure 17: Change of the lateral extent of a map unit after comparison with drilling data.

If the lateral extent of a geologic unit was not mapped correctly, this can be detected by wells which have traced the geologic unit outside of the map polygon. The map polygon has to be corrected in such a way that it includes all wells with the geologic unit (**Figure 17**).

If wells that reach the depth level of a geologic unit do not contain a geologic unit, although they are located inside of the map polygon, the lateral extent of the geologic unit has to be reduced.

Sometimes, a systematic error of the Z-values of the well data and map data can be observed. In this case, the map data have to be considered as less reliable. If in this case both well and map data are used for 3D modelling, large sedimentary horizons will get a convex or concave shape, which cannot be explained by processes of their formation. The shape of the modelling result will rather correspond to the morphology of the Earth's surface, which is younger than the geologic unit. In this case, the extent of a polygon has to be re-digitized completely.

Model input – raw data

D.3.8.4. Cross sections

General remarks

Cross sections usually do not match the 3D geometry properly. A quality check is very important!

Description of workflow steps

Inconsistencies of cross sections

Changes in apparent dip

If the base line of the cross section has a kink, this is not directly seen in the cross section, since this is drawn on one plane. However, the apparent dip of a geologic unit changes at the kink, such that the user gets the impression that the dip itself is changing.

Proper points of intersection of units drawn in different cross sections

If two sections cross one another, but the lines tracing the borders of geologic surfaces do not intersect, this has to be corrected by shifting, stretching, rotating of one of the cross sections. If the result is not getting better while using these operations, the lines may be interrupted in the vicinity of their crossing, such that the inconsistency is not digitized.

Inconsistencies with map and well data

If a cross section is inconsistent with map data, this has to be corrected by shifting, stretching, rotating of one of the cross sections. If the result is not getting better while using these operations, the lines may be interrupted in the vicinity of their crossing, such that the inconsistency is not digitized.

D.3.8.5. Isohypse maps

General remarks

The quality check mainly includes a consistency check against the borehole data.

Description of workflow steps

If the isohypse map is old, it usually has a bad not consistent with the well data.

- A systematic error can be corrected by shifting the isohypses.
- A local systematic error can be corrected by shifting parts of the isohypses and leaving spaces to the unshifted parts which are big enough to avoid kinks and irregularities in the modeled object.

D.3.9. Harmonized sets of input data

General remarks

Harmonized input data sets meet the following requirements:

- They directly feed into the elaboration of harmonized output datasets.
- They are available in a digital data format having a geographical reference.
- They are in line with a harmonized list attributes and parameters, which organizes the thematic content and the physical units.
- They use the joint coding of age and pilot area number.
- Each data set is accompanied by a metadata sheet.

Description of workflow steps

The rules for producing the harmonized set of input data can be found in the deliverable D.T2.3.1 „Set-up of harmonized data management infrastructure for GeoPLASMA-CE“.

For each set of input data, a data and metadata set has to be produced, e.g., one for all borehole data, one for all map data, one for all fault data.

D.3.10. 3D modelling

D.3.10.1. Modelling workflow

General remarks

The term 3D structural modelling comprises all mathematical and computer-scientific methods allowing the uniform mapping of topology, geometry and properties of geologic objects while taking into account all kind of data related to these objects. The result of 3D structural modelling is a set of geometrically feasible and geologically reasonable objects representing the structure of the subsurface on a certain level of simplification.

Description of workflow steps

3D modelling is performed by every partner with its own software and interpolation algorithm.

International boundaries

Partners in international pilot areas have to take care to generate a consistent 3D model along the political boundaries. Therefore, a buffer zone of 2 km width on each side of the border has to be specified. The 3D model is first generated inside the buffer zone by both partners in common. After this model has been generated and quality-checked, it will be fixed and not changed again. Then, the 3D model is extended to both sides of a pilot area.

Geologic concept

The first step in 3D modelling is to **generate a conceptual model** about the structure of the pilot area. This has to be done by respecting the most recent geologic knowledge and can be supported by constructing cross sections.

Construction of the 3D bodies

The fault network has to be modelled first, because it displaces lithological bodies. **Then, the lithological units are modelled.** Finally**, the ground water level can be modelled crossing all lithological boundaries.**

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.

Volumes cannot yet be displayed in the Web by GiGa. Therefore, **boundary surfaces** have to be modelled. It is recommended to model **the tops of the lithological units**, since these are needed as input for the calculation of the thermal conductivities and heat extraction capacities.

D.3.10.2. Quality check

Description of workflow steps

Do you see intersections with the DEM not represented in the geologic map?

In regions where not many data are available, the horizons may cross the DEM representing the upper boundary of the model. This is not feasible. There are two ways how to handle this sort of inconsistencies:

- Cut the crossing horizon at the DEM and delete the part above the ground surface. This will produce an erosional structure and is only allowed if it is geologically feasible.
- Move the inconsistent part of the horizon below the ground surface, if this is geologically feasible.

Are all important structures present in the 3D model?

Are horizon intersections feasible?

Horizons of conformable sedimentary units must never cross. If they do so in the model, the horizon representing the base of one unit has to be moved below the horizon representing the top of the same unit.

If the unit is unconformable, a horizon intersection has to occur. If the unconformity is erosional, the base horizon of one unit has to be cut off by the top horizon of the unit. If the unconformity is baselap, the top horizon of one unit has to be cut off by the base horizon of the unit.

Is the number of unconformities correct?

Are there sudden and local thickness changes? This may indicate:

- Faults,
- Political boundaries or map boundaries,
- Erroneous input data.

Are the fault blocks consistently modelled?

In a completely brittle environment the fault blocks have to be completely confined by faults and the fault displacement has to be kinematically feasible.

If ductile deformation is known in the region, faults may appear only locally and a consistence check is more difficult. However, the conceptual model will aid in analyzing whether the fault orientation and the soft linkage zones are represented in a geologically feasible way.

Is the fault displacement feasible?

The analysis of the fault displacement can be performed using Allan's diagram plotting the horizon-cutoffs along the fault plane (**Figure 18**). Inconsistencies may be indicated by a local shift from normal to reverse faulting or by discontinuities.

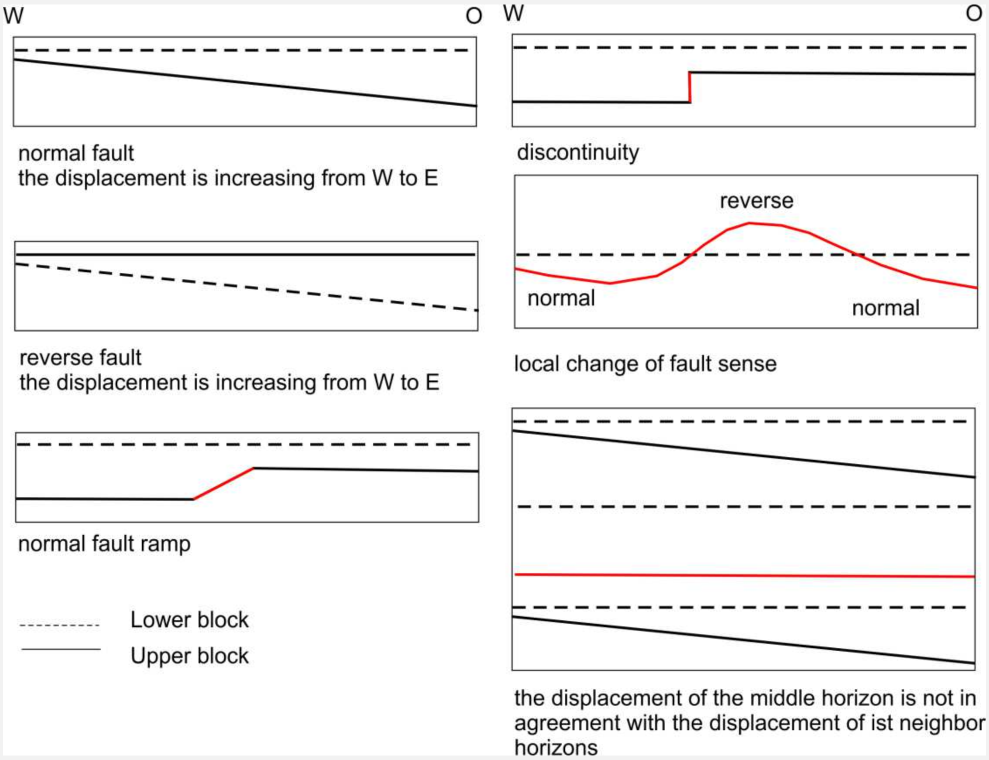


Figure 18: Quality check of fault displacement in a 3D model.

Is the fold structure coincident with the conceptual model and the input data?

Additional fold generations may be artefacts produced by the modelling algorithm (at least in SKUA-GOCAD™).

Which structures in the 3D model are not constrained by data? Are they artefacts (Figure 19)?

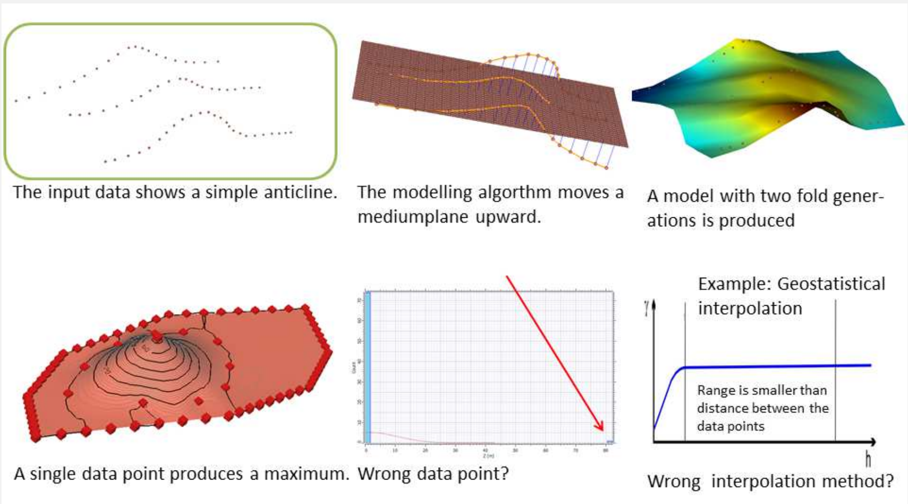


Figure 19: Examples for artefacts in a 3D model.

D.3.11. Standardized set of output data

D.3.11.1. Triangulated irregular network for 3D visualization and decision support tool

General remarks

Harmonized output data sets have to meet the following requirements:

- They are in line with the harmonized lists of attributes, parameters and coding, which organizes the thematic content and physical units.
- They have to be delivered in a **harmonized format** and at a **harmonized spatial reference system.**
- They are displayed on the web portal.

Description of workflow steps

- The TIN objects have to be delivered in GOCAD_ASCII format.
- A table with the age and petrography coding for all units of one pilot area has to be delivered.
- A metadata table has to be filled for the full 3D model.

D.3.11.2. 2D grid orthogonal raster for potential mapping

General remarks

Harmonized output data sets have to meet the following requirements:

- They are in line with the harmonized lists of attributes, parameters and coding, which organizes the thematic content and physical units.
- They have to be delivered in a **harmonized format** and at a **harmonized spatial reference system.**
- They are displayed on the web portal.

Description of workflow steps

Representation of the tops of geological units in a raster format is necessary for mapping of the geothermal potential for closed loop systems. Overturned units have to be represented piece-by-piece. Simplify this sort of structures, if possible.

- If the top of a geological body is formed by a fault, the Z-value of the stratigraphic unit will be -9999 in this region. You have to copy the Z-values of the fault to this region in order to describe the whole boundary of the geological body.
- The 2D grid has the spatial reference system, location, resolution and extent of the master grid. Additionally, one table with the age and petrography coding for all units of one pilot area has to be delivered.
- One metadata table has to be filled for the full 3D model.

E. Harmonized workflow for mapping land-use conflicts and risk factors

E.1 The workflow – a brief description

Geothermal energy is clean, emission-free and sustainable. However, every intervention in the subsurface has consequences which may eventually cause hazards or damages. Therefore, a proper professional installation of geothermal plants taking into account risk factors is important for the development of energy concepts using shallow geothermal energy. On the other hand, some geological conditions or anthropogenic interventions may reduce the efficiency of a geothermal plant or cause health problems or injury.

Existing conflict and risk factors can be presented as a:

- **Conflict layer:** A conflict layer is a thematic map representing one conflict factor without interpretation of its impact on a land-use like shallow geothermal energy. This kind of uninterpreted representation is well suitable for experts who know the impact of on a land-use like shallow geothermal energy.
- **Extent layer**: The extent layer provides information on where the data set specifying one conflict is available. If in a conflict layer a location is not marked, this can mean that there is no conflict or it can mean that no data set was available and that it is not clear, whether a conflict exists. Both cases have to be distinguished! Therefore, each conflict layer has to be combined with an extent layer. The extent layer is also considered for processing the traffic light map. A no-data region has to be included with the yellow light because this indicates that it is not known whether there is no conflict or whether shallow geothermal use is forbidden. This has to be clarified by an individual case check.
- **Conflict map:** The conflict map is a combination of a conflict layer and an extent layer. It will be produced for each conflict factor relevant for a pilot area.
- **Traffic light map:** A traffic-light map in the project's context is an interpreted thematic map which combines various data sets in order to give a short overview of the use of shallow geothermal energy. It consists of 3 categories: Shallow geothermal plants are generally possible (green), attention: more information needed (yellow), shallow geothermal plants are generally prohibited (red). It is an interpreted map where the conflict factors leading to the assignment of each point to a particular category is not obvious anymore. The traffic light map is especially useful for public users who want to get information on whether geothermal use is possible in their region. The traffic-light maps will be produced for open loop and closed loop systems separately.

The first step of mapping land-use conflicts and hazard risk is to develop an inventory of possible risk and conflict factors. After investigating which land-use conflict and risk factors are relevant for each pilot area and after collecting the data describing the factors, the input data concerning the data structure has to be analysed (**Figure 20**). A table helps to sort data describing the conflict factors by the aspects of property group, feature class and data model, because the following workflow is the same for objects of the same data structure regardless on whether the factor is anthropogenic or geogenic. The structure of data describing any factor may be different from pilot area to pilot area and from country to country. Therefore, each partner has to sort his conflict layers according to his needs and input data.

The workflows to generate conflict maps and traffic light maps are provided for raster and vector data (**Figure 21**). If input data are mixed concerning these data models, 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.

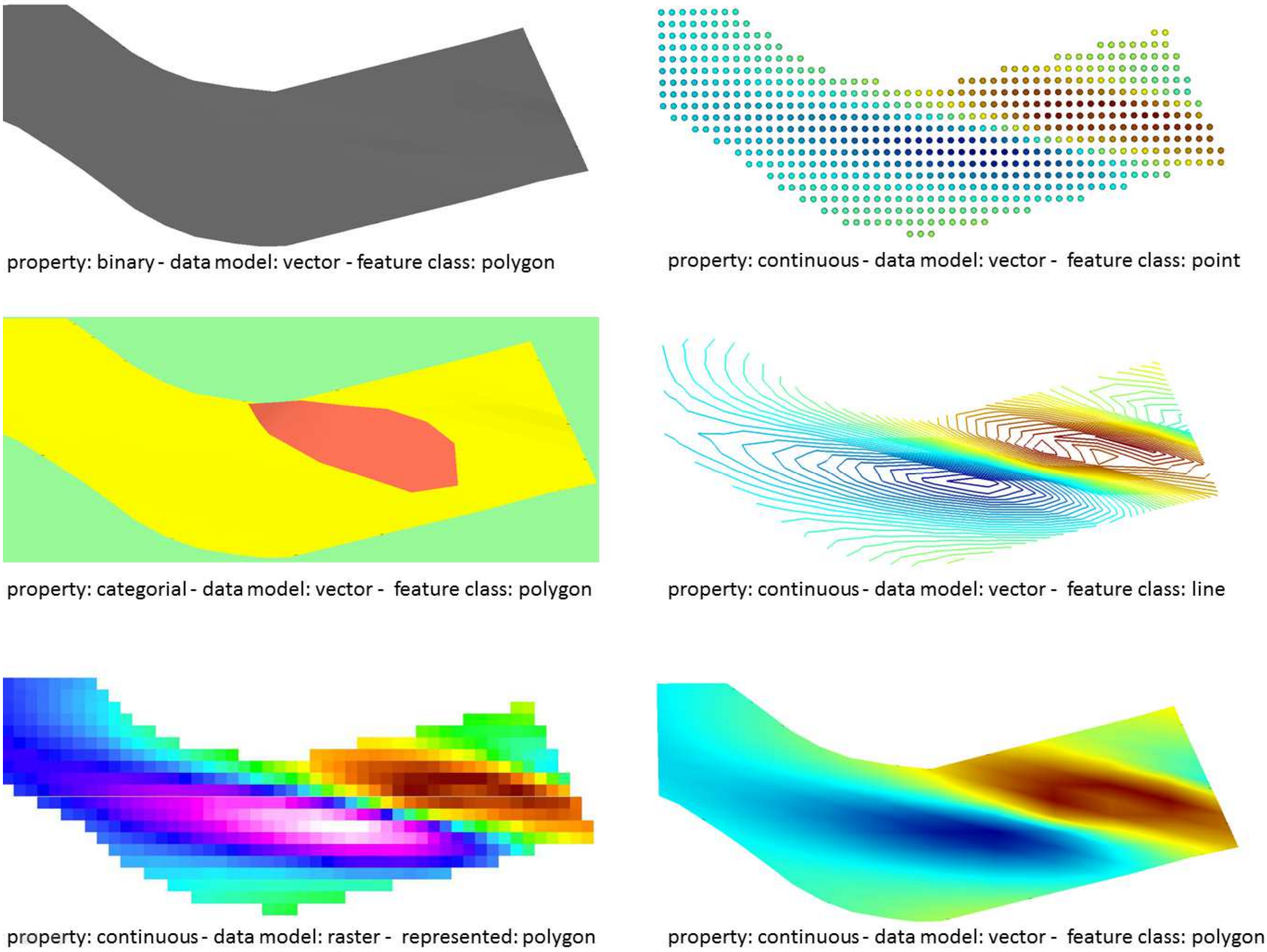


Figure 20: Various representations of the same unit of swellable rocks. The unit can be represented just by its presence (binary property), by categories like limitation of drilling depth (categorial property), by the depth of its top (continuous property). The depth of the top can be represented by a raster or a vector data model. In case of using a vector data model, it can be represented by point, line or polygon features. The processing of the data for a conflict map or a traffic-light map depends mainly on the data structure of the available data set describing each conflict factor.

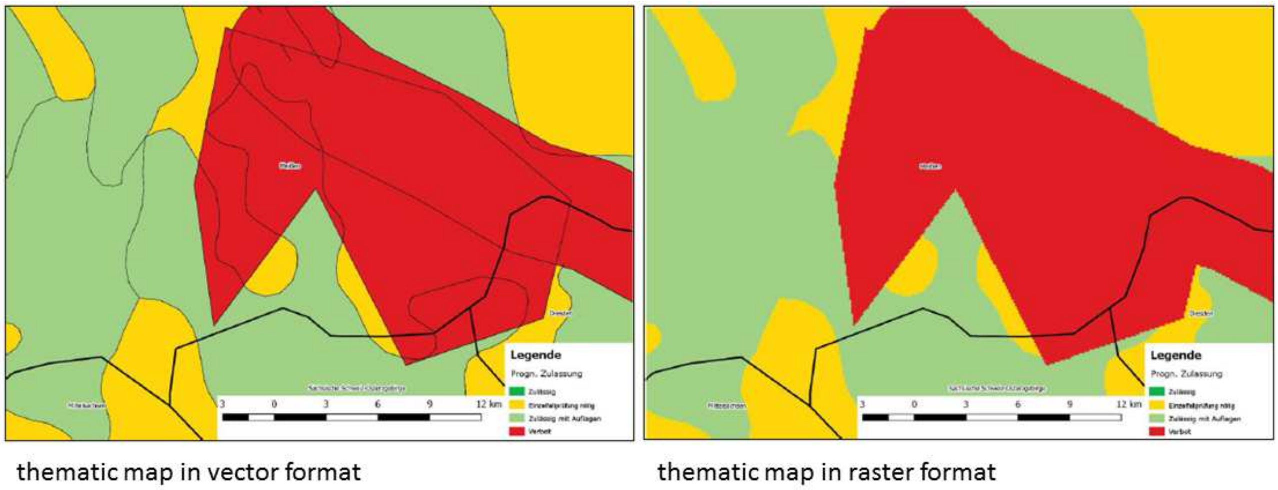


Figure 21: Comparison of a map represented in the vector data model (left) and raster data model (right).

After collecting the data for all relevant conflict factors, an extent layer has to be generated for each factor. This extent layer shows areas where no data are available. In order to prepare the conflict layers, all objects need an attribute describing their conflict or land-use risk. The conflict map is calculated by combining both layers.

While the standardized output of conflict maps for web-visualization is a raster data model, the conflict and extent layers produced in the vector-data workflow have to be used for the compilation of the traffic light map.

The workflow generating the traffic light map uses the conflict layers and the extent layers prepared in the previous step. Since some of the conflict layers may consist of point or line features while the extent layer will always consist of polygons, all point and line features have to be converted into polygons either by buffering or by calculating a convex hull around the data set.

All attributes present in any conflict layer have to be reclassified to one of the three categories of the traffic light map:

- Generally possible (1-green),
- Attention: Additional information needed (2-yellow),
- Generally not allowed (3-red).

This interpretation and reclassification has to be performed by the project agent since the interpretation may be different from pilot area to pilot area, e.g. drilling may be completely forbidden in a natural reserve in one country, while it is allowed after an individual check in another country. All no-data regions of the extent layers have to be attributed with “2” - individual case check. Point and line features have to be converted into polygon features either by specifying of a buffer zone or by calculation of a convex hull. They have to be classified by the categories of the traffic light map afterwards. After reclassification of all layers, one traffic light map for each open and closed loop geothermal plants can be produced either by union and subtraction of all polygon layers for vector data or by map algebra for raster data. The harmonized output is a raster data set coinciding with the master grid.

The workflow was written for ArcGIS. Version 10.2.2 for Desktop (basic license) was used for compiling the workflow. Additionally, the following are required for the preparation of conflict maps and traffic light maps:

- Spatial Analyst
- Geostatistical Analyst
- An Advanced ArcGIS Licence is required if the Vector Data Workflow is to be used for the creation of traffic light maps ("erase" tool), but not for the Raster Data Workflow

The following points provide an overview of the workflow steps (compare with **Figure 22**):

1. Documentation of the project

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

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

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

Standardization of output in raster format

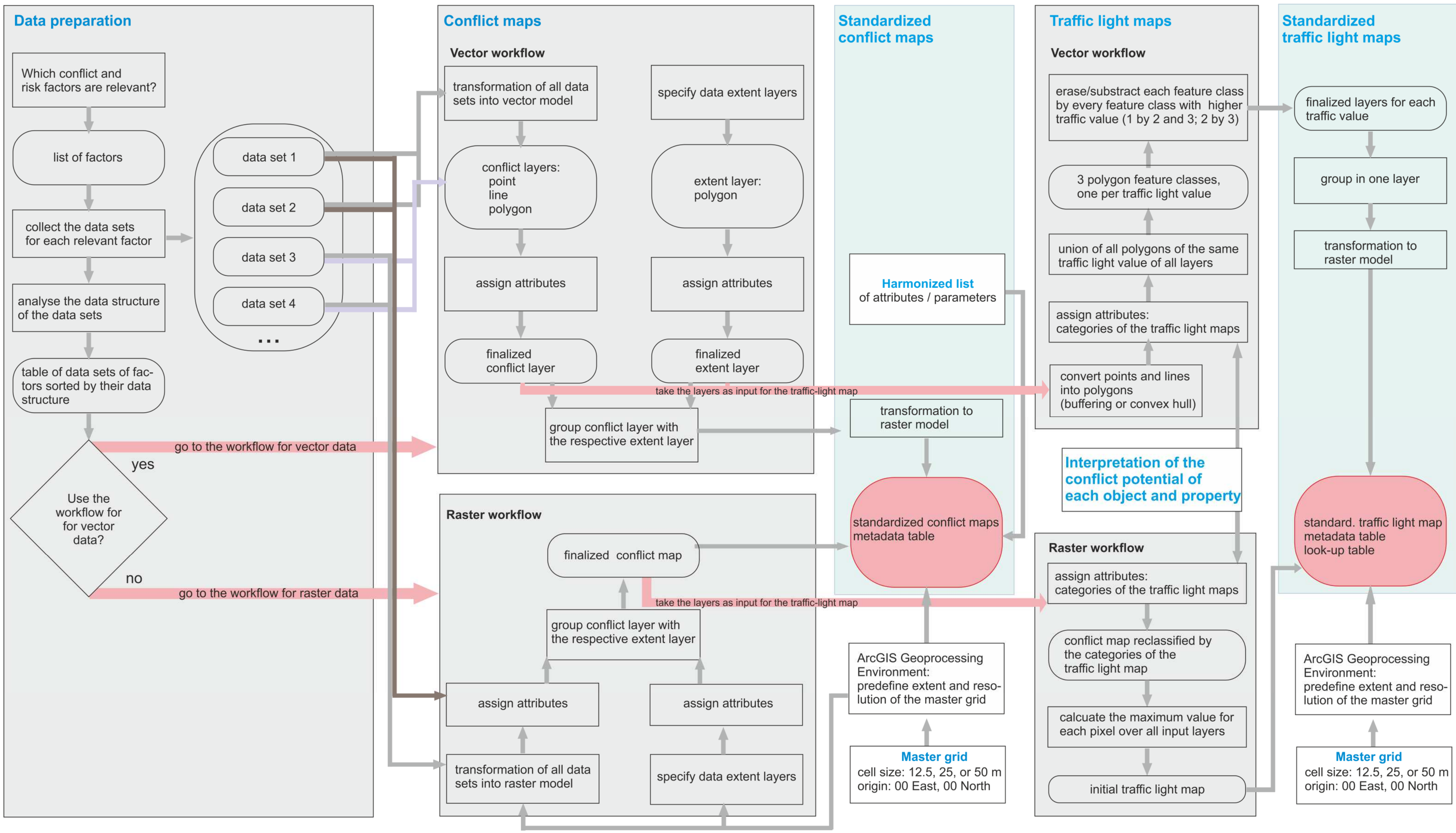


Figure 22: GeoPLASMA-CE workflow for mapping conflicts with shallow geothermal use and generating traffic light maps for the suitability of open or closed loop systems.

E.2 Rules and mandatory specifications - checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters →See D.T2.3.1 for specification
Elevation reference system	EVRF2007 →See D.T2.3.1 for specification
Extent layer	Binary property no_data_cat • Attribute for a region with data: 9999 • No data value: -9999
Conflict map	Attributes from the joint attribute and parameter list →See D.T2.3.1 for specification
Traffic light map	Categorial property traffic_va (short integer) 1… shallow geothermal installations are generally possible (green) 2… attention: more information required (yellow) 3... shallow geothermal installations are generally prohibited (red)
Transfer the raster data to the master grid	Grid resolution: 12.5, 25 or 50 m Borders of the grid cells at (00,00) coordinates →See D.T2.3.1 for specification
Export data format of all raster data	.adf -ESRI grid
Completed metadata template	Metadata table for conflict layers Metadata table for traffic light maps Look up tables connecting the attributes of the conflict maps with the traffic light maps →See D.T2.3.1 for specification
Project documentation	Table for the documentation of the project progress →See D.T2.3.1 for specification

E.3 Tool kit for mapping land-use conflict and risk factors for shallow geothermal use

Input data

E.3.1. Analysis of relevant land-use conflict and risk factors

General remarks

A conflict is a disagreement of aims. In 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.

Each activity has consequences. Some consequences are wanted and expected; other consequences are unwanted and are considered to be negative. Some of these negative consequences may cause damage, harm or injury. A risk is the possibility of loss, damage or injury. A risk factor is a variable associated to an increased risk.

Shallow geothermal use can be inefficient, dangerous or forbidden (e.g. due to land-use conflicts). In order to plan a geothermal plant, the risk and land-use conflict factors have to be known by the user, planning office, drilling company and authority.

A conflict layer displays a single existing land-use conflict or risk factor.

Description of workflow steps

Identify conflict and risk factors relevant for your pilot area (compare to **Table 20**).

Table 20: 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

Input data

E.3.1.1. Order the relevant conflict and risk factors by their data structure

General remarks

The work steps described in the workflow are valid for all conflict layers of the same data structure. Each land-use conflict or risk factor can be described by different data structures.

The property type displayed in a conflict layer can be:

- Binary: The conflict layer shows whether a particular factor is present or not, e.g natural reserves are present or not.
- Categorial: The conflict layer shows various groups of objects, e.g. a layer with anthropogenic lines is composed of the groups electric line, telephone line, water pipeline, gas pipeline.
- Sequential: The conflict layer shows categories which are ordered by a sequence, e.g. groundwater protection zone S1, S2, S3a, S3b. You know that S1 is more protected than S2 and S2 is more protected than S3.
- Continuous: The conflict layer displays a variable which is usually a real number and can take any value at each location, e.g. the depth of a unit of swellable rocks or the slope of the ground surface.
- Discrete: A discrete property is similar to a continuous property, however, only natural numbers are possible, e.g. the number of existing geothermal plants per pixel.

Dimensionality of objects displayed in a conflict layer:

- Point: 0-dimensional,
- Line: 1-dimensional,
- Polygon: 2-dimensional.

Data model used:

- Raster data model: A raster data model is based on a square-based tessellation of the 2D plane into cells. Each raster cell is associated with numbers quantifying the observed attribute.
- Vector data model: A vector data model is a representation of the world using points, lines, and polygons. All of these objects consist of points, and sometimes (in case of lines and polygons) of segments connecting them. Each point is specified by the coordinates of its position vector.

Description of workflow steps

Each conflict factor can be represented by different property groups. In the example in **Figure 20**Figure 20, a swellable rock unit is represented just by specifying where it is located (binary), by specifying different categories: Absent (green), drilling allowed with limitation of the drilling depth (yellow), drilling forbidden (red), and by a continuous variable specifying its Z-value.

All three of the representations can be provided as raster or as vector data. The last data set representing the continuous variable can be available as point, line or polygon feature.

Depending on the data structure, different work steps have to be applied. That's why it is necessary to analyse the data structure of all data sets (**Table 21**).

1.) Which variable type is used for describing the conflict or risk? Is it

- binary,
- categorial/nominal or ordinal/sequential,
- discrete or continuous?

3.) Are the objects available as

- raster data,
- vector data?

2.) Are the specified objects

- points,
- lines or
- polygons?

Make a table to order your data describing the conflict factors concerning these aspects, because the following workflow is the same for objects of the same data structure regardless of the meaning of the conflict factor. The assignment may be different from pilot area to pilot area and from country to country. Therefore, each partner has to order his conflict layers according to his needs and input data.

Table 21: Possible variable types, features and data models.

Variable types	Feature	Data model	Conflict layers -examples
binary	point	vector	Location of drinking water production well Location of industrial water production well
		raster	Anonymized points with existing geothermal usage
	line	vector	Mining galleries Pipeline Underground network Fault and fracture zone
		raster	Scanned map of mining gallery
	polygon	vector	Floodplain Natural reserve Extent of a unit with swellable rocks Extent of confined/artesian groundwater Extent of karst Extent of quick sand Extent of public property Extent of contaminated sites Extent of deposits Mining concession or license
		raster	Scanned map containing floodplains
categorial/ sequential	point	vector	Location of water production wells for drinking water, mineral water, curative water Shallow gas leakage (CO_2, radon, methane)
		raster	Scanned map of water production wells
	line	vector	Anthropogenic lines (electric, gas, water, telephone)
		raster	Scanned map of anthropogenic lines
	polygon	vector	Groundwater protection zones of level 1, 2, 3a, 3b Region with mineralized groundwater concentration (small, medium, high)
		raster	Scanned map of groundwater protection zones
discrete/ continuous	point	vector	
		raster	
	line	vector	
		raster	
	polygon	vector	Groundwater isohypses Aquifer thickness isolines Aquifer yield isolines
		raster	Top of a unit of swellable rocks Depth of confined/artesian aquifer

E.3.2. Conflict maps (vector data workflow)

E.3.2.1. Data-extent layer

General remarks

The extent layer is a map showing where the data describing one land-use risk or conflict factor are available or not. This information is very important. If it was not specified, this could generate the impression that no risk is present. However, we simply do not know whether a risk is present or not.

Description of workflow steps

Create an extent layer

Copy the pilot area polygon for each conflict layer you want to use

Table of contents (TOC) → right-click on the layer with the pilot_area → copy

TOC → Layers → paste layer

Click into the name of the pasted layer in the TOC → give it a new name (e.g. gw_protection_extent)

Create a field: no_data_cat: short integer

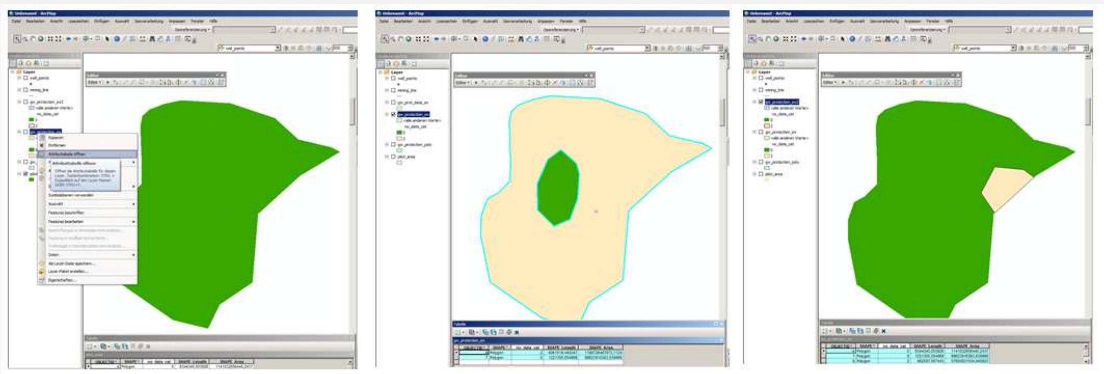
TOC → right-click on gw_protection_ext → attribute table → table options → add field → no_data_cat: short integer

Assign the no_data_cat:

9999 …if data are available

-9999 …if no data are available

These numbers will be used for combining the extent layer with the conflict layer in order to compile a conflict map. Three cases for specifying the extent layer can be distinguished:



The data set for a conflict layer is available in the whole pilot area. | The data set for a conflict layer is available in one region pilot area. | The data set for a conflict layer is **not** available in one region pilot area.

Figure 23: Specification of polygons in the extent layer: The large polygon represents a pilot area.

The data set is valid for the whole pilot area (**Figure 23 left**).

In this case, you have to assign a 9999 as no_data_cat value for the pilot area polygon (**Figure 24**).

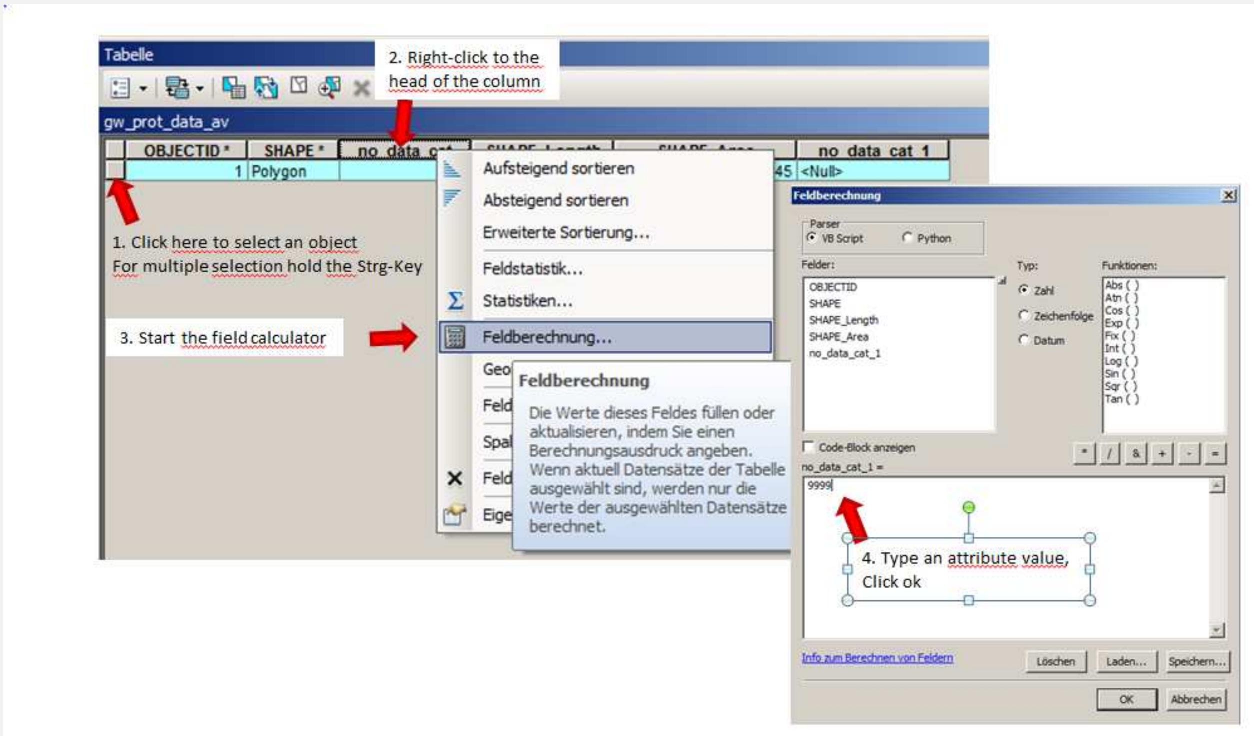


Figure 24: Attribute table in ArcGIS: How to assign the attributes of the extent layer.

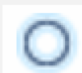
TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click into the header of the column no_data_cat → select the field calculator → type 9999

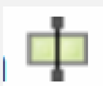
The data set is only valid for one polygon inside of the pilot area (**Figure 23 middle**).

In this case you have to assign the no_data_cat value of -9999 for the whole pilot area polygon, to cut a polygon specifying the extent of the data set into the pilot area polygon and assign a no_data_cat value of 9999 for this inner polygon.

TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click in the header of the column no_data_cat → select the field calculator → type -9999

TOC → Right-click on the gw_protection_extent → edit layer → select the pilot area polygon

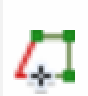
Activate the tool "snip / catch at point" 

Activate the tool "cut polygons" 

Digitize the region that contains the data set, such that a closed polygon is generated

Right-click on the new polygon → attributes → type 9999

Stop editing and save the edits

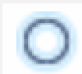
If you want to use an existing polygon select the trace tool  *to digitize the polygon*

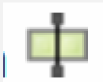
The data set is not available for some regions of the pilot area polygon (**Figure 23 right**).

In this case you have to assign the no_data_cat value of 9999 for the whole pilot area polygon, cut a polygon specifying the extent of the no-data region into the pilot area polygon and assign a no_data_cat value of -9999 for this polygon.

TOC → open attribute table → Select the polygon by clicking in its row to the left of the first column → right-click in the header of the column no_data_cat → select the field calculator → type 9999

TOC → Right-click on the gw_protection_extent → edit layer → select the pilot area polygon

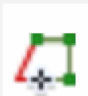
Activate the tool "snip/ catch at point" 

Activate the tool "cut polygons" 

Digitize the region that contains the data set, such that a closed polygon is generated

Right-click on the new polygon → attributes → type -9999

Stop editing and save the edits

If you want to use an existing polygon select the trace tool  *to digitize the polygon*

E.3.2.2. Transformation of raster data into vector data

General remarks

A data transformation converts a set of data from the data format of a source data system into the data format of a destination data system. It is needed if input data are available in different data structures.

Description of workflow steps

From the following, select the paragraph which is applicable to the data structure of your conflict layer! In some cases automatic conversion and manual digitizing are described.

Binary property -points -automatic conversion (Figure 25**):**

This method is inaccurate! Check the location of the points in comparison to the original map!

Resample the raster with a suitable resolution to ensure that each point is assigned to only one raster cell and therefore can be vectorized as one point::

ArcToolbox → data management tools → raster → raster processing → resampling → select the input file, the desired resolution and the location for storage of the output file

Create a point feature:It can be useful to convert the input raster to a monochromatic raster first, i.e. ensuring that the raster contains only cells of a single constant value and "no data" cells. The background colour can be removed by using the tools "Set Null" or "Reclassify". After converting the raster into a point feature, the output will only contain valid data points.

Alternatively, raster sets containing two or more values (e.g. 0 and 1, or 0 - 255) can be converted to a point feature first and then reduced to the desired data points by using a query expression:

ArcToolbox → Conversion tools → from raster → raster to point → select the value_field

Selection by attribute → select all points where the [grid_code] > 'color _value'

Right-click on the point feature → start editing → right-click → delete all selected points

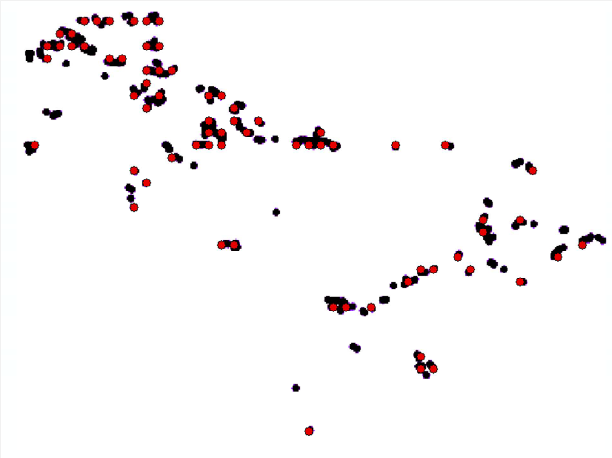
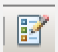
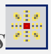


Figure 25: Result of automatic vectorization: Original points are black, extracted points are red.

Binary property -points -conversion by manual digitizing (Figure 26)

Generate a point feature class in ArcCatalogue, e.g. a feature well_points

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool "create feature"  *→ go to the window "create feature" and select "well_points" → go to the window "construction tools"→ select "points" → go to the editor tool bar and digitize the points* 

Save the edits and exit the editor toolbar

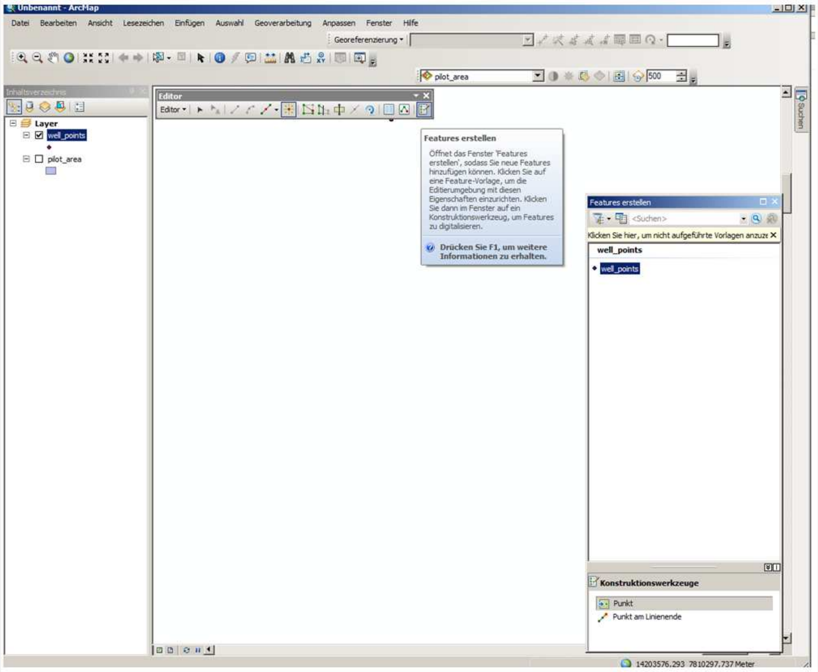


Figure 26: ArcGIS digitizing toolbar.

Binary property -lines -automatic conversion

ArcToolbox → Spatial Analyst tools →Reclass → Reclassify → classify→create two classes assign value 1 to the class with the line and NoData to the class of the background *around the lines → the result is a raster which contains only the lines*

Note: If the input raster is two-coloured (i.e. contains the values 0 and 1), the step above can be omitted and the "no data" value assigned to the background colour during the conversion to a vector file.

ArcToolbox →Conversion tools → from raster → raster to polyline → select the value_field and set the background value to "zero".

Smooth the line by using the editor toolbar (**Figure 27**):

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth 

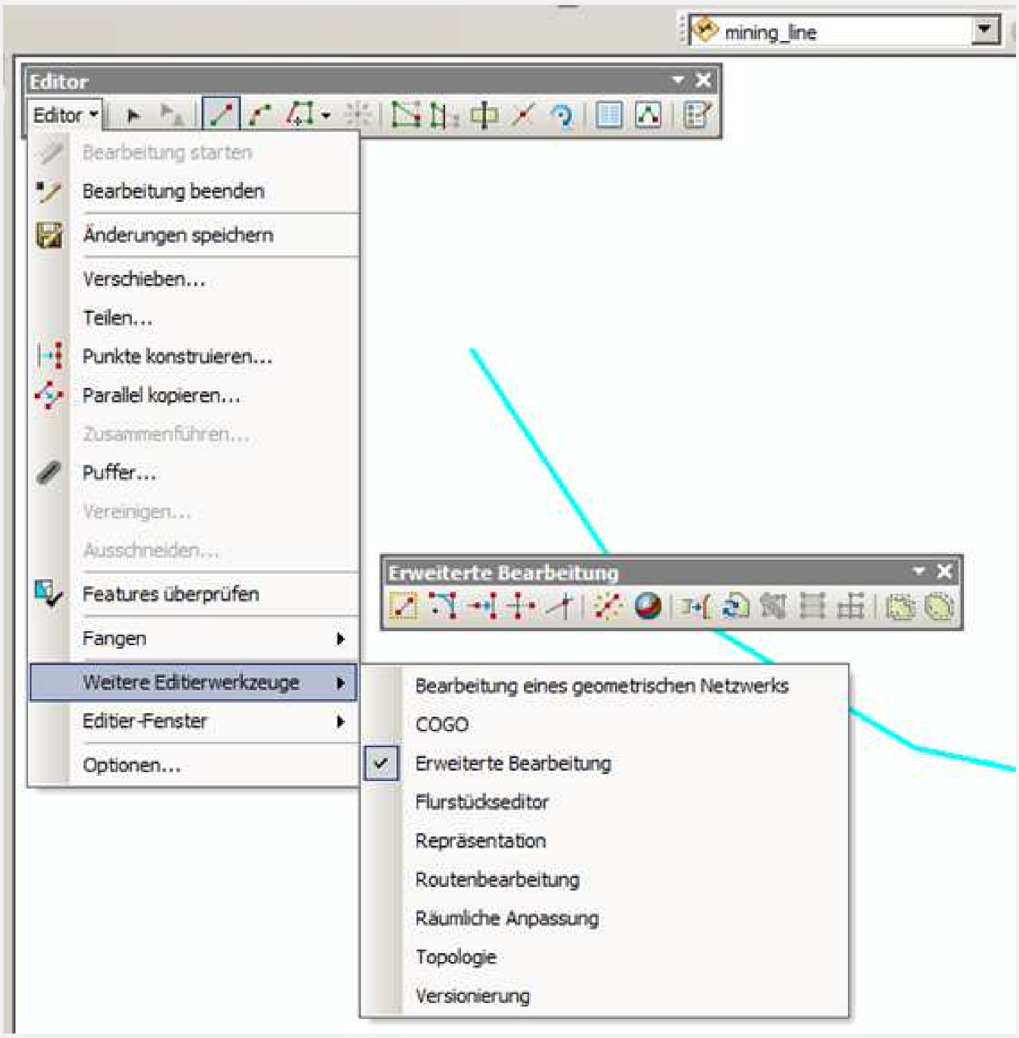


Figure 27: ArcGIS advanced editing toolbar.

Binary property -lines -conversion by manual digitizing

Generate a line feature class in ArcCatalogue, e.g. a feature mining_galleries

Add the feature class to ArcMap → right-click the feature class in the TOC → start *editing → select the tool "create feature" → go to the window "create feature" and select "mining_galleries" → go to the window "construction tools"→ select "polyline" → go to the editor tool bar and digitize straight or curved line segments*

Binary property -polygons -automatic conversion

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify→create two classes; assign value 1 to the class with the line and NoData to the class of the background around the polygons → the result is a raster which contains only the lines

ArcToolbox → Conversion tools → from raster → raster to polygon → select the value_field

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced edting toolbar → smooth

Binary property -polygons -conversion by manual digitizing

Generate a polygon feature class in ArcCatalogue, e.g. a feature natural_reserve

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool "create feature" → go to the window "create feature" select "natural_reserve" → go to the window "construction tools"→ select "polygon" → go to the editor tool bar and digitize straight or curved line segments

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced edting toolbar → smooth

Categorial or sequential property -points -automatic conversion

Resample the raster with a suitable resolution to ensure that each point is assigned to only one raster cell and therefore can be vectorized as one point::

ArcToolbox → data management tools → raster → raster processing → resampling → select the input file, the desired resolution and the location for storage of the output file

ArcToolbox → Spatial Analyst Reclass → reclassify → create new classes according to the categories you have → add the background as NoData class

Create a point feature:

ArcToolbox → Conversion tools → from raster → raster to point → select the value_field

Categorial or sequential property - points -conversion by manual digitizing

Generate a point feature class in ArcCatalogue, e.g. a feature well_points with the attribute to be specified, e.g. production_type as string (for text attributes like "mineral water", "drinking water", "curative water").

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing →select the tool "create feature" → go to the window "create feature" and select "well_points" → select "points" → go to the editor tool bar and digitize the points

open the attribute table → assign the attributes for "production_type"

Categorial or sequential property -lines -automatic conversion

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → classify→create new classes according to the categories you have → add the background as NoData class

→ the result is a raster which contains the lines of different categories in different classes

ArcToolbox →Conversion tools → from raster → raster to polyline → select the value_field

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth

Categorial or sequential property - lines -conversion by manual digitizing

Generate a line feature class in ArcCatalogue, e.g. a feature anthrop_lines with the attribute to be specified, e.g. line_type as string (for text attributes like "electric", "water", "telephone").

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool "create feature" → go to the window "create feature" and select "anthrop_lines" → select "polyline" → go to the editor tool bar and digitize the lines

open the attribute table → assign the attributes for "line_type"

Categorial or sequential property -polygons -automatic conversion

ArcToolbox → Spatial Analyst tools →Reclass → Reclassify → classify→create new classes according to the categories you have → add the background as NoData class

→ the result is a raster which contains only the polygons

ArcToolbox → Conversion tools → from raster → raster to polygon → select the value_field

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth

Categorial or sequential property - polygons -conversion by manual digitizing

Generate a polygon feature class in ArcCatalogue, e.g. a feature gw_prot_zone with the attribute to be specified, e.g. protection_zone_classification as string (for text attributes like "S1", "S2", "S3a", "S3b").

Add the feature class to ArcMap → right-click the feature class in the TOC → start editing → select the tool "create feature" → go to the window "create feature" and select "gw_prot_zone" → select "polygon" → go to the editor tool bar and digitize the polygon

open the attribute table → assign the attributes for "protection_zone_classification"

Discrete or continuous property - polygon - automatic conversion

ArcToolbox → Spatial Analyst tools → Surface → contour line → add contour interval and base

Smooth: Start the Editor toolbar → select the line features → Editor toolbar menu → select the advanced editing toolbar → smooth

E.3.2.3. Example: Layer showing limitations of drilling depth

General remarks

Limitation of drilling depth is necessary for regions with swellable rocks and artesian groundwater and a set of hydraulically separated aquifers which must not be connected (e.g. a salt and a fresh water aquifer).

Description of workflow steps

The example comprises three 2D grids representing the absolute Z-values of the tops of units which must not be drilled. The geometry of these objects was produced in the 3D modelling software and then exported into ArcGIS. They can represent units consisting of swellable rocks or containing an artesian aquifer. In addition, the digital elevation model is given. A map representing the limitation of drilling depth has to display the relative depth below the ground surface of the shallowest layer with limitation and a "drilling allowed" value outside of the extent of these geologic units. If you want to stay on the safe side, you can add a safety margin. For including the conflict layer in the traffic-light map, you have to transform the data set into a vector model.

The data are given as raster data sets exported from the 3D modelling software (**Figure 28**).

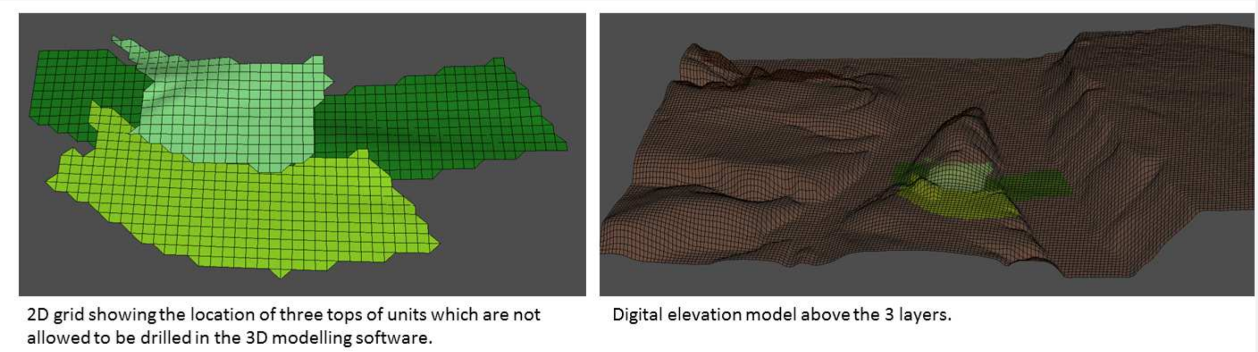


Figure 28: 3D view of the tops of three units where drilling is prohibited.

The workflow for calculation of the limitation in drilling depth comprises the following steps:

Importing a 2D grid into XYZ format

In this example, the 2D grids specifying the geologic units were generated in SKUA-GOCAD™. The import may be slightly different from other software. However, it is important to set the coordinates, extent and resolution for all raster data sets to the properties of the master grid.

Import: data → add data → add XY data → X-field: X→ Y: field: Y → Z-field: Z

Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size→ ok

ArcToolbox → Conversion Tools → in raster → point to raster→ value field: Z→ mean → cell size as specified in the master grid

Calculate the minimum depth (maximum elevation) of all horizons with drilling limitations

This calculates the maximum elevation sub sea level of all units which need a limitation of drilling depth (**Figure 29**):

ArcToolbox → spatial analyst tools → local → cell statistics →

maximum→ output: maximum_absolute

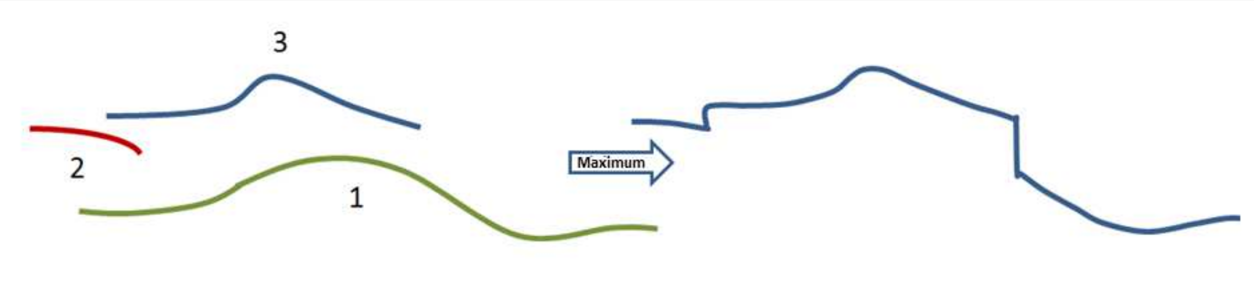


Figure 29: Schematic visualization of the calculation of the maximum elevation of the 3 horizons.

Calculate a raster with the allowed drilling depth (from surface) by subtracting the maximum elevation of the horizons with drilling limitation from the elevation of the ground surface.

ArcToolbox → spatial analyst tools → Math → Minus →Raster 1: DEM → Raster 2: maximum_absolute → output: drilling_depth

Optional: Add a safety margin (e.g. -10 m)

ArcToolbox → spatial analyst tools → map algebra → raster calculator →

Con("drilling_depth" > 10, Con("drilling_depth" < 9000, "drilling_depth" - 10, "drilling_depth"), "drilling_depth")→ output: drilling_depth_safe

Set all values outside of the horizons from "no data" to 9999 to indicate that there is no limitation of drilling depth.

Spatial Analyst Tools → Map Algebra → Raster Calculator → Con(IsNull("drilling_depth"),9999,"drilling_depth")

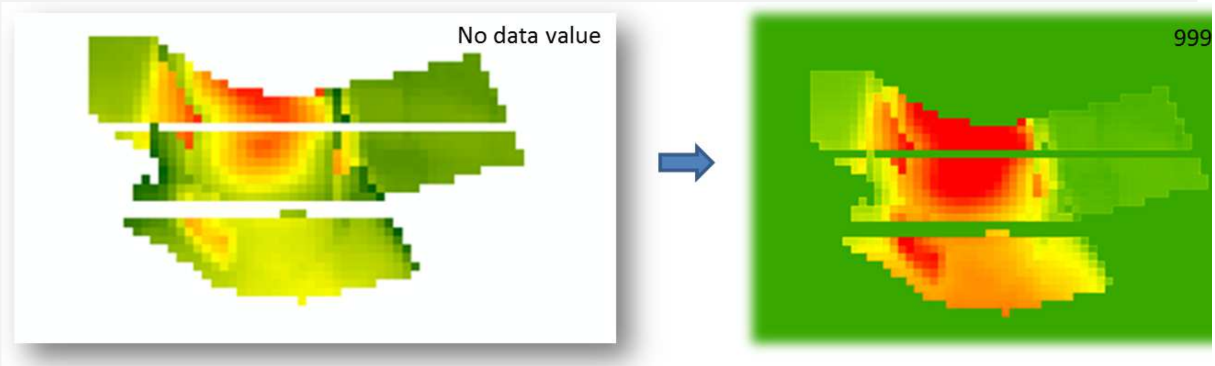


Figure 30: Limitations of drilling depth in an area (left). All locations outside of the critical units are specified by a no data value, although it is known that no limitation to the drilling depth is applicable in these locations. Therfore, the no data value is converted into a very large value, indicating that deep drilling is possible (right).

Calculate contour lines

ArcToolbox → Spatial Analyst tools → Surface → contour line → add contour interval and base

E.3.2.4. Attributes of the conflict layers

General remarks

Attribute data is that part of geodata which contains 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.

Description of workflow steps

In most cases, this step has already been completed when you load a data set. Check whether attribution is available for all data sets! If not, follow the workflow.

Create a new attribute by adding a field to the attribute table

Right-click on the conflict layer in the TOC → open attribute table → table options → add new field

Binary property

Right-click into the header of the new field column → field calculator → type the name/value of the attribute

Categorial and sequential property

Case 1: An attribute exists which can be used for grouping of the categories:

Main menu bar → selection → by attribute → select the attribute and the value you need from the conflict layer

Be aware of the "select from selection" and "add to current selection" options!

Right-click on the conflict layer in the TOC → open attribute table → table options → add new field

Right-click into the header of the new field column → field calculator → type the name/value of the attribute (this assigns only to the selected features!)

Case 2: Select by hand in the editor mode

If no attributes are assigned, you have to assign the attributes by hand for each object:

Right-click the feature class in the TOC → start editing → open the attribute table → select the feature you want to attribute → write the attribute into the new field of the attribute table

Classify your conlict layers as specified in table 22!

Water protection zone	Categorial Protection zone	0 -9999 Category	No protection zone No data available Individual classification for each pilot area	255 255 255 200 200 200	
Natural reserve	Binary presence	0 -9999 1	No reserve No data available Natural reserve	255 255 255 200 200 200 000 255 000	
Limitation of drilling depth	Continuous depth	0 -9999 1 2 3 4 5 6 7 8 9 10	No limitation No data available 20 m 40 m 60 m 80 m 100 m 120 m 140 m 160 m 180 m >200 m	255 255 255 200 200 200 227 030 036 247 123 107 247 155 115 254 208 154 252 199 093 254 204 000 250 236 084 255 243 131 255 251 219 221 228 137	
Confined and artesic groundwater	Binary presence	0 -9999 1	No confined/ artesian groundwater No data available Confined/artesic aquifer	255 255 255 200 200 200 114 178 252	
Tectonics /faults	Binary precense	0 -9999 1	No fault No data available fault	255 255 255 200 200 200 025 025 025	
Cavities /mining sites	Binary presence	0 -9999 1	No cavity / mine No data available Cavity /mine	255 255 255 200 200 200 175 151 120	
Landslides	Binary presence	0 -9999 1	No Landslide No data available Landslide	255 255 255 200 200 200 158 090 002	
Shallow gas leakage	Categorial gas	0 -9999 1 2 3	No leakage No data available CO_2 Radon Methane	255 255 255 200 200 200 080 080 080 000 152 070 255 255 102	
Karst	Binary presence	0 -9999 1	No karst No data available	255 255 255 200 200 200 183 120 206	
Hydraulically separated aquifers	Binary presence	0 -9999 1	No separated aquifer No data available Hydraulically separated aquifers	255 255 255 200 200 200 025 044 168	
Existing geothermal utilization	Discrete Number per pixel	0 -9999 1 2 3 4 5 6 7	No utilization No data available 1-3 3-5 6-10 11-20 21-50 51-100 >100	255 255 255 200 200 200 250 221 182 250 193 118 204 118 118 250 128 128 215 053 053 250 000 000 245 112 030	
Electric lines - pipelines	Categorial	0 -9999 1 2 3 4 5	No protection zone No data available Electrical Water Gas Telephone Other	255 255 255 200 200 200	
Contaminated sites	Binary presence		No protection zone No data available Contaminated site	255 255 255 200 200 200 113 115 049	

Table 22: Standardized classification of cell-related output attributes.

E.3.2.5. Combination of conflict and extent layer

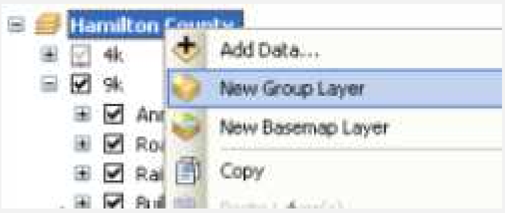
Description of workflow steps

Generate empty group layers and add data sets to the project

Right-click on layer in the TOC and select new group layer

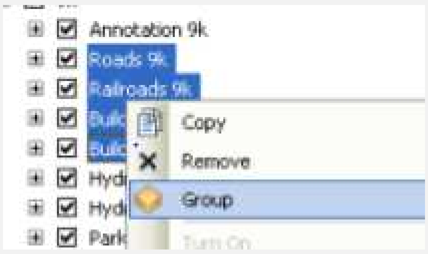
Repeat for each conflict factor → click into the name "new group layer" and type the name of each conflict factor

Add data by right-clicking the name of the group layer → add data



Organize existing layers to a group layer

Select the layers you want to group by clicking on them while holding the Ctrl-Key → right-click → group



E.3.3. Traffic light maps (vector data workflow)

E.3.3.1. Conversion of point and line features to polygon features

General remarks

For calculating a traffic light map, all point and line features have to be converted into polygon features (**Figure 31**). 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.

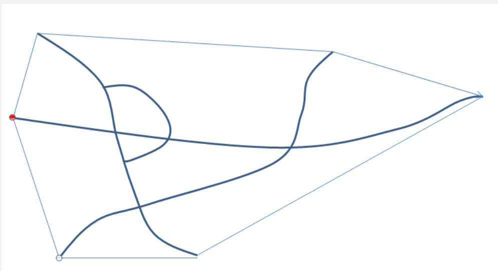


Figure 31: Conversion of points and lines to polygons can be realized either by generating the convex hull or by creating a buffer.

Description of workflow steps

The project's agent has to make a decision about 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.

Convex hull

> *ArcToolbox → data management tools → features → minimum bounding geometry→ convex_hull*

Create a buffer around a point or line

If the data set contains points or lines of different categories, and different buffer sizes are required for each category, this can be accomplished by assigning the buffer size to each object in the attribute table prior to buffering.

> *Open attribute table→ add new field → name field "buffer_size" → perform query selection for each category → right-click into the field header and chose the field calculator→ assign the desired buffer size to the selected objects.*

Repeat the query and the assignment of buffer size for each type of object until all objects have a buffer size assigned to them.

ArcToolbox → Analysis tools → proximity → buffer → input feature class → set distance to "field" and chose the field buffer_size → select the side type (whether the buffer is generated on the left, right or both sides) → select the end type

If there is only one type of object, or all objects will have the same buffer size, the buffers can be created directly, without adding a new field to the attribute table:

ArcToolbox → Analysis tools → proximity → buffer → input feature class → specify the buffer diameter in linear units (m) → → select the side type (whether the buffer is generated on the left, right or both sides) → select the end type

E.3.3.2. Classification of the conflict layers according to the categories of the traffic light map

General remarks

All features need an attribute which specifies their class/category in the traffic light map. This step requires the interpretation of the project's agent. All attributes available in the conflict layers have to be converted into the categories of the traffic light map depending on the impact of a conflict factor and the governmental regulations valid in each pilot area.

The categories, into which all properties have to be transformed, are:

1… shallow geothermal installations are generally possible

No conflicts and risks known.

2… 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 generally allowed or prohibited.

3... shallow geothermal installations are generally prohibited

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

Description of workflow steps

Create a new attribute by adding a field to the attribute table

Right-click on the conflict layer in the TOC → open attribute table → table options → add new field named traffic_va as short integer

Binary property

TOC → open attribute table → table options → Select all

Right-click into the header of traffic_va → field calculator → type the value of traffic_va

Categorial and sequential property

Main menu bar → selection → by attribute → "attribute"=x

Be aware of the "select from selection" and "add to current selection" options!

Right-click on the conflict layer in the TOC → open attribute table → Right-click into the header of the field traffic_va → field calculator → type the value of traffic_va (this assigns only to the selected features!)

Discrete or continuous property

For this property, a reclassification is necessary prior to assigning the traffic light value.

Example: You have got a set of isohypse contours describing the depth of a swellable rock unit. You want to specify the following categories:

If the top of the swellable rock unit is buried less than 50 m, drilling is completely forbidden (traffic_va = 3),

If the depth of the unit is greater than 50 meters, an individual case check is necessary (traffic_va = 2).

If no swellable unit is present, no limitation is necessary (traffic_va = 1). These locations were attributized with a drilling depth of 9999 in the conflict layer.

Main menu bar → selection → by attribute → method: new selection → “drill_depth”<=50

Attribute table → Right-click into the header of the traffic_va→ field calculator → type the value of traffic_va: 3

Main menu bar → selection → by attribute → method: new selection → “drill_depth”<=200 AND “drill_depth”>50

Attribute table → Right-click into the header of the traffic_va→ field calculator → type the value of traffic_va: 2

Main menu bar → selection → by attribute → method: new selection → “drill_depth”>200

Attribute table → Right-click into the header of the traffic_va→ field calculator → type the value of traffic_va: 1

E.3.3.3. Compilation of the traffic light map from the conflict and extent layers

Description of workflow steps

The compilation of the traffic-light map consists of two steps:

- Calculate the union of all polygons from all conflict layers with the same traffic-light value,
- Stepwise erase united polygons of a small category by polygons of the greater categories.

Calculate the union of all polygons with the same traffic-light value

Binary property

A layer with a binary property can be used for the calculation.

Categorial property

For a layer containing categories, select the traffic_va you are working with. The union operation is performed only for the selected features. If necessary, generate new layers containing the polygons with one traffic_va as separated sets.

Main menu bar → selection → by attribute → method: new selection → [traffic_va]=1

Right-click on the layer in the TOC → data → export data → selected features

Calculate the union

ArcToolbox → analysis tools → overlay → union → select all layers containing features with traffic_va=1

Repeat this for all three categories. Consider choosing “only FID” when selecting the attributes to be preserved during the union. This will reduce file size and processing time.

Stepwise erase the polygons

Note: An advanced license is required to utilize the “erase” tool.

ArcToolbox → analysis tools → overlay → erase → input feature: union of all polygons with the traffic_va 1 → erase feature: union of all polygons with the traffic_va 2,3

The output feature contains polygons with traffic light value 1 in only in those places where there is no traffic value 2 present. Use this output feature as input feature and repeat the step, using the union of all polygons with a traffic_va of 3 as erase feature.

The output feature now contains polygons with traffic light value 1 only in those places where neither a value of 2 nor a value of 3 is present.

Similarly, create a feature containing polygons with traffic_va = 2 only in those places where there is no traffic light value of 3 present:

> *ArcToolbox → analysis tools → overlay → erase → input feature: union of all polygons with the traffic_va 2 → erase feature: union of all polygons with the traffic_va 3*

Assign the RGB color codes for the classes:

Traffic light value: 1   205 245 122   green

2   255 255 190   yellow

3   255 061 084   red

E.3.4. Conflict maps (raster data workflow)

E.3.4.1. Preparation of the data extent layer

General remarks

The extent layer is a map showing where the data describing one land-use risk or conflict factor are available or not. This information is very important. If it was not specified, this could generate the impression that no risk is present. However, we simply do not know whether a risk is present or not.

Description of workflow steps

The extent layer is binary with a property no_data_cat.

Assign the no_data_cat:

9999 …if data are available

-9999 …if no data are available

These numbers will be used for combining the extent layer with the conflict layer in order to compile a conflict map.

Preparation of the extent layer consists of two steps:

- Digitizing the polygons of no-data and data regions,
- Conversion to the raster data model.

For digitizing the extent layer

See toolkit E.3.2.1.

Conversion to raster data model

Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok

ArcToolbox → Conversion tools → to raster → polygon to raster → value field: no_data_cat

E.3.4.2. Transformation of vector data into raster data

General remarks

A data transformation converts a set of data from the data format of a source data system into the data format of a destination data system. It is needed if input data are available in different data structures.

Description of workflow steps

Predefine the settings of the master grid as extent and resolution for all rasters you produce

Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok

Binary property -points

ArcToolbox →Conversion tools → to raster → point to raster

ArcToolbox → Spatial Analyst tools →Reclass → Reclassify → create two classes; assign value = 1 to the class with the points and NoData to the class of the background around the objects

Binary property -lines

ArcToolbox → Conversion tools → to raster → line to raster

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create two classes; assign value = 1 to the class with the line and NoData to the class of the background around the objects

Binary property -polygons

ArcToolbox →Conversion tools → to raster → polygon to raster

ArcToolbox → Spatial Analyst tools →Reclass → Reclassify → create two classes; assign value = 1 to the class with the line and NoData to the class of the background around the objects

Be careful to select a cell size which does not exceed the resolution of the smallest polygon! Otherwise you will lose information.

Categorial or sequential property - points

ArcToolbox → Conversion tools → to raster → point to raster

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class

Categorial or sequential property - lines

ArcToolbox → Conversion tools → to raster → line to raster

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class

Categorial or sequential property - polygons

ArcToolbox → Conversion tools → to raster → polygon to raster

ArcToolbox → Spatial Analyst tools → Reclass → Reclassify → create new classes according to the categories you have → add the background as NoData class

Discrete or continuous property - polygons

Conversion of continuous vector data like contour lines into a raster data set requires a step of data analysis, since various interpolation methods are available in ArcGIS, but not all methods are suitable for every data set. E. g. for interpolation of a variable with trend you have to use a different Kriging method than for variables without trend. ArcGIS provides various tools for data analysis which can be used prior to deciding which interpolation method is appropriate.

Main menu → customize → extensions → select the geostatistical analyst

See the separate ArcGIS tutorial how to work with the geostatistical analyst

Raster-data workflow for the conflict maps

E.3.4.3. Attributes of the conflict layers

General remarks

Attribute data is that part of geodata which contains thematic information for one 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.

Description of workflow steps

For raster data only numerical values can be assigned. Again, you can have binary, categorial or sequential and continuous / discrete properties.

The properties can be assigned either by reclassification or by the raster calculator.

> *ArcToolbox → spatial analyst tools → reclass → reclassify→ classify →specify the number of classes you need*
>
> *ArcToolbox → spatial analyst tools → map algebra → raster calculator →type a formula in order to assign a property, e.g. Con("miningsite"==1,"miningsite",0)*

Classify your conlict layers as specified in table 12 in toolkit E.3.2.4!

E.3.4.4. Combination of conflict and extent layers

Description of workflow steps

Combine the conflict and the extent layer (**Figure 32**).

Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok

ArcToolbox → spatial analyst tools → map algebra → raster calculator →Con("extent_layer", "conflict_layer","extent_layer")

With this operation, the conflict map receives

- the values of the conflict layer if the extent layer has the value 1 (i.e. is "true"),
- the no-data value if the extent layer has the value no data (i.e. is "false").

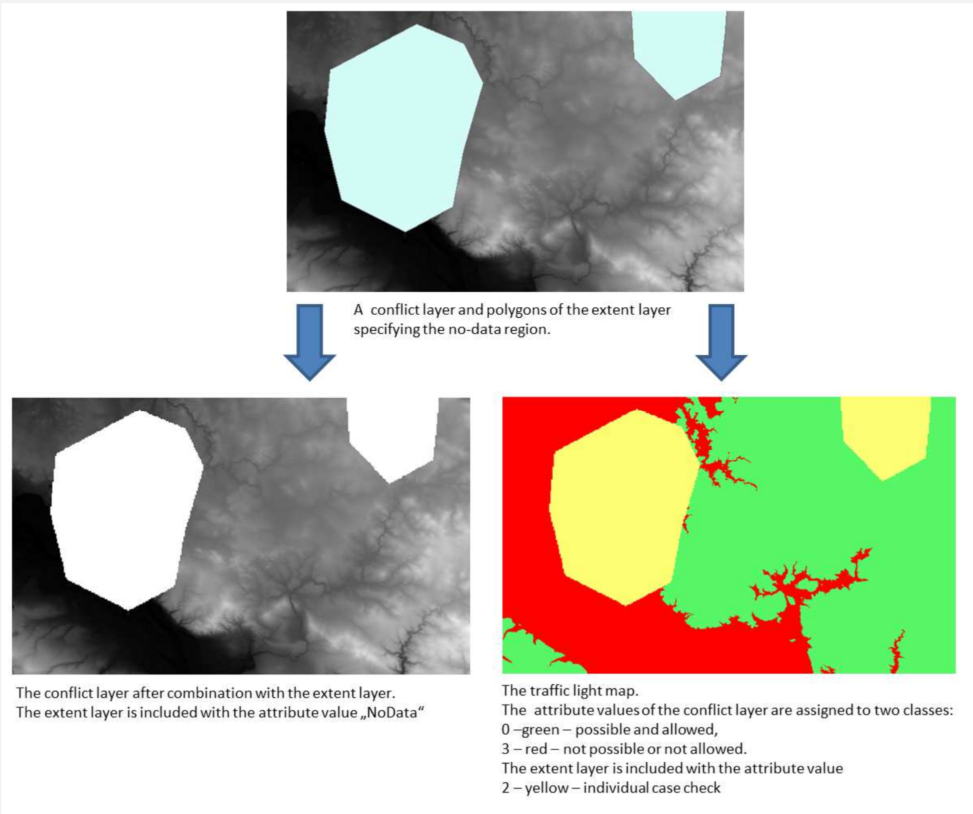


Figure 32: Possibilities for combining a conflict layer and a data-extent layer in the raster data format.

Raster-data workflow for the traffic light maps

E.3.5. Traffic light maps (raster data workflow)

E.3.5.1. Classification of the conflict layers according to the categories of the traffic light map

General remarks

All features need an attribute which specifies their class/category in the traffic-light map. This step requires the interpretation of the project's agent. All attributes available in the conflict layers have to be converted to the categories of the traffic-light map depending on the impact of a conflict factor and the governmental regulations valid in each pilot area.

The categories, to which all properties have to be transformed, are:

1… shallow geothermal installations are generally possible

No conflicts and risks

2… 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 generally allowed or prohibited.

3... shallow geothermal installations are generally prohibited

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

Description of workflow steps

Reclassify all properties such that the map consists only of the three categories available in the traffic-light map.

Binary and categorial properties

ArcToolbox → spatial analyst tools → reclass → reclassify→ go to the column "new value" and replace -9999 of the conflict layer by 2 for the traffic light map

Replace all other categories by the values needed in the traffic-light map.

Continuous and discrete properties

Continuous and discrete properties have to classified first.

ArcToolbox → spatial analyst tools → reclass → reclassify→ classify →specify maximum 3 classes

Raster-data workflow for the traffic light maps

E.3.5.2. Compilation of the traffic light map

General remarks

After assigning the categories of the traffic-light maps to all conflict layers and extent layers, the polygons of all steps have to be combined by taking the maximum value present at each location. This means, if in any layer an attribute 3 (forbidden or not possible) appears, this is selected to represent the location in the traffic-light map. If at one location no layer has the value 3, the next biggest is assigned, e.g. if no data are available for any of the layers. The resulting traffic-light map always displays the maximum risk appearing in any of the layers.

Description of workflow steps

The maximum value of all layers for each pixels can be calculated if all layers have the same extent, resolution and cell number.

Spatial analyst tools → local → cell statistics → maximum

Assign the RGB color codes for the classes:

Traffic light value: 1 205 245 122 green

2 255 255 190 yellow

3 255 061 084 red

Output data

E.3.6. Standardized output

Description of workflow steps

Ensure that the conflict, extent and traffic light layers are specified in the master grid coordinates, resolution and extent when a raster data model is calculated in the workflow for the first time. This is done by setting the environment resolution, coordinates and extent to the master grid in

Geoprocessing → *Environments*!

Use the harmonized classification specified in the workflow!

F. Workflow for modelling the geothermal potential of closed loop systems

F.1 The workflow – a brief description

Geothermal closed loop systems are in general tubulars of polyethylene inside of a borehole. The annulus is filled up with a mixture of bentonite and cement to give a good bond between the formation and the tubulars. The tubulars are closed and filled up with a mixture of water and antifreeze. A ground source heat pump inside a building circulates this mixture in the pipe loop. Heat from the ground is absorbed into the fluid, and then passes via heat exchanger into the heat pump.

Geothermal mapping of closed loop systems has to consider the specific thermal conductivities of rocks, the availability of groundwater and secondarily the geothermal gradient. Geothermal potentials are represented by the parameters specific thermal conductivity, heat extraction capacity and/or temperature. Together with the thermal conductivity maps, the temperature data provides a base for professional planning of a specific geothermal plant. In contrast to that, the maps of heat extraction capacity in Watts per Meter give a good overview of geothermal potential for public users.

Since comparable maps for all pilot areas can only be obtained if the rock classification schemes, the scale and level of detail and the geological interpretation is the same among the project partners, the modelling steps are harmonized or standardized. In subsequent steps, the geothermal potential maps will be used for a web representation. The presented workflow provides the base for the production of a standardized output.

The workflow comprises steps of data preparation, the calculation of the thermal conductivity considering wet and dry properties of rocks, the calculation of the heat extraction capacity, the compilation of a temperature map and of the geothermal gradient in each pilot area.

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 33**). 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.

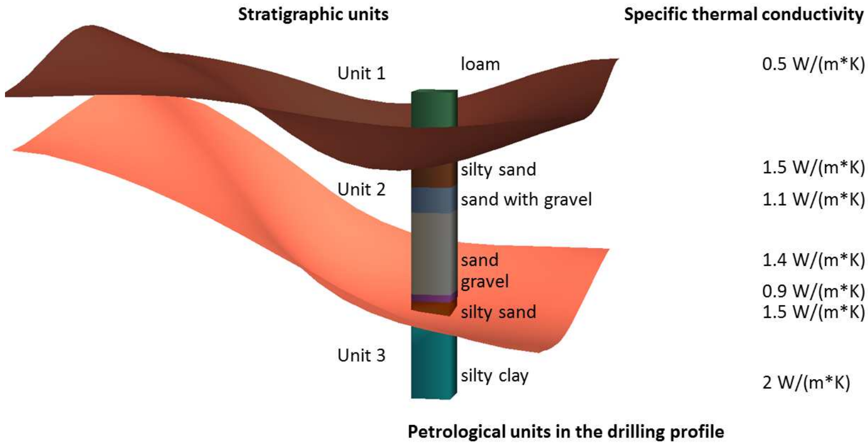


Figure 33: Connection of stratigraphic and petrographic information: A 3D model comprises three units (unit 1, unit 2, unit 3). Each unit has a variable petrography documented in the borehole profiles (unit 2 consists of silty sand, sand with gravel, sand, gravel, silty sand). For each petrography, physical parameters can be specified. A thickness averaged parameter will be assigned to the unit.

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, 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 (**Figure 34**). 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 points below the ground water table, the wet thermal conductivity is used.

The heat extraction capacity (HEC) in W/m can also be calculated with the ArcGIS extension using an empirical formula which was determined with simulation software for a standard single-family house with a specified annual heat production time. For the GeoPLASMA-CE project, an annual production time of 2,400 h will be used. **The formula is valid for a double U probe!** It is calculated by applying the formula:

$$HEC = -0.85 \cdot \lambda^2 + 12.39 \cdot \lambda + 26.26 \quad (1)$$

where HEC is the heat extraction capacity in W/m and λ is the thermal conductivity in W/(m·K).

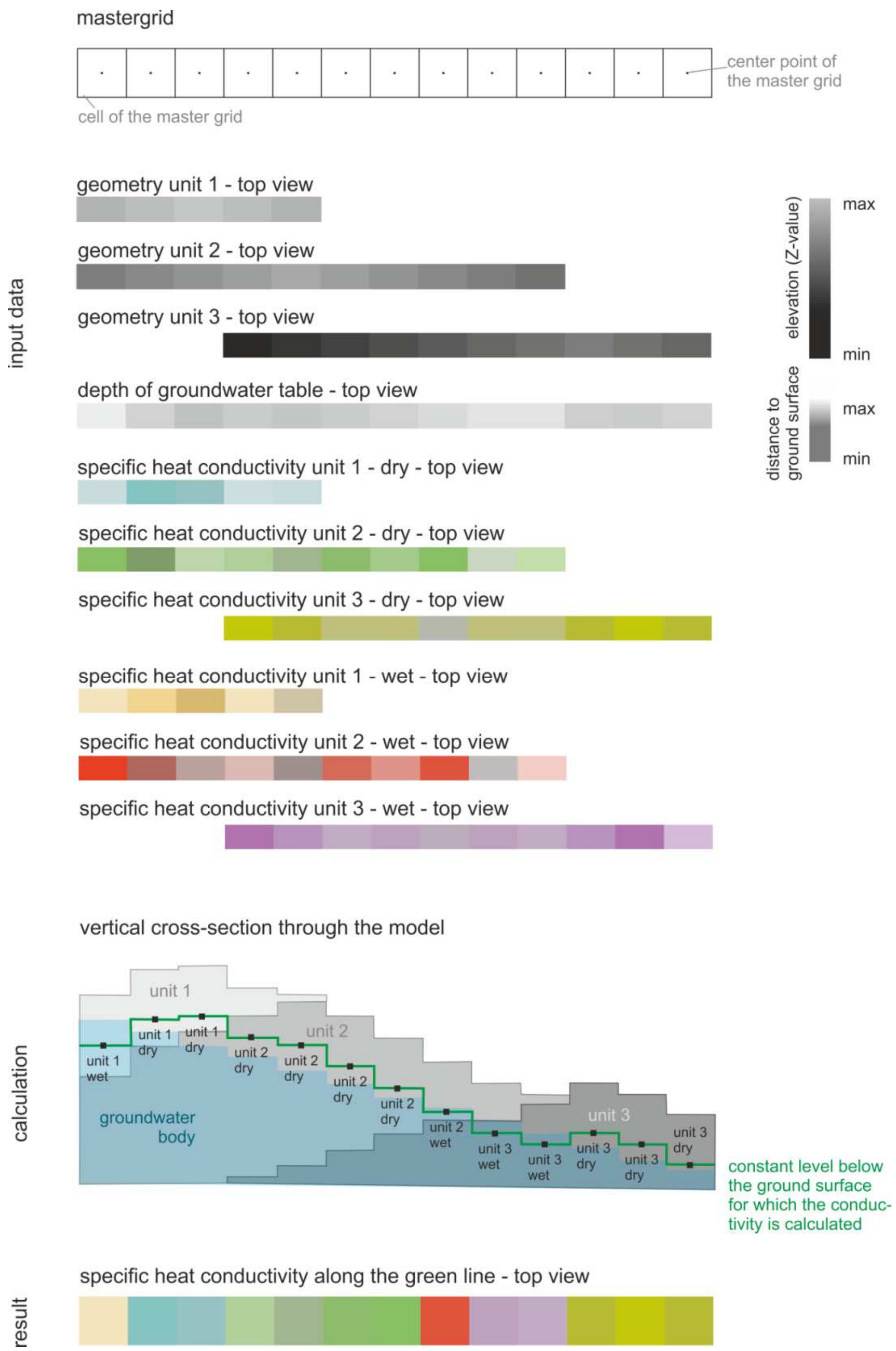


Figure 34: Schematic illustration of the steps required for calculating the average thermal conductivity for a depth interval below surface. The data are discretized with the cell resolution and location of the master grid of one pilot area. The input data consist of a set of raster data representing the absolute depth at top of the geological units in m sub sea level. Additionally, the distance of the groundwater table to the ground surface is required. The representative thermal conductivities have been calculated for wet and dry material from specific thermal conductivities provided in a harmonized parameter table. They are specified for each geological unit. The average thermal conductivity will be determined for the interval between the ground surface and a constant depth below the ground surface (green line). As the vertical cross-section illustrates, the line transects all three geological units and is in some instances located above, in others below the groundwater table. The respective thermal conductivity is assigned to each grid cell.

The formula was developed basing on single-case calculations of specific heat extraction capacities with the EED software. Groundwater flow is neglected. The formula is valid for the following parameters of the subsurface and the geothermal plant:

Subsurface Temperature:	8,75 °C
Heat flux:	0,07 W/m²
Specific heat capacity:	2,0 MJ (m^3 * K)$^{-1}$
Array:	2 heat exchangers
Distance between wellbores:	6 m
Wellbore diameter:	152 mm
Flow rate per heat exchanger:	0,001 m^3/s
Borehole heat exchanger type:	Double U-tubes, PE DN 32 PN 10
Center-to-center distance:	0,07 m
Thermal conductivity of grout:	0,7 W (m * K)-1
Thermo-vector fluid:	Monoethylene glycol (MEG)
Simulation period:	20 years
Heat exchanger output:	11,8 kW
	28,32 MWh/a at 2400 h
Seasonal performance factor:	3,5
Min. fluid temperature:	- 5°C
Max. fluid temperature:	15 °C
Basis load:	includes some hot water generation

The specific heat extraction capacities presented in the heat extraction maps are only valid for these boundary conditions. If some of the parameters vary, the true specific heat extraction capacity of a geothermal plant will change.

In order to provide an overview map for the geothermal potential of closed loop systems independent on the technical parameters of the plant and on legal regulations, a categorial map of rock properties is provided. This map might be an addition or an alternative to the heat extraction maps. It is produced by reclassification of the average thermal conductivity in 200 m depth by reclassifying it to four categories.

The mean annual temperature can be represented as ground surface temperature or as air surface temperature. Temperature data are provided by the meteorological surveys. Air surface temperatures have to be corrected in order to obtain ground surface temperatures. If temperature maps for a pilot area are available, these should be used. If only point data is available, this can be used for interpolation by geostatistical methods which respect trends and anisotropies in the spatial distribution of the temperature.

The geothermal gradient is generally a difference in temperature in a given distance. Hence a 3D environment, the geothermal gradient is usually referenced to a difference in temperature between two points defined by their vertical distance, i.e. depth or thickness of the layer as far as temperature is known at a top and base of the horizon.

The geothermal gradient can be directly calculated from temperature logging in boreholes and by calculating the change of temperature over measured length by:

$$g_{th} = \frac{\delta T}{\delta z} = \frac{T_{bot} - T_{top}}{zbot - z_{top}} \quad (2)$$

where: g_{th} – geothermal gradient, *T*- temperature (˚C, K), *z*- depth (m), indexes *bot* and *top* indicate bottom (base) and top of the respective borehole section.

Due to daily and seasonal temperature variations at the ground surface, the upper 10 m of the soil and rock (depending on thermal diffusivity it can be more) is affected by diurnal and annual temperature waves. To calculate a geothermal gradient in this shallow zone, it must be compensated for variations in surface temperatures, which requires detailed physical data on rocks and a complicated procedure. Beneath this seasonal zone, a neutral zone follows down to a depth of 30-50 m, which is characterized by an almost constant temperature, before the temperature is increasing downward due to the geothermal heat flow. A justifiable approach is to discard the topmost temperature measurements from the seasonal and neutral zones and to start with a value from the shallowest unaffected measurement specifying T_{top}. The geothermal gradient will be represented by the unit K/100m.

Special care has to be taken when calculating the geothermal gradient in urban regions, since the geothermal regime is strongly influenced due to anthropogenic activity. The neutral zone may reach to a depth of 100m, the geothermal gradient may be even negative, and heat islands are likely to occur. Therefore, the calculation of the geothermal gradient in urban areas requires enough temperature log data specifying the depth of the anthropogenic influenced zone as well as the geometry of heat islands. Additionally, the geothermal gradient in urban regions is variable with time; therefore, the presentation of the modelling result requires a specification of the time interval covered by the input data. These complications are the reason why only one project partner will produce an output addressing the geothermal gradient in the urban areas. Therfore, no harmonized workflow is necessary.

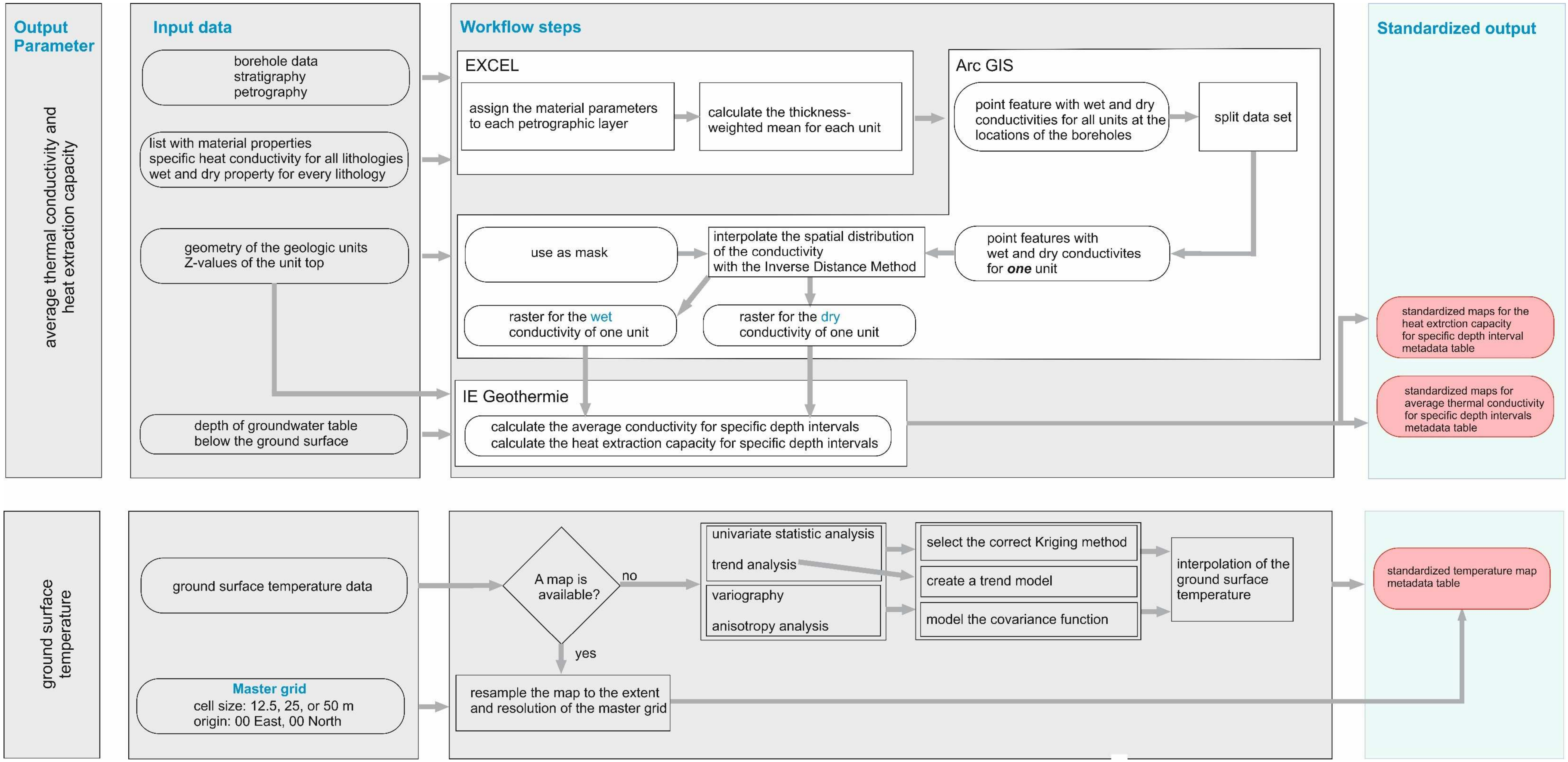


Figure 35: GeoPLASMA-CE workflow for mapping the geothermal potential for closed loop systems.

The workflow is written for ArcGIS. Version 10.2.2 for Desktop (basic license) was used to compile the workflow. In addition to the basic ArcGIS license, the following are required:

- Spatial Analyst
- Geostatistical Analyst
- IE Geothermie

The following points give an overview of the workflow steps (compare with **Figure 35**):

1. Documentation of the project

2. Thermal conductivity and heat extraction capacity

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

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

Load the borehole data to ArcGIS

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

Quality check the input data

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

Are the rock parameters feasible?

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

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

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

Calculate the heat extraction capacity for 2,400 h/a

Standardized output

One standardized raster data set for each map with the attributes as specified in the deliverable D.T2.3.1

One attribute table for each group of maps with the relevant depth level for each map

One metadata table for each group of maps

3. Mean annual ground surface temperature

Input data

Geometry data for geologic units

Depth of the groundwater table below the ground surface

Research for temperature maps from the meteorological surveys

If you find processed temperature maps, use these

Get a permit to publish the map on the web!

Production of the standardized output in raster format

Interpolation of the ground surface temperature

Perform a statistical data analysis

Perform a trend analysis

Perform a spatial data analysis

Decide which Kriging method is appropriate for the data set

Specify a trend model

Specify an anisotropic variogram model

Interpolate one raster data set with the Kriging method

Standardized output in raster format

F.2 Harmonized rules and specifications - checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters → See D.T2.3.1 for specification
Elevation reference system	EVRF2007 → See D.T2.3.1 for specification
Geometry data	Standardized output of the 3D model
Material parameter specific thermal conductivity wet/dry	Use the parameter list of GeoPLASMA-CE produced in TWP 3
Transfer the raster data to the master grid	Grid resolution: 12.5, 25 or 50 m Borders of the grid cells at (00,00) coordinates
Export data format of all raster data	.adf -ESRI grid
Completed attribute table	One attribute table for each group of maps specifying the depth level of each map
Completed metadata table	Metadata table for each group of maps
Project documentation	Table for the documentation of the project progress →See D.T2.3.1 for specification

F.3 Tool kit for mapping the geothermal potential of closed loop systems

Thermal conductivity and heat extraction capacity – input data

F.3.1. Thermal conductivity and heat extraction capacity

F.3.1.1. Input data - geometry data for the geological units

General remarks

The geological units are described by their tops.

For each geological unit, a raster data set is needed which has to coincide with the master grid by the cell location and resolution as well as the extent of the raster. Raster cells outside of a geologic unit are specified by the no-data value (-9999).

Description of workflow steps

This data corresponds to the standardized output of the 3D modelling workflow (chapter C.4).

The data have to be loaded to the ArcGIS software (**Figure 36**).

You can import the data directly as a raster data if the 3D modelling software provides a corresponding export function.

Main Menu → data → add data

If no appropriate export function is available in the 3D modelling software, the data can be exported as XYZ file. You can load them as point feature and then convert them into a raster data set.

Main Menu → data → add data→ add XY data → specify the Z-value

Main Menu → Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size→ ok

ArcToolbox → Conversion Tools → in raster → point to raster→ value field: Z→ mean or nearest → cell size as in the master grid

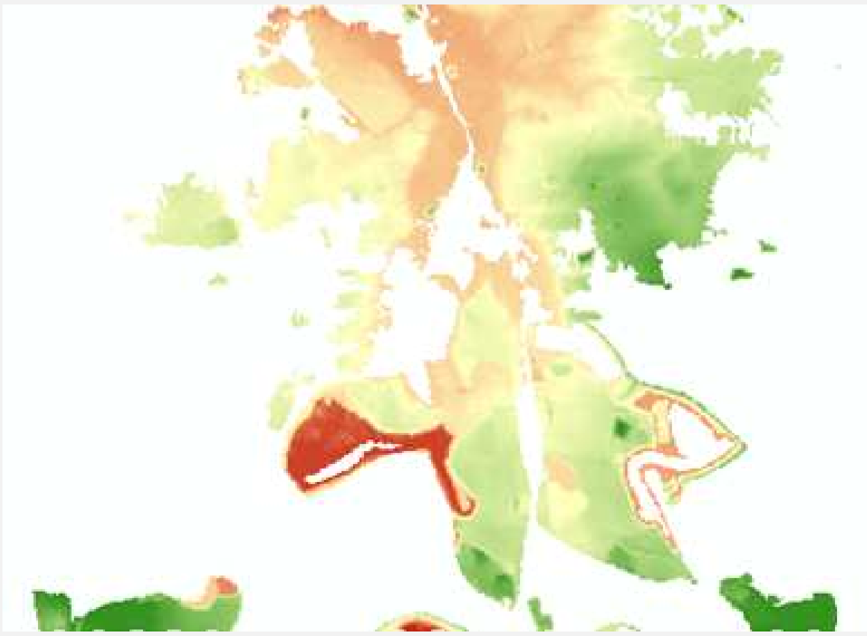


Figure 36: Example for a raster specifying the extent and the depth of the top of a geological unit.

F.3.1.2. Input data - groundwater depth below ground surface

General remarks

This data set has to be provided as a raster data set coinciding with the master grid by the cell location and resolution as well as the extent of the raster.

If the ground water table was calculated, the ground water depth can be determined as its difference from the ground surface.

Description of workflow steps

For the calculation of the groundwater depth, two raster data sets have to be loaded to ArcGIS, the DEM and the ground water table. Both raster data sets have to coincide with the master grid by the cell location and resolution and the extent of the raster.

ArcToolbox → spatial analyst tools → Math → Minus → Raster 1: DEM → Raster 2: groundwater_table → output: groundwater_depth

F.3.1.3. Input data - borehole data

General remarks

One table for all wells is needed which specifies the thickness of all petrological layers and assigns them to a model body (unit ID) (**Figure 33**).

Description of workflow steps

Table 23 shows the header of a table with borehole data which is needed for the workflow.

Table 23: Header of a file with borehole data needed for the workflow.

Borehole ID	Easting	Northing	Thickness	Unit ID	Pet key

F.3.1.4. Input data - material parameter list

General remarks

The specific thermal conductivity is a material property describing how well a material conducts heat. Its unit is W/(m·K).

Description of workflow steps

The parameter of the specific thermal conductivity has to be either determined by measurements or estimated from literature values. One **list with parameters** comprising the thermal conductivity for all rocks (wet and dry) will be worked out in TWP 3. This list can be used by all partners.

F.3.1.5. Assign the specific thermal conductivity to each petrological layer at boreholes

General remarks

The specific thermal conductivity depends on the mineralogical composition, the grain size and the water content of a rock. In each lithological unit, several petrographic layers are recorded in the drilling profiles. These subunits describe the variability of the specific thermal conductivity within one stratigraphic unit represented in the model.

Description of workflow steps

The parameter of the specific thermal conductivity has to be assigned for both water saturated and dry rocks since the specific thermal conductivity of porous sedimentary rocks strongly depends on the water contents. If a rock is dense, like granite, the specific thermal conductivity of wet and dry rocks is the same. However, the calculation algorithm requires also specifying the wet and dry specific thermal conductivity for these rocks (**Table 24**).

Table 24: Header of a file with borehole data after assignment of the specific thermal conductivities.

Borehole ID	Easting	Northing	Thickness	Unit ID	Pet key	thermal conductivity dry	thermal conductivity wet

Extend the table with the drilling data by two fields and assign the specific thermal conductivity for wet and dry rocks to each PET key number.

A macro-script will prepared for the partners to do this automatically.

F.3.1.6. Calculate the thickness-weighted mean for each geologic unit at boreholes

General remarks

The thickness-weighted mean describes the average thermal conductivity along a borehole profile for a geologic unit composed of various petrological layers. Each petrological layer is weighted by its vertical thickness in the drilling profile. A thickness-weighted mean is calculated as representative value for the thermal conductivity for each geologic unit and for each borehole.

Description of workflow steps

The thickness-weighed mean is calculated by the following two formulas:

$$\lambda_{layer}^{weighted} = \frac{thickness\ layer}{thickness\ unit} \cdot \lambda_{layer} \qquad (3)$$

$$\lambda_{unit} = \sum_{layer} \lambda_{layer}^{weighted} \qquad (4)$$

λ is the specific thermal conductivity.

A script (Excel-macro) will prepared for the partners to do this automatically.

A new table will be produced which contains only one entry per geological unit (Table 25).

Table 25: File header after calculating the weighted mean of the thermal conductivity for each unit. In this table, each unit is represented by one row, a petrographic differentiation is not specified anymore.

Borehole ID	Easting	Northing	Thickness	Unit ID	Weighted thermal conductivity dry	Weighted thermal conductivity wet

F.3.1.7. Split the data set in point features for each geologic unit

General remarks

A point feature comprising the representative weighted means of the specific thermal conductivities in all boreholes is needed for each geologic unit. It can be selected from the full data set.

Description of workflow steps

Load the table to ArcGIS:

> *Main Menu → data → add data → add XY data → specify X field: Easting; Y field: Northing*

The data set consists of many points with the same XY coordinates for a vertical borehole. Split the data set by selecting all geologic units:

> *Main Menu → selection → by attributes → drilling data → create new selection → borehole data → "unit"=00108040202*
>
> *TOC borehole data → right-click → data → export → selected features*

F.3.1.8. Quality check of the location of the drilling data and of the material parameters

Description of workflow steps

Check whether all input data of a unit are located inside of the geometry raster of that unit (**Figure 37**).

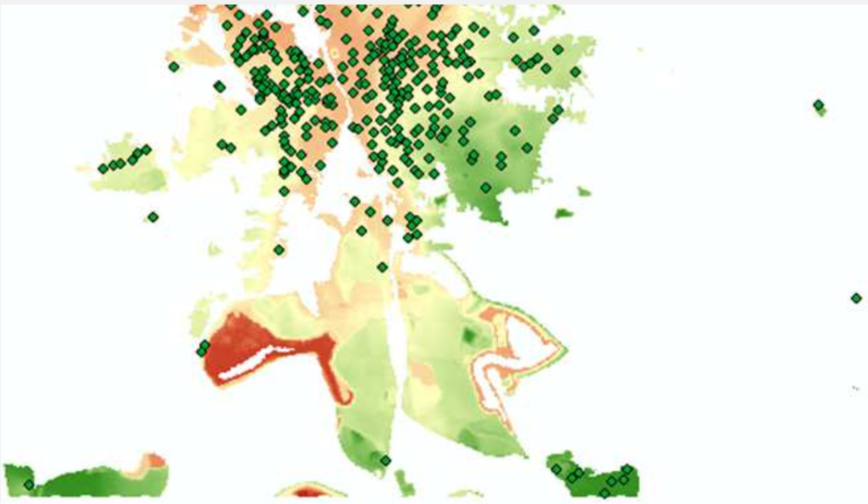


Figure 37: Raster with the extent and depth of a geological unit and the borehole data referring to this unit, loaded as point shape in ArcGIS.

ArcToolbox → Conversion tools → from raster → raster to polygon → select the value_field

Select all points of the point feature:

Right-click on the conflict layer in the TOC → open attribute table → table options→ select all

Or *Take the selection tool* *and draw a square with the mouse including all points of the shape*

Main Menu → selection → by location → remove from selection → is completely inside → unit polygon feature

This shows all points outside of the polygons. You can save them by

TOC borehole data → right-click → data → export → selected features

Check the data and correct the errors.

Check the material parameters

Open the attribute table and check whether fields for the wet and dry thermal conductivity are present. Check whether the values are reasonable.

Right-click on the conflict layer in the TOC → open attribute table → right-click into the header

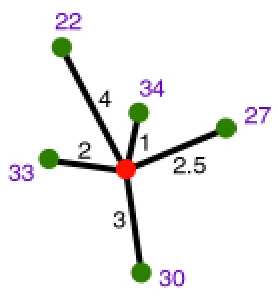
of the thermal conductivity fields → statistics
Thermal conductivity and heat extraction capacity - interpolation

F.3.1.9. Interpolate wet and dry thermal conductivity with the Inverse Distance Method

General remarks

The data for wet and dry specific thermal conductivity will be interpolated in order to estimate these parameters at locations where no data are available. The results of this work step are two raster data sets per geologic unit, one raster describing the thermal conductivity for wet rocks and one for dry rocks.

Inverse Distance Weighting (IDW) is a type of deterministic method for the interpolation with a known scattered set of points. The estimated values at unknown points are calculated with the weighted average of the values available at the known points (**Figure 38**). The weight a particular point is assigned in the calculation depends upon the sampled point's distance to the non-sampled location. The method can be applied for spatially dependent variables which similarity decreases with increasing distance. Anisotropies and trends cannot be respected by the mathematical model. When the exponent p = 2, the method is called inverse distance squared weighted interpolation. A maximum number of points included in the calculation can be specified. It is 12 per default.



$$Z(x) = \frac{\Sigma w_i z_i}{\Sigma w_i} = \frac{\frac{34}{1^2} + \frac{33}{2^2} + \frac{27}{2.5^2} + \frac{30}{3^2} + \frac{22}{4^2}}{\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{2.5^2} + \frac{1}{3^2} + \frac{1}{4^2}} = 32.38$$

Figure 38: Illustration of the inverse distance method. The value for one location without data is estimated by the neighbouring data points which are weighted by their distance. If the exponent p=2, the distance is squared.

You have to interpolate the wet and the dry material properties for each geologic unit.

Description of workflow steps

Interpolate the specific thermal conductivity for a single unit

Set the coordinates, extent and cell size of the master grid as default in order to produce a standardized output (if you have not done it before).

> *Main Menu → Geoprocessing → environment → output coordinates → master grid → extent → master grid → resolution → type the resolution specified for the master grid → raster analysis → cell size → ok*

The interpolation of the thermal conductivity for each geologic unit is performed with the thickness-weighted mean values as input data (**Figure 39**).

ArcToolbox → spatial analyst tools → interpolation → IDW

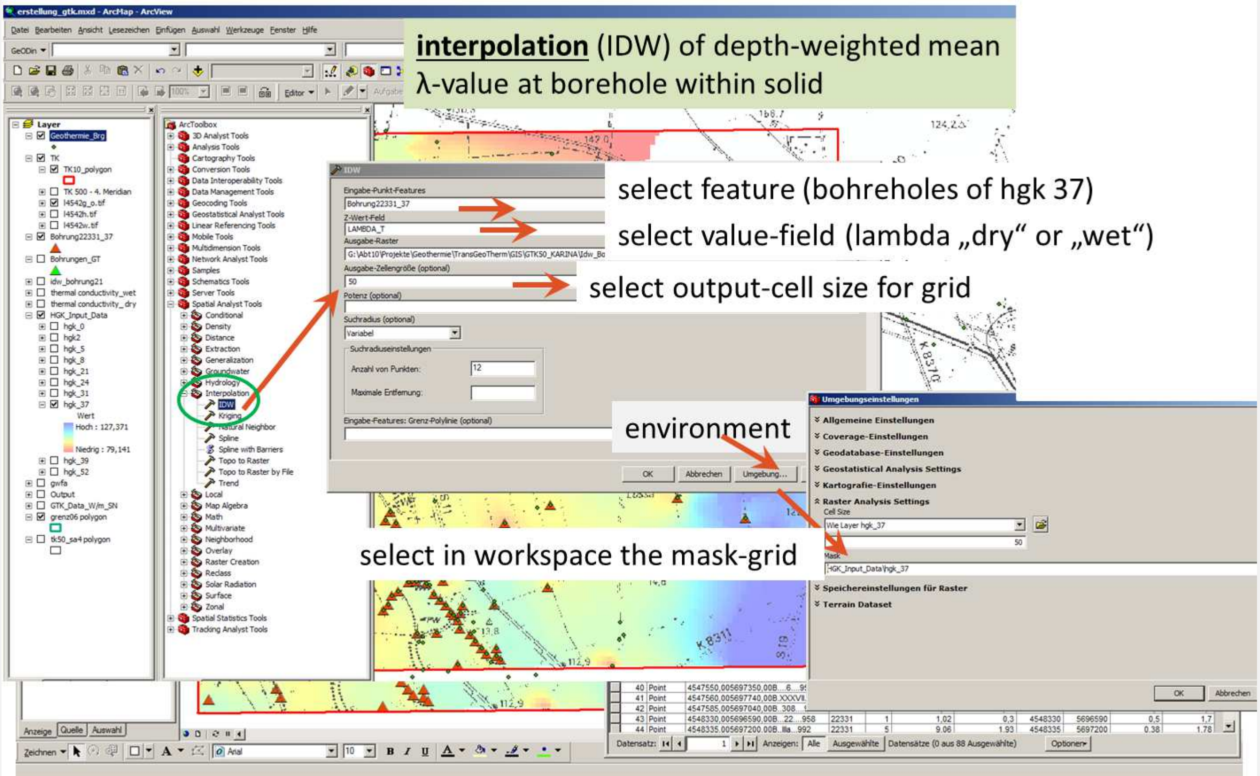


Figure 39: Spatial Analyst toolbox with the inverse distance weighting tool used for this workflow step.

A modelling result for the whole pilot area, including the area outside of the geologic unit, is obtained (**Figure 40**). In order to run the interpolation only inside of the geologic unit, you have to specify the geometry raster of the unit as mask (**Figure 41**):

ArcToolbox → spatial analyst tools → interpolation → IDW→ environment → raster analysis → mask → select the geometry raster of the geologic unit

Processing extent → snap raster → select the geometry raster of the geologic unit

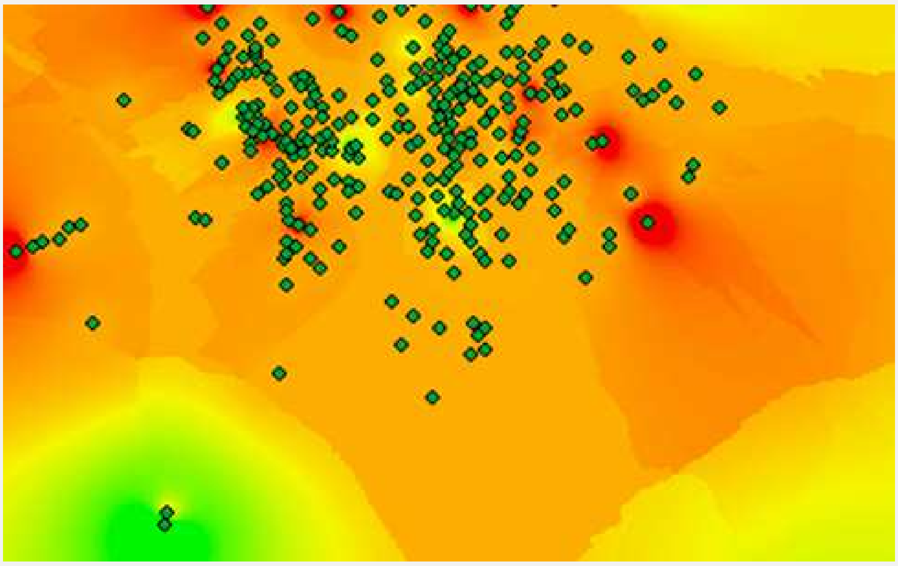


Figure 40: Interpolation result without specification of the raster environment.

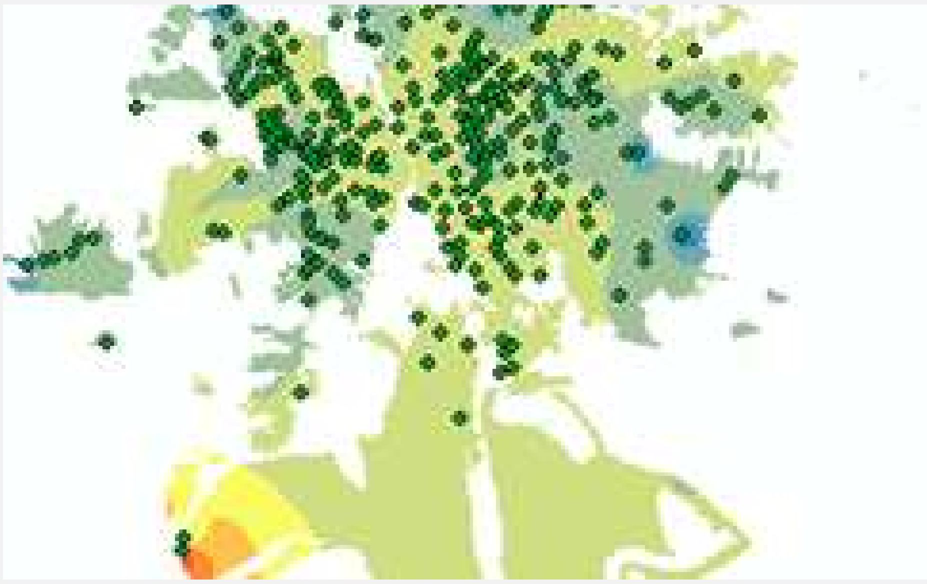


Figure 41: Interpolation result with specification of the raster environment.

Use the batch mode to interpolate the thermal conductivity for many units

Start the interpolation tool in the batch mode (**Figure 42**):

> *Right-click on the IDW tool in ArcToolbox → spatial analyst tools → interpolation*
>
> *Select batch*

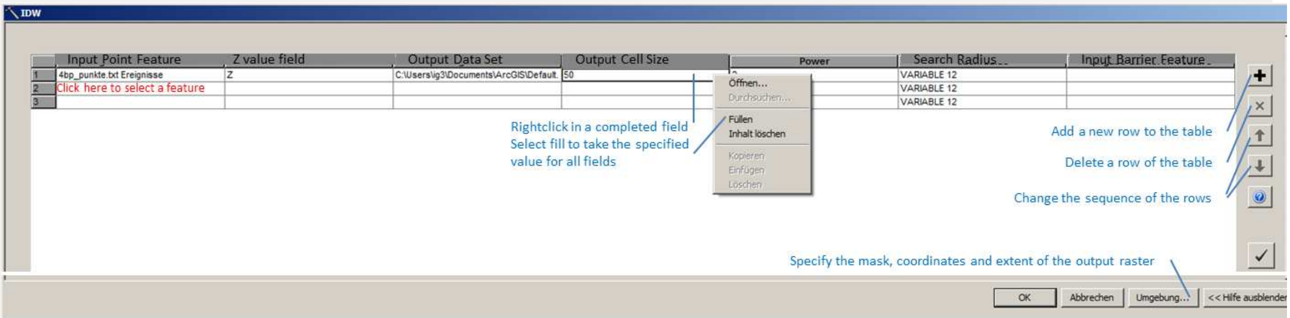


Figure 42: Specifications for the batch mode.

Click on the "+" icon to add new rows to the table

Click into a field and select the input feature, the variable that has to be interpolated, the output path, the output cell size, the exponent used for the interpolation and the number of data included into the interpolation

If you have many fields, and you want to fill them with the same entry, specify the parameter for the first row, right-click into the filled field and select fill. This completes all fields of the column

For specifying the output mask, go to environment → raster analysis → mask → select the geometry raster of the geologic unit

Processing extent → snap raster → select the geometry raster of the geologic unit

Since the mask has to be different for each geologic unit, you can only interpolate the wet and dry thermal conductivity for one unit in one step!

F.3.1.10. Quality check and correct interpolation result

Description of workflow steps

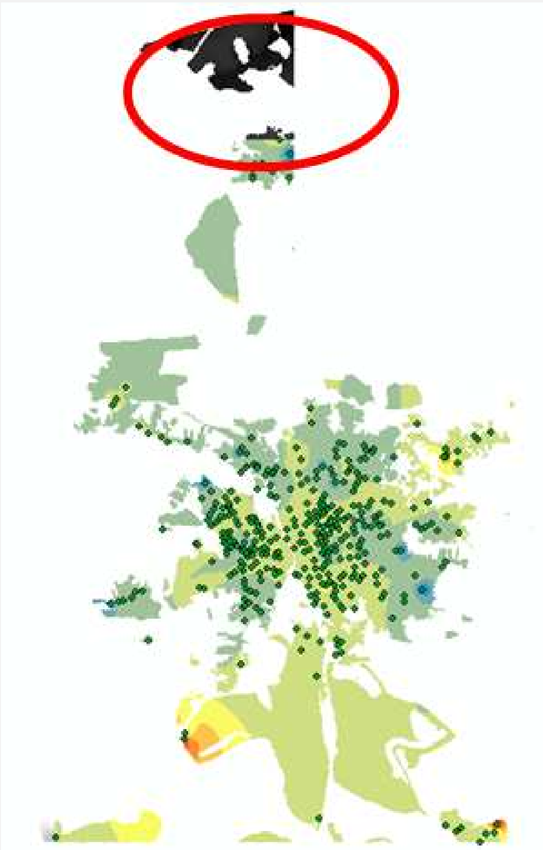


Figure 43: Check of the interpolation result: Regions with no data were not interpolated properly.

Figure 43 shows the interpolation result. Some bodies of the geologic unit, where no drilling data are available, were not included in the interpolation (red ellipse). In order to obtain an interpolation result for the full extent of the geologic unit, artificial points have to be added (**Figure 44**). The artificial points have to be placed in the centre of each body and in all corners. Since only one input data set can be specified for the interpolation, the artificial data have to be added to the original point feature by digitizing.

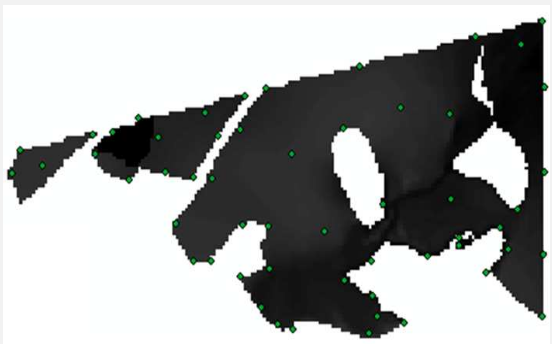


Figure 44: Erroneous region with artificial data points.

Right-click the feature class in the TOC → start editing → select the tool "create feature" → go to the window "create feature" and select "unit1" → select "points" → go to the editor tool bar and digitize the points

Save the edits and exit the editor mode

Right-click the feature class in the TOC → open attribute table → click into the header of the conductivity field → sort the data in ascending order

click into the header of both conductivity fields → statistics → read the mean value

select all fields with no data for the wet conductivity → click to the left of the first column in the first line with no data → press the shift-key → click to the left of the first column in *the last line with no data*

click into the header of the wet conductivity field → field calculator → type the mean value of the wet conductivity

click into the header of the dry conductivity field → field calculator → type the mean value of the dry conductivity

click into the header of the borehole name field → field calculator → type 'virtual point'

Don't forget to reactivate the full data set!

Main menu → selection → clear selected features

Repeat the interpolation and check the result.

F.3.1.11. Calculate thermal conductivity and heat extraction capacity for various depth levels

General remarks

In this work step, the data sets for the wet and dry specific thermal conductivity of several geological units are combined in order to calculate the average thermal conductivity for a defined depth interval below the ground surface. In the same step, the heat extraction capacity can be calculated for the same depth levels.

Note: The calculation of the 10 m intervals is necessary for the location query of the conductivities and heat extraction capacities!

For a map visualization of these parameters, few representative levels may be selected, not all 10 m intervals have to be shown.

Description of workflow steps

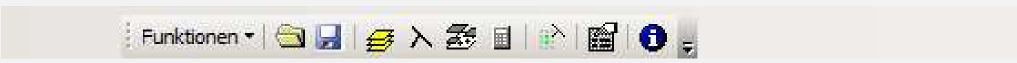
Start the extension

Precondition: The license for the spatial analyst tool must be available and activated.

Main Menu → Customize → Extensions → tick IE Geothermie

Main Menu → Customize → Toolbars → tick IE Geothermie

The IE Geothermie toolbar appears in the head of your ArcGIS viewer(**Figure 45**)



The function ("Funktionen") menu contains all available tools. The same tools are also provided as icons next to the drop down menu. Lambda stands for the thermal conductivity in W/(m·K).The first step is to select the input data (“Eingangsdaten auswählen”).

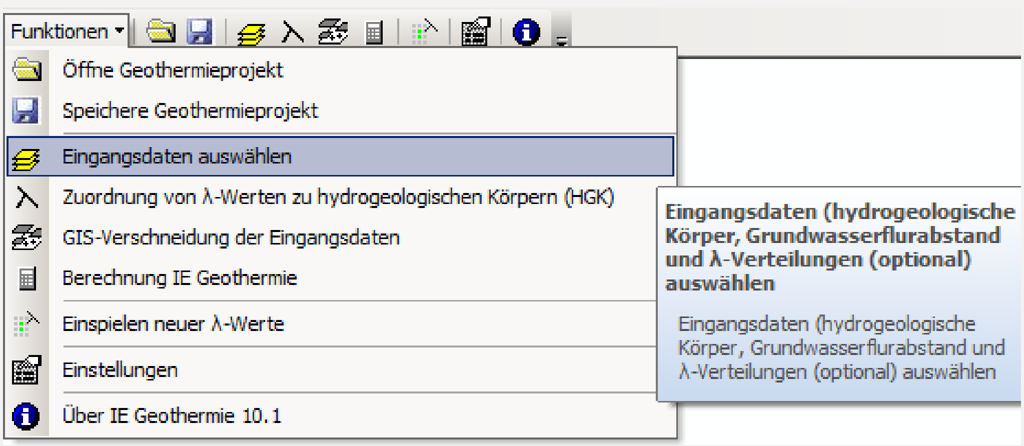


Figure 45: The menu bar of the IE Geothermie extension for ArcGIS.

You have to insert triples of data sets (geometry, λ dry and λ wet) for each geologic unit in the model (**Figure 46**). Additionally, a data set specifying the depth of the groundwater table below surface is needed.

Finish the data input with close ("Schliessen").

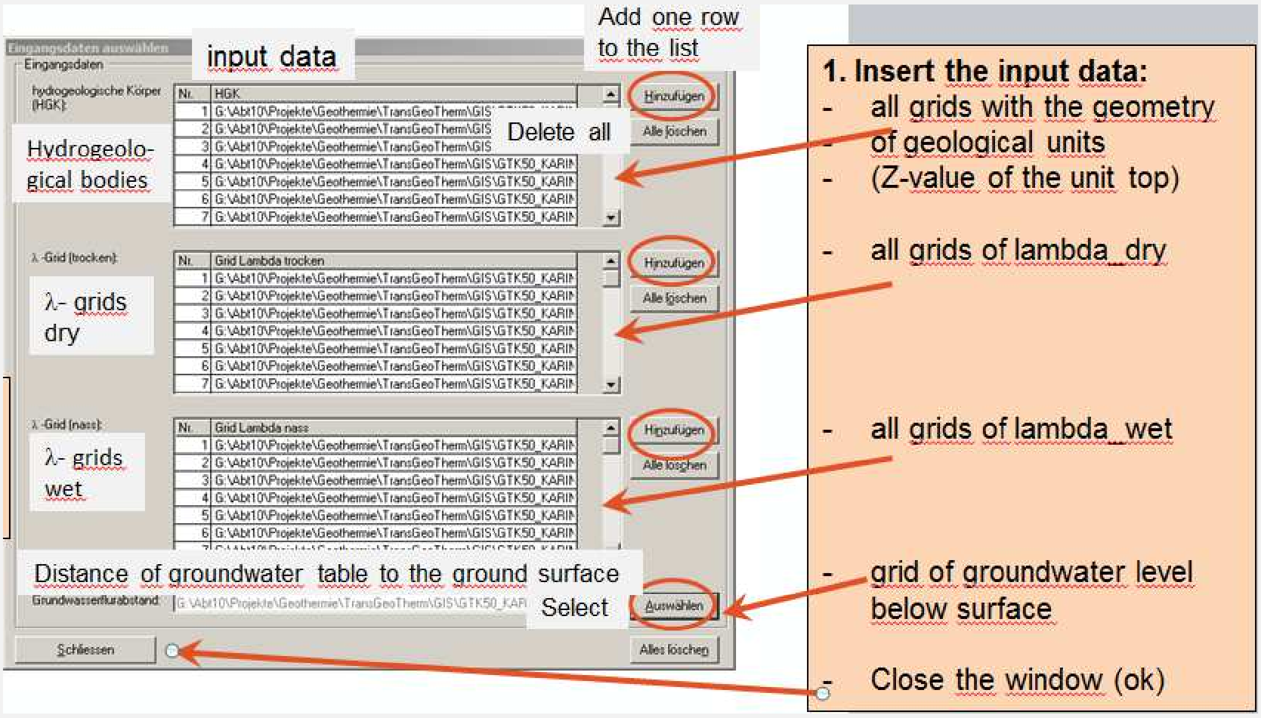


Figure 46: The menu point "select input data".

In the next step, you have to order the triples of the data sets for each unit (**Figure 47**). Start the tool "assignment of λ-grids to geological grids" ("Zuordnung von λ-Werten zu hydrogeologischen Körpern").

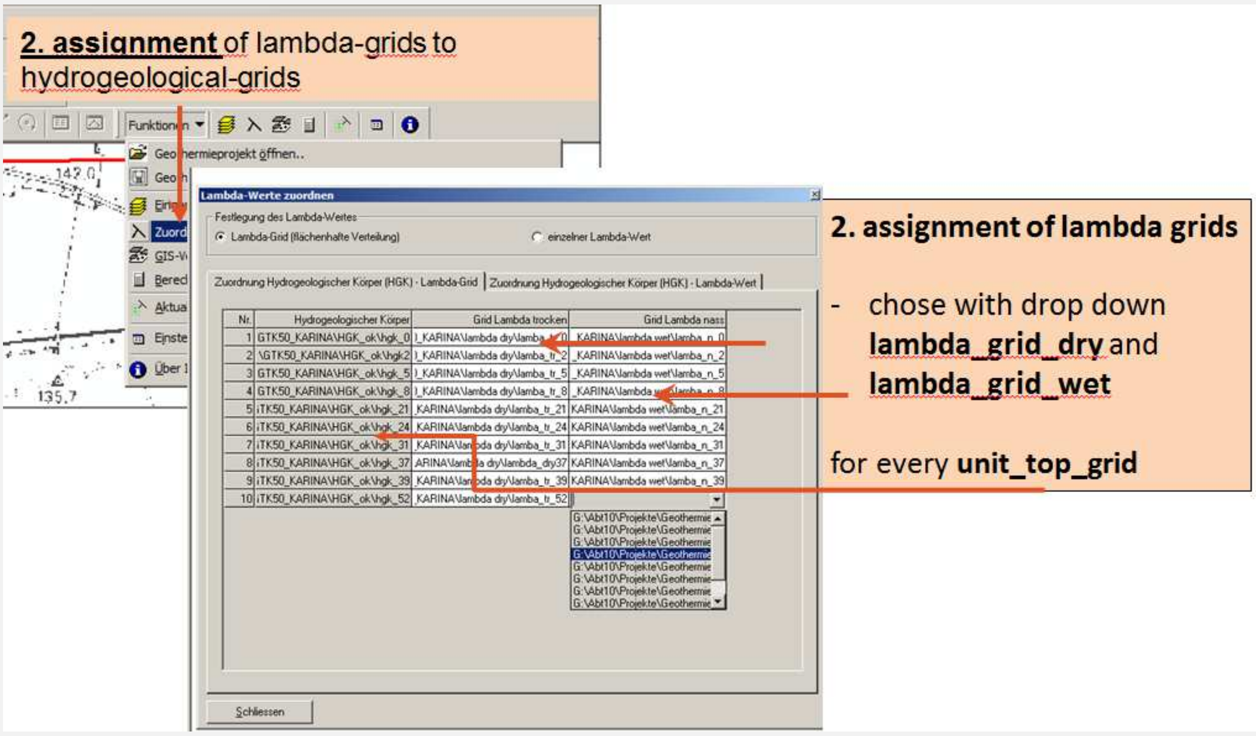


Figure 47: Menu point "Assignment of λ -grids to geological grids".

Next, use the tool "GIS-intersection of the input data" ("GIS-Verschneidung der Eingangsdaten") .

This tool combines the data from the wet and dry λ-grids, depending on whether the geological units are located above or below the ground water table (**Figure 48**).

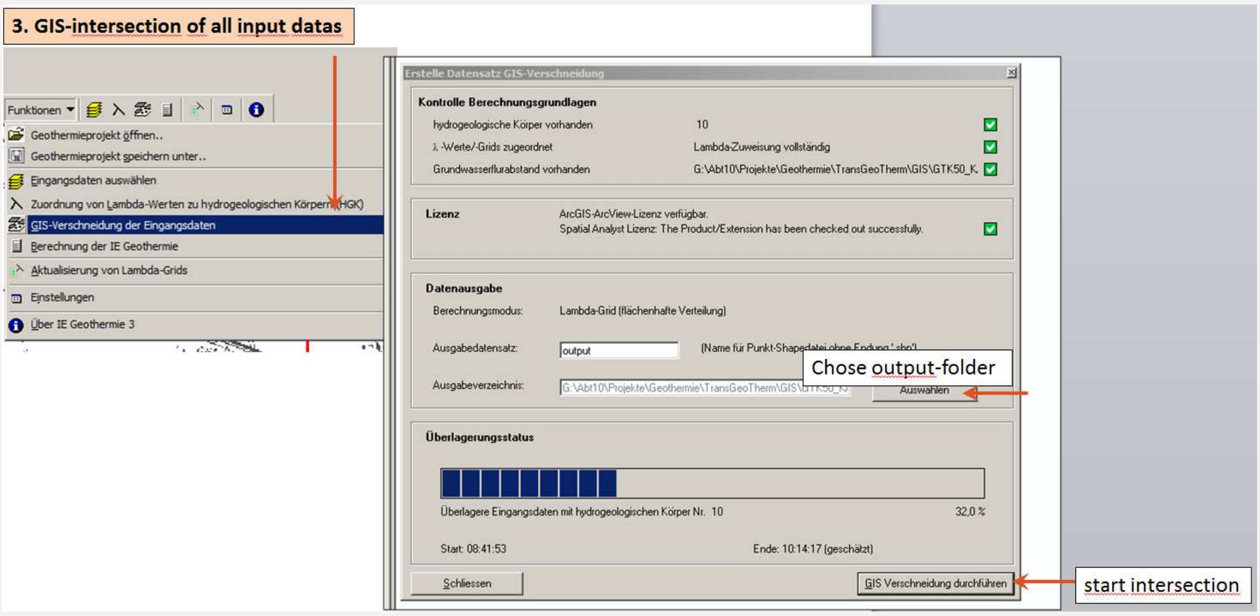


Figure 48: Menu point „GIS intersection".

The first two boxes show whether all input data and licenses are available. If so, a green checkbox is shown. Select an output folder and click on "start intersection" ("GIS-Verschneidung durchführen").

This operation can take more than 12 hours!

This tool generates an intermediate point data set (shape) which will be loaded for the calculation of the conductivities and heat extraction capacities at specific depth level. For this calculation, start the tool "calculation of the geothermal information" ("Berechnung der IE Geothermie") .

You have to load the shape calculated during the previous work step. Then you have to specify the annual operational hours. Select 2,400 h/a, as the GeoPLASMA-CE partners agreed during the technical workshop in Vienna 2017. Select all depth levels you want to output. Select the parameter you want to calculate. You can choose between the thermal conductivity and the heat extraction capacity. Select the output folder (**Figure 49**) and go to "start calculation" ("Berechnung Geothermieebene").

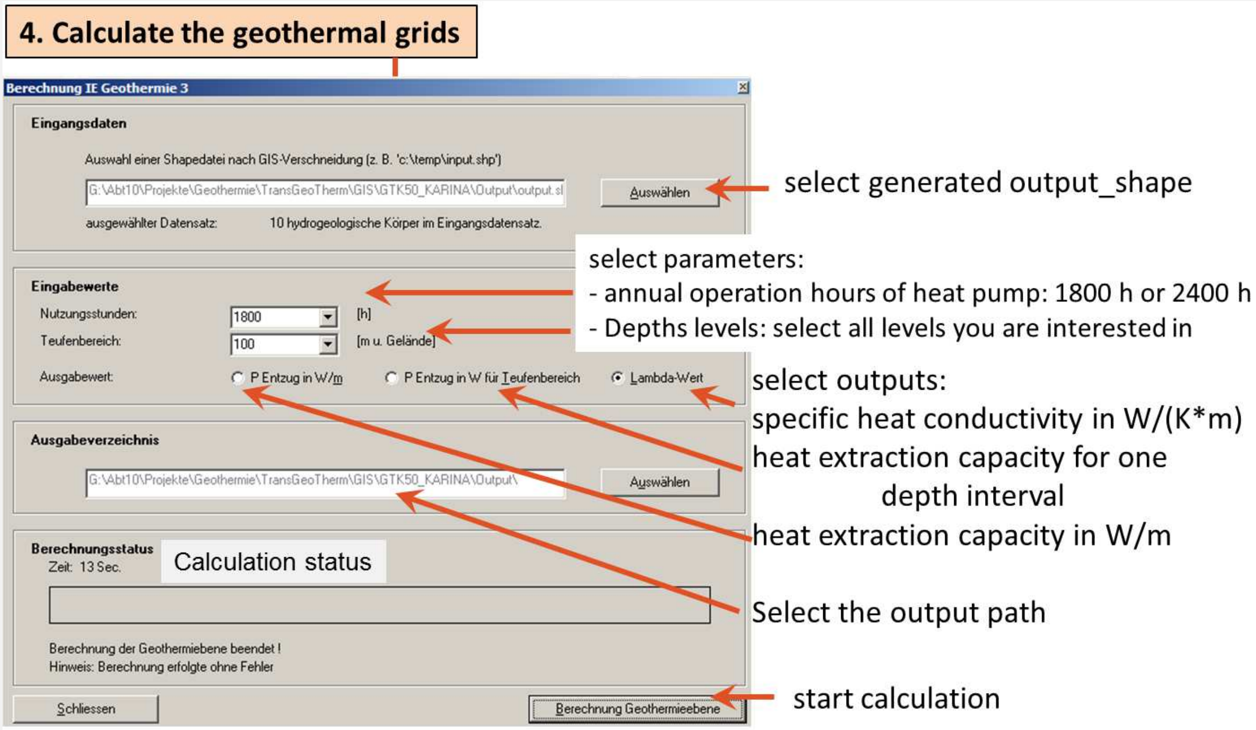


Figure 49: Menu point „Calculate geothermal grids".

Finally, you get a set of rasters where names are specified by the depth interval (**Figure 50**) and the operational hours.

The formula which was used for calculating the heat extraction capacity is valid for a double U probe!

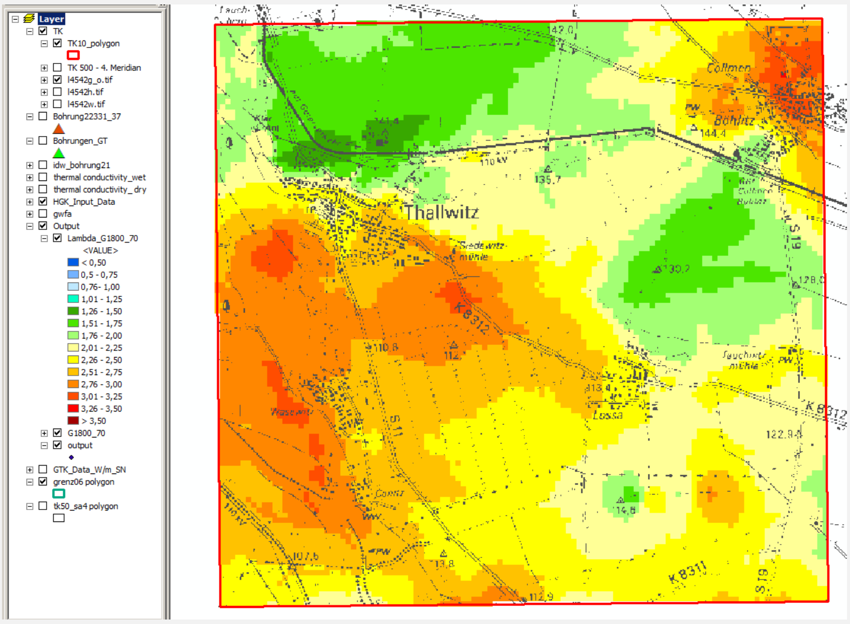


Figure 50: Calculation result: The thermal conductivity at a depth interval to 70 m below surface.

Reclassify the conductivity maps for the harmonized GeoPALSMA-CE output (**Table 26**):

> *Spatial analyst toolbox → reclassify → reclassify → classify → 10 or 11 classes → specify the break points as listed in the table*

Average thermal conduc-tivity	continuous	-9999	No data available	200 200 200
		1	<0.3	000 000 255
		2	0.3-0.6	000 102 255
		3	0.6-0.9	093 224 255
		4	0.9-1.2	063 205 148
		5	1.2-1.5	000 204 000
		6	1.5-1.8	000 255 000
		7	1.8-2.1	227 250 152
		8	2.1-2.4	247 233 129
		9	2.4-2.7	236 155 036
		10	2.7-3.0	250 109 022
		11	>3.0	255 000 000
Heat extraction capacity	continuous	-9999	No data available	200 200 200
		1	<40	000 000 255
		2	40.0-42.5	000 102 255
		3	42.5-45.0	093 224 255
		4	45.0-47.5	063 205 148
		5	47.5-50.0	000 204 000
		6	50.0-52.5	000 255 000
		7	52.5-55.0	227 250 152
		8	55.0-57.5	247 233 129
		9	57.5-60.0	236 155 036
		10	>60.0	255 000 000

Table 26: Standardized classification of the output.

F.3.1.12. Classify a categorial map characterizing the rock properties

General remarks

In order to give a brief overview on the geothermal rock properties for public users, a categorized version of the conductivity map in 200 m is provided. The map comprises four categories:

- Small thermal conductivity,
- Medium thermal conductivity,
- Large thermal conductivity,
- Very large thermal conductivity.

Description of workflow steps

Reclassify the conductivity map in 200 m depth:

Spatial analyst toolbox → reclassify → reclassify → classify → 4 classes → specify the break points 1.7, 2.0, 2.3

The RGB colour codes used for the visualization are:

-9999	No data available	200 200 200
1	0-1.7	068 101 137
2	1.7-2.0	190 210 255
3	2.0-2.3	255 255 190
4	>2.3	255 167 127

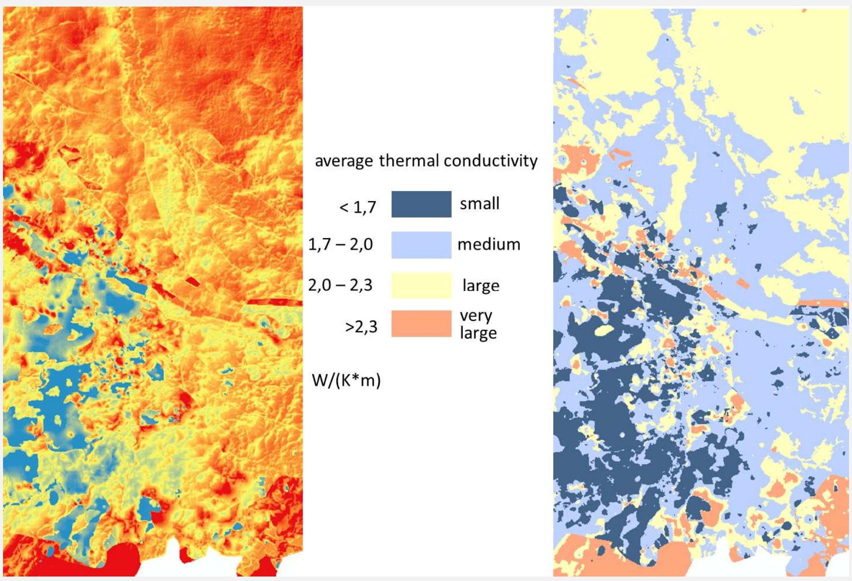


Figure 51: The thermal conductivity map for the base of the modelling domain (200m depth, left) and the rock property map derived from it by reclassification (right).

F.3.1.13. Standardized output maps

General remarks

The standardized output of all maps is an **ESRI raster of the .adf file format**. The cell location and size has to be coincident with the master grid. The no-data value is specified with -9999.

An attribute table specifying the depth level for each map is necessary.

In addition, a metadata table has to be completed for each group of data (e.g. one for all thermal conductivity maps).

Description of workflow steps

Ensure that the layers in the master grid coordinates, resolution and extent are specified when you calculate a raster data model for the first time in the workflow. This is done by setting the environment resolution, coordinates and extent to the master grid!

Use the standardized classification specified in the workflow!

Mean annual surface temperature

F.3.2. Mean annual temperature

F.3.2.1. Input data - mean annual surface temperature

General remarks

Ground Surface Temperature (GST) is defined as the surface or near-surface temperature of the ground (bedrock or surficial deposit), measured in the uppermost centimetres of the ground.

The surface air temperature (SAT) is measured 1 m above the surface, in shade, not affected by artificial influences.

The land surface temperature (LST) can be measured by satellites like the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. The thermal infrared signature received by satellite sensors is determined by surface temperature, surface emissivity/reflectivity, and atmospheric emission, absorption and scattering actions upon thermal radiation from the surface, and the solar radiation in daytime.

Description of workflow steps

For the design and calculation of geothermal closed loop systems, the information on the annual average ground surface temperature is necessary. Therefore, the temperature map provides important information for experts.

There are many climate web portals where data for the mean annual temperature might be available. Check these sources first!

This portal provides data for the whole of Europe: http://www.geodati.fmach.it/eurolst.html

It is derived from daily MODIS LST data for the period 2000 – 2013. The spatial resolution is 250 m, temperature resolution is 0.1 °C. There are annual mean temperatures as well as mean winter and summer temperatures (BIO1, BIO10 and BIO11). The data are free as long as the products derived also remain free (Open Database License).

Local data sources are:

Austria: Surface temperature map of Vienna

Czech Republic: http://portal.chmi.cz/historicka-data/pocasi/mapy-charakteristik-klimatu?l=en

Germany: https://www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html

Poland: http://klimat.pogodynka.pl/en/climate-maps/#Mean_Temperature/Monthly/2010/1/Winter

http://www.eumetsat.int/website/home/News/DAT_3312875.html

Slovakia: http://klimat.shmu.sk/kas/

Slovenia: http://gis.arso.gov.si/atlasokolja/profile.aspx?culture=en-US&id=Atlas_Okolja_AXL@ARSO

Land Surface Temperature: https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD_LSTD_CLIM_M

Make sure that you get a permit to present the temperature data on the web!

If you get map data produce a standardized output.

If you get temperature point data go to the interpolation step. Select and if necessary correct the data.

- If point GST data are available and representative for the pilot area, use this data and make spatial distribution of GST by interpolation.
- If point GST data are available but sparse, define a relation between GST and SAT. Since SAT (and GST) is usually dependent on altitude, use temperature correction for spatial distribution of SAT/GST values.
- If no GST measurements are available, use SAT (mean annual) values.

F.3.2.2. Interpolation by Kriging

General remarks

The surface temperature is a spatially continuous variable. Therefore, you can use interpolation methods to estimate the temperature in places where no measurement was performed. If a spatial covariance and continuity of the property is assumed, T(x) has values similar to the ones found in the neighbourhood. The spatial distribution of the temperature data may be characterized by anisotropies and trends. Therefore, geostatistical prediction methods are suitable, because they include all knowledge about the spatial distribution of the data.

Description of workflow steps

Spatial data analysis

Tools for spatial analysis

If we want to include much knowledge in the prediction model, we have to analyse the data set very carefully prior to performing an interpolation. Spatial data analysis comprises all techniques analysing the distribution of a property in space. Spatial data analysis is the fundamental step in geostatistical property interpolation since it provides the parameters that are used for the specification of the prediction model. In ArcGIS, spatial analysis can be performed with the Geostatistical analyst.

Start the geostatistical analyst with

Main menu → customize → Toolbars → select Geostatistical analyst

Geostatistical analyst toolbar → explore data

Aim of spatial analysis

Each data set has to fulfil modelling assumptions of the Kriging method applied for prediction. This means that, according to the results of the data analysis, you have to select the proper interpolation method:

- the mean is constant and known → simple Kriging,
- the mean is unknown and locally constant, the variability is constant → ordinary Kriging,
- an unknown trend exists → universal Kriging with a Trend model.

Trend analysis

A trend is a systematic change in the mean value (**Figure 52**). It can be described by a deterministic mathematical function. This means, the trend is fixed, and if you simulate data again and again, then the trend never changes. You do see fluctuations in the simulated surfaces due to the autocorrelated random errors. If a trend is present in the data set, you have to use universal Kriging; ordinary Kriging is not suitable.

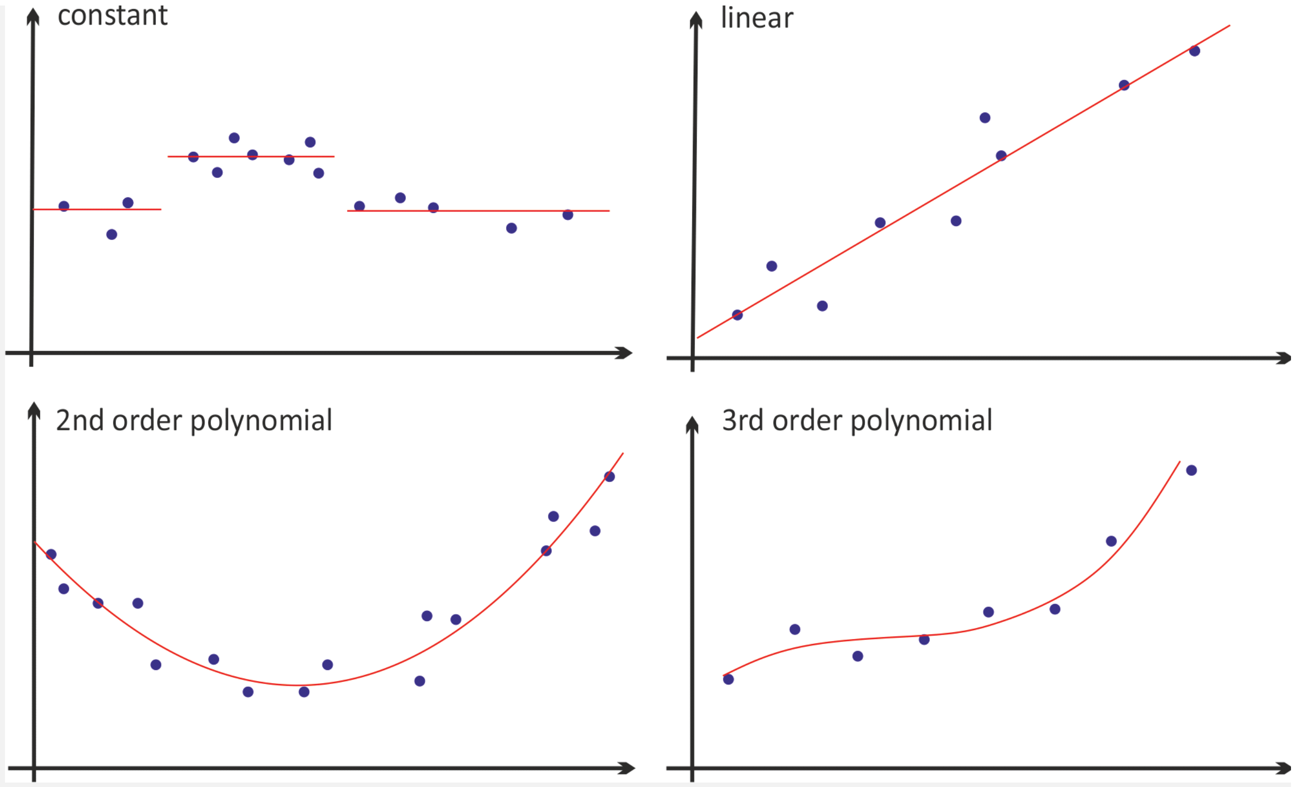


Figure 52: Examples for trend models.

Trend models

Geostatistical analyst → Explore data → Trend

Empirical variogram

The main instrument used for exploring spatial relationships between the data is the (semi)variogram.

Geostatistical analyst toolbar → Geostatistical wizard → Kriging/CoKriging

The variogram describes the degree of spatial dependence in a data set. It relates the variance of the difference in a property at pairs of sample points to the directed separation distance h between those pairs. This means, you take all pairs of data that have a similar distance and direction from each other. For most natural phenomena it is generally expected that the spatial variability increases as the length of h increases. The mean of all variabilities for one length of h gives one point in the empirical variogram.

The ArcGIS variogram (**Figure 53**) shows the variability of the data pairs (red). Due to computing limitations, if the input dataset has more than 5000 observations, Geostatistical Analyst will randomly select 5000 observations for the structural analysis and variogram model fitting (this provides about 12 million pairs of points). The resulting interpolated surface is usually not affected by the random sampling since all the data are used to generate the predicted values. The blue crosses show the mean variability for each h.

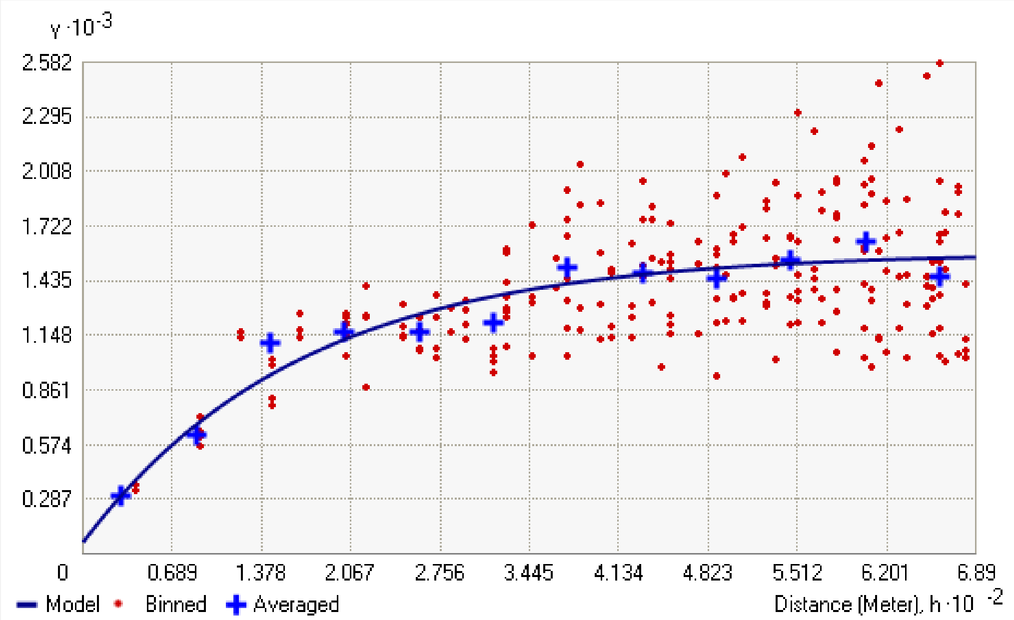


Figure 53: ArcGIS variogram.

The empirical variogram is used to read the parameters of the theoretical variogram. The parameters specifying an theoretical variogram function are:

- NUGGET EFFECT: Microvariability, the intercept in the theoretical variogram,
- RANGE: The distance to which spatial dependence can be determined,
- SILL: The variance of the data set outside of the range.

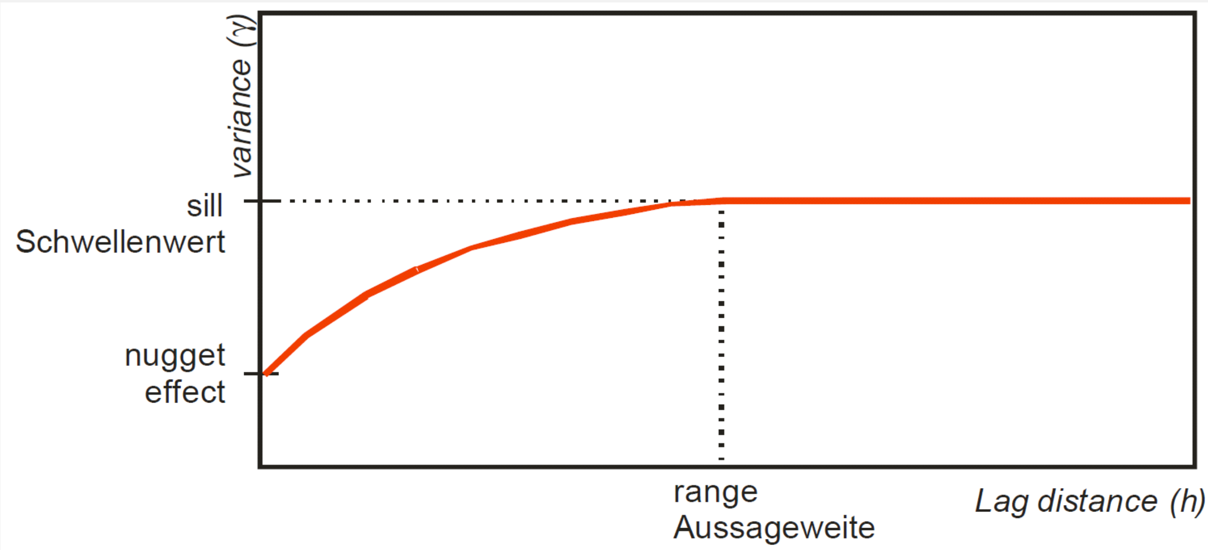


Figure 54: Parameters of a theoretical variogram.

Theoretical variogram

The theoretical variogram (**Figure 54**) allows calculating a variogram value for any distance h. The theoretical variogram contains all knowledge derived from the data and is the basis for the Kriging interpolation. Since every value in the variogram is a variance, it can never be negative. This is guaranteed by using a set of mathematically proven positive definite functions. Variogram modelling involves user decisions and is to some extent subjective. Parameters that are important for generating the theoretical variogram are:

- LAG SIZE: The lag distance defines the incremental distance at which the variogram is calculated. The lag size should be at least equal to the minimum sample spacing. On the other hand, it has to be several times smaller than the range, if this is to be displayed properly. Since the range is not known when starting a spatial data analysis, the lag size has to be changed and played with. As a rule of thumb, use a lag distance of half the diagonal of the data extent divided by 20.
- LAG NUMBER: Specifies the maximum number of length-steps; usually, a number >20 should be chosen in order to get enough data points for modelling the theoretical variogram.
- NUGGET EFFECT: Think whether there might be a nugget effect for the interpolated property. If so, read it from the empirical variogram.
- MODEL TYPE: The variogram model fitted to the empirical data should pass through the center of the cloud of binned values and pass as closely as possible to the averaged values (blue crosses).

The variogram model is displayed by a blue solid line. The model parameters are written at the bottom of the variogram.

Fit a variogram model by changing lag size and number!

Display the corresponding covariance model: General → Variable → Covariance

Anisotropy

Anisotropy is a directional dependency of a property. The range and sill can vary depending upon the direction, e.g. the direction of a valley or the aspect of a hill slope. This effect can be quantified by directional variograms. The anisotropic model reaches the sill more rapidly in some directions than others. The length of the longer axis to reach the sill is called the major range, the length of the shorter axis to reach the sill is called the minor range, and you also have the angle of rotation of the line that forms the major range.

The variogram map (**Figure 55Fehler! Verweisquelle konnte nicht gefunden werden.**) displays the variogram values as a surface. The color scale represents the calculated variogram value with lower values shown in blue and green and higher values shown in orange and red. The x-axis on the variogram graph is the distance from the center of the cell to the center of the variogram surface.

Explore the dissimilarity in data points for a certain direction with the Search Direction tool. This allows you to examine directional influences on the variogram chart. It does not affect the output surface:

Type a new Lag size value of 15000 reducing the lag size → change the Show search direction → true.

Note the reduction in the number of variogram values. Only those points in the direction of the search are shown in the graph.

View setting → search direction → true → drag the search direction tool (red pentangle)

As you change the direction of the search, note how the variogram graph changes. Only the variogram surface values within the direction of the search are plotted on the variogram graph above.

Include anisotropy in the variogram model

To actually account for the directional influences on the variogram model for the surface calculations, you must calculate the anisotropic variogram

Model#1 → anisotropy → change the anisotropy → true

The blue ellipse on the variogram surface indicates the range of the variogram in different directions. In this case, the major axis lies approximately in the NNW-SSE direction. Anisotropy will now be incorporated into the model to adjust for the directional influence of autocorrelation in the output surface.

View Settings → change the search direction angle from 0 to 61.35 to make the directional pointer coincide with the minor axis of the anisotropic ellipse

Note that the shape of the variogram curve increases more rapidly to its sill value.

View Settings → change the search direction angle under from 61.35 to 151.35 to make the directional pointer coincide with the major axis of the anisotropic ellipse

*Click **next** to apply the variogram model*

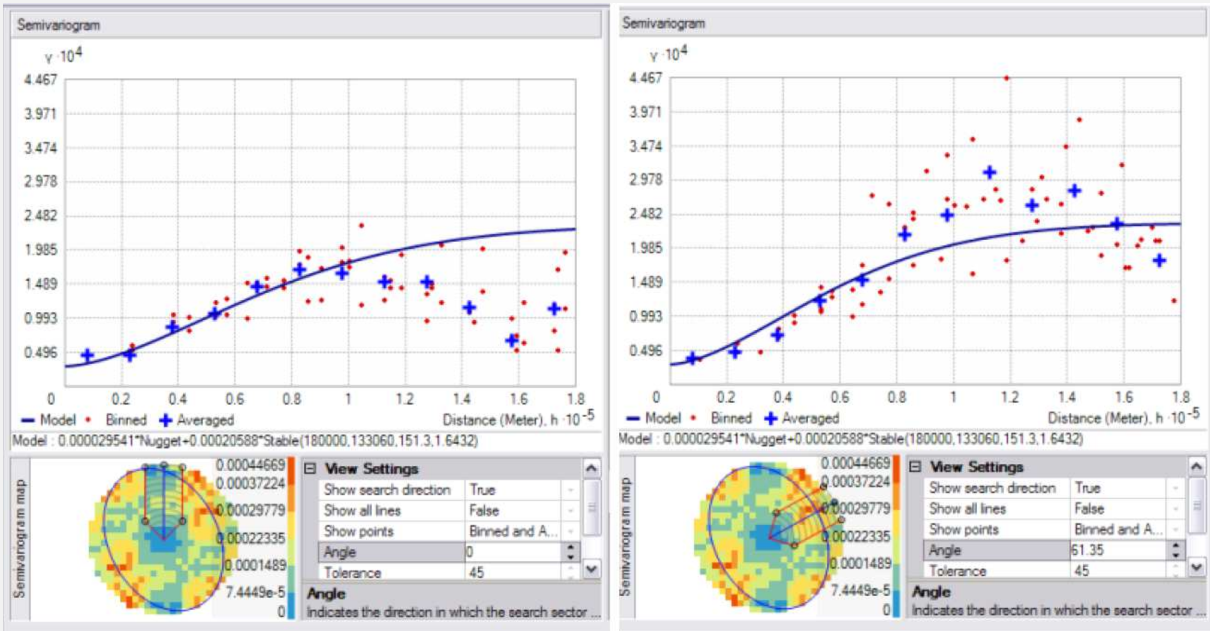


Figure 55: Variogram and variogram map.

Specify the search neighborhood

To predict a value, you can use the values at the measured locations. You know that the values of the closest measured locations are most alike to the value of the unmeasured location that you are trying to predict. It is common practice to limit the data included in the estimation by defining a circle (or ellipse) to enclose the points that predict a value at an unmeasured location. Additionally, to avoid bias in a particular direction, the circle can be divided into sectors from each of which an equal number of points is selected.

Click on the surface preview → select a prediction location → note the change in the selection of data locations

Weights → display the weights of the data → select a prediction location

Searching Neighborhood dialog box → specify the number of points (a maximum of 200) → specify the radius (or major/minor axis) → specify the number of sectors of the circle.

Use the default!

The points selected in the data view window indicate the weights that will be associated with each measured value to predict a value for the location marked by the crosshair. The larger the weight, the more impact that value will have on the prediction for the location at the crosshair.

Mean annual ground surface temperature – standardized output

F.3.2.3. Standardized output maps

General remarks

The standardized output of all maps is an **ESRI raster of the .adf file format**. The cell location and size has to be coincident with the master grid. The no-data value is specified with -9999.

In addition, a metadata table has to be completed.

Description of workflow steps

Take care to specify the layers in the master grid coordinates, resolution and extent when you calculate a raster data model in the workflow for the first time. This is done by setting the environment resolution, coordinates and extent to the master grid!

Reclassify the raster for the harmonized GeoPALSMA-CE output as specified in **Table 27**:

> *Spatial analyst toolbox → reclassify → reclassify → classify → 13 classes → specify the break points as listed in the table*

-9999	No data avaible	200 200 200	
1	<3	000 000 255	
2	3-4	000 102 255	
3	4-5	093 224 255	
4	5-6	068 234 179	
5	6-7	102 255 102	
6	7-8	204 255 153	
7	8-9	255 255 083	
8	9-10	255 255 153	
9	10-11	253 204 107	
10	11-12	252 174 057	
11	12-13	255 153 000	
12	13-14	253 098 049	
13	14-15	255 000 000	

Table 27: Standardized classification of the output.

G. Workflow for modelling the geothermal potential of open loop systems

G.1 The workflow – a brief description

Shallow geothermal open loop systems use groundwater for heating and/or cooling of buildings and domestic hot water. An open loop system consists of at least two wells. The extraction well pumps groundwater out of the aquifer, the water passes through the heat exchanger of a heat pump, or in case of free cooling through a heat exchanger not connected to a heat pump. In heating mode the water transfers its heat on to heat exchanger and it is injected back into the aquifer having a lower temperature via the second well. In cooling mode, the water absorbs heat in the heat exchanger and it is injected with a higher temperature. This creates so called temperature plumes (the warm or cold reinjected water), that spread downstream as shown in Figure 56.

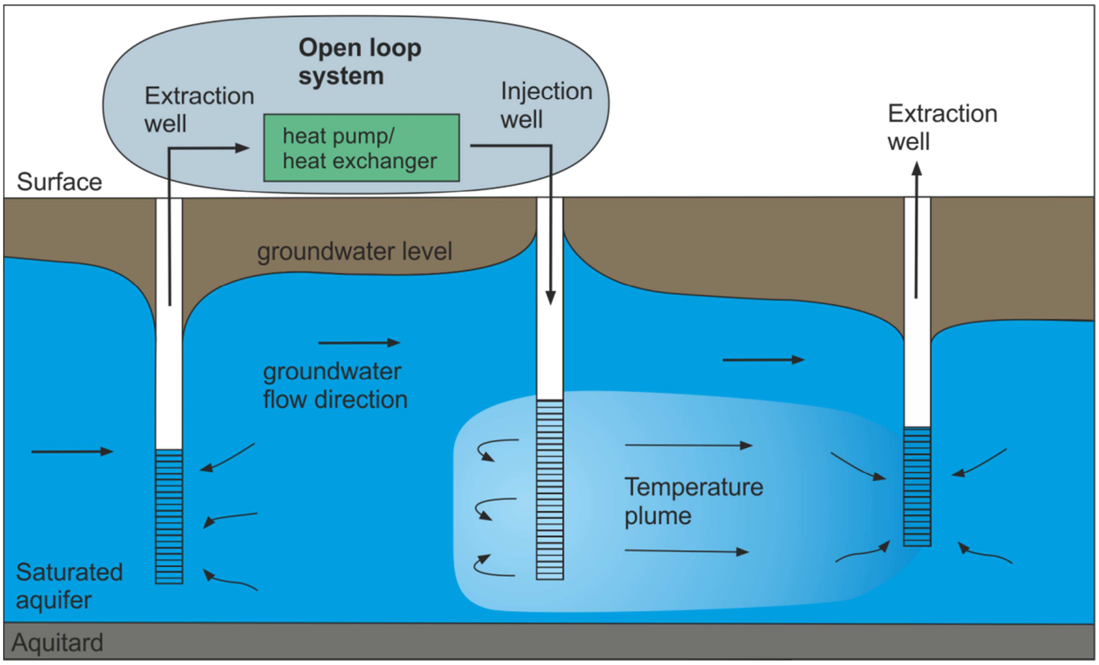


Figure 56: Impact of open loop systems on extraction wells located downstream.

Due to this operating principle, open loop systems can impact other already existing water extractions negatively or positively, depending on the operational mode of the application located downstream. An open loop system for heating upstream and one for cooling downstream results in a positive interference as well as a cooling system upstream and a heating system downstream. Two systems with the same operational mode, however, influence each other negatively. Until now in all GeoPLASMA-CE countries, each open loop system is treated separately in the licensing procedure following the principle “first come, first serve”. This process, however, neglects a sustainable use of the groundwater for heating and cooling. The strategies, which will be developed for the pilot areas (D.T4.2.3), and the general strategy to foster the use of shallow geothermal methods (D.T4.4.1) will include concepts for an integrative management of shallow geothermal use to overcome the “first come, first serve” principle. Geothermal potential maps provide the base for these strategies.

The geothermal potential of open loop systems depend mainly on the availability of groundwater. The natural groundwater temperature in Central Europe is usually in the temperature range which allows water to be used by heat pumps. However, in some areas, a low groundwater temperature can limit the use of open loop systems. In order to maintain the natural groundwater temperature to a certain degree, legal requirements have been established. These legal limitations of each pilot area will be included in the workflows. Due to this consideration the geothermal potential of open loop systems remains not solely scientific.The projects partners answered a survey about the legal requirements of open loop systems for D.T2.4.1. All surveys will be analysed in this deliverable and the outcomes fed into the workflows. However, not all parameters indicating the geothermal potential of open loop systems, include legal restraints. They are purely scientific, such as aquifer outline and hydraulic productivity. The parameters energy content and thermal capacity disregard the share of the heat pump and only indicate the geothermal energy. The following chapters describe workflows for all output parameters listed in Table 28. An Excel template to calculate the output parameters is provided separately.

Table 28: Output parameters indicating the geothermal potential of open loop systems.

	Description of output parameter	Unit	Publication
Aquifer outline	Overall availability of groundwater	-	Web Portal - all users
Thermal productivity	Groundwater temperature at representative day for maximum temperatures	°C	Web Portal - all users
	Groundwater temperature at representative day for minimum temperatures	°C	Web Portal - all users
	Qualitative overview of temperature shift available	-	Web Portal - all users
	Temperature shift available of well doublet for balanced use	ΔT	Web Portal - experts
	Temperature shift available of well doublet for unbalanced use (cooling)	ΔT	Web Portal - experts
	Temperature shift available of well doublet for unbalanced use (heating)	ΔT	Web Portal - experts
Energy content	Energy content available for balanced use	MWh/yr	Web Portal - all users
	Energy content available for unbalanced use	MWh/yr	Web Portal - all users
Hydraulic productivity	Available yield for open loop system at peak load	m^3/s	Web Portal - experts
	Available yield for open loop system at base load	m^3/s	Web Portal - experts
Thermal capacity	Available thermal capacity for open loop system at peak load	MW	Web Portal - all users
	Available thermal capacity for open loop system at base load	MW	Web Portal - all users

The preliminary work to elaborate the workflows was to analyse the workflow of existing projects about geothermal potential mapping. All projects were summarized in the synopsis D.T2.2.2. The most important findings of this study are now considered in the workflow. The workflow consists of analytical calculations and was harmonized as far as possible to be applicable in all pilot areas, although it includes enough space to adapt it to specific preconditions in the pilot areas. Therefore, different approaches are described for some parts of the workflow, where the project partners can choose, mostly depending on the input data available in their pilot areas. The potential calculation itself will be performed in ESRI ArcGIS (input data preparation) and Microsoft Excel (potential calculation), or other comparable software.

The workflows for each output parameter consist of the parts “General remarks”, “Input parameter and data preparation” and “Description of workflow steps”. In the first part general information about the elaboration of the output parameter is provided. The second part describes what input data is needed and how it has to be prepared to perform the calculations, which comprise the last part. All input data absolutely necessary are listed in black colour; and data not entirely necessary, but useful to substitute missing information, are marked in grey colour. All physical terms used in the workflow for open loop systems are listed in Table 30.

Pilot area specifics - General

All information specific for the pilot areas is described in this “pilot area specifics” box. The project partners will describe why they chose a specific approach in the explanatory notes of the potential maps. The explanatory notes will be available together with the potential maps on the GeoPLASMA-CE web portal.

According to a survey performed preliminary to the elaboration of these workflows, the responsible partners for the pilot areas decided to elaborate the geothermal potential parameters of open loop systems shown in Table 29. Except in pilot area Bratislava and Broumov/Wałbrzych, where the energy content is not planned to be calculated, in every other PA all parameters will be elaborated. All outcomes of Table 29 will be classified in data ranges and prepared as raster data set. This data set will later be implemented in the GeoPLASMA-CE web portal (A.T1.3).

Table 29: Planned output parameters for the pilot areas of GeoPLASMA-CE

Pilot area	Thermal capacity (kW)	Energy content (MWh/yr/ha)	Hydraulic productivity (l/s)	Thermal productivity (°C)
Vogtland / W-Bohemia				
Broumov / Wałbrzych				
Krakow	x	x	x	x
Vienna	x	x	x	x
Bratislava	x		x	x
Ljubljana	x	x	x	x

The workflow has already been validated for the city quarter "Berres-Podhagskygasse" in the pilot area Vienna with a numerical model developed in FEFLOW. A recovery factor was determined via a comparison of the energy content calculated with the workflow described in this report and the energy content, which can be withdrawn from the aquifer according to the outcomes of the numerical simulations. This recovery factor is implemented in the workflow to calculate the energy content. The validation procedure is described in the last section of this workflow for other pilot areas, where a validation can be conducted.

Pilot area specifics

The partners calculating the energy content in other pilot areas are encouraged to test the workflows as well and determine the recovery factor, which might be different in their pilot areas. FEFLOW is a suitable software for the validation, however other programmes for numerical simulations can be used as well.

Table 30: Physical terms used in the workflow for open loop systems

Symbol	Physical term	Unit
a	Thermal difussivity of aquitard	m^2/s
A	Size of calculation area	m^2
c_{vA}	Volumetric heat capacity of saturated aquifer	$MJ/m^3/K$
c_{vB}	Volumetric heat capacity aquitard	$MJ/m^3/K$
c_{vw}	Volumetric heat capacity of water	$MJ/m^3/K$
E_1	Energy content available in calculation area for balanced use of open loop system	MWh/yr
E_2	Energy content available in calculation area for unbalanced use of open loop system	MWh/yr
$E_{storage}$	Energy content stored in the aquifer	MWh/yr
$E_{surface}$	Energy recharge of the aquifer from the surface	MWh/yr
$E_{underground}$	Energy recharge of the aquifer from the underlying aquitard	MWh/yr
E_{tot_an}	Energy content available after 20 years based on analytical calculation	MJ
E_{tot_mod}	Energy content available after 20 years based on simulation	MJ
$E_{welldoublet}$	Energy content available per well doublet according to simulation results for 20 years	MJ
GD_m	Mean groundwater depth in the calculation area	m
H	Hydraulic head in a confined aquifer	m
kf	Coefficient of hydraulic conductivity	m/s
LT	Life time of open loop system	yr
P_1	Thermal capacity at peak load	MW

Symbol	Physical term	Unit
P_2	Thermal capacity at base load	MW
Q_1	Maximum yield available at peak load for unconfined aquifers	m^3/s
Q_2	Maximum yield available at peak load for confined aquifers	m^3/s
Q_3	Maximum yield available at base load	m^3/s
Q_{val_b}	Yield available for constant use in balanced operational mode	m^3/s
Q_{val_ub}	Yield available for constant use in unbalanced operational mode	m^3/s
q10	Heat flow density from aquitard in x meters distance and after ten years	-
R	Hydraulic range of influence of a well	m
rf	Recovery factor	-
SZ_m	Mean thickness of saturated zone in the calculation area	m
ΔT	Temperature shift between the extraction and the injection well	K
$\Delta T_{heating}$	Temperature shift available for heating	K
$\Delta T_{cooling}$	Temperature shift available for cooling	K
$\Delta T_{overview}$	Qualitative temperature shift for heating and/or cooling	-
ΔT_{val_i}	Temperature shift available according to modelling results	K
T_{inj}	Temperature of injected water	°C
T_{max}	Maximum temperature measured	°C
T_{min}	Minimum temperature measured	°C
T_{nat}	Undisturbed groundwater temperature at well location	°C
t_i	Time step of simulation	s
t_{yr}	Hours of one year	h
t_{op}	Operational hours of an open loop system per year	h
x	Distance from aquifer to aquitard, where the heat flow density (q10) is calculated	m
λ_{Bott}	Thermal conductivity of aquitard	W/m/K
λ_{OB}	Thermal conductivity of overburden	W/m/K

The following points give an overview of the workflow steps:

1. Documentation of the project

2. Aquifer Outline

Input data

Hydrogeological map

Geological map

Geological cross sections

Hydrogeological mapping

Processing of the input data

Definition of aquifer outline

Split aquifer into smaller areas for further calculations

3. Thermal productivity

Input data

Groundwater temperatures

Legal requirements or other constraints for temperature shift

Processing of the input data

Format groundwater temperature data

Statistical analysis – extract dates with min and max temperatures

Determine min and max groundwater temperatures

Interpolation

Create maps for min and max groundwater temperatures

Create temperature shift maps for heating, cooling, and balanced use

Processing of temperature shift maps

Assign thermal productivity indicator

Standardized output

Create overview map with 5 categories for thermal productivity

4. Energy content

Input data

Optional: Numerical model including all existing open loop systems

Determine size of calculation area in ArcGIS

DEM

Mean groundwater level

Depth to groundwater

Aquitard depth

Temperature shift maps

Volumetric heat capacity of aquifer

Thermal conductivity of overburden

Processing of the input data

Interpolate mean groundwater level and create map

Calculate mean thickness of saturated zone from aquitard elevation and mean water table

Calculate Energy content

Calculate energy content available for balanced use

Calculate energy content available for unbalanced use

5. Hydraulic productivity

Input data

Hydraulic conductivity

Map of mean groundwater level

Map of aquifer thickness derived from depth of aquitard and DEM

Map of mean thickness of saturated zone

Temperature shift map for balanced use

Maximum licensed pumping rate

Calculation

Calculate hydraulic productivity at peak load

Validation

Compare licensed pumping rates with maximum yield

Calculation

Calculate hydraulic productivity at base load

6. Thermal capacity

Input data

Maximum hydraulic productivity

Thermal productivity

Energy content available for unbalanced use

Calculation

Thermal capacity at peak load

Thermal capacity at base load

7. Workflow validation

Prepare input data

Calculate validation yield

Create well layer and locate wells in ArcGIS

Prepare well table

Assign yields for balanced and unbalanced use

Construct numerical model

Develop 3D model in FEFLOW or comparable software

Use same parameters as in calculation of validation yield above

Import well layer into FEFLOW

Transform into multi-layer wells and assign information

Set temperature boundary conditions

Run simulation

Compare modelled and analytically calculated energy content

Export FEFLOW chart to EXCEL

Calculate temperature shift for each time step of the simulation

Calculate energy content for each well

Calculate total energy content for the calculation area

Calculate recovery factor

G.2 Rules and mandatory specifications - checklist

Spatial reference system	ETRS1989-TM 33 / ETRS1989-TM 34 meters → See D.T2.3.1 for specification
Elevation reference system	EVRF2007 → See D.T2.3.1 for specification
Geometry data	Standardized output of the 3D model
Transfer the raster data to the master grid	Grid resolution: 12.5, 25 or 50 m Borders of the grid cells at (00,00) coordinates
Export data format of all raster data	.adf -ESRI grid
Thermal productivity	Five categories as per table Table 33
Completed metadata table	Metadata table for each map
Project documentation	Table for the documentation of the project progress →See D.T2.3.1 for specification

G.3 Tool kit for the specification of the geothermal potential of open loop systems

Aquifer outline – input parameters and data preparation

G.3.1. Aquifer outline

G.3.1.1. Input data and data preparation

General remarks

The most important requirement to determine the geothermal potential for open loop systems, is the availability of a potent aquifer. Therefore, the first step of the workflow is to delimit the outline of the aquifer. This outline shows where sufficient groundwater is available for open loop systems. All other geothermal potential parameters will be calculated in this area.

Description of workflow steps

- Hydrogeological map
- Geological map
- Geological cross sections
- Hydrogeological mapping

Hydrogeological, geological maps and geological cross sections in addition to hydrogeological experience in the pilot area are necessary input data to delimit the aquifer. Since the scale of the input map also determines the minimum scale of the output maps, it is important to use input maps with the scale of the output map wanted. Geological cross sections provide detailed information about the overall thickness of the aquifer and the overburden thickness, which can influence the delimitation.

Hydrogeological mapping can be conducted to gain missing information and complement existing maps and cross section.

G.3.1.2. Definitions and calculations

General remarks

Based on hydrogeological and geological maps the expert of hydrogeology in the pilot area delimits a suitable aquifer. The definition of a suitable aquifer can be different in the pilot areas.

Description of workflow steps

The following aspects should be considered in the process of delimitation of the aquifer outline, depending on their importance in the pilot areas.

Hydrogeological aspects

- Sufficient yield or natural recharge available in the aquifer
- Maximum overburden thickness
- Uppermost groundwater body with mostly phreatic behaviour
- Zones reserved for drinking water supply

Non geoscientific aspects

- Areas dedicated to permanent settlement
- Urban- or industrial land use

Definition of areas for further calculations

The following parameters will be calculated for small areas, in the following referred to as “calculation areas”, within the aquifer. Hence, the aquifer has to be split. This separation can be performed based on city quarters, construction fields, raster cells or hydrogeological homogenous areas.

Pilot area specifics

The selection of the unit, on which the division of the aquifer will be performed, can be different in the pilot areas. It strongly depends on the available input data and the requirements in the pilot area. For the regional potentials city quarters might be sufficient in order to avoid long calculation times. For local small scale pilot areas in urban development areas, it might be useful to divide the pilot area into construction fields. If no information about construction fields area available, the more preferable way would be to use raster cells. Other possible units are hydrogeological homogenous areas.

G.3.2. Thermal productivity

G.3.2.1. Input data and data preparation

General remarks

As outputs of the thermal productivity two groundwater temperature maps will be prepared and three maps indicating the temperature shift available between extraction and injection well. The first output provides a general overview of the minimum and maximum groundwater temperatures and remains purely scientific. However, particular legal requirements also influence the temperature shift available per well doublet. Hence, they will be included in the maps showing the temperature shift available. These maps combine information about the groundwater temperature and legal requirements. A survey conducted for D.T2.4.1 revealed different legal situations in the pilot areas. It is recommended to follow the harmonized approach, if no other regulations apply. Legal requirements have to be considered, if these limitations about groundwater temperature are stricter, than in the approach.

In the following approach selected for this workflow, the temperature of the reinjected groundwater is limited to a minimum of 5 °C and a maximum of 18 °C. A maximum temperature shift *[ΔT]* between extraction and injection well of 5 K can be considered in the calculations. These boundary conditions have been chosen based on existing guidelines (German VDI4640-1 and Austrian OEWAV 207) and considerations about how to ensure a sustainable use of groundwater.

The minimum and maximum groundwater temperature determined for the temperature map in combination with the minimum and maximum reinjection temperature might limit the temperature shift. This means, that the groundwater temperature has to be in the range of 10 °C and 13 °C in order to enable a maximum use of 5 K temperature shift. The temperature shift is lower in areas with lower or higher groundwater temperatures and it also might vary depending on the operational mode. To cover all scenarios, three quantitative maps will be developed (Table 31).

Table 31: Quantitative outputs of the thermal productivity

Operational mode	Temperature shift displayed on map	Publication
Balanced use	Minimum value of shift available for heating and cooling	Open to expert users of GeoPLASMA-CE web portal
Unbalanced use	Heating	Open to expert users of GeoPLASMA-CE web portal
Unbalanced use	Cooling	Open to expert users of GeoPLASMA-CE web portal

An overview map displays areas where heating, cooling or both modes are restricted and where the entire legally allowed temperature shift is available. Depending on the groundwater temperature, it is possible, that one operational mode is more restricted than the other. This information will be displayed qualitatively for all users of the GeoPLASMA-CE web portal. The quantitative versions of the temperature shift will be included in the calculations for energy content, thermal capacity and hydraulic productivity. In order to avoid a large number of potential maps, both maps covering the temperature shift for unbalanced use will be published on the GeoPLASMA-CE web portal for expert users, but will be disregarded in further potential calculations. Otherwise the potential maps for energy content, thermal capacity and hydraulic productivity would have to be elaborated separately for heating and cooling as well.

Pilot area specifics

It was decided to only use the temperature shift for balanced use in all further potential calculations, to avoid a large amount of potential maps. However, if the thermal productivity shows significant differences for heating and cooling in a pilot area, it should be considered for unbalanced use to elaborate outputs separately for heating and cooling. This decision has to be made based on the outcomes of the thermal productivity for heating and cooling.

Description of workflow steps

Groundwater temperature data

The successful development of a groundwater temperature map depends on the availability of temperature data. The groundwater is measured in observation wells, either at a single depth or at multiple depths. In case of multiple depths, a large amount of data is gathered and the data preparation is time consuming. The best way to prepare the data for analysis is the following data format, shown in Table 32. Microsoft Access can be a helpful tool to semi automatically bring the data in the desired format.

Table 32: Example of data format suitable for groundwater (GW) temperature analyses

Name of observation well	Date	Time	GW level	Measuring depth	Depth below GW level	GW temperature
Test well	dd. mm. yyyy	hh:mm	Depth of GW level below top of observation well [cm]	Depth below top of observation well at which GW temp. was measured [cm]	Depth of temperature measurement minus depth to GW level [cm]	GW temperature at measuring depth [°C]

Air temperature data

In pilot areas with low data density, air temperature data and groundwater temperature can be used to calibrate numerical models and elaborate groundwater temperature maps.

Data analysis

When the data is in a format to prepare analyses of the temperatures quickly, as an example is shown in Table 32, statistical calculations are performed using Microsoft Access, Microsoft Excel or another suitable software. The dates with a minimum and maximum temperature in most observation wells has to be found. For these two representative days the temperature map will be determined.

G.3.2.2. Elaborations of temperature maps

General remarks

The minimum and maximum groundwater temperature is determined for the temperature map in combination with the minimum and maximum reinjection temperature.

Description of workflow steps

The temperatures of the representative days are plotted in ArcGIS. The data is interpolated for each calculation area using an automatic interpolation method or manual interpretation of the data, depending on the data density. In case of a high data density, an interpolation method provided by ArcGIS can be used. "Topo to Raster" has been identified as most suitable method. However one disadvantage of this triangulation method is, that the interpolation is only conducted within the area covered by temperature measurements. To get a temperature map covering the entire pilot area, data outside of the pilot area has to be available as well. "Kriging" has been identified as the second most applicable interpolation method.

Otherwise an interpretation of the spatial distribution of the groundwater including information about the catchment area might be more suitable. Information about the watershed helps to interpret the temperature data and identify areas with an anthropogenic disturbed groundwater temperature. This is of great importance in urban areas. In both cases the temperature data will be shown on the map in data classes with a range of at least 1 K.

Pilot area specific alternative for the elaboration of groundwater temperature maps

In pilot areas with a general low data density, it might not be possible to derive a groundwater temperature map. An alternate way to determine the spatial distribution of the groundwater temperature is to use temperature data available from air and groundwater. In a 3D numerical simulation (e.g. with FEFLOW), the air temperature is set as boundary condition and the model is calibrated with existing groundwater temperature data.

In the case of even less temperature data, the mean annual groundwater temperature derived from all available observation wells can be determined. It can be obtained from showing the data on a map, instead the information will be included in the location specific queries. One mean value for the groundwater temperature shows a significant inaccuracy. If possible, it is recommended to determine mean annual groundwater temperatures for different homogenous areas of the aquifer.

G.3.2.3. Elaboration of temperature shift maps

General remarks

The temperature shift maps specify the temperature change between extraction and injection well.

As a first step a temperature shift *(ΔT)* between extraction and injection well, and a temperature range for the reinjection well have to be identified, which are in accordance with legal requirements. If no legal limitations apply, a temperature shift of 5 K, and a temperature range of 5 °C to 18 °C are recommended.

Pilot area specifics - Legal requirements for the thermal productivity

The partner survey performed for D.T2.4.1 revealed the following requirements for the temperature shift and the temperature range for reinjection. The specific requirements in the countries stated below are either legally binding or suggestions included in guidelines.

	Country / State	ΔT [K]	Temp-range for reinjection [°C]
Austria	Vienna	6	5 - 18
	Burgenland	3 - 5	5 - 20
	Lower Austria	6	5 - 20
	Poland	3 - 5	< 35
	Germany	6	< 20
	Slovenia	Not regulated	
	Slovakia	Not regulated	
	Czech Republic	Not part of any legal act, but in construction plan, authority has to approve it	

Description of workflow steps

Elaborate temperature shift map - for unbalanced use (cooling)

To determine the temperature shift available for cooling, the maximum groundwater temperature in the calculation area is subtracted from the upper temperature boundary for reinjection (18 °C if no stricter legal requirements apply). If the calculated temperature shift is larger than the maximum temperature shift allowed (5 K if no stricter legal requirements apply), the maximum temperature shift allowed is assigned.

This can be calculated, as shown in Eq. 1 for the default boundary conditions described above, easily in Microsoft Excel with an if-clause for each calculation area:

$$\Delta T_{cooling} = if(18 - T_{max} > 5; 5; 18 - T_{max}) \quad \text{Eq. 1}$$

Elaborate temperature shift map - for unbalanced use (heating)

To determine the temperature shift available for cooling, the lower temperature boundary for reinjection (5°C if no stricter legal requirements apply) is subtracted from the minimum groundwater temperature in the calculation area. If the calculated temperature shift is larger than the maximum temperature shift allowed (5 K if no stricter legal requirements apply), the maximum temperature shift allowed (5K) is assigned.

This can be calculated, as shown in Eq. 2 for the default boundary conditions described above, easily in Microsoft Excel with an if-clause for each calculation area:

$$\Delta T_{heating} = if\,(T_{min} - 5 > 5; 5; T_{min} - 5) \quad \text{Eq. 2}$$

Elaborate temperature shift map - for balanced use

The temperature shift map for balanced use combines the temperature shifts for both heating and cooling. The minimum shift available of both operational modes determines the temperature shift for both heating and cooling.

This can be calculated, as shown in Eq. 3 for the default boundary conditions described above, easily in Microsoft Excel with the minimum-function for each calculation area:

$$\Delta T_{balanced} = min(5;\ 18 - T_{max}, T_{min} - 5) \quad \text{Eq. 3}$$

The temperature shift will be shown on the map in data classes with a range of at least 1 K on the GeoPLASMA-CE web portal for expert users.

Elaborate overview map

The overview map displays where use for heating or cooling is more strongly restricted than the other operational mode ($\Delta T_{overview}$), where both are restricted the same and where the entire temperature shift legally allowed is available. This is achieved in Microsoft Excel, where the temperature shift for heating and cooling are listed in two separate columns. In the third column the when-clause of Eq. 4 has to be implemented:

$$\Delta T_{overview} = WHEN(AND(\Delta T_{heating} < 5; \Delta T_{cooling} < 5); 2 \cdot SIGN\left((\Delta T_{cooling} - \Delta T_{heating}) + 0.0000001\right); WHEN(OR(\Delta T_{heating} < 5; \Delta T_{cooling} < 5); SIGN(\Delta T_{cooling} - \Delta T_{heating}); 0)) \quad \text{Eq. 4}$$

“5” can be substituted with the legally allowed temperature shift between injection and extraction well [K].

The results of this function symbolize the following:

Table 33: Legend of overview map about thermal productivity

Label	Description
0	NO temperature boundary violated
1	ONLY heating boundary violated
-1	ONLY cooling boundary violated
2	BOTH boundaries violated, but heating boundary more violated (or violated the same amount)
-2	BOTH boundaries violated, but cooling boundary more violated

G.3.3. Energy content

G.3.3.1. Input data and data preparation

General remarks

The energy content available depends on the operational mode of the open loop system. For a balanced use where the same amount is used for heating and for cooling, more energy is available, due to the forced recovery of the groundwater temperature. If the open loop system operates unbalanced, the groundwater temperature cannot recover, the impact on the aquifer is stronger and hence less energy is available for a sustainable use. Therefore, the energy content will be calculated for both operational modes analytically.

Figure 57 shows the theoretical background of the calculation method of the energy content. In case of a balanced use, it is assumed, that the entire saturated aquifer below each calculation area can be cooled down and warmed up of 5 K. Due to the balanced operational mode, the annual mean temperature of the aquifer remains the same and no heat flows into the aquifer from outside. The annually available energy for balanced use equals the energy stored in the saturated aquifer ($E_{storage}$). In case of an unbalanced use, the aquifer can be warmed up or cooled down of a specific temperature range in the entire operational life time (LT), which changes the mean annual aquifer temperature. The thermal productivity described in chapter thermal productivity, represents the temperature shift available for each calculation area. This temperature difference between the aquifer and its surroundings leads to a heat flow from the surface ($E_{surface}$) and from the underground ($E_{underground}$) into the aquifer. Both heat flows from the top layer and below recharge the saturated aquifer to a certain degree. This recharge is considered in the calculations for the energy content for unbalanced use. Due to technical limitations and mutual interferences of wells it is not possible to extract the entire energy calculated. The recovery factor (rf) takes these limitations into account. A default value for the recovery factor can be used for pilot areas, where the recovery factor cannot be determined in a validation procedure. The default value is derived from the validation performed for the pilot area Vienna for unbalanced use. Since the dependency of the recovery factor on aquifer parameters (depth to groundwater, aquifer thickness) is unknown, a more conservative estimate is recommended as default value. The recovery factor was determined only for the energy content of balanced use for this first version of the workflows. Until further evaluation it is assumed, that the recovery factor for unbalanced use equals the one for balanced use.

The results of the energy content for unbalanced use will then be used to determine the maximum hydraulic productivity and maximum thermal capacity for each calculation area.

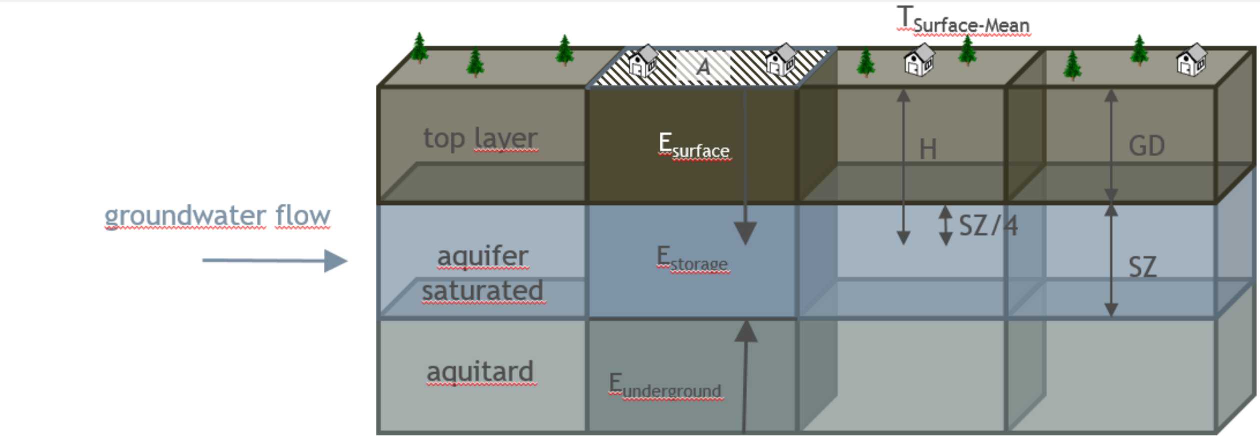


Figure 57: Energy content for balanced use: $E_{storage}$. Energy content available for balanced use: $E_{surface}$ + $E_{underground}$ + $E_{storage}$

In the calculation of the energy content, it is possible to consider already existing open loop systems. All energy consumed annually by existing systems for one calculation area is subtracted from the available energy at the respective area. However, in order to subtract the energy already spent from the actually affected area, the impact of the existing applications on the groundwater has to be known. This can only be determined with numerical modelling (e.g. with FEFLOW). In small local study areas, this is a feasible approach. In the city quarter "Berres-Podhagskygasse" of the pilot area Vienna, which was used for validating the workflow, it would be possible to include existing open loop systems. However, for the entire pilot areas it is not considered to be feasible, since this is a very time consuming operation.

Pilot area specifics- Existing open loop systems

Whether existing open loop systems are included in the calculations for the energy content, has to be decided for each pilot area. First, it depends on the availability of a numerical 3D model in the pilot area. This is necessary to consider cumulative effects of existing users. Furthermore, in pilot areas with a large amount of existing users, it might not be feasible to implement them in a numerical model, since this is a very time consuming procedure.

Input parameters

- Size of calculation area

The size of the calculation area (*A*) is determined in ArcGIS. All calculation areas have to be available in one shapefile. In a new field for the size of the calculation area, choose "size" in "calculate geometry". This function will automatically determine the size of each calculation area.

- Digital elevation model

A map of the digital elevation model is needed for the calculation of the depth to groundwater.

- Mean groundwater level

A map of the mean groundwater level is derived from groundwater level measurements of one representative day with a mean level of a certain time period. With a suitable interpolation method (Topo to raster or kriging), the spatial distribution of the groundwater level is calculated from the data of the observation wells.

- Groundwater depth

The mean groundwater depth *DG* [m] of each calculation area is determined in ArcGIS. At first a map of the groundwater depth is derived by subtracting the mean groundwater level from the digital elevation model. From this map the mean groundwater depth of each calculation area is established using the tool "zonal statistics as table".

- Mean thickness of saturated zone

A map of the thickness of the saturated zone is developed through the subtraction of the elevation of the aquitard from the mean water table of the calculation area in ArcGIS. From this map the mean thickness of the saturated zone for each calculation area is established using the tool "zonal statistics as table".

- Thermal productivity

The temperature shift ΔT [K] available for each calculation area developed in chapter Thermal productivity will be used to calculate the energy content.

- Volumetric heat capacity of aquifer

A mean value of the volumetric heat capacity of the aquifer c_{vA} [MJ/m^3/K] is considered applicable for this calculation. A look up table of the values for the most common porous aquifers is provided in the German guideline VDI 4640-1 (available in English).

- Thermal conductivity of overburden

A mean value of the thermal conductivity of the overlying units on top of the aquifer λ_{OB} [W/m/K] is considered applicable for the calculations. A look up table of the values for overburden is provided in VDI 4640-1.

G.3.3.2. Calculation of the energy content

General remarks

The evaluation of the energy content is performed for each calculation area. A suitable tool for little time consuming calculations is Microsoft Excel. The workflow steps are explained separately for balanced and unbalanced use.

Description of workflow steps

Energy content available for balanced use

The energy stored in the saturated aquifer ($E_{storage}$) depends on the following parameters and is calculated using Eq. 5:

c_{vA}	Volumetric heat capacity of the saturated aquifer [MJ/m³/K]
A	Size of the calculation area [m²]
SZm	Mean thickness of the saturated zone in the calculation area
ΔT	Maximum change of temperature of the aquifer for balanced use. Default value: 5 K.
rf	recovery factor. Default value: 0.75

$$E_1\,[MWh/yr] = E_{storage} = \frac{C_{VA} \cdot A \cdot GWm \cdot \Delta T}{3600} \cdot rf \qquad \text{Eq. 5}$$

Energy content available for unbalanced use

Aside from the energy stored in the saturated aquifer ($E_{storage}$) from Eq. 5, the energy content for unbalanced use includes heat flow from the surface ($E_{surface}$ in Eq. 7) and the underground ($E_{underground}$ in Eq. 8 and Eq. 9). For unbalanced use, $E_{storage}$ is available for the entire life time (*LT*) of an open loop system, which is set to 20 years in this workflow.

The heat flow from the surroundings ($E_{surface}$ in Eq. 7 and $E_{underground}$ in Eq. 8 and Eq. 9) depends on the following parameters:

λ_{OB}	Thermal conductivity of overburden [W/m/K]
A	Size of the calculation area [m²]
ΔT	Maximum change of temperature in the aquifer for unbalanced use. Default value: 5 K
GDm	Mean groundwater depth in the calculation area [m]
SZm	Mean thickness of saturated zone in the calculation area [m]
q10	Heat flow density from aquitard in x meters distance and after t = 10 years [-]
x	Distance from aquifer to aquitard, where the heat flow density is calculated [m]

a	Thermal diffussivity of aquitard [m²/s] (λ_{Bott}/c_{vB}/1000000)
λ_{Bott}	Thermal conductivity of aquitard [W/m/K]
c_{vB}	Volumetric heat capacity of aquitard [MJ/m³/K]
rf	recovery factor. Default value: 0.75

$$E_2\ [MWh/yr] = (\frac{E_{storage}}{LT} + E_{surface} + E_{underground}) \cdot rf \quad \text{Eq. 6}$$

$$E_{surface}[MWh/yr] = \frac{\lambda_{OB} \cdot A \cdot \Delta T}{GDm + SZm/4} \cdot 8760\ h \quad \text{Eq. 7}$$

$$E_{underground}[MWh/yr] = q_{10} \cdot A \cdot \Delta T \cdot 8760\ h \quad \text{Eq. 8}$$

$$q_{10} = erfc\left(\frac{x}{2\sqrt{a \cdot t}}\right) \quad \text{Eq. 9}$$

A template to calculate *q10* in Eq. 9 is included in Annex 13 to this workflow.

G.3.4. Hydraulic productivity

G.3.4.1. Input parameters and data preparation

General remarks

The hydraulic productivity determines the maximum yield of a doublet in m^3/s. In this workflow it is calculated at peak power and at base load of the open loop system. For the visualisation of the hydraulic productivity as a layer for the expert users of the GeoPLASMA-CE web portal, it was decided to show the results of both operational settings. The maximum yield at peak power ($Q_{1,max}$ for unconfined and $Q_{2,max}$ for confined aquifers) depends on the properties of the aquifer and is therefore independent from the size of the calculation area. It represents the overall maximum yield available in the aquifer. In strongly confined aquifers, difficulties for the injection might arise. The calculation of the maximum yield disregards this case and the possibility of injection has to be investigated separately for each aquifer. The maximum yield at base load ($Q_{3,max}$) is derived from the energy content available for unbalanced use. As shown in Figure 58, there is a strong connection between energy content and yield (and thermal capacity). At peak load the maximum yield is available only for short times during the operation of the open loop system. The maximum yield at base load represents the yield available during the entire annual time of operation. One operational year is considered to contain 2400 hours of operation.

The maximum yield at peak power depends on the aquifer properties and is calculated based on Thiem's[1] well equation for unconfined aquifers and on Dupuit's[2] well equation for confined aquifers. Adaption of both approaches were developed for this workflow, with the well radius set to 1 m and the hydraulic range (R) calculated after Sichardt[3]. In order to ensure a sustainable use of the groundwater, the maximum draw down is set to 1/3 of the saturated zone for unconfined aquifers or the hydraulic head for confined aquifers respectively.

Input parameters

- Hydraulic conductivity

Sources for the hydraulic conductivity are pumping tests and 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.

If it is possible to gather more data and the hydraulic conductivities are known to vary in the pilot area, a data base of hydraulic conductivities should be established. A map showing the spatial

[1] Thiem, G. (1906): Hydrologische Methoden. Gebhardt, Leipzig.

[2] Dupuit, A.J. (1863): Etudes théorétiques et practiques sur le mouvement des eaux à travers les terrains permeables. 2nd edition, Dunod, Paris.

[3] Sichardt, W. (1928): Das Fassungsvermögen von Rohrbrunnen und seine Bedeutung für die Grundwasserabsenkung, insbesondere für größere Absenkungstiefen. Springer, Berlin.

distribution of hydraulic conductivities can be derived, based on the results of pumping tests and sieving grain analyses.

- Map of mean groundwater level

A map of the mean groundwater level is derived from groundwater level measurements of one representative day with a mean level of a certain time period. With a suitable interpolation method, the spatial distribution of the groundwater level is calculated from the data of the observation wells.

- Map of aquifer thickness

The aquifer thickness equals the distance between the bottom of the units overlying the aquifer and the top of the aquitard below the aquifer. The map of the aquifer thickness is therefore derived from the maps showing the elevation of the overburden and the aquitard.

- Mean thickness of saturated zone

A map of thickness of the saturated zone for unconfined conditions is developed through the subtraction of the elevation of the aquitard from the mean water table of the calculation area in ArcGIS using the tool "zonal statistics as table". The thickness of the saturated zone for confined conditions has to be derived from the maps showing the elevation of overburden and aquitard. In this case the map of aquifer thickness equals the thickness of the saturated zone.

- Map of mean hydraulic head

The hydraulic head in confined aquifers is determined from hydraulic head measurements, which are similar to the measurements of the groundwater level in unconfined aquifers. The map is derived also from measurements of one representative day with a mean head of a certain time period. With a suitable interpolation method, the spatial distribution of the groundwater level is calculated from the data of the observation wells.

- Thermal productivity

The temperature shift ΔT [K] available for balanced use developed in chapter G.3.2 Thermal productivity will be used to calculate the energy content.

- Licensed pumping rates

The maximum licensed pumping rates can be used for validating the hydraulic productivity.

G.3.4.2. Calculation of the hydraulic productivity at peak and base load

Pilot area specifics

For aquifers with a high thickness of the saturated zone, a drawdown of 1/3 might lead to an unreasonably high potential, which might require deep wells and therefore high investment costs. To display a more accessible potential, it is suggested to limit the hydraulic productivity to 100 l/s in pilot areas, where this might be the case.

In pilot areas, where there is not sufficient data available to calculate the maximum yield, it is suggested to estimate the maximum yield with the help of licensed pumping rates. They indicate a minimum of the yield available for homogenous areas.

Description of workflow steps

Calculation of the hydraulic productivity at peak load for unconfined (Q_1) and confined (Q_2) aquifers

The maximum yield available for peak load Q_1 [m³/s] in an unconfined aquifer depends on the hydraulic conductivity *kf* [m/s], the mean thickness of the saturated zone SZm [m] in the area and the hydraulic radius *R* [m]. It is calculated with Eq. 10 (after Thiem[4]) and Eq. 12 (after Sichardt[5]) for each calculation area. The maximum yield available for peak load Q_2 [m³/s] in a confined aquifer depends on the same parameters as Q_1 and additionally includes the hydraulic head [H]. It is calculated with Eq. 11 (after Dupuit[6]) and Eq. 12 to determine the hydraulic radius [R].

$$Q_1 = \pi \cdot kf \cdot \frac{5 \cdot SZ_m^2}{9 \cdot lnR} \qquad \text{Eq. 10}$$

$$Q_2 = \pi \cdot kf \cdot 2 \cdot SZ_m \frac{H}{3 \cdot lnR} \qquad \text{Eq. 11}$$

$$R = 3000 \cdot \sqrt{kf} \cdot \frac{SZ_m}{3} \qquad \text{Eq. 12}$$

Calculation of the hydraulic productivity at base load (Q_3)

The hydraulic productivity at base load Q_3 [m³/s] depends on the following parameters and is calculated with Eq. 13 for each calculation area:

E_2 Energy content for unbalanced use derived from Eq. 6 for each calculation area [MWh/yr]

[4] Thiem, G. (1906): Hydrologische Methoden. Gebhardt, Leipzig.

[5] Sichardt, W. (1928): Das Fassungsvermögen von Rohrbrunnen und seine Bedeutung für die Grundwasserabsenkung, insbesondere für größere Absenkungstiefen. Springer, Berlin.

[6] Dupuit, A.J. (1863): Etudes théorétiques et practiques sur le mouvement des eaux à travers les terrains permeables. 2nd edition, Dunod, Paris.

c_{vW}	Volumetric heat capacity of water [MJ/m³/K]. Default value: 4.1 MJ/m³/K
ΔT	Temperature shift between extraction and injection well for balanced use [K]. Default value: 5 K
t_{op}	Operational hours of an open loop system per year [h]. Default value: 2400 h

$$Q_3\ [m^3/s] = \frac{E_2}{c_{vW} \cdot \Delta T \cdot t_{op}} \quad \text{Eq. 13}$$

Hydraulic productivity - validation

G.3.4.3. Validation of the hydraulic productivity at peak load

Description of workflow steps

Validation of the hydraulic productivity at peak load (Q_1)

In the validation process the licensed pumping rates are compared with the estimated maximum yield in the area. The estimated maximum yield has to be always larger than the licensed rates.

G.3.5. Thermal capacity

G.3.5.1. Input parameters and data preparation

General remarks

The thermal capacity (P) is the energy available for a certain operational time. Hydraulic productivity and the thermal capacity are proportional, as shown in Eq. 14 and additional parameters defining the thermal capacity are the volumetric heat capacity of water (c_{vW}) and the temperature shift (ΔT). Figure 58 shows the relation between energy content and thermal capacity, and hydraulic productivity respectively. The annual energy content available (E) can be distributed over the year, either a high capacity for a short time or a low capacity for a longer time. Either way, the energy content remains the same. Hence, not only the energy content, but also the thermal capacity are important for a successful design of an open loop system.

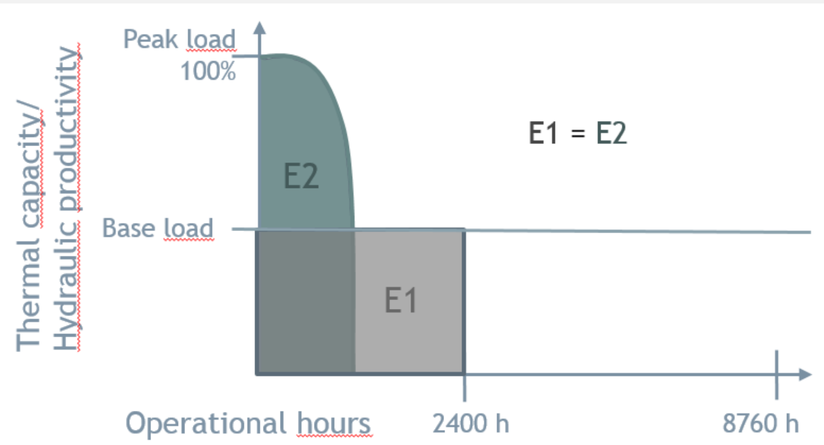


Figure 58: Relation between energy content (E) and thermal capacity/hydraulic productivity shows that both parameters are necessary for a successful design of an open loop system.

The peak load in Figure 58 equals the maximum thermal capacity available P_1 [MW] and depends on the maximum yield available in the aquifer of Eq. 10. The base load represents the thermal capacity, which is available for the time of operation in one year P_2 [MW]. One year of operation is considered to contain 2400 hours of operation.

Input parameters

- Maximum hydraulic productivity (Q_1)

The maximum yield available at peak load per well doublet Q_1 [m^3/s] is described in Eq. 10.

- Thermal productivity (ΔT)

The temperature shift ΔT available for balanced use developed in chapter Thermal productivity will be used to calculate the energy content.

- Energy content available for unbalanced use (E_2)

The energy content available for unbalanced use E_2 [MWh/yr] is defined in Eq. 6.

G.3.5.2. Calculation of the thermal capacity

Description of workflow steps

Thermal capacity at peak load (P_1)

The thermal capacity at peak load *(P_1)* depends on the following parameters and is determined for each calculation area:

Q_1 Maximum yield available at peak load per well doublet in each calculation area [m³/s]

ΔT Maximum temperature shift available for balanced use in each calculation area [ΔT]

c_{vW} Volumetric heat capacity of water [MJ/m³/K]. Default value: 4.1 MJ/m³/K

$$P_1\,[MW] = Q_1 \cdot \Delta T \cdot c_{vW}$$ Eq. 14

Thermal capacity at base load (P_2)

The thermal capacity at base load (P_2) depends on the following parameters and is determined for each calculation area:

E_2 Energy content for unbalanced use derived from Eq. 6 for each calculation area [MWh/yr]

t_{op} Operational hours of an open loop system per year [h]. Default value: 2400 h

$$P_2\,[MW] = \frac{E_2}{t_{op}}$$ Eq. 15

G.3.6. Validation of the workflow

General remarks

The validation of this workflow has successfully been performed for the energy content available for unbalanced use in a small case study area “Berres-Bodhagskygasse-Heidjöchl” in the pilot area Vienna. One output of the validation is the determination of a recovery factor and furthermore a rough estimation about the accuracy of the potential calculation. Due to technical limitations, it is not possible to use the entire analytically calculated energy content. The recovery factor takes these limitations into account. It has to be investigated, whether the recovery factor for balanced use differs from the one for unbalanced use. Therefore, both recovery factors should be determined in the validation process.

For the simulation settings, it was found suitable to use steady state fluid flow and transient state for transport. The steady state flow shortens the time of simulation and requires a constant well rate. Transient state for heat transport allows to document the development of the temperature plumes.

Description of workflow steps

Calculation of validation yield

The maximum yield will be allocated to wells in the numerical model (FEFLOW or comparable software). It depends on the energy content E_1 [MWh/yr] and E_2 [MWh/yr]. Both yields for balanced Q_{val_b} [m³/s] and unbalanced use Q_{val_ub} [m³/s] are calculated based on Eq. 13, however using 8760 hours instead of 2400 hours for t_{op}. In this way, the well rate can be assigned as constant value in the simulation. Calculations for both validating rates are presented in Eq. 16 and Eq. 17, using the following parameters:

E_1	Energy content for balanced use derived from Eq. 5 for each calculation area [MWh/yr]
E_2	Energy content for unbalanced use derived from Eq. 6 for each calculation area [MWh/yr]
c_{vW}	Volumetric heat capacity of water [MJ/m³K]. Default value: 4.1 MJ/m³/K
ΔT	Temperature shift between extraction and injection well for balanced use and unbalanced use respectively [K]. Default value: 5 K
t_{yr}	Hours of one year. Default value: 8760 h

$$Q_{val\_b}\,[m^3/s] = \frac{E_1}{c_{vW} \cdot \Delta T \cdot t_{yr}} \qquad \text{Eq. 16}$$

$$Q_{val\_ub}\,[m^3/s] = \frac{E_2}{c_{vW} \cdot \Delta T \cdot t_{yr}} \qquad \text{Eq. 17}$$

Preparation of well layer

In a first step, virtual well doublets are located in the calculation areas. A large number of calculation areas, automatically leads to a large number of virtual well doublets in a validation area (47 in case of the pilot area Vienna), therefore it is easier to locate the wells in ArcGIS first. The locations of wells have to be in optimum configuration regarding the hydraulic situation: Extraction well upstream, injection well down stream, maximum distance possible between extraction and injection wells. It is recommended to place more than one well doublet in large calculation areas.

The well rates determined in Eq. 16 and Eq. 17 provide the yield available for one calculation area. The yields for balanced Q_{val_b} [m³/s] and unbalanced use Q_{val_ub} [m³/s] are assigned to the wells under consideration of the sign (Table 34). If more than one well doublet are located for one calculation area, the well rate has to be adapted accordingly. The attribute table of the wells should additionally contain the following parameters in Table 34:

Table 34: Parameters of well table prepared in ArcGIS

Name of validation well	Well rate	Well radius	Aquifer thickness	Depth to top	Depth to bottom
Suggestion: Use name of calculation area	Consider sign for extraction (+) and injection (-) [L/s]	Default value: 0.25 m	Mean aquifer thickness of calculation area [m]	Mean groundwater depth in calculation area [m]	Depth to top + thickness of saturated zone [m]

It is furthermore useful for the following step to provide a separate shapefile showing the location of the extraction and injection wells.

Construction of numerical model

A 3D model is developed in FELFOW or a comparable software with the same input parameters used for the analytical calculation of the energy content. The well layer developed in the previous step is imported into FEFLOW, they are transformed into multi-layer wells and the information Table 34 is assigned.

Temperature boundary conditions are used to implement the undisturbed groundwater temperature (T_{nat}) and to assign the temperature of the injected water. In order to set the undisturbed groundwater temperature, a time series can be used to include information about the seasonal change of the groundwater temperature. A simpler approach would be to assign a mean annual groundwater temperature on the top most slice and on all nodes along the upstream border of the model domain.

Temperature boundary conditions for the injected water temperature (T_{inj}) are set on to the deepest slice of the injection well. It has to be done this way in FEFLOW, because in this software water is injected (and also extracted) always on the deepest point of a multi-layer well. The temperature boundary condition will be determined for each injection well and for unbalanced and balanced use separately, using Eq. 18.

ΔT Temperature shift between extraction and injection well for balanced use and unbalanced use respectively, which was used to determine Q_{val_b} and Q_{val_ub} [K].

T_{nat} Undisturbed groundwater temperature [°C] at well location.

$$T_{inj}\ [°C] = T_{nat} - \Delta T \qquad \text{Eq. 18}$$

The numerical simulation is set to run for the entire life time of an open well system (default value: 20 years).

Comparison of modelled and analytically calculated energy content

FEFLOW 7.0 automatically records the temperature at the extraction wells, this is a useful feature for the analysis of the results. The temperatures are stored in the chart "average-temperature history" and can be exported for further analysis in Microsoft Excel. Figure 59 shows the temperature chart for the validation in the pilot area Vienna.

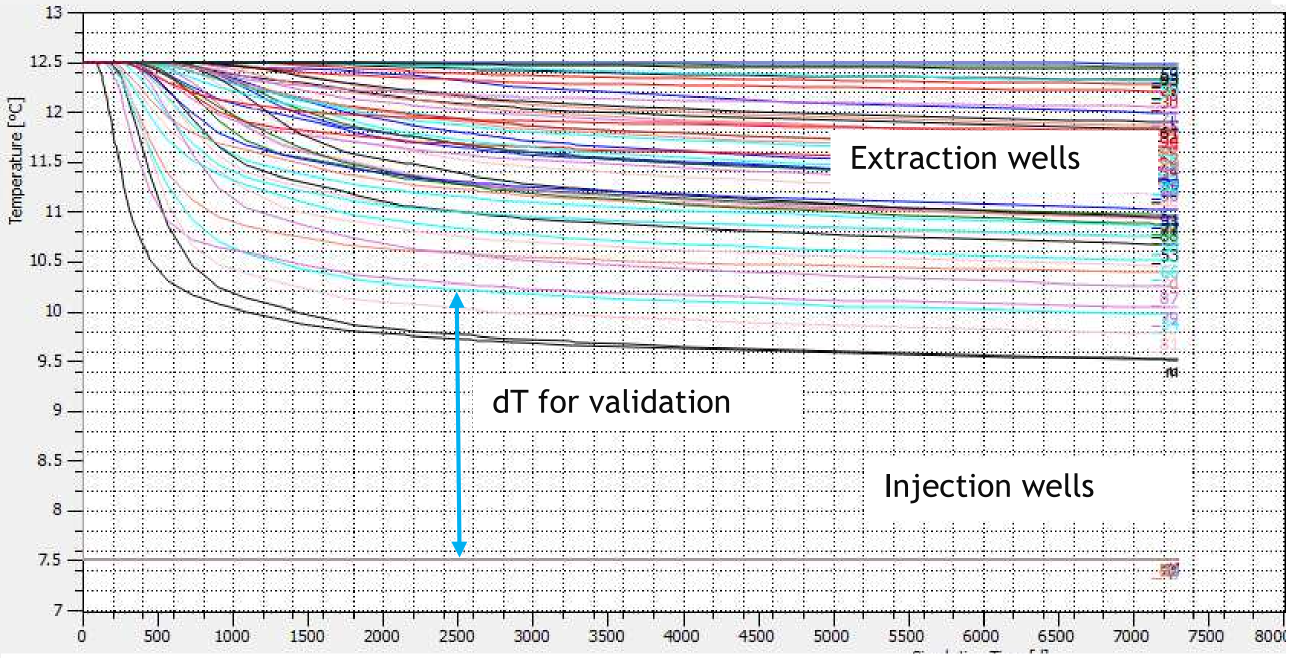


Figure 59: Results of simulation. Temperature difference between extraction and injection well will be used to calculate the modelled energy content available. Temperature at injection wells remains constant

Due to mutual interferences of the open loop systems it is most likely the temperatures in the extraction wells decrease (Figure 59), wheras the temperatures at the injection wells remain constant. Therefore, the modelled energy content available depends on the temperature difference between extraction and injection well (ΔT_{val}). Due to the change of temperature in the extraction well, the temperature shift has to be calculated for each time step of the simulation. The energy content available according to the simulation for each well doublet ($E_{welldoublet}$) equals the sum of the energy available at each time step (Eq. 19). In this way the energy available according to the simulation can be determined for each calculation area and the total amount of energy available equals the sum of all calculation areas (E_{tot_mod}). The recovery factor is derived from the division of the energy available according to the simulation (E_{tot_mod}) by the energy content available according to the analytical calculation (E_{tot_an}) after 20 years (Eq. 20).

$$E_{welldoublet}\,[MJ] = \sum_{i=0}^{20years} \left(Q \cdot t_i \cdot \Delta T_{val\_i} \cdot c_{vW}\right) \qquad \text{Eq. 19}$$

$$rf = \frac{E_{tot\_mod}}{E_{tot\_an}} \quad \text{Eq. 20}$$

H. List of electronic appendixes

No	Script / template /software	Data type	Status	Responsible partner
	General			
1	Template documentation	EXCEL spreadsheet	available	PP04
2	Templates attribute data	ACCESS table	Has to be prepared	LP
3	Templates metadata	ACCESS table	Has to be prepared	LP
4	Glossary of terms		available	LP
5	Master grid	EXCEL macro ArcGIs workflow	available	PP04
6	Specification of the spatial reference system	Text	available	LP/PP04
	3D modelling			
7	Instruction for age and petrographic coding	Text	available	PP04
	Closed loop workflow			
8	Parameter list with specific thermal conductivities of rock samples	EXCEL spreadsheet	Has to be prepared	PP05
9	Assignment of conductivity-values wet /dry to the borehole data	EXCEL macro	Has to be prepared	PP04
11	Calculation of the thickness weighted mean of the conductivity-values for all geological units in the borehole data tables	EXCEL macro	Has to be prepared	PP04
12	Calculation of the thermal conductivity and heat extraction maps	ArcGIS extension IE Geothermie	Has to be prepared	PP04
	Open loop systems			
13	Template to calculate potentials	EXCEL spreadsheet	available	LP