LOw Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure enviromental risks

LOCAL

Research Fund for Coal & Steel

LoCAL Deliverable 1.2

Documentation of code

(English and Spanish versions)

WP number	**WP1**
Partner responsible	**University of Oviedo (UoO)**

Universidad de Oviedo

In the previous deliverable (D.1.1) the source and executable simulation code of LoCAL-PANR were provided. The following sheets compile the code documentation, constituting the PANR user's guide. At this document, the theoretical basis of the tool is explained and the working of PANR itemised in tabs is described.

The architecture, flowchart and interface of the tool are presented, including several screen captures. The required input data is summarized in a table that provides some useful information to the user.

A Spanish version of the User's guide has been written. Both versions can be checked at the tab "Info" of the excel file.

PANR USER'S GUIDE, Version 2.0

LoCAL

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Universidad de Oviedo

University of Glasgow

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1. Introduction

PANR (Pumped abstraction – Natural recharge) is a heat transfer calculator addressed for the scenarios of an underground mine whose water is pumped with a geothermal purpose. The heat is extracted from or dumped into the pumped water and consecutively, the water is disposed of to a surface water. At this scenario, there is no deliberate reinjection of thermally spent water.

2. Theoretical basis of the tool

Water from a given hydrogeological mine system with an area of infiltration *A* is pumped at a rate *Q*. The rainfall *R (mm/year),* whose temperature is T_0 (approximately average ambient temperature), infiltrates in the area A above the mine, being the total recharge $L_0 = A \cdot R$ (L/year, convertible to e.g. L/s). This water recharge gradually seeps into the rocks overlying the mine system, which are assumed to be originally permeable or whose permeability has been induced by the mining activity, so we can consider them as an "aquifer". This cold water goes through these rocks, extracting heat from them and gradually depleting their heat. The recharge water moves downwards at a velocity R/φ, where φ is effective porosity. However, the heat signal is retarded relative to this hydraulic velocity and the thermal velocity v_{th} is given by $R \cdot \rho_{wat} \cdot c_{wat} / \rho_{aq} \cdot c_{aq}$, where $\rho \cdot c$ is volumetric heat capacity (in $J/(m^3\ K)$, here *wat* refers to water and *aq* refers to bulk aquifer material. R will decrease in the vertical direction (at a rate that will depend on the flow distribution).

The passage of this cold recharge through the rocks can be simulated by a simple 1-D thermal advection-dispersion model which is directly analogous to the Ogata-Banks chemical advection-dispersion model (Ogata y Banks, 1961)[1]. Such a 1-D model allows the temperature (T_{zt}) at any depth (z) in the recharge-to-the-mine system to be calculated at any time (t), Fig 1.

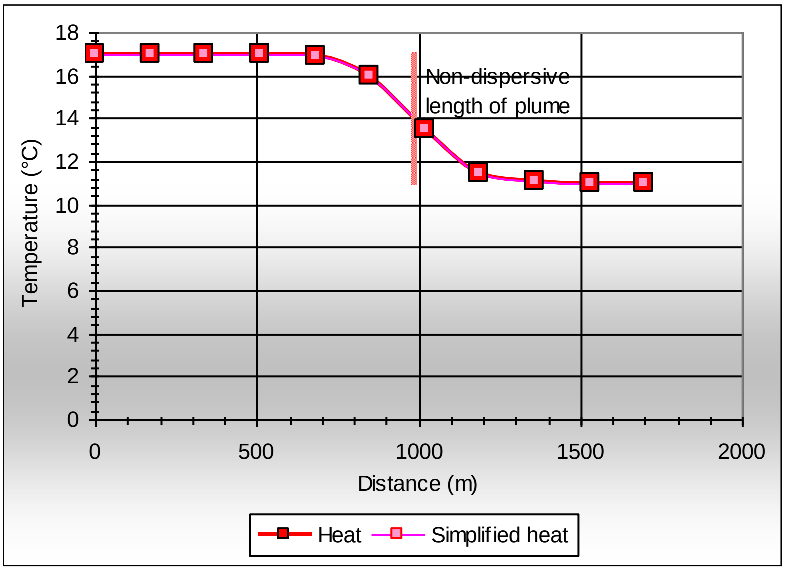


Fig 1. A simple advective dispersive 1-D heat transport model

[1] Ogata, A., Banks, R.B., 1961. A solution of the differential equation of longitudinal dispersion in porous media. U. S. Geol. Surv. Prof. Pap. 411-A.

The temperature (T_{zt}) of this vertically derived recharge water L_0 at any depth z thus varies with time t. If the mine water is only coming from this pluvial recharge, so no lateral flows are involved, then $Q = A \times R = L_0$. Fig 2 illustrates this, where t_1, t_2 and t_3 show the temperature profile evolution of the recharge water (increasing times following commencement of pumping).

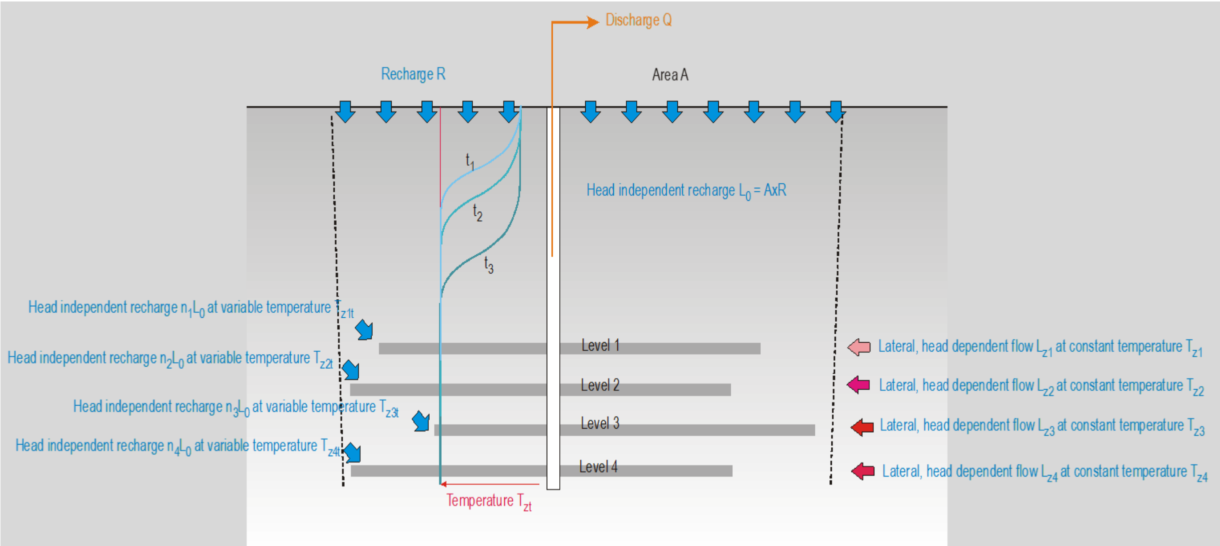


Fig 2. Conceptualisation of the physical model.

However, in many mine systems $Q > A \times R$, which means that there is also an inflow of lateral regional groundwater, in addition to the recharge inflow from above. This lateral inflow may come from different levels in the mine (L_{z1}, L_{z2}, L_{z3}, L_{z4} ....), each with a constant temperature (T_{z1}, T_{z2}, T_{z3}, T_{z4}....), dependent on depth. The lateral inflows may be hydraulically dependent on the water level (head) in the mine voids (see Banks, 2001)[2]. Therefore, in a general case, the total pumped water Q from the mine should be split between:

- Head-independent recharge: $A \times R = L_0$
- Head dependent lateral flows: L_{z1}, L_{z2}, L_{z3}, L_{z4} ....

Being the total pumped water: $Q = L_0 + L_{z1} + L_{z2} + L_{z3} + L_{z4} + ...$

And consequently, the temperature of the pumped water (T_{tot}) at any time:

$$T_{tot} = (L_0 T_{zt} + L_{z1} T_{z1} + L_{z2} T_{z2} + L_{z3} T_{z3} + L_{z4} T_{z4} + ...)/Q$$

In many cases, it is probably that T_{zt} could be set at z_1 (the uppermost extensive worked level of the mine, i.e. if the upper mine level intercepts all down-ward draining recharge). Alternatively, a proportion of the recharge water (n_1, n_2, n_3, n_4...) can be assigned to each of the levels, such that $n_1 + n_2 + n_3 + n_4 + \ldots = 1$. In this case: $T_{tot} = (n_1L_0T_{z1t} + n_2L_0T_{z2t} + n_3L_0T_{z3t} + n_4L_0T_{z4t}....+ L_{z1}T_{z1} + L_{z2}T_{z2} + L_{z3}T_{z3} + L_{z4}T_{z4} +....)/ Q$

The advective-dispersive model needs to consider the fact that the velocity of the vertically derived recharge decreases with depth, as proportions are assigned to specific levels.

[2] Banks, D., 2001. A variable-Volume, Head-Dependent Mine Water Filling Model (MIFIM). Gr. Water, 39, 362–365. doi:10.1111/j.1745-6584.2001.tb02319.x

2.1. Basics on thermal dispersion

The 1-dimensional advective-dispersive transport of a conservative, solute species is given by de Marsily (1986) as:

$$D' \frac{\partial^2 C}{\partial x^2} - v_i \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}$$

Where $v_i$is the linear groundwater (tracer) velocity (U/n_e) and D' is the dispersion coefficient relative to linear groundwater (tracer) velocity, according to the following expression:

$$D' = \frac{D}{n_e} = d_m + \alpha\,|v_i|$$

Being D the dispersion coefficient relative to Darcy flux (U), $n_e$the porosity, d_m the molecular-scalar-scale diffusion coefficient (m^2/d) and α the hydrodynamic dispersivity (m).

Similarly, for 1-dimensional advective- dispersive transport of heat (where temperature is effectively the "concentration "of heat), de Marsily (1986) gives:

$$D'_{th} \frac{\partial^2 \theta}{\partial x^2} - v_{th} \frac{\partial \theta}{\partial x} = \frac{\partial \theta}{\partial t}$$

Where v_{th} is the thermal velocity of the heat front (heat plume), being:

$$v_{th} = U\,\frac{VHC_{wat}}{VHC_{aq}}$$

Here, VCH_{aq} refers at the volumetric heat capacity of saturated aquifer. This is typically between 2 and 2.5 M J/m^3/K.

VCH_{wat} refers to the volumetric heat capacity of water. For fresh water and within the range of temperatures typically considered, this can be treated as a constant value (c. 4.19 MJ/m^3/K).

Thus, if hydrodynamic dispersion ($\beta\ v_{th}$) exceeds conductive dispersion (λ_0/VHC_{aq}), the dispersive shape of the plume is largely dependent on the value of dispersivity (β) and to a minor degree on the thermal properties of the saturated aquifer.

De Marsily (1986) reviews empirical data and concludes that, for practical purposes, the value of thermohydrodynamic dispersivity is essentially indistinguishable from hydrodynamic dispersivity; in other words: β= α.

In two-dimensional modelling, the shape of the plume will be governed by both longitudinal dispersion and transverse dispersion. Most modelling approaches (e.g. CONSIM, FEFLOW®) tend to assume that longitudinal dispersivity is around 10 times transverse dispersivity:

α_L=10 α_T and thus β_L=10 β_T

2.2. Ogata-Banks solution

Ogata and Banks (1961) developed an analytical solution to the 1D advection-dispersion equation. The analytical solution can determine the concentration of a contaminant (i.e. heat) down-gradient from a constant source, at a given distance x, and time t:

$$C(x,t) = \frac{1}{2}C_0\left[erfc\left(\frac{x-\frac{v}{R}t}{\sqrt{4\frac{D}{R}t}}\right) + e^{v\frac{x}{D}}erfc\left(\frac{x+\frac{v}{R}t}{\sqrt{4\frac{D}{R}t}}\right)\right]$$

Where v/R is the retarded contaminant transport velocity which, in the case of heat is simply v_{th}. The term D/R in the equation is simply the thermal dispersion D'_{th} , relative to the thermal velocity.

If the contaminant is the heat, and considering the previous statements, the equation of Ogata-Banks gfor thermal dispersion would be as follows:

$$T = T_{ground} + \frac{T_{inlet} - T_{ground}}{2} * \left[erfc\left(\frac{y - v_{th} * t}{2\sqrt{D_{th} * t}}\right) + e^{\frac{v_{th}*y}{D_{th}}} * erfc\left(\frac{y + v_{th} * t}{2\sqrt{D_{th} * t}}\right)\right]$$

erfc is the complementary error function, Fig 3 (also called complementary Gauss error function) defined by the following expression:

$erfc(z) = 1 - \mathrm{erf}(z) = \frac{2}{\sqrt{\pi}}\int_z^\infty e^{-t^2}\,dt$

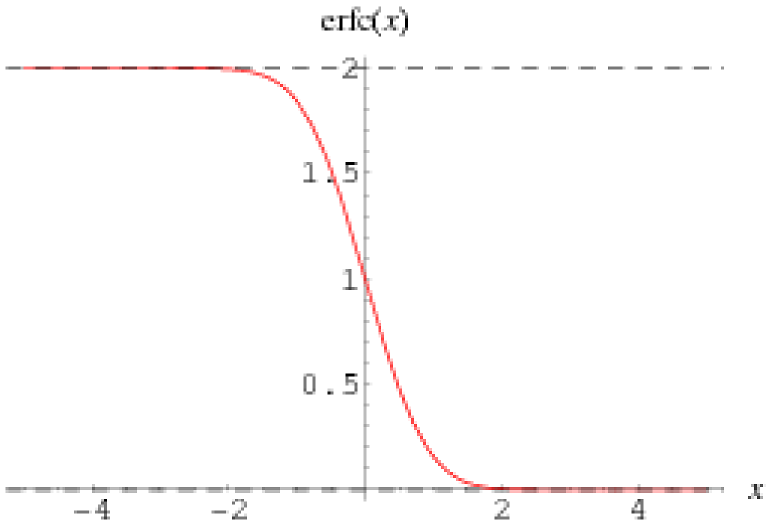


Fig 3. Erfc(x)

3. Heat transfer calculator workbook

LoCAL PANR is built in an excel workbook. This workbook was designed to simulate the evolution of the temperature of the water pumped from a flooded mine system, typically over a scale of decades or centuries. It is not, in itself, a hydraulic model.

There is a single outflow from the studied pumped shaft or borehole. This pumping rate is assumed to be equal to the sum of the various inflows to the mine and is not specified independently. As explained before, the inflows to the mine are of two types: Head-independent inflow and Head-dependent inflows.

3.1. Head-independent inflow

The head independent inflow (rainfall recharge) enters from the "top" of the model at the average ambient temperature T_0. It percolates downwards to the uppermost mine gallery. It acquires the heat contained in the progressively warmer rocks as it progresses downwards – effectively "leaching" the heat from these.

The initial vertical temperature profile of the rock mass with depth can be either:

a) Calculated from the geothermal temperature gradient of the rocks

b) Manually assigned

The option can be selected by using the "Use geothermal gradient to distribute temperature" option in the Model Options of the Data Input sheet.

The Ogata-Banks 1-D advection-dispersion equation (modified for thermal dispersion rather than solute dispersion) is used to simulate the progress of the recharge water heat front down through the rocks overlying the mine. It is possible to calculate the evolution of temperature in this recharge water as it enters the uppermost mine gallery at depth z_1. In many cases, it is appropriate to assume that all of the head-independent recharge is captured by the uppermost gallery. In other cases, a proportion of the head-independent recharge can be assigned to the deeper galleries (up to 5 levels of galleries can be assigned), and the Ogata-Banks equation simulates the continued downward migration of the thermal front towards these.

The "Use relative length of galleries to distribute recharge" option in the Model Options of the Data Input sheet can be used to either:

a) Distribute the head-independent recharge manually between the various levels

b) Distribute the recharge automatically, in proportion to the total gallery length at each level.

3.2. Head-dependent inflows

Up to 5 head-dependent inflows can be assigned: one to each gallery at elevations z_1, z_2, etc. Each inflow is assigned a constant temperature. This can be done either:

a) Manually

b) Automatically, based on the geothermal gradient.

The option can be selected in the Model Options of the Data Input sheet, "Use geothermal gradient to distribute temperature".

The magnitude of each inflow can either:

a) Be entered manually, if the option "Calculate head-dependent flows" = N, in Model Options

b) Be calculated, if the option "Calculate head-dependent flows" = Y, in which case the Worksheet "Head-dependent flows" is activated.

In the second case, the flow is calculated as a function of:

i. An inflow specific capacity (which must be entered manually – in m^3 per s per m of head difference)

ii. The head difference between the inflow's static head and the water level in the mine (or the inflow level if the mine water level is below the inflow level (see Banks, 2001).

The water level in the mine is simply the "Default pumping water level" specified on Input Data. The static water level can either be assigned individually to each inflow or can be set to the "Default static water level" specified on the input sheet.

4. Architecture of PANR

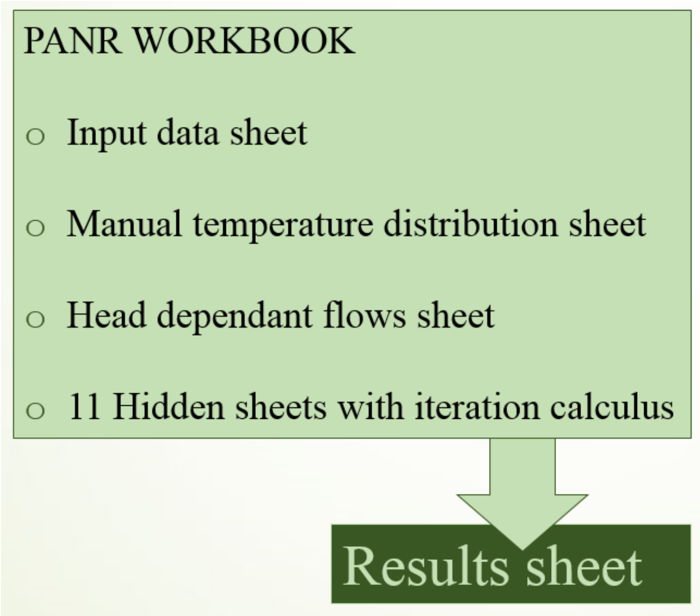


Fig 4. Architecture of PANR

PANR interacts with the users by means of 4 sheets. However, there are other 11 additional sheets that constitute the mathematical basis of the model, Fig 4. These calculation sheets which hold some intermediate results are originally hidden but the user can check them by selecting this option. The flowchart of LoCAL PANR is advanced at Fig 5.

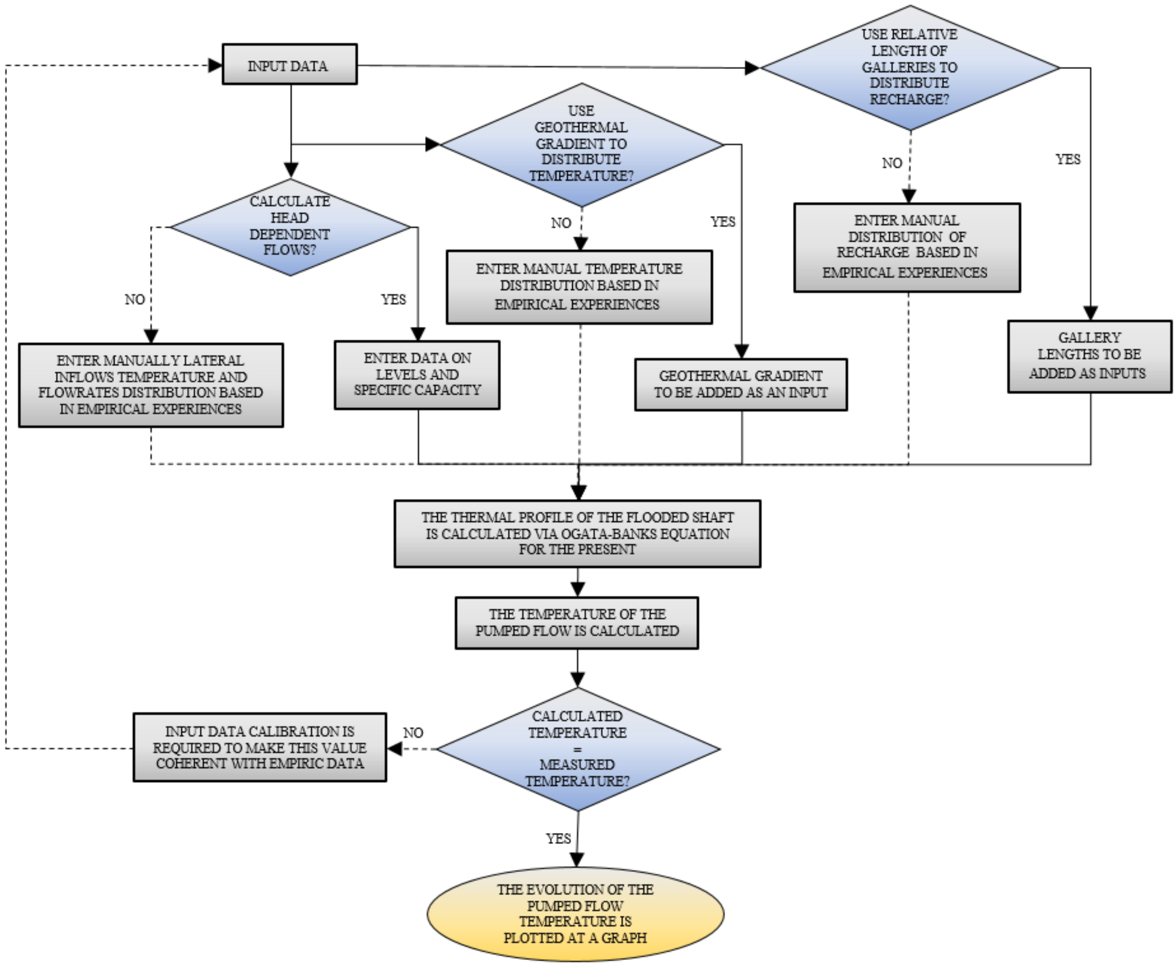
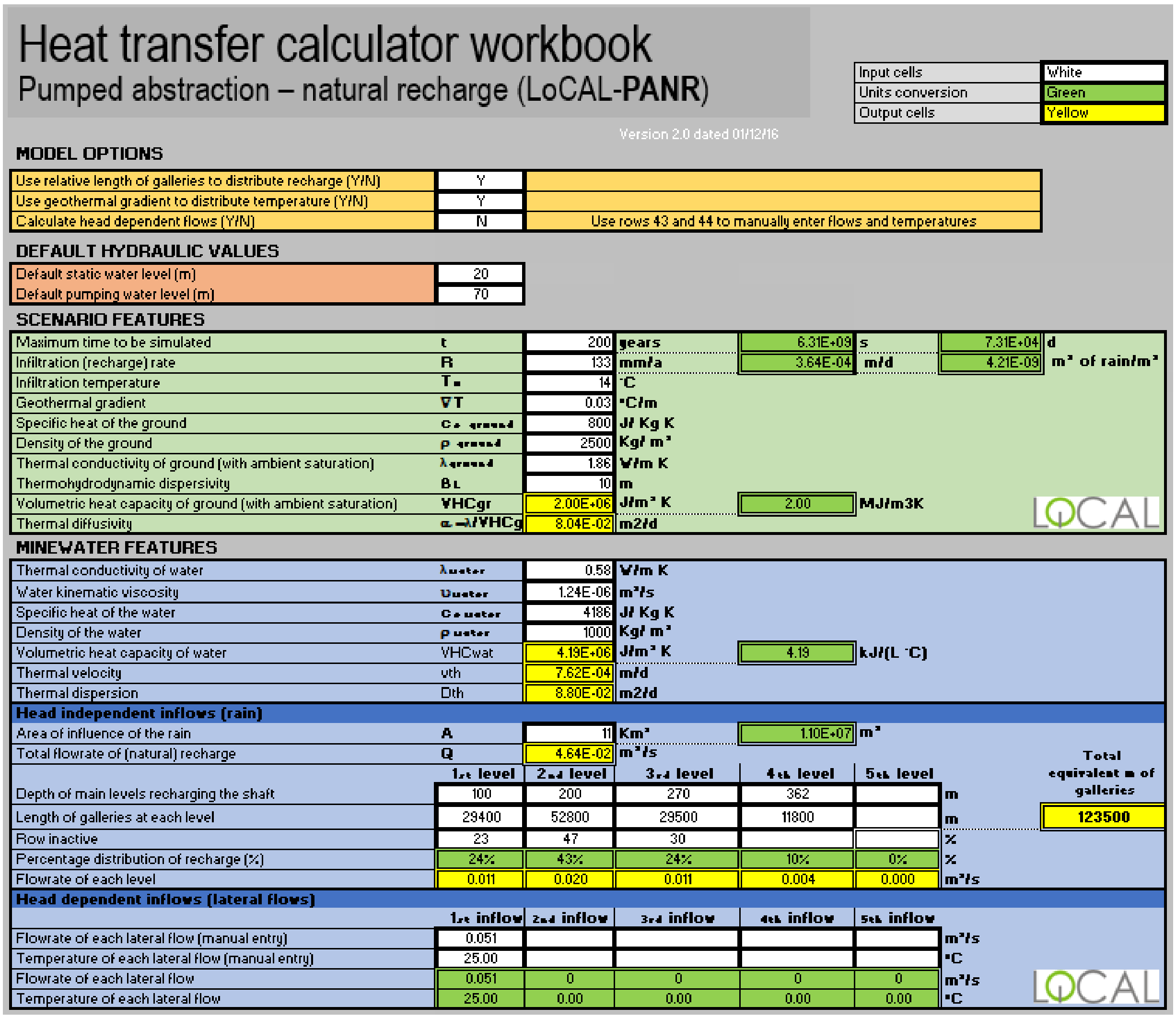


Fig 5. PANR flowchart

5. Input Data

The main inputs must be provided to the workbook at the Data Input sheet). The parameters are classified in: i) Model Options, ii) Default Hydraulic Values, iii) Scenario, iv) Features and v) Minewater Features, which is subdivided in Head Independent and Dependent inflows. The input cells are colored in white, the unit conversion cells in green and the output cells in yellow. The user can only modify the content of the input white cells, Fig 6. The inputs required by PANR are summarized at Table 1.



Heat transfer calculator workbook
Pumped abstraction – natural recharge (LoCAL-PANR)

Input cells	White
Units conversion	Green
Output cells	Yellow

Version 2.0 dated 01/12/16

MODEL OPTIONS

Use relative length of galleries to distribute recharge (Y/N)	Y	
Use geothermal gradient to distribute temperature (Y/N)	Y	
Calculate head dependent flows (Y/N)	N	Use rows 43 and 44 to manually enter flows and temperatures

DEFAULT HYDRAULIC VALUES

Default static water level (m)	20
Default pumping water level (m)	70

SCENARIO FEATURES

Maximum time to be simulated	t	200	years	6.31E+09	s	7.31E+04	d
Infiltration (recharge) rate	R	133	mm/a	3.64E-04	m/d	4.21E-09	m³ of rain/m²
Infiltration temperature	T_o	14	°C				
Geothermal gradient	∇T	0.03	°C/m				
Specific heat of the ground	$c_{p\ ground}$	800	J/ Kg K				
Density of the ground	ρ_{ground}	2500	Kg/ m³				
Thermal conductivity of ground (with ambient saturation)	λ_{ground}	1.86	W/m K				
Thermohydrodynamic dispersivity	β_L	10	m				
Volumetric heat capacity of ground (with ambient saturation)	VHCgr	2.00E+06	J/m³ K	2.00	MJ/m3K		
Thermal diffusivity	α =λ/VHCg	8.04E-02	m2/d				

MINEWATER FEATURES

Thermal conductivity of water	λ_{water}	0.58	W/m K		
Water kinematic viscosity	υ_{water}	1.24E-06	m²/s		
Specific heat of the water	$c_{p\ water}$	4186	J/ Kg K		
Density of the water	ρ_{water}	1000	Kg/ m³		
Volumetric heat capacity of water	VHCwat	4.19E+06	J/m³ K	4.19	kJ/(L °C)
Thermal velocity	vth	7.62E-04	m/d		
Thermal dispersion	Dth	8.80E-02	m2/d		

Head independent inflows (rain)

Area of influence of the rain	A	11	Km²	1.10E+07	m²
Total flowrate of (natural) recharge	Q	4.64E-02	m³/s		

	1st level	2nd level	3rd level	4th level	5th level		Total equivalent m of galleries
Depth of main levels recharging the shaft	100	200	270	362		m	
Length of galleries at each level	29400	52800	29500	11800		m	123500
Row inactive	23	47	30			%	
Percentage distribution of recharge (%)	24%	43%	24%	10%	0%	%	
Flowrate of each level	0.011	0.020	0.011	0.004	0.000	m³/s	

Head dependent inflows (lateral flows)

	1st inflow	2nd inflow	3rd inflow	4th inflow	5th inflow	
Flowrate of each lateral flow (manual entry)	0.051					m³/s
Temperature of each lateral flow (manual entry)	25.00					°C
Flowrate of each lateral flow	0.051	0	0	0	0	m³/s
Temperature of each lateral flow	25.00	0.00	0.00	0.00	0.00	°C

Fig 6. Input Data sheet

Table 1. Summary of the required input data

Sheet/ Section	Input data	Symbol	Units	Description
Input Data/ Default hydraulic values	Default static water level	-	m	In mbgl (meters below ground line)
Input Data/ Default hydraulic values	Default pumping water level	-	m	In mbgl (meters below ground line)
Input Data/ Scenario features	Maximum time to be simulated	t	years	From the starting of the mine system coal exploitation
Input Data/ Scenario features	Infiltration rate	R	mm/a	Rate of recharge (rainfal), tipically in the order of a hundred (can be taken from a closed metereological station)
Input Data/ Scenario features	Infiltration temperature	To	°C	The average ambient temperature can be assumed

Input Data/ Scenario features	Geothermal gradient	∇T	ºC/m	The global average value (0.03 ºC/m) can be considered if the local value has not been measured
Input Data/ Scenario features	Specific heat of the ground	ce_{ground}	J/ Kg K	To estimate from the geological composition
Input Data/ Scenario features	Density of the ground	ρ_{ground}	Kg/ m³	To estimate from the geological composition
Input Data/ Scenario features	Thermal conductivity of ground	λ_{ground}	W/m K	To estimate from the geological composition (considering the ambient saturation).
Input Data/ Scenario features	Thermohydrodynamic dispersivity	$ß_L$	m	Typically 10m
Input Data/ Minewater features	Thermal conductivity of water	λ_{water}	W/m K	Typically 0.58
Input Data/ Minewater features	Water kinematic viscosity	υ_{water}	m²/s	c. 1.004E-06 m²/s at 20ºC
Input Data/ Minewater features	Specific heat of the water	ce_{water}	J/ Kg K	c. 4182 J/ Kg K at 20 °C
Input Data/ Minewater features	Density of the water	ρ_{water}	Kg/ m³	c. 1000 Kg/ m³ AT 20°C
Input Data/ Minewater features	Area of influence of the rain	A	Km²	Surface drained by the mine system
Input Data/ Minewater features	Depth of main levels recharging the shaft	-	m	Introduce up to 5 levels (mbgl)
Input Data/ Minewater features	Length of galleries at each level	-	m	Used to calculate the proportion of the recharge water assigned to each level, if the option is activated
Input Data/ Minewater features	Percentage distribution of recharge	n	%	Used to calculate the proportion of the recharge water assigned to each level, if the option is activated
Input Data/ Minewater features	Flowrate of each lateral flow	L_z	m³/s	Head dependent flows, introduce up to 5 levels, if the option is activated
Input Data/ Minewater features	Temperature of each lateral flow	T_z	°C	Head dependent flows, introduce up to 5 levels, if the option is activated

Manual Temp Distribution	Temperature Distribution with Depth (°C)	-	-	If this option is activated, all the cells should be filled, if some values are unknown, they can be calculated by interpolation
Head-Dependent Flows	Level of inflow	L_z	m	Introduce up to 5 levels (mbgl), if the option is activated
Head-Dependent Flows	Temperature	T_z	°C	Introduce the temperature for up to 5 levels, if the option is activated
Head-Dependent Flows	Specific capacity	-	m3/s	m3/s per m drawdown. If the option is activated
Head-Dependent Flows	static water level manually for each fracture	-	m	To fill just if the option is activated (in mbgl)
Results/ Energy calculator	ΔT geothermal heat pump	-	ºC	Temperature gap of the incoming-outcoming mine water before-after the energy extraction
Results/ Energy calculator	COP geothermal heat pumps	-	-	Heat pump's coefficient of performance

The model options are itemized at Fig 7. Depending on the user choice, the sheets “Manual temperature distribution sheet” and “Head dependent flows sheet” will be activated or deactivated. The row number refers to the position in the worksheet.

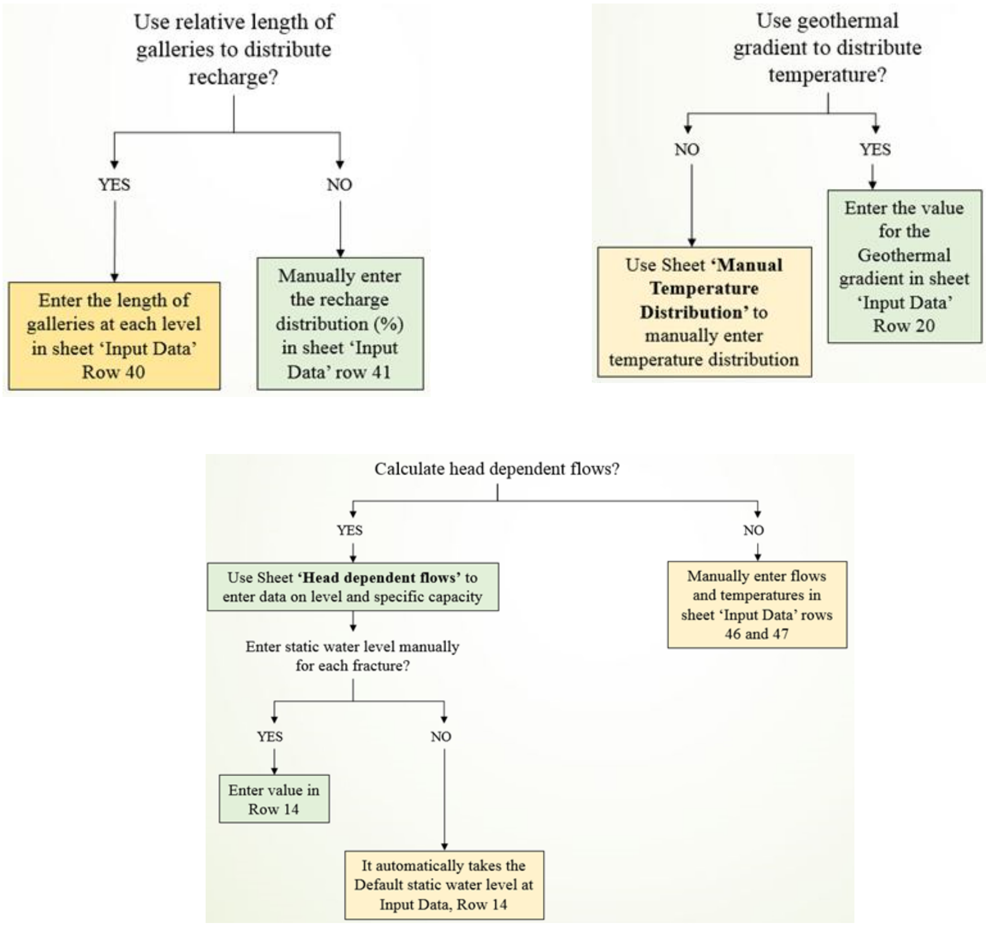


Fig 7. Model options diagram

5.1. Manual temperature distribution sheet

Denying the use geothermal gradient to distribute temperature (model option) will activate the Manual temperature distribution sheet. At this sheet the user will need to provide the temperatures of some requested depths (Fig 8).

Temperature Distribution with Depth (°C)		
Depth m	Manual	Applied
0.01	14.00	14.00
36.2	15.00	15.00
72.4	16.00	16.00
108.6	17.20	17.20
144.8	18.00	18.00
181	19.00	19.00
217.2	20.10	20.10
253.4	21.00	21.00
289.6	22.00	22.00
325.8	23.00	23.00
362	24.00	24.00
398.2	25.00	25.00
Individual gallery horizons (must be compatible with above)		
100	14.00	14.00
200	20.00	20.00
270	22.00	22.00
362	24.00	24.00
0.01	14.00	14.00

Fig 8. Manual temperature distribution sheet

5.2. *Head dependent flows sheet*

Choosing the model option "Calculate head dependent flows" will activate the sheet Head dependent flows sheet. The user will need to provide the levels of inflows, specific capacity and the static water level, if known.

Inflow		1 (shallow)	2	3	4	5 (deep)
Level of inflow	m below ground level	50	230			
	Row inactive	17	20			
Temperature	°C	15.50	20.90	14.00	14.00	14.00
Specific capacity	m3/s per m drawdown	0.001	0.0005			
Enter static water level manually for each fracture (Y/N)			N			
Row inactive		10	10			
Static water level	m bgl	20	20	20	20	20
Drawdown	m	30	50	0	0	0
Flow rate	m3/s	0.03	0.025	0	0	0

Fig 9. Head dependent flows sheet

6. Results

As it was stated in Section 4, PANR have a Results Sheet were the outputs of the program are displayed, although there are 11 additional unseen sheets that hold the calculation algorithms and some intermediate results. These ensembles of sheets are set as invisible as default; however, the user can check them just by right clicking in any tab sheet and selecting the option: show hidden sheets.

6.1. *Iterative calculations and intermediate results*

These sheets keep the mathematical basis of the model that can be checked at the Section 2 (Theoretical basis of the model). The appearance of these sheets is shown in Fig 10**Błąd! Nie można odnaleźć źródła odwołania.**.

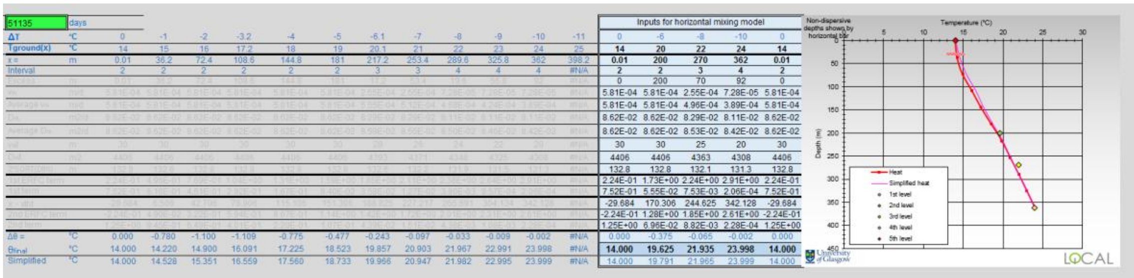


Fig 10. Iterative calculations

6.2. *Output Display*

The results of the model are displayed at the sheet Results. They are classified in: i) Results summary, ii) Evolution of the temperature of the pumped flow and iii) Energy calculator.

The main outputs are summarized at "Results summary", including:

- Total pumping rate (assuming that the mine water level in the shaft is constant i.e. all the incoming flows are pumped out)
- The temperature of the pumped water at the end of the selected period

- The difference between the temperature of the pumped mine water at the beginning and that at the end of the selected period

The table "Evolution of the temperature of the pumped flow" contains the depth of non-dispersed front (depth of the zone thermally-affected) and the temperature of the pumped flow. To study the temporal evolution of these two parameters, the selected period is divided in 10 sub-periods. The same information is graphically plotted at the right side of the table (Fig. 9).

Heat transfer calculator workbook

Pumped abstraction – natural recharge (LoCAL-PANR)

RESULTS SUMMARY

Total Pumping Rate:	97.36	L/s
Pumped temperature after 200years	22.33	°C
ΔT (Temperature decreased)	0.410	°C

EVOLUTION OF THE TEMPERATURE OF THE PUMPED FLOW

Depth of non-dispersed front (m)	Temperature (°C)	Time (y)
0.003	22.73906	0.01
5.567	22.73631	20
11.135	22.71385	40
16.702	22.68102	60
22.270	22.64286	80
27.837	22.59937	100
33.404	22.55099	120
38.972	22.49869	140
44.539	22.44358	160
50.106	22.38666	180
55.674	22.32874	200

ENERGY CALCULATOR

Minewater flowrate	97.36	L/s
Minewater density	1000	kg/m³
Minewater specific heat	4186	J/(kg °C)
ΔT geothermal heat pump	5	°C
COP geothermal heat pumps	4	
Minewater Thermal Potential	2.04	MW
Heat pump Thermal Potential	2.72	MW

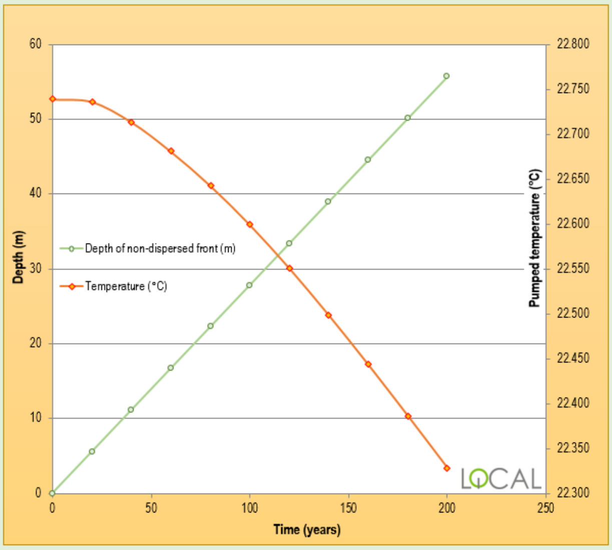


Fig 11. Results sheet

In the "Energy calculator", the mine water thermal potential is calculated based on the flowrate, available temperature gap and mine water characteristics (density and specific heat). The heat pump thermal potential is calculated by means of the COP (Coefficient of Performance).