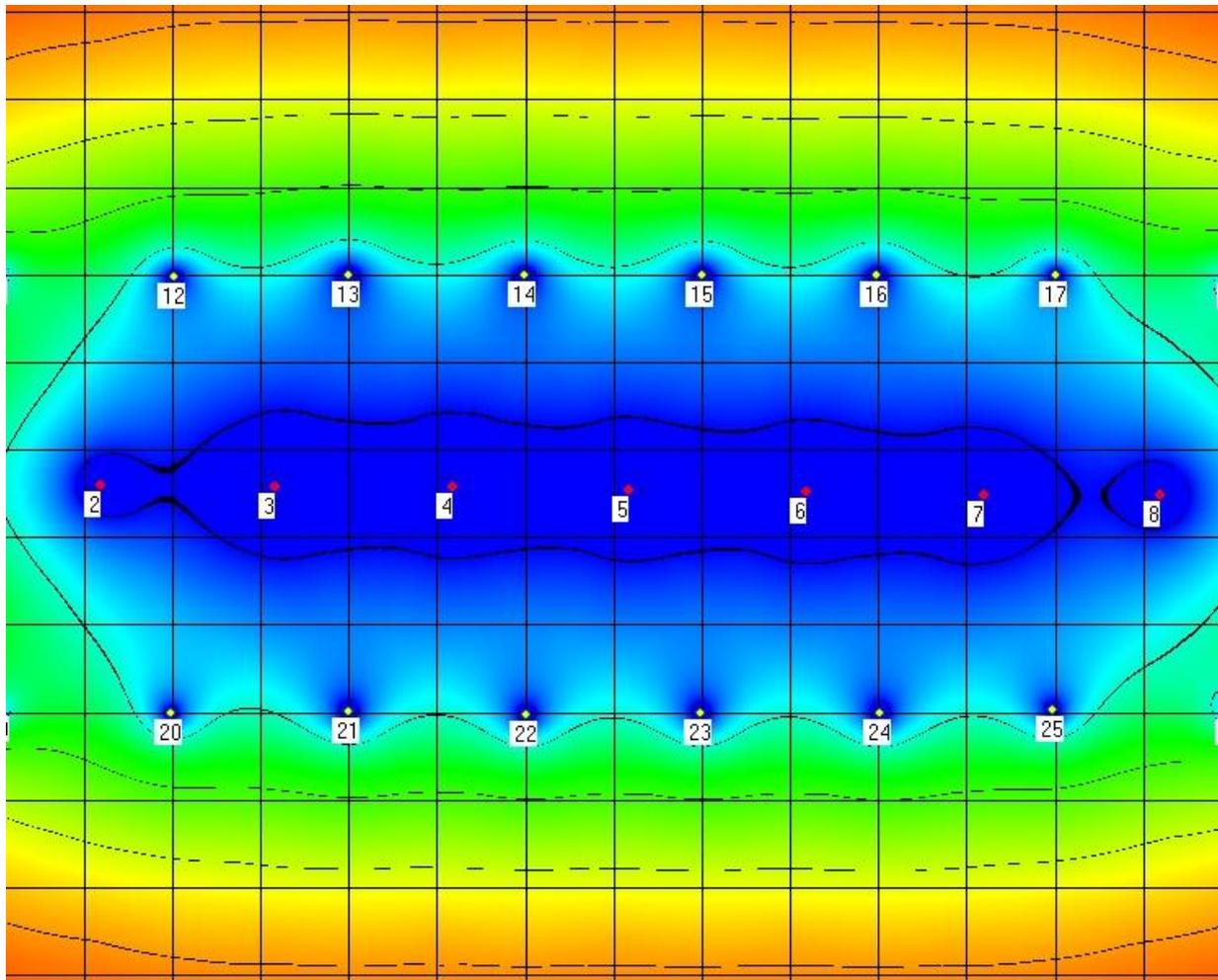


# Software Manual

## Program EWS

Version 5.3

### Calculation of Borehole Heat Exchangers



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# 1 Software Manual

## 1.1 Content and use of the program EWS

The Basic version of the program EWS calculates the behavior of borehole heat exchangers. This is done by numerically solving the heat equation of the ground and the heat transfer from the boreholes. The program calculates the outlet and inlet temperatures as well as the heat extraction performance of the boreholes (single boreholes or fields of boreholes) with hourly resolution up to a period of 200 years. The program EWS allows to take into account all major influences. The ground can be vertically divided into maximum 10 layers with different types of ground materials and backfills, such as the corresponding properties. Since the program EWS is able to do unsteady calculations of the fluid, it offers the possibility to calculate “start-up processes” and “thermal response tests”.

The Full extension version allows graphical input of fields of boreholes on imported schemes (cadastral maps, ground plots, district plans) and entire systems for direct cooling over borehole heat exchangers can be calculated. Based on the return temperature of the building’s cooling system (TABS, cooling ceiling and ventilation), it is possible to simulate a hydraulic linking of the borehole heat exchanger with the ventilation or the hydraulic cooling system. Even simulations with complex ventilation schedules are feasible.

The Pro version allows consideration of groundwater influence, solar collectors and neighboring borehole heat exchangers.

## 1.2 What is new about version 5.3

Version 5.3 has brought, among others, following improvements:

- Free borehole arrangement for up to 150 boreholes (full extension) / 600 (Pro version)
- New, smaller borehole illustration with grids of 5m – 50m for the illustration of entire district plans on the original plan (Pro version)
- Consideration of neighboring boreholes (Pro version) with same and different load profile
- Depiction of soil temperature for borehole fields and whole districts (Pro version)
- Display of borehole temperatures for borehole fields over the entire year for the whole simulation duration
- Influence of groundwater for one or two aquifers (Pro version)
- Solar borehole regeneration with thermal solar collectors (Pro version)
- Double-paged, significant report of the simulation results

## 1.3 Further literature

During the elaboration of the program EWS it was paid attention highly to the fact, that users with no deeper comprehension of the models or numerical background, should be able to use the program. Hence a default value for each set of input is provided. In most cases these default values lead to reasonable results. The manual does not present all the models that are used in the code. But these models are published in very detailed manner (sometimes even with source code of the program) in scientific reports and publications (including validations). An overview of the publications can be found in the reference list.

The program EWS contains the EWS module, which was supported by the Swiss Federal Office of Energy (ref. [5], [6], [8]).

## 2 Installation and licensing

### 2.1 System requirements

The following requirements must be fulfilled to ensure a smooth use of the program EWS on your personal computer:

- operating system: Windows XP / Windows Vista / Windows 7 / Windows 8 / Windows 10
- free disk space: at least 100 MB
- screen resolution: at least 1024 x 768 pixel

### 2.2 Program delivery

For legal reasons the program EWS will not be delivered on a physical data medium. It can only be downloaded from the internet or sent by email. It must be unlocked with a license number.

### 2.3 Language versions

The program EWS is available in different language versions (English, German, French, Italian, and Spanish). For loading the program EWS in languages other than German, the translation file "Sprache.ews" must be in the same folder as "Ews.exe". The language can be changed anytime by selecting the favored language in the pull-down menu "info".

### 2.4 Program licenses

The acquisition of a program license authorizes to the installation of the program EWS on one computer of the client. It is feasible to obtain a second license number for a second working station (e.g. laptop, home computer) at the same location without additional charge if the computer is exclusively used by the same person. In the case of the substitution of the old computer, one can apply for a third license.

In all other cases, supplementary program licenses must be purchased for additional installations. For additional licenses of the same client, there will be a 50% price reduction.

Program licenses are unassignable and must not be resold.

Schools and educational institutes get special conditions. Educational licenses are not allowed to be used for commercial calculations.

## 2.5 Installation

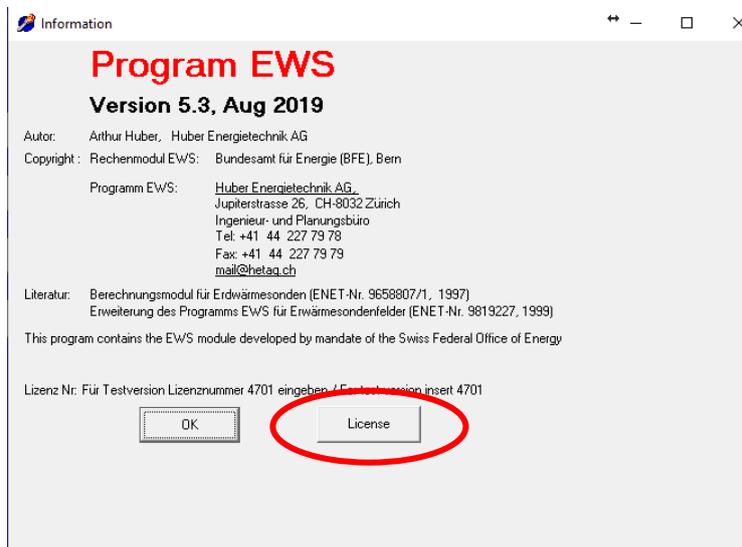
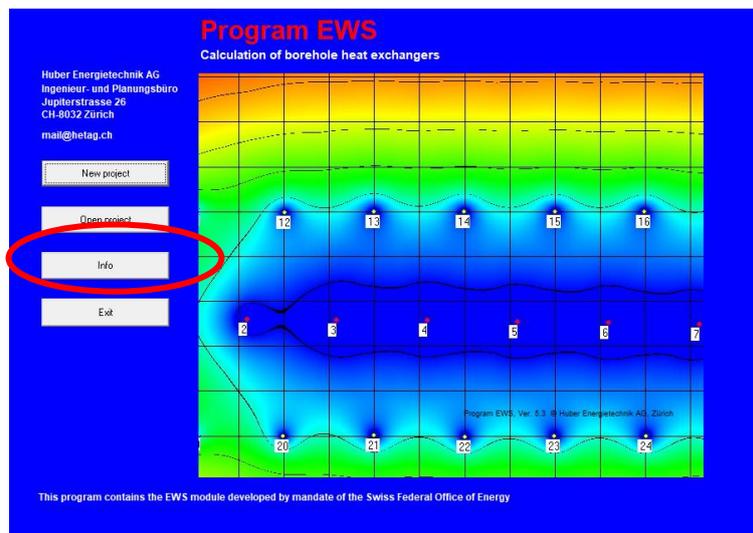
The program EWS requires no installation. Just copy the file “Ews.exe” into your favored program folder on the computer. The program EWS can be unlocked by the entry of the license number. Thereby, 4 types of license numbers are distinguished:

1. license number for test version (4701)
2. license number for a Basic installation
3. license number for Full version
4. license number for Pro version

According to the license number a different functional range is available.

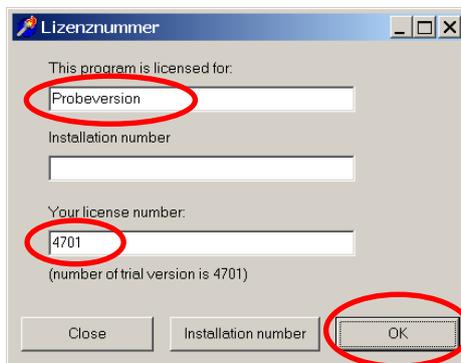
## 2.6 Input of the license number

The test version, the Basic version, the Full version and Pro version must be unlocked by the input of a license number. The corresponding procedure is described in the following:



**Test version:**

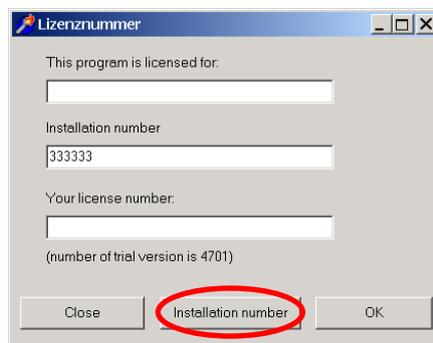
The word **“Probeversion”** must be written in the designated field instead of the company name to unlock the test version. The license number of the test version is **4701**.



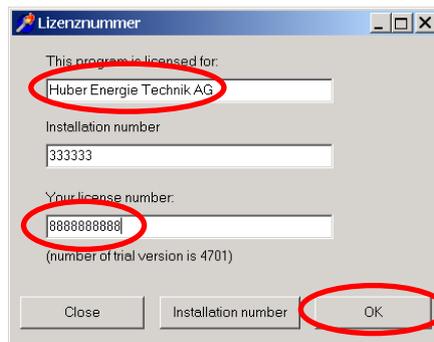
The test version offers everybody the complete functional range of the full program version. But there are some restrictions to a part of entries that cannot be changed (e.g. length of the boreholes, substance properties).

**Basic, full and pro version:**

The installation number is shown by pushing the button “Installation number”. This number has a particular and different value for each personal computer. This number has to be sent together with the name of the company by e-mail to **mail@hetag.ch**. The individual license number will be sent back to you within 48 hours.



The license number and the company name should be entered into the designated fields. Keep the license number saved since after a certain time it might be necessary to enter the license number again.



After the finalization of the installation it is necessary to do one calculation run with the program EWS by using its unchanged default values. Only now it is possible to move on to the data input.

## 3 Data input

### 3.1 Basics of the data input

#### 3.1.1 Missing file „Lizenz.ews“

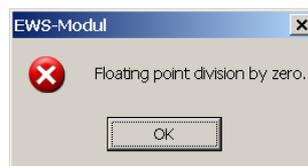
There is no license number entered yet (see chapter 2.6), if the following error message appears during the startup of the program.



If you have already entered the license number and the error message still appears, please assure that the file „Lizenz.ews“ is in the same folder as the program „Ews.exe“. Is this not the case, copy the file „Lizenz.ews“ into the current program folder or enter the license number once more according to chapter 2.6.

#### 3.1.2 Decimal points

It is important that inputs are always entered with decimal points and never with decimal commas. All input information after a decimal comma is ignored by the program and may produce the error message „Floating point division by zero“.



#### 3.1.3 Default values

A default value is allocated for each parameter at the start up of the program. These values were chosen carefully with the aim to represent the most common and useful cases. Generally, the calculation can be made with the default value if a simulation parameter is unknown or its meaning is unclear.

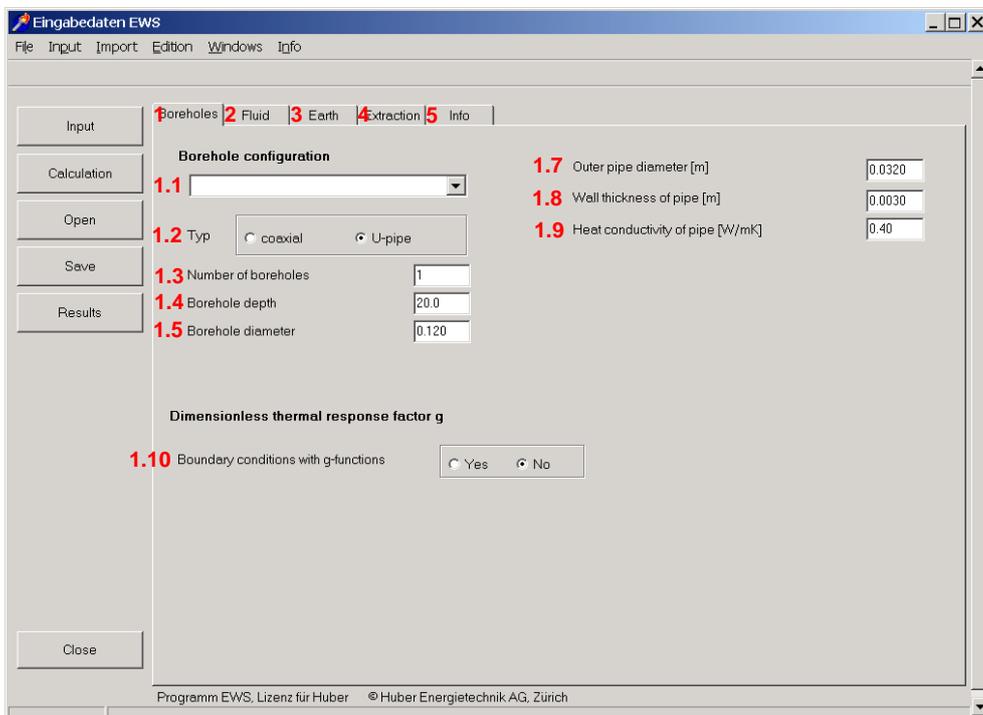
#### 3.1.4 Pull-down menus

Various input fields offer a pull-down menu as a help for the data input. Normally, several input parameters are set to the corresponding values by the selection of an option in the pull-down menu. Nevertheless, please note that these input values can still be changed manually, afterwards. In such a case it may happen that the input values do not agree anymore with the pull-down menu. The EWS Program deals with this inconsistency by using the manually entered values and by ignoring the pull-down selection.

→ **Generally, the EWS Program does not calculate with the values from the selection in the pull-down menu, but always with input field associated to the input parameter. These input fields can be changed in every case, independently of the pull-down menu.**

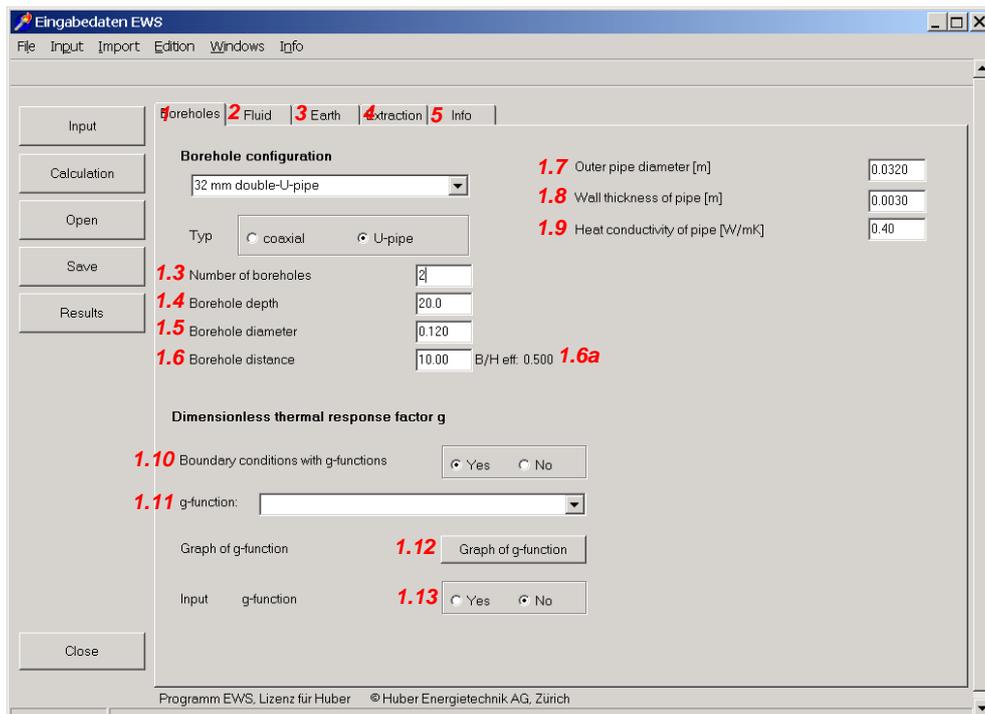
### 3.2 The sheet “Boreholes”

The number of boreholes, the borehole depth H, the type of the boreholes and their configuration can be defined on the sheet “Boreholes”.



**Fig. 3.1: The sheet “Boreholes” and its default values.**

In field 1.4 you enter the depth of the boreholes and in field 1.3 the number of boreholes. Additional input fields appear (see Fig. 3.2), if more than one borehole is entered in the field 1.3. Now the borehole distance can be entered in field 1.6 and in field 1.11 it is possible to choose the borehole configuration.



**Fig. 3.2: On the sheet “Boreholes”, additional input fields appear, if 2 or more boreholes are entered in field 1.3**

### 3.2.1 Selection of the borehole type

By selecting one of the options in the pull-down field 1.1 (see Fig. 3.3) the program automatically fills in the default values for the borehole type (double-U- or coaxial pipes, field 1.2), the borehole diameter  $[2 \times r_1]$  (field 1.5), the outer pipe diameter  $[2 \times r_s]$  (field 1.7), the wall thickness of the pipe  $[r_s - r_o]$  (field 1.8) and the heat conductivity  $\lambda_s$  of the pipe (field 1.9). But these parameters can still be adjusted manually.

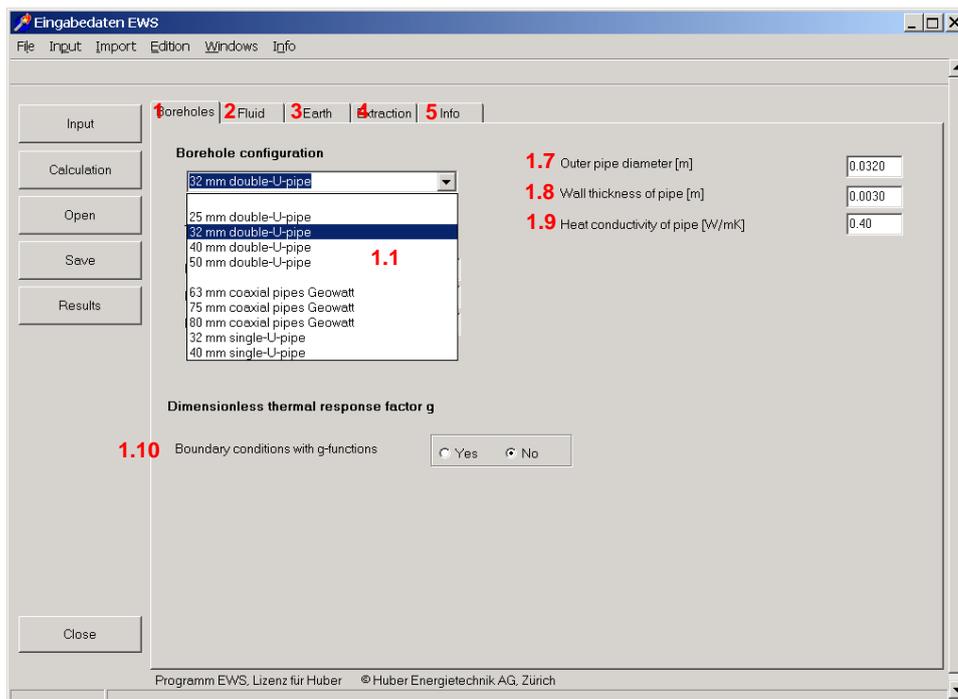


Fig. 3.3: The sheet “Boreholes” with its options to choose in field 1.1.

Especially for the borehole diameter there can be bigger deviations from the default value, depending on the ground properties and the used drilling technology. Check the borehole diameter carefully (field 1.5).

### 3.2.2 Boreholes with double-U-pipes

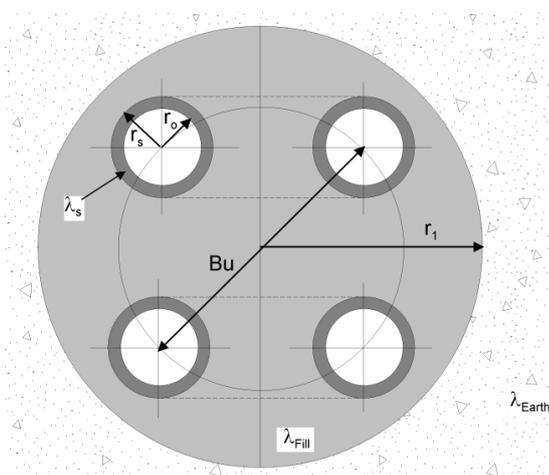


Fig. 3.4: Double-U-pipe nomenclatures.

The borehole disposition can be entered in the following manner:

- field 1.5 Borehole diameter =  $2 \times r_1$
- field 1.7 Outer pipe diameter =  $2 \times r_s$
- field 1.8 Wall thickness of the pipe =  $r_s - r_o$
- field 1.9 Heat conductivity of the pipe  $\lambda_s$
- field 3.11 Shank spacing = Bu
- field 3.3 Heat conductivity of the filling  $\lambda_{Fill}$

### 3.2.3 Coaxial pipe-systems

The additional input fields 1.22, 1.23 and 1.24 appear if coaxial pipes are selected in field 1.2.

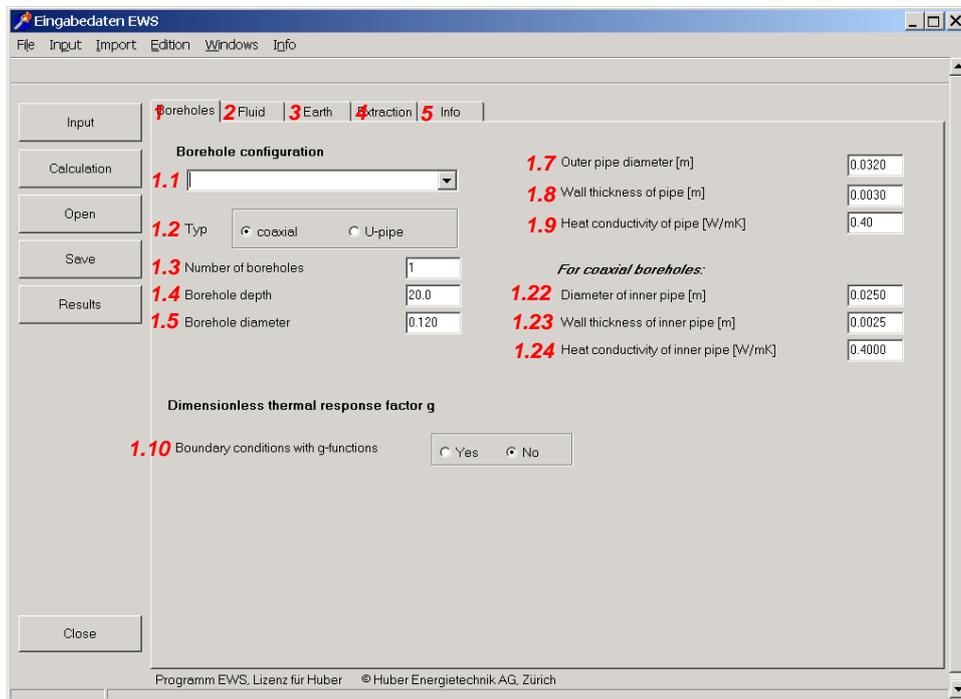


Fig. 3.5: The sheet “Boreholes”, selecting of coaxial pipes in field 1.2.

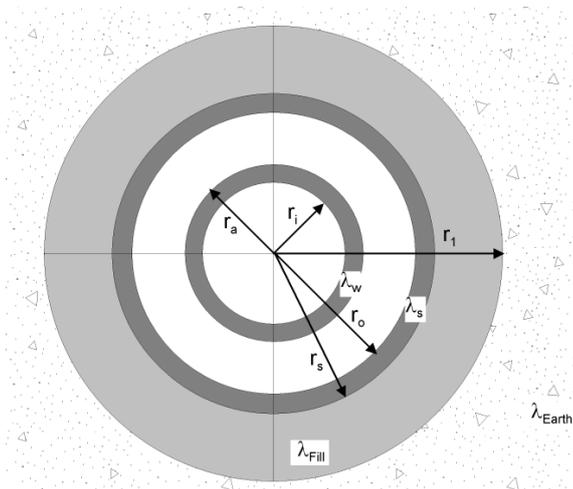
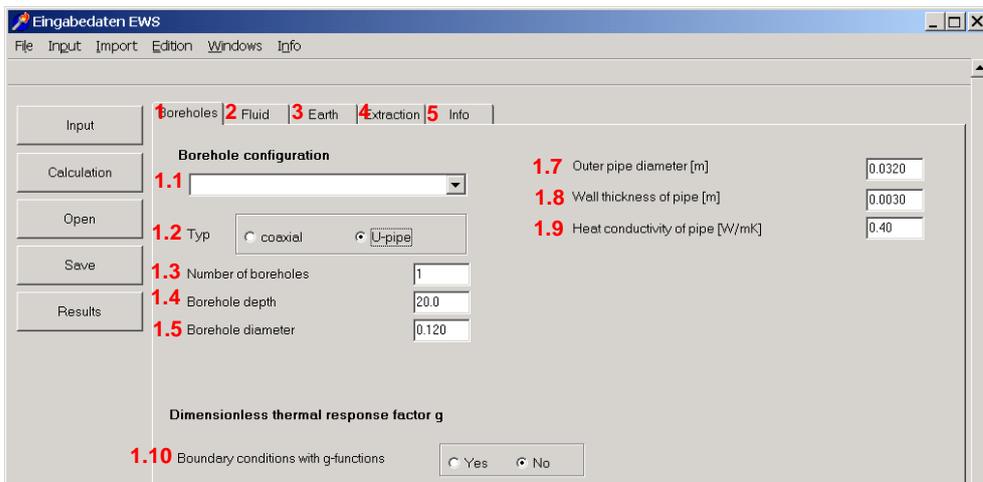


Fig. 3.6: Coaxial pipe nomenclatures.

The borehole disposition can be entered as following:

- field 1.5 Borehole diameter =  $2 \times r_1$
- field 1.7 Outer pipe diameter =  $2 \times r_s$
- field 1.8 Wall thickness of the pipe =  $r_s - r_o$
- field 1.9 Heat conductivity of the pipe  $\lambda_s$
- field 1.22 Outer Diameter of the inner pipe =  $2 \times r_a$
- field 1.23 Wall thickness of the inner pipe =  $r_a - r_i$
- field 1.24 Heat conductivity of the inner pipe  $\lambda_w$
- field 3.3 Heat conductivity of the filling  $\lambda_{Fill}$

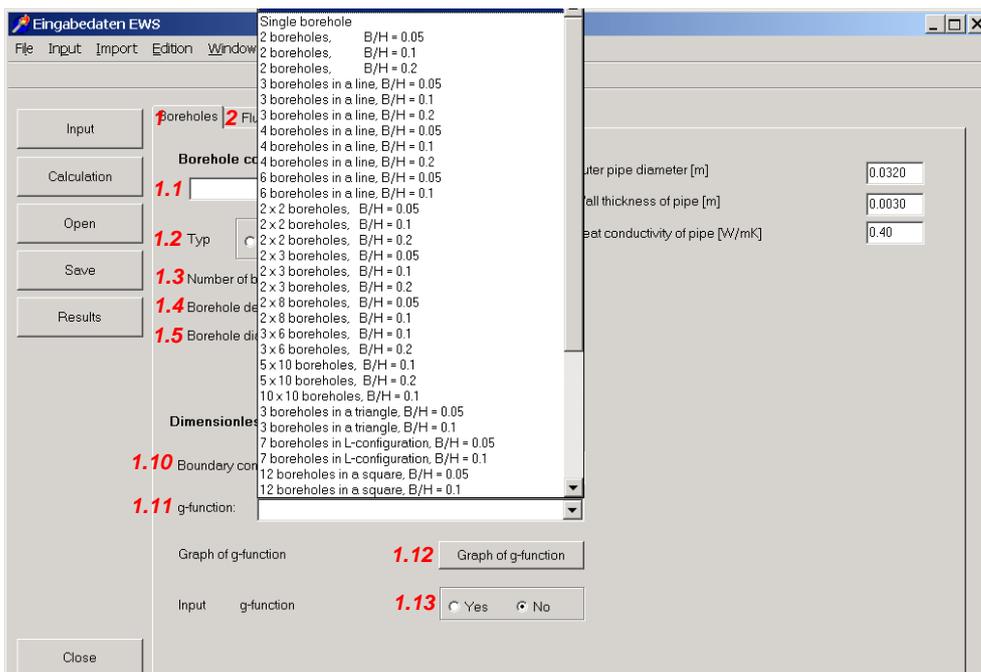
### 3.2.4 Selection of the borehole configuration (single borehole or field of boreholes)



**Fig. 3.7: The Sheet “Boreholes” with its default values.**

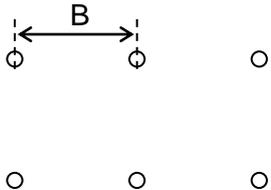
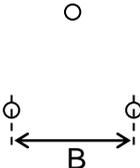
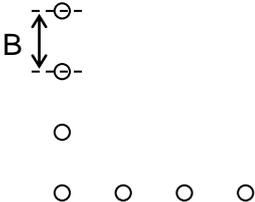
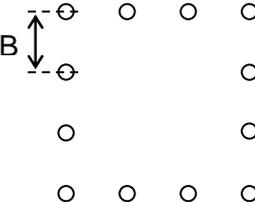
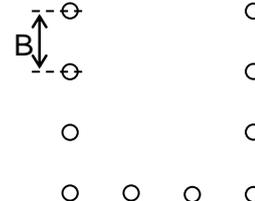
Each type of borehole configuration can be described by its dimensionless thermal response function  $g$  (see eq. 0.8). The program EWS sets the outer boundary condition of the simulation area to this thermal response. For single boreholes, a second possibility is the use of the analytical solution for infinite line sources, described by Carslaw & Jaeger [1] (see eq. 0.11). **Field 1.10** defines which solution is applied. The program EWS sets the boundary condition with the  $g$ -function, if the field 1.10 is set to “yes”, otherwise it uses the equation of Carslaw & Jaeger. The boundary condition calculated by Carslaw & Jaeger is only adequate for single boreholes and simulation periods up to the response time from eq. 0.12.

Once the entered number of boreholes (**field 1.3**) exceeds one, **field 1.10** is set to “yes” and the boundary conditions are calculated with the  $g$ -functions of Eskilson ([2] and [3]). As a consequence the pull-down **field 1.11** appears with a choice of the borehole configurations. There, B/H stands for the ratio of the borehole distance B and the borehole depth H.



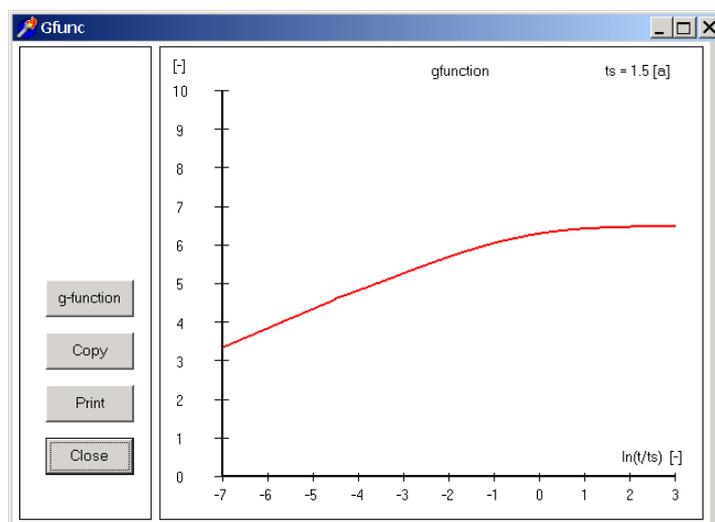
**Fig. 3.8: The sheet “Boreholes” with the borehole configurations to choose from in field 1.11.**

In the following the options for the borehole configuration in **field 1.11** are explained:

<ul style="list-style-type: none"> <li>• „single borehole“:</li> </ul>	<p>The g-function for single boreholes by Eskilson is used.</p>
<ul style="list-style-type: none"> <li>• 1 x n boreholes, e.g. 1 x 4 boreholes:</li> </ul>	
<ul style="list-style-type: none"> <li>• m x n boreholes, e.g. 2 x 3 boreholes:</li> </ul>	
<ul style="list-style-type: none"> <li>• 3 boreholes in a triangle:</li> </ul>	
<ul style="list-style-type: none"> <li>• 7 boreholes in a L-shape:</li> </ul>	
<ul style="list-style-type: none"> <li>• 12 boreholes in a square (around a building):</li> </ul>	
<ul style="list-style-type: none"> <li>• 10 boreholes in a U-shape:</li> </ul>	
<ul style="list-style-type: none"> <li>• „not defined“:</li> </ul>	<p>Each borehole is calculated with the equations by Carslaw &amp; Jaeger (eq. 0.11) (single infinite line sources).</p>
<ul style="list-style-type: none"> <li>• „special input“:</li> </ul>	<p>Description see chapter 3.2.5.</p>

Please pay attention to the following: The number in field 1.3 will not be adjusted automatically if the number of boreholes in the field 1.3 is not consistent with the selection in field 1.11! All calculations are always based on the value in field 1.3.

Each g-function is only valid for a specific ratio of the borehole distance B to the borehole depth H. If the effective  $B/H_{\text{eff}}$  ratio (field 1.6a) differs from the B/H value of the selected g-function, the g-function will automatically be extrapolated to  $B/H_{\text{eff}}$ . This extrapolation is based on findings from Huber & Pahud [6]. Since all extrapolations are afflicted to an uncertainty, always use the g-function with the B/H ratio closest to the effective value in the field 1.6a. This extrapolated g-function, which is used for the calculation, will be shown graphically by pressing the button 1.12.

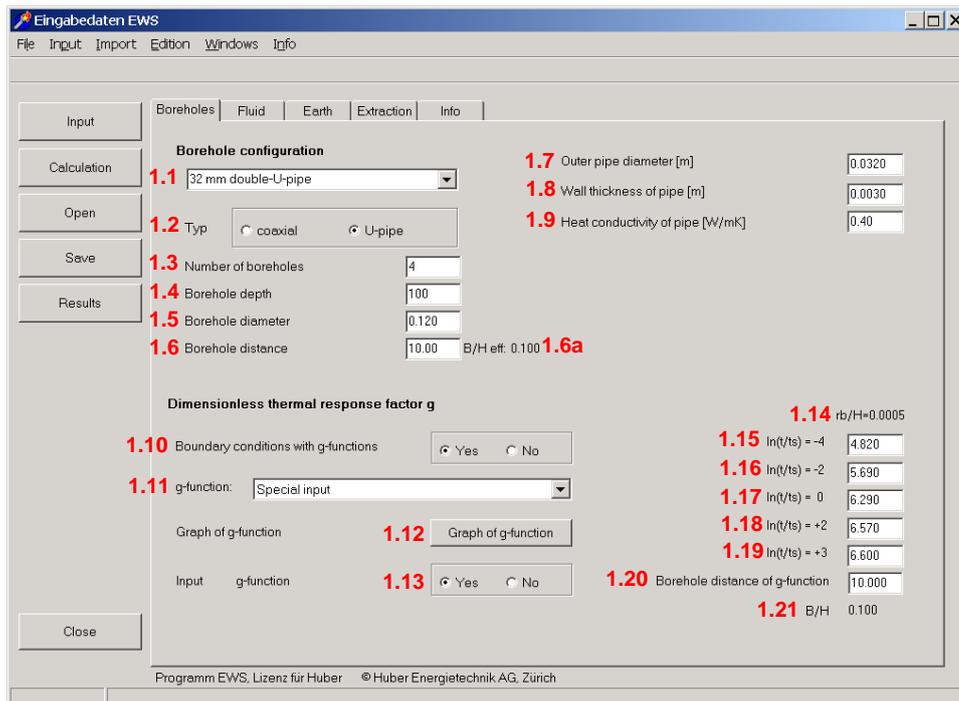


**Fig. 3.9:** The Sheet “Boreholes” with the graph of the extrapolated g-function.

### 3.2.5 Input of a particular g-function

The EWS Program offers the possibility to enter a particular g-function as an alternative to the selection of a borehole configuration from the library (field 1.11). There is a number of published g-functions in the literature (e.g. [3]). Additionally, new g-functions can be interpolated from the existing library values. For instance, the borehole configuration 1 x 5 boreholes, if desired, can be interpolated to a sufficient accuracy from the borehole configuration of 1x 4 and 1 x 6 boreholes.

In the following, it is shown how the user can enter a particular g-function. This is only necessary, if the borehole configuration cannot be described by one of the options in the field 1.11. To enter a g-function, chose “special input” in the field 1.11 and then select “yes” in the fields 1.10 and 1.13. Thereafter, the fields 1.14 to 1.21 (see Fig. 3.10) appear on the right hand side.



**Fig. 3.10:** The Sheet “Boreholes” during the input of a particular g-function.

The fields 1.15 to 1.19 describe the g-function by giving the function values of the data points  $\ln(t/t_s) = -4, -2, 0, +2, +3$ . Published or self-calculated g-functions are always valid for a specific B/H ratio. The B/H ratio in the field 1.21 is calculated from the borehole distance B (field 1.20) and the borehole depth H (field 1.4). First, the field 1.21 must be harmonized with the B/H ratio of the favored g-function. This can be done by adjusting the borehole distance in field 1.20 (The borehole depth in the field 1.4 must not be changed). Thereafter, the function values of the favored g-function on the data points  $\ln(t/t_s) = -4, -2, 0, +2, +3$  can be entered in the fields 1.15 to 1.19. The g-function is now completely defined by the fields 1.15 to 1.21.

Remarks:

- Field 1.14 shows the ratio of the borehole radius  $r_b$  and the borehole depth H. This ratio is 0.0005 for all g-functions in the program library (and for most of the published g-functions). It cannot be changed and it is published for the sake of completeness.
- It is still the effective ratio  $B/H_{eff}$  from the field 1.6a (and not the B/H ratio from the field 1.21) that defines the result of the calculation. During the next calculation, the EWS Program will automatically extrapolate the entered g-function to the effective  $B/H_{eff}$  ratio.
- If the g-function was entered under “special input” in the field 1.11 as described above, this g-function can be saved and later be reloaded from the option “special input”.
- More detailed information about the g-function can be found in the ANNEX.

### 3.3 A freely designed borehole configuration: The sheet „Field of boreholes“

Only in the Full version (and Pro version) of the program EWS, an additional, smart option is offered to enter any kind of borehole configurations in a field. To take advantage of this option choose “Field of boreholes” in the menu “Input” (see Fig. 3.11).

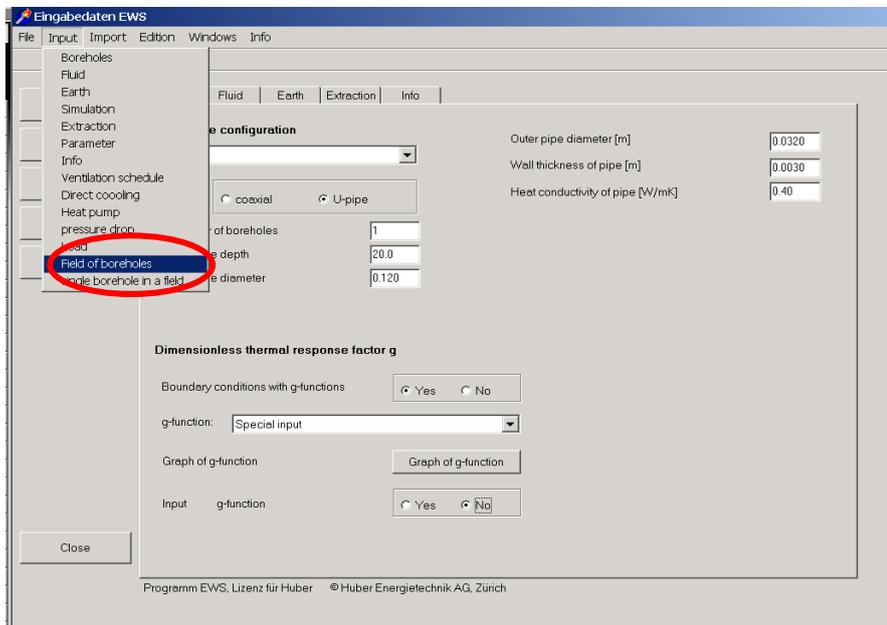


Fig. 3.11: The selection of the sheet “Field of boreholes” in the menu “input”

The Full version of the program EWS now shows the sheet “Field of boreholes” with a grid. The distance between two grid lines is one meter. Every ten meters there is a thicker grid line. The grid lines correspond to a net of coordinates in which the left, upper corner has the coordinates 0/0.

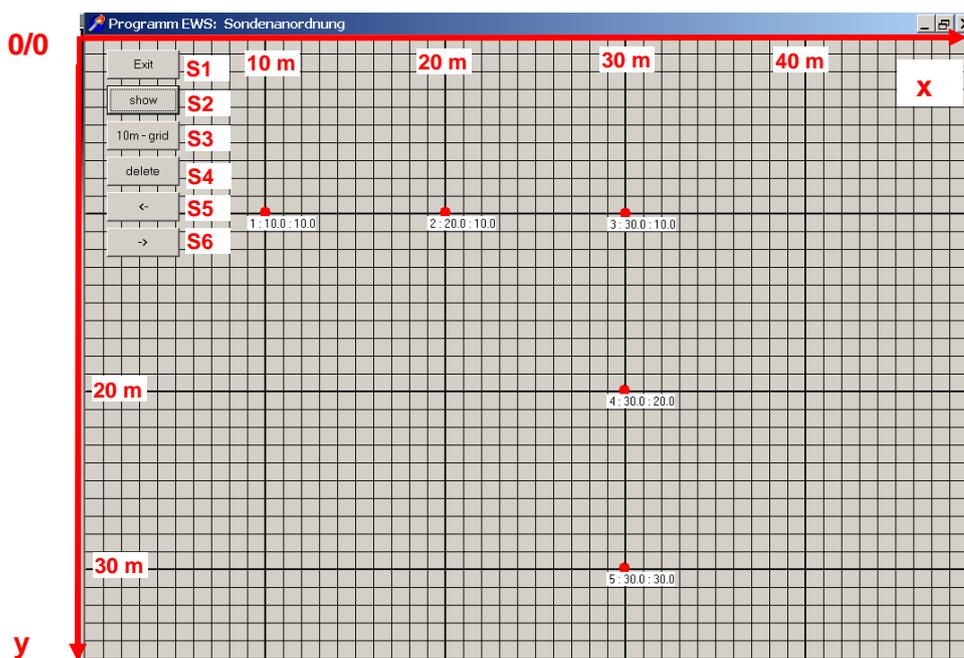
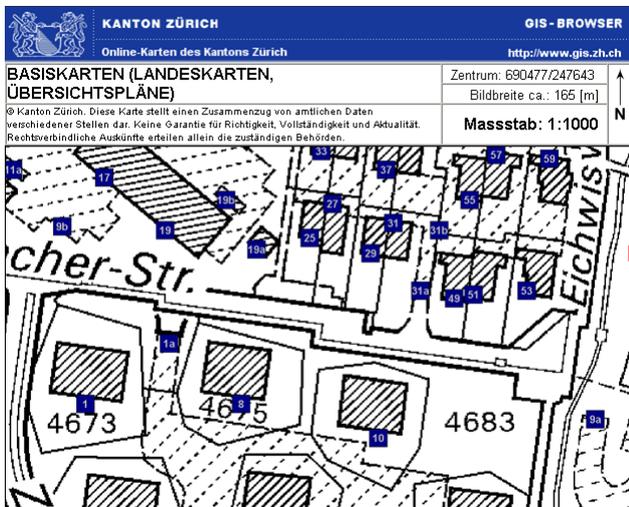


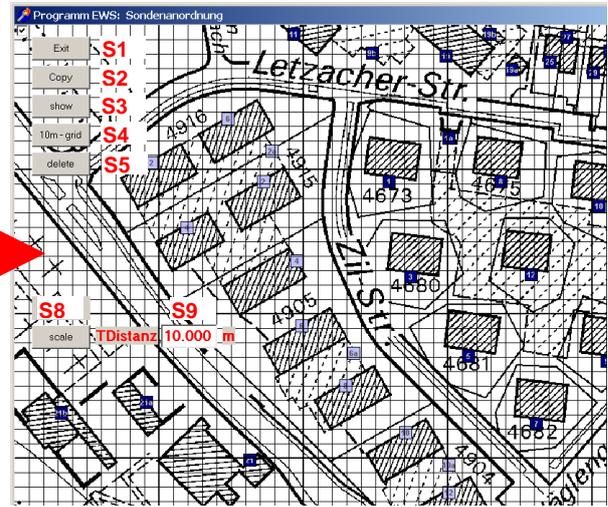
Fig. 3.12: The Sheet “Field of boreholes” with the grid (1 line per meter).

### 3.3.1 Inserting a background-map in 4 easy steps:

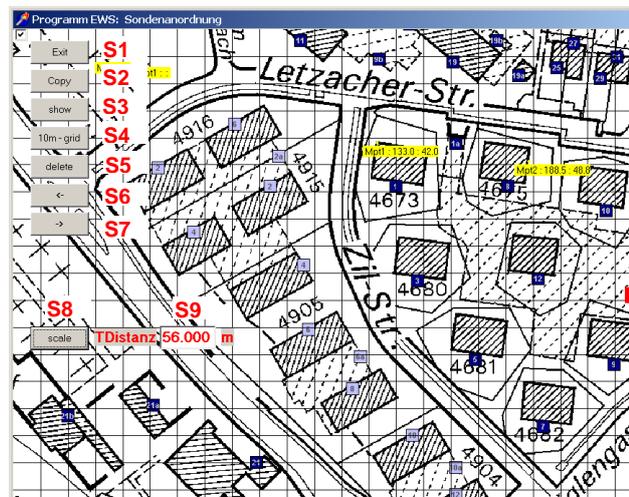
In the Full version of the program there is the possibility to insert a background-map. This map can be scaled. The picture of the map has to be in the BMP-format and must be stored in the clipboard first (e.g. by getting a „print screen“ of one of the existing GIS-browsers) and can then be pasted into the sheet „field of boreholes“ by pressing on the **middle mouse button (mouse wheel)**. Mac-users (no mouse wheel), may choose “Mac” by clicking Info in the main menu: This will add a button “Clipboard in the Field of Boreholes. In the next step the grid must be scaled to fit to the inserted map. To do so, with the button **S8** („scale“) a well-known distance can be inserted in field **S9** and defined on the map by marking the starting point Mp1 and the ending point Mp2 with the left mouse button. With the buttons **S6** and **S7** the map and the grid finally can be set to the favored size on the screen. Now we are ready to define the positions of the borehole as described in 3.3.2. As soon as the first borehole is set, the background map cannot be changed any more. In the following pictures the 4 steps to insert a background map are shown in detail:



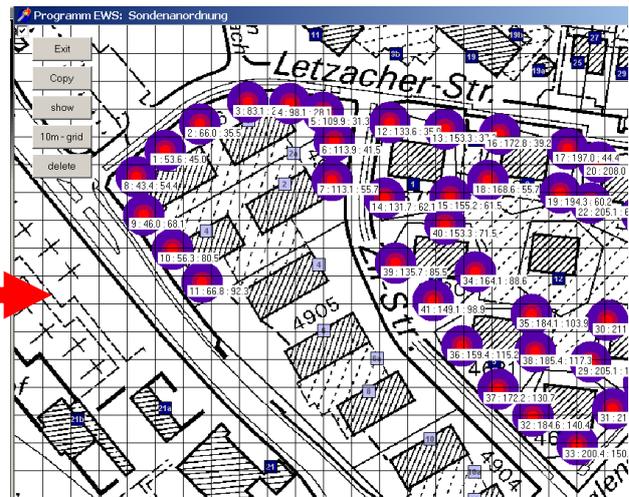
**Fig. 3.13:** 1. step: Store an appropriate map in the clipboard (e.g. by getting a print screen of one of the existing GIS-browsers as [www.gis.zh.ch](http://www.gis.zh.ch))



**Fig. 3.14:** 2. step: By pressing the middle mouse button / mouse wheel into the sheet “field of boreholes” the clipboard is pasted on the screen.



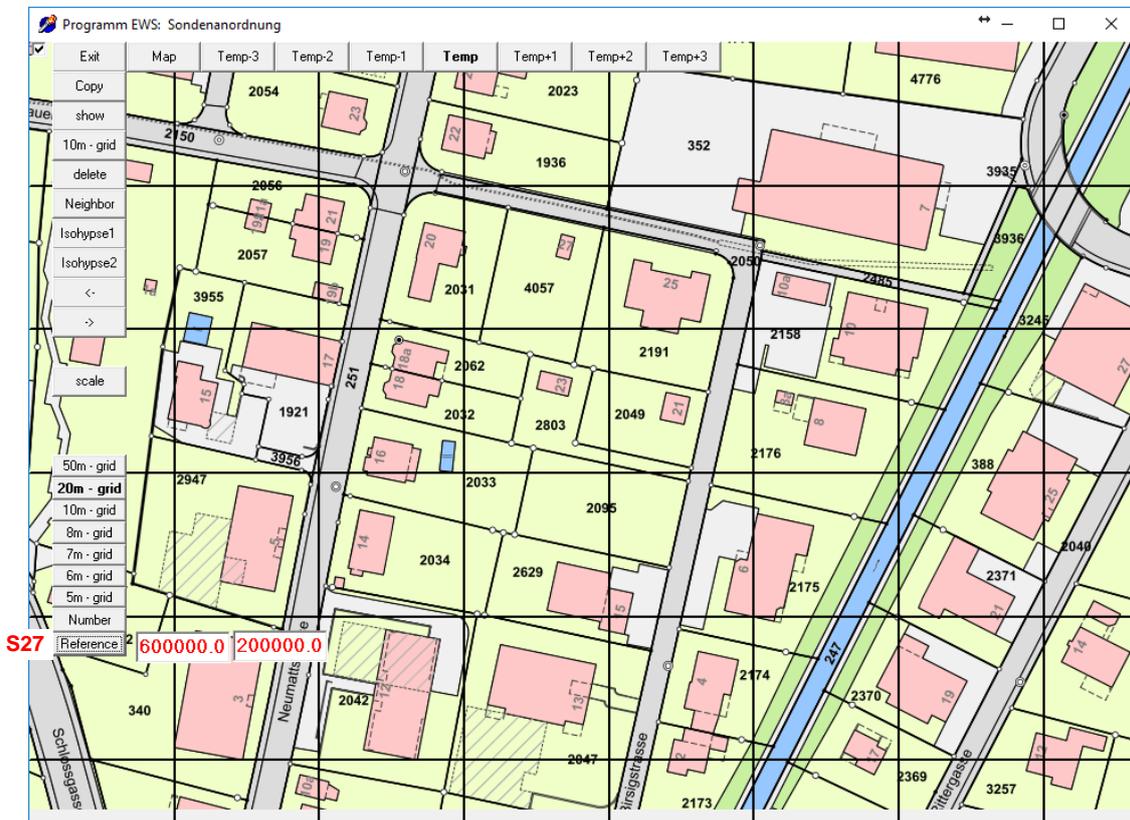
**Fig. 3.15:** 3. step, scaling the map: Choose 2 well known points on the map, define the distance of these 2 points (field **S9**) and mark the 2 points by pressing the left mouse button on this points. Finalize this step by just clicking into the map.



**Fig. 3.16:** 4. step: With the buttons **S6** and **S7** the map and the grid finally can be set to the favored size on the screen. Now insert the borehole positions as described in 3.3.2. **Note:** As soon as the first borehole is set, the map cannot be changed anymore!

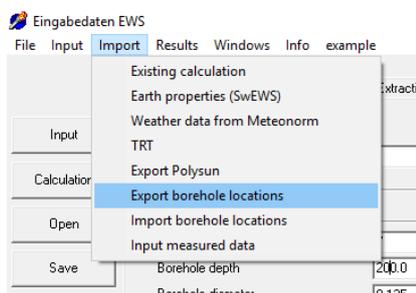
### 3.3.2 Set coordinates on map

It is possible to define an own coordinate grid, if a background map was provided (according to chapter 3.3.1). To do so, one must choose the button **S27** "Reference". Two fields with the abscissa (x-axis) and the ordinate (y-axis) appear. These can be changed by the user and the defined reference point can be placed on the map by a left mouse click.



**Fig. 3.17:** The sheet "Field of boreholes" with the option to set an own coordinate grid.

Now boreholes can be placed according to chapter 3.3.3. The coordinates of the placed boreholes will be defined relatively to the appointed coordinate grid and their position can be exported for subsequent reproduction.



To save the borehole positions, one must exit the field of boreholes window and click the "Import" from the main menu, to then choose "Export borehole locations" and save this file to an appropriate folder.

The location file can later on be imported ("Import" from main menu and "Import borehole locations") in a different EWS project with a different grid background or plan (chapter 3.3.1), before the boreholes are placed. The new reference point must be set to be the same as the original reference point placement, in order to secure the correct borehole placement.

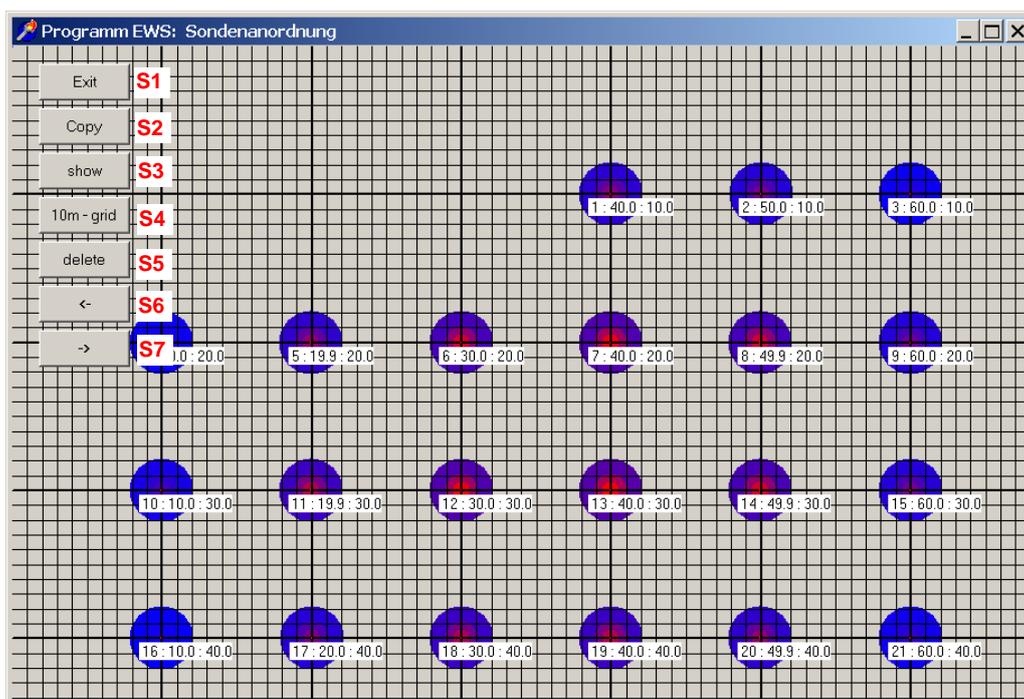
### 3.3.3 Set, dislocate and delete boreholes in a field of boreholes

It is possible to freely arrange up to 150 boreholes (600 in the Pro version) on a field of boreholes by clicking with the left mouse button. Directly below each of the boreholes appears the borehole number (counting up from 1 in the order of the borehole placement), followed by the x-coordinate and the y-coordinate of the borehole. The x-coordinate and the y-coordinate correspond to the distance in meter from the left, upper corner of the grid. With the button **S4** the grid spacing can be changed from 1 m to 10 m. Each borehole can be set with a precision of 10 cm and can be **dislocated** with the mouse anytime. To dislocate the borehole, select the centre of the borehole with the **left mouse button** and dislocate it, still keeping the left mouse button pressed. It is also possible to **delete** boreholes. To do so, select the centre of the borehole with the **right mouse button** and remove the borehole, while still pressing the right mouse button. Thereby, the corresponding borehole disappears. Immediately, all other boreholes are newly numerated.

Clicking on the button **S3**, 3 concentric circles around each borehole appear, whereof the colors give a hint about the g-value of the field of boreholes: Red indicates a high g-value and blue stands for a low value. The color scale is not an absolute scale but a relative one: The highest value in the field of boreholes always has the same red while the lowest value has the same blue. The colors give a hint about the relative distribution of the temperature in the ground around the borehole.

It is possible to zoom in (button **S7**) and to zoom out (button **S6**) of the borehole field if the field of boreholes is bigger than the displayed range. Thereby, the left, upper corner always keeps the coordinate 0/0. The button “delete” (**S5**) deletes **all** boreholes.

By pressing the button **S2** the whole sheet can be copied into the clipboard and thus be used for reporting in other programs, such as Word. The sheet “Field of boreholes” can be quit with the button **S1**, whereby all input data will be saved (number of boreholes, coordinates of the boreholes, distances of the boreholes, g-function). The values of the g-function are transferred to the fields 1.15 to 1.19 of the sheet “Boreholes” and can be checked there.



**Fig. 3.18:** The sheet “Field of boreholes” with 21 boreholes. The “blue” boreholes give a higher yield, the “red” boreholes give a lower yield.

### 3.3.4 Optimization of borehole fields

The procedure of the optimization of a field of boreholes shall be illustrated on an example with 5 x 10 boreholes. The blue colored boreholes have the highest yield. Boreholes with lower yields (they are located in the centre of the field where the heat hardly flows to) are purple at the borders and dark red in the centre. The **button 1.12** shows a graph of the g-function which makes the difference easily visible: The g-function can be reduced by 8% with the relocation of the 4 central boreholes. This means that the borehole temperature in the balance condition in the right example will sink 8% less, than the one on the left.

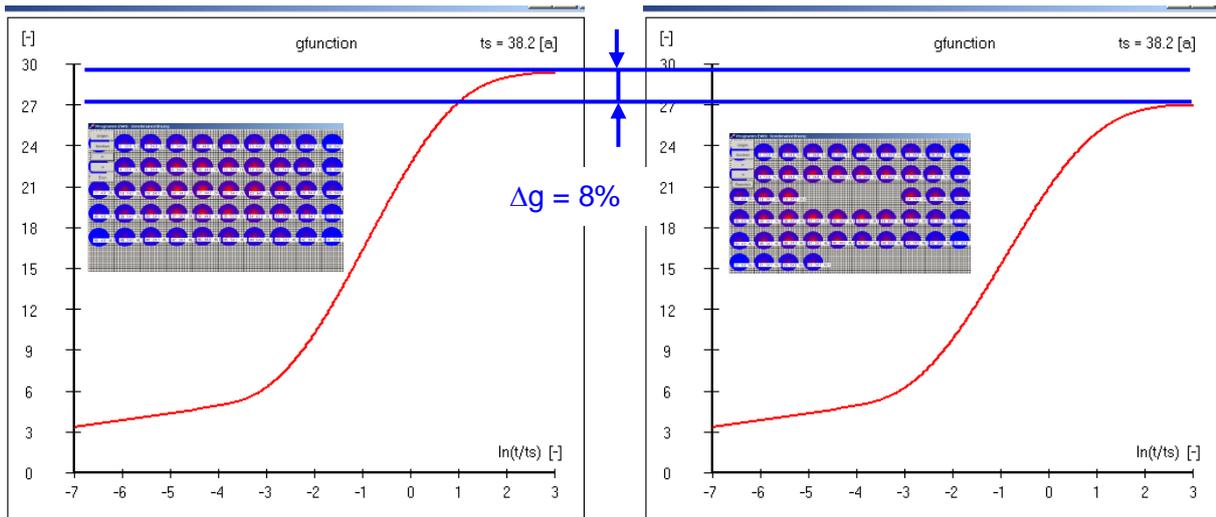


Fig. 3.19: The comparison of 2 borehole fields with 50 boreholes of 100m depth and 10m distance.

### 3.3.5 Calculation of a single borehole in a field of boreholes

There exists the possibility to calculate the g-function of a single borehole in a field of boreholes (see Fig. 3.20) if the borehole field was defined according to the description in chapter 3.3.

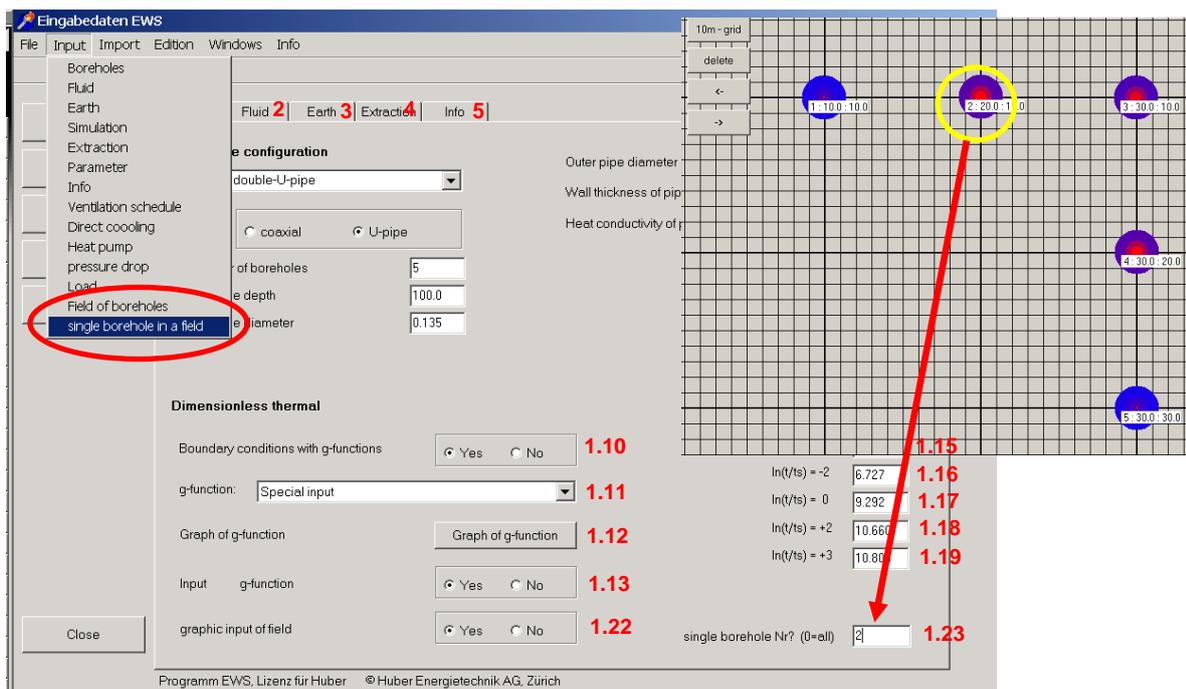
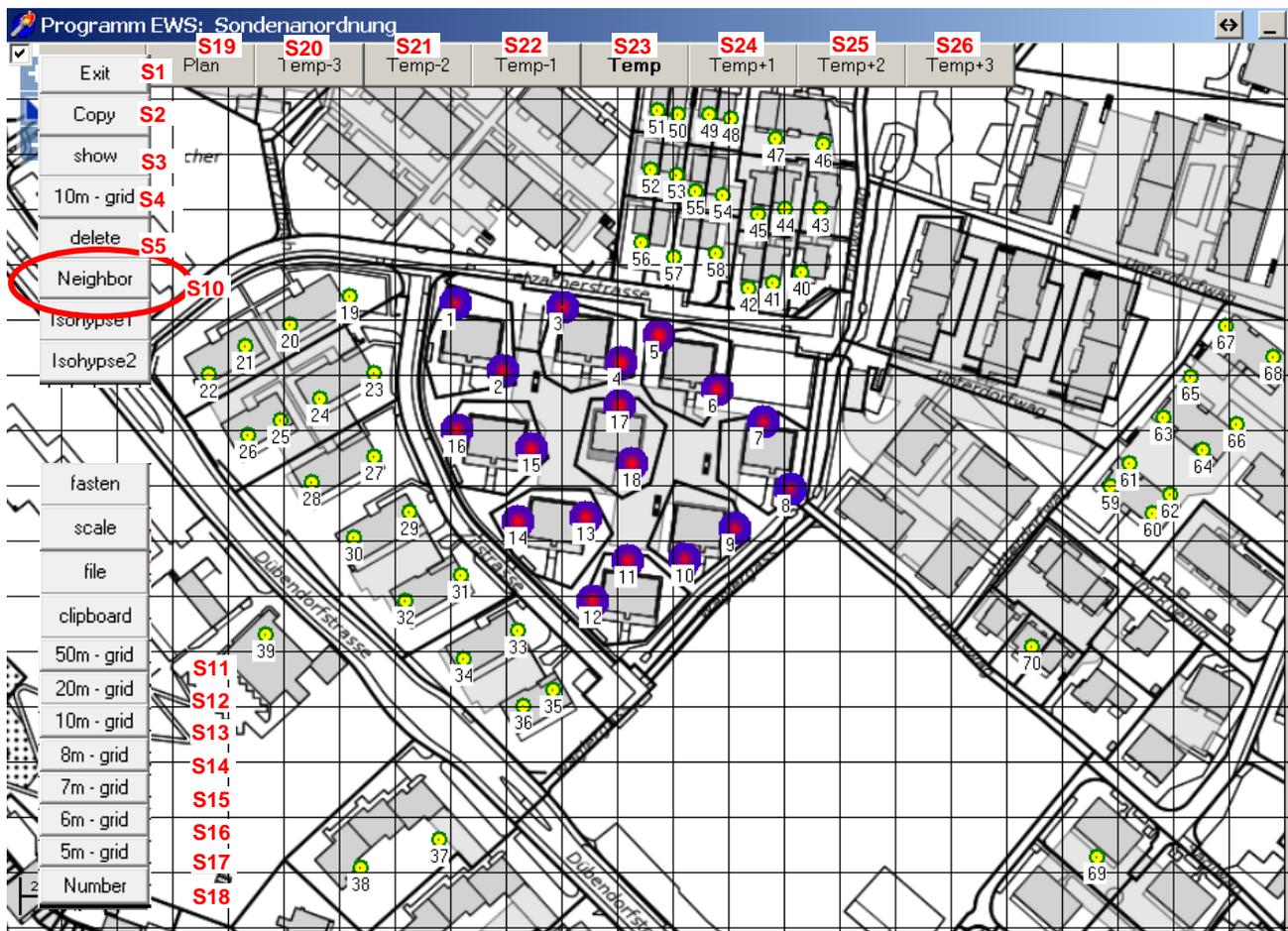


Fig. 3.20: The calculation of a single borehole in a field of boreholes.

### 3.3.6 Neighboring boreholes and new borehole configuration in the Pro version

In the Pro version there is the possibility to consider neighboring boreholes. Thereby the program EWS assumes that the neighboring boreholes have the same thermal load as the ones being used in the present project. The description of the calculations is in Chapter 6.5.

Button **S10**, called “Neighbor”, appears only when a map is inserted according to chapter 3.3.2 in the pro-version. Clicking this button switches you to the “neighbor mode”. In this mode all the added boreholes are marked yellow, as neighboring boreholes. Neighboring boreholes do not belong to the present project, but affect the g-function and the calculation result. By pressing the button “Neighbor” again, the mode is set back to normal and boreholes of the present project can be added again. Neighboring boreholes can be moved and deleted just as normal boreholes.

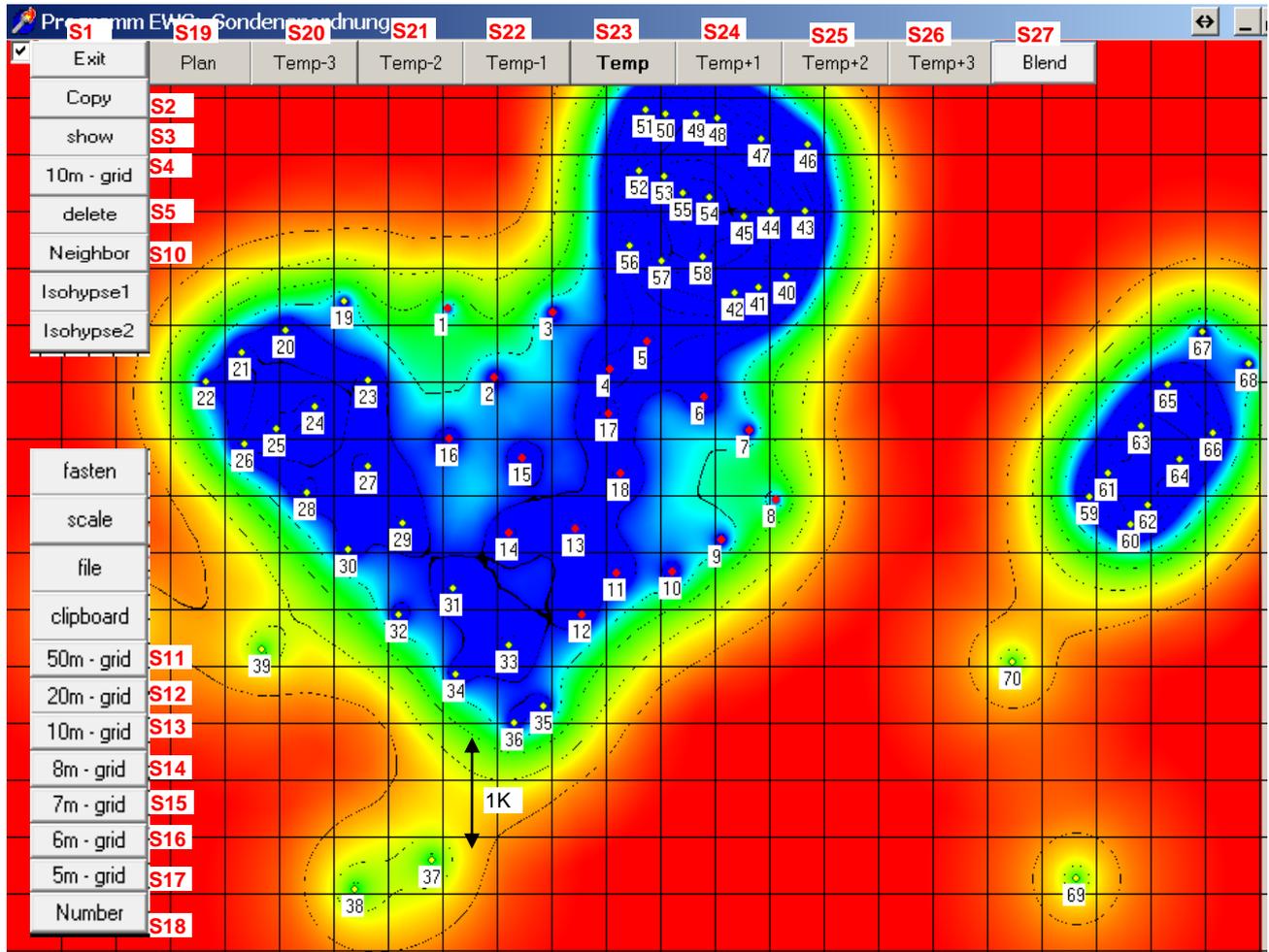


**Fig. 3.21: Input of neighboring boreholes (yellow) in the pro-version**

In the pro-version an additional display format was implemented, which is suitable for mapping entire districts with up to **600 boreholes**. In this new display format, the boreholes are smaller. The coordinates of each borehole are now only shown when a borehole is being moved with the mouse. The borehole number can be enabled or hidden by pressing button **S18**. The new display format can be activated by choosing the grid size of 5m to 50m with the buttons **S11 up to S17**. The chosen grid size is marked in bold on the corresponding button (S11 to S17).

### 3.3.7 Display of ground temperature in the pro-version

In the Pro version of EWS, the cooling down (or warming up) of ground temperatures after 50 years in the yearly average can be displayed. Color-wise, a cooling down and a warming up are displayed equally. The seasonal temperature fluctuations near the boreholes, which result from the load profile throughout the year, are not displayed. The fine, black lines mark isothermal lines, the difference between these lines amounts to 1°K temperature difference. The color scale can be set with the buttons **S20 to S26**. Ground temperatures can only be shown, if a map was previously provided as described in chapter 3.3.1. With the button **S27** a continuous fading of the map and of the temperature fields can be set.



**Fig. 3.22: Display of ground temperatures after 50 years in the Pro version.**

Ground temperatures can only be displayed correctly, if previously the borehole field was calculated with the correct load profile. For this purpose the sheet „Field of Boreholes“ must be properly closed with the button **S1** after finishing the placement of the boreholes and a new calculation must be carried out. After this the sheet „Field of Boreholes“ can once again be opened (see Fig. 3.11). The desired grid size can now be chosen (**S11 – S17**) and then with the buttons **S20 to S26** the ground temperature can be calculated and displayed. **Buttons S20 through S26** differ only by the displayed color scale. By pressing button **S19** or by changing the grid size, one returns back to the plan view. Attention: The use of screenshot-tools (e.g. SnippingTool) is not supported and can lead to a black screen. We advise the use of the „Copy“-button **S2** or the „screenshot-function“ of Acrobat Reader.

### 3.3.8 Location Marker and Neighboring Boreholes with different Load Profiles

If the ground temperature is chosen (Pro version), one can set a location marker with **Button S28** and a mouse-click on a chosen location. A red point appears on this location with the marker “Stao”, followed by the coordinates and the temperature cooling after 50 operation years. This is possible as well, in the continuous fade mode (**Button S27**).

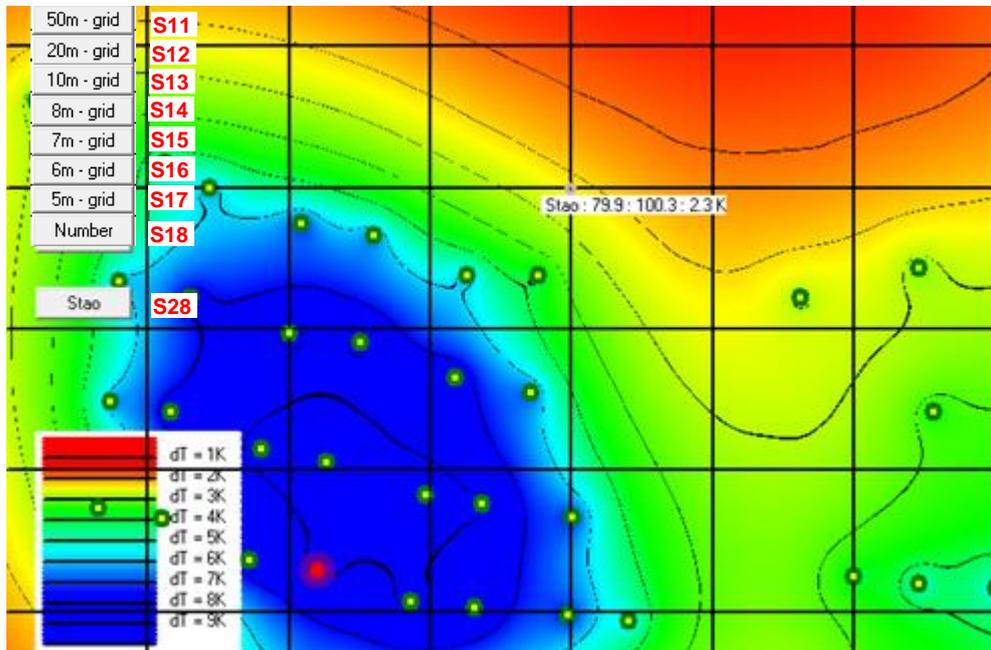


Fig. 3.23: Setting the Location marker S28 and display of the temperature cooling after 50 years.

If the marker is set, the yearly temperature cooling at this location can be exported in a file named “Stao.ews”. For this, leave the sheet “Field of Boreholes” and on the Menu bar select *Import -> Export Temp Stao*. By doing this, the file “Stao.ews” is written and saved. This is a text file and can be opened with any text editor or Excel.

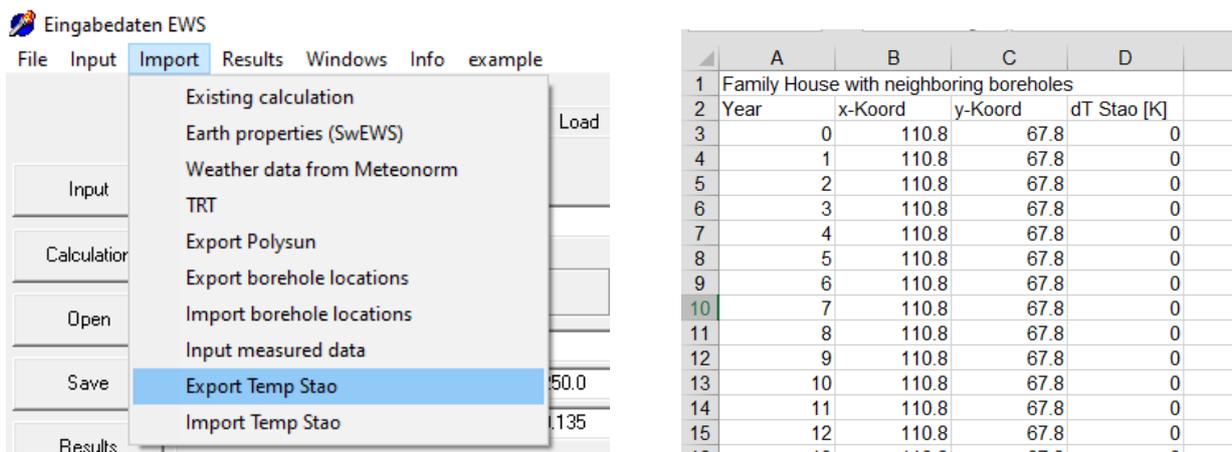


Fig. 3.24: Export of the temperature cooling at the location of the Stao Marker into the file “Stao.ews”

For a new project planned at the location of the marker, one can now consider the influence of neighboring boreholes by importing the file Stao.ews (**Menu bar -> Import -> Import Temp Stao**). The temperature marginal condition for the simulation subtracts the yearly temperature cooling (4<sup>th</sup> column in the file Stao.ews), thus, accounting for the influence of neighboring boreholes. The influence of neighboring boreholes with different load profiles and different operation beginnings, can be considered by superposition of the values in the 4<sup>th</sup> column of the “Stao.ews” file.

### 3.4 The sheet “Fluid”

The data about the borehole fluid and filling can be entered in the sheet “Fluid”.

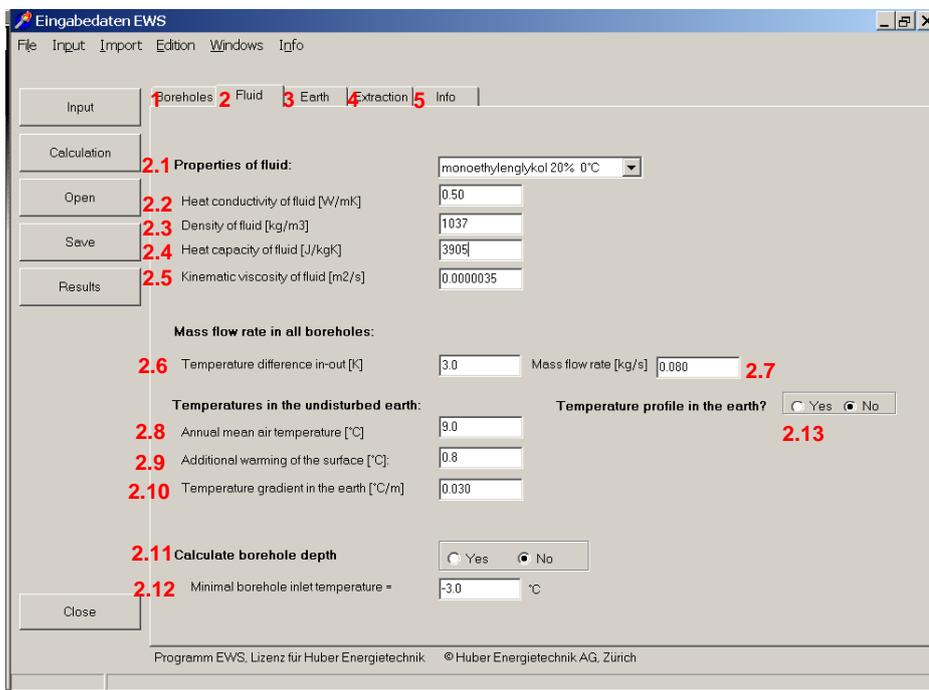


Fig. 3.25: The sheet “Fluid”.

**field 2.1** By selecting one composition of the fluid in the pull-down **field 2.1** all corresponding data (the heat conductivity, the density, the specific heat capacity and the kinematic viscosity of the fluid) are inserted automatically. If the used fluid is not listed in the pull-down field 2.1, there is the possibility to select “not defined” and to manually enter the values of **fields 2.2 to 2.5**.

**fields 2.6/2.7** The required input in **field 2.7** is the designed mass flow rate (cumulated mass flow of all boreholes together). If this mass flow rate is unknown, there is the possibility to enter the temperature difference between the borehole inlet and the borehole outlet temperature in **field 2.6**. Immediately, the program adjusts the mass flow rate (**field 2.7**) using eq. 3.1 and the inputs of the heat extraction rate (**field 4.4**), based on the temperature difference (**field 2.6**) and the heat capacity of the fluid (**field 2.4**). It is important to know that the program does all calculations using the value of the mass flow rate (**field 2.7**). The value in field 2.7 can be changed anytime without causing an adjustment of other variables, while changes of the other variables (fields 2.4, 2.6, 4.4) result in an adjustment of the mass flow rate.

$$\dot{m} = \frac{\dot{Q}}{\Delta T \cdot c_p} \tag{eq. 3.1}$$

Hence, it is possible that the four variables are inconsistent and do not fulfill eq. 3.1 if the last of the four entries concerned is in **field 2.7**. In such a case the program neglects the entry in **field 2.6** and calculates with the value of the **field 2.7**. But be aware that if the heat extraction rate (**field 4.4**) is entered after the designed mass flow rate (**field 2.7**), the program adjusts the value of the **field 2.7** and no longer calculates with the desired mass flow rate. Thus, check the mass flow rate after the three other variables are entered and correct the value, if necessary. It is recommended always to enter the designed temperature difference (**field 2.6**).

### 3.4.1 The temperatures in the undisturbed ground

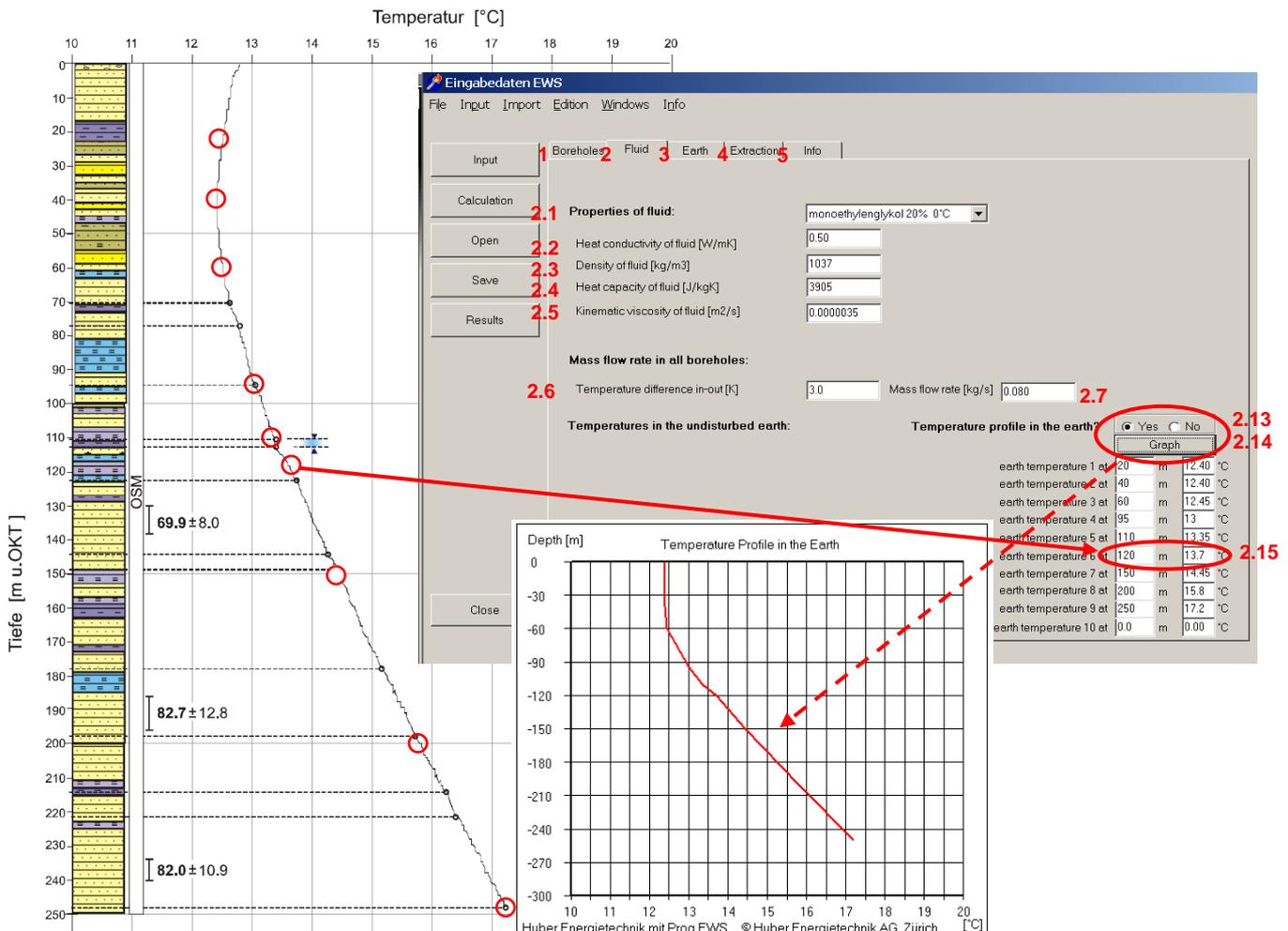
There are 2 methods to insert the data for the undisturbed temperature in the ground (starting condition for the simulation):

1. Entering the annual mean air temperature (**field 2.8**), the additional warming of the surface (**field 2.9**) and the temperature gradient  $\Delta T_{Grad}$  in the ground depth (**field 2.10**). With the mean air temperature, the dependency on altitude must be taken into account (reduction of some 0.47K per 100m higher altitude). The mean air temperature and the additional warming of the surface are simply added in the program. For the temperature gradient  $\Delta T_{Grad}$ , the geothermal heat flux  $\dot{q}_{geo}$  and the thermal conductivity of the earth  $\lambda_{Earth}$  exists the following correlation:

$$\dot{q}_{geo} = \lambda_{Earth} \cdot \Delta T_{Grad} \quad [W / m^2] \quad \text{eq. 3.2}$$

2. Directly entering the temperature profile in the undisturbed ground in a maximum of 10 points (**fields 2.15**). The surface temperature will in this case be extrapolated linearly out of the first two inserted values and the temperature in the depth out of the last two inserted values.

To change from method 1 to method 2, **field 2.13** must be set to „Yes“. In this case, the input fields 2.8 – 2.10 will disappear and the **fields 2.15** and **button 2.14** („Graph“) will appear instead. With these, the temperature profile in the earth can be defined.



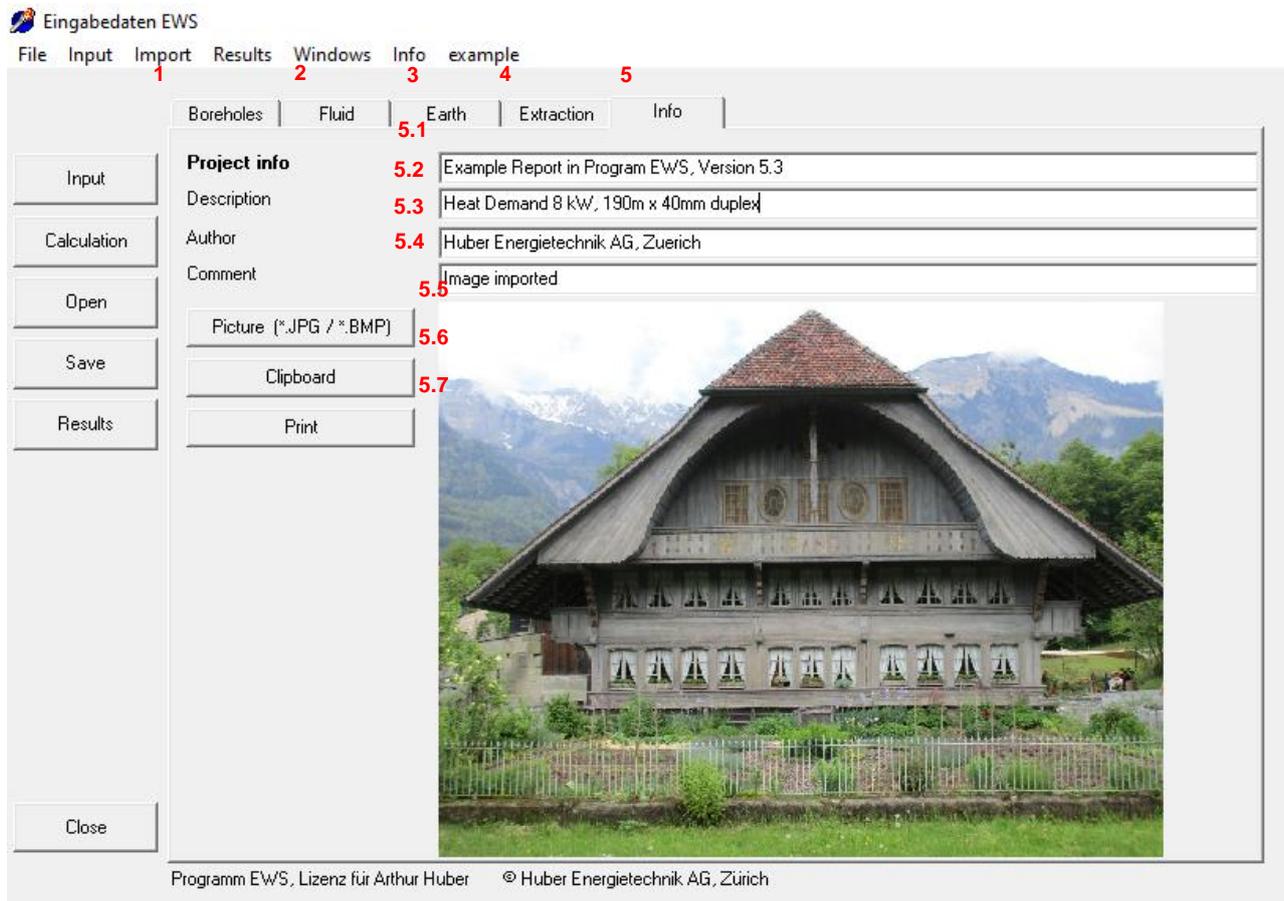
**Fig. 3.26: Input of the undisturbed temperature profile in the earth out of a measurement. (Example from a measurement of Dr. U. Schärli / E. Rohner [19]).**

### 3.4.2 Automatically calculated borehole length

The program EWS is able to automatically calculate the necessary borehole length according to the norm SIA 384/6 [21]. To do so, the simulation period in field 4.8 or field 10.15 has to be set to **50 years** and the minimal borehole inlet temperature in **field 2.12** and the temperature difference over the borehole in **field 2.6** have to be set according to the norm SIA 384/6 (minimal mean temperature of the brine must add up to -1.5°C, e.g. minimal borehole inlet temperature in **field 2.12** set to -3.0°C and the temperature difference in **field 2.6** set to 3.0 K). To start the calculation, the **field 2.11** must be set to “Yes” and the calculation can be started with the button “Calculation”. The program EWS now calculates the minimal borehole length with which the imposed conditions are respected. The resulted length can be read in **field 1.4**.

### 3.5 The sheet “Info”

This sheet helps to specify the project, to describe the variant and to name the author as well as to add some remarks (**Buttons 5.1-5.4**). This project description also appears on the Report-print (see chapter 5.6). Additionally, using **Button 5.5**, an image in JPG or BMP format can be uploaded. Alternatively, with **Button 5.6**, an image in image in the clipboard can be pasted. The image appears in the report as well, which can be started with **Button 5.7** (only Windows 8, 8.1 or 10)

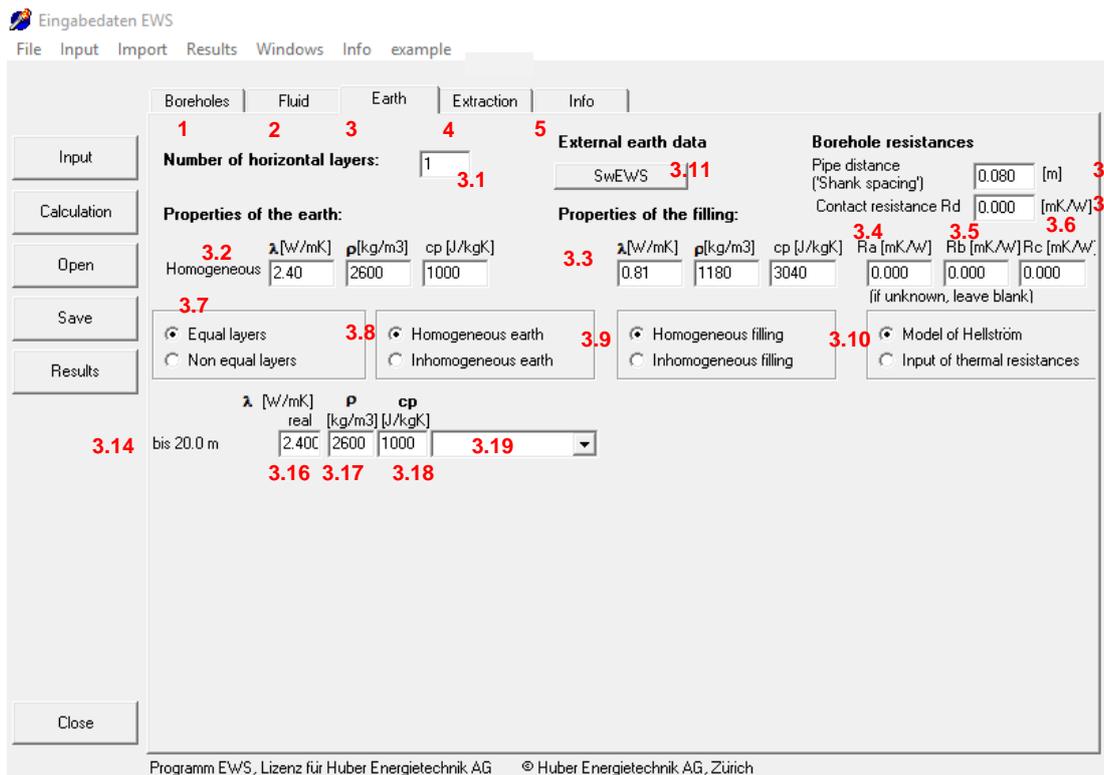


**Fig. 3.27: The sheet “Info”.**

### 3.6 The sheet “Earth”

On the sheet “Earth” the thermal properties of the ground and the filling material can be defined. Furthermore, the number of horizontal layers in the earth are defined on this sheet (field 3.1, maximum 10 layers). The thermal borehole resistances  $R_a$  and  $R_b$  are entered in the fields 3.4 and 3.5. If the borehole resistances are unknown, they can be calculated from the borehole geometry and the properties of the filling material using two methods (see chapter 5.14).

#### 3.6.1 Basic Inputs



**Fig. 3.28:** The sheet “Earth” (with a single, horizontal layer).

**3.1** First, the user defines the number of horizontal layers in the earth. The calculations are executed using equal layers (see below). Calculations with only one horizontal layer (and averaged properties) save computing time but provide less accurate results (because of the coarse calculation grid). Nevertheless, this is often precise enough for boreholes up to a depth of 100 m or for a first, rough dimensioning.

Due to numerical reasons the program EWS internally calculates with a uniform calculation grid in the vertical direction of the boreholes, even if in field 3.7 unequal layers are selected (which is possible only in the full version of the program). The program EWS then internally averages the physical properties of the earth for every vertical calculation layer (field 3.14 – 3.19). The averaging is done prior to every calculation run. Thus, even in the case of a variation in the borehole depths, there is no need for adjustments of the earth’s definition.

**3.2** “Properties of the earth”: The averaged physical properties of the earth (heat conductivity  $\lambda$  [W/mK], density  $\rho$  [kg/m<sup>3</sup>] and specific heat capacity  $c_p$  [J/kgK]) can be entered in the field 3.2 if in the field 3.7 “equal layers” and in the field 3.8 “homogeneous earth” are selected. In this case, the values are transferred

automatically to the **fields 3.16 – 3.18**. The program EWS always computes internally with the values from the **fields 3.16 – 3.18**. If the user adjusts the values in the **fields 3.16 – 3.18** in a later phase, it might happen that the inputs (**field 3.2** and **fields 3.16 – 3.18**) are no longer consistent. In such a case, the values in the **field 3.2** are ignored and they are adjusted in the next calculation run.

Furthermore, the program EWS calculates the arithmetic mean of the “properties of the earth” for the whole borehole depth during each run. The results are showed after the run in **field 3.2**.

Hence, on the one hand, **fields 3.2** are an input assistance and on the other hand they are an output field for the arithmetic mean of the physical earth properties for the whole borehole depth. In no case a further calculation is made with these values.

**3.3** In **field 3.3** the “properties of the filling” (heat conductivity  $\lambda$  [W/mK], density  $\rho$  [kg/m<sup>3</sup>] and specific heat capacity  $c_p$  [J/kgK]) can be entered if in **field 3.9** “homogenous filling” is selected (what usually is the case) or if the calculations are done with a single horizontal layer. The “properties of the filling” are used for the calculation of the thermal borehole resistances  $R_a$  and  $R_b$  (see chapter 5.14).

**3.13** The contact resistance  $R_d$  is an additional resistance between the borehole hole and the filling. The value of  $R_d$  is always added to the value of  $R_b$ .

**3.4 – 3.6** The borehole resistances  $R_a$ ,  $R_b$ ,  $R_c$  can be found in the **fields 3.4 – 3.6**. The definition of the resistances  $R_a$ ,  $R_b$ ,  $R_c$  are given in chapter 5.14.

The default setting of the program EWS calculates the borehole resistances with the equations given by Hellström (see chapter 5.14, option **field 3.10**). In this case the inputs in the **fields 3.4 – 3.6** are ignored (**there is no need for an input**). The borehole resistances are calculated prior to each run using the equation by Hellström and considering the properties of the filling material (**field 3.3**), the mass flow rate in the code case (**field 2.7**) and the distance between the pipes in the borehole (**field 3.12**). The calculated values for  $R_a$ ,  $R_b$  and  $R_c$  are showed in the **fields 3.4 – 3.6** after each run.

The internal resistance  $R_a$  (**field 3.4**) and the resistance of the borehole  $R_b$  (**field 3.5**) can be entered if in the **field 3.10** “Input of thermal resistance” is selected. **In this case  $R_c$  (field 3.6) must be set to zero**. Otherwise the value for  $R_c$  (field 3.6) is used to calculate  $R_b$  (eq. 0.33) and the input of  $R_b$  will be replaced by this new  $R_b$ . In case of any adjustment of the mass flow rate (**field 2.7**),  $R_a$  and  $R_b$  (but not  $R_c$ ) are set to zero and recalculated with the new mass flow rate (eq. 0.33), since  $R_a$  and  $R_b$  depend on the flow velocity of the fluid (by the heat transfer rate  $\alpha$ ). The detailed calculation and all possible options are given in [5].

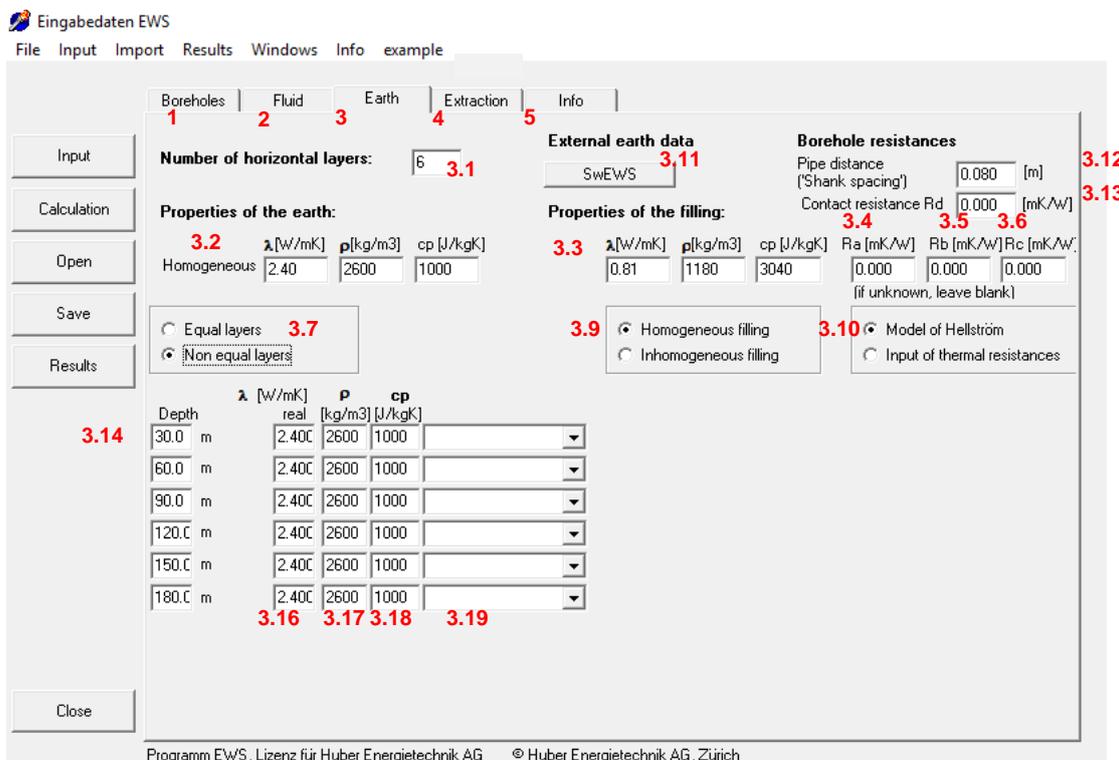
**3.10 / 3.12** There is no need to enter the values of the thermal resistances in the **field 3.4 – 3.6** if “Model of Hellström” in **field 3.10** is selected. In this case, the program EWS calculates the thermal resistances in the next run. But the distance between the up-going and down-going pipe (shank spacing, **field 3.12**) must be entered (see chapter 3.2.2) using the “Model of Hellström”. Generally, the default value for the pipe distance can be used. The default value for the pipe distance is calculated from the borehole diameter and the pipe diameter under the assumption that the pipes are placed at the borehole’s wall. However, a later adjustment of the borehole diameter is not automatically considered for the pipe distance.

**3.11** With **button 3.11** earth data of the Swiss molasses basin can be imported from the program SwEWS [11].

**Caution:** The number of horizontal layers must always be entered before property data from a SwEWS are imported.

### 3.6.2 Input of multiple horizontal layers

The earth is divided into multiple horizontal layers by entering the corresponding number (>1) in **field 3.1** (see Fig. 3.31). The maximal number of layers which can be defined is 10. The layers are equally spaced if “equal” is selected in **field 3.7**. The option “unequal” in field 3.7 must be selected to enter layers with variable depths (**available only in the full version**). The selected number of layers also corresponds to the number of layers in the numerical calculation but these layers are always equally spaced over the borehole depth (see chapter 3.6.1). The depth of the deepest geological layer must always be  $\geq$  the borehole depth.



**Fig. 3.29: The sheet „Earth“ with 6 horizontal layers of variable thickness.**

**Caution:** The depth does not indicate the thickness of the corresponding layer but the distance from the deepest point of the layer to the surface of the earth.

After defining the number of horizontal layers, data about their respective properties can be entered into the suitable fields. It is possible to define layers which are deeper than the borehole itself. These layers are neglected as long as the borehole does not reach them. Therefore, it is recommended to enter the entire data of the known geology. This allows a later variation of the borehole depth without a need for adjustment in geology.

A horizontal variation of the filling material can be entered by selecting “inhomogeneous filling” in field 3.9. This option is only available if the layers are equally spaced what implies the selection of “equal layers” in field 3.7. Similar to the division of the earth, a field with additional lines appears, that can be used to enter the properties of the filling material (field 3.20) as well as of the borehole resistances (field 3.21) (see figure below)

The default values are taken from the field 3.3 and 3.4 – 3.6.

- 3.16 The physical properties of the filling material can be entered directly into these cells.
- 3.17 The procedure to set the values of the borehole resistances  $R_a$ ,  $R_b$  and  $R_c$  is analog to the one for the fields 3.4 – 3.6 in chapter 3.6.1.
- 3.3 – 3.6 The arithmetic averages of field 3.20 and 3.21 are shown after each run in the fields 3.3 – 3.6.

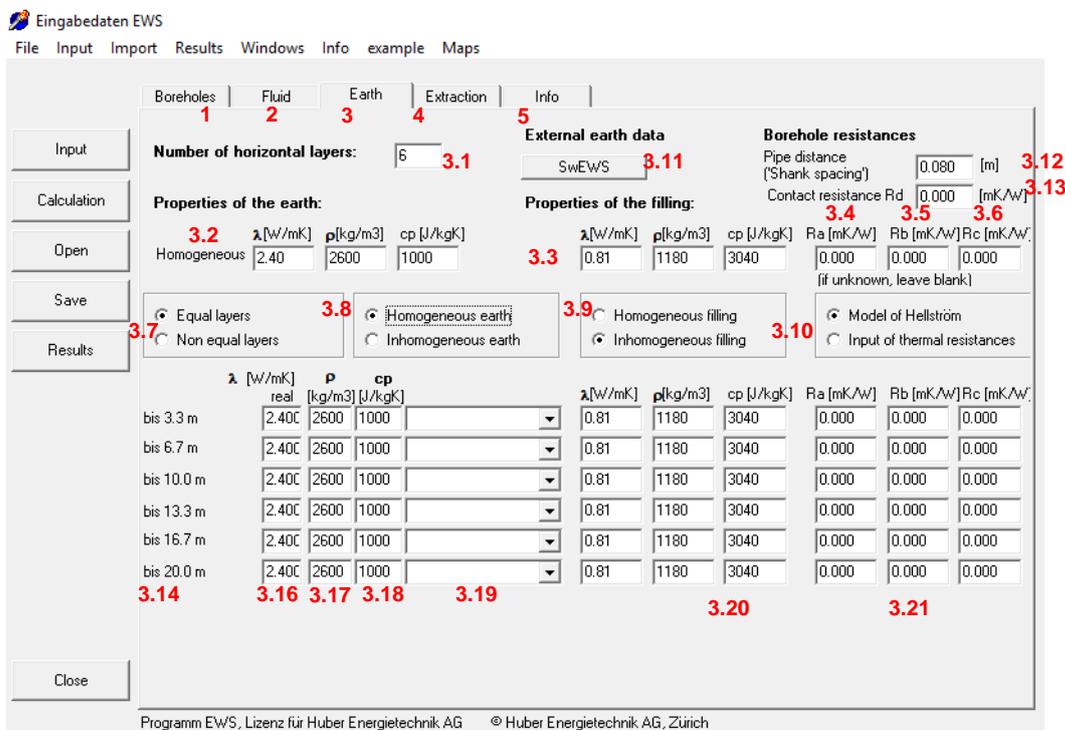


Fig. 3.30: The sheet „Earth“ with an inhomogeneous filling of the borehole.

### 3.6.3 Physical properties of the earth input

A field for each horizontal layer appears, to enter its properties. Either the properties can be entered directly (field 3.15 to 3.18) into the cells or an earth type can be selected from the pull-down menu. The earth types in the pull-down menu are linked with the appropriate physical properties (see Fig. 3.31).

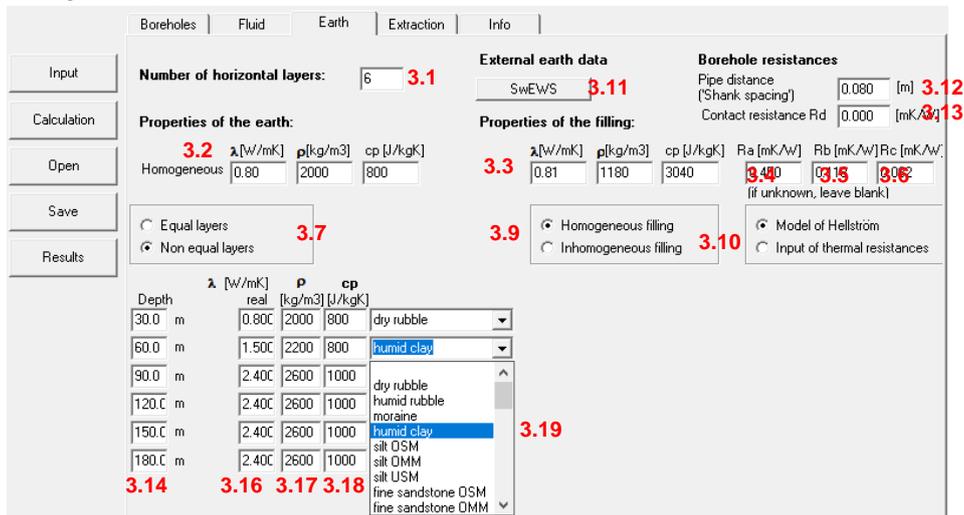


Fig. 3.31: The sheet „Earth“ offers a selection of rocks in the pull-down menu.

The program EWS also offers the option to enlarge the library in the pull-down menu by adding new earth types with their own names and physical properties (see Fig. 3.32). This can easily be done by entering the data manually into the suitable cells (field 3.19). After a run, the new defined earth types appear at the bottom of the pull-down menu.

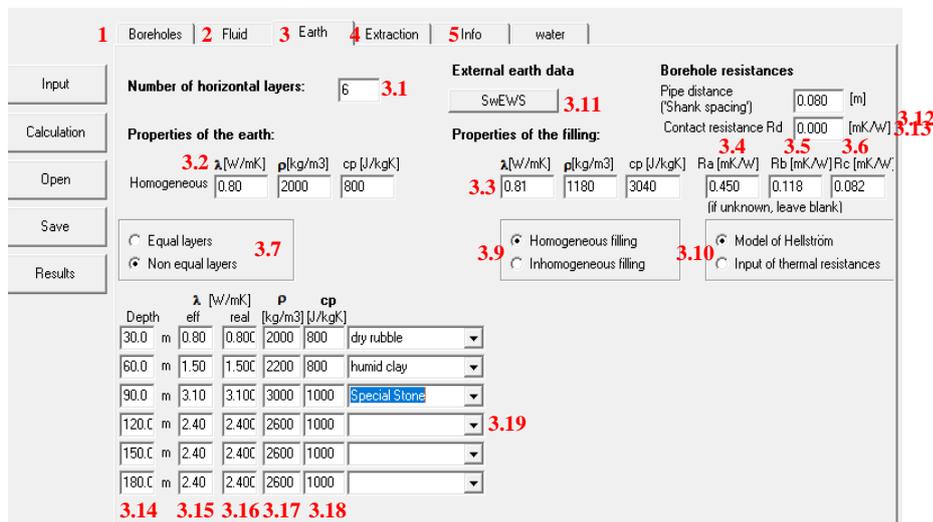


Fig. 3.32: The sheet „Earth“, nomenclature of rocks and the input of their property data.

3.15 If groundwater must be considered, and W1 in the field groundwater is clicked, an additional column 3.15 appears with the „effective thermal conductivity“  $\lambda_{eff}$ .  $\lambda_{eff}$  is the apparent thermal conductivity when considering the groundwater influence.  $\lambda_{eff}$  can for example be defined by a thermal response test (TRT), whereas  $\lambda_{real}$  (thermal conductivity without groundwater influence) is defined e.g. by measuring a rock sample. With groundwater,  $\lambda_{eff}$  is used for calculations inside the simulation radius and  $\lambda_{real}$  is used for calculations of the g-functions, because in this area the groundwater is accounted for separately.

### 3.6.4 Creation of a user defined geological library

The program EWS offers the possibility to create a user defined, geological library with a maximum of 30 different earth types and their physical properties. Once the library is established, it is loaded automatically when the program is started and the entries appear in the pull-down menu (field 3.19).

The first step to establish a library is to create a table in excel with the name of the earth/ground types and the appropriate physical properties (see Fig. 3.33). The names and the properties must be entered below the header (row 2 –31). The names must be entered in the first column, the  $\lambda$ -values in the second column, the  $\rho$ -values in the third column and the specific heat capacity in the fourth column. There are two different types of limestone (limestone region Baden and limestone region Jura) defined in the example given below (see Fig. 3.33). The table must be saved as a text file (\*.txt) with the name “Geologie.txt” in the **same folder as the program EWS**. In a next step it must be renamed to “Geologie.ews”. Thereafter, the created library is available in the pull-down menu (see Fig. 3.34).

**Caution:** The program EWS can only deal with decimal points (no decimal commas). Entries with decimal commas cause an error.

**Hint:** Change country settings to German (Switzerland)

1	name	lambda	rho	cp
2	Limestone Baden	2.6	2400	1100
3	Limestone Jura	2.8	2500	1350
4	rock 3	2.4	800	2200
5	rock 4	2.4	800	2200
6	rock 5	2.4	800	2200
7	rock 6	2.4	800	2200
8	rock 7	2.4	800	2200
9	rock 8	2.4	800	2200
10	rock 9	2.4	800	2200
11	rock 10	2.4	800	2200
12	rock 11	2.4	800	2200
13	rock 12	2.4	800	2200
14	rock 13	2.4	800	2200
15	rock 14	2.4	800	2200
16	rock 15	2.4	800	2200
17	rock 16	2.4	800	2200

Fig. 3.33: Definition of the user-defined, geological library in the excel sheet “Geologie.ews”

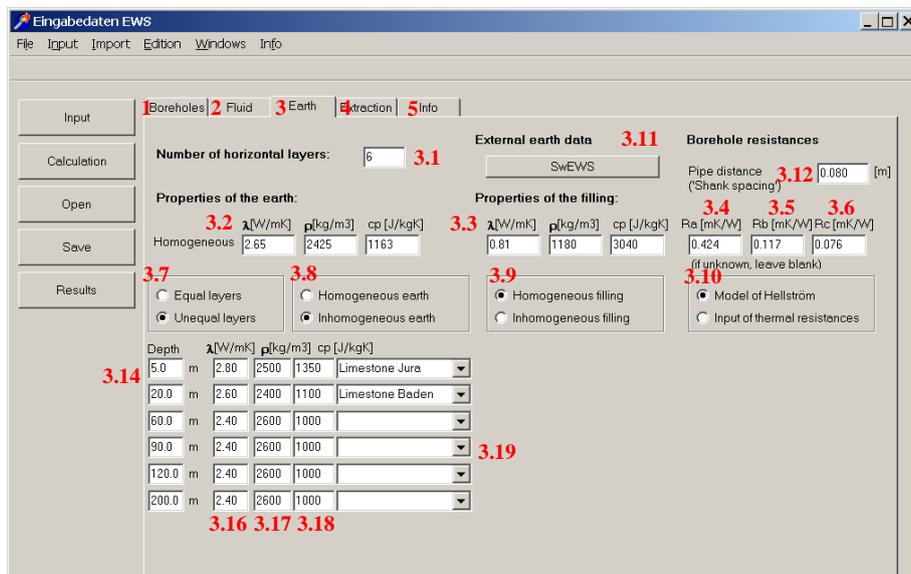
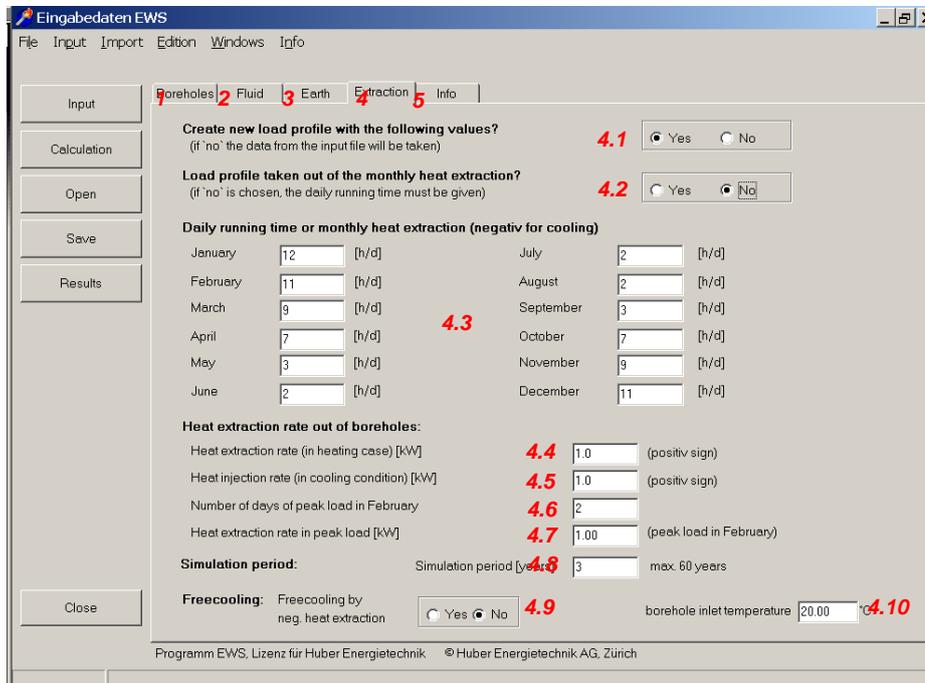


Fig. 3.34: The sheet „Earth“ with the properties from the user-defined library “Geologie.ews”

### 3.7 The sheet “Extraction”

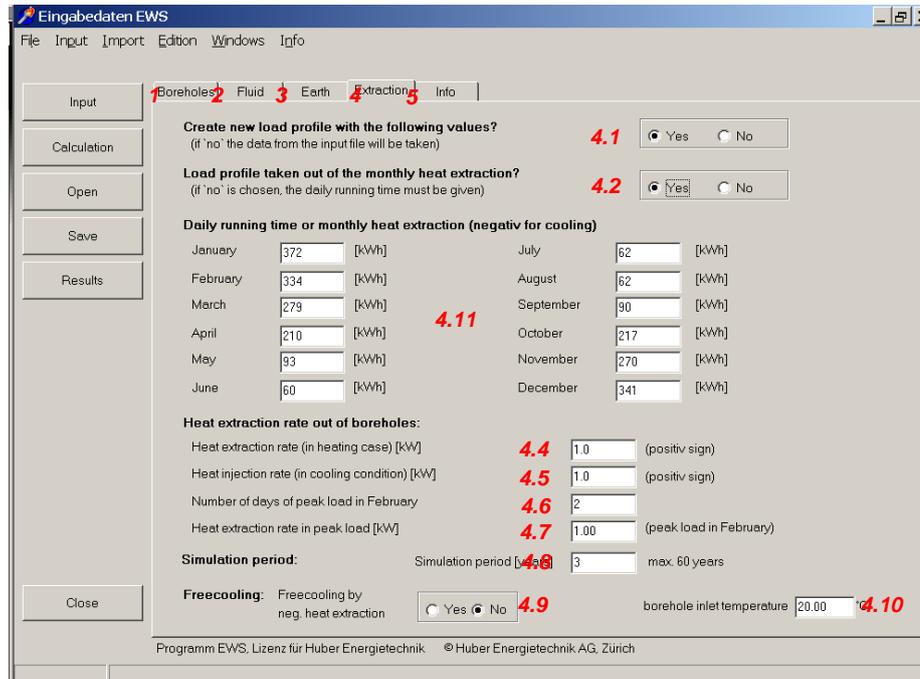
The load profile of the boreholes is entered in sheet “Extraction” (see. Fig. 3.35).



**Fig. 3.35: The sheet “Extraction” with the input of the daily running time of the heat pump.**

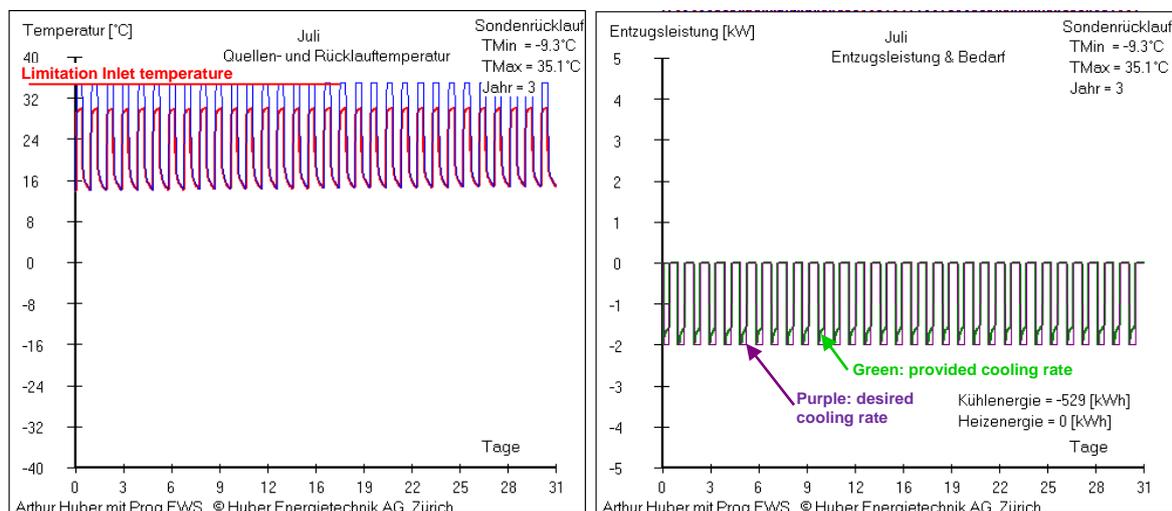
- 4.1 If the question “create new load profile with the following values?” is answered with “yes”, a load profile with the input data, which must be defined, is created. If the answer is “no”, the program uses the hourly input data from an external predefined input file and a new input is futile.
- 4.2 There are two options to create a load profile: The input of daily running time of the borehole heat pump or the input of the monthly heat extraction.
- 4.3 The fields 4.3 require a daily running time (different for each month), if “no” is selected in the field 4.2. A minus must be added to the running time in the correspondent months in which the boreholes are used for cooling (which implies that heat is transferred to the borehole).
- 4.11 If “yes” is selected in the field 4.2, the fields 4.11 require a monthly heat extraction as an input (see Fig. 3.36). The cooling load must be written with a minus in this option, as well.
- 4.4 The heat extraction rate in the heating case must be noted with a positive sign. If the heat extraction rate is changed, the mass flow rate in field 2.7 (in the sheet “fluid”) is adjusted automatically (see description 2.6/2.7).
- 4.5 The heat injection rate in cooling condition must be noted with a **positive** sign, too.

4.6/4.7 There is an option to simulate the peak load in the heating case by calculating a non-stop heating period. The duration of this period is defined in days with the input in field 4.6. The period always is simulated at the end of February which is the coolest period of the year. The field 4.7 defines the heat extraction rate during this period (which is normally equal the heat extraction rate in field 4.4).



**Fig. 3.36: The sheet “Extraction” with the input of the monthly heat extraction**

4.9 /10 Field 4.9 activates a maximum limit for the borehole inlet temperature, which is defined in field 4.10. If the borehole inlet temperature exceeds the defined limit, the program EWS reduces the cooling rate until the maximum temperature condition is met. On the rate-output-graph the desired rate is marked purple, the provided rate is marked green, resulting in the „Coverage of the cooling demand“ on the result page. The function is identical with the fields 10.28 and 10.29 on the page „Load“.



**Fig. 3.37: Limitation of the maximum borehole inlet temperature in the cooling case.**

### 3.8 The sheet “Load”

#### 3.8.1 Creation of a load profile suggestion in the program EWS

The full version of the program EWS offers alternatively to the direct input of the heat extraction in the sheet “Extraction” (chapter 3.7) another possibility to enter the borehole load. Thereto, the sheet “Load” can be opened under the pull-down “Input” (see Fig. 3.38). The sheet “Load” requires the monthly heating energy as an input, to calculate the heat extraction of the boreholes using the given COP of the heat pump. The sheet “Load” cannot be combined with the sheet “Heat pump”.

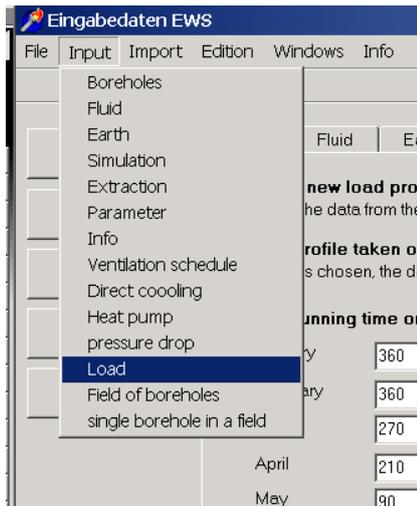


Fig. 3.38: The selection of the sheet “Load”.

The sheet “Load” appears (Fig. 3.39) and the sheet “Extraction” is hidden.

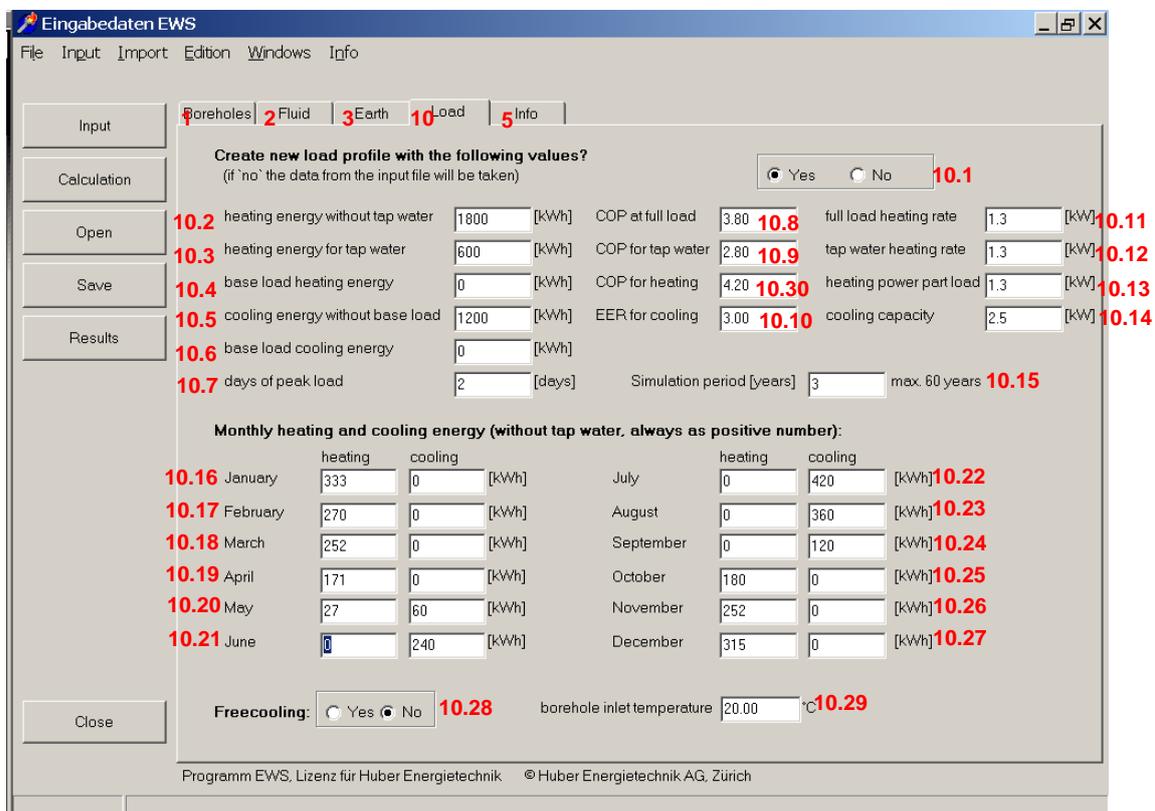
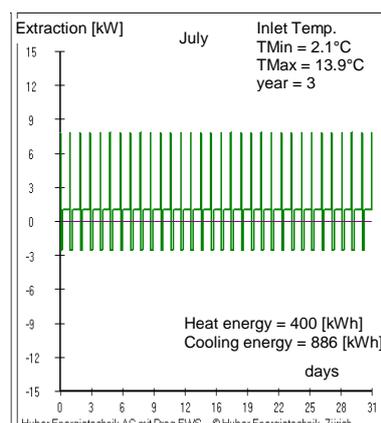


Fig. 3.39: The sheet “Load” with the input of the heating energy.

In the sheet “Load” the monthly heating and cooling energy demand is defined. In contrast to the sheet “Extraction”, the heating and the cooling energy in the sheet “Load” are in kWh and both with a positive sign. The program EWS calculates a load profile for an intermittent mode under consideration of the COP, the energy demand and the heating and cooling load of the heat pump. Excluded from this intermittent load is the base load (field 10.4 and field 10.6) which influences the load profile independently of the installed heating or cooling power. In the heating case, the borehole heat extraction rate is reduced by the compressor power load which can be calculated with the COP. The heat injection rate in cooling condition is increased by the compressor power and is calculated with the EER (COP-1).

The mass flow rate (field 2.7) is adjusted to the heat extraction rate considering the eq. 3.1 and the temperature difference (field 2.6) (this means a variable mass flow rate).

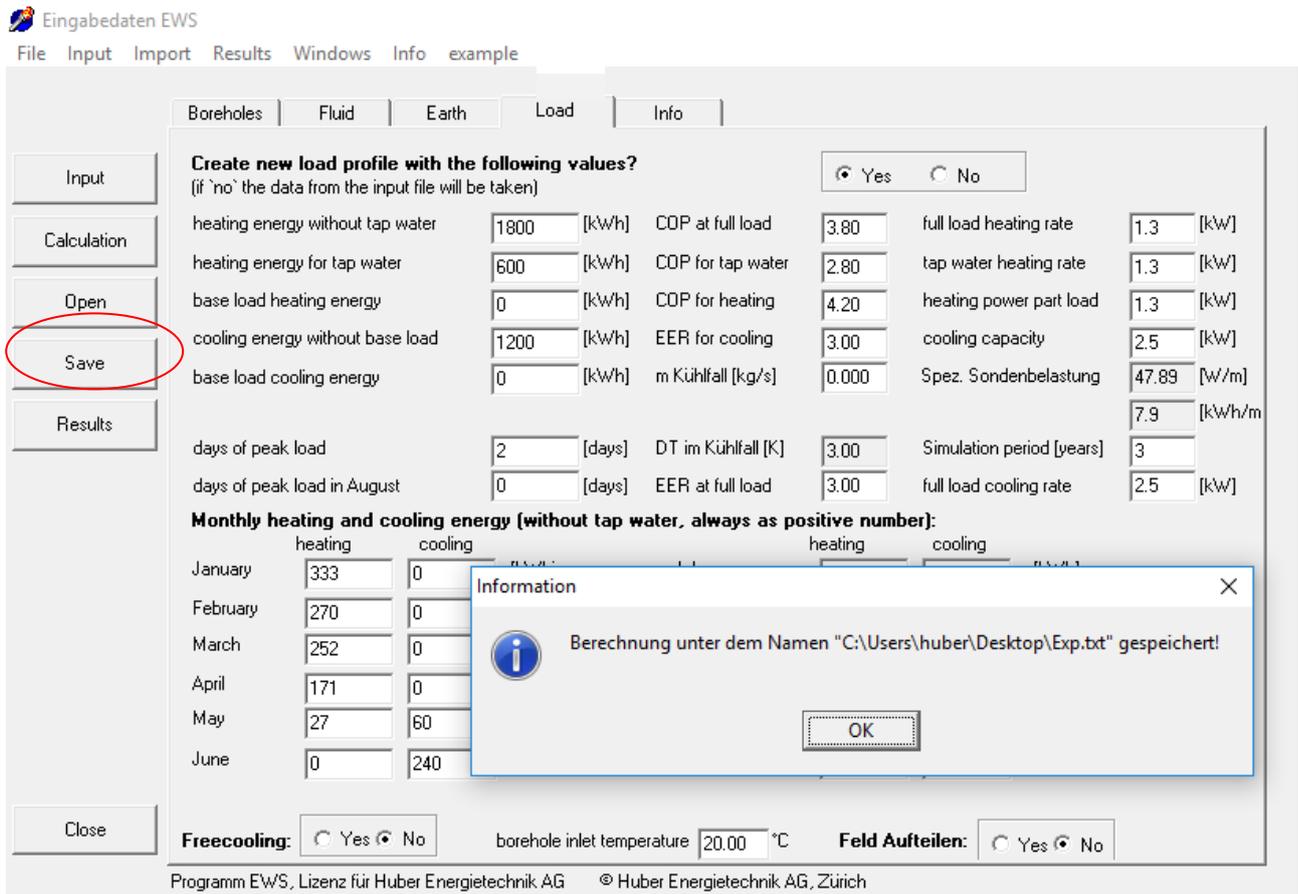
- 10.1** If the question “Create a new load file with the following values?” is answered with “yes”, the load profile is calculated with the values from the fields 10.2 – 10.27. If the answer is “no”, the load profile is taken from the input file and the inputs 10.2 – 10.29 are ignored.
- 10.7** Duration of the peak load (non-stop operation) at the end of February.
- 10.8** COP of the heat pump during the full load (10.11). Corresponds to the code case (full load).
- 10.10** Input of the EER of the cooling machine (= cooling-COP<sub>c</sub>, i.e. the ratio of the cooling energy and the consumed electric power). There a high value should be entered (e.g. 999) if the freecooling option in field 10.28 is selected.
- 10.11** The performance (rate) during the maximal load, end of February. The duration is defined in the field 10.7.
- 10.13** The performance (rate) during a part load. This heat extraction rate is rounded so the total heating energy of 10.16 – 10.27 can be met.
- 10.15** The duration of the simulation (maximal 200 years). Always the last year of the period is evaluated.
- 10.28** The cooling temperature of the borehole inlet is limited if the freecooling option is selected. The percentage of coverage of the cooling demand can be seen on the sheet “Results”. This can also be used, to limit the borehole inlet temperature in the case of active cooling.
- 10.29** The borehole inlet temperature in the freecooling case. **Attention:** The borehole inlet temperature mostly is lower than the return temperature of the cooling loop (because of the heat exchanger).
- 10.30** Mean COP of the heat pump in the heating period (at part load 10.13).



**Fig. 3.40:** The extraction rate profile of an intermittent mode, created with the sheet “Load”.

### 3.8.2 Input of own load profile in hourly steps

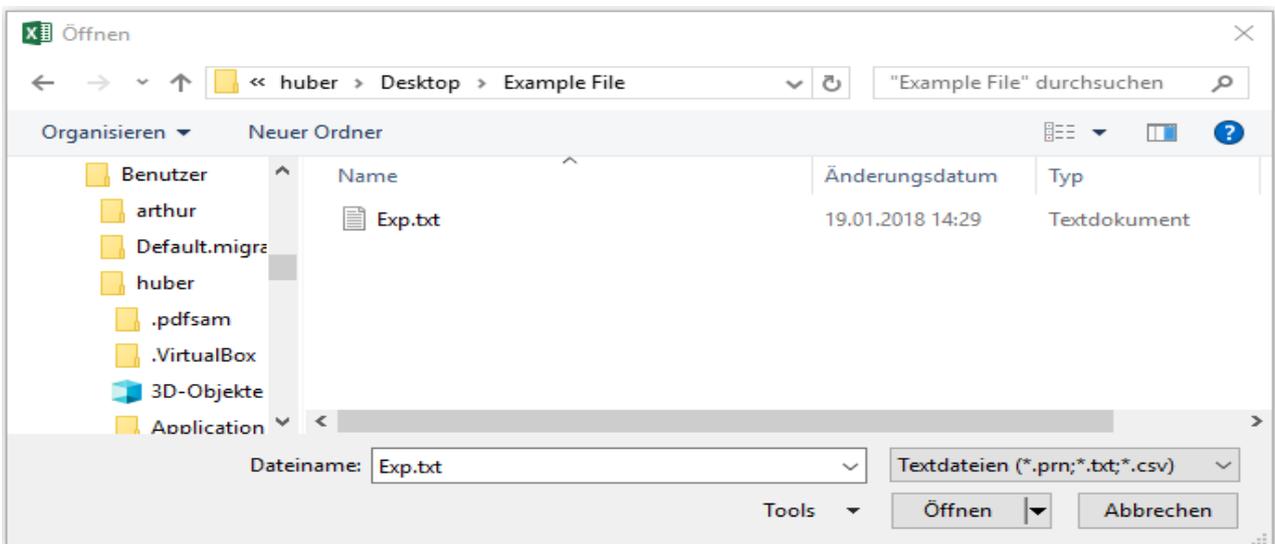
The program EWS offers the possibility to create hourly load profiles for the heat withdrawal from the boreholes. This can be done following the next steps:



**Fig. 3.41: Input of own load profile: 1. Save Calculations.**

In a first step all the inputs for the calculation are defined and the calculation is saved. In this case, it's the file "Exp". After this the program EWS is closed.

In the next step the saved file, "Exp", is opened with Excel. Important is to notice it is a .txt file.



**Fig. 3.42: Input of own load profile: 2. Open saved file in Excel.**

The saved file can be opened with Tabstops as separation sign:

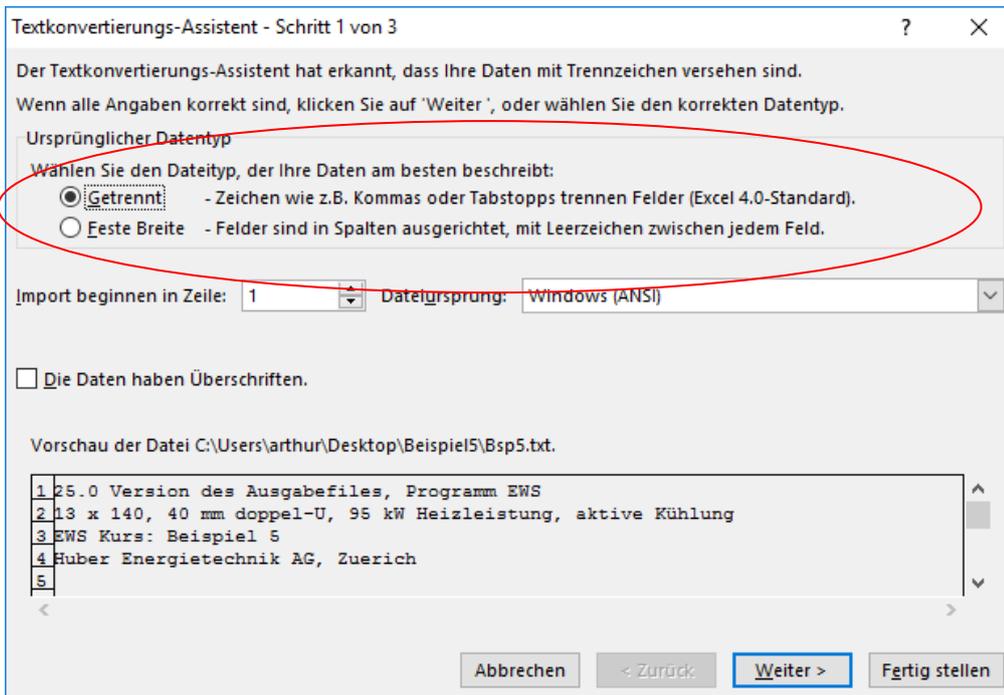


Fig. 3.43: Input of own load profile: 3. Saved file with Tab stops

In Germany and Austria Excel settings must be changed to the decimal point (in Switzerland this is not necessary). For this, open “Data” in Excel, then “Options”, “Advanced”, “Editing Options” and Remove the selection “Use system separators”, then add the decimal separator “.”.

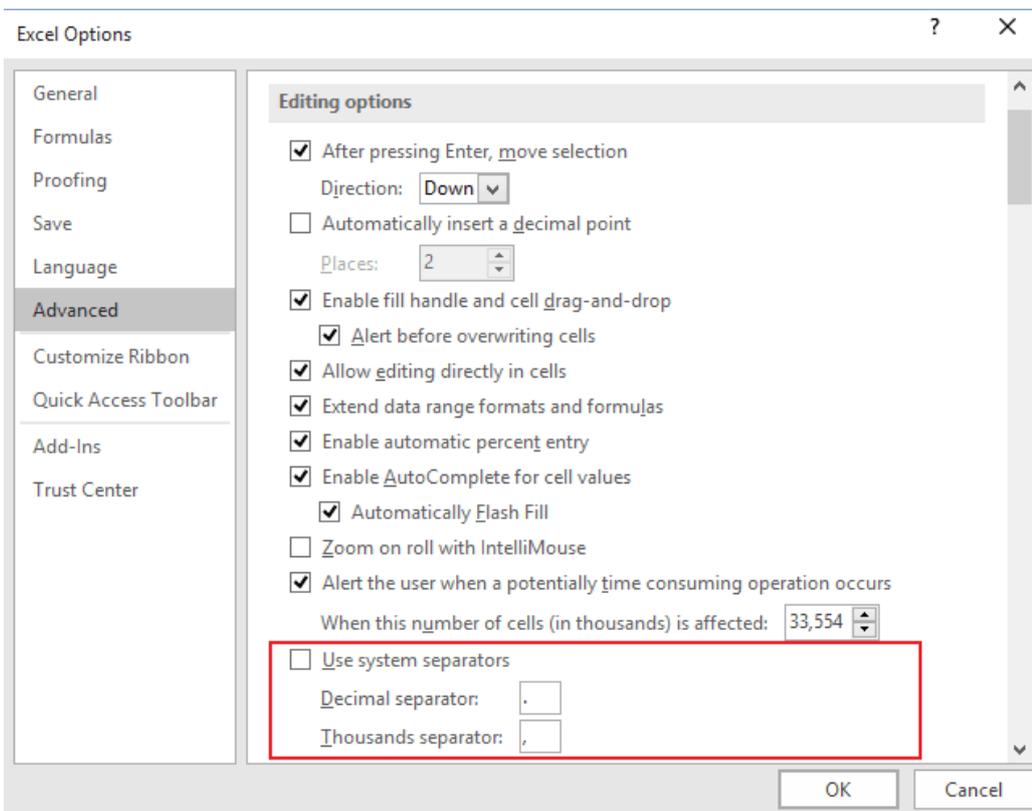


Fig. 3.44: Input of own load profile: 4. Changing Excel settings to decimal point (if necessary).

The calculation parameters are in the first 1000 lines of the file. Starting from line number 1001 the hourly values follow.

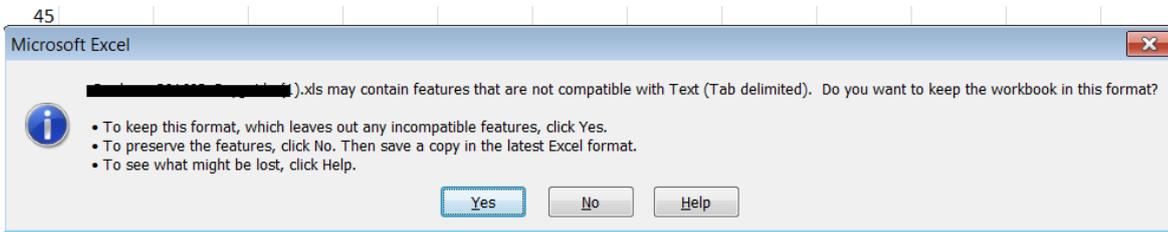
	A	B	C	D	E	F	G	H	I	J
992	0 °C		Starttemperatur der 4. Schicht		Starttemperatur[4]					
993	0 °C		Starttemperatur der 5. Schicht		Starttemperatur[5]					
994	0 °C		Starttemperatur der 6. Schicht		Starttemperatur[6]					
995	0 °C		Starttemperatur der 7. Schicht		Starttemperatur[7]					
996	0 °C		Starttemperatur der 8. Schicht		Starttemperatur[8]					
997	0 °C		Starttemperatur der 9. Schicht		Starttemperatur[9]					
998	0 °C		Starttemperatur der 10. Schicht		Starttemperatur[10]					
999	6.00E+01 °C		Warmwasser - Temperatur		WWTemperatur					
1000	0.00E+00 W/mK		scheinbares Lambda Erde der		lambdaErde_eff[10]					
1001	Step	M [kg/s]	TSink max [°C]	Qsoll [kW]	TSource [°C]	TMonitor	p [Pa]	laminar?	Qeff [kW]	TSink eff [°C]
1002	1	4.187	7.488	49.234	10.501	11.71	9832	TRUE	49.234	7.502
1003	2	4.187	7.186	49.234	10.2	11.5	9832	TRUE	49.234	7.2
1004	3	4.187	7.007	49.234	10.021	11.36	9832	TRUE	49.234	7.021
1005	4	4.187	6.873	49.234	9.886	11.25	9832	TRUE	49.234	6.887
1006	5	4.187	6.761	49.234	9.775	11.15	9832	TRUE	49.234	6.775
1007	6	4.187	6.664	49.234	9.678	11.06	9832	TRUE	49.234	6.678
1008	7	4.187	6.582	49.234	9.596	10.99	9832	TRUE	49.234	6.596
1009	8	4.187	6.507	49.234	9.521	10.92	9832	TRUE	49.234	6.521
1010	9	4.187	6.438	49.234	9.452	10.86	9832	TRUE	49.234	6.452
1011	10	4.187	6.376	49.234	9.39	10.8	9832	TRUE	49.234	6.39
1012	11	0	9.375	0	11.978	11.98	0	FALSE	0	11.978
1013	12	0	11.963	0	12.424	12.42	0	FALSE	0	12.424
1014	13	0	12.409	0	12.639	12.64	0	FALSE	0	12.639
1015	14	0	12.623	0	12.774	12.77	0	FALSE	0	12.774
1016	15	0	12.759	0	12.878	12.88	0	FALSE	0	12.878

Fig. 3.45: Input of own load profile: 5. Starting from line 1001 the hourly hours are saved.

The hourly mass flow rate (total value in kg/s) is shown in column B, the maximum borehole inlet temperature (limit value upwards) is shown in column C and the hourly withdrawal rate (positive prefix) or energy insertion (negative prefix) in the boreholes (total value over the hours in kWh) are shown in column D. These can now be adapted.

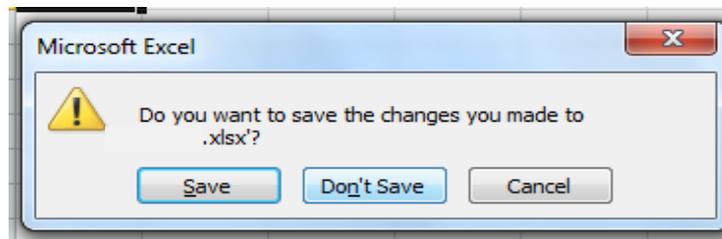
	A	B	C	D	E	F	G	H	I	J
992	0 °C		Starttemperatur der 4. Schicht		Starttemperatur[4]					
993	0 °C		Starttemperatur der 5. Schicht		Starttemperatur[5]					
994	0 °C		Starttemperatur der 6. Schicht		Starttemperatur[6]					
995	0 °C		Starttemperatur der 7. Schicht		Starttemperatur[7]					
996	0 °C		Starttemperatur der 8. Schicht		Starttemperatur[8]					
997	0 °C		Starttemperatur der 9. Schicht		Starttemperatur[9]					
998	0 °C		Starttemperatur der 10. Schicht		Starttemperatur[10]					
999	6.00E+01 °C		Warmwasser - Temperatur		WWTemperatur					
1000	0.00E+00 W/mK		scheinbares Lambda Erde der		lambdaErde_eff[10]					
1001	Step	M [kg/s]	TSink max [°C]	Qsoll [kW]	TSource [°C]	TMonitor	p [Pa]	laminar?	Qeff [kW]	TSink eff [°C]
1002	1	4.187	7.488	49.234	10.501	11.71	9832	TRUE	49.234	7.502
1003	2	4.187	7.186	49.234	10.2	11.5	9832	TRUE	49.234	7.2
1004	3	4.187	7.007	49.234	10.021	11.36	9832	TRUE	49.234	7.021
1005	4	4.187	6.873	49.234	9.886	11.25	9832	TRUE	49.234	6.887
1006	5	4.187	6.761	49.234	9.775	11.15	9832	TRUE	49.234	6.775
1007	6	4.187	6.664	49.234	9.678	11.06	9832	TRUE	49.234	6.678
1008	7	4.187	6.582	49.234	9.596	10.99	9832	TRUE	49.234	6.596
1009	8	4.187	6.507	49.234	9.521	10.92	9832	TRUE	49.234	6.521
1010	9	4.187	6.438	49.234	9.452	10.86	9832	TRUE	49.234	6.452
1011	10	4.187	6.376	49.234	9.39	10.8	9832	TRUE	49.234	6.39
1012	11	0	9.375	0	11.978	11.98	0	FALSE	0	11.978
1013	12	0	11.963	0	12.424	12.42	0	FALSE	0	12.424
1014	13	0	12.409	0	12.639	12.64	0	FALSE	0	12.639
1015	14	0	12.623	0	12.774	12.77	0	FALSE	0	12.774
1016	15	0	12.759	0	12.878	12.88	0	FALSE	0	12.878

Now the adapted load profile can be saved. Excel will ask if the file shall be saved as “Text File”, this must be answered with “Yes”



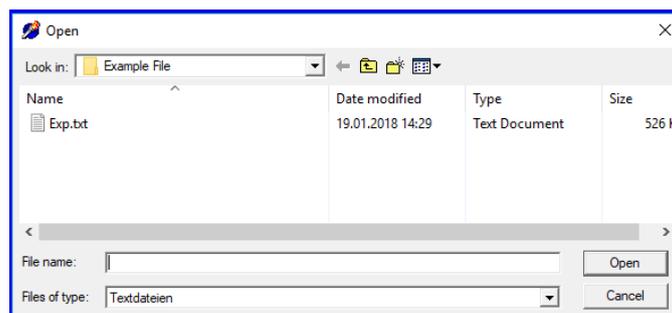
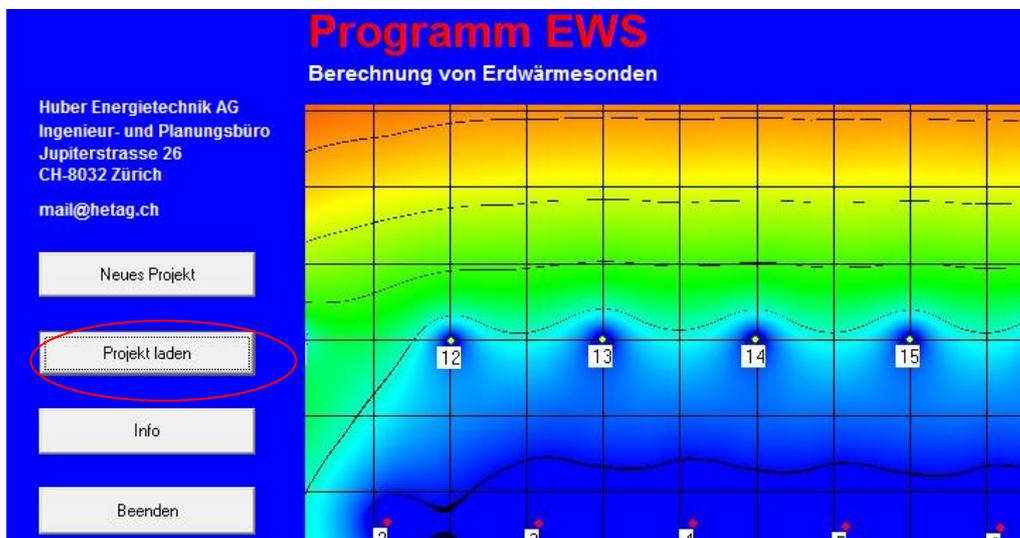
**Fig. 3.47:** Input of own load profile: 7. Saving new load profile as .txt file.

Now Excel can be closed. Now Excel will once more ask you if the file shall be saved in "Excel Format". This must be answered with "Don't Save"



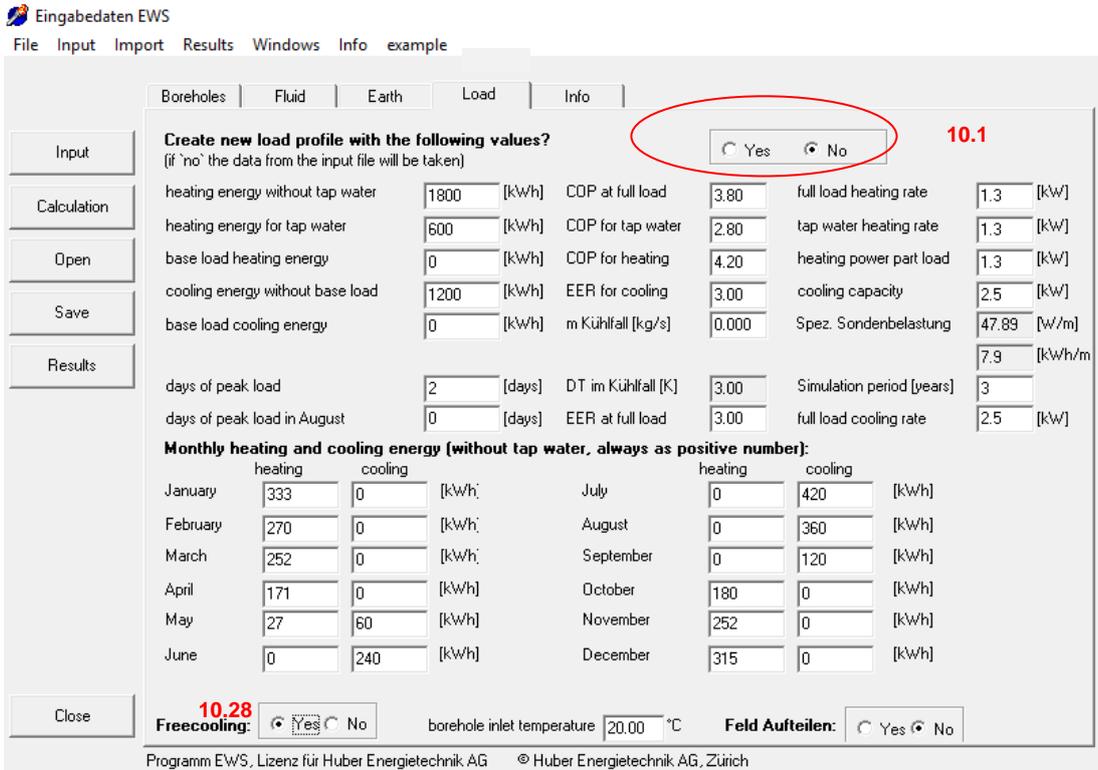
**Fig. 3.48:** Input of own load profile: 8. Leave Excel without saving!

Now open EWS once more and load the previously saved text-file.



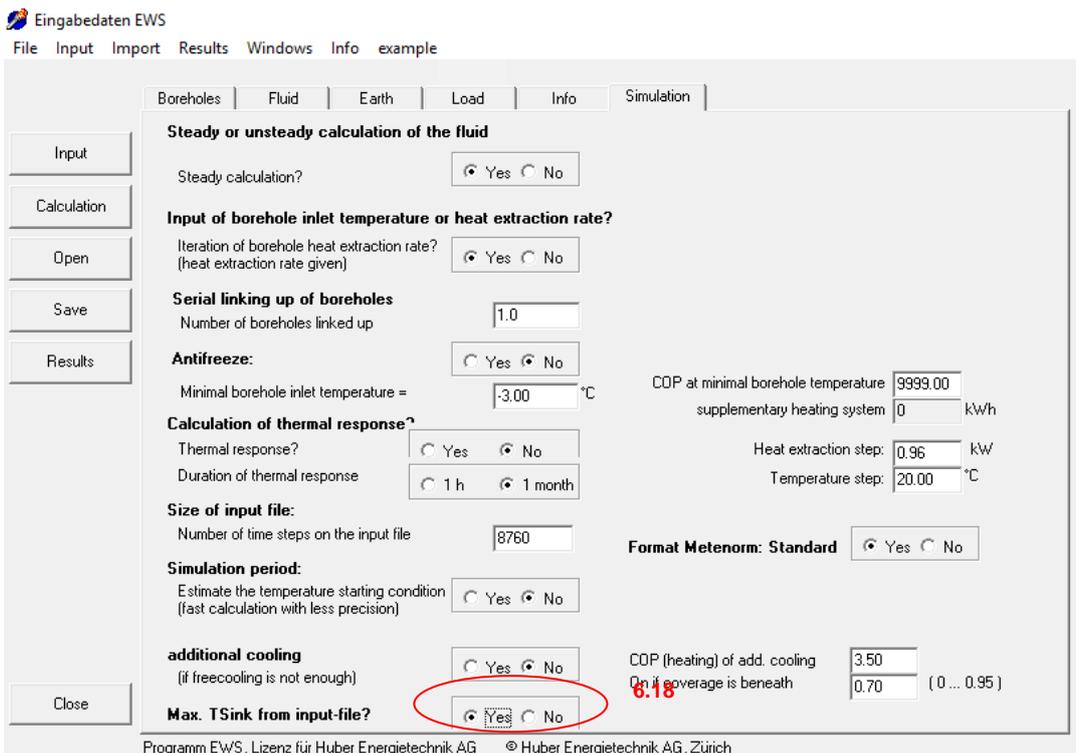
**Fig. 3.49:** Input of own load profile: 9. Load saved Text File in EWS

Now go to the page “Load” and set **10.1** to “No”



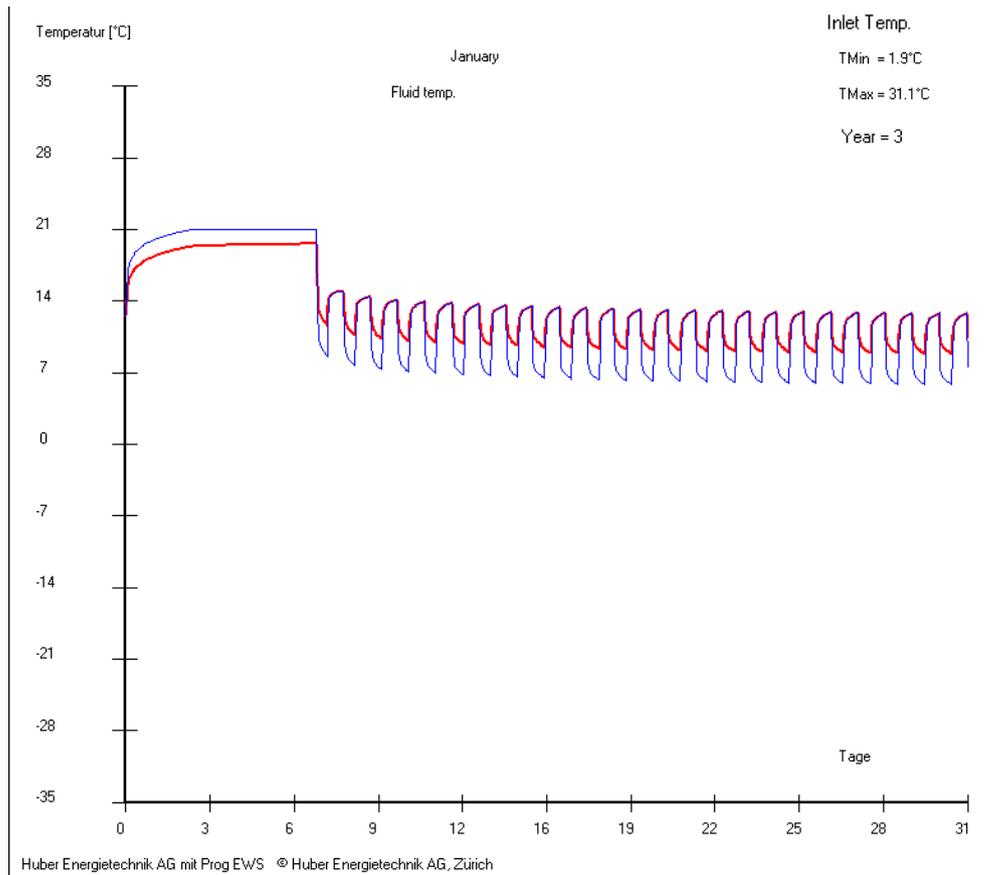
**Fig. 3.50: Input of own load profile: 10. Page “Load”, Nr. 10.1 set to “No”.**

If the temperature of the borehole inlet should be limited upwards, Freecooling must be set to “Yes” (10.28). If the maximum borehole inlet temperature must be taken from the input file, 6.18 on the page “Simulations” must be set to “Yes”



**Fig. 3.51: Input of own load profile: 11. Set 6.18 to “Yes” on page Simulation.**

If the simulation is now started, the inputs to the page “load” are ignored and the values for the load profile in the external load file are considered. This is also visible in the graphical output. In our example in the first week of January a constant heat performance of 50 kW was set for the energy insertion into the borehole and the maximum borehole inlet temperature was set to 21°C. This leads to the fact that after the third day the 50kW heat performance are not delivered entirely.

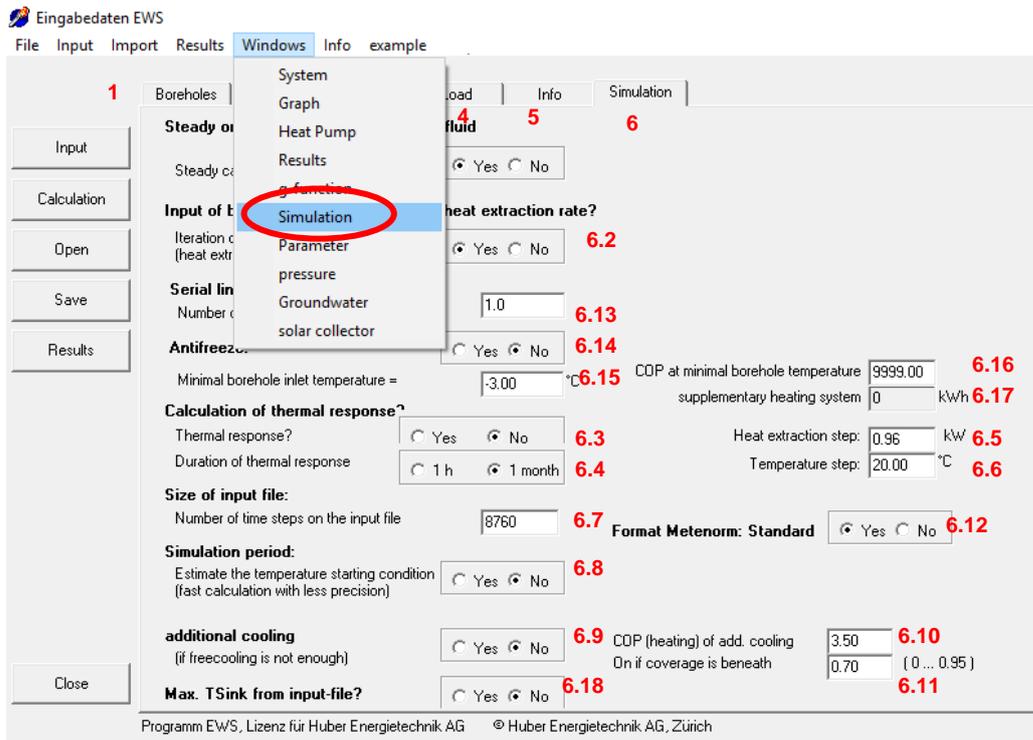


**Fig. 3.52: Input of own load profile: 12. Calculation**

### 3.9 The sheet “Simulation”

#### 3.9.1 Show the sheet “Simulation”

Various special calculations can be done with the sheet “Simulation”. Open the sheet “Simulation” with the pull-down menu “Windows” from the menu bar and select “Simulation” (see Fig. 3.53).



**Fig. 3.53:** The opening of the sheet “Simulation”.

The following, special calculations can be executed with the sheet “Simulation”:

- The unsteady calculation of the fluid (field 6.1). The default setting of the program does steady state calculations of the fluid like it can be found in ref. [5] and [6].
- The input of the extraction rate, e.g. forced by the heat pump or the borehole inlet temperature (e.g. direct cooling). For these cases, the field 6.2 must be selected (“yes”). The default setting calculates the needed outlet and inlet temperature of the borehole fluid to generate the wanted extraction rate of the heat pump.
- The calculation of the thermal response (response test, field 6.3). More details can be found in chapter 5.9.3.
- The size of the input file (field 6.7). The default setting calculates 8760 steps of 60 minutes. But it is possible to calculate a time period of less than one year and hence, to calculate with a smaller input files. **Note:** There are max. 8760 time steps possible.
- The estimation of the start temperature (field 6.8). This option results in a shorter calculation time for long simulation periods (>10 years). But the results are less precise and they should only be used for rough estimations.

### 3.9.2 Input of the heat extraction rate and the borehole inlet temperature

The borehole inlet temperature in **field 6.6** or in **field 4.10** is taken as a base for the calculations of the possible heat extraction rate (i.e. the heat extraction rate is not determined by the heat pump) if in **field 6.2** “no” is selected.

### 3.9.3 The active, additional cooling if freecooling is not sufficient

If in the **field 6.9** “yes” is selected, there is an additional cooling machine installed which uses the boreholes as a back cooling. The cooling machine is activated if the freecooling covers less than a certain fraction of the total cooling demand (the fraction is defined in the **field 6.11**). In this case, the boreholes have to absorb the compressor power of the cooling machine which is calculated with the heating COP (=EER +1) of the cooling machine (**field 6.10**).

### 3.9.4 Serial connection of boreholes or energy poles

With short boreholes and energy poles, it can happen that with a parallel connection the flow turns out to be laminar. This can reduce the performance bigly. To avoid this, usually the boreholes or energy poles are connected serially. This increases the flow rate. This is considered and reproduced in the program EWS in the **field 6.13**, with the input of the number of boreholes which are connected serially.

### 3.9.5 Antifreeze (minimal brine temperature) und bivalent heat pump systems

To ensure the anti-freeze protection and to take into account bivalent heat pump systems, a minimal brine temperature can be set in **field 6.15**. To activate the anti-freeze protection, the **field 6.14** must be set to “Yes”. Now when the brine temperature falls below the minimal temperature in **field 6.15**, the heat pump reduces its work and there is no heat extraction from the borehole any more. In order to be able to calculate the missing heat when the heat pump stops to work, the COP of the heat pump at the minimal brine temperature must be given in **field 6.16**. In **field 6.17** the missing heat production of the heat pump is added up after the calculation of the system.

### 3.9.6 The response test

Open the sheet “Simulation” (menu bar “Windows”) to check the thermal response test (see Fig. 3.53).

Select the thermal response on the sheet “Simulation” (**field 6.3**). This automatically changes various default values:

- It is only possible to calculate reasonable results for the unsteady borehole fluid. Therefore, **field 6.1** is set to “no”.
- The calculation of the thermal response must be done with the maximal number of ground layers. Thus, the number of horizontal layers in the earth is set to 10 (**field 3.1**).
- The time steps for the simulation of the fluid and of the earth are reduced. For this purpose the time step factor of the fluid (**field 7.5**, “security 1”) is changed from 4 to 40 and that of the earth (**field 7.6**, “security 2”) from 2 to 20.
- The time step to calculate the boreholes is set to 1 minute (**field 7.4**) if the duration of the thermal response is set to 1 h (**field 6.4**).
- The size of the input file for the thermal response (**field 6.7**) is adapted to the duration of the thermal response.

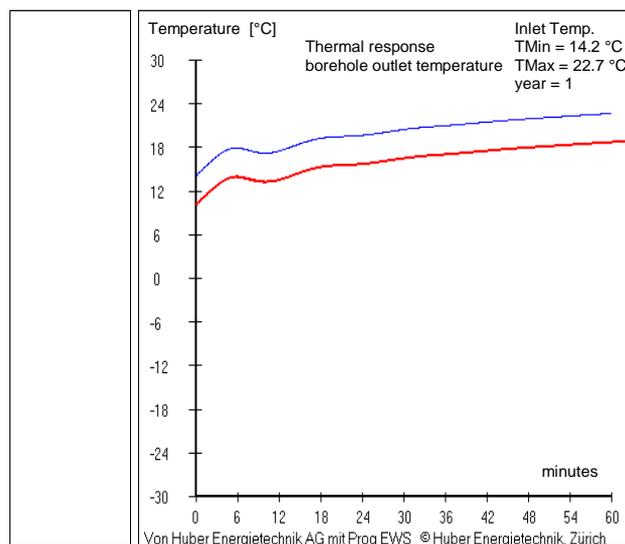
The classical case of the thermal response test extracts or adds a constant heat rate from the ground. This rate must be entered in field 6.5. Thereby, to the convention of the signs must be paid attention to:

- positive sign: -> heat extraction from the earth
- negative sign: -> heat induction to the earth

The temperature step (field 6.6) is ignored in this type of response test.

Do not forget to enter the correct mass flow rate of the borehole (field 2.7)!

Fig. 3.54 illustrates the first 60 minutes of the thermal response of a borehole (40mm double-U-pipe, depth: 150 m, mass flow rate: 0.7 kg/s of 33% Monoethylenglykol, heat input of 10kW). The first temperature maximum after 6.5 minutes is clearly visible (Halftime of the borehole cycle). This maximum is a consequence of the piston-effect of the fluid.



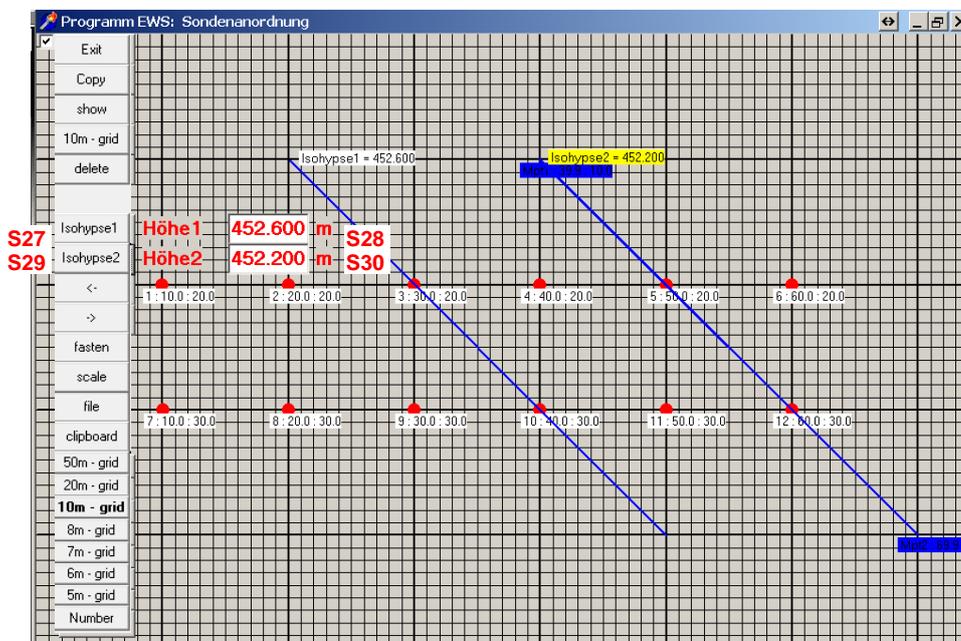
**Fig. 3.54:** The example of the thermal response of a borehole during the first hour.

There is another type of the thermal response test which is less frequently used. In this type the borehole inlet temperature is constant and the borehole outlet temperature and the borehole heat extraction rate is analyzed. For this type of response test field 6.2 (“Iteration of borehole heat extraction rate? (Heat extraction rate given)”) must be set to “no” and the constant borehole inlet temperature must be entered in field 6.6. This type of thermal response test ignores the “heat extraction step” (field 6.5).

### 3.10 The sheet “Water” (Groundwater influence)

The sheet “water” is only available in the Pro Version of the program and it allows the consideration of groundwater influence in the earth such as the seasonal fluctuation at the surface. The sheet “water” is chosen in the dropdown from the menu bar “Windows”.

The program EWS uses a balance method for the consideration of the groundwater influence. For this the stream cross section under the influence of the borehole is defined. For this the groundwater flow direction must be defined in the sheet “field of boreholes”. This can be done by adding two Isohypse-lines (equal height lines) with the groundwater surface. Groundwater usually flows perpendicularly to its surface isohypse. By pressing the **button S27** the **field S28** appears, in which the absolute height of the first isohypse can be added. After the beginning and end point of the isohypse line can be added (left mouse click), a third click anywhere on the map will confirm the isohypse line. This process is to be repeated with **Button S29** and **field S30** for the second isohypse line. If these two lines are not parallel to each other, the programs calculates the stream cross section based on the angle bisector line and the stream direction perpendicular to it. The boreholes are now projected perpendicular onto it and the largest distance is calculated. This distance plus 4m, multiplied with the depth of the aquiferous layers (field W16-W19) results in the cross section stream area of the aquiferous layer which is influenced by the borehole. The program EWS assumes that the groundwater temperature is always equal to the untouched ground temperature of the correspondent ground layer. On the outer layer of the simulation area (see chapter 6.1) the energy balance is made and the average ground temperature is calculated based on the sum of the extracted energy from the boreholes and the net heat inflow of the groundwater with help of the g functions (see Eq. 6.21). In accordance with this model, the effective thermal conductivity  $\lambda_{eff}$  is used inside of the simulation radius (with groundwater, input in **field 3.15**, see chapter 3.6.3), yet  $\lambda_{real}$  is used for the marginal conditions (without groundwater, input in **field 3.16**).



**Fig. 3.55: Input of the groundwater surface height with isohypse lines on the sheet “field of boreholes”**

Caution: the groundwater influence is not applicable if neighboring boreholes have been defined (see chapter 3.3.6)

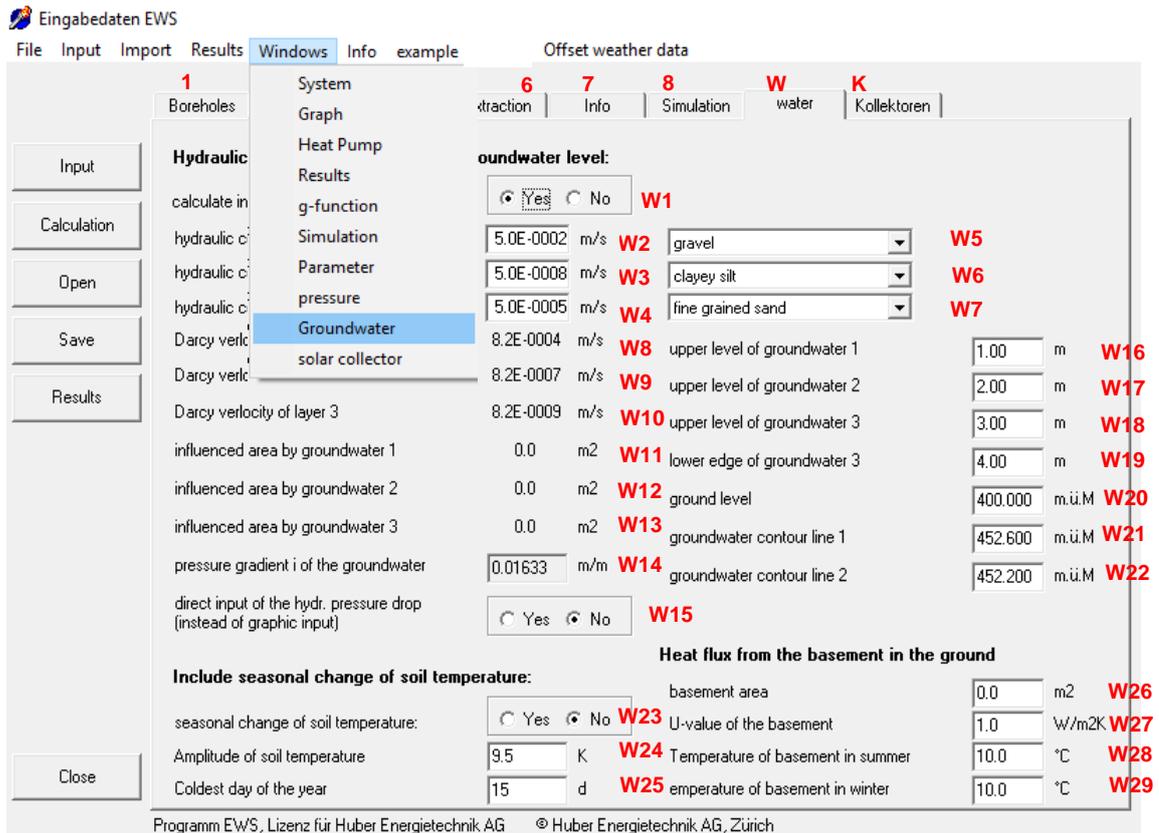
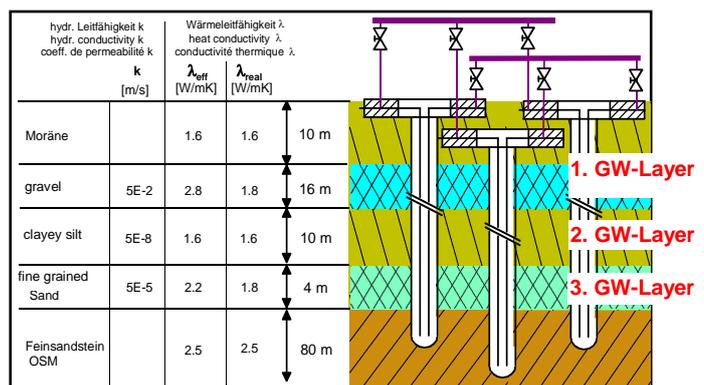


Fig. 3.56: Sheet “water” for the consideration of groundwater influence and seasonal fluctuation.

- W1** Groundwater Influence is only considered if field W1 is set to “yes”
- W2–W7** The hydraulic conductivity  $k_f$  (permeability parameter) is a property of the aquiferous layer. The pulldown menus W5–W7 suggest typical values, yet calculations are always made with values of W2–W4.
- W16–W19** The aquiferous layers are defined by depth under ground level in fields W16–W19. It is assumed that the ground until the first aquiferous layer is without water. The example on the right represents the situation described in Fig. 3.56.
- W23–W25** The seasonal fluctuations of the earth surface can optionally be added. This makes sense especially in the case of strong groundwater flows or not very deep boreholes or energy poles. In this case the ground temperature is corrected according to following equation, depending on the depth  $z$ :
 
$$T = T_{mo} - \Delta T_o \cdot \exp\left(-z \cdot \sqrt{\frac{\pi}{a \cdot t_a}}\right) \cdot \cos\left(\frac{2\pi}{t_a} t - z \cdot \sqrt{\frac{\pi}{a \cdot t_a}}\right) \quad \text{eq. 3.3}$$
- W26–29** If the heat flow of a building over energy poles should be calculated, according to eq. 6.21, the fields W26–W29 are to be filled.



### 3.11 The sheet “solar collector” (solar regeneration)

The sheet “solar collector” is only available in the Pro Version. It allows the calculation of solar borehole regeneration, according to the schematic in Fig. 3.57.

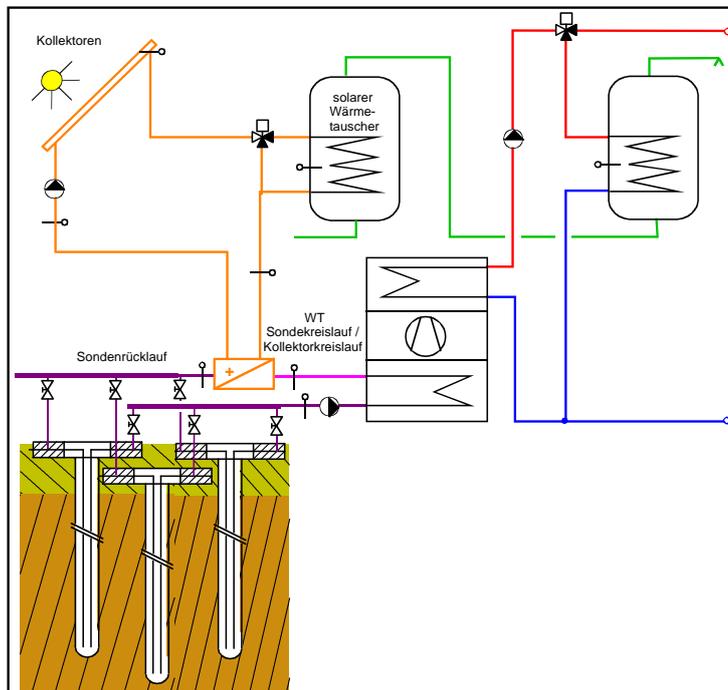


Fig. 3.57: Schematic of the solar regeneration.

The solar yield of the collectors is newly calculated in hourly steps, under consideration of the heat pump operation and the borehole temperatures.

For the choice of the weather data (solar radiation and air temperature), collector slope, azimuth and horizon shadowing the Standard-Format of the Meteorological Norm [17] can be imported with the **button K12**. In this case the Standard-Format data of the Meteorological Norm is imported and the **fields K8 and K9** disappear from the sheet “collectors”. The weather only influences the solar yield but not the load profile of the heat pump.

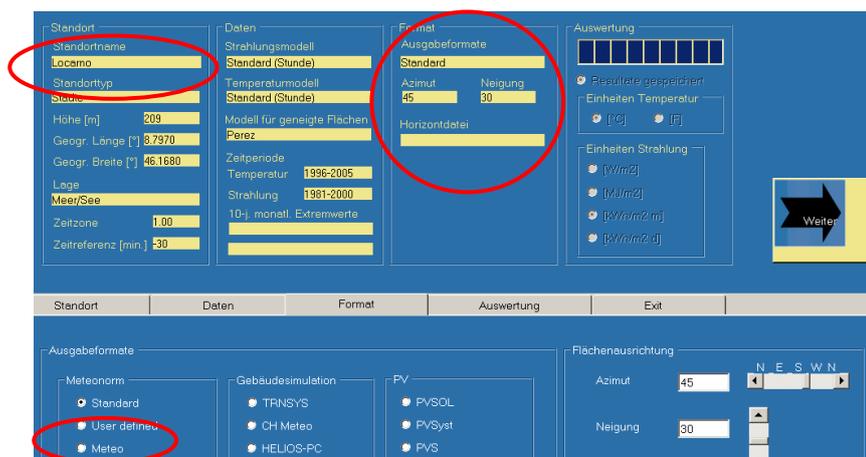
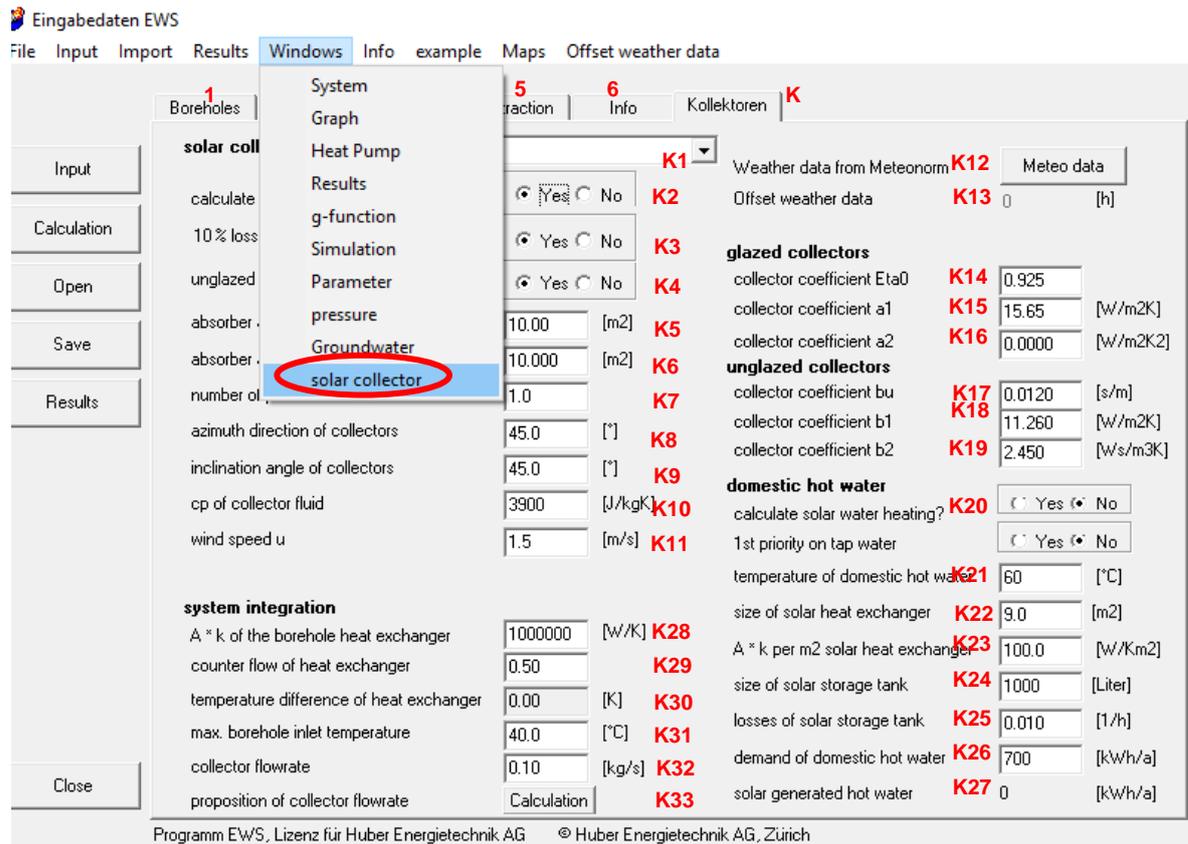


Fig. 3.58: Input of weather data, Azimuth (east= -90°, south= 0°, west= 90°), slope and horizon in the program METEONORM [17]

If no meteorological data is imported, the default is the DRY-Database for Zürich SMA. Azimuth and slope of the collectors must then be imported to **fields K8 and K9**.



**Fig. 3.59: Sheet “solar collectors” for the calculation of solar regeneration.**

- K1** Pulldown-Menu for the choice of a limited amount of solar collectors. Not obligatory input, since calculations are always based on characteristic collector values.
- K2** To enable solar regeneration, K2 must be set to „Yes“.
- K3** If K3 is set to „Yes“, the solar yield has a 10% loss, which accounts for thermal losses in the collector pipes and a real regulation.
- K4** If K4 is set to „Yes“ (unglazed collectors), the collector constants in fields K14-K16 are to be filled out, with glazed collectors this is the case for fields K17-K19.
- K5** K5 is the input field for the net absorber area, not the gross collector area
- K11** The wind speed is only considered in the case of unglazed collectors. The wind speed is not taken from the weather dataset, but as a constant from field K11 for the entire year.
- K13** For the solar yield it is substantial, if the heat pump runs during the day or the night. In the standard load profile (Offset = 0h) the heat pump runs until midnight for domestic warm water and after midnight for the heating demand, as long as it needs to reach the total daily heat demand. With the offset, the running time of heat pump can be transferred into daytime. E.g. with an offset of 10h the heat pump runs until 10 a.m. for the domestic warm water heating and after 10 a.m. it runs for the heating demand. The offset can be defined in the main menu under „Offset weather data“.
- K20-K27** The calculation of the direct use share for the solar domestic water pre-heating is merely an approximation. The heat demand for domestic warm water use which must be generated by the heat pump (field 10.3 on the sheet „Load“) must be reduced by the amount in field K27.

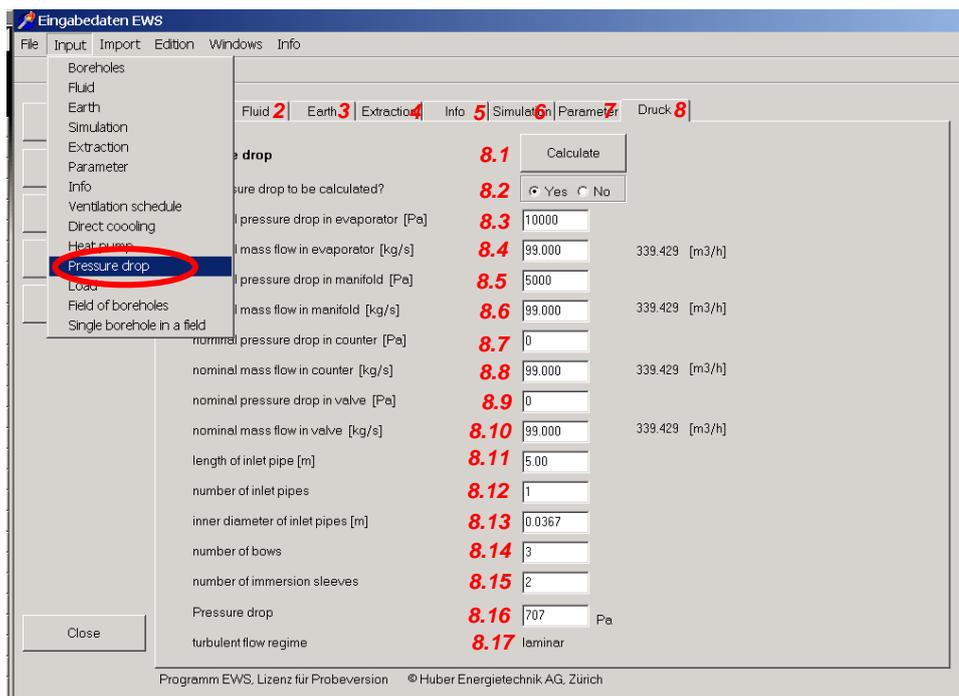
### 3.12 The sheet “Pressure”

To open the sheet “Pressure”, open the pull-down menu “Windows” from the menu bar and select the sheet “Pressure” or open the pull-down menu “Input” from the menu bar and select “Pressure drop” (see Fig. 3.61). This option is only available in the complete version of the program EWS.



**Fig. 3.60:** Error message, if no full version of the EWS Program is available.

In the sheet “Pressure” it is possible to calculate the pressure drop in the borehole. Additionally the flow regime is calculated (laminar or a turbulent flow regime in the pipes). A more detailed description of the used model is given in reference [11].



**Fig. 3.61:** The sheet “Pressure”.

- 8.1 After each change of the input data, the button “Calculate” must be clicked to calculate the new results.
- 8.2 If field 8.2 is set to “yes”, the pressure drop in the borehole pipes (without the supply pipes) is calculated for each time step and written into the result file (one per hour). Hence, the pressure drop in the result file represents only the pipe itself, without the supply pipe and without the pressure drop in the evaporator, etc.

- 8.3-8.10** The input of the nominal pressure drop of single components at nominal mass flow rates. The nominal mass flow rate can vary for each component. The conversion to the effective pressure drop is done with the parable approach.
- 8.11** The length of the supply pipe (normally from the head to the manifold of the pipe). The program EWS calculates the total pressure drop from the pressure drop of the borehole plus the sum of the single components from the borehole loop plus 2 times the pressure drop from the supply pipe (from and to the borehole).
- 8.12** The number of parallel inlet pipes for the pressure drop calculation (from the head of the pipe to the manifold). E.g. if the pipes of a double-U-pipe go separately towards the manifold, the input in field 8.12 should be 2, but if the pipes are united at the head of the pipe, the correct input is 1. It is the same behavior if two boreholes are entering the house by a manifold. If the pipes of two double-U-pipes are going separately to the manifold, the correct input in the field 8.12 is 4. If the pipes are united at each head of the two double-U-pipes, a 2 should be entered. If the manifold is very close to the two double-U-pipes and there is a long supply pipe to the house, the input is 1.
- 8.13** The inner diameter of the supply pipes (normally from the head of the pipe to the manifold). The inner diameter of the inlet pipe DN 40 usually is 0.032 m (for DN 50 it is 0.037 m).
- 8.14-8.15** The number of immersion sleeves and bows in the borehole loop (enter the number of the total loop, add the bows in the inlet AND outlet pipe). The pressure drop is calculated with:

$$\Delta p = \zeta \frac{\rho_{Sole}}{2} v^2 \quad \text{eq. 3.4}$$

in which  $\zeta = 2$  is entered for each bow and  $\zeta = 1$  for each immersion sleeve.

- 8.16** The pressure drop for the whole borehole loop. Please note that after each change of any input data, the button “Calculate” must be pressed to adjust the result.

The pressure drop  $\Delta p$  of the flow in the borehole and in the inlet pipe is calculated with:

$$\Delta p = \xi \frac{2H}{D_i} \frac{\rho_{Sole}}{2} v^2 \quad \text{eq. 3.5}$$

In the laminar case ( $Re < 2'300$ ),  $\xi$  is calculated with:

$$\xi = \frac{64}{Re} \quad \text{eq. 3.6}$$

In the turbulent case ( $Re > 2'300$ ) the approach by Petukhov is used:

$$\xi = [0.790 \ln(Re) - 1.64]^{-2} \quad \text{eq. 3.7}$$

All other pressure drops are converted from the nominal mass flow to the effective borehole mass flow using the parabolic approach.

- 8.17** Information about the flow regime in the borehole (laminar or turbulent). The transition from laminar to turbulent flow occurs at a Reynold's number of 2'300.

### 3.13 The sheet “Parameter”

Select the sheet “Parameter” from the pull-down menu “Windows” in the menu (see Fig. 3.62). The simulation grid, the simulation time steps and the stop criterion for the iteration can be defined in the sheet “Parameter”.

Additionally the option to write the results in the output file can be chosen.

Normally, the user has no need to fill in the sheet “Parameter”, since it can be calculated with the default values for most cases.

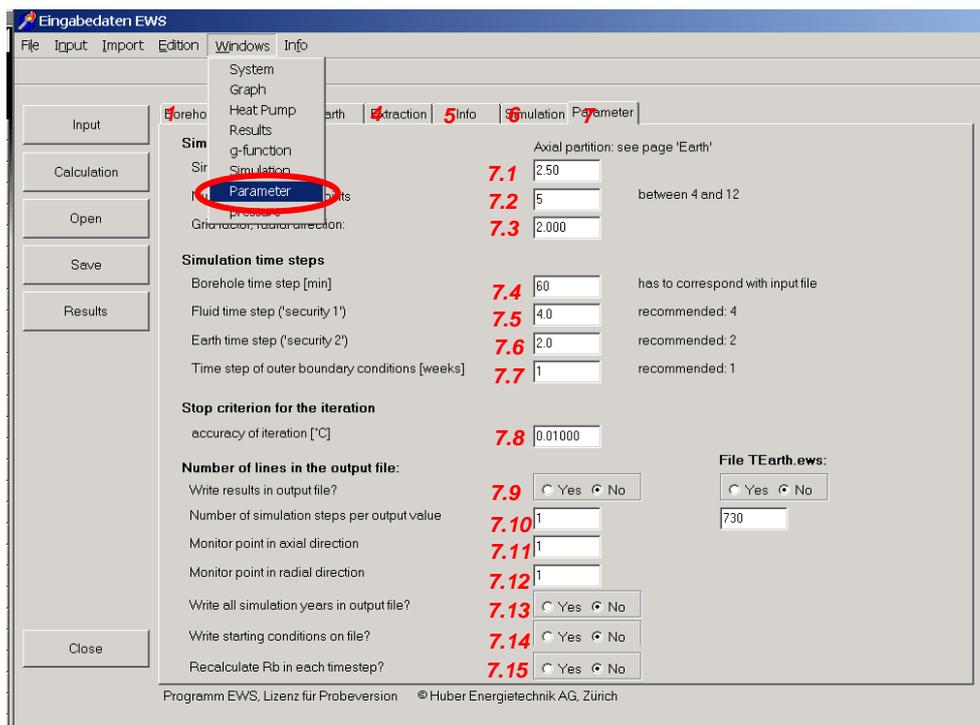


Fig. 3.62: The sheet “Parameter”.

In field 7.15 is defined whether the thermal borehole resistance  $R_b$  is recalculated for each calculation step. The borehole resistance  $R_b$  (thermal resistance between borehole and fluid) is basically a parameter which is influenced by geometrical factors of the borehole, by the properties of the filling material and by the pipes. Additionally, it includes the heat transfer coefficient  $\alpha$  (from the piping wall to the fluid) which depends on the mass flow rate in the pipes. Since the program EWS offers the option to simulate a variable mass flow rate, the user gets two options: Either the heat transfer coefficient  $\alpha$  (and thereby the thermal borehole resistance  $R_b$ ) is recalculated for each calculation step or  $R_b$  is kept constant for the whole simulation. If the field 7.15 is left on the default setting (“no”),  $R_b$  is calculated at the beginning of the simulation on the basis of the design mass flow rate (field 2.7). This choice has an influence on the computation speed.

### 3.14 Properties of the heat pump and of the supplementary heating system

The complete version of the program EWS is able to include additional information about the heat pump as well as about the additional heating system. Select the sheet “Heat pump” from the pull-down menu “Windows” in the menu bar (see Fig. 3.63). In the following, the sheet “heat pump” appears (see Fig. 3.64). The sheet “Heat Pump” cannot be combined with the sheet “Load”.

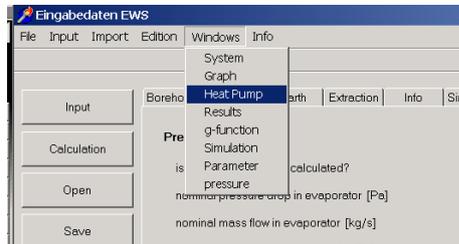


Fig. 3.63: The opening of the sheet “heat pump”.

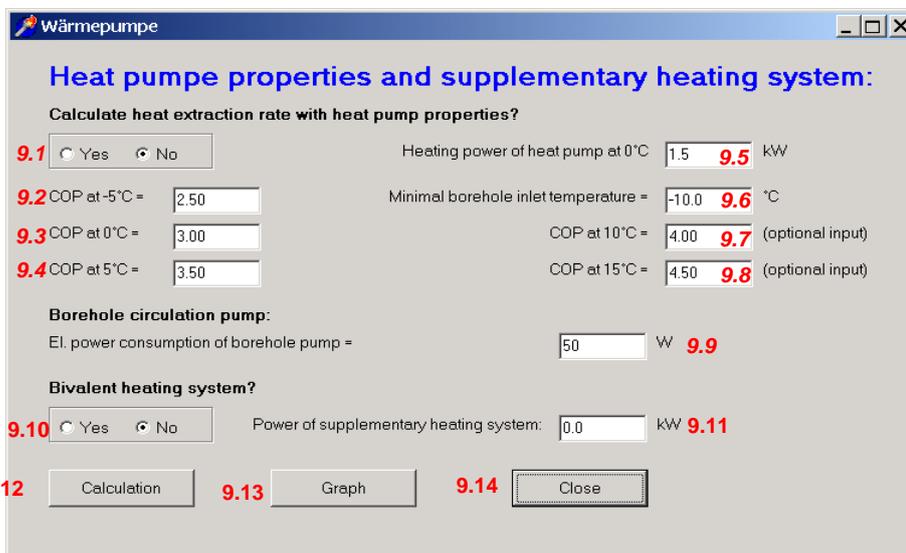


Fig. 3.64: The input mask of the heat pump properties and the additional heating system.

9.1 The inputs from this mask are used for the calculation, if the question “Calculate heat extraction rate with heat pump properties?” is answered with “yes”. In a first step, the program checks the consistency of the input data in field 9.5 (heating power of the heat pump), in field 9.3 (COP at 0°C borehole outlet temperature) and in field 4.4 (evaporator power, extraction rate). In the case of inconsistent input data, the program EWS asks if the input in field 4.4 should be adjusted. If then the field 4.4 is not adjusted, field 9.5 is ignored for all further calculations.

The extraction rate  $Q_{\text{outlet}}$  (field 4.4) is taken as the evaporator performance at 0°C borehole outlet temperature if “yes” is selected in field 9.1. In each calculation step the effective evaporator performance is adapted to the effective COP. Thereby, the program EWS assumes a constant heating power (corresponding to the input in field 9.5).

9.2-9.4, 9.7-9.8 In these fields the COP of the various fluid temperatures are entered. The inputs in field 9.7 and 9.8 are optional. If these values are not known, these fields can be set to zero and the program calculates them by linear extrapolation.

9.9 The electric power consumption of the borehole pump ought to be entered in this field.

9.10/9.11 In case of a bivalent heating system, the power of the supplementary heating system can be entered in the field 9.11. The field 9.10 must be set to “yes” (applied only in the case of a complete “system simulation”).

### 3.15 Direct cooling

The complete version of the program EWS offers the option to enter data about direct cooling. Select the sheet “System” from the pull-down menu “Windows” in the menu bar (see Fig. 3.65). In the following the sheet “Systemdefinition” appears (see Fig. 3.66).

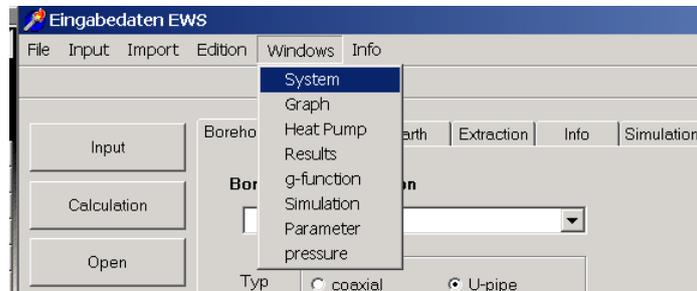


Fig. 3.65: Selection of the input mask “System” of direct cooling.

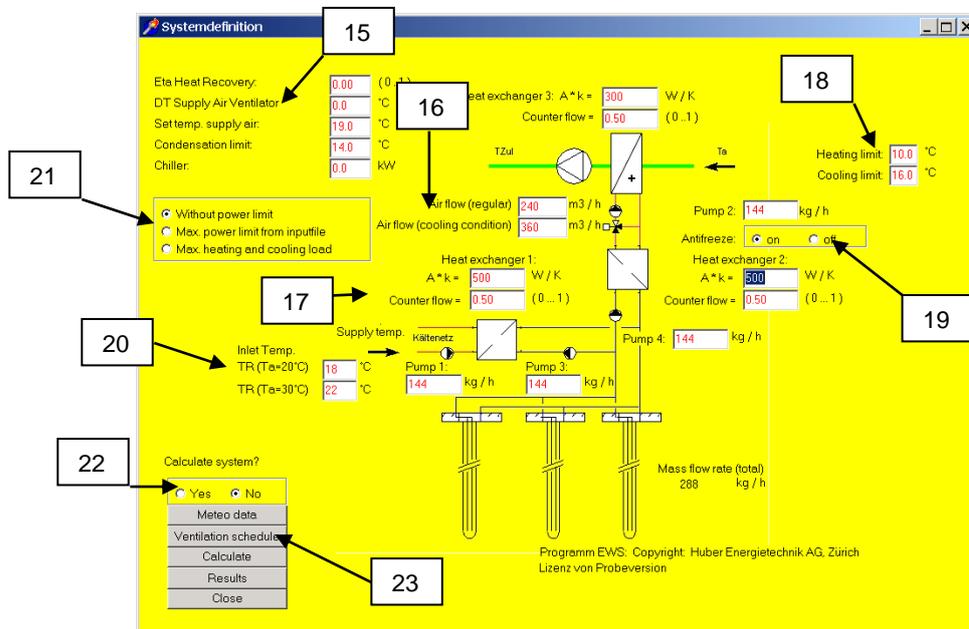


Fig. 3.66: The input mask “Systemdefinition” for direct cooling systems (without HP).

15. The following data must be entered in **field 15** (top down): The degree of the efficiency of the heat recovery system, the temperature rise in the supply air ventilator, the desired temperature of the supply air, the condensation limit (minimum supply temperature) and the installed cooling power of an additional chiller (not shown).
16. The regular air flow and the air flow in cooling condition are entered here.
17. **Field 17** requires the characteristics of the various heat exchangers in the system (3 units). Additionally, there are 4 pumps available for which the mass flow rate can be entered.
18. The input in **field 18** defines the heating and cooling limits. If the outdoor temperature is higher than the cooling limit, the system is in cooling mode, if the outdoor temperature is lower than the heating limit, the system is in heating mode.

19. The program offers the option to protect the heat exchanger to the borehole loop against freezing by controlling the flow rate in the intermediate loop between the air heat exchanger and the borehole heat exchanger. To activate this, put the “Antifreeze” option button **field 19** to “on”.
20. The return temperature of the cooling system in the building, in function of the outdoor air temperature can be defined in **field 20**. Set the value for the return temperature, if the outdoor air temperature is 20°C and if it is 30°C. In between, the system interpolates linearly. Below 20°C outdoor air temperature and above 30°C outdoor air temperature a constant return temperature of the cooling system is assumed.
21. In **field 21** it is defined whether it is calculated without a limit of the direct cooling rate, or with the maximal cooling rate from the input file or if the maximal heating and cooling load should be calculated with data from the sheet “Extraction”. This option should always be checked when calculating variants.
22. If “yes” is selected in **field 22**, all calculations are done with the data from this input mask. If “no” is selected, the inputs of this sheet are ignored and the calculations are based on the inputs of the page “Extraction”.
23. Click on the button “Ventilation schedule” to define a ventilation schedule.

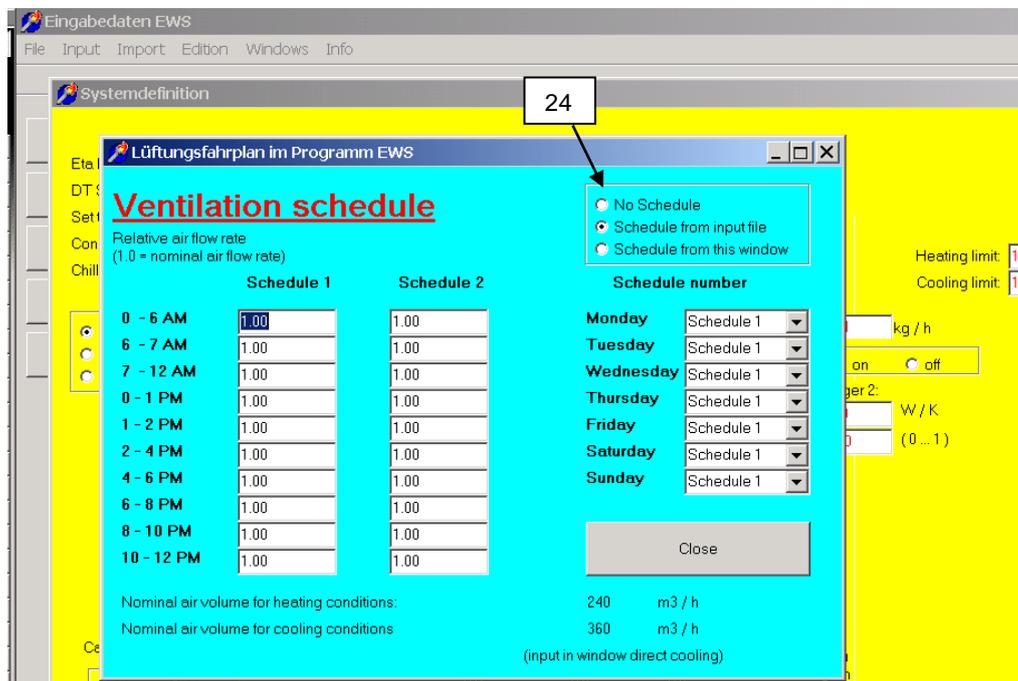


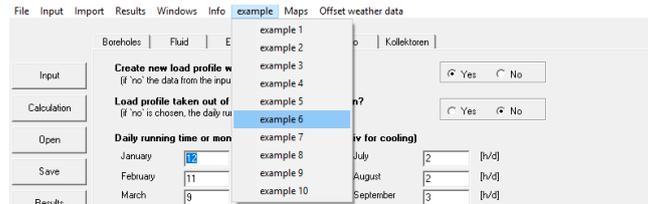
Fig. 3.67: The input mask “Ventilation schedule”.

24. The program EWS is able to generate a ventilation schedule. It exists also the possibility to define an hourly ventilation schedule for the whole year in the input file.

## 4 Examples

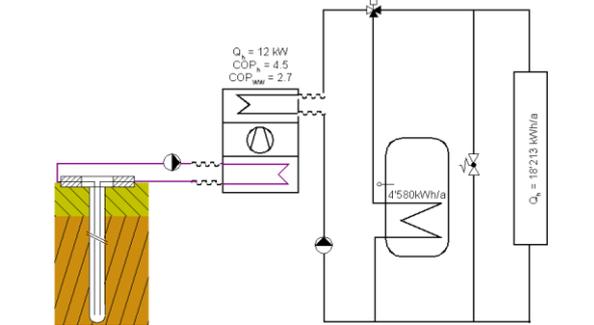
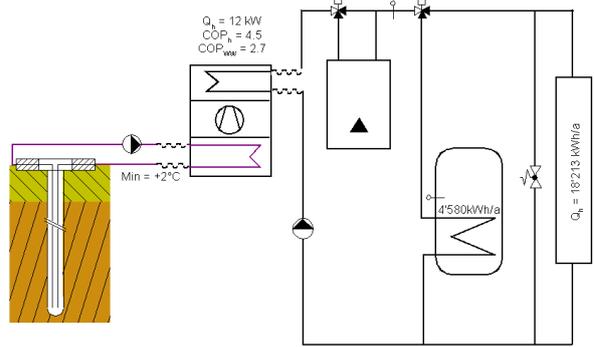
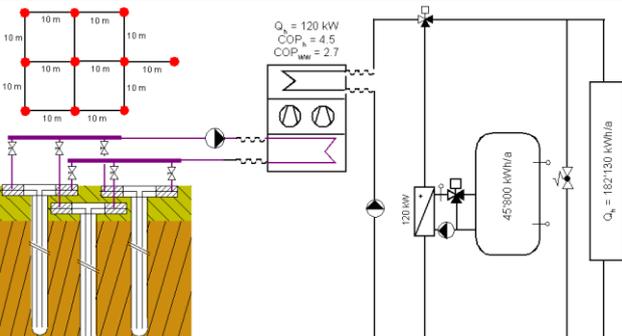
### 4.1 Selecting and loading the examples

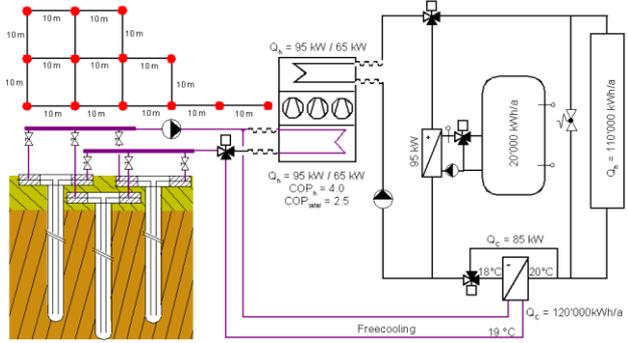
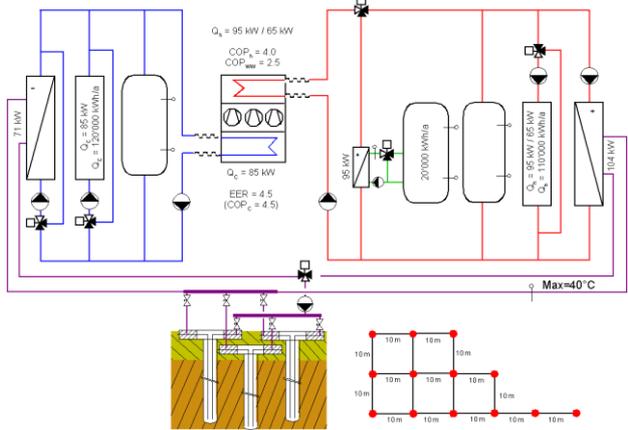
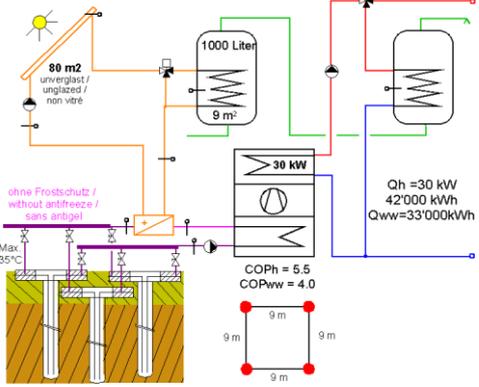
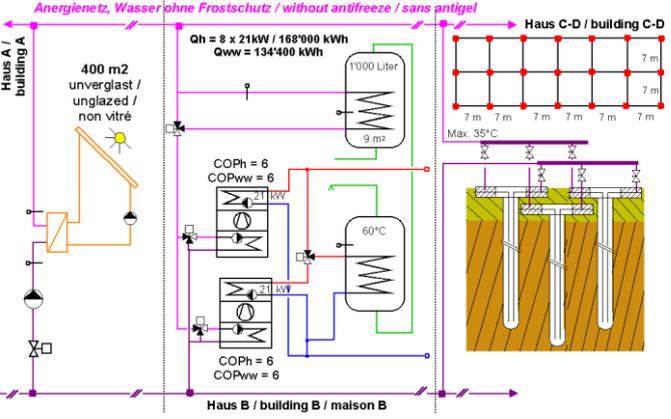
In the Pro-Version of the program EWS there is a collection of calculation examples which can be selected directly into the program. The examples can serve as base for own calculations. These examples are described in Chapter 4.2. These can be seen and calculated with, by selecting “example” in the main menu bar.

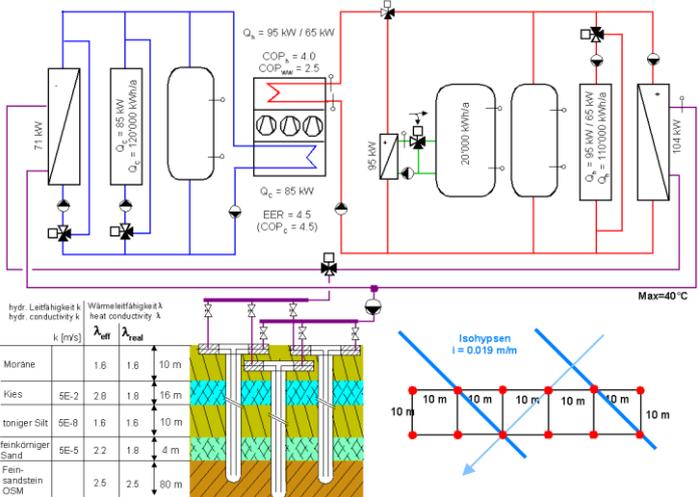
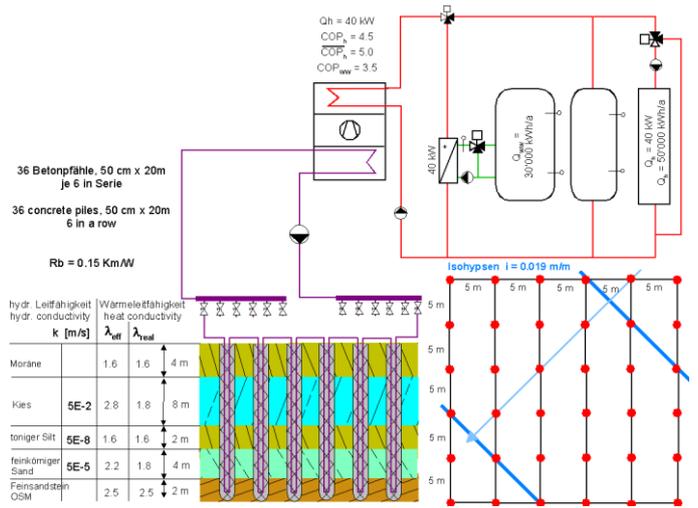
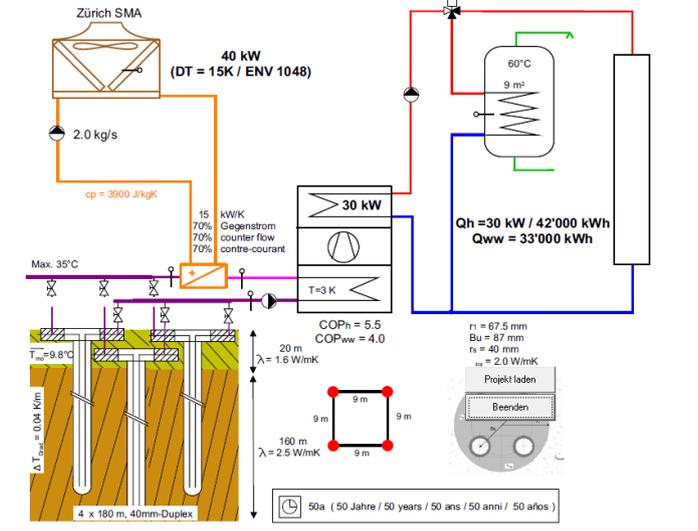


### 4.2 Examples in the Program EWS

Following examples are available in the Pro-Version of the EWS program:

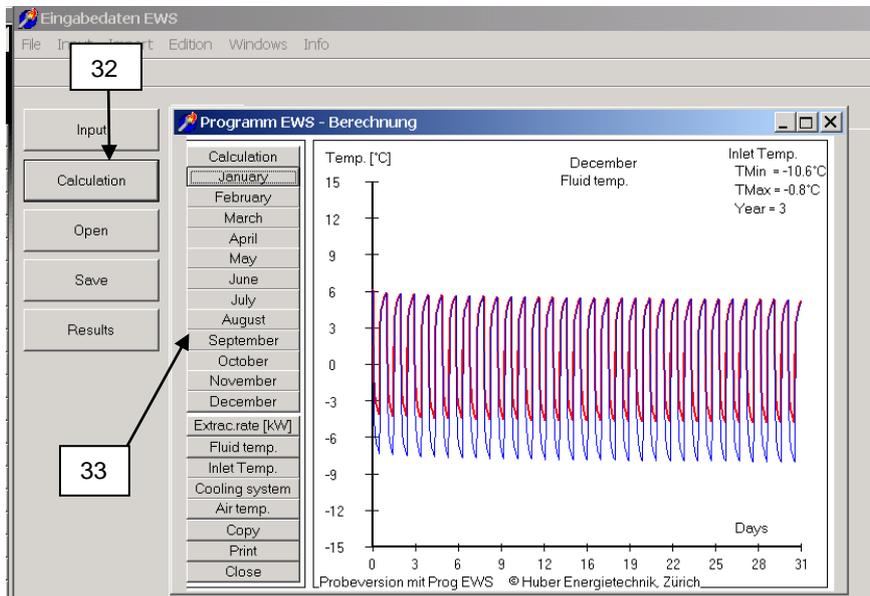
<p><b>Example 1:</b></p> <ul style="list-style-type: none"> <li>• Amount of boreholes: 1</li> <li>• Borehole length: 185 m</li> <li>• Borehole type: 40 mm duplex</li> <li>• Heat output heat pump: 12 kW</li> <li>• Heating demand: 18'213 kWh</li> <li>• COP heating: 4.5</li> <li>• Heat demand domestic water: 4'580 kWh</li> <li>• COP domestic water: 2.7</li> </ul>	<p><b>Single house with monovalent heating heat pump</b></p> 
<p><b>Example 2:</b></p> <ul style="list-style-type: none"> <li>• Amount of boreholes: 1</li> <li>• Borehole length: 210 m</li> <li>• Borehole type: 40 mm duplex</li> <li>• Heating perf. heat pump: 12 kW</li> <li>• Heating demand: 18'213 kWh</li> <li>• COP heating: 4.5</li> <li>• Heat demand domestic water: 4'580 kWh</li> <li>• COP domestic water: 2.7</li> <li>• Minimal borehole inlet temp.: 2°C</li> <li>• Additional heating: Gas heater</li> </ul>	<p><b>Bivalent heat pump with 1 borehole</b></p> 
<p><b>Example 3:</b></p> <ul style="list-style-type: none"> <li>• Amount of boreholes: 10</li> <li>• Borehole length: 210 m</li> <li>• Borehole type: 40 mm duplex</li> <li>• Heat output heat pump: 120 kW</li> <li>• Heating demand: 182'130 kWh</li> <li>• COP heating: 4.5</li> <li>• Heat demand domestic water: 45'800 kWh</li> <li>• COP domestic water: 2.7</li> </ul>	<p><b>Borehole-yield for multiple-households (10 boreh.)</b></p> 

<p><b>Example 4:</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 13</li> <li>Borehole length: 140 m</li> <li>Borehole type: 40 mm duplex</li> <li>Heat output heat pump: 95 kW</li> <li>Heating demand: 110'000 kWh</li> <li>COP heating: 4.0</li> <li>Heat demand domestic water: 20'000 kWh</li> <li>COP domestic water: 2.5</li> <li>Cooling energy demand: 120'000 kWh</li> <li>Max. freecooling - inlet: 19 °C</li> </ul>	
<p><b>Example 5</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 13</li> <li>Borehole length: 140 m</li> <li>Borehole type: 40 mm duplex</li> <li>Heat output heat pump: 95 kW</li> <li>Heating demand: 110'000 kWh</li> <li>COP heating: 4.0</li> <li>Heat demand domestic water: 20'000 kWh</li> <li>COP domestic water: 2.5</li> <li>Cooling chiller: 85 kW</li> <li>Cooling energy demand: 120'000 kWh</li> <li>EER (=COPc) cooling: 4.5</li> <li>Max. borehole inlet: 40 °C</li> </ul>	<p><b>Monovalent heating with active cooling</b></p> 
<p><b>Example 6:</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 4</li> <li>Borehole length: 180 m</li> <li>Borehole type: 40 mm duplex</li> <li>Heat output heat pump: 30 kW</li> <li>Heating demand: 42'000 kWh</li> <li>COP heating: 5.5</li> <li>Heat demand domestic water: 33'000 kWh</li> <li>COP domestic water: 4.0</li> <li>max. borehole - inlet :35 °C</li> <li>Area unglased collectors: 80 m<sup>2</sup></li> <li>Weather Dataset: Zürich SMA</li> <li>Offset weather: 7 h</li> </ul>	<p><b>Solar borehole regeneration</b></p> 
<p><b>Example 7:</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 21</li> <li>Borehole length: 180 m</li> <li>Borehole type: 40 mm duplex</li> <li>Heat output per heat pump: 21 kW</li> <li>Amount Heat pumps total: 2</li> <li>Heating demand all homes: 168'000 kWh</li> <li>COP heating: 6.0</li> <li>Heat demand domestic water: 134'400 kWh</li> <li>COP domestic water: 6.0</li> <li>max. borehole-inlet: 35 °C</li> <li>Area unglased collectors: 400 m<sup>2</sup></li> <li>Weather Dataset: Zürich SMA</li> <li>Offset weather: 7 h</li> </ul>	<p><b>Energy network with solar seasonal storage</b></p> 

<p><b>Example 8:</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 12</li> <li>Borehole length: 120 m</li> <li>Borehole type: 40 mm duplex</li> <li>Heat output heat pump: 95 kW</li> <li>Heating demand: 110'000 kWh</li> <li>COP heating: 4.0</li> <li>Heat demand domestic water: 20'000 kWh</li> <li>COP domestic water: 2.5</li> <li>Cooling capacity chiller: 85 kW</li> <li>Cooling energy demand: 120'000 kWh</li> <li>EER (=COPc) Cooling: 4.5</li> <li>Depth groundwater (GW): 8 m</li> <li>Material GW-Layer: Gravel</li> <li>hydr. conductivity GW-Layer: 0.05 m/s</li> <li>Pressure gradient GW: 0.019 m/m</li> <li>Eff. thermal conductivity Gravel (with GW influence, from TRT): 2.8 W/mK</li> <li>Thermal conductivity Gravel (w.o. GW influence): 1.8 W/mK</li> </ul>	<p><b>Heating and active cooling with GW influence</b></p>  <table border="1"> <thead> <tr> <th></th> <th>hydr. Leitfähigkeit k</th> <th>hydr. conductivity</th> <th>Wärmeleitfähigkeit λ<sub>eff</sub></th> <th>heat conductivity λ<sub>real</sub></th> </tr> </thead> <tbody> <tr> <td>Moräne</td> <td>1.6</td> <td>1.6</td> <td>1.8</td> <td>1.8</td> </tr> <tr> <td>Kies</td> <td>5E-2</td> <td>2.8</td> <td>1.8</td> <td>1.8</td> </tr> <tr> <td>toniger Schluff</td> <td>5E-8</td> <td>1.6</td> <td>1.6</td> <td>1.6</td> </tr> <tr> <td>feinkörniger Sand</td> <td>5E-5</td> <td>2.2</td> <td>1.8</td> <td>1.8</td> </tr> <tr> <td>Feinsandstein OSM</td> <td>2.5</td> <td>2.5</td> <td>2.5</td> <td>2.5</td> </tr> </tbody> </table>		hydr. Leitfähigkeit k	hydr. conductivity	Wärmeleitfähigkeit λ <sub>eff</sub>	heat conductivity λ <sub>real</sub>	Moräne	1.6	1.6	1.8	1.8	Kies	5E-2	2.8	1.8	1.8	toniger Schluff	5E-8	1.6	1.6	1.6	feinkörniger Sand	5E-5	2.2	1.8	1.8	Feinsandstein OSM	2.5	2.5	2.5	2.5
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Feinsandstein OSM	2.5	2.5	2.5	2.5																											
<p><b>Example 9:</b></p> <ul style="list-style-type: none"> <li>Amount energy poles: 36 Pcs.</li> <li>Amount poles in series: 6 Pcs.</li> <li>Length energy poles: 20 m</li> <li>Pole type: Cement, 50cm</li> <li>„Borehole resistance“ Rb: 0.15 Km/W</li> <li>Heat output Heat pump: 40 kW</li> <li>Heating demand: 50'000 kWh</li> <li>COP Heating full load: 4.5</li> <li>COP Heating average: 5.0</li> <li>Heat demand domestic water: 30'000 kWh</li> <li>COP domestic water: 3.5</li> <li>Depth groundwater (GW): 8 m</li> <li>Material GW-Layer: Gravel</li> <li>hydr. conductivity GW-Layer: 0.05 m/s</li> <li>Pressure gradient des GW: 0.019 m/m</li> <li>Eff. therm. conduct. gravel (w. GW): 2.8 W/mK</li> <li>Therm. conductivity gravel (w.o. GW): 1.8 W/mK</li> </ul>	<p><b>36 Energy pole (cement piles) in groundwater</b></p>  <table border="1"> <thead> <tr> <th></th> <th>hydr. Leitfähigkeit k</th> <th>hydr. conductivity</th> <th>Wärmeleitfähigkeit λ<sub>eff</sub></th> <th>heat conductivity λ<sub>real</sub></th> </tr> </thead> <tbody> <tr> <td>Moräne</td> <td>1.6</td> <td>1.6</td> <td>1.6</td> <td>1.6</td> </tr> <tr> <td>Kies</td> <td>5E-2</td> <td>2.8</td> <td>1.8</td> <td>1.8</td> </tr> <tr> <td>toniger Schluff</td> <td>5E-8</td> <td>1.6</td> <td>1.6</td> <td>1.6</td> </tr> <tr> <td>feinkörniger Sand</td> <td>5E-5</td> <td>2.2</td> <td>1.8</td> <td>1.8</td> </tr> <tr> <td>Feinsandstein OSM</td> <td>2.5</td> <td>2.5</td> <td>2.5</td> <td>2.5</td> </tr> </tbody> </table>		hydr. Leitfähigkeit k	hydr. conductivity	Wärmeleitfähigkeit λ <sub>eff</sub>	heat conductivity λ <sub>real</sub>	Moräne	1.6	1.6	1.6	1.6	Kies	5E-2	2.8	1.8	1.8	toniger Schluff	5E-8	1.6	1.6	1.6	feinkörniger Sand	5E-5	2.2	1.8	1.8	Feinsandstein OSM	2.5	2.5	2.5	2.5
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feinkörniger Sand	5E-5	2.2	1.8	1.8																											
Feinsandstein OSM	2.5	2.5	2.5	2.5																											
<p><b>Example 10:</b></p> <ul style="list-style-type: none"> <li>Amount of boreholes: 4</li> <li>Borehole length: 180m</li> <li>Borehole type: 40mm Duplex</li> <li>Borehole distance: 9m</li> <li>Heat output heat pump: 30 kW</li> <li>Heating demand: 42'000 kWh</li> <li>COP Heating: 5.5</li> <li>Heat demand domestic water: 33'000 kWh</li> <li>COP domestic water: 4.0</li> <li>Air-heat-exchanger: 40 kW (ENV 1048)</li> <li>Weather data set: Zürich SMA</li> <li>Offset weather data: 7h</li> <li>Radius borehole r1: 67.5mm</li> <li>Shank spacing Bu: 87mm</li> <li>Outer radius borehole pipe rs: 40mm</li> <li>Heat conduct. borehole filling: 2 W/mK</li> </ul>	<p><b>Borehole Regeneration with Air-heat-exchanger</b></p> 																														

## 5 Calculations

### 5.1 Diagram of the inlet and outlet temperature of the borehole fluid



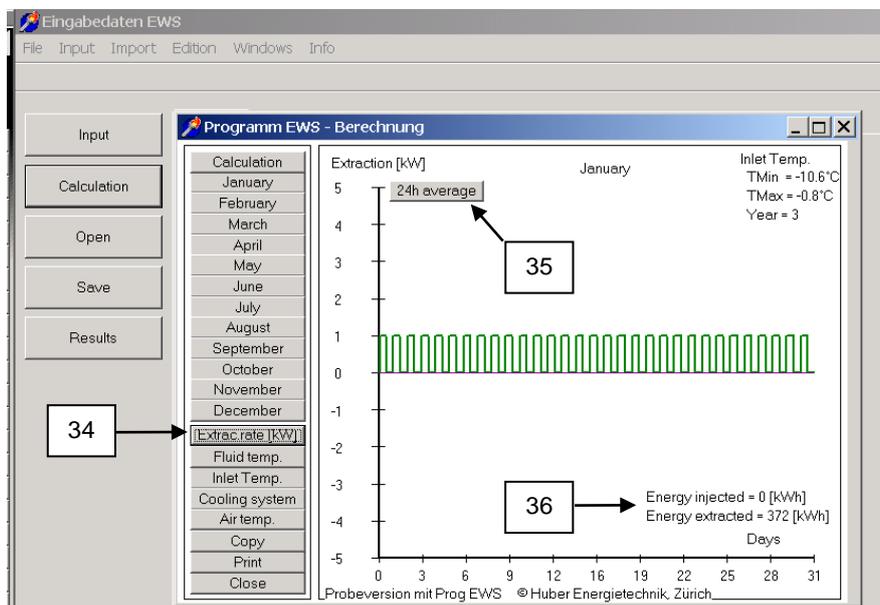
**Fig. 5.1: Diagram of the inlet and outlet temperature of the fluid in December.**

32. If all fields are completed correctly, the simulation is executed and illustrated by clicking on the button “Calculation”.

The red line (outlet temperature) and the blue line (inlet temperature) in the diagram give the fluid temperature of the corresponding month. The two extreme values given in the right, upper corner represent the minimal and the maximal temperature ( $T_{min}$  and  $T_{max}$ ) during the entire simulation period.

33. The results for each month can be viewed, printed or copied (e.g. into a Word file) by clicking on the required month.

### 5.2 The diagram of the heat extraction rate

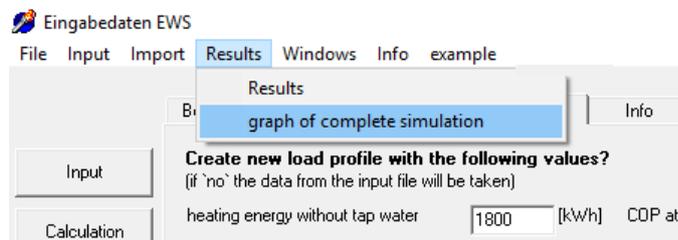


**Fig. 5.2: The diagram of the heat extraction rate.**

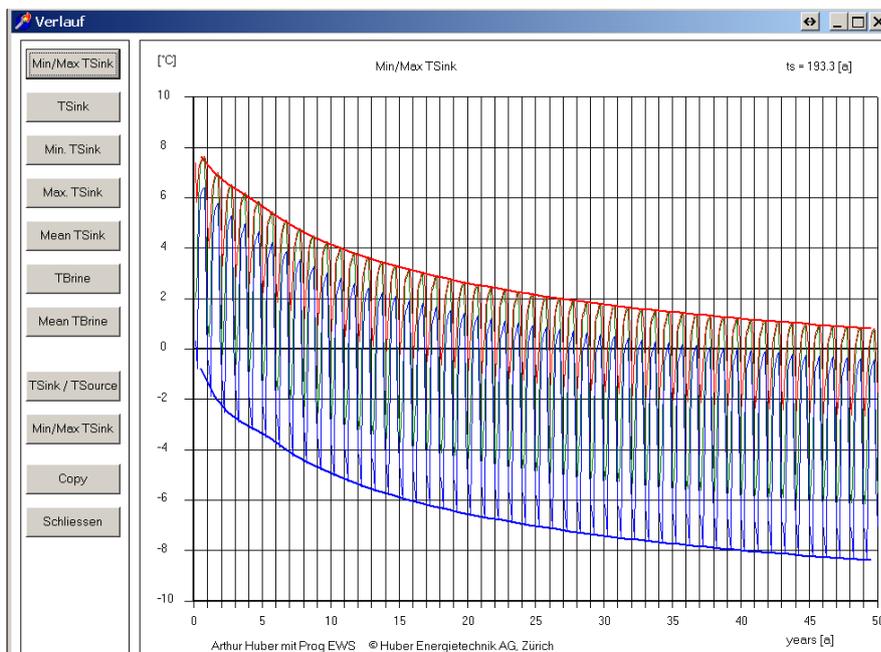
34. The heat extraction rate of the boreholes during each month can be viewed by clicking the button “Extrac. rate”. If the sign of the heat extraction rate is positive, the heat energy is extracted from the boreholes. A negative sign means that heat is injected in the borehole.
35. The averaged heat extraction rate over one day is shown by clicking on the button “24h average”.
36. The cooling and the heating energies of the selected month are shown in the diagram “Extrac. rate”. All input parameters can be saved and opened for a new session by clicking on the button “Open project”.

### 5.3 Temperature course over entire simulation period

Instead of monthly visualizations also the entire final year of the simulation period or the entire simulation period can be displayed. For this the option “Results” in the main menu bar must be clicked and then “graph of complete simulation” (Or double click the monthly visualization).

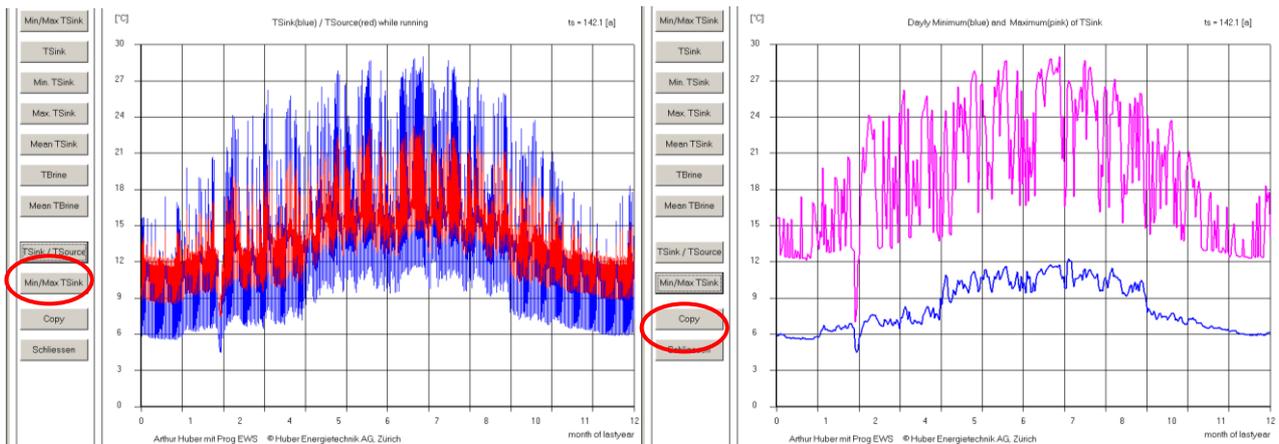


The course over the entire simulation period appears. Depending on the choice, one can visualize the monthly maximum temperature (red), minimum temperature (blue) or the average temperature (green) of the borehole inlet temperature (TSink = Borehole inlet temp.), such as the sole temperature TBrine (pink, average temperature of borehole inlet and outlet,  $T_{Brine} = (T_{Sink} + T_{Source}) / 2$ ).



**Fig. 5.3:** Graphical visualization of the sole temperature over the entire simulation period. In this example the monthly maximum (red), average (green) and minimum (blue) of the borehole inlet are represented.

### 5.4 Visualization of yearly course (last simulation year)



**Fig. 5.4:** Graphical visualization of the sole temperature over the entire last year of the simulation period. Left: effective course of the borehole temperatures (Without still stand time); Right: Daily extrema.

### 5.5 The sheet “Results”

Instead of viewing the results in a diagram, the results can be shown in a table, too. The sheet “Results” is opened by selecting it from the pull-down field “Windows” in the menu bar. Here there is an overview of several results from calculations, such as the coverage of Freecooling.

Case description:		Graph	
Projekt Erdwaermesonden		Modify	
Programm EWS, Ver 3.9 mit Default-Werten		Calculate	
		Close	
Input data:		Results:	
Heat conductivity of the earth =	2.4 W/mK	Energy injected in earth =	0 kWh
Number of boreholes =	1	Energy extracted out of earth =	2416 kWh
Borehole depth =	20.0 m	Cooling demand of TABS =	kWh
Borehole distance =	m	Cooling demand of building =	kWh
Outer pipe diameter =	32 mm	Coverage of the cooling demand by the boreholes =	%
Heat extraction rate in heating condition =	1.0 kW	Min. inlet temperature to the borehole =	-10.6 °C
Heat injection rate in cooling condition =	1.0 kW	Max. inlet temperature to the borehole =	-0.8 °C
Number of days of peak load in February =	4 Tage	Max. cooling rate of boreholes =	0.0 kW
Heat extraction rate in peak load =	1.0 kW	Max. heating rate of boreholes =	1.0 kW
Max. needed cooling rate =	0.0 kW	Medium borehole load in July and August =	0.0 W/m
Max. needed heating rate =	0.0 kW	Number of hours above cooling temperature limit =	0 h
DT Supply Air Ventilator =	0.0 °C	Cooling energy produced by chiller =	0 kWh
Ete heat recovery system of the supply air =	0.00	Energy gain of heat recovery system =	0 kWh
El. power consumption of borehole pump =	W	Total heat demand =	2416 kWh
Power of supplementary heating system =	kW	Not covered by heat pump =	0 kWh
COP of heat pump at -5°C =		- covered by supplementary heating =	kWh
COP of heat pump at 0°C =		Electrical power consumption of heat pump =	0 kWh
COP of heat pump at 5°C =		Electrical power consumption of circulation pump =	kWh
COP of heat pump at 10°C =		Average COP of heat pump =	0.00
COP of heat pump at 15°C =		Seasonal performance factor of heat pump =	0.00
Annual running time of heat pump =	2416 h	Pressure drop in borehole =	610 Pa

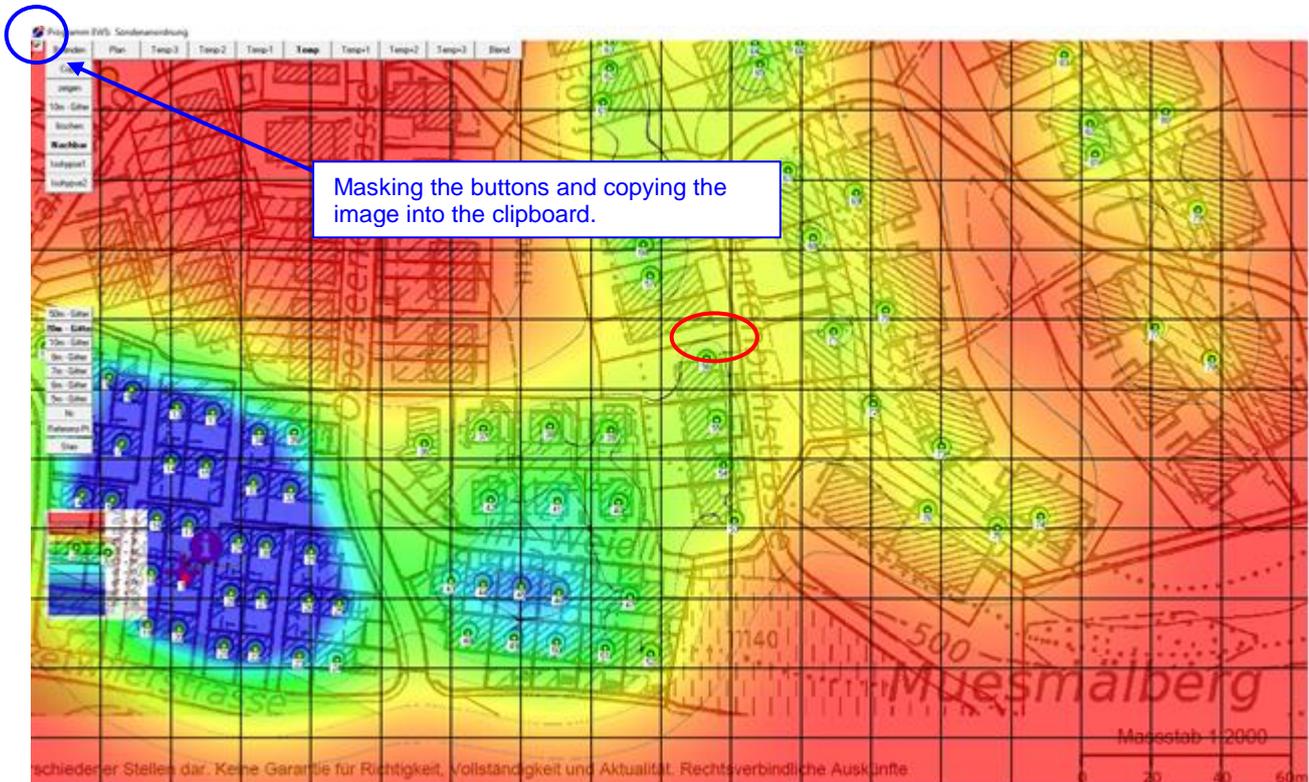
**Fig. 5.5:** The sheet “Results”.

The following points must be taken into account:

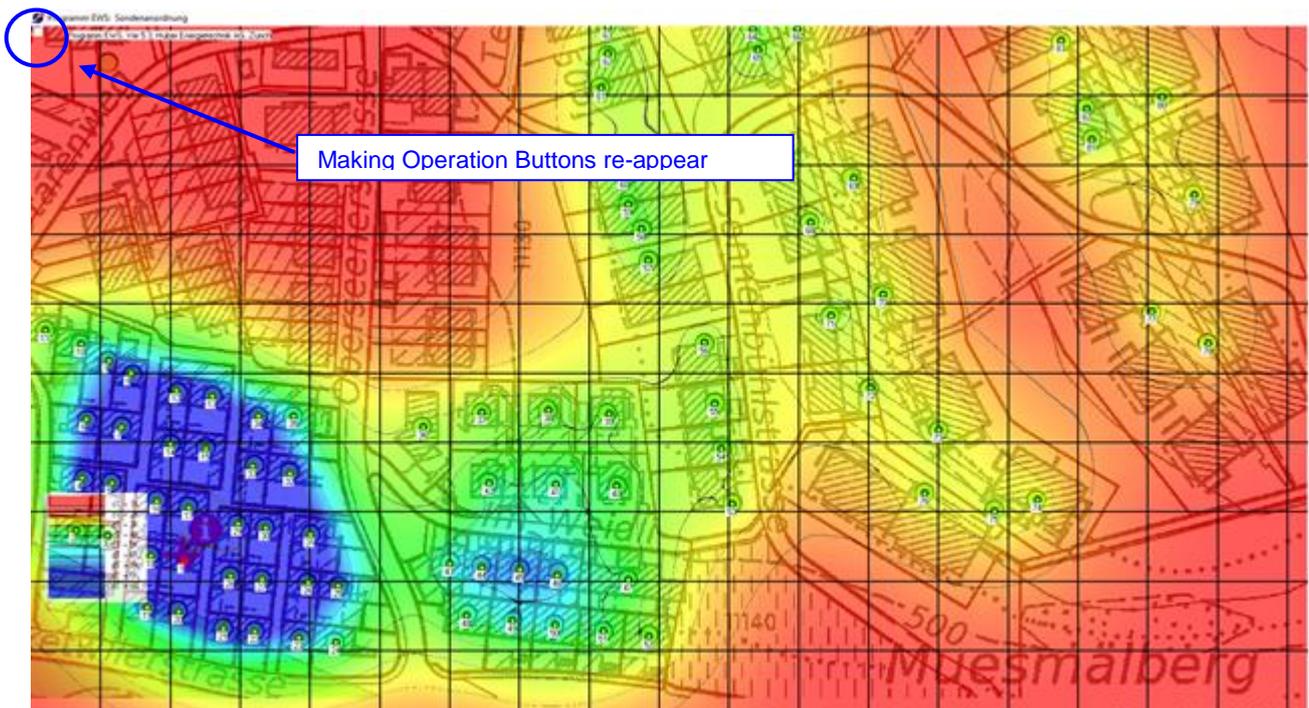
- The indicated pressure loss for the designed mass flow rate considers only the borehole heat exchanger (without the pressure loss in the supply pipe and in the vaporizer). The pressure loss of the whole borehole heat exchanger loop and information about laminar or turbulent flow in the borehole can be found in the sheet “Pressure” (chapter 3.12). Additionally, the result file shows hourly pressure loss values.
- The total heat demand: If the load was defined with the sheet “Extraction” (chapter 3.7) this field shows the sum of the heat extraction of the borehole during the last year. If the load was defined with the sheet “Load” (chapter 3.8) the field “total heat demand” indicates the heat demand of the building.

### 5.6 Report Set Up (Windows 8, 8.1, 10)

To set up a report (only available in Windows 8, 8.1 or 10), the information about the project must be filled in according to chapter 3.5. After that a representative image, e.g. the borehole field, needs to be copied into the clipboard, according to chapter 3.5, and using button 5.6, must be inserted in the sheet Info. In the full version the image from the “Borehole Configuration” can be copied into the clipboard, by checking the box at the top left.

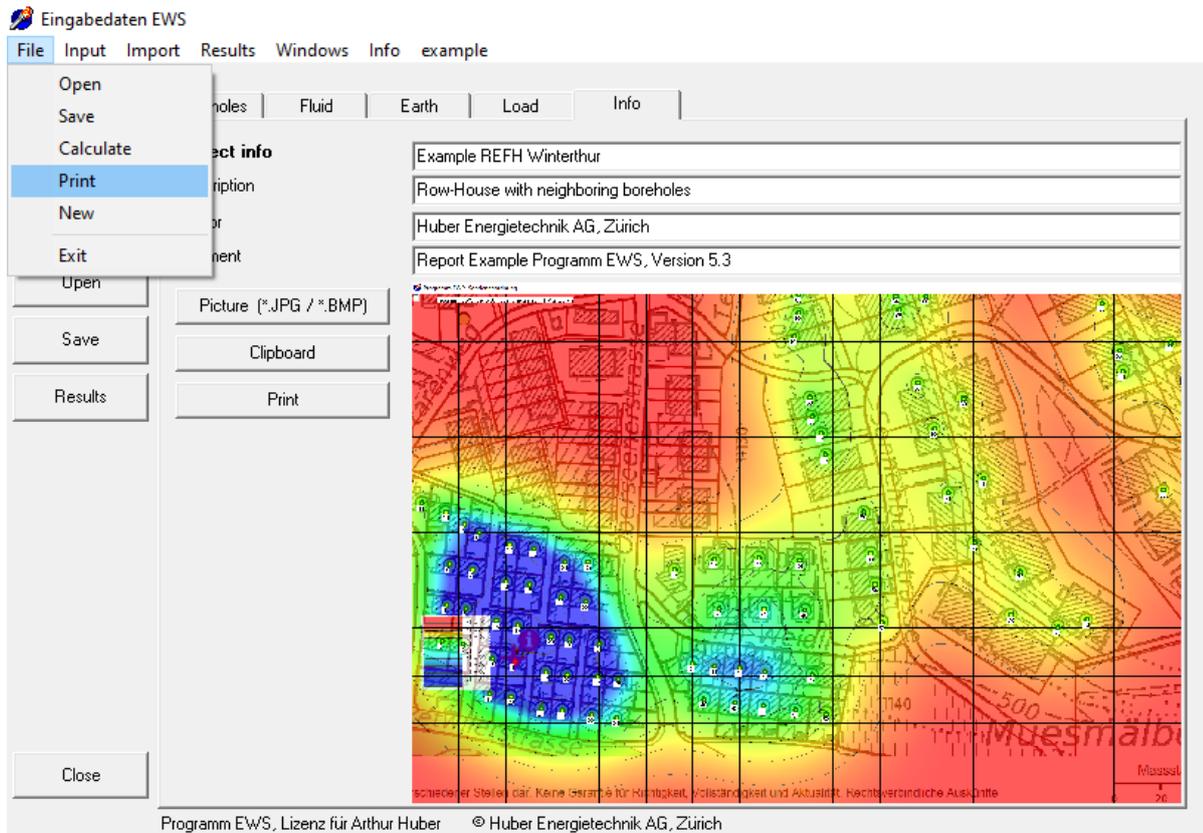


**Fig. 5.6: Hiding the button and copying of the image into the clipboard in the sheet “Field of Boreholes”**



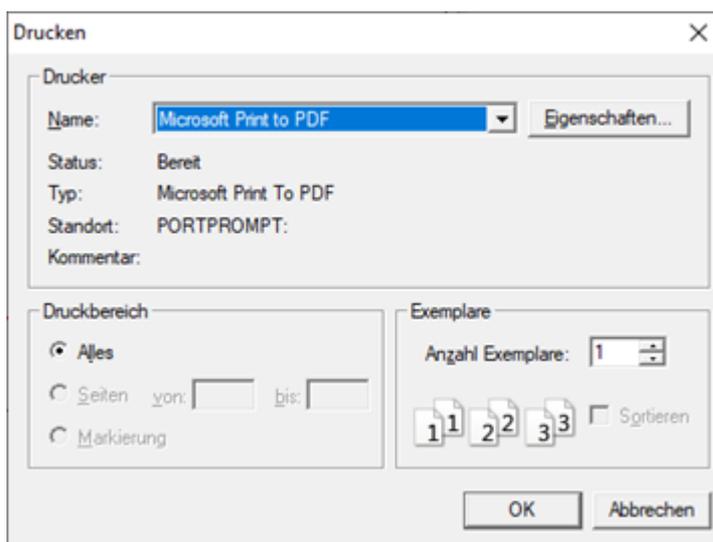
**Fig. 5.7: Making the Operation Buttons visible again and leaving the sheet “Borehole Configuration”.**

To set up the report, one can simply press on the Menu bar: File -> Print. Alternatively, on the sheet "Info", button 5.7 "Print" can be pressed.



**Fig. 5.8: Create report by selecting Menu Info -> Print**

After selecting the menu "Print", the project is calculated again and a print menu appears, with the printer choice. To create a PDF, a PDF printer must be chosen, e.g. "Microsoft Print to PDF".

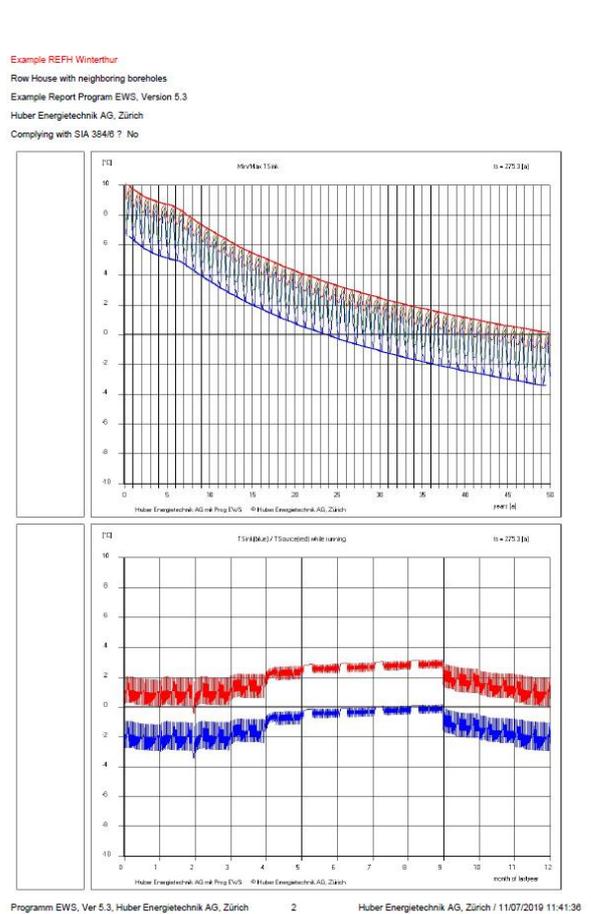
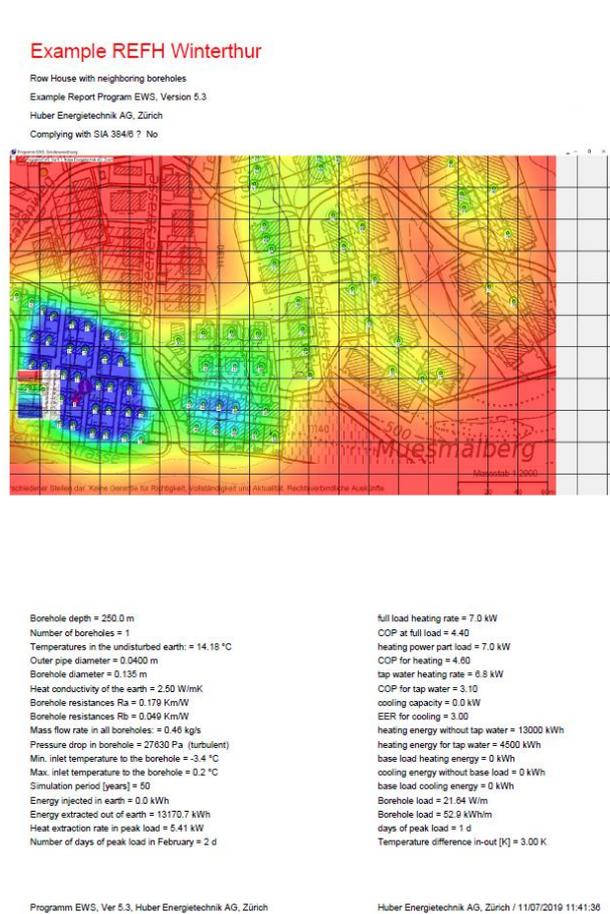


**Fig. 5.9: Create PDF Report by choosing a PDF printer, e.g. "Microsoft Print to PDF"**

**Hint:** If there is an error message showing up during the printing process, there is possibly not enough virtual memory allocated in the system settings of windows.

The report consists of 2 pages. On the first page, initially the project description and the chosen representation image. As next, the most important data for the simulation is shown (incl. load profile). The temperature in the undisturbed earth refers to the average temperature over the whole borehole length before the simulation started.

On the second page the temperature trend of the borehole-inlet (entering the boreholes) is shown over the whole simulation period. The second image shows the borehole temperature in the borehole outlet (Source temp., red) and borehole return flow (Entrance in Borehole, blue) during the last year of the simulation.



**Fig. 5.10: Report Printout on 2 pages (left: page 1, right: page 2).**

**Hint:** The pictures on the second page only show up, if a picture in the sheet “Info” is imported (Button 5.5 or 5.6)

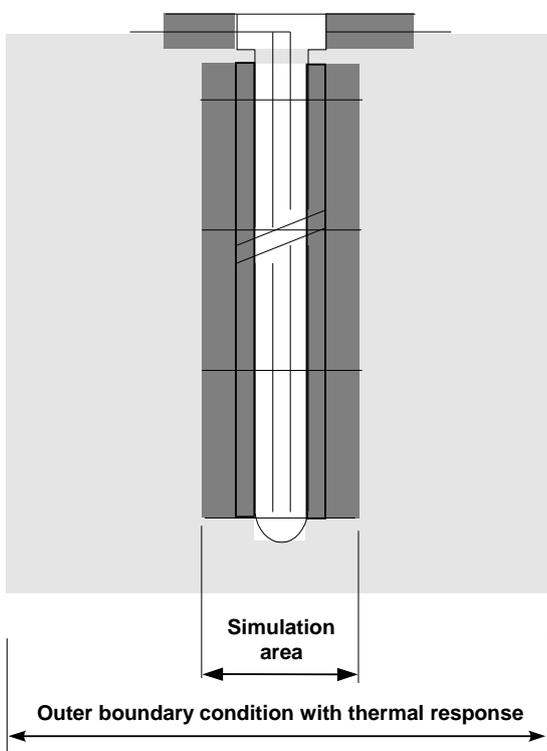
If the simulation period is set to 50 years (Enter in Field 10.15), the program checks the compliance with SIA Norm 384/6:2010 (or the base requirement R1 of the SIA Norm 384/6:2019) and displays the compliance with these norms in the header of the report. It must be pointed out, that for the compliance with these norms, a minimal uninterrupted-run-time (Field 10.7) of 1 day is necessary. By entering an own hourly demand load profile a correct verification of the norm is not possible.

## ANNEX A: Description of the model

Extractions of the models in the EWS Program are given in the following. However, only the parts are shown which are required for the comprehension of the input parameters. A more complete model description can be found in [5], [6] and [8].

### 5.7 Simulation area

The vertical heat conduction close to the borehole (< 3m distance to the borehole) only has a marginal influence on the ground temperature in this area, when the borehole depth is more than 50 m. Therefore, for this area the calculations neglects the vertical heat conduction. As a consequence, the heat equation in cylindrical coordinates can be solved one-dimensionally for each layer. Thus, it is possible to define different layer properties. This allows to calculate the common case in which the ground consists of various layers with different properties.



The Crank-Nicholson-method is used for the simulation of the ground temperatures close to the boreholes (1.5 - 3m).

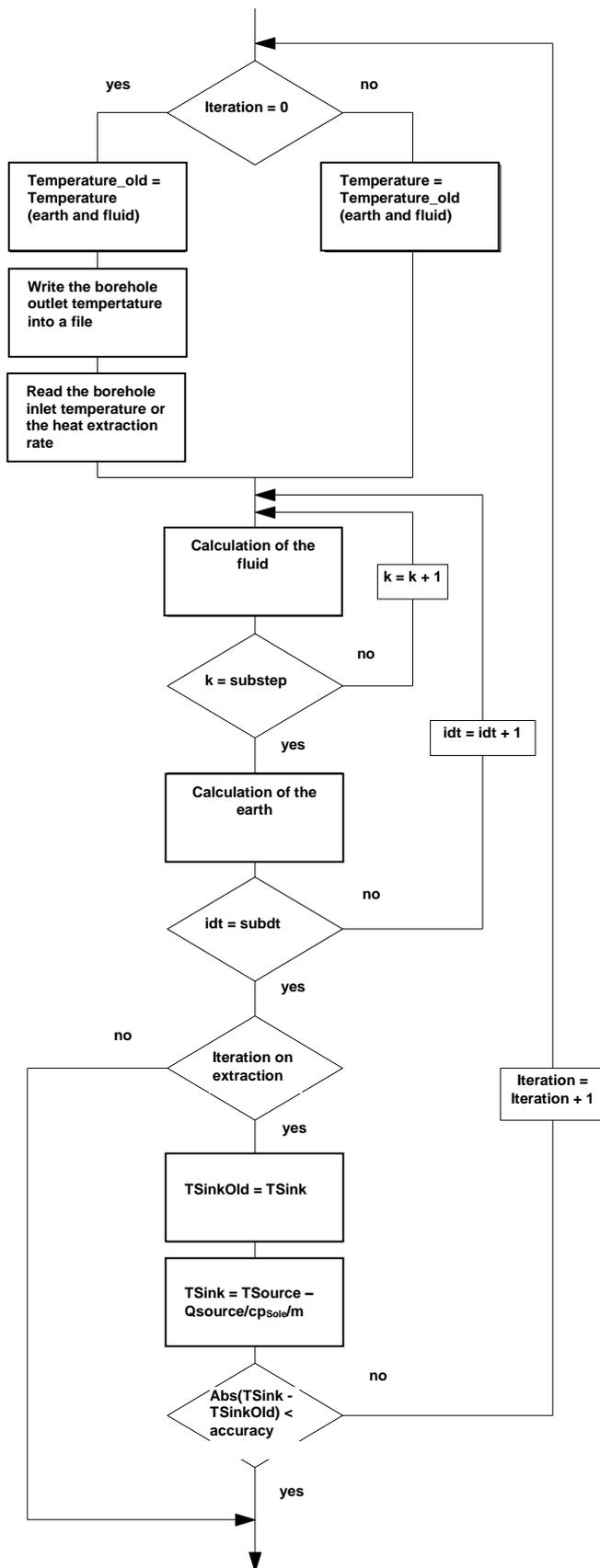
The averaged sole temperature of the corresponding layer is taken as an inner boundary condition. The sole is simulated unsteadily with an explicit time step procedure. Thus, it is possible to calculate the start-up behavior of the borehole.

The outer boundary condition is calculated with the dimensionless thermal response factor (g-functions, see 5.9.3). There is the option to choose between the methods of Carslaw & Jaeger [1] or the one of Eskilson [3]. The problem of the inconstant heat extraction rate and the regeneration of the earth can be solved by the superposition of an optional number of constant heat extraction rates which start at different times.

The chosen method allows us to use different time steps within the program: The shortest time step is used for the unsteady calculation of the fluid, while the

Crank-Nicholson calculation in the simulation area is done with a larger time step. Even a time step of one week is sufficient for the calculation of the ground with the g-functions outside of the simulation area. The different time steps are plausible because of the following reasons: The smallest time step is needed close to the boreholes since temperature disturbances always come from the boreholes. Farther from the boreholes only averaged heat extractions or inputs are observed. The use of different time steps allows us to simulate the boreholes with less computing time (compared to other methods) and without a loss of accuracy.

5.7.1 The simulation of the time step

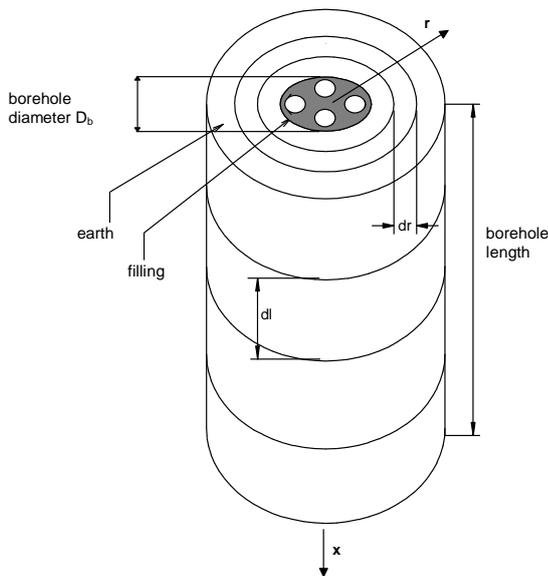


Basically, there are two operation modes for boreholes:

1. Cooling of the borehole outlet temperature with a given heat extraction ( $Q_{\text{Outlet}}$ , [kW]) of a heat pump.
2. Heating or cooling of the borehole to a given temperature ( $T_{\text{Inlet}}$ ) during a process (e.g. use of the borehole for the cooling of a building).

The program EWS provides both operation modes. The iteration goes towards the extraction rate if the input parameter “heat extraction rate given” is set to “yes” (field 6.2). No intern iteration is done if “no” is selected in the field 6.2. In this case the borehole outlet temperature ( $T_{\text{Outlet}}$ ) is calculated for a given borehole inlet temperature ( $T_{\text{Inlet}}$ ). Therefore, the input of the borehole inlet temperature is necessary. The entered borehole inlet temperature is only used as a first approximation for the start of the iteration, if field 6.2 is set to “yes”.

### 5.8 Calculation grid



The calculations are done in an axially symmetric grid. The ground is divided in the axial direction into equal segments of the length  $dl$ .

The grid is variable in the radial direction. The grid is defined by the grid factor  $f$ :

$$\text{Grid Factor } f = \frac{r_{j+1} - r_j}{r_j - r_{j-1}} \tag{eq. 0.1}$$

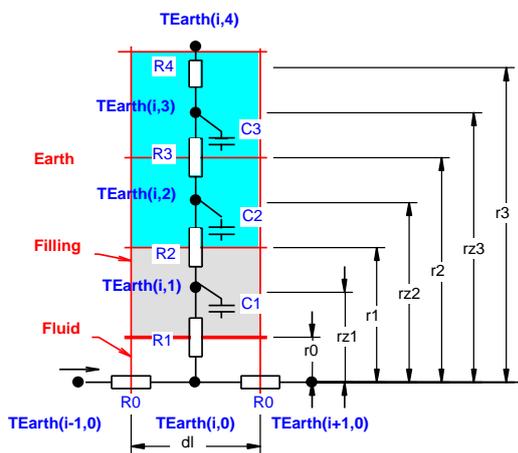
The grid can be calculated as given in eq. 0.2 to eq. 0.4 if the simulation area is set to the maximal calculation radius  $r_m$ , whereof  $m$  represents the number of calculation points in the radial direction:

Fig. 0.1: The simulation grid of the borehole.

$$r_0 = \frac{D_i}{2} \tag{eq. 0.2}$$

$$r_1 = \frac{D_b}{2} = \frac{\text{borehole\_diameter}}{2} \tag{eq. 0.3}$$

$$\text{for } j \geq 2: \quad r_j = r_{j-1} + (r_m - r_1) \frac{1-f}{1-f^{m-1}} f^{j-2} \tag{eq. 0.4}$$



A grid factor of 2 doubles the difference of the radius between two calculation volumes.

The mass balance point, which is important for the determination of the thermal resistance, can be calculated as showed below:

$$\text{Def: } rz_j = \sqrt{\frac{(r_j^2 + r_{j-1}^2)}{2}} \tag{eq. 0.5}$$

Fig. 0.2 The calculation grid of the borehole.

## 5.9 Heat Equation and the thermal response g

### 5.9.1 Heat Equation

For the following considerations, it is assumed that the dominant heat transport mechanism in the earth is the heat conductivity. Hence, the convective heat transport by water flows in the earth is negligible. The problem of the heat conductivity of the earth around a borehole is axially symmetric. The heat equation in radial direction around a borehole can be written in axial coordinates as:

$$\frac{1}{a} \cdot \frac{\partial T_{\text{Earth}}}{\partial t} = \frac{\partial^2 T_{\text{Earth}}}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_{\text{Earth}}}{\partial r} \quad \text{eq. 0.6}$$

whereby the thermal diffusivity  $a$  is defined with

$$\text{Def: } a = \frac{\lambda}{cP_{\text{Earth}} \cdot \rho_{\text{Earth}}} \quad \text{eq. 0.7}$$

The heat equation is linear. Hence, single boreholes as well as borehole fields with geometric similarity, have similar thermal responses. The similarity is for the temperatures in the earth for all radiuses  $r$  around the boreholes and for all times  $t$ .

Thus, the heat extraction rate from a borehole causes a temperature drop  $\Delta T_{\text{Earth}}$  in the earth around the borehole compared to the unaffected earth (= temperature funnel). This funnel grows radially with the ongoing extraction. The temperature drop  $\Delta T_{\text{Earth}}$  can be made dimensionless by using the specific extraction rate  $\dot{q}$  and the heat conductivity  $\lambda_{\text{Earth}}$ :

$$\text{Def: } g(r, t) = \frac{\Delta T_{\text{Earth}}(r, t) 2\pi \lambda_{\text{Earth}}}{\dot{q}} \quad \text{eq. 0.8}$$

### 5.9.2 The radial temperature funnel

In the steady case the radial heat flow in the borehole close-up range is constant and the following equation can be used:

$$\frac{\dot{q}}{2 \cdot \pi \cdot r} = \frac{\partial T_{\text{Earth}}}{\partial r} \cdot \lambda_{\text{Earth}} = \frac{\partial g}{\partial r} \cdot \frac{\dot{q}}{2 \cdot \pi} \quad \text{eq. 0.9}$$

The integration from  $r$  to  $r_1$  results in:

$$g(r) = g(r_1) - \ln\left(\frac{r}{r_1}\right) \quad \text{eq. 0.10}$$

This relation allows us to estimate the temperature behavior of the borehole with a single thermal response. Additionally, if the thermal response  $g$  on the point  $r_1$  is known, the thermal response  $g$  on point  $r$  can be concluded on. But please note that the assumption of the steady case can produce major deviations for small time steps.

### 5.9.3 The dimensionless thermal response g

Carslaw & Jaeger [1] solved the heat equation for infinite line sources analytically and found the following relation for g:

$$g = \frac{1}{2} \cdot \left[ -\gamma - \ln\left(\frac{r^2}{4 \cdot t \cdot a}\right) - \sum_{n=1}^{\infty} (-1)^n \frac{\left(\frac{r^2}{4 \cdot a \cdot t}\right)^n}{n \cdot n!} \right] \cong \frac{1}{2} \cdot \left[ \ln\left(\frac{4 \cdot t \cdot a}{r^2}\right) - \gamma \right] \quad \text{eq. 0.11}$$

in which  $\gamma=0.5772..$  is the Euler constant.

Werner, A.; Bigler, R.; Niederhauser, A. et. al. [18] got an identical solution using an analogy from the water well equation. In the program EWS, eq. 0.11 is implemented. This equation can be used for an outer boundary condition of the simulation area as an alternative to the g-function by Eskilson.

The approach by Carslaw and Jaeger leads to a continuous growth of the temperature funnel since for an infinite line source neither the inflow of heat from the top nor from the bottom is possible (due to symmetrical reasons). No equilibrium condition can be reached with the approach by Carslaw and Jaeger. The University of Lund developed an approach for boreholes with a finite borehole length H. This, because shallow boreholes use primarily the heat which is stored in the earth through the surface.

According to Claesson and Eskilson [2] the boreholes have a time constant  $t_s$ , with which the temporal behavior of the ground around the borehole can be made dimensionless:

$$t_s = \frac{H^2}{9a} \quad \text{eq. 0.12}$$

Thus, the dimensionless Eskilson number  $Es$

$$Es = \frac{t}{t_s} = \frac{9a}{H^2} t \quad \text{eq. 0.13}$$

can be treated as a dimensionless time for single boreholes and fields of boreholes. Further information on this topic can be found e.g. in Loose [21].

Especially for unbalanced, annual heat extraction balances the knowledge of the time constant t is fundamental. Until the time  $Es = 0.1$  one must consider strong cooling or heating of the earth. After this only small temperature changes occur. The equilibrium condition between heat extraction and heat inflow from the surrounding earth is reached after approximately  $Es = 10$ .

For a single borehole such as for field of boreholes, the dimensionless thermal response g (= "g-function") by Eskilson (1987) is only a function of the dimensionless time  $Es$  and the dimensionless borehole distance  $r_b/H$ . This is based on the assumption of a constant, specific heat extraction rate per borehole length ( $\dot{q}$ ).

For single boreholes within a range of  $5r_1^2/a < t < t_s$  the g-function can be approached with a maximal deviation of 7% by

$$g(t, r_1) = \ln\left(\frac{H}{2r_1}\right) + 0.5 \ln(Es) \tag{eq. 0.14}$$

For time periods longer than  $t_s$ , the single borehole converges to the following equilibrium condition:

$$g(r_1) = \ln\left(\frac{H}{2 \cdot r_1}\right) \tag{eq. 0.15}$$

As an example, the g-function of two boreholes with a distance B between the boreholes is shown in Fig. 0.3. As a comparison, the g-function of a single borehole is illustrated with a dashed line. Other thermal responses for borehole fields can be found in Fig. 0.4.

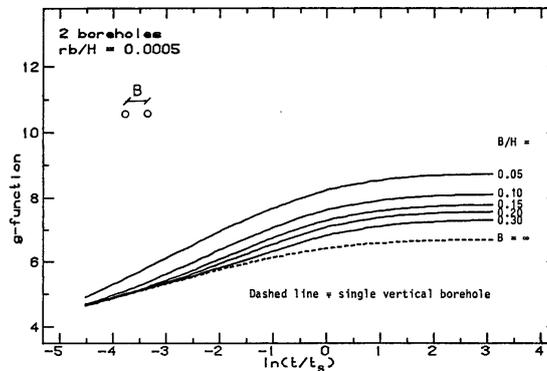


Fig. 0.3 The dimensionless thermal response g for 2 boreholes with a distance B by [3].

### 5.9.4 The comparison of the models

In Fig. 0.4 the approach by Carslaw & Jaeger for an infinitely deep borehole is compared to the approach by Eskilson for a borehole with a depth of 10m, 100m and 500m respectively. There is almost no deviation observed of the models until the time constant  $t_s$  is reached.

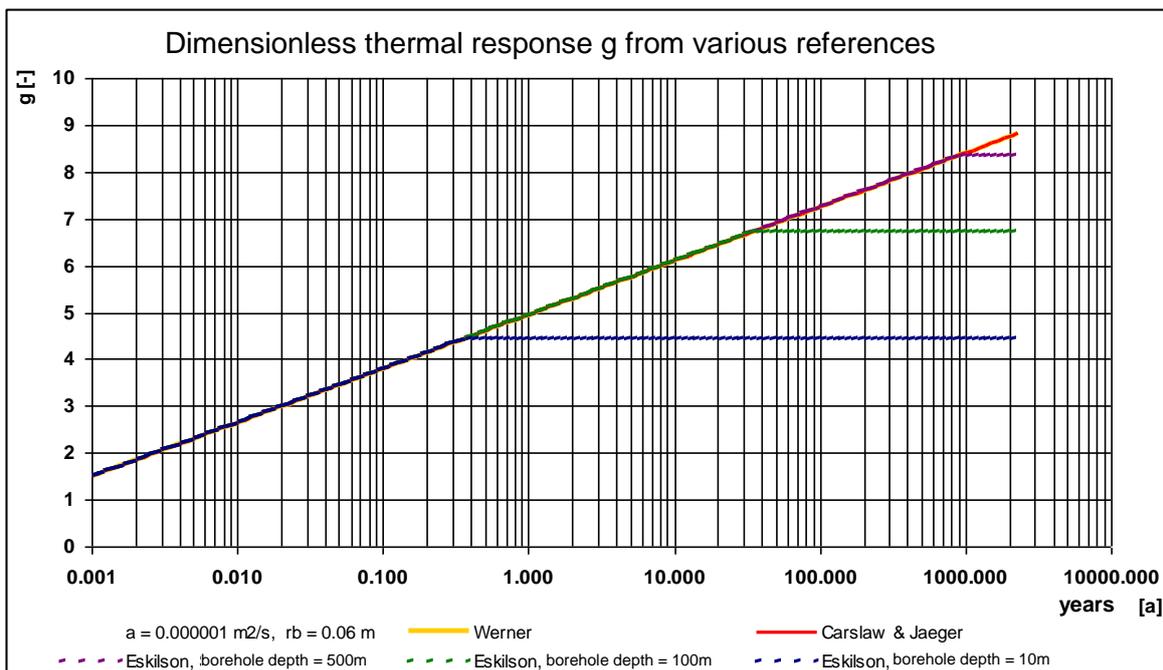


Fig. 0.4 The dimensionless thermal response g by Carslaw & Jaeger [1] and Eskilson [3]

### 5.10 The calculation of the g-function with the principle of superposition

Normally, each borehole in a field of boreholes is fed with a fluid of the same borehole inlet temperature by a manifold. Hence, the load is attached parallel to all boreholes. In this case the g-function of a borehole field can be approached by the superposition of various single boreholes. We do not have to think about a deviation for shorter time steps (unsteady effects) since the program EWS only uses the g-functions as an outer boundary condition which usually is calculated in time steps of one week. Thus, the accuracy of the steady equation is sufficient to approximate the influence of the borehole field on a single borehole x. The stationary equation 6.10 can thus be used to estimate the influence of a borehole x on borehole y with sufficient accuracy. The borehole distance  $A_{xy}$  between the borehole x and the borehole y is used instead of  $r_1$ :

$$g_x(r) = g(r_1) - \ln\left(\frac{r}{r_1}\right) + \sum_{y=1}^{y=n/x < y} \left( g(r_1) - \ln\left(\frac{A_{xy}}{r_1}\right) \right) \quad \text{eq. 0.16}$$

With a parallel operation of the boreholes, the g-function of the whole borehole field can be calculated with the average value of all n boreholes:

$$g(r) = g(r_1) - \ln\left(\frac{r}{r_1}\right) + \frac{1}{n} \cdot \sum_{x=1}^{x=n} \left[ \sum_{y=1}^{y=n/x < y} \left( g(r_1) - \ln\left(\frac{A_{xy}}{r_1}\right) \right) \right] \quad \text{eq. 0.17}$$

### 5.11 The consideration of neighboring boreholes

In the Pro version of the program EWS there is the new possibility to consider neighboring boreholes. Hereby the program assumes that neighboring boreholes have the same thermal load as the boreholes of the present project, such as the same depth. Under these assumptions the g-function  $g(r)$  that considers neighboring boreholes becomes:

$$g(r) = g(r_1) - \ln\left(\frac{r}{r_1}\right) + \frac{1}{n-m} \cdot \sum_{x=1}^{x=n/x \neq Neighbor} \left[ \sum_{y=1}^{y=n/x < y} \left( g(r_1) - \ln\left(\frac{A_{xy}}{r_1}\right) \right) \right] \quad \text{eq. 0.18}$$

Where n is the total number of boreholes (project boreholes + neighboring boreholes) and m the amount of neighboring boreholes (that do not belong to the present project). This means the g-functions of the single boreholes under consideration of all the boreholes (Project boreholes and neighboring boreholes) is calculated like a large borehole field according to equations in chapter 5.10 and is then averaged for all boreholes of the present project.

This concept of consideration of neighboring boreholes is indeed quite simplifying. Yet experience often shows that neighboring boreholes are designed with the same criteria as the present project boreholes, due to the same norms and legal conditions serving as base for the design/dimensioning. The time sequence of the borehole projects leads to the fact that older projects do not anticipate the following projects and the borehole depth tends to be too low. Considering this, the results of eq. 6.18 lead to optimistic results. This equation is well suited for regional planning and for the calculation of future legal requirements for the consideration of neighboring boreholes over the property borders.

### 5.12 Geothermal heat flux and temperature gradient

The heat equation, written in form of the Fourier law, looks like the following, for the geothermal heat flux  $\dot{q}_{geo}$  from the interior of the earth in stationary conditions:

$$\dot{q}_{geo} = \lambda \cdot \Delta T_{geo} \quad [\text{W/m}^2] \quad \text{eq. 0.19}$$

Where  $\Delta T_{geo}$  is the temperature gradient in the depth and  $\lambda$  is the thermal conductivity of the earth layer. In the outer earth crust in flat terrain and stationary condition the geothermal heat flux in the depth is approximately constant, but the temperature gradient fluctuates with the thermal conductivity of the stone layers. A higher thermal conductivity leads to a lower geothermal gradient. Groundwater flows and topography (mountains, valleys) can lead to  $\dot{q}_{geo}$  not being constant in the depth.

### 5.13 The borehole temperature $T_b$ and the fluid temperature $T_f$

The thermal response  $\Delta T$  has to be subtracted from the undisturbed earth temperature at the beginning  $T_m$  to get the temperature in the earth (principle of superposition). The temperature on the border of the borehole  $T_{Earth}(r_1)$  (=borehole temperature  $T_b$ ) can be calculated from  $g$  and  $T_m$  with:

$$T_b(z) = T_m(z) - R_g \cdot \dot{q} = T_m(z) - \frac{\dot{q}}{2 \pi \lambda_{Earth}} g(t, r_1) \quad \text{eq. 0.20}$$

$T_m$  is the average earth temperature in the depth  $z$  under undisturbed conditions. This is calculated with the averaged, annual surface temperature of the earth  $T_{mo}$  and the temperature gradient  $\Delta T_{Grad}$ .

The specific heat extraction rate  $\dot{q}$  is defined in the program EWS by the total heat extraction from the boreholes  $\dot{Q}_{Boreholes}$ , minus possible following heat fluxes from groundwater  $\dot{Q}_{GW}$  or the building influence  $\dot{Q}_{Building}$ , divided by the borehole depth  $H$  and the amount of boreholes  $n$ .

$$\dot{q} = \frac{\dot{Q}_{Sonden} - \dot{Q}_{GW} - \dot{Q}_{Building}}{n \cdot H} \quad \text{eq. 0.21}$$

The influence of groundwater  $\dot{Q}_{GW}$  is calculated based on eq. 6.42.

The averaged, annual surface temperature is equal to the averaged air temperature plus a mean surface warming which usually is between 0.8 and 2°C. The temperature gradient  $\Delta T_{Grad}$  typically ranges from 0.025 to 0.045 K/m in Switzerland.

The mean borehole temperature over the borehole depth  $\overline{T_b}$  is defined as

$$\text{Def} \quad \overline{T_b} = \frac{1}{H} \cdot \int_0^H T_b(z) \cdot dz \quad \text{eq. 0.22}$$

In the case of a constant heat extraction rate per borehole length ( $\dot{q}$ ) it is possible to calculate the mean borehole temperature over the borehole depth  $\overline{T_b}$  with

$$\overline{T_b} = \overline{T_m} - R_g \cdot \dot{q} = \overline{T_m} - \frac{\dot{q}}{2 \pi \lambda_{Earth}} g(t, r_1) \quad \text{eq. 0.23}$$

whereby

$$\overline{T_m} = T_{mo} - \Delta T_{Grad} \cdot \frac{H}{2} \quad \text{eq. 0.24}$$

### 5.13.1 The fluid temperature $T_f$

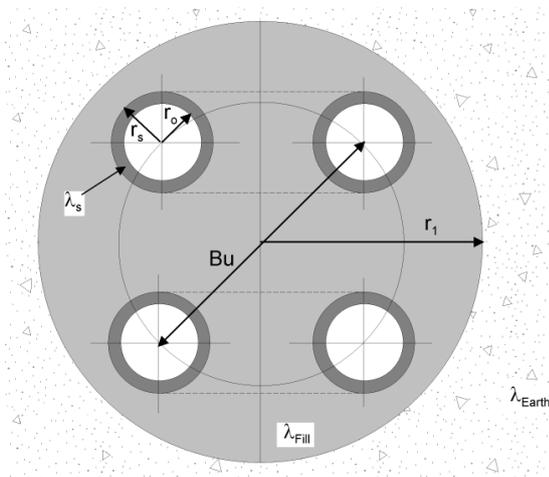
The mean fluid temperature  $T_f$  is defined as the arithmetic mean of the upward and downward flowing borehole fluid.

$$\text{Def: } T_f(z) = \frac{T_{\text{up}}(z) + T_{\text{down}}(z)}{2} \quad \text{eq. 0.25}$$

Hence, the fluid temperature  $T_f$  is a function of the depth  $z$  in the borehole. The mean fluid temperature  $\overline{T}_f$  is defined as

$$\text{Def: } \overline{T}_f = \frac{1}{2} \cdot (T_{\text{Outlet}} + T_{\text{Inlet}}) \quad \text{eq. 0.26}$$

### 5.14 Thermal resistances $R_a$ and $R_b$ in the double-U-pipe



An idealized double-U-pipe with the borehole radius  $r_1$  and 4 borehole pipes (with an inner radius  $r_o$  and an outer radius  $r_s$ ) is shown in the picture on the left. In two borehole pipes the borehole fluid is flowing downward while in the other pipes the fluid flows upward. The heat conductivity of the filling is  $\lambda_{\text{Fill}}$ , the one of the borehole  $\lambda_s$  and the surrounding earth's heat conductivity is  $\lambda_{\text{Earth}}$ . The exact position of the 4 borehole pipes can be described with the eccentricity parameter  $b$ .

$$b = \frac{Bu}{2 \cdot r_1} \quad \text{eq. 0.27}$$

**Fig. 0.5** The nomenclature on the double-U-pipe.

The eccentricity parameter  $b$  is defined by the pipe distance  $Bu$  ("shank spacing") (see Fig. 0.5). The geometrically maximal limit of the eccentricity  $b_{\text{Max}}$  is:

$$b_{\text{Max}} = \frac{2 \cdot r_1 - 2 \cdot r_s}{2 \cdot r_1} = 1 - \frac{r_s}{r_1} \quad \text{eq. 0.28}$$

The geometrically minimal limit of the eccentricity (for a not centered borehole pipe) is:

$$b_{\text{Min}} = \frac{r_s}{r_1} \quad \text{eq. 0.29}$$

The conductivity parameter  $\sigma$  is defined as a pure substance property by:

$$\sigma = \frac{\lambda_{\text{Fill}} - \lambda_{\text{Earth}}}{\lambda_{\text{Fill}} + \lambda_{\text{Earth}}} \quad \text{eq. 0.30}$$

The intern thermal borehole resistance  $R_a$  [Km/W] is a characteristic value for the thermal losses  $\Delta q_i$  [W/m] (related to the length) of the upward flowing fluid to the downward flowing fluid.  $R_a$  is independent from the depth of the borehole:

$$\text{Def: } R_a = \frac{T_{\text{up}}(z) - T_{\text{down}}(z)}{\Delta q_i(z)} \quad \text{eq. 0.31}$$

The thermal borehole resistance  $R_b$  is defined by the mean fluid temperature  $T_f$  in the borehole and the borehole temperature  $T_b$ :

$$\text{Def: } R_b = \frac{T_b(z) - T_f(z)}{\dot{q}} \quad \text{eq. 0.32}$$

The borehole resistance  $R_b$  is independent from the borehole depth and consists of the resistance of the borehole filling  $R_c$  and the resistance of the heat transfer from the filling to the borehole fluid  $R_\alpha$ :

$$R_b = R_\alpha + R_c \quad \text{eq. 0.33}$$

The resistance of the heat transfer  $R_\alpha$  can be calculated for double-U-pipes with

$$R_\alpha = \frac{1}{8 \cdot \pi \cdot \alpha \cdot r_o} \quad \text{eq. 0.34}$$

#### 5.14.1 The internal borehole resistance $R_a$ by Hellström [4]

According Hellström [4] (1991, P. 147, formula 9.149) the internal borehole resistance  $R_a$  for double-U-pipes with a symmetric configuration of the pipes can be calculated with:

$$R_a = \frac{1}{\pi \cdot \lambda_{\text{Fill}}} \left[ \ln\left(\frac{\sqrt{2} \cdot b \cdot r_1}{r_o}\right) - \frac{1}{2} \cdot \ln\left(\frac{2 \cdot b \cdot r_1}{r_o}\right) - \frac{1}{2} \cdot \sigma \cdot \ln\left(\frac{1-b^4}{1+b^4}\right) \right] + \frac{1}{2 \cdot \pi \cdot r_o \cdot \alpha} + R_s \quad \text{eq. 0.35}$$

in which the thermal resistance  $R_s$  of the pipe wall is calculated with:

$$R_s = \frac{1}{2 \cdot \pi \cdot \lambda_s} \cdot \ln\left(\frac{r_s}{r_o}\right) \quad \text{eq. 0.36}$$

#### 5.14.2 The borehole resistance $R_b$ by Hellström [4]

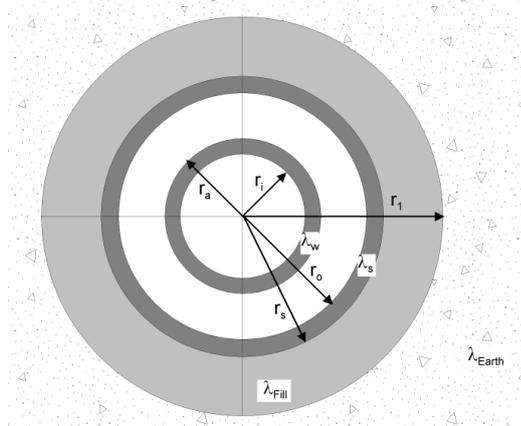
The borehole resistance for a double-U-pipe can be calculated by Hellström [4] (P. 89, eq. 8.69) with:

$$R_b = \frac{1}{8 \cdot \pi \cdot \lambda_{\text{Fill}}} \cdot \left[ \beta + \ln\left(\frac{r_1}{r_o}\right) + \ln\left(\frac{r_1}{Bu}\right) + \sigma \cdot \ln\left(\frac{r_1^4}{r_1^4 - \frac{Bu^4}{16}}\right) - \frac{\frac{r_o^2}{Bu^2} \left[ 1 - \sigma \cdot \frac{\frac{1}{4} Bu^4}{\left(r_1^4 - \frac{Bu^4}{16}\right)} \right]^2}{\left\{ \frac{1+\beta}{1-\beta} + \frac{r_o^2}{Bu^2} \left[ 1 + \sigma \cdot \frac{Bu^4 \cdot r_1^4}{\left(r_1^4 - \frac{Bu^4}{16}\right)^2} \right] \right\}} \right] \quad \text{eq. 0.37}$$

and

$$\beta = 2 \cdot \pi \cdot \lambda_{\text{Fill}} \cdot [R_\alpha + R_w] = \lambda_{\text{Fill}} \cdot \left[ \frac{1}{r_o \cdot \alpha} + \frac{1}{\lambda_s} \cdot \ln\left(\frac{r_s}{r_o}\right) \right] \quad \text{eq. 0.38}$$

### 5.15 Thermal resistances $R_a$ / $R_b$ of a coaxial borehole



#### Nomenclature of a coaxial borehole

The idealized coaxial borehole is shown in Fig. 0.6. The borehole with the borehole radius  $r_1$  is colored in gray.

The filling has the heat conductivity  $\lambda_{Fill}$ , the inner borehole pipe  $\lambda_w$ , the outer borehole pipe  $\lambda_s$  and the earth  $\lambda_{Earth}$ .

The inner and the outer radii of the inner borehole pipe are  $r_i$  and  $r_a$ . The inner and the outer radii of the outer borehole pipe are  $r_o$  and  $r_s$ .

Fig. 0.6 Nomenclature of a coaxial borehole.

#### 5.15.1 Modeling of the internal borehole resistance $R_a$

The definition of the internal borehole resistance  $R_a$  in eq. 0.31 is valid for the coaxial borehole, as well. Hence, the thermal resistance is the sum of the heat transfer resistances of the upward flowing fluid to the inner borehole pipe (1<sup>st</sup> term), of the thermal resistance of the inner borehole pipe (2<sup>nd</sup> term) and of the heat transfer resistance from the inner borehole pipe to the downward flowing fluid (3<sup>rd</sup> term):

$$R_a = \left[ \frac{1}{2 \cdot \pi \cdot r_i \cdot \alpha_i} + \frac{1}{2 \cdot \pi \cdot \lambda_w} \cdot \ln\left(\frac{r_a}{r_i}\right) + \frac{1}{2 \cdot \pi \cdot r_a \cdot \alpha_a} \right] \quad \text{eq. 0.39}$$

#### 5.15.2 Modeling of the borehole resistance $R_b$

In the case of a coaxial borehole,  $R_b$  is defined as the thermal resistance of the outer borehole fluid (normally the downward flowing fluid) to the wall of the borehole (at the radius  $r_1$ ):

$$R_b = \left[ \frac{1}{2 \cdot \pi \cdot r_o \cdot \alpha_o} + \frac{1}{2 \cdot \pi \cdot \lambda_s} \cdot \ln\left(\frac{r_s}{r_o}\right) + \frac{1}{2 \cdot \pi \cdot \lambda_{Fill}} \cdot \ln\left(\frac{r_1}{r_s}\right) \right] \quad \text{eq. 0.40}$$

### 5.16 Heat load of groundwater flow

According to the Darcy-law the specific flow rate  $v_f$  (=Darcy speed) is the product of the hydraulic conductivity  $k_f$  and the pressure gradient  $i$  of the groundwater:

$$v_f = k_f \cdot i \quad \text{eq. 0.41}$$

Assuming the flowing groundwater has the same temperature as the untouched ground layer it flows in, the delivered heat load by groundwater over the flow cross section  $A_{GW}$  out of the temperature funnel (cooling of ground temperature compared to untouched ground, due to the borehole) can be defined as:

$$\dot{Q}_{GW} = v_f \cdot A_{GW} \cdot c_{p_{Water}} \cdot \rho_{Water} \cdot \Delta T \quad \text{eq. 0.42}$$

## 5.17 The analytical borehole equation

### 5.17.1 The concept of thermal resistances

The concept of thermal resistances is based on a “steady” condition and postulates a linear relationship between the temperature gradient and the specific heat loss:

$$T_{User} - T_{Heatsource} \equiv \sum R \cdot \dot{q} \tag{eq. 0.43}$$

The thermal resistance of the borehole heat exchanger systems can be split up as follows:

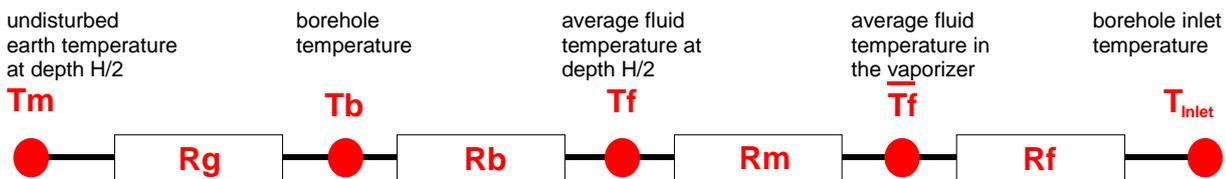
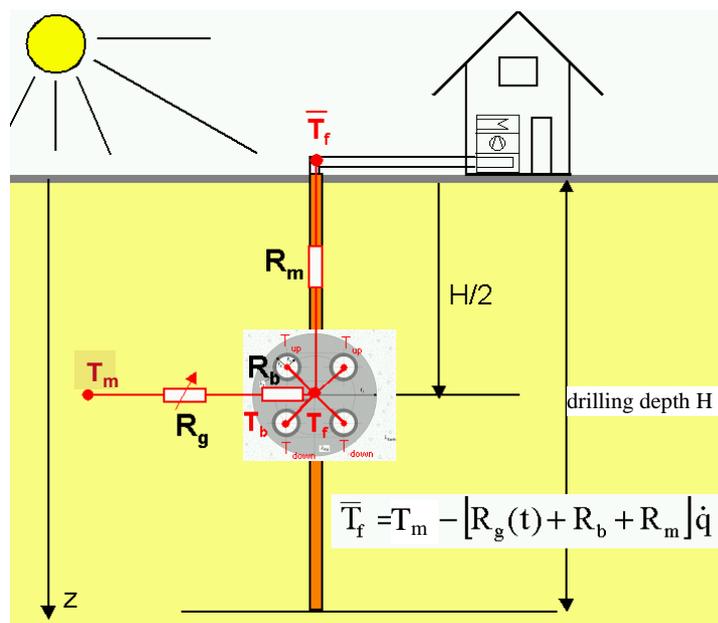


Abb. 0.7: Thermal resistance of a borehole heat exchanger systems

### 5.17.2 Thermal resistance $R_f$ (evaporator)

In a steady condition, the heat balance of the evaporator and the earth can be written as:

$$(T_{Outlet} - T_{Inlet}) \cdot \dot{m} \cdot cp_{Fluid} = \dot{Q}_{Vaporizer} = \dot{Q}_{Borehole} = H \cdot \dot{q} \tag{eq. 0.44}$$

Considering eq. 0.26 the following equation for the **thermal resistance of the evaporator  $R_f$**  can be defined as:

$$T_{Outlet} = \bar{T}_f + \frac{H}{2 \cdot \dot{m} \cdot cp_{Fluid}} \dot{q} \equiv \bar{T}_f + R_f \cdot \dot{q} \tag{eq. 0.45}$$

$$T_{Inlet} = \bar{T}_f - \frac{H}{2 \cdot \dot{m} \cdot cp_{Fluid}} \dot{q} \equiv \bar{T}_f - R_f \cdot \dot{q} \tag{eq. 0.46}$$

### 5.17.3 Thermal resistance $R_m$ (temperature loss along the borehole)

In the heat extraction case the highest average fluid temperature  $T_f$  is at the bottom of the borehole heat exchanger. During the transport of the fluid from the bottom of the borehole, the fluid yields a part of its heat energy to the downward flowing fluid and sometimes also to the upper earth layers. Assuming that there is a constant specific heat extraction rate for the entire borehole length  $\dot{q}$  (which is a reasonable assumption for most boreholes), the following relationship for the fluid temperature results [8]:

$$T_{up}(z) = T_{mo} + \Delta T_{Grad} \cdot \frac{H}{2} - \left[ \frac{g(t, H)}{2\pi \lambda_{Earth}} + R_b + \frac{1}{R_a} \cdot \frac{H^2 - z \cdot H + \frac{z^2}{2}}{\dot{m}^2 \cdot cp_{Fluid}^2} - \frac{H - z}{2 \cdot \dot{m} \cdot cp_{Fluid}} \right] \dot{q} \quad \text{eq. 0.47}$$

$$T_{down}(z) = T_{mo} + \Delta T_{Grad} \cdot \frac{H}{2} - \left[ \frac{g(t, H)}{2\pi \lambda_{Earth}} + R_b + \frac{1}{R_a} \cdot \frac{H^2 - z \cdot H + \frac{z^2}{2}}{\dot{m}^2 \cdot cp_{Fluid}^2} + \frac{H - z}{2 \cdot \dot{m} \cdot cp_{Fluid}} \right] \dot{q} \quad \text{eq. 0.48}$$

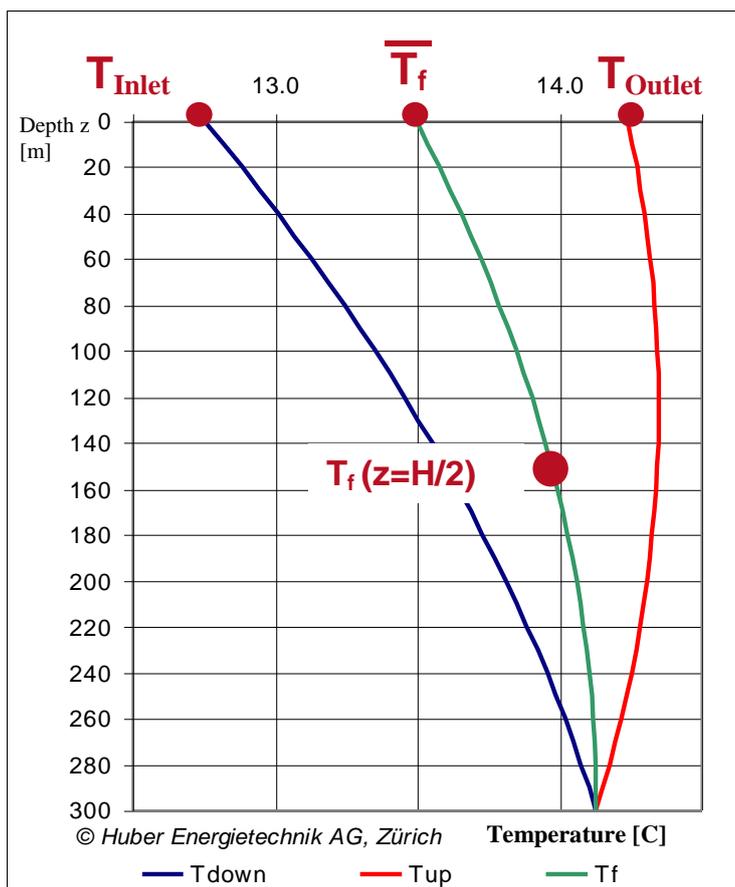


Abb. 0.8: Temperature profile of the fluid according to [8].

Thus, the thermal transport resistance  $R_m$  can be defined as:

$$T_f \left( z = \frac{H}{2} \right) - \bar{T}_f \equiv R_m \cdot \dot{q} = \left( \frac{1}{3 \cdot R_a} \cdot \frac{H^2}{\dot{m}^2 \cdot cp_{Fluid}^2} \right) \cdot \dot{q} \quad \text{eq. 0.49}$$

### 5.17.4 Thermal resistance of the earth $R_g$

The thermal resistance of the earth  $R_g$  follows from the temperature difference between the borehole surface temperature and the temperature level of the undisturbed earth on the same depth. The definition of  $R_g$  follows from the definition of the g-function (eq. 0.8):

$$T_m - T_b = \Delta T(r = r_b, t) = \frac{\dot{q}}{2\pi\lambda} \cdot g(r_b, t) = R_g \cdot \dot{q} \quad \text{eq. 0.50}$$

The particularity of the thermal resistance  $R_g$  is that it is a function of the time and that it is permanently increasing under a constant heat extraction rate (see chapter 5.9).

### 5.17.5 The analytical borehole equation

The analytical borehole equation follows from the combination of the different thermal resistances of the borehole and its surroundings:

$$T_{Outlet} = T_m - (R_g + R_b + R_m - R_f) \cdot \dot{q} \quad \text{eq. 0.51}$$

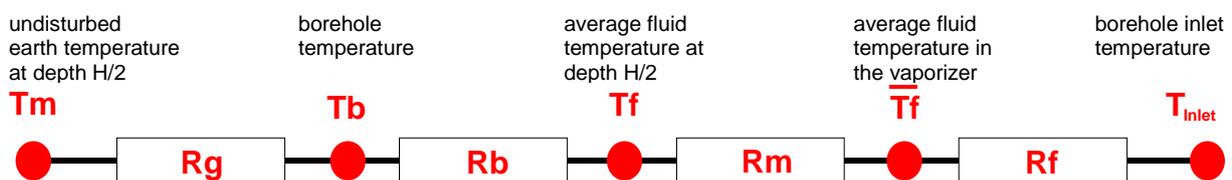
$$T_{Inlet} = T_m - (R_g + R_b + R_m + R_f) \cdot \dot{q} \quad \text{eq. 0.52}$$

Replacing  $T_m$  with eq. 0.24,  $R_g$  with eq. 0.50,  $R_m$  with eq. 0.49 and  $R_f$  with eq. 6.45 in the analytical borehole equation:

$$T_{Outlet} = T_{mo} + \Delta T_{Grad} \cdot \frac{H}{2} - \left[ \frac{g(t, r_1)}{2\pi \lambda_{Earth}} + R_b + \frac{1}{3} \cdot \frac{1}{R_a} \cdot \frac{H^2}{\dot{m}^2 \cdot cp_{Fluid}^2} - \frac{H}{2 \cdot \dot{m} \cdot cp_{Fluid}} \right] \dot{q} \quad \text{eq. 0.53}$$

and

$$T_{Inlet} = T_{mo} + \Delta T_{Grad} \cdot \frac{H}{2} - \left[ \frac{g(t, r_1)}{2\pi \lambda_{Earth}} + R_b + \frac{1}{3} \cdot \frac{1}{R_a} \cdot \frac{H^2}{\dot{m}^2 \cdot cp_{Fluid}^2} + \frac{H}{2 \cdot \dot{m} \cdot cp_{Fluid}} \right] \dot{q} \quad \text{eq. 0.54}$$



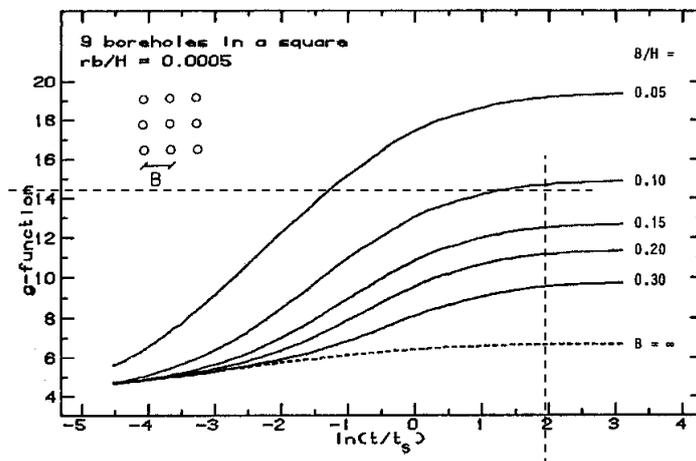
**Abb. 0.9:** Thermal resistance of a borehole heat exchanger.

The analytical borehole equation is suited perfectly as a tool to assess the dimension of a result or to check the plausibility of a result.

## 6 ANNEX B: Input of a particular g-function

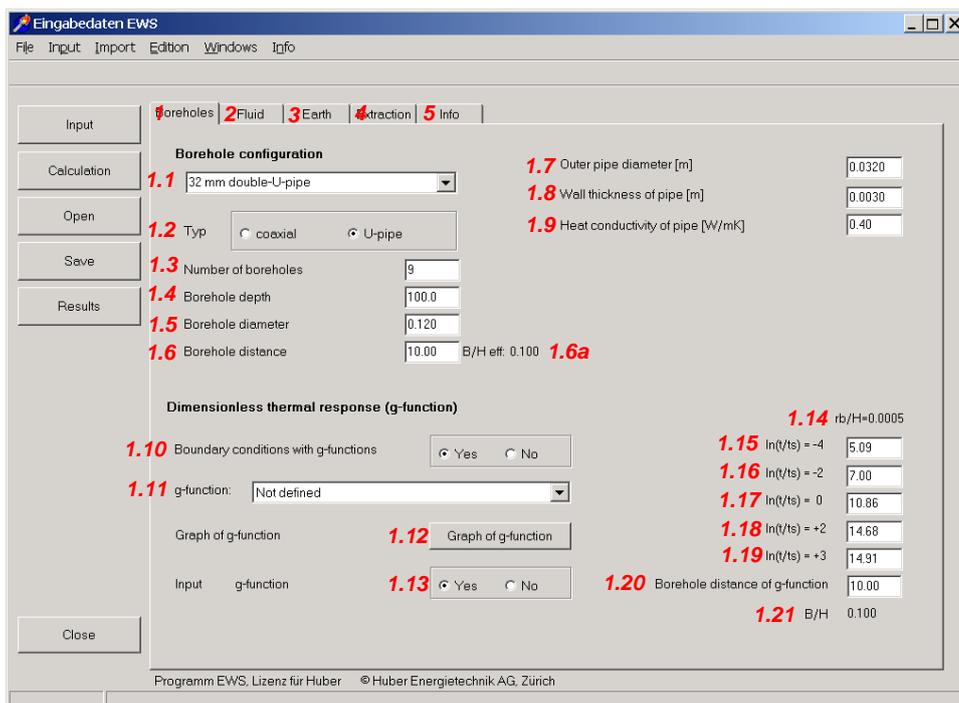
### 6.1 Example 1: The input of a g-function by the values of the function

The g-function published by Eskilson [3] with 9 boreholes in a quadratic configuration (see Fig. 6.1) and  $B/H = 0.10$  shall be entered as unique g function. The borehole length  $H$  is 100 m.



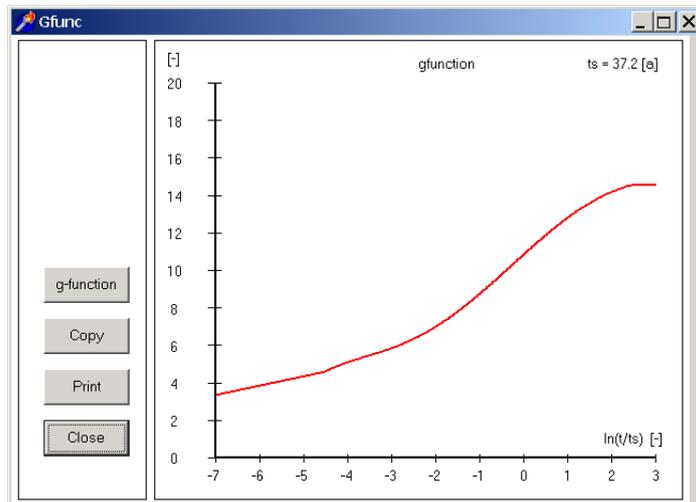
**Fig. 6.1:** Example of a published g-function (from [3]) and the reading of the function value on the supporting point  $\ln(t/t_s) = 2$ .

Select the last option in the field 1.11 which is “special input”. Then, select “yes” in the fields 1.10 and 1.13. The function values of the g-function are read from the graph in Fig. 6.1 on the supporting points  $\ln(t/t_s) = -4, -2, 0, +2, +3$ . The values are:  $g[\ln(t/t_s)=-4] = 5.09$ ,  $g[\ln(t/t_s)=-2] = 7.00$ ,  $g[\ln(t/t_s)=0] = 10.86$ ,  $g[\ln(t/t_s)=+2] = 14.68$ ,  $g[\ln(t/t_s)=+3] = 14.91$ . These function values are to be entered in the fields 1.15 to 1.19. The borehole distance must be adjusted in field 1.20 in a way that the  $B/H$  ratio in field 1.21 is equal to 0.1. This means that the input in field 1.20 must be 10m since the length of the borehole  $H$  is given (100m).



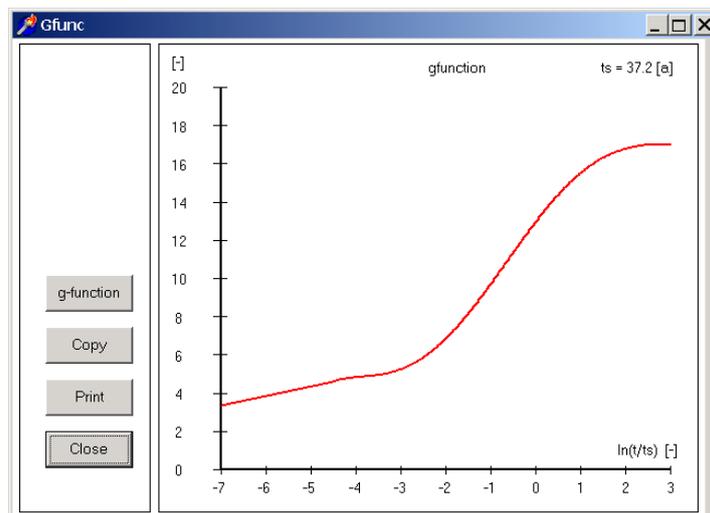
**Fig. 6.2:** The sheet “Boreholes”, example of a particular g-function for a 3 x 3 borehole field with a quadratic configuration and  $B/H = 0.10$ .

The entered g-function, respectively the spline-interpolation which is used by the program, can be checked visually and quantitatively by clicking on the field 1.12. It is necessary to adjust the  $B/H_{eff}$  ratio (field 1.6) to the  $B/H$  ratio of the g-function (field 1.20) if the  $B/H_{eff}$  ratio (field 1.6a) differs from the  $B/H$  ratio of the g-function (field 1.21). The g-function would be extrapolated from the  $B/H_{eff}$  ratio if the adjustment is not done. The graph of the entered g-function is showed in Fig. 6.3.



**Fig. 6.3:** The graph of the particularly entered g-function from Fig. 6.2.

The program EWS uses an automatically extrapolated g-function if the effective ratio  $B/H_{eff}$  (field 1.6a) differs from 0.1. This extrapolated g-function can be shown by clicking on the field 1.12. This means for the above example that if the effective borehole distance  $B$  is 8 m, this value has to be entered in the field 1.6. Hence, the effective  $B/H_{eff}$  ratio is 0.08. The extrapolated g-function (using the value in field 1.12) is shown in Fig. 6.4.



**Fig. 6.4:** The graph of the g-function in Fig. 6.2 extrapolated from  $B/H_{eff} = 0.08$ .

## 7 Table of symbols

### 7.1 Latin symbols

$a$	thermal diffusivity	[m <sup>2</sup> /s]
$A_{GW}$	flow cross section of the groundwater in the area of the boreholes	[m <sup>2</sup> ]
$b$	eccentricity parameter of a double-U-pipe	[-]
$B$	distance between different boreholes	[m]
$B_u$	shank spacing between the pipes of the upward and the downward flowing fluid	[m]
$cp_{Sole}$	specific heat capacity of the fluid	[J/(kgK)]
$cp_{Wasser}$	specific heat capacity of the groundwater	[J/(kgK)]
$D_i$	inner diameter of the borehole pipe	[m]
$Dim_{Axi}$	number of calculation nodes in axial direction	[-]
$Dim_{Rad}$	number of calculation nodes in radial direction	[-]
$Es$	Eskilson number, dimensionless time	[-]
$f$	grid factor for the calculation grid in radial direction	[-]
$g$	g-function, dimensionless thermal response of the earth by Eskilson	[-]
$H$	borehole length, borehole depth	[m]
$i$	pressure gradient of groundwater	[m/m]
$k_f$	hydraulic conductivity = coefficient of permeability	[m/s]
$\dot{m}$	mass flow rate, mass flow rate in the boreholes	[kg/s]
$m$	number of calculation nodes in the radial direction (=DimRad)	[-]
$m$	number of neighboring boreholes (do not belong to present project)	[-]
$n$	number of boreholes in a field of boreholes (including neighboring boreholes)	[-]
$Nu$	Nusselt number	[-]
$Pr$	Prandtl number	[-]
$\Delta p$	pressure drop	[Pa]
$\dot{q}$	specific heat extraction rate of the borehole per length	[W/m]
$\dot{q}_{geo}$	natural, undisturbed geothermal heat flow	[W/m <sup>2</sup> ]
$\Delta q_i$	heat loss of the upward flowing fluid to the downward flowing fluid	[W/m]
$\dot{Q}$	extraction rate, injection rate, power	[W]
$\dot{Q}_{GW}$	heat output of groundwater flow	[W]
$\dot{Q}_{Building}$	heat input into earth through building floor or earth poles	[W]
$Re$	Reynolds number	[-]
$r_0$	inner radius of the borehole pipe	[m]
$r_s$	outer radius of the borehole pipe	[m]
$r_i$	inner radius of the inner coaxial borehole pipe	[m]
$r_a$	outer radius of the inner coaxial borehole pipe	[m]
$r_1$	borehole radius	[m]
$r_b$	radial distance from the borehole axis (variable)	[m]
$R_\alpha$	heat transfer resistance from the fluid to the wall of the borehole pipe	[Km/W]
$R_a$	internal borehole resistance (from the upward to the downward flowing fluid)	[Km/W]
$R_b$	thermal borehole resistance (from the fluid to the borehole radius)	[Km/W]
$R_c$	thermal borehole resistance (from the borehole pipe to the borehole radius), $R_c = R_b - R_\alpha$	[Km/W]
$R_d$	thermal contact resistance (from borehole radius to the filling material)	[Km/W]
$R_f$	thermal resistance of the evaporator, $(T_{source} - \overline{T_f}) / \dot{q}$	[Km/W]
$R_m$	thermal transportation resistance in the fluid between the depth H/2 and the earth surface	[Km/W]

St	Stanton number	[-]
TRT	Thermal Response Test	
$t_a$	period duration of the seasonal fluctuation(= 1 year = 8760 h * 3600 s/h )	[s]
$\Delta T(r)$	cooling of the earth around a borehole, compared to untouched conditions	[K]
$\Delta T_{Grad}$	vertical temperature gradient in the undisturbed earth	[K/m]
$T_b$	borehole temperature in the depth z (on the radius $r_1$ )	[°C]
$\overline{T}_b$	borehole temperature averaged over the borehole depth (on the radius $r_1$ )	[°C]
$T_f$	mean fluid temperature in the depth z	[°C]
$\overline{T}_f$	averaged fluid temperature, $\frac{1}{2} (T_{outlet} + T_{inlet})$	[°C]
$T_{down}$	temperature of the downward flowing fluid in the depth z	[°C]
$T_{Air}$	longtime mean temperature of the outer air	[°C]
$T_m$	mean temperature of the undisturbed earth	[°C]
$T_{mo}$	averaged, annual temperature on the earth's surface	[°C]
$T_{outlet}$	outlet temperature (temperature of the out streaming borehole fluid)	[°C]
$T_{inlet}$	inlet temperature (temperature of the inflowing borehole fluid)	[°C]
$T_{up}$	temperature of the upward flowing fluid on the depth z	[°C]
$t_s$	borehole time constant	[s]
$v$	flow velocity	[m/s]
$v_f$	Darcy-velocity = specific percolation = filter velocity	[m/s]
$w$	wall thickness of the inner pipe of a coaxial borehole ( $r_a - r_i$ )	[m]
$z$	depth in the earth, measured from the earth's surface	[m]

## 7.2 Greek symbols

$\alpha$	heat transfer coefficient of the borehole fluid	[W/(m <sup>3</sup> K)]
$\beta$	dimensionless thermal resistance from the borehole pipe to the fluid	[-]
$\xi$	dimensionless pressure loss coefficient (pipe friction number, often $\lambda$ )	[-]
$\gamma$	Euler constant, 0.5772..	[-]
$\nu$	kinematic viscosity of the borehole fluid	[m <sup>2</sup> /s]
$\lambda_{Earth}$	heat conductivity of the earth	[W/(mK)]
$\lambda_{eff}$	Heat conductivity of the earth with groundwater influence (from TRT)	[W/(mK)]
$\lambda_{real}$	Heat conductivity of the earth without groundwater influence	[W/(mK)]
$\lambda_{Fill}$	heat conductivity of the borehole filling	[W/(mK)]
$\lambda_{isol}$	heat conductivity of the isolated borehole pipe	[W/(mK)]
$\lambda_s$	heat conductivity of the borehole pipe	[W/(mK)]
$\lambda_w$	heat conductivity of the inner pipe of a coaxial borehole	[W/(mK)]
$\rho_{Wasser}$	groundwater density	[kg/m <sup>3</sup> ]
$\sigma$	conductivity parameter of the borehole filling	[-]

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