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Report on the benchmark methodology and the results

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1. Introduction

Achieving sustainable exploitation of geothermal aquifers based on good governance is a recurrent challenge on a global scale. In many cases these aquifers are transboundary, i.e. shared by several countries and necessitating the use of common assessment methodologies, monitoring procedures, and data-sharing.

An innovative benchmarking methodology for managing the region around Lake Geneva in Switzerland (based on the work of Lachavanne and Juge [2009]) has been further developed and refined within several previous projects, e.g. Transenergy (Prestor et al. 2015, Szőcs et al. 2018) and DARLINGe Nádor (ed) 2019; https://www.darlinge.eu/#/benchmarkingIntro). This aim of the previously developed benchmarking tool was to quantify and compare the state of geothermal water management at different scales on a unique and harmonised way, and to support measures for more efficient energy production. During its development the main criteria were to make it transparent, harmonized, well-defined and have an understandable terminology; a methodology with worldwide applicability and which is not dependent on local geothermal exploitation characteristics; informative, showing quantitative results; and a clear delineation concerning the availability of information.

It has been developed for aquifers exploited by multiple users and/or in neighbouring countries. It comprises a set of indicators presented on charts using five categories (from very poor to very good) and being calculated from allocated points based on physical data or metadata information using transparent formulae. The input requires detailed data on production, monitoring, permits per a well or sites, etc.

The originally established 12 benchmark indicators have been completed with a new one in the GeoConnect^{3}d project, i.e. with the indicator on multiple use. The complemented methodology will be tested on 3 pilot areas with the Pannonian Basin: the Mura-Zala basin, the Battonya, and the Bosnia and Herzegovina pilot areas.

The potential beneficiaries of the benchmarking methodology are: 1) management authorities, including international organizations, 2) licencing authorities, 3) thermal water and other subsurface users, 4) investors in geo-energy resources, and 5) research organizations and universities,

The key issues which can affect the quality of benchmarking are: the existence of actual data, availability and reliability of information, reference dates, types of geothermal objects to be included, and weight assignment of the indicator.

2. Indicators

The 13 benchmark indicators are summarised in Table 1. The required data collection and presentation / evaluation levels were also defined for each indicator. The resulting calculation is grouped into five categories (namely: (i) high need for improvement, (ii) need for improvement, (iii) reasonable practice, (iv) good practice, and (v) very good practice).

1. Table: List of benchmarking indicators, data collection and presentation level. The multiple use indicator has been developed within the GeoConnect³d project.

Name of the indicator	Smallest data collection level	Smallest data presentation level	Indicator type
Licencing procedure	Site/Country	Site or country	Management
Monitoring requirements	Site/Country	Site or country	Management
Monitoring setup	Object/Site	Site	Management
Passive monitoring	Aquifer/Region	Aquifer/Region	Management
Multiple use	Aquifer/Region	Aquifer/Region	Management
Operational issues	Object	Site	Technology & energy
Cascade use	Site	Site	Technology & energy
Thermal efficiency	Object	Site	Technology & energy
Utilisation efficiency	Object	Site	Technology & energy
Reinjection	Object/Site	Site	Environmental
Over-exploitation	Site	Site	Environmental
Status of water balance assessment	Object/Site	Site	Environmental
Public awareness	Site	Site	Social

2.1. Indicators related to management

2.1.1. Licencing procedure (I_{LIC})

This indicator describes the national or regional legislation transparency and simplicity.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{LIC} = \sum_{i=1}^{n} P_i$$

Very good practice: $I_{LIC} > 15$
Good practice: $12 < I_{LIC} \leq 15$
Reasonable practice: $9 < I_{LIC} \leq 12$
Need for improvement: $< I_{LIC} \leq 9$
High need for improvement: $I_{LIC} \leq 6$

P_i = number of assigned points to a geothermal object i

Table 2: Licencing procedure criteria and related points

Licencing procedure	Yes/No	Points
Licencing is required to use thermal water.	Yes	3
	No	0
At least 80% of active objects have a licence granted.	Yes	3
	No	0
Only one licence type exists to use thermal water for geothermal heat production (e.g. only mining or only water licence).	Yes	1
	No	0
Public information exists on licenced objects (names of wells and springs, location, at least as the nearest settlement if not coordinates).	Yes	1
	No	0
Public information exists on licenced quantity (either per site or per an object, either cumulative abstraction or discharge rate).	Yes	1
	No	0
Concession fee has to be paid to an authority annually after the licence is granted.	Yes	1
	No	0
Annual concession fee for heat production and cascade use of thermal water is lower than for only balneological use.	Yes	1
	No	0
Only one type of concession fee has to be paid to produce thermal water by licence annually (irrespective of utilization type).	Yes	1
	No	0
Concession fee depends on actual abstracted quantity of water in each year.	Yes	1
	No	0
Official time for a decision on granting the licence after the submitted application is complete is shorter than 2 months.	Yes	1
	No	0
Actual time for a decision on granting the licence after the submitted application is complete is shorter than 2 months.	Yes	1
	No	0
The user with a licence has to report to maximum two authorities about its actual annual thermal water abstraction in the past year.	Yes	1
	No	0
Geothermal energy use (to produce more geothermal) is supported through officially declared/accepted strategies, action plans…	Yes	1
	No	0
Sustainable use of thermal water (to prevent deterioration of state) is supported through officially declared/accepted strategies, river basin management plans, action plans….	Yes	1
	No	0
Professional guidelines exist on drilling, monitoring, reinjection, observation well, liquidation of wells (at least one of this).	Yes	1
	No	0

2.1.2. Monitoring requirements (I_{REQ})

Monitoring requirements describe what the licence owners are obliged to monitor and report for the licence they have. The points have to be assigned only once for all types of reports. For example, if ministry 1 demands regular measurement of abstracted water cumulative quantity and agency 2 not, all points have to be assigned to this criteria, as this is demanded and data is produced.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{REQ} = \sum_{i=1}^{n} P_i$$

Very good practice: $I_{REQ} > 17$
Good practice: $11 < I_{REQ} \leq 17$
Reasonable practice: $9 < I_{REQ} \leq 11$
Need for improvement: $3 < I_{REQ} \leq 9$
High need for improvement: $I_{REQ} \leq 3$

P_i = number of assigned points to a geothermal object i

Table 3: Monitoring requirements criteria and related points

Monitoring requirements	Yes/No	Points
Regular* measurement of abstracted water cumulative quantity (e.g., m^3 in a day or year)	Yes	3
	No	0
Regular* measurement of discharge rate (e.g. l/s on an hourly interval)	Yes	2
	No	0
Regular* measurement of piezometric level in an object	Yes	3
	No	0
Regular* measurement of thermal water temperature (in the well or outflowing)	Yes	3
	No	0
Regular* chemical analysis of thermal water	Yes	2
	No	0
Regular* performance of hydraulic testing of wells to determine their maximum and/or optimal discharge rate (pumping tests, step tests,...)	Yes	1
	No	0
Regular* interpretation of measured values	Yes	3
	No	0
Regular* reporting on monitoring to an authority	Yes	1
	No	0
Need for approval on reported monitoring results by an authority	Yes	1
	No	0
Permanent archiving of monitoring document by the user	Yes	3
	No	0
Sporadic observation of any of the parameters	Yes	1
	No	0
Well tests done regularly*	Yes	1
	No	0

* Regular is not uniformly defined as it stands for fulfilling the legislative requirements of individual countries or permits.

2.1.3. Monitoring setup (I_{MON})

The monitoring setup indicator is linked to actually recorded parameters where data are available on an object level. It shows whether the monitoring of production and reinjection wells at a user site or a basin is carried out and may serve for evaluation of aquifer state. Inactive production wells with licences have to be included.

The indicator calculation formula and corresponding classification are:

$$I_{MON} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Very good practice: $I_{MON} > 10$
Good practice: $6 < I_{MON} \leq 10$
Reasonable practice: $3 < I_{MON} \leq 6$
Need for improvement: $1 < I_{MON} \leq 3$
High need for improvement: $I_{MON} \leq 1$

P_i = number of assigned points to a geothermal object i
N_{tot} = total number of geothermal objects on the basin level or user site

Table 4: Monitoring setup criteria and related points

Monitoring setup criteria	Yes/No	Points
Active monitoring carried out by water producers: Continuous* automatic measurement of abstracted water quantity	Yes	3
	No	0
Active monitoring carried out by water producers: Regular** measurement of abstracted water quantity	Yes	2
	No	0
Active monitoring carried out by water producers: Continuous* automatic measurement of piezometric level in the aquifer, also as wellhead pressure	Yes	3
	No	0
Active monitoring carried out by water producers: Regular** manual measurement of piezometric level in the aquifer, also as wellhead pressure	Yes	1
	No	0
Active monitoring carried out by water producers: Continuous* automatic measurement of water temperature	Yes	2
	No	0
Active monitoring carried out by water producers: Regular** measurement of water temperature	Yes	1
	No	0
Active monitoring carried out by water producers: Regular** chemical water analysis	Yes	2
	No	0
Yearly report of monitoring results submitted by concessionaire/licenser and approved by granting authority	Yes	3
	No	0
Sporadic observations of any of the parameter	Yes	1
	No	0

* Continuous measurement stands for constant automatic measurements (usually, hourly or daily averages are calculated from these and stored).
** Regular is not uniformly defined as it stands for fulfilling the legislative requirements of individual countries or permits. Therefore, it may happen that two sites have assigned all points even if the first does e.g., the analyses annually and the second every three years but both according to their official requirements. However, the difference must be clearly stated in the interpretation.

2.1.4. Passive monitoring (I_{MONP})

Passive monitoring is a regionally specific indicator whether there are observation wells monitored by a national/regional environmental agency, or similar organization. Thermal water users have nothing to do with these wells, monitoring, or interpretation of results.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{MONP} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Very good practice: $I_{MONP} > 5$
Good practice: $3 < I_{MON\,P} \leq 5$
Reasonable practice: $1 < I_{MONP} \leq 3$
Need for improvement: $0 < I_{MONP} \leq 1$
High need for improvement: $I_{MONP} \leq 0$

P_i = number of assigned points to an observation well i
N_{tot} = total number of observation wells in a selected region/aquifer

Table 5: Passive monitoring setup criteria and related points

Passive monitoring setup criteria	Yes/No	Points
Passive monitoring in observation well: Continuous* automatic measurements of piezometric level in the aquifer, also as wellhead pressure	Yes	3
	No	0
Passive monitoring in observation well: Regular** measurements of piezometric level in the aquifer, also as wellhead pressure	Yes	2
	No	0
Passive monitoring in observation well: Regular** measurements of water temperature in the well	Yes	2
	No	0
Passive monitoring in observation well: Regular** sampling of groundwater for chemical and/or isotopic analysis	Yes	2
	No	0
Sporadic observations	Yes	1
	No	0

* Continuous measurement stands for constant automatic measurements (usually, hourly, or daily averages are calculated from these and stored).
** Regular is not uniformly defined as it stands for fulfilling the legislative requirements of individual countries or permits. Therefore, it may happen that two sites have assigned all points even if the first does e.g., the measurements of groundwater piezometric level daily and the second every two weeks, but both according to their official requirements. However, the difference must be clearly stated in the interpretation.

2.1.5. Multiple use (I_{MULT})

This indicator assesses the multiple use of the subsurface from a thermal water use perspective and provides information on how advanced the different subsurface use types are recognized and their interactions studied.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{MULT} = \sum_{i=1}^{n} P_i$$

Very good practice: $I_{MULT} > 15$
Good practice: $12 < I_{MON\,P} \leq 15$
Reasonable practice: $8 < I_{MONP} \leq 12$
Need for improvement: $4 < I_{MONP} \leq 8$
High need for improvement: $I_{MONP} \leq 4$

P_i = number of assigned points

Table 6: Multiple use criteria and related points

Multiple use of subsurface	Yes/No	Points
To be assessed for the entire pilot area		
Does national legislation recognize / mention multiple subsurface use and its management in any form?	Yes	2
	No	0
Are permits / concessions to use thermal water officially delineated in 3D/subsurface layers so that the aquifer top and bottom extent are well defined?	Yes	2
	No	0
Are hydrocarbon reservoirs officially delineated in 3D/subsurface layers so that their top and bottom extent are well defined and do not grant exclusive right to the "centre of the Earth"?	Yes	2
	No	0
Are drinking water permits officially delineated in 3D/subsurface layers so that the aquifer top and bottom are well defined?	Yes	2
	No	0
Do authorities that control the exploitation of drinking and thermal water, and hydrocarbons or other subsurface use cooperate, and at least annually jointly evaluate monitoring results of all sectors and possible emerging issues among various subsurface use and their impacts?	Yes	3
	No	0
When granting a permit to use reservoirs deeper than the exploited geothermal aquifer (e.g for hydrocarbons, EGS or deep geoprobes) – are there any special requirements set in the permit to evaluate and monitor potential interactions?	Yes	2
	No	0
To be assessed for each site separately within the pilot area, if possible, please provide the name of the site and calculate the average value which you add into the final equation		
1. Are there any other ongoing "deep subsurface utilization" activities in the area that potentially interact with thermal water production? (hydrocarbon, underground gas storage, salt production, EGS, CCS, deep geoprobes etc.) *If there are more, answer sub-questions below separately*		
Only thermal water production exists, other deep uses are geologically not possible.	Yes	3
	No	0
If (1) is yes and studies exist where interactions are assessed by numerical models.	Yes	3
	No	0
If (1) is yes and studies exist where interactions are assessed by expert judgements (based on analogues, etc.).	Yes	2
	No	0
If (1) is yes, but only awareness on potential interactions exists, but no studies	Yes	1

Multiple use of subsurface	Yes/No	Points
were done.	No	0
2. Are there any drinking water resources that potentially interact with thermal water production (in their recharge areas or where waste thermal water is emitted to surface waters in the drinking water protection areas)? *If there are more, answer sub-questions below separately*		
Only thermal water production exists, linkage to drinking water aquifers is geologically not possible and waste thermal water is not emitted withing the drinking water protection areas.	Yes	3
	No	0
If (2) is yes and studies exist where interactions are assessed by numerical models.	Yes	3
	No	0
If (2) is yes and studies exist where interactions are assessed by expert judgements (based on analogues, etc.).	Yes	2
	No	0
If (2) is yes and only awareness on potential interactions exists and is possible, but no studies were done.	Yes	1
	No	0

2.2. Indicators related to Technology and Energy

2.2.1. Operational issues (I_{BAT})

The operational issues indicator shows whether appropriate technical parameters exist at well installations, how efficiently the operational problems are mitigated, and it also describes the overall status of documentation at a user site. If good mitigation of operational issues is being implemented, this will lead to a reduced operational cost, safer operation, and usage efficiency. At the same time any environmental pollution will be reduced. Weighting per annually produced water quantity from each object must be applied for each site.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{BAT} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i}$$

Very good practice: $I_{BAT}>5$
Good practice: $4<I_{BAT}\leq 5$
Reasonable practice: $3<I_{BAT}\leq 4$
Need for improvement: $1<I_{BAT}\leq 3$
High need for improvement: $I_{BAT}\leq 1$

I_i = number of assigned points to a geothermal object i
Q_i = annual production rate of a geothermal object i (m3/y)

Table 7: Operational issues use criteria and related points

Operational issues criteria	Yes/No	Points
The well and wellhead are properly constructed (isolated, protected from unfavourable weather conditions and unauthorized persons, has enough fittings to install monitoring equipment for heads, temperature and abstraction rate).	Yes	2
	No	0
Problems of operation are successfully mitigated (scaling, blowouts, explosion zones, clogging of screens, free gases, corrosion, cavitation of pump, sand abrasion of pump particles discharge). If there are no problems, assign 2.	Yes	2
	No	0
If free gas is also produced from the well, it is used further (e.g. burning of methane for electricity, bottling and selling CO2....). If no free gas is present, assign 1.	Yes	1
	No	0
Supporting technical, lithological, hydrogeological and chemical documentation, as well as records of well-maintenance work is well-kept and regularly updated.	Yes	1
	No	0

2.2.2. Cascade use (I_{CAS})

Cascade use is related to a site energy abstraction practice. The cascade use means utilizing geothermal resources for more than one application sequentially according to decreasing temperature demand. Cascade use supports increased net efficiency and improves economics of the system.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{CAS} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Very good practice: $I_{CAS}>5$
Good practice: $4<I_{CAS}\leq 5$
Reasonable practice: $3<I_{CAS}\leq 4$
Need for improvement: $1<I_{CAS}\leq 3$
High need for improvement: $I_{CAS}\leq 1$

P_i = number of assigned points to a geothermal site i
N_{tot} = total number of sites in an investigated region/aquifer/country

Table 8: Cascade use criteria and related points

Cascade use criteria	Yes/No	Points
Thermal water is used based on the principles of a cascade system.	Yes	2
	No	0
There are more than three successive stages of energy extraction (delta T).	Yes	1
	No	0
Thermal water is not additionally heated prior to its use.	Yes	1
	No	0
Thermal water is not cooled down by mixing with cold water prior to its use.	Yes	1
	No	0
No surplus of unused heat: wastewater temperature is 12 °C.	Yes	1
	No	0
The site has a backup energy resource –another energy source which operates if the wells are not active or in peak-load heat demands. So geothermal is only a baseline energy.	Yes	1
	No	0

2.2.3 Thermal efficiency (I_{TEF})

Thermal efficiency is determined from the ratio between the used and the available annual heat energy. The mean annual air temperature (T_o) is used as a reference, which is site specific, and in the long-term it is supposed to be very close to the average annual fresh groundwater temperature. In this methodology, we applied the same threshold as for optimum temperature of waste thermal water, which is 12 °C.

Lowering the temperature of the waste thermal water through the use of e.g. cascade systems will increase the thermal efficiency. This also leads to a reduction in the total amount of abstracted thermal groundwater and reduces the threat of thermal and chemical pollution of surface waters coming from discharge of waste thermal waters.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{TEF} = \frac{\sum_{i=1}^{n} \eta_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \, [\%]$$

Where:

$$\eta_i = \frac{T_{whd} - T_{out}}{T_{whd} - T_o}$$

In case of reinjection:

$$\eta_{r\,i} = \frac{Q_i(T_{whd} - T_{out})}{Q_i(T_{whd} - T_{out}) + Q_{ww\,i}(T_{out} - T_o)}$$

Very good practice:	$I_{TEF} > 70$
Good practice:	$60 < I_{TEF} \leq 70$
Reasonable practice:	$40 < I_{TEF} \leq 60$
Need for imprpvement:	$30 < I_{TEF} \leq 40$
High need for improvement:	$I_{TEF} \leq 30$

η i = thermal efficiency of a geothermal object i without applied reinjection (%)
Qi = annual production rate of a geothermal object i (m3/y)
To = average annual air temperature at a geothermal site, assigned as 12 °C
Tout = temperature of waste thermal water at an individual geothermal site (°C)
Twhd = outflow temperature of a geothermal object i (at the wellhead of a well or at a spring) (°C)
η ri = thermal efficiency of a geothermal object i with applied reinjection (%)
Qww i = annual discharge rate of waste thermal water of a geothermal object i (m3/y)

2.2.4. Utilization efficiency (I_{UEF})

The ratio of the average annual water production to the maximum water quantity that could theoretically be produced gives the utilization efficiency. A maximum value for production can be taken from:

1. the currently installed pump capacity that was actually tested ($Q_{cap\ i}$)
2. the licenced allowed maximum production

We use the maximum annual licenced production as Q_{cap} by default. If no licence is granted, the installed pump capacity will be applied as a divider.

If the amount of water used is greater than the licenced amount, the indicator result also has to be 'bad'.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{UEF} = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n} Q_{cap\ i}} \cdot 100\ [\%]$$

Very good practice:	I_{UEF} >60
Good practice:	45< I_{UEF} ≤60
Reasonable practice:	30< I_{UEF} ≤45
Need for improvement:	15< I_{UEF} ≤30
High need for improvement:	I_{UEF} ≤15; I_{UEF} >100

Qi = annual production rate of a geothermal object i (m3/y)
Qcap i = installed pump capacity of a geothermal site i (≈ maximum allowed annual production as defined in water permit) (m3/y)

2.3. Indicators related to the Environment

2.3.1. Reinjection(I_{REIN})

Reinjection status at a site can be used as a test for sustainable thermal water exploitation. Reinjection is permitted only for non-treated and uncontaminated thermal water (i.e., used only for its heat energy). Reinjection rate (R_R) is the ratio of the volume of reinjected and abstracted thermal water used only for geothermal energy production. In practice, reinjection often operates into shallower aquifers. This is in contradiction with the guidelines of the Water Framework Directive since shallow reinjection can lead to the introduction of higher organic matter and/or trace element content into these aquifers with chemically different thermal water.

$$R_R = \sum_1^n \frac{Q_{reinj\,i}}{Q_{abs\,i}}\ [\%]$$

The indicator calculation formula and corresponding classification/scoring are:

$$I_{REIN} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i}$$

Very good practice:	$I_{REIN} > 5$
Good practice:	$3 < I_{REIN} \leq 5$
Reasonable practice:	$1 < I_{REIN} \leq 3$
Need for improvement:	$0 < I_{REIN} \leq 1$
High need for improvement:	$I_{REIN} = 0$

Ii = number of assigned points to a geothermal site i
Qi = annual production rate at a geothermal site (m3/y)
Qabs i = annual production rate of thermal water of a geothermal object i used solely for geothermal heat production (m3/y)
Qreinj i = annual reinjection rate of thermal water of a geothermal object i used for geothermal heat production (m3/y)

Table 9: Reinjection criteria and related points

Reinjection criteria	Yes/No	Points
More than 80% of produced thermal water may be reinjected (is not polluted).	Yes	1
	No	0
Reinjection rate (R_R) is 60% or more.	Yes	4
	No	0
Reinjection rate (R_R) is between 40% and 60%.	Yes	3
	No	0
Reinjection rate (R_R) is between 20% and 40%.	Yes	1
	No	0
Water is reinjected in hydraulically connected layers so that the recovery of water is possible.	Yes	1
	No	0
Water is reinjected in layers (aquifer) with similar water chemistry (±20%) and no additional pollution threat exists e.g., phenols, organics, arsenic….	Yes	1
	No	0

2.3.2. Over-exploitation (I_{OE})

Exploitation of thermal water can clearly have an impact on the aquifer being exploited. For this reason an over-exploitation indicator has been developed to characterise the status of the aquifer at a site. Potential impacts include disequilibrium change (showing significant trends as in the Water Framework Directive) of piezometric groundwater level, water temperature, groundwater availability, water quality change, the groundwater dependent ecosystem and subsidence. The change has to be taken into account on a time-scale when the production should have already caused the establishment of a quasi-steady state in the geothermal aquifer at the site. Very good state is achieved when a new quasi-equilibrium is reached during production. Also, the points (1) should not be assigned when at least one of the wells at the site shows such changes.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{OE} = \frac{\sum_{i=1}^{n} I_i \cdot Q_i}{\sum_{i=1}^{n} Q_i}$$

Ii = number of assigned points to a geothermal object i
Qi = annual production rate of a geothermal object i (m3/y)

Very good practice:	$I_{OE} > 4$
Good practice:	$3 < I_{OE} \leq 4$
Reasonable practice:	$2 < I_{OE} \leq 3$
Need for improvement:	$1 < I_{OE} \leq 2$
High need for improvement:	$I_{OE} \leq 1$

Table 10: Over-exploitation criteria and related points

Over-exploitation criteria	Yes/No	Points
No significant decrease of piezometric level	Yes	1
	No	0
No significant decrease in water quality	Yes	1
	No	0
No significant decrease in outflow water temperature	Yes	1
	No	0
No significant decrease in groundwater availability (lower yield, pump lowering)	Yes	1
	No	0
No significant impact on dependent ecosystems	Yes	1
	No	0

2.3.3. Status of water balance assessment (I_{WBA})

The status of water balance assessment is a measure of the level of the depth and reliability of information on the water quantity status of an aquifer at a site. Reliable, good quality, regional hydrogeological data are needed in order to make an estimate on the natural recharge of a geothermal aquifer. If there is an ongoing national monitoring programme, and data interpretation can be combined with data from users' 'active' monitoring, then more accurate estimates can be calculated. It is proposed that every 3 to 6 years the annual data for water balance assessment and regional hydrogeological evaluation should be assessed and evaluated since only after this period will any trends become evident.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{WBA} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Very good practice:	$I_{WBA} > 3$
Good practice:	$2.5 < I_{WBA} \leq 3$
Reasonable practice:	$1.5 < I_{WBA} \leq 2.5$
Need for improvement:	$1 < I_{WBA} \leq 1.5$
High need for improvement:	$I_{WBA} \leq 1$

Pi = number of assigned points to a geothermal object i
Ntot = total number of objects in an investigated region/aquifer

Table 11: Status of water balance assessment criteria and related points. Only one criteria can be allocated to one well. If no information exists, zero points are assigned.

Status of water balance assessment criteria	Yes/No	Points
Renewable and available volume of water is assessed. Critical point of abstraction and critical level are both defined. Study is made and updated on the basis of actual measurements.	Yes	4
	No	0
Renewable and available volume of water is assessed. Critical point of abstraction and critical level are both defined. Study is made on the basis of old / regional data and knowledge	Yes	3
	No	0
Critical level is defined (based on average yearly minimum level value from previous years at the location)	Yes	2
	No	0
Critical level is defined (not based upon measurements on the location but from other available data / locations)	Yes	1
	No	0

2.4 Social

2.4.1. Public awareness (I_{INF})

Public engagement is considered an important aspect of the exploitation of any natural resource, including thermal waters. For this reason, a public awareness indicator has been developed based on a range of data which can allow the public to make an informed decision. Relevant parameters in the calculation include open-access information on monitoring, operational issues, the quantity status of aquifers, the quality of discharged thermal wastewater, and thermal efficiency.

The indicator calculation formula and corresponding classification/scoring are:

$$I_{INF} = \frac{\sum_{i=1}^{n} P_i}{N_{tot}}$$

Very good practice: $I_{INF} > 8$
Good practice: $7 < I_{INF} \leq 8$
Reasonable practice: $4 < I_{INF} \leq 6$
Need for improvement: $2 < I_{INF} \leq 4$
High need for improvement: $I_{INF} \leq 2$

Pi = number of assigned points to a geothermal object i
Ntot = total number of objects in an investigated region/aquifer

Table 22: Public awareness criteria and related points

Public awareness criteria	Yes/No	Points
There is a visitor centre at the site, or the users organise guided tours where geothermal objects and use of thermal water are shown and explained to public.	Yes	2
	No	0
Public information exists on thermal water source (well or spring, approximate depth of the aquifer)	Yes	2
	No	0
Public information exists on thermal water temperature	Yes	2
	No	0
Public information exists on thermal water chemistry (TDS or main components or gases or special chemical parameters)	Yes	1
	No	0
Public information exists on thermal water utilization type (for heating, balneology…)	Yes	1
	No	0
Public information exists on monitoring results (groundwater level, or temperature or chemistry…)	Yes	1
	No	0
Public information exists on best available technology and operational issues (on any of the criteria at the operational issues indicator)	Yes	1
	No	0
Public information exists on wastewater (treatment or temperature or where discharge is …)	Yes	1
	No	0

3. Evaluation of testing the methodology by a new indicator for multiple use

Previous indicator results are taken from the evaluations performed within the DARLINGe project (Nador A. (ed.), 2019). Here, we discuss only the indicator values for multiple use.

3.1. Pilot area Mura-Zala basin

3.1.1. Slovenia

In Slovenia, national legislation does recognize multiple subsurface use and its management but not literally – but when granting a concession to use thermal water several ministries are invited to amend/comment the decrees and add requirements which we can count as recognition of possible multiple uses of the subsurface. The Ministry of Infrastructure grants the Mining Concession to produce geothermal electricity or heat when using a geothermal doublet, while the Ministry of the Environment and Spatial Planning grants the Water Concession when no or partial reinjection is planned for heat production or balneological use. Thermal water concessions do not have officially delineated 3D surfaces but public (not official) maps of top and bottom of aquifers do exist. The Water Management Plan has officially declared aquifers within water bodies (named by depth as 1st, 2nd, 3rd) which are defined by lithostratigraphy and hydraulic properties but not yet by layer-topography maps. So additional geological information is needed to be provided to properly manage the subsurface in 3D. Water permits do have aquifer depths and lithostratigraphy described (at a well level, maybe cross-section), but 3D models are not used to grant individual permits. Locally, 3D geological and numerical models of flow and heat transfer exist but are not yet used in the concession granting process officially.

Hydrocarbon exploitation (e.g. Mining) concession has no depth limit, but the productive reservoirs are described lithostratigraphically and in 2D maps or cross-sections. But no 3D models are used by authorities yet. In Slovenia, reservoirs deeper than exploited geothermal aquifers occur only for hydrocarbons, while potential for deep/electricity from geothermal reservoirs is yet not proven economically. In the submitted documents, it is necessary to evaluate possible effects on waters (where we can count also drinking water and geothermal reservoirs) and suggest measures to prevent any harm.

Authorities (these two ministries and their agencies) do cooperate, mostly during the process of assessing the submitted documentation for granting a concession decree. Later, evaluation of quality and quantity state is done for drinking and geothermal aquifers with Water Concessions annually, however, no information is provided or communicated for geothermal doublets under the Mining Concession. So this exchange of information should be improved.

In most cases, only geothermal aquifers are of interest for future use of subsurface at investigated 32 wells/16 sites. Studies on (geological) interaction among geothermal and depleted hydrocarbon reservoirs (never been economically interesting) are reported for Banovci and Moravske Toplice area. In the area of Lendava town, active hydrocarbon concession is granted and analytical studies have been performed but numerical models have not been done for the purpose of such interaction. Here, it is also expected that deep geoprobes (close-loop systems) will be applied in near future, so interaction will have to be assessed.

Regarding the effects on drinking water aquifers, most geothermal wells are not positioned in the water protection areas, so no harmful effects are expected. Such situation exists in Ptuj (Figure 1) but no studies were yet done, while in Renkovci few evaluations of the cloud of emitted waste thermal water were done in the past but no water protection area exists there at the moment, so it is irrelevant.

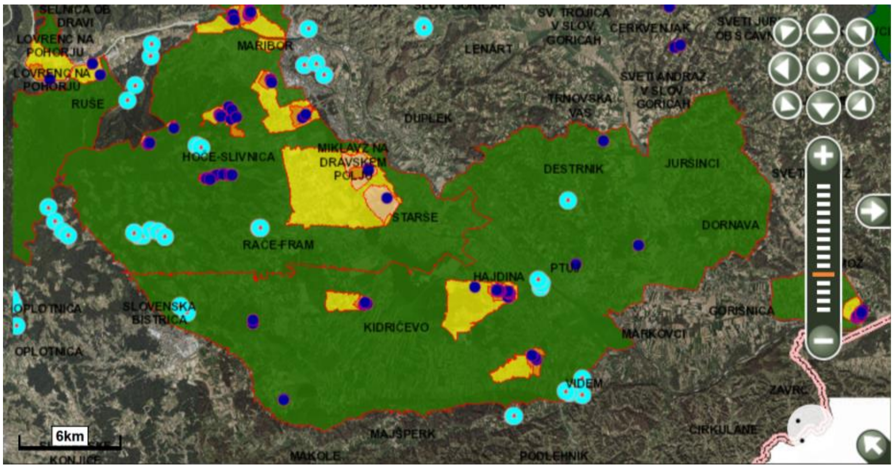

Figure 1: Example of thermal water concession wells (light blue circles) which lay within the water protection areas. Reference : Atlas Okolja portal

Numbering of results for multiple use has given points: 2 + 2.63 + 2.78 = 7.41. This ranks into the second category, which shows serious **need for improvement**. Development should support establishment of 3D geological models and their incorporation into the management process, regardless which geopotential will be assessed. Also, interaction between various uses where geologically possible should be evaluated in more details by focused studies, so that types and extent of interaction would be clearly identified. Therefrom possible mitigation measures or monitoring systems can be evolved.

3.3.2. Croatia

As in Slovenia, national legislation in Croatia recognizes multiple subsurface use. The use of geothermal aquifers defines the legislative framework under which the state will ensure sustainable management of the geothermal resource. If geothermal resource is used for balneological, recreational, medical purposes or bottling, then the management of the geothermal resources is according to the Water Act (OG 153/09, 63/11, 130/11, 56/13, 14 / 14). However, if geothermal resource is used for the production of electricity and/or heating, then the management of the geothermal resources is according to the Hydrocarbon Exploration and Exploitation Act (OG 52/18, 52/19). The Ministry of Economy and Sustainable Development is responsible for both legislative frameworks. The Hydrocarbons Agency (under the authority of the above mentioned Ministry) is responsible for conducting tenders under the Hydrocarbons Exploration and Exploitation Act (OG 52/18, 52/19) while Croatian Waters (which is also under the authority of the same Ministry) performs activities under the Water Act (OG 153/09, 63/11, 130/11, 56/13, 14/14). So according letter said, 3D surfaces officially exist if thermal water is used for heating and non-officially for balneological purpose. In addition, non-official tops and bottoms surfaces exist for drinking water (especially) alluvial aquifers and it is necessary to create the flow model for it also.

Authorities do control the exploitation of drinking and thermal water, and also hydrocarbons. Annual evaluation of monitoring results is done only separately never jointly, so there is no knowledge if and how hydrocarbon exploration effects deep geothermal aquifers.

In the study area, exploration of geothermal aquifers and hydrocarbons (field Vučkovec) exists only in the area of Spa Sv. Martin. Beside this hydrocarbon field, three more exist in the study area: Vukanovec, Zebanec and Mihovljan. Currently, there are no studies which can show whether there is any interaction between these two media and reservoirs. Considering drinking and geothermal water aquifers, they are not in hydraulic connection because at the most places they are dived by semi-permeable quite thick layers.

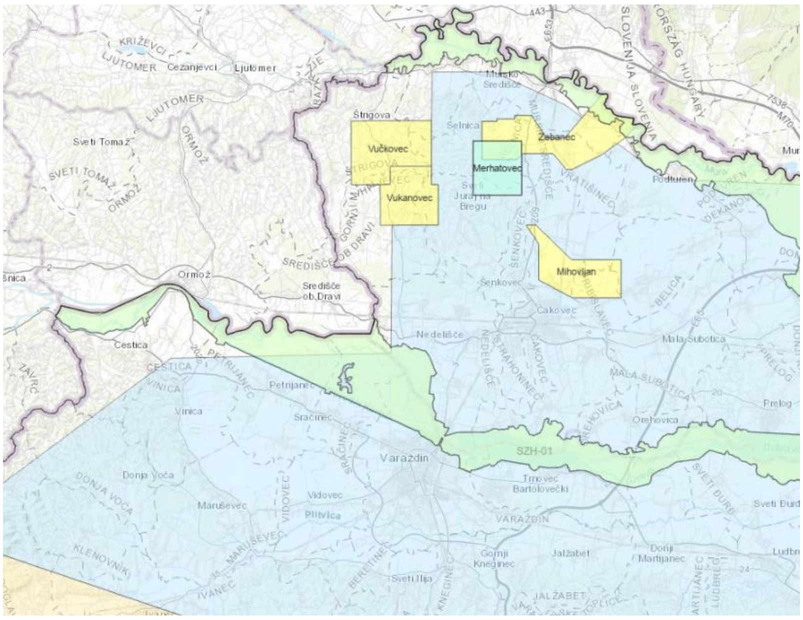

Figure 2: Hydrocarbon exploitation fields (marked in yellow) and in aquamarine clour geothermal exploration filed (https://gis.azu.hr/portal/apps/webappviewer/index.html?id=6b2324ed725a4a2e9d1a5a665d23262a)

Numbering of results for multiple use for Croatia has given: 3.56 + 2.71 + 3 = 9.27 and it ranks into **Reasonable practice** category. This still shows possibilities for improvement. At least 3D geological knowledge and models should be incorporated into the management decision procedures soon.

3.3.3. Hungary

The national legislation in Hungary recognizes multiple subsurface use, however not in a single act, but scattered in different pieces of legislation. While "thermal water" is related to water management and is under the umbrella of the LVII. Act on Water Management (1995) and many related governmental decrees specifying the various details, "geothermal energy" is regulated by the XLVIII. Mining Act (1993), similarly to hydrocarbons, CO_2 storage and underground gas storage.

The exploration and exploitation of hydrocarbons can happen only in the frame of a concessional procedure. For geothermal energy the Hungarian regulation distinguishes open and closed areas, i.e. areas below 2500 m (from the surface) are considered as close areas, whereas above 2500 m it is an open area. In open areas the wells (i.e. prospection and utilization of thermal waters) are licensed by the Regional Directorates for Disaster Management (as competent authorities for water management). In closed areas exploration and exploitation of geothermal energy can happen only in the frame of concession under the auspices of the Mining Authority. Nevertheless if a deep (>2500 m) well is expected to produce thermal water, it also has to be permitted by the water management authorities.

In the frame of "subsurface management" the terminology and application of various "protection zones" is of utmost importance, also related to mineral and medicinal waters. The protection zones of mineral and medicinal waters is regulated in details under Governmental Decree 123/1997 (VII.18.) on the protection of water resources. According to article 2, the protection of such groundwater resources means the delineation and maintenance of protection blocks and zones, which have to be divided into inner-, outer- and hydrogeological protection zones. The boundaries of these zones have to be outlined on the basis of hydrogeological conditions, the actual, or potential water exploitation of the water resource. The task of the inner protection zone is the technical protection of the well itself and the protection of the water resource from direct contamination. The outer protection zone should safeguard the water resources from other degrading and bacterial contaminations, while the hydrogeological protection zone should protect the resources from non-degrading contamination which has to be outlined for parts, or for the entire recharge area. The dimensioning of the protection zones is based on the travel times, calculated from permanent groundwater flow velocity (i.e. the time necessary for a pollutant, or water particle to reach the abstraction site). Article 8 summarizes the main aspects of delineation of the different protection zones, such as the targeted depth interval, the amounts of water with abstraction permits, brief geological, characterization of the aquifers of the protected water resources, restrictions in land-use, necessary measures and monitoring and their assessment. According to article 10, only those activities can be performed in the different protection zones, which do not endanger the quality or quantity of the water to be abstracted. Article 11 regulates and gives restrictions for activities to be performed in the inner protection zone, article 12 for the outer protection zone and article 13 for the hydrogeological protection zones. Such activities are potential pollutions from agriculture, animal farming, industry, etc.

For geothermal energy the Mining Act defines the term of the geothermal protection zone, but only for areas below 2500 m. According to the law, the protection zone has to be delineated based on numerical models, where temperature change is less than 1 °C and pressure change is less than 0,1 bar (hydrostatic systems) or 1 bar (overpressured systems). So far geothermal protection zones have been delineated only at 2 sites.

For hydrocarbon exploration, only the mining plots are officially outlined as 3D blocks, but this is an administrative unit, following the horizontal and vertical boundaries as set in the permits.

There is a good and detailed understanding on the top and bottom bounding surfaces of the various reservoirs (for hydrocarbons, thermal- and drinking water resources), however these are not acknowledged as “official” units. Unfortunately there is no cooperation among authorities that control the exploitation of drinking and thermal water, and hydrocarbons (as a result of divided authority tasks among mining and water management).

On the HU part of the Mura-Zala pilot area hydrocarbon production and thermal water production are the 2 main “competitors”, however interactions are assessed by expert judgements. Thermal water reservoirs are in hydrogeological connection with the shallow drinking water resources, but again – apart from a few local numerical models – interactions are assessed only by expert judgements.

Numbering of results for multiple use for Hungary has given: 4 + 2+ 2 = 8 and it ranks into **Need for Improvement** category. At least 3D geological knowledge and models should be incorporated into the management decision procedures. However it has to be emphasized, that the geothermal protection zone is a very promising approach and should be expanded.

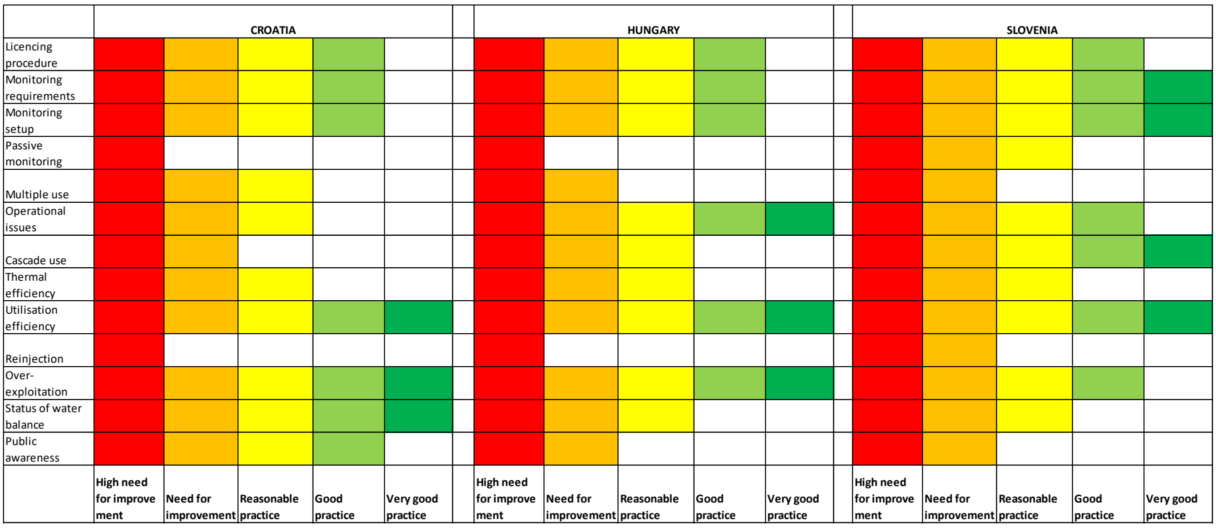

Figure 3: Results of benchmark evaluation with a new „multiple use" indicator for Mura-Zala Basin for three countries

3.2 Pilot area Battonya

In the frame of the GeoConnect³d project no additional information was received from Romania, whilst for the multiple use indicator in Hungary the same are valid as described in chapter 3.3.3. Results are summarised on Fig. 4. On the HU part of the Battonya pilot area hydrocarbon production and thermal water production are the 2 main "competitors", however interactions are assessed by expert judgements. Thermal water reservoirs are in hydrogeological connection with the shallow drinking water resources, but again – apart from a few local numerical models – interactions are assessed only by expert judgements.

Numbering of results for multiple use for Hungary has given: 4 + 2+ 2 = 8 and it ranks into **Need for Improvement** category. At least 3D geological knowledge and models should be incorporated into the management decision procedures. However it has to be emphasized, that the geothermal protection zone is a very promising approach and should be expanded.

	ROMANIA						HUNGARY				
Licencing procedure											
Monitoring requirements											
Monitoring setup											
Passive monitoring											
Multiple use	no data										
Operational issues											
Cascade use											
Thermal efficiency											
Utilisation efficiency											
Reinjection											
Over-exploitation											
Status of water balance assessment											
Public awareness											
	High need for improve ment	Need for improvement	Reasonable practice	Good practice	Very good practice		High need for improve ment	Need for improvement	Reasonable practice	Good practice	Very good practice

Figure 4: Results of benchmark evaluation with a new „multiple use" indicator for the Battonya pilot area for two countries

3.3. Pilot area Bosnia and Herzegovina

3.3.1. Bosnia and Herzegovina

In DARLINGe project, two countries joined information for this transboundary area (Nador, 2019) but in the GeoConnect³d project, only information from Bosnia and Herzegovina is available and supplemented (Fig. 5).

National legislation in BiH recognizes/mentions multiple subsurface use or its management. Exploration and exploitation of various mineral raw materials is possible in one exploration / exploitation area in accordance with the Law on Geological Exploration and the Law on Mining (refers to both entities-Federation of Bosnia and Herzegovina and Republic of Srpska). Legal entities that intend to carry out exploration / exploitation in the same area agree on the manner of performing works. This agreement must be approved by the competent entity ministry.

Regarding to exploration and exploitation thermal waters the waters permits / concessions define: a) exploration area on the surface of terrain limited by coordinates (Exploration permit), 2) reserves and quality of thermal water (Decision on confirmation of quantity and quality of thermal water) and allowed/agreed amount (capacity) of use (Concession Contract). Regulations do not require that aquifer top and bottom be defined in permits/contract, but in the documentation on the basis of which the permits are issued, the forecast geological cross-section must be given (minimum condition).

There is no exploitation of hydrocarbons in Bosnia and Herzegovina; the competent ministries for oil and gas exploration and exploitation have been making an effort over the last few years to develop regulations in this area and prepare the ground for potential interested oil companies. Therefore, hydrocarbon reservoirs are not officially delineated in 3D/subsurface layers so that their top and bottom extent are not known. Permits / contracts define blocks for exploration and exploitation, delineated in 2D. In the Federation of BiH the area of the block cannot be larger than 1440 km^2.

Drinking and thermal waters are researched and used according to the same regulations, so there are no differences in the permits for drinking and thermal waters.

If necessary, the authors cooperate in the exchange of information and data for which they are in charge, but there is no joint evaluation of monitoring results and planning further activities. The exchange of monitoring data is prescribed by the Water Law, Law on Geological Exploration, etc.; it is binding among public and government institutions, but there is no joint analysis of monitoring results and taking measures that could lead to better subsurface management.

The research company is obliged to determine and keep records of the basic characteristics of other mineral raw materials (including all types of groundwaters) discovered during the survey in accordance with the Law on Geological Exploration; for example, if a thermal water reservoir is found during drilling for hydrocarbon, the quantity and quality of this water must be determined at least by short-term testing. More detailed research such as monitor potential interactions is not mandatory.

The Semberija region, where the Dvorovi and Slobomir wells are located, was considered as promising for oil and gas exploration in the past but results of five deep wells gave negative results (S-1, SV-1, BiJ-1, S-2 and DV-1), so based on today's level of research we can assume that this area is promising only for the use of geothermal energy. It is assumed that deeper drilling at both locations (Slobomir and Dvorovi) could only produce larger capacities of water in the same aquifer (Triassic limestones) in relation to those capacities obtained at wells Dvorovi and Slobomir, but not higher temperature values.

Interaction of drinking and thermal water geologically is not possible at both locations (Dvorovi and Slobomir), but the used thermal waters (waste waters) are discharged into the alluvial aquifer at both locations. Interactions of waste thermal and drinking alluvial water are not assessed by numerical models. There are no studies and expert judgements related to the influence of thermal wastewater on alluvial drinking groundwater. Experts are aware of potential interactions, but studies have not been done.

Numbering of results for multiple use for Bosnia and Herzegovina has given: 2.0 + 3.0 + 1.0 = 6.0 and it ranks into **Need for improvement** category. This shows that reasonable efforts are needed to reach improvement. Information on reservoir top and bottoms and/or 3D geological models should be incorporated into the management decision procedures and joint evaluation of state should be performed. Where drinking water resources interact with geothermal, studies on their interconnections should be performed.

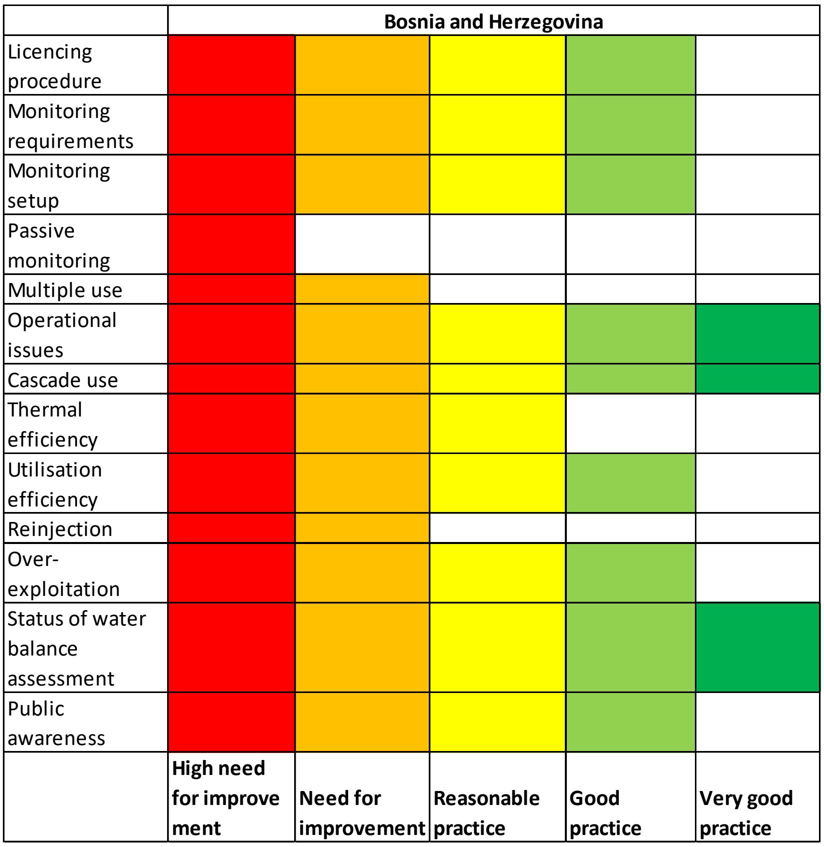

Figure 5: Results of benchmark evaluation with a new „multiple use" parameter for Bosnia and Herzegovina

4. Conclusions

We have supplemented the originally established 12 benchmark indicators with a new one in the GeoConnect³d project, i.e. with the indicator on multiple use. It was tested on pilot areas within the Pannonian Basin: the Mura-Zala basin, the Battonya, and the Bosnia and Herzegovina pilot areas.

The new indicator pointed out that multiple use of subsurface, either drinking or hydrocarbon resources over geothermal reservoirs are possible in most countries. Legislation is not yet properly developed everywhere, nor studies are performed to investigate these relations in more details. We identified that it is necessary to develop and apply 3D subsurface geological models in all project countries, as their use is not yet generally widespread.

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