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Prediction of the radon-prone areas in the Slovak Republic and its experimental verification

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Introduction

- the **EU Council Directive 2013/59/Euratom** – establishment of ***national action plans*** addressing long-term risks from radon exposures in buildings
- identification of the areas, where the radon concentration in buildings exceeds the relevant **national reference level** – **300 Bq/m^3**
- regions, where indoor radon concentration is increased for natural (geogenic) reasons = ***radon prone areas*** [Bossew, 2014], are identified:
  - **directly** – indoor measurements [WHO handbook, 2009]
  - **indirectly** – ^{226}Ra, ^{222}Rn concentrations, porosity, permeability, water content, soil type, etc.

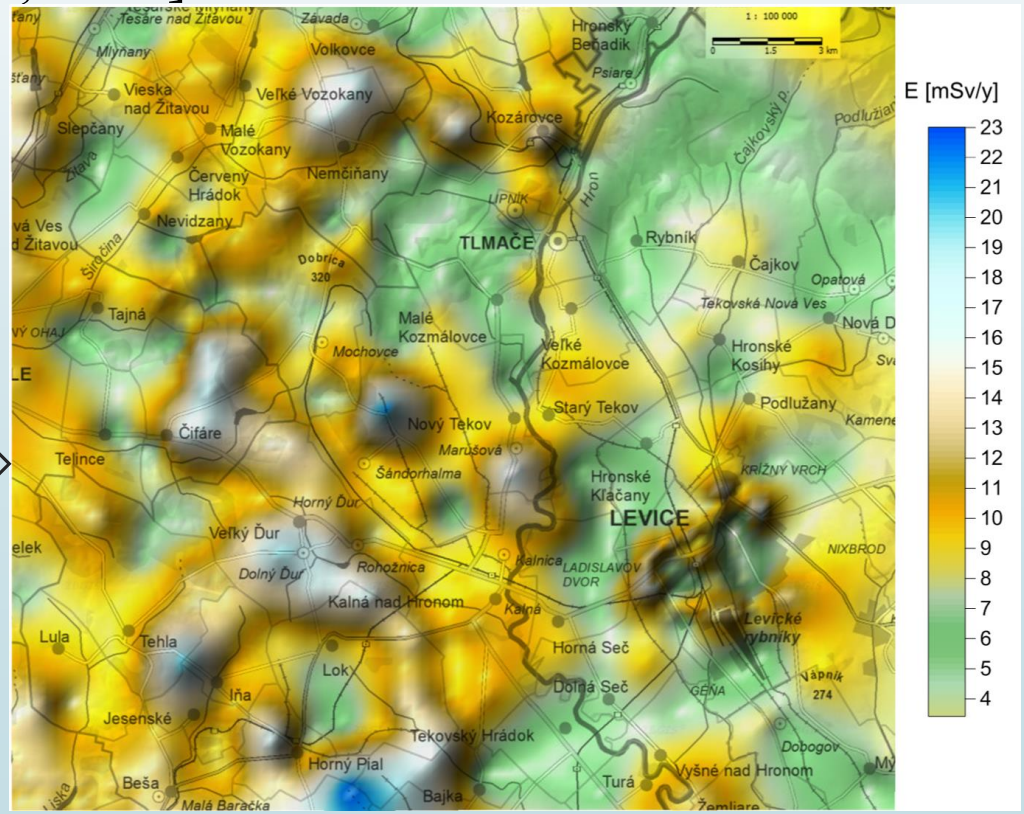
Pilot study – locality

Mochovce, Slovakia **(24 x 22)** km^2

- High denstiy of measurement points:
  - ⇒ ~ 0.6 measurement points per km^2 (**soil air ^{222}Rn concentrations**)
  - ⇒ ~ 2 points per km^2 (**^{238}U, ^{232}Th** a **^{40}K)** [ŠGÚDŠ, 2020]

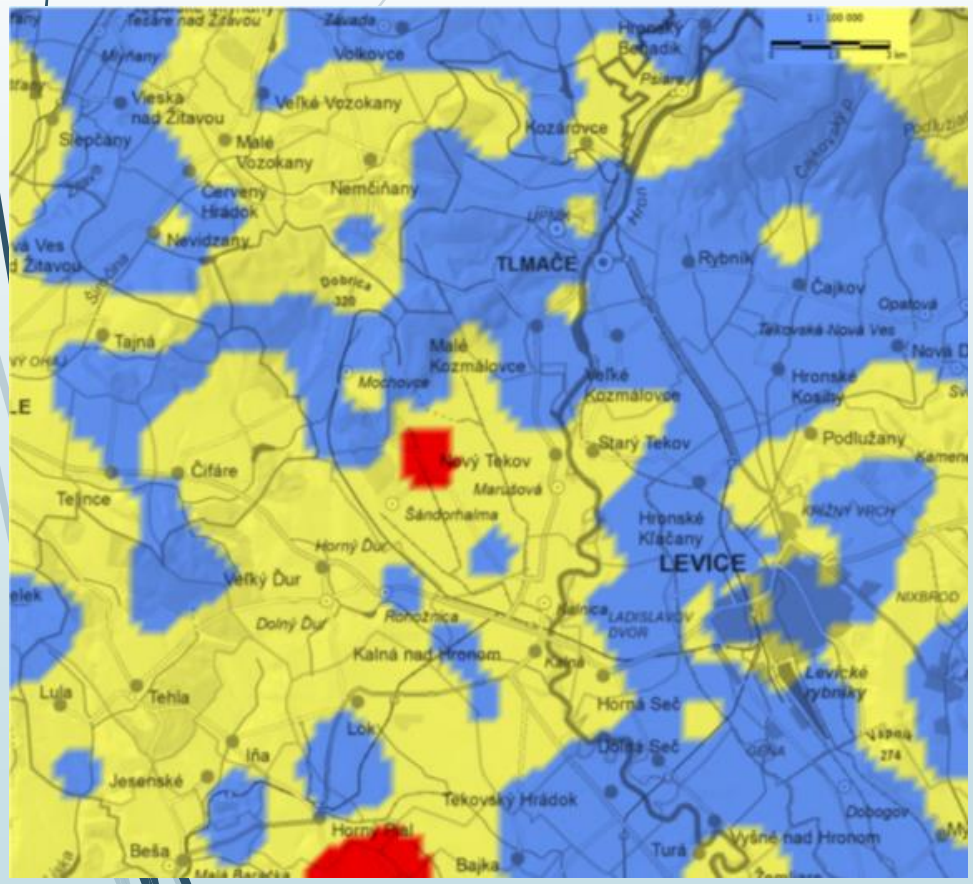
- Increased incidence of deaths due to lung cancer
  - ⇒ **not caused by Mochovce NPP!**

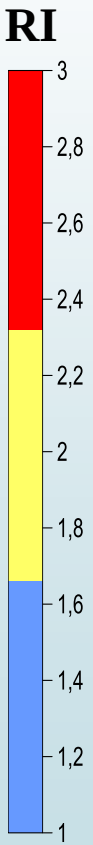
- E [mSv/year] to the population [Bulko et. al., 2014] ⇒
- **Radon potential distribution** → the form of map
  - → geostatical software ***Surfer 11*** **(*kriging*)**



I. Approach [Neznal et al., 2004]

- ***C_A [kBq/m³]*** – soil gas RAC (***0,8 m)***
- Permeability – using grain size analysis





Radon index (RI)	C_A [kBq/m³]		
Low (**1**)	$C_A < 30$	$C_A < 20$	$C_A < 10$
Medium (**2**)	$30 \leq C_A < 100$	$20 \leq C_A < 70$	$10 \leq C_A < 30$
High (**3**)	$C_A \geq 100$	$C_A \geq 70$	$C_A \geq 30$
Permeability	Low	Medium	High

Radon risk:

- High
- Medium
- Low

Fraction „f“	Permeability
f > 65%	Low
15% < f ≤ 65%	Medium
f ≤ 15%	High

Qualitative estimation of weight percentage of the **fine-grained** particle fraction **f** (< **63 µm)**

II. Approach [Neznal et al., 2004]

$$RP = \frac{C_A - 1}{-\log k - 10}$$

$C_A\,[kBq/m^3]$ – soil gas RAC (***0,8 m***)

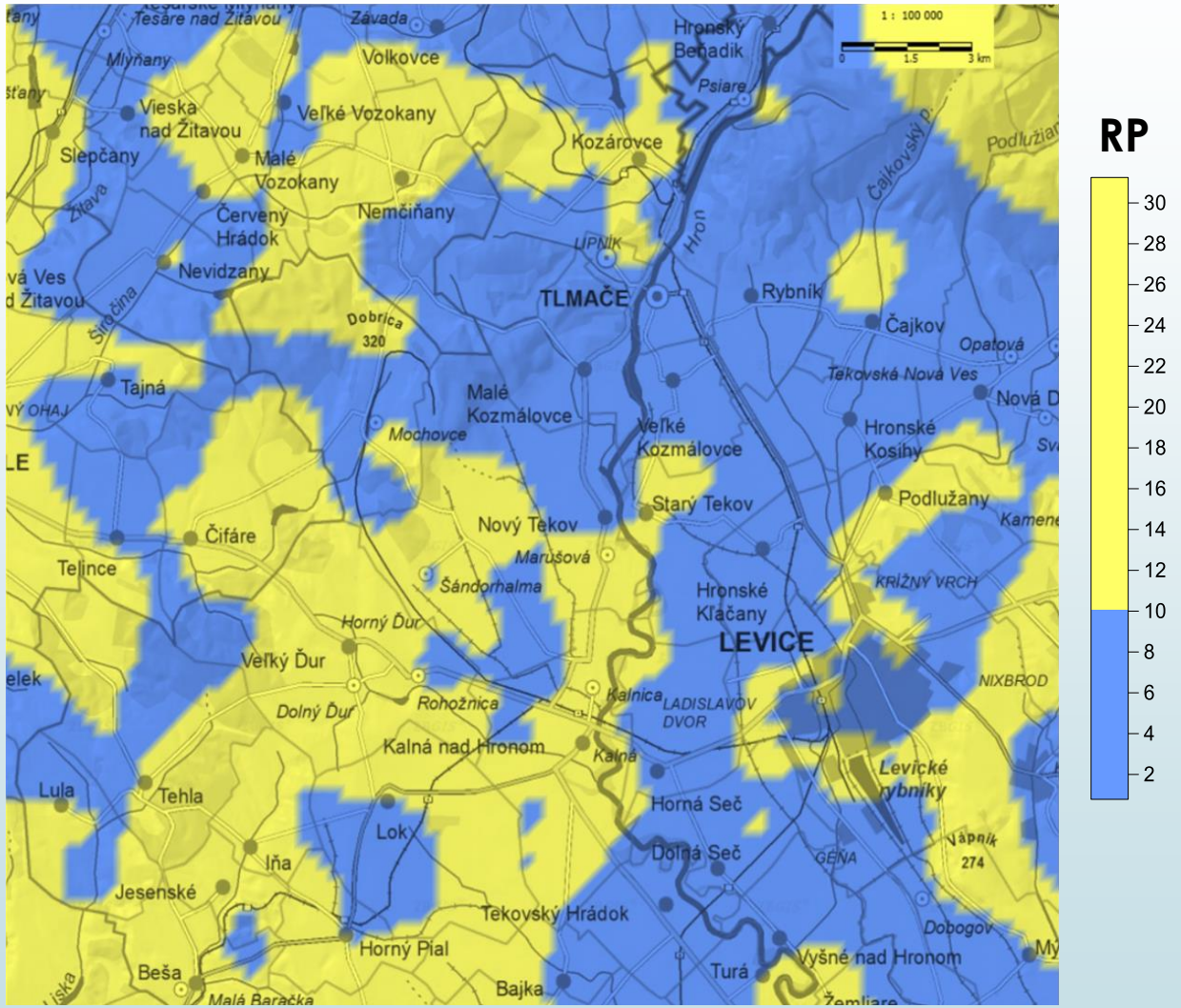
permeability $k\,[m^2]$ – **experiment**

Low (***k* = 5,2.10^{-14} m^2**)
Medium (***k* = 1.10^{-12} m^2**)
High (***k* = 4.10^{-11} m^2**)

[Neznal et. al., 2004]

[Nazaroff, Nero 1998]

RP	**Radon index (RI)**
RP < 10	*Low*
10 ≤ RP < 35	*Medium*
35 ≤ RP	*High*



III. Approach [Slunga, 1988]

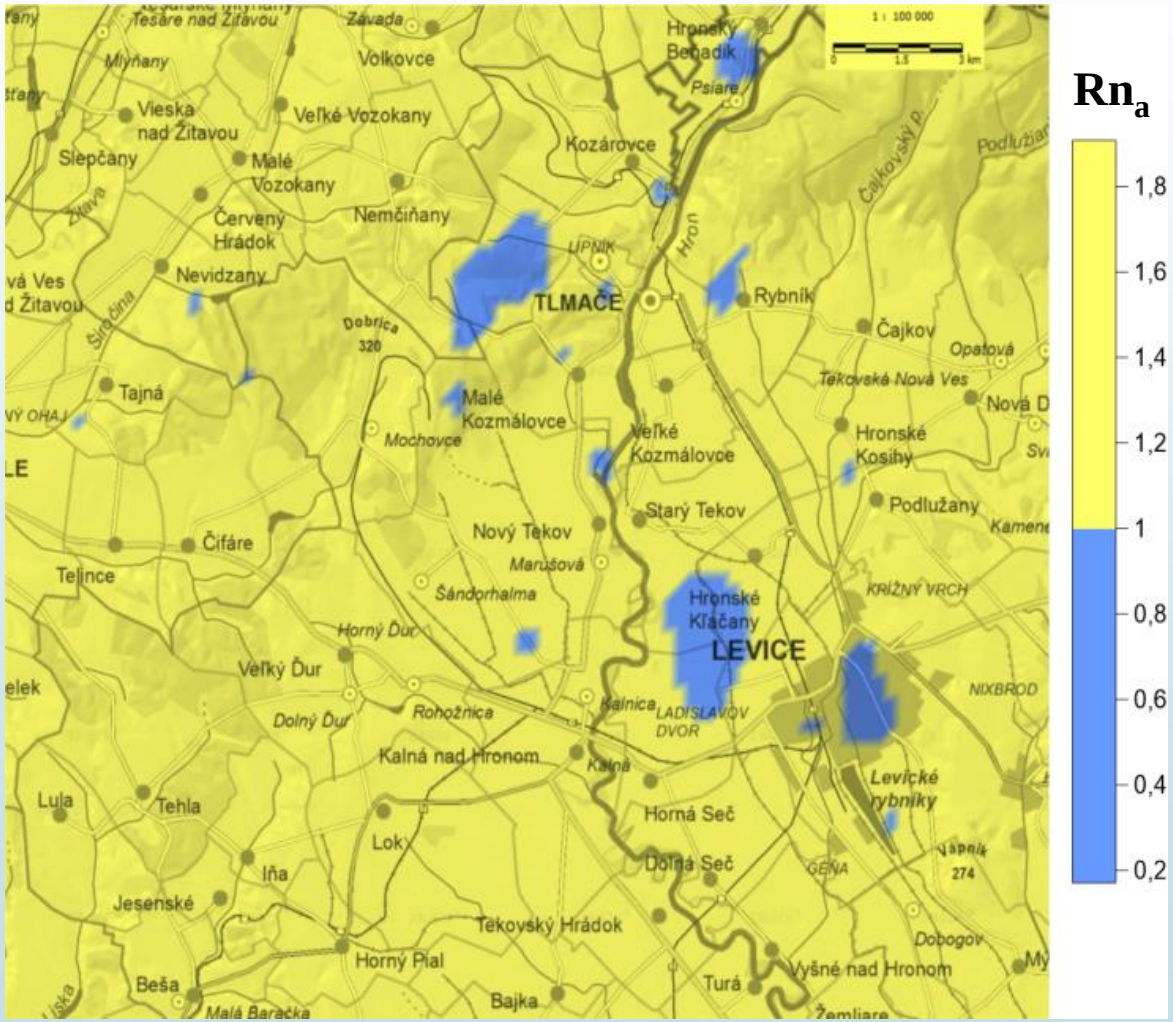
$$Rn_a = log_{10}(6C_{sb}k^{0,077}) - 3$$

k **[m^2]** – permeability

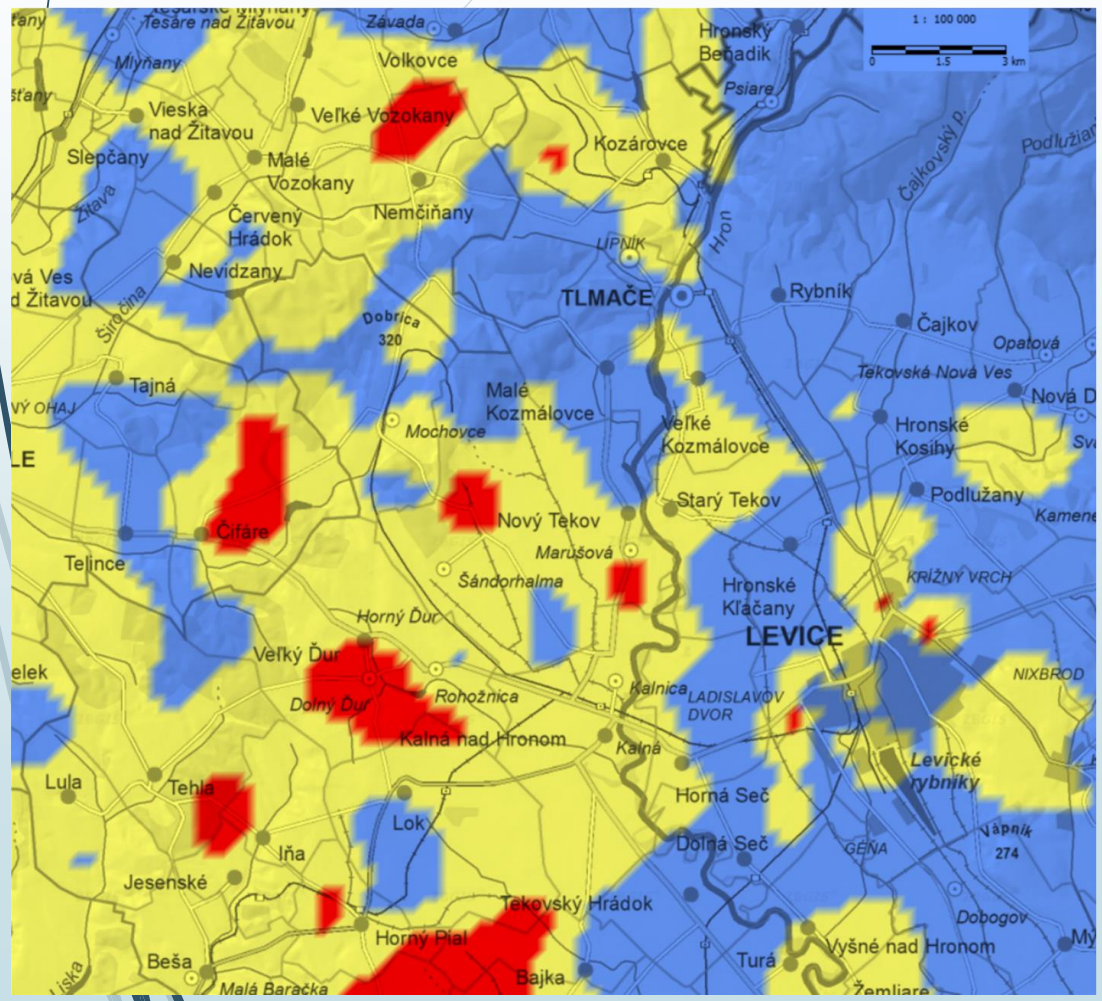
C_{sb} **– Saturated ^{222}Rn concentracion** in the soil air

$$C_{Sb} = C(z)/\left(1 - e^{-\frac{z}{L}}\right)$$

Rn_a	Radon risk category
$Rn_a < 1$	*Negligible*
$1 < Rn_a < 2$	*Low*
$2 < Rn_a < 3$	*High*
$3 < Rn_a$	*Very high*



IV. Approach [Tanner, 1988]



- ***RAN*** *(„radon availability number“)*

$$RAN = C_\infty M \leftarrow M = \varepsilon L$$

- Saturated RAC in the soil air:

$$C_\infty = C(z)/\left(1 - e^{-\frac{z}{L}}\right)$$

- ***M*** **– mean migration distance**

Radon risk category:

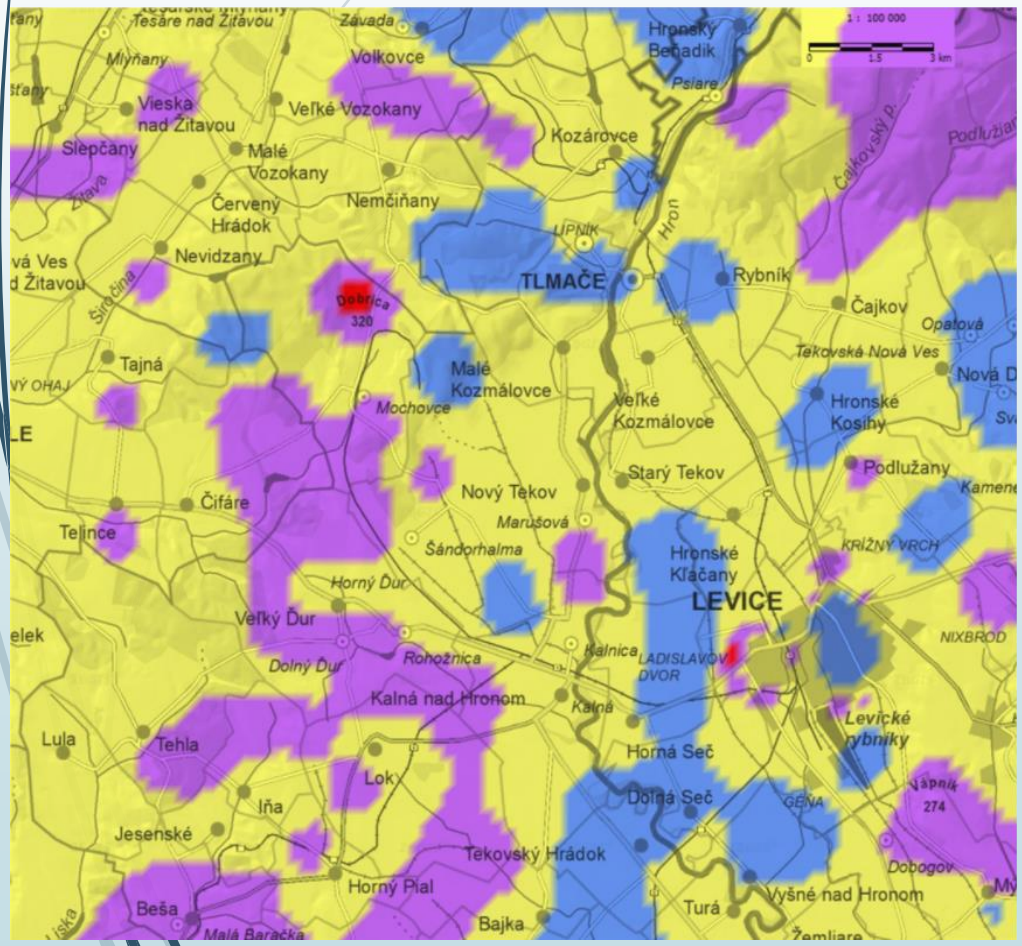
Low *– RAN < 20 kBq/m²*

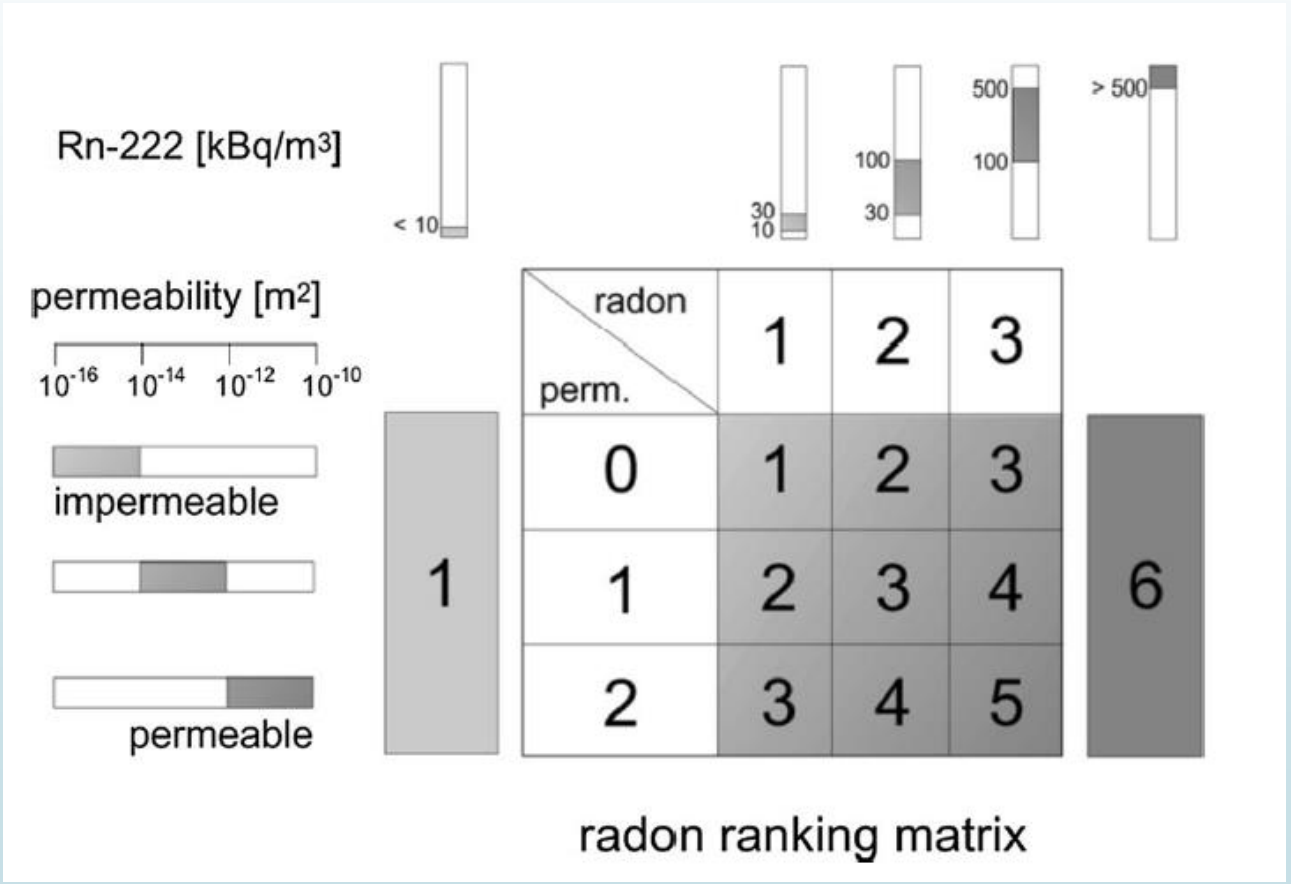
Medium *– 20 kBq/m² ≤ RAN < 45 kBq/m²*

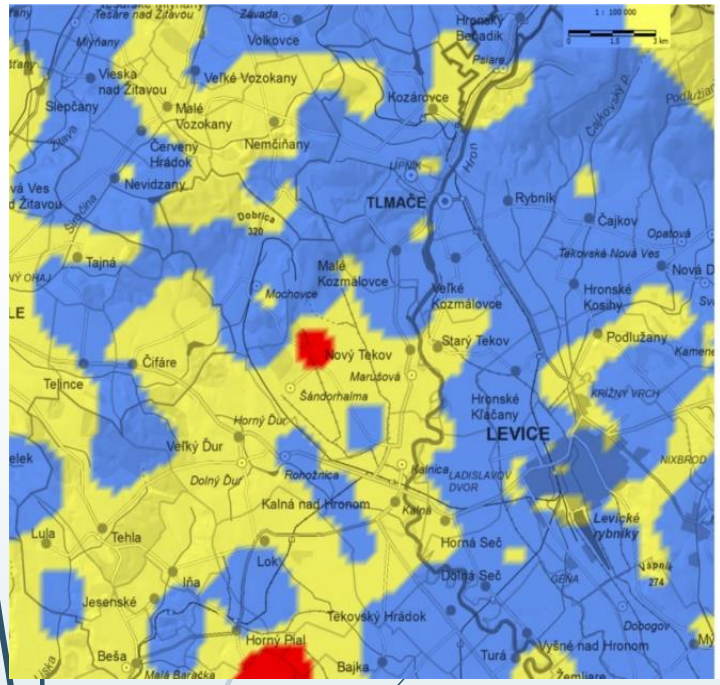
High *– RAN ≥ 45 kBq/m²*

V. Approach [Kemski a kol., 2001]

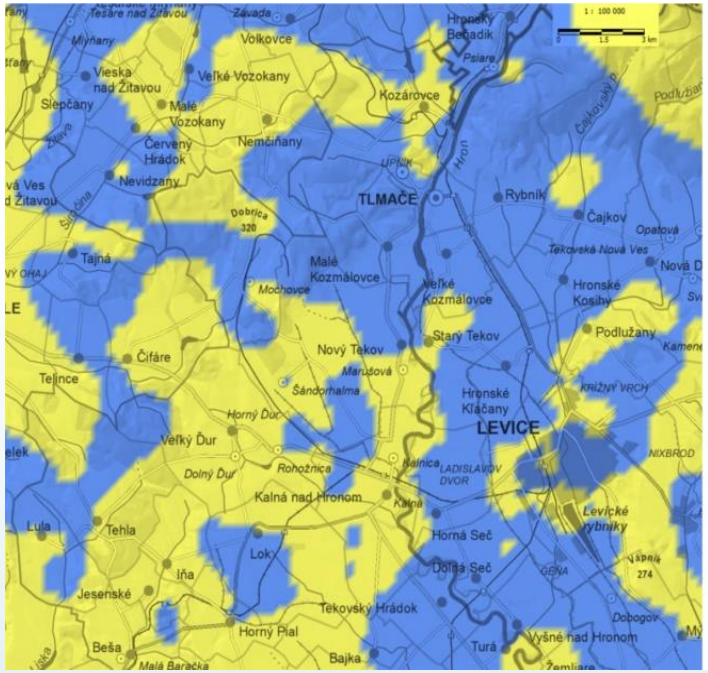
RAC [Bq/m^3] – the **maximum measured RAC** in soil gas at each measuring site
Permeability of the soil







A



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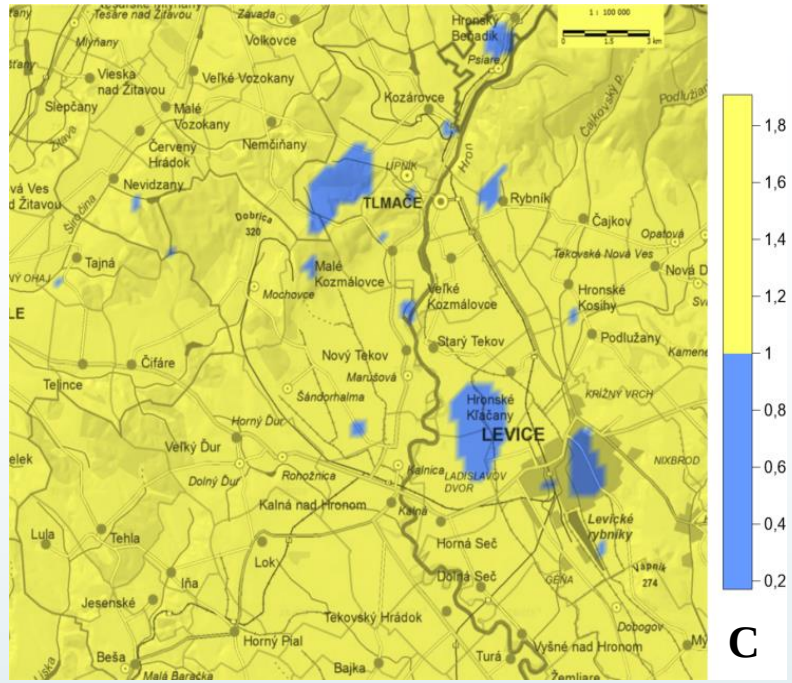

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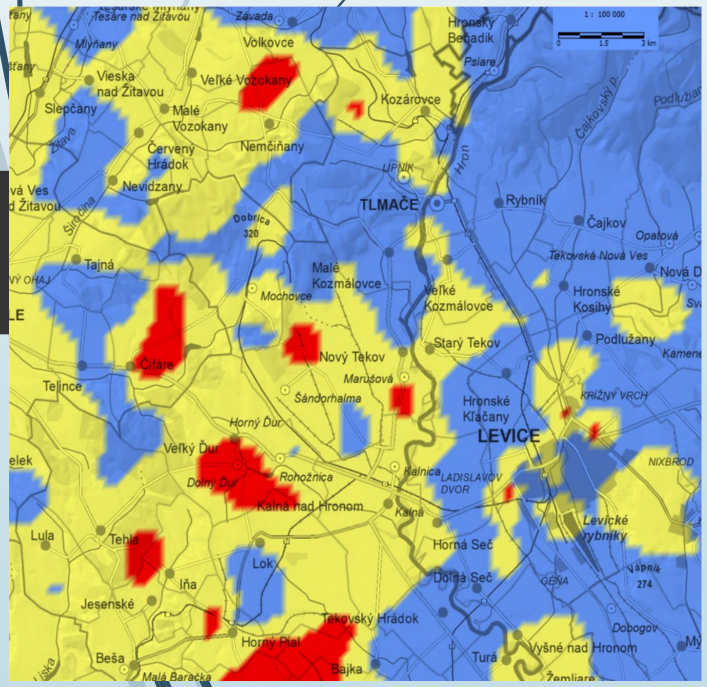

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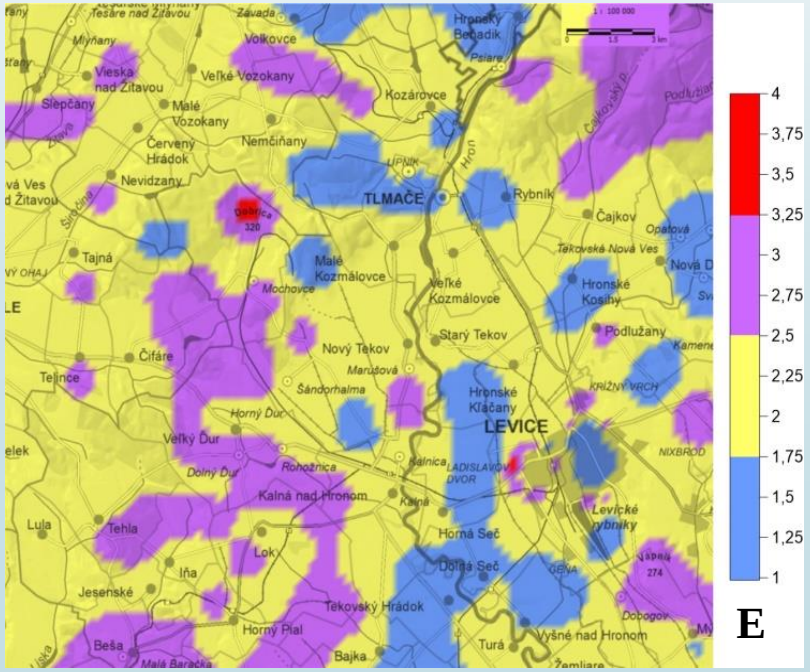


E

A) I. Approach [Neznal et al., 2004]

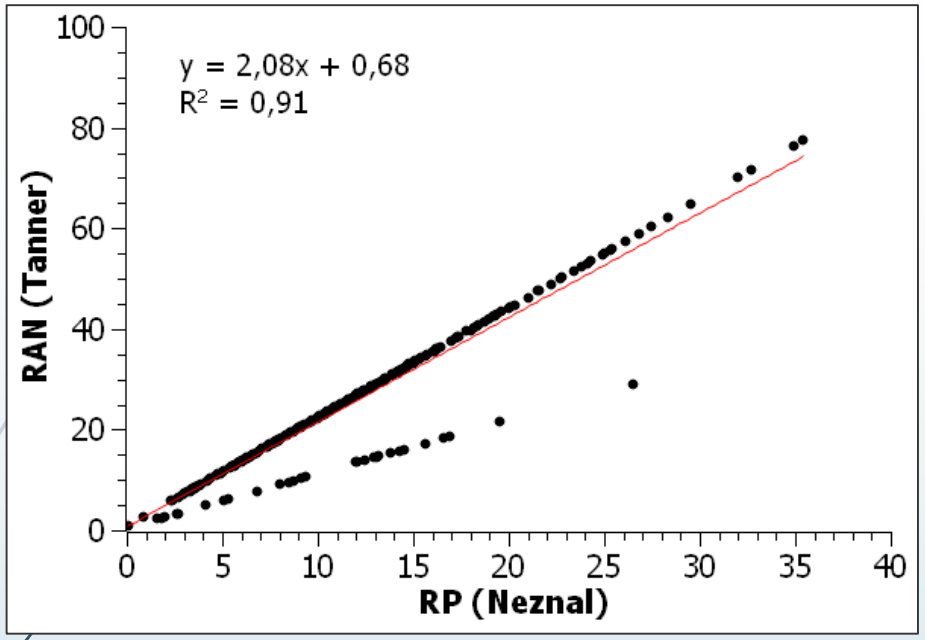
B) II. Approach [Neznal et al., 2004]

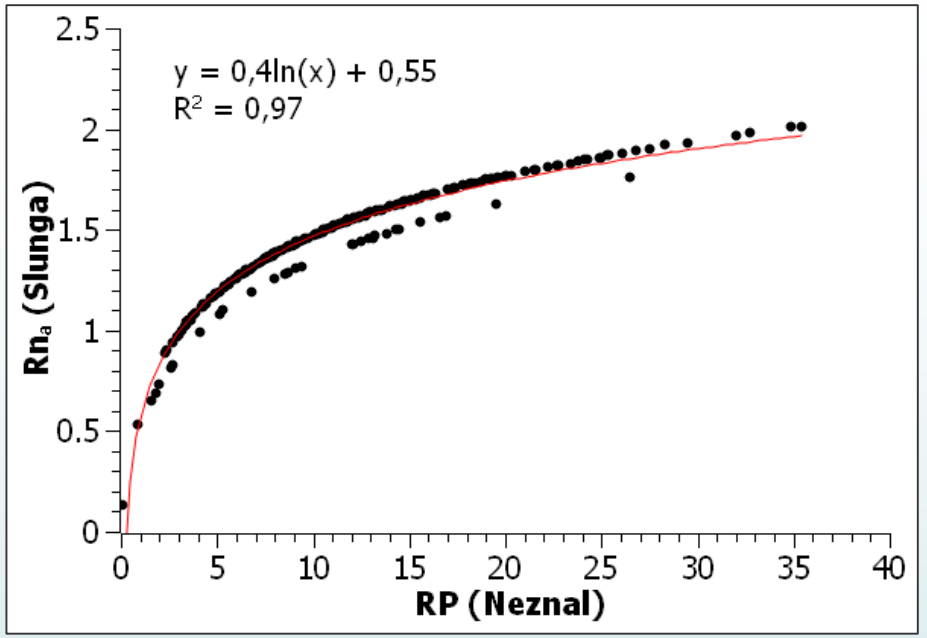
C) III. Approach [Slunga, 1988]

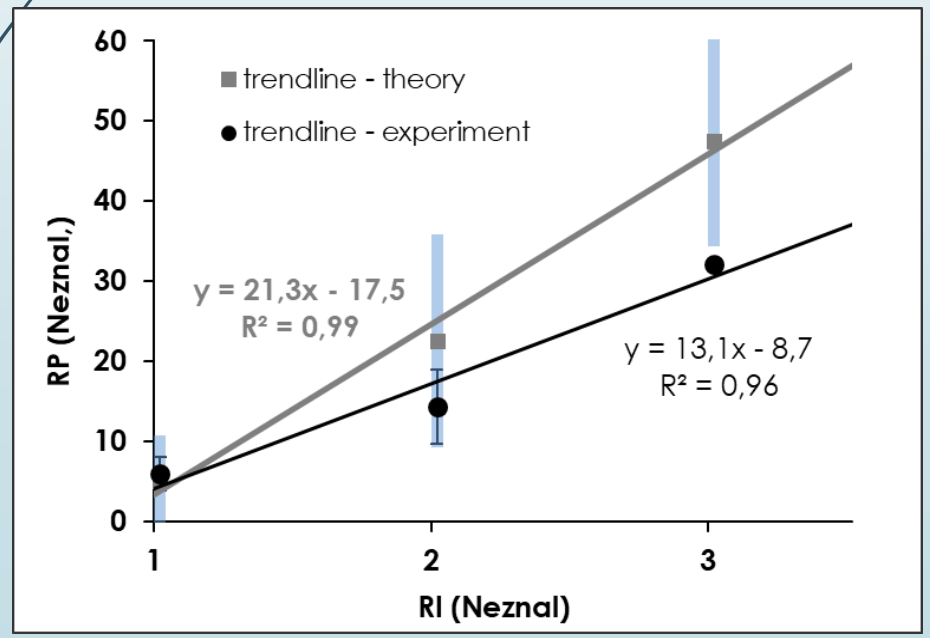
D) IV. Approach [Tanner, 1988]

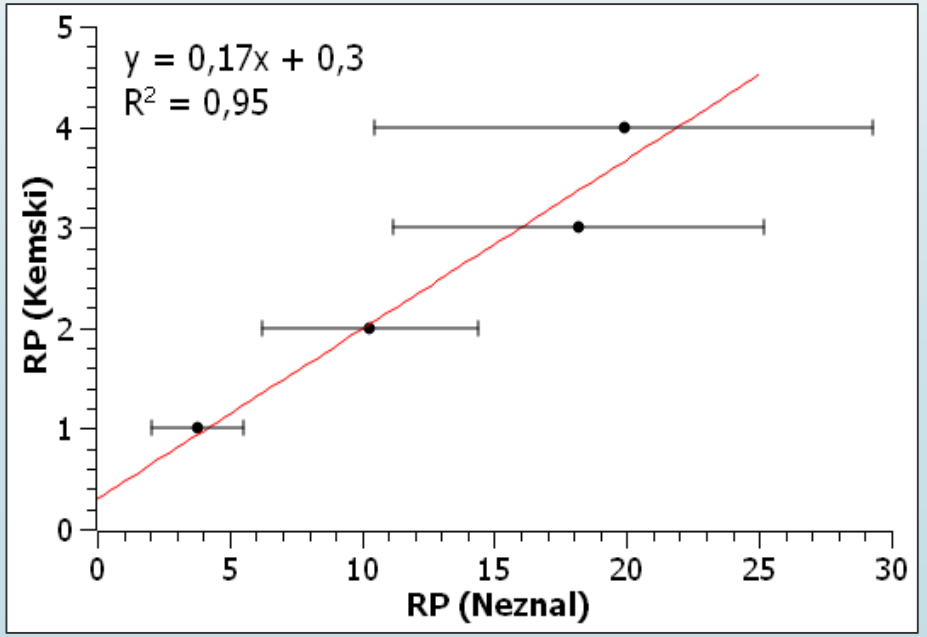
E) V. Approach [Kemski et al., 2001]

Relationships between RP values





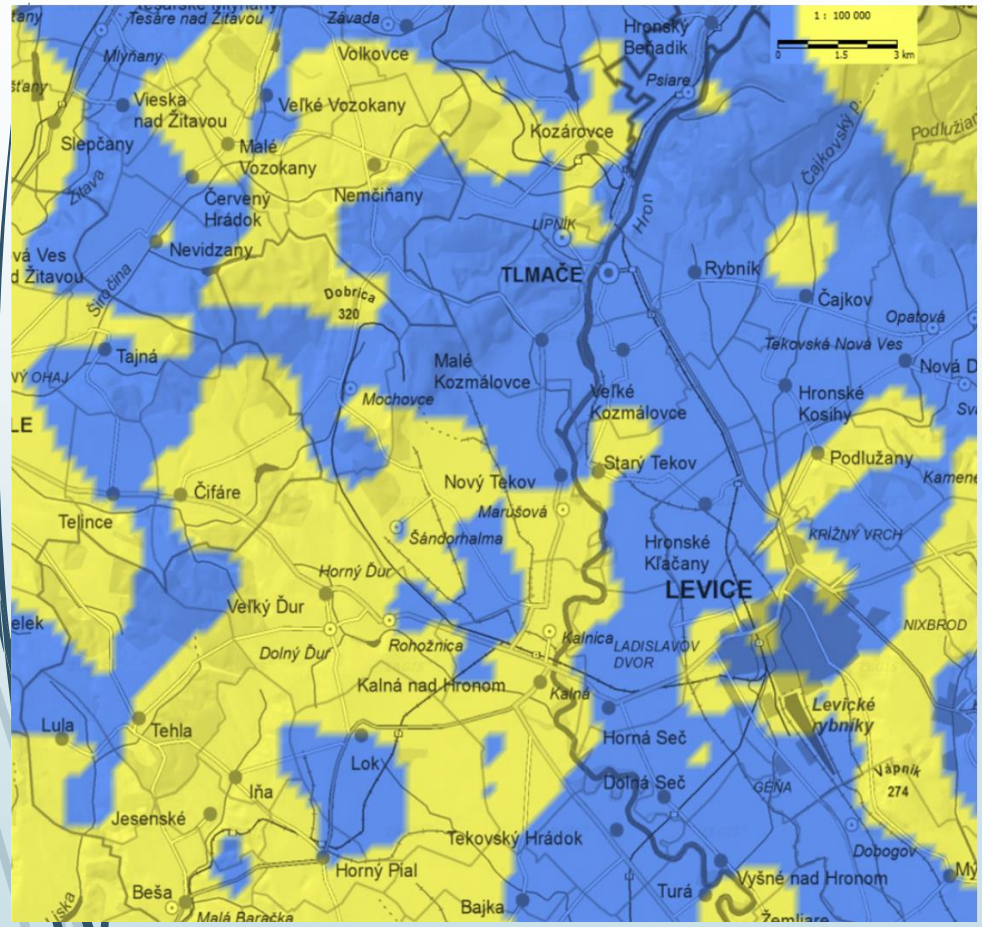


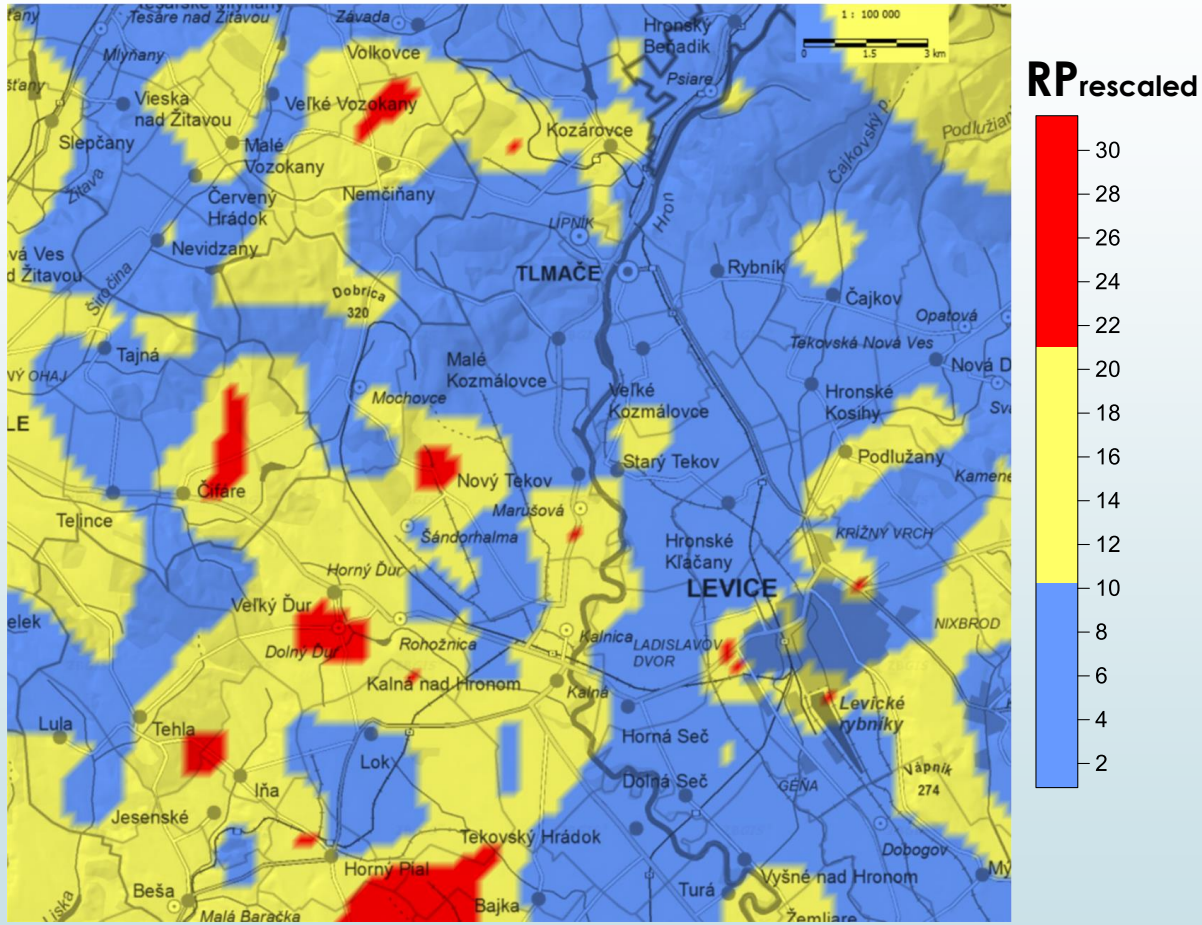


Recsaling the RP scale

II. Approach [Neznal et al., 2004]

$$RP = \frac{C_A - 1}{-\log k - 10}$$





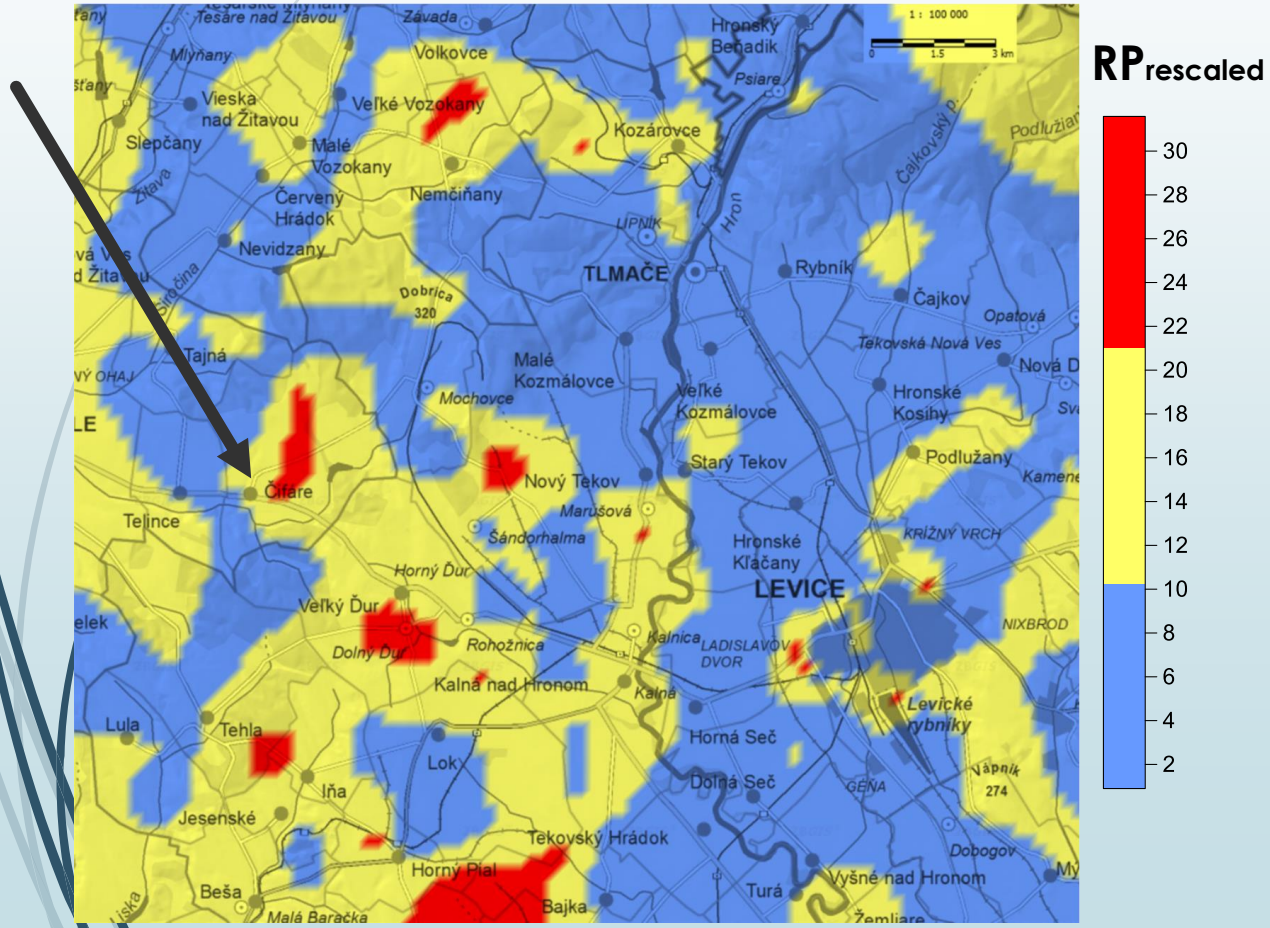
- $35 \leq RP$
- $10 \leq RP < 35$
- $RP < 10$

- $21 \leq RP$
- $10 \leq RP < 21$
- $RP < 10$

Experimental verification of the RP prediction

Čifáre

- Indoor RAC interval ⟶ ***130 – 900 Bq/m³***, (average ***368 ± 180 Bq/m³***) [Moravcsík, 2015]
- **56 % cases** with indoor RAC above the reference level ***300 Bq/m³***



Neznal RP approach[Neznal a kol., 2004]

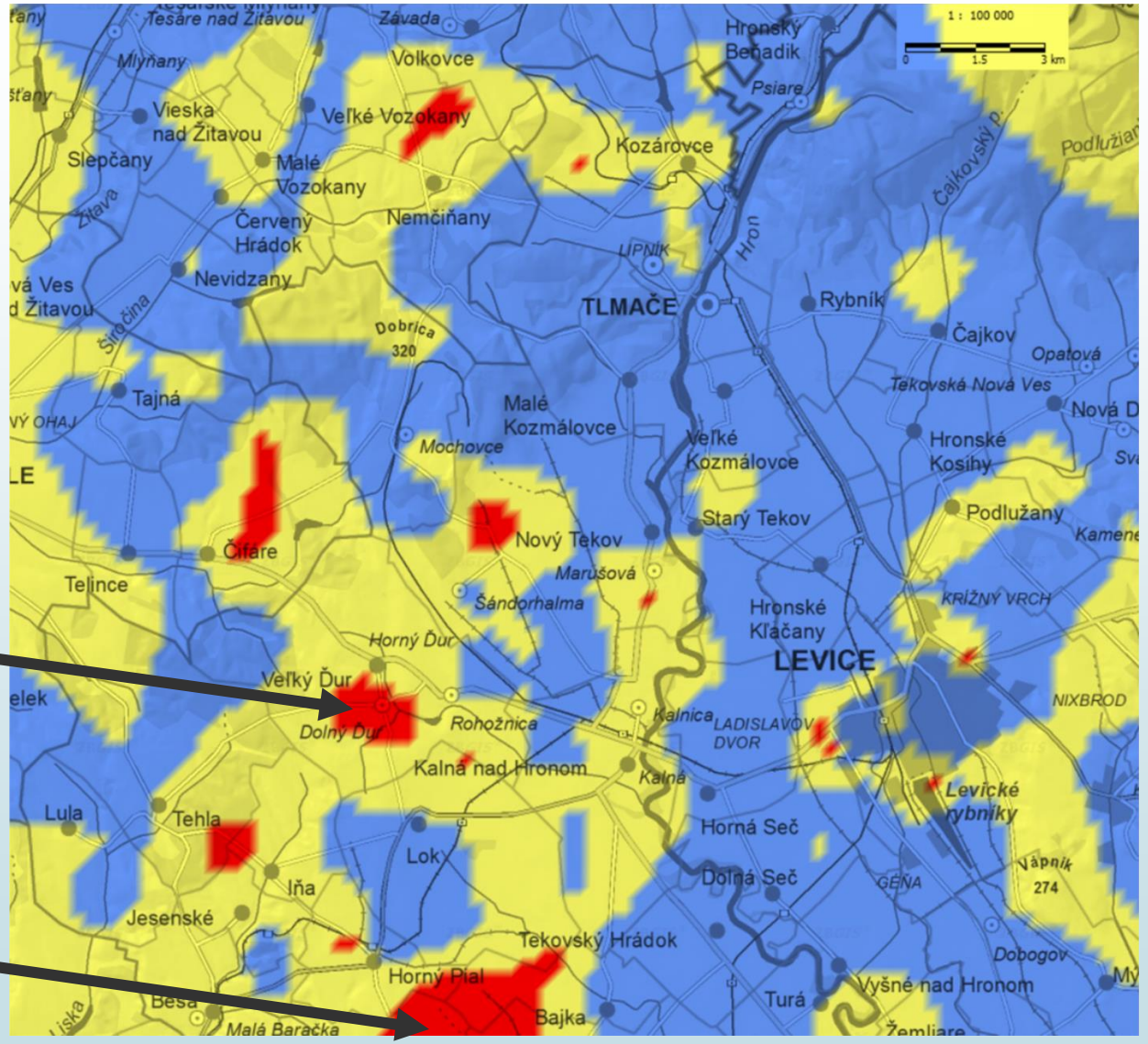
$$RP = \frac{C_A - 1}{-\log k - 10}$$

- $21 \leq RP$
- $10 \leq RP < 21$
- $RP < 10$

After rescaling the RP map ⟶ other municipalities located in the areas with **high RP prediction**

Veľký Ďur

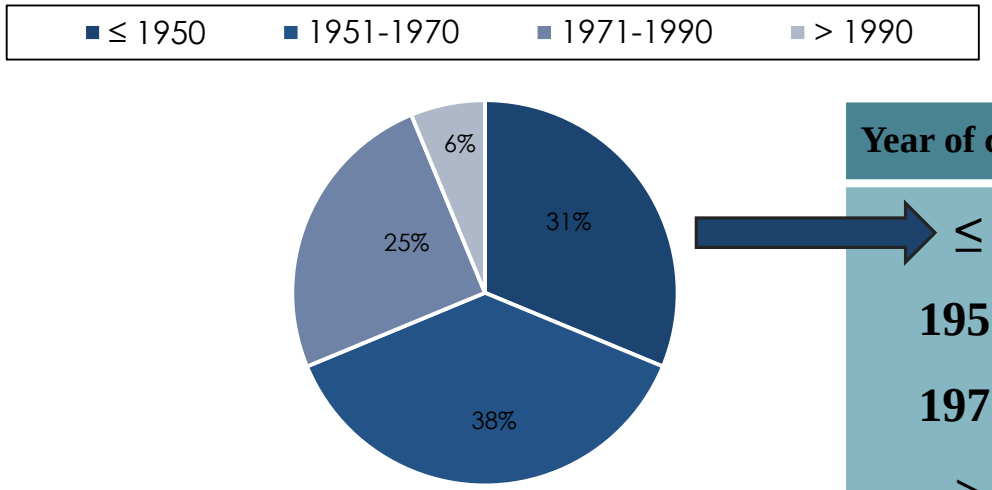
Dolný Pial



The results of indoor radon measurement during winter season

Locality	Veľký Ďur		Dolný Pial	
	all houses	contact with subsoil	all houses	contact with subsoil
Number of rooms	24	16	40	32
Average RAC [Bq/m³]	314 ± 184	401 ± 160	355 ± 275	365 ± 269
Median	275	398	273	278
MAX	720	**720**	1040	**1040**
MIN	105	150	80	80
above **300 Bq/m³**	46 %	**68 %**	35%	**34 %**
75. percentile - RAC [Bq/m³]	418	485	417	387
Average RAC [Bq/m³] - 4. quartile	563 ± 104	622 ± 66	730 ± 235	756 ± 254

Percentage of houses by year of their construction



Year of construction	Percentage of houses	Percentage of houses with RAC above RL
≤ 1950	**31 %**	**90 %**
1951-1970	38 %	58 %
1971-1990	25 %	13 %
> 1990	6 %	0 %

Relationship between RP and indoor RAC measured in winter season

- **Indoor RAC** [Bq/m^3] – experimentally measured
- C_A [kBq/m^3], k [m^2] **(**map server of the **ŠGÚDŠ)** ⟹ **RP**

$$RP = \frac{C_A - 1}{-\log k - 10}$$

Municipalities:

Ružomberok

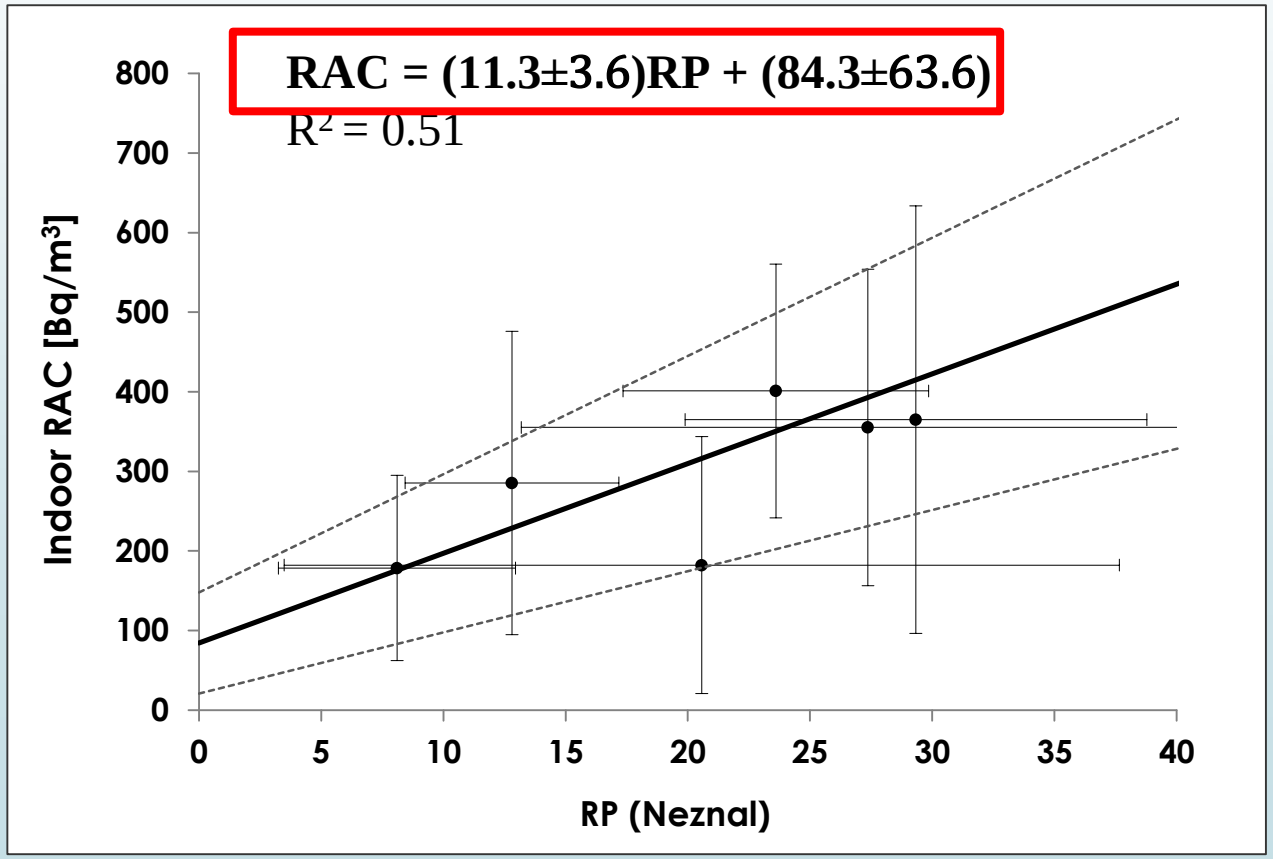
Záhorská Bystrica

Nevidzany

Veľký Ďur

Čifáre

Dolný Pial



RP

⇩

RAC [Bq/m^3]

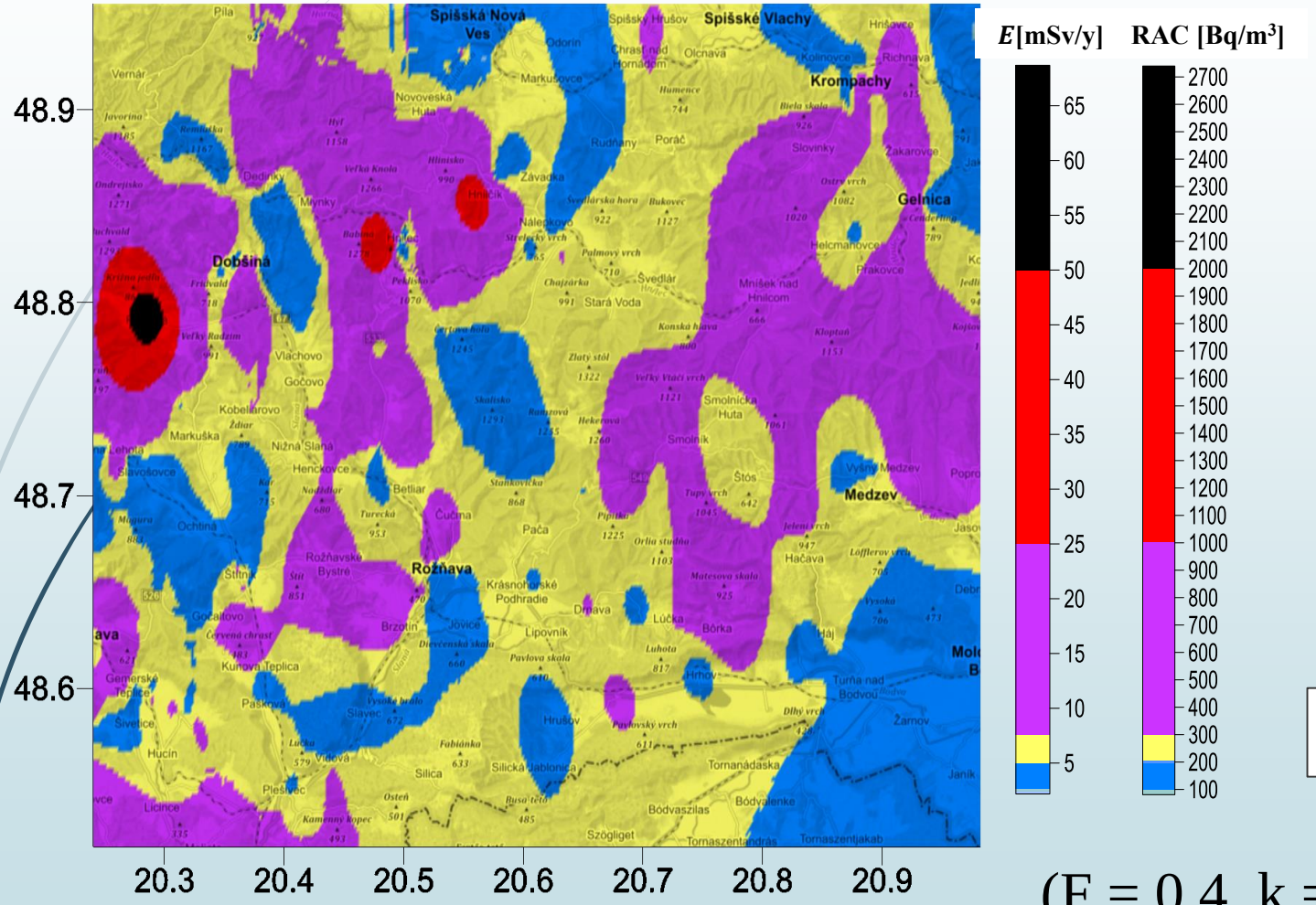
⇩

E [mSv/y]

$$E[\text{mSv/y}] = \boldsymbol{RAC} \,.\, F \,.\, k \,.\, T$$

Conservative estimate of the effective dose to the population from ^{222}Rn

Rožňava and surroundings



OAR = (11.3±3.6)RP + (84.3±63.6)

RP

⇩

RAC [Bq/m³]

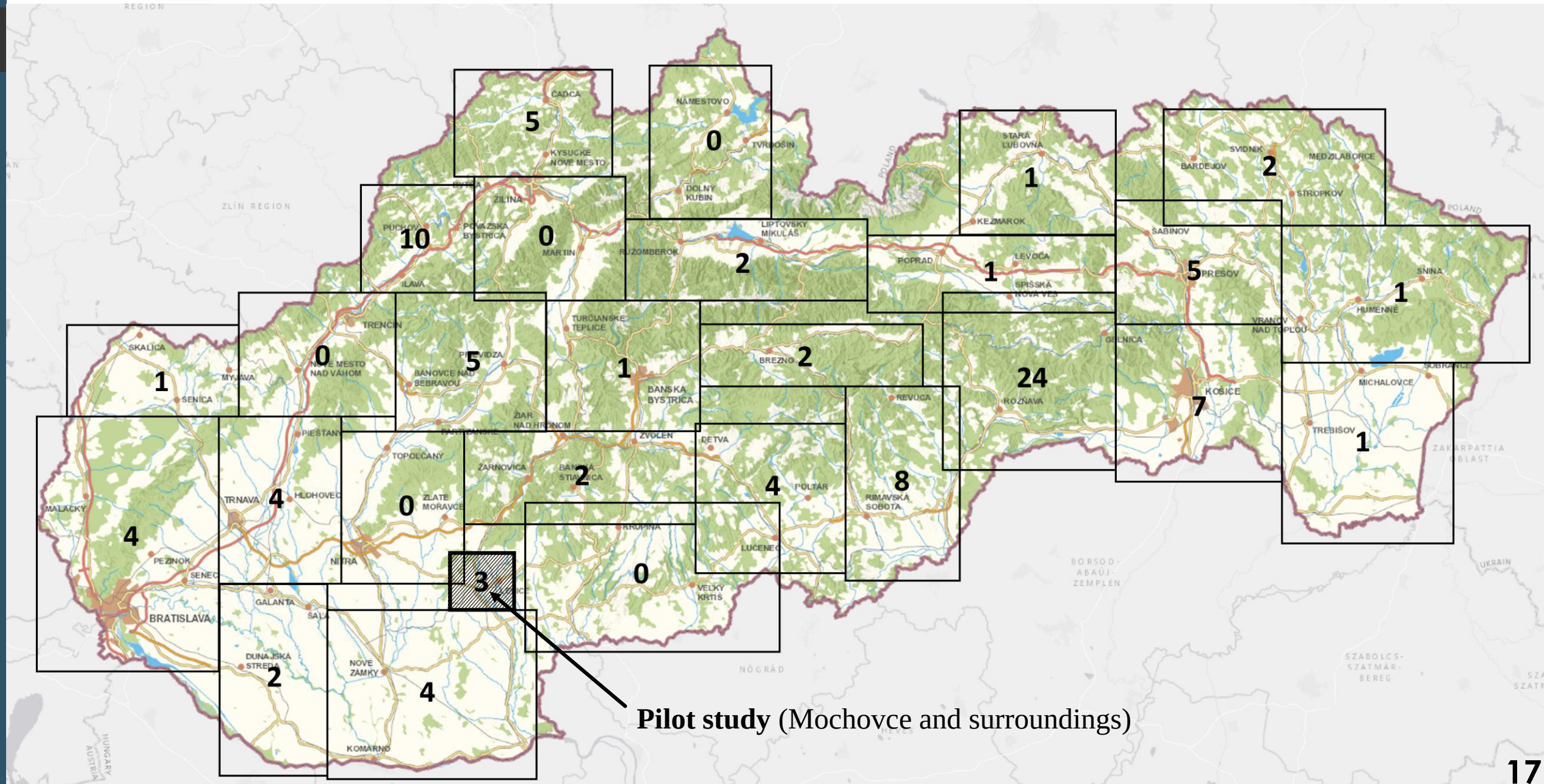
⇩

E [mSv/y]

$$E[\text{mSv/y}] = OAR \,.F\,.k\,.T$$

(F = 0.4, k = 9 nSv (Bq h m^{-3})$^{-1}$, T = 7000h) [UNSCEAR, 2000]

28 areas ⟶ **RP maps, RPAs predictions** (indoor RAC above 300 Bq/m^3)

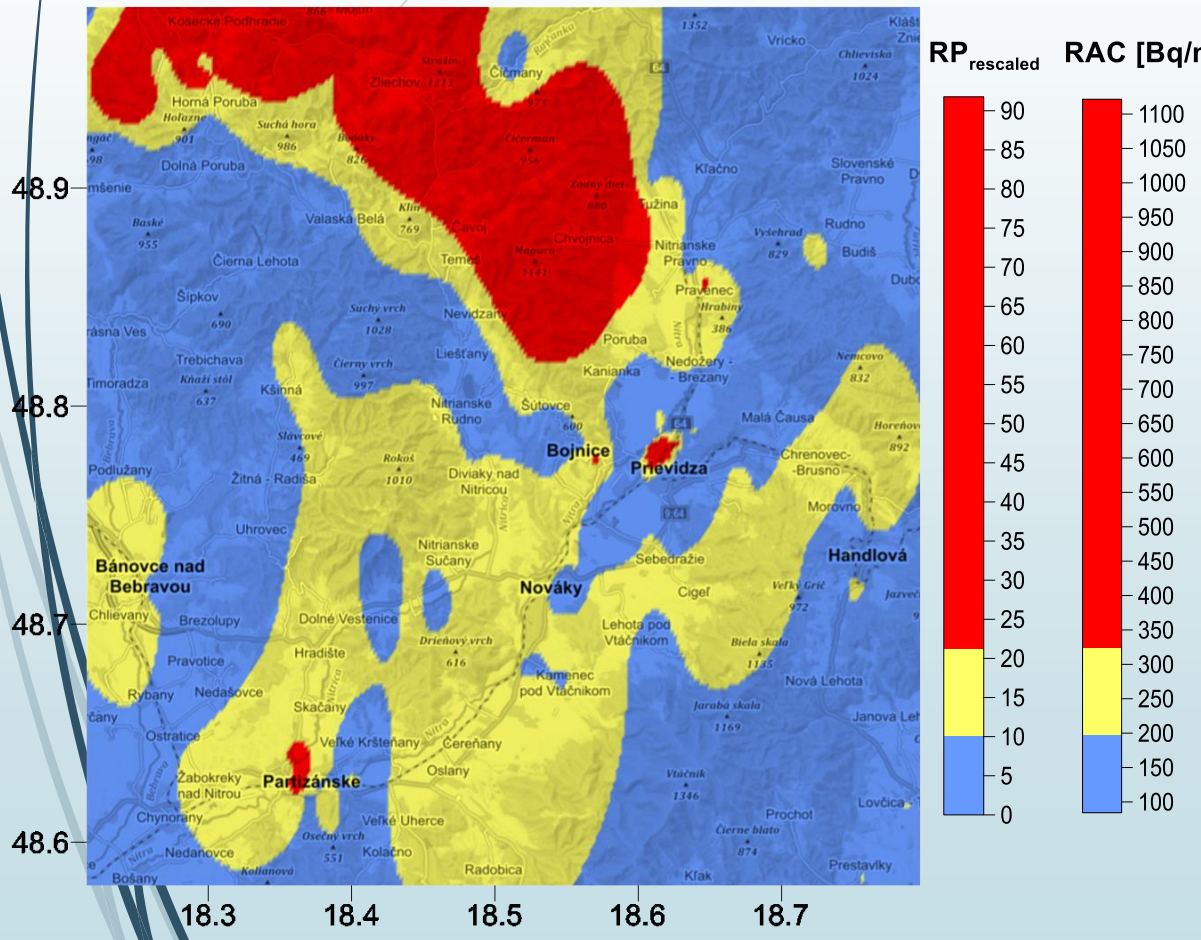


Pilot study (Mochovce and surroundings)

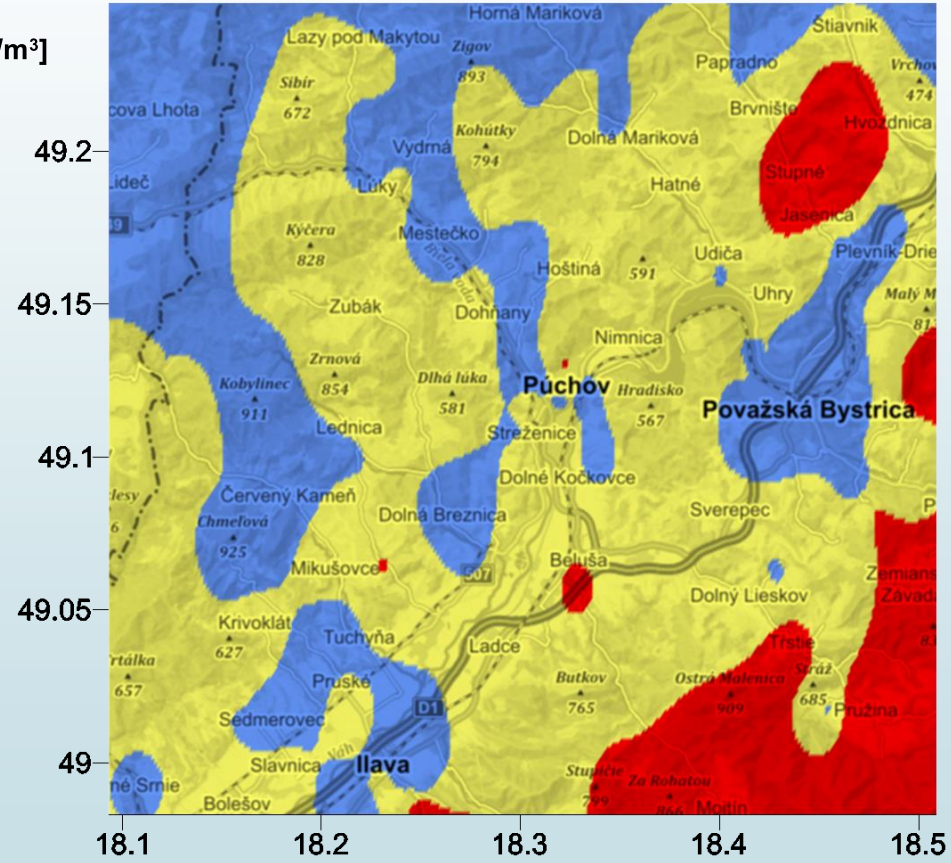
Rescaled RP maps and indoor RAC predicon for other regions of the SR - selection

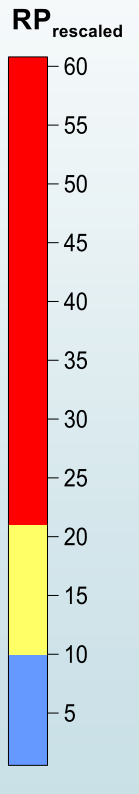
Western Slovakia

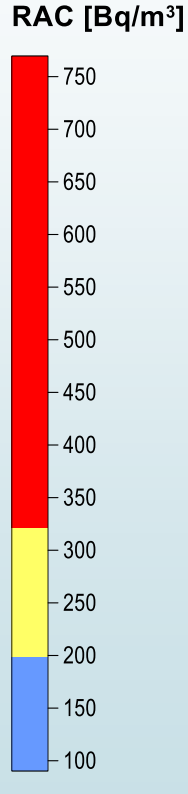
Prievidza, Bánovce nad Bebravou and surroundings



Púchov, Považská Bystrica and surroundings

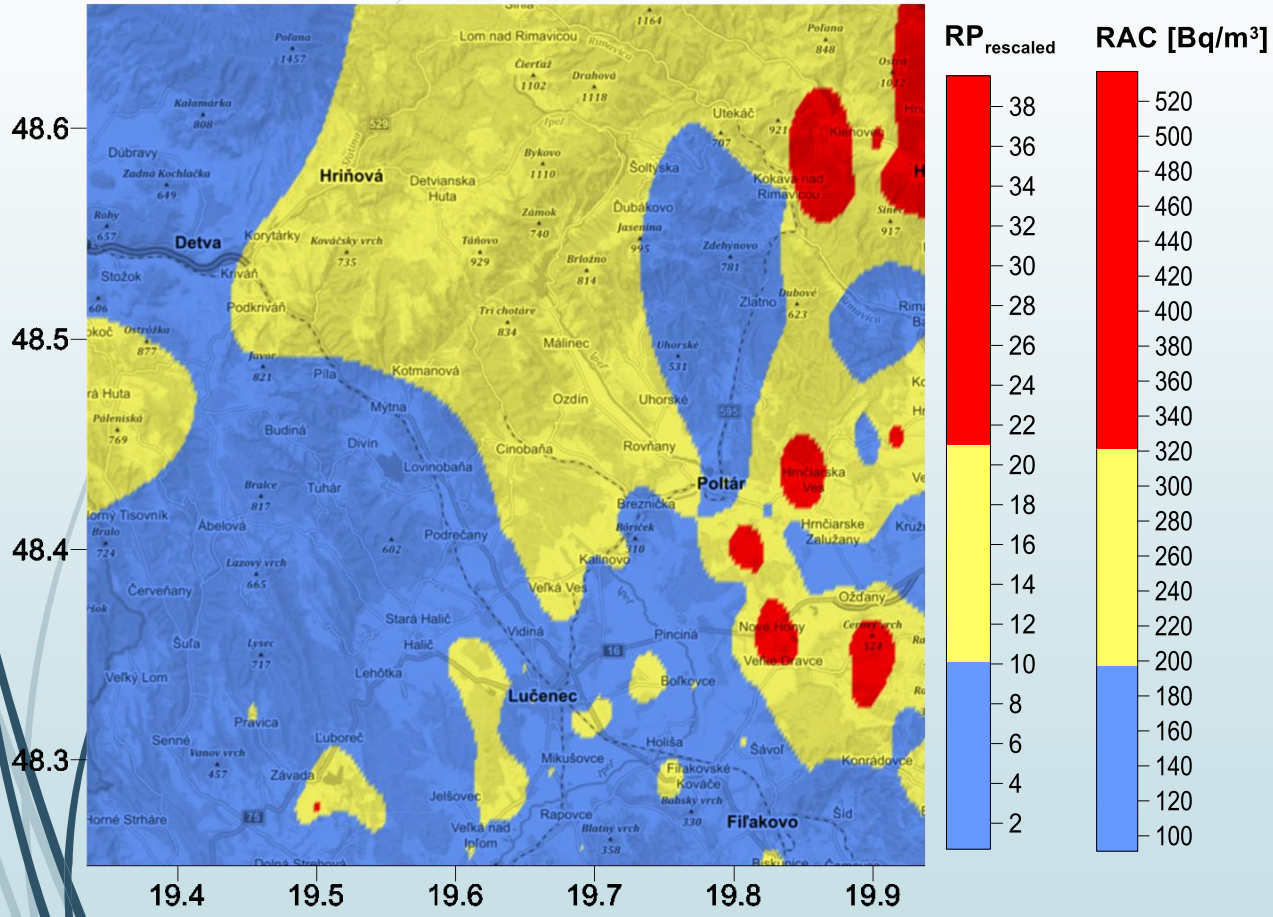




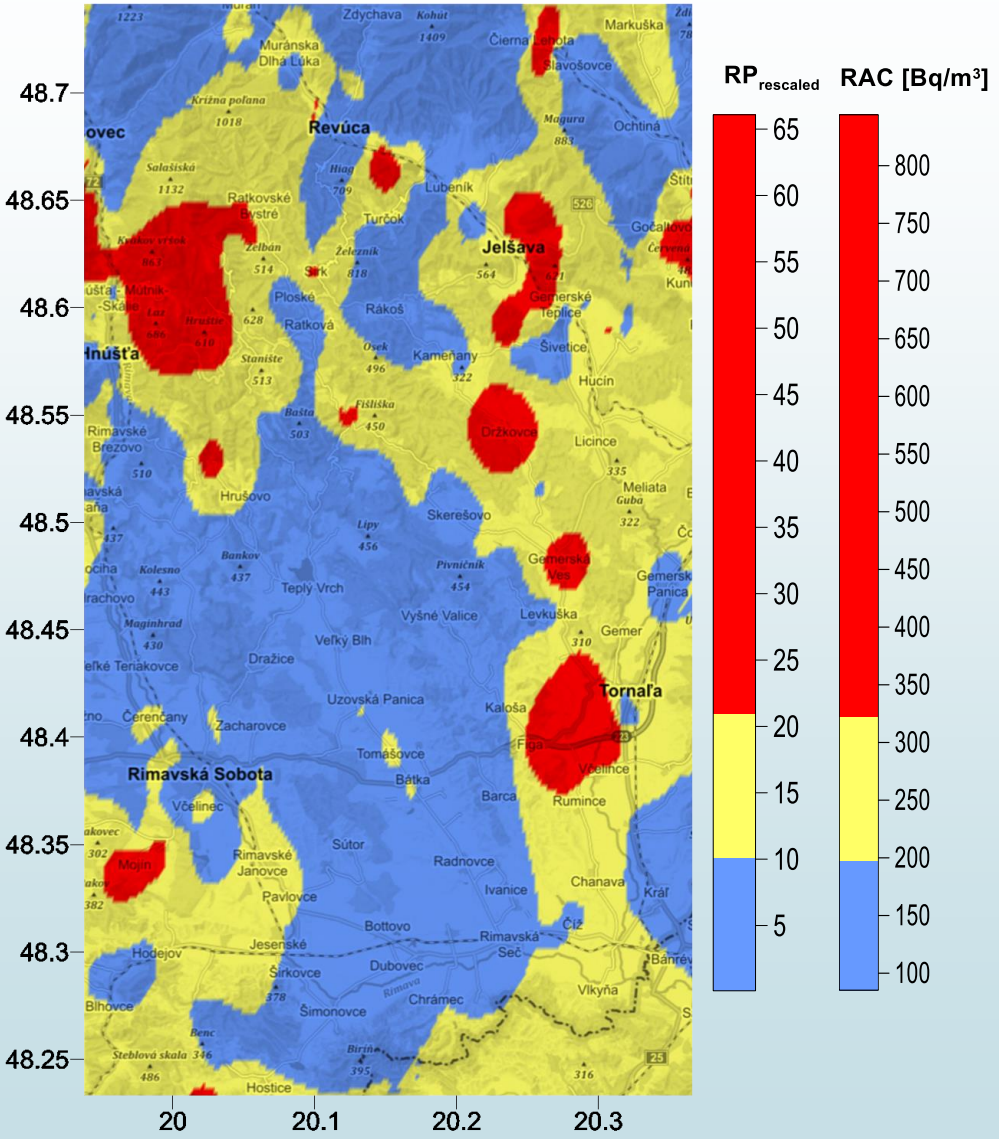


Central Slovakia

Detva, Lučenec and surroundings

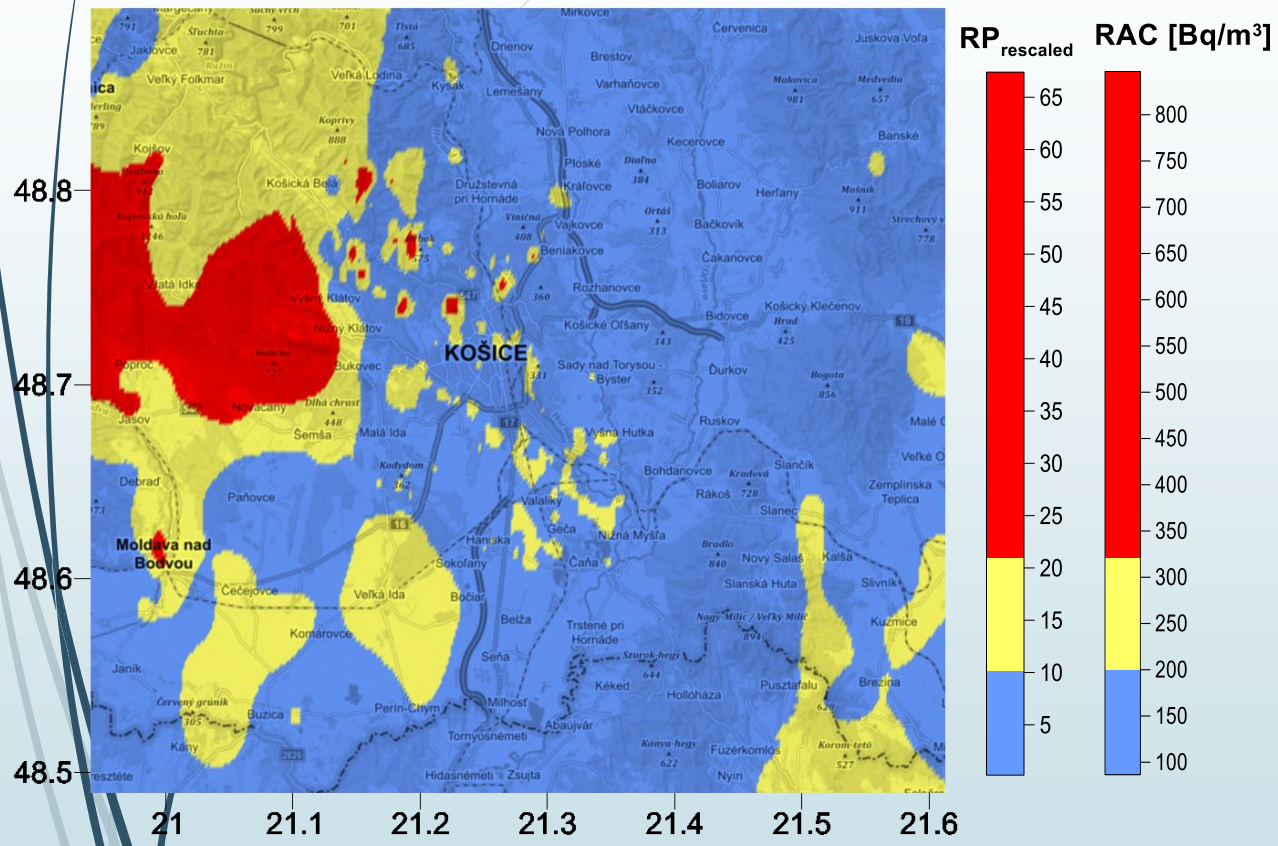


Rimavská Sobota, Revúca and surroundings

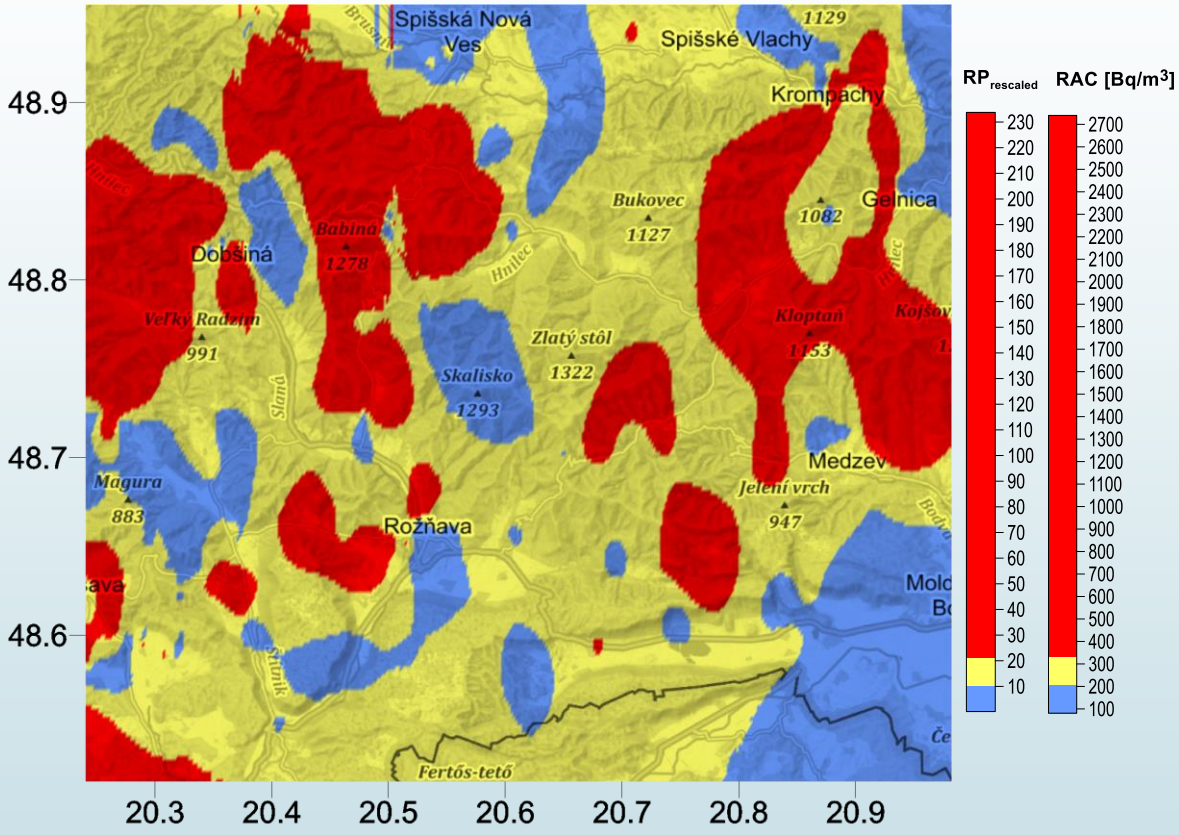


Eastern Slovakia

Košice and surroundings



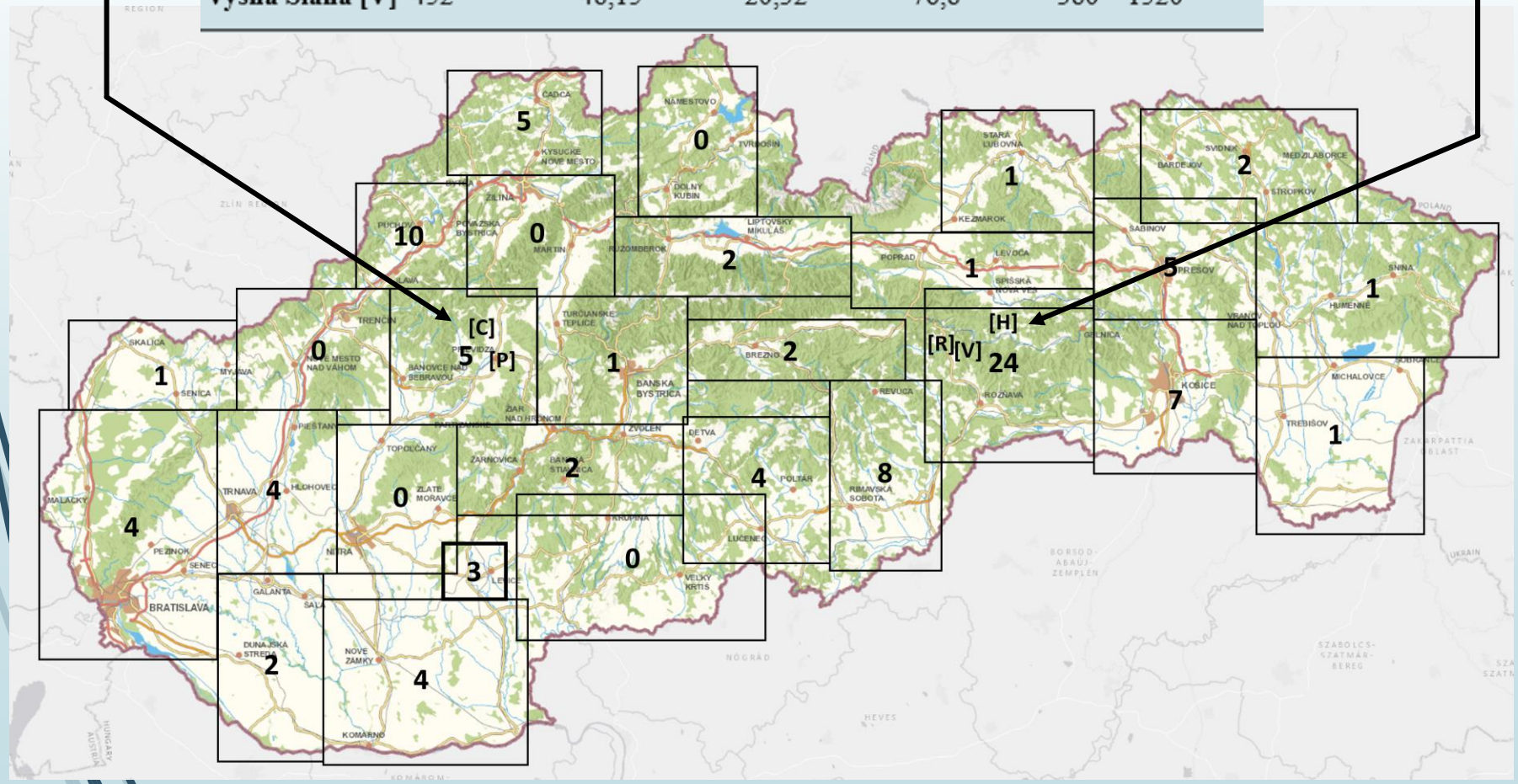
Rožňava and surroundings



The Rožňava region is known for its **ore and mineralogical uranium deposits.**

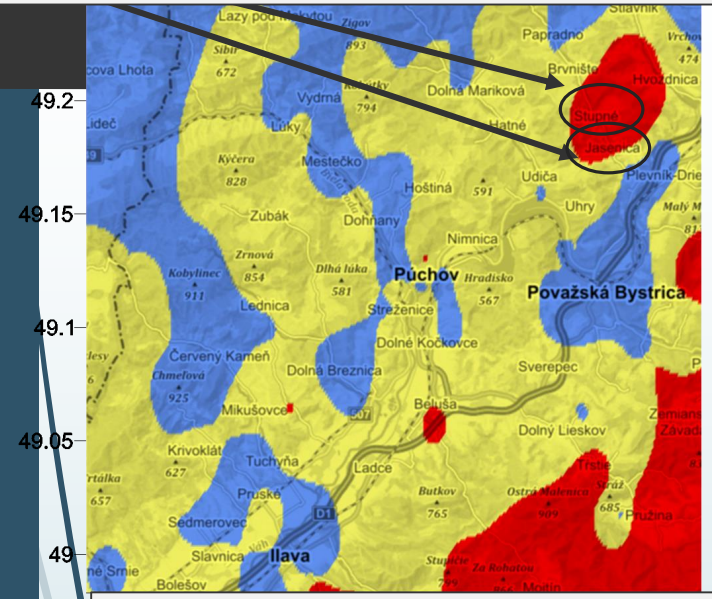
99 municipalities of the SR with predicted **indoor RAC above RL, 5 municipalities** with RAC **above 1000 Bq/m^3**

Municipality	Number of inhabit.	Latitude [°]	Longitude [°]	Average RP	Range of RAC [Bq/m^3]
Hnilčík [H]	522	48,87	20,56	73	310 – 1510
Chvojnica [C]	1614	48,88	18,56	67	660 – 1020
Prievidza [P]	45 141	48,77	18,62	53,5	300 – 1080
Rejdová [R]	765	48,79	20,28	176,5	1440 – 2720
Vyšná Slaná [V]	452	48,15	20,32	76,8	380 – 1520

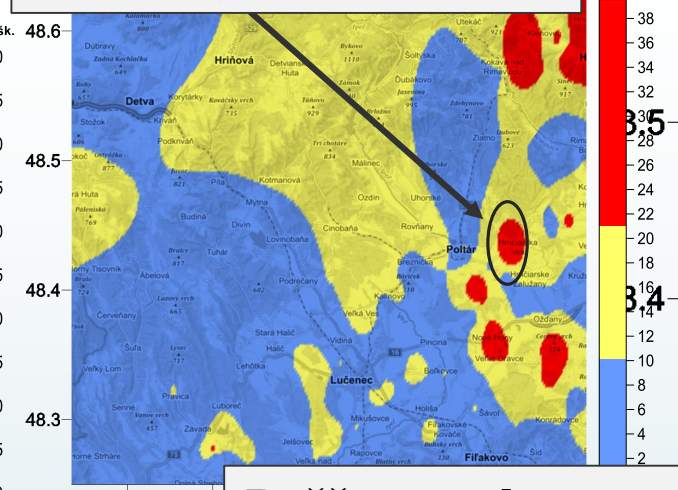


Integral measurements of indoor RAC in contact with subsoil – 12 localities

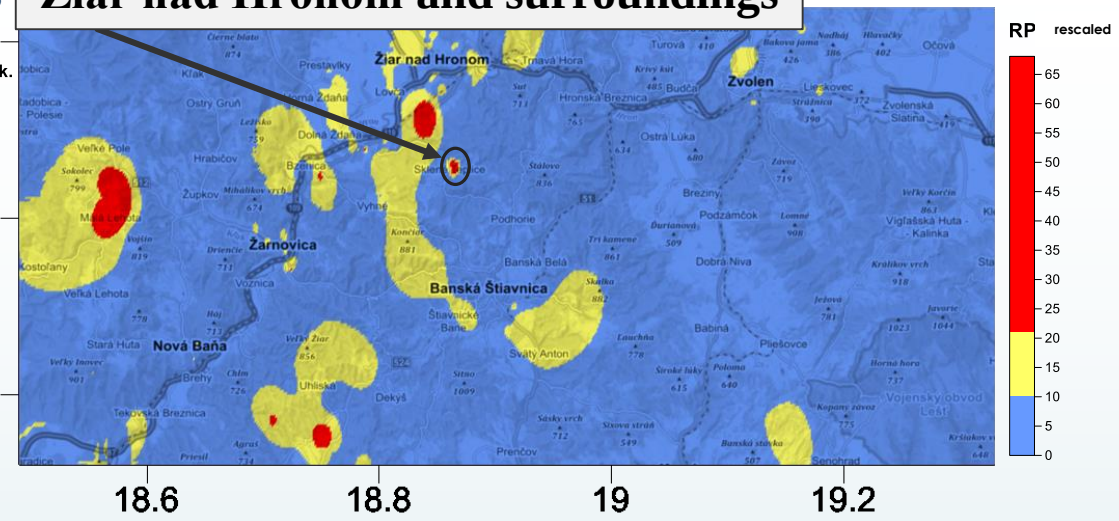
Púchov, Považská Bystrica and sur.



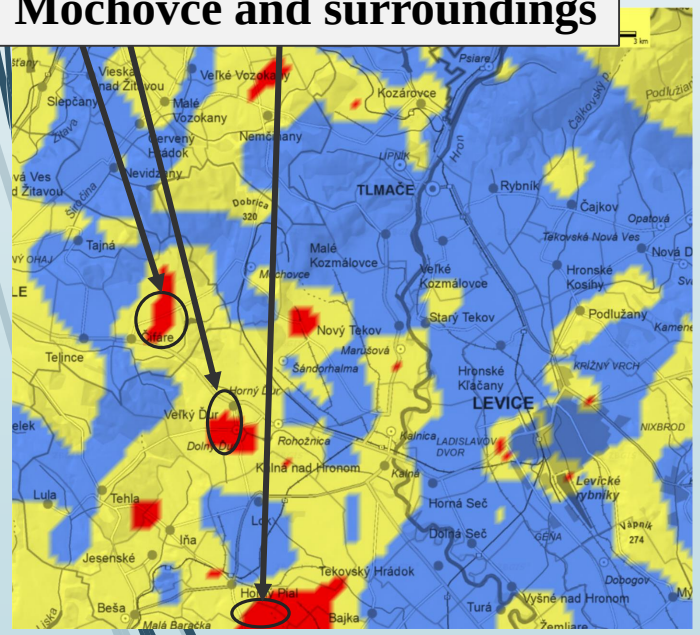
Lučenec, Poltár and sur.



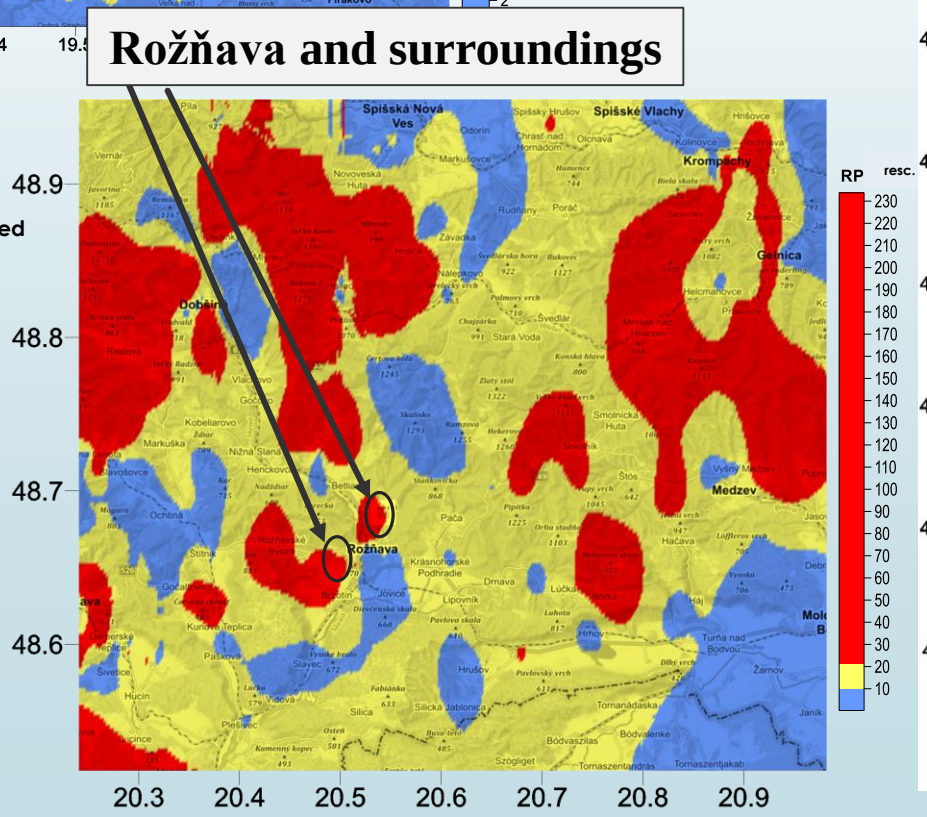
Žiar nad Hronom and surroundings

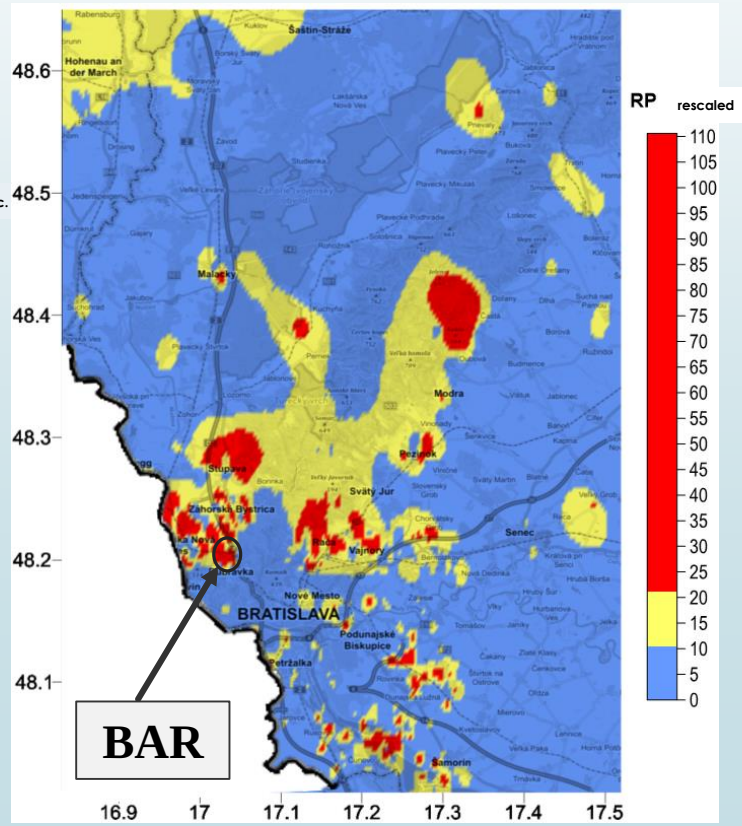


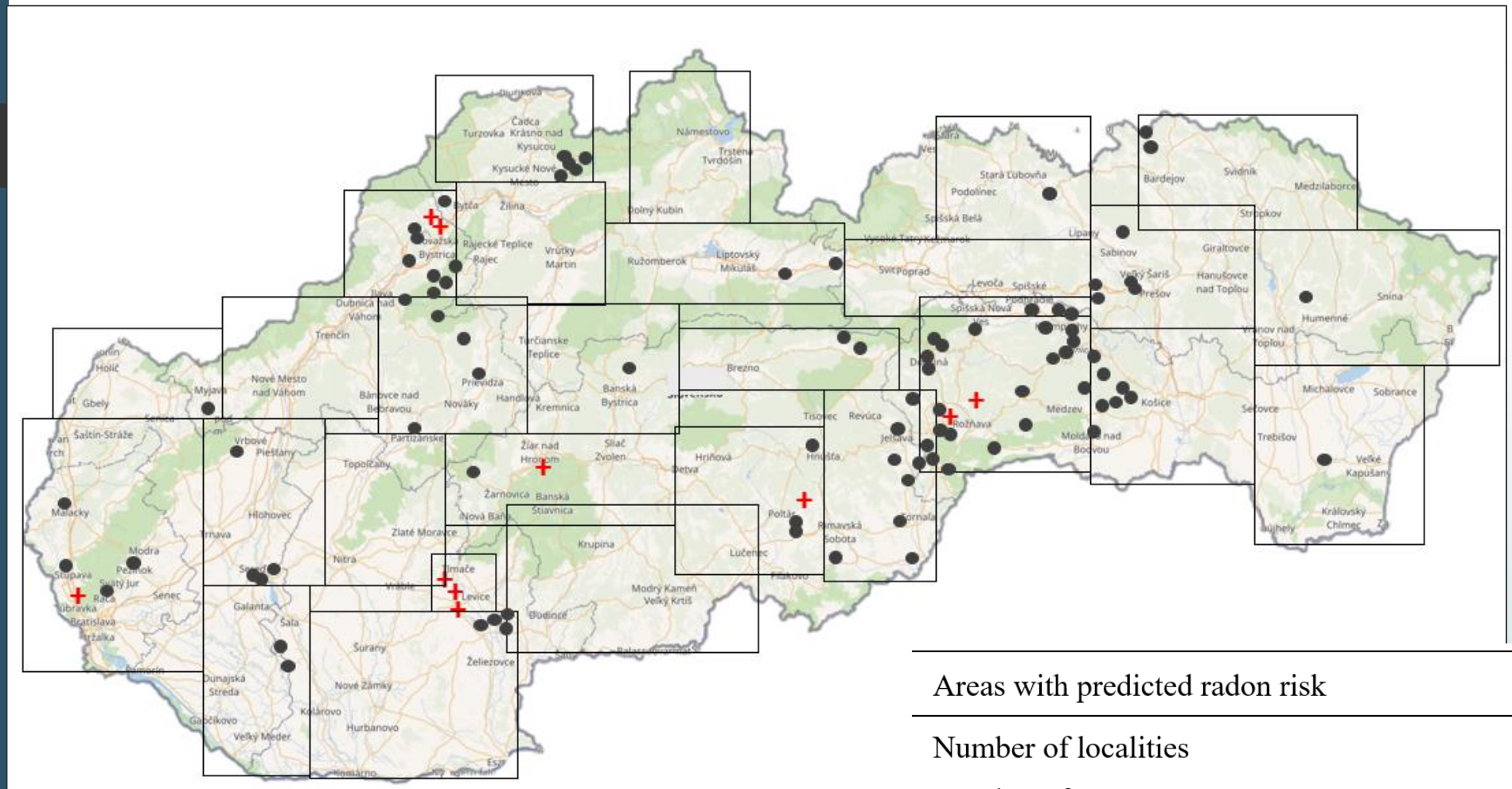
Mochovce and surroundings



Rožňava and surroundings

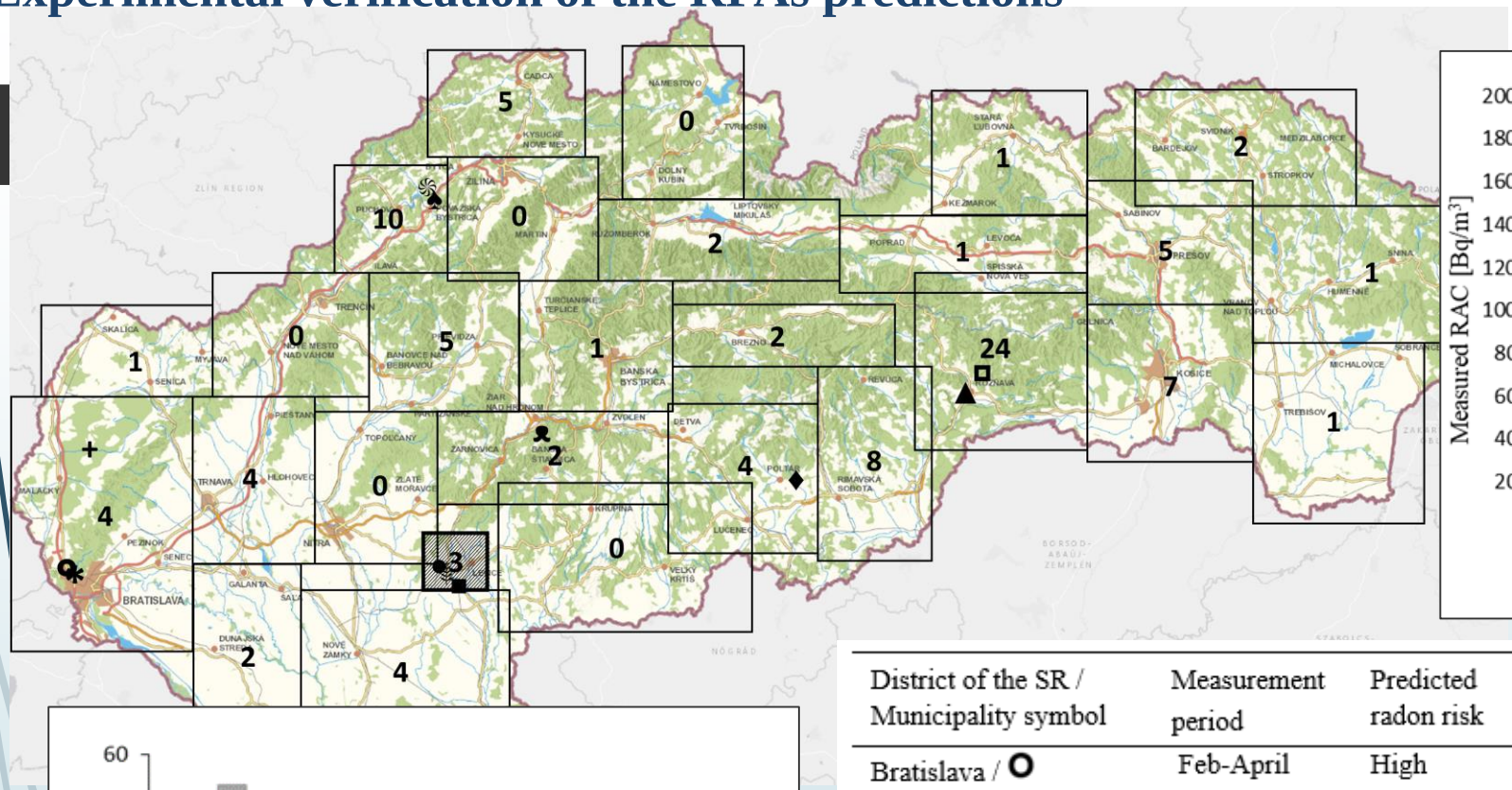


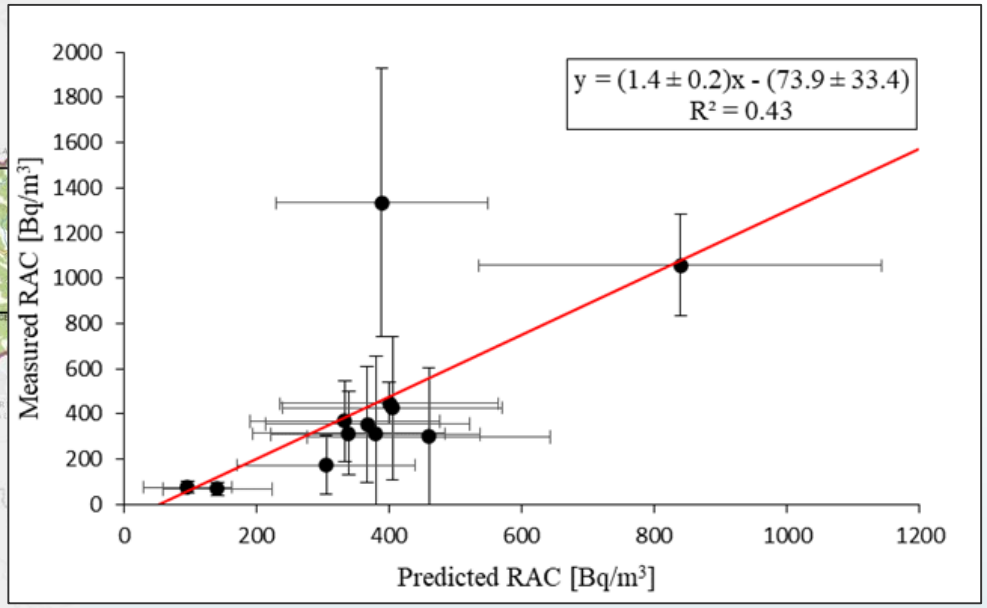


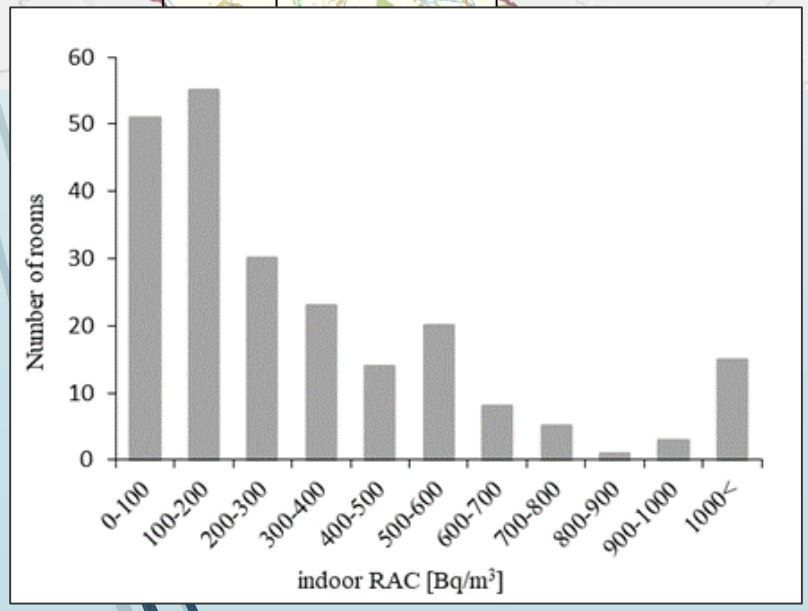


Areas with predicted radon risk	High	Low
Number of localities	10	2
Number of rooms	126	19
Min. RAC [Bq m^{-3}]	45	30
Max. RAC [Bq m^{-3}]	2400	680
Average RAC [Bq m^{-3}]	402	123
Median RAC [Bq m^{-3}]	290	70
Geometric mean RAC [Bq m^{-3}]	286	78
Percentage of buildings with RAC above 300 Bq m^{-3} (%)	43	11

Experimental verification of the RPAs predictions

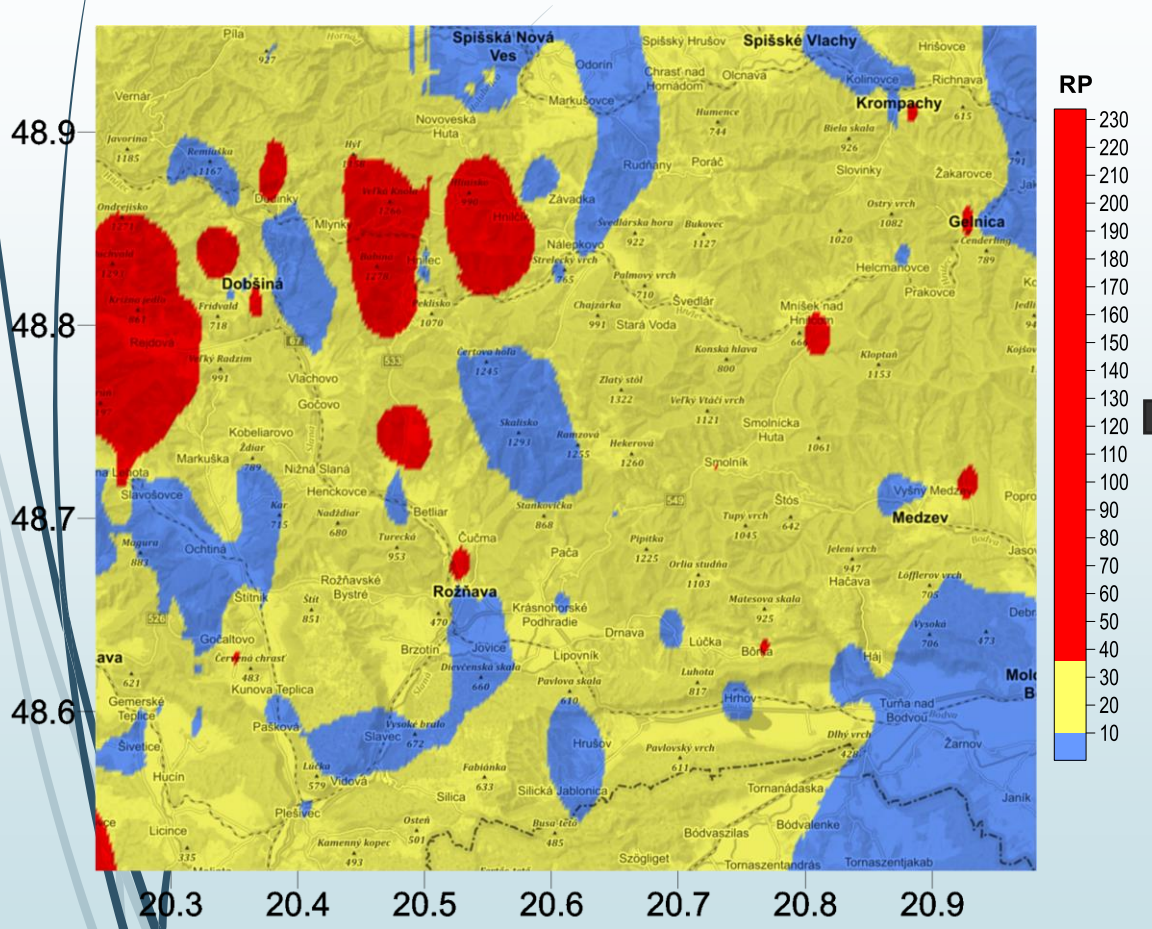




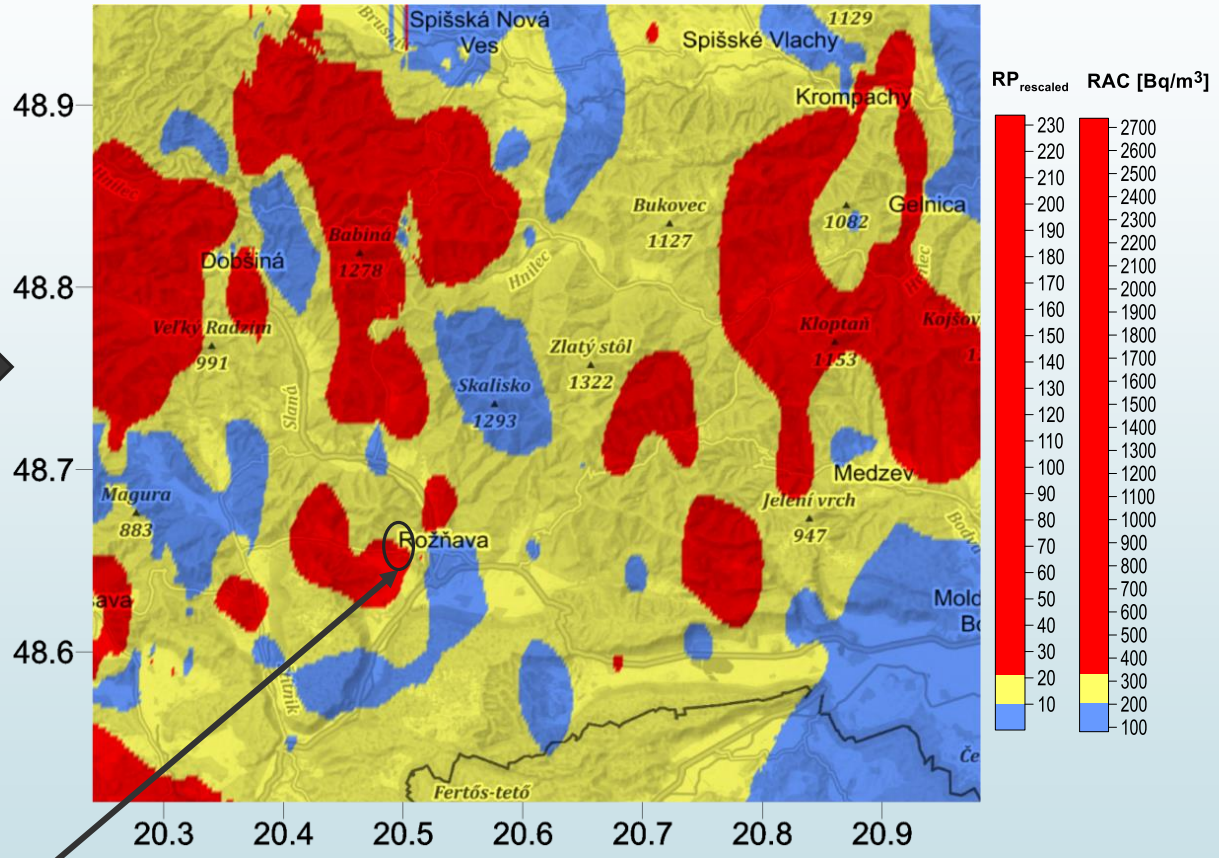


District of the SR / Municipality symbol	Measurement period	Predicted radon risk	Predicted RP value	Predicted RAC [Bq m^{-3}]	Measured RAC [Bq m^{-3}]
Bratislava / ○	Feb-April	High	28	400 ± 164	446 ± 93
Bratislava / ✱	Feb-April	Low	5	141 ± 82	68 ± 27
Malacky / ✚	Dec-March	Low	1	96 ± 67	76 ± 27
Rožňava / □	1 year	High	27	389 ± 160	1334 ± 594
Žiar n. Hr. /	1 year	High	67	840 ± 304	1057 ± 225
Nitra / ●	Dec-March	High	22	333 ± 143	368 ±180
Levice /	Jan-March	High	22.5	339 ± 145	314 ± 184
Levice / ■	Jan-March	High	25	367 ± 154	355 ± 257
Rožňava / ▲	Dec-May	Medium-High	19.5	305 ± 134	186 ± 123
Poltár/ ♦	Dec-March	High	28.5	405 ± 166	426 ± 317
Považská Bystrica /	Dec-March	High	33.5	460 ± 183	298 ± 305
Považská Bystrica / ♠	Dec-March	High	26	380 ± 158	310 ± 343

Rožňava and surroundings



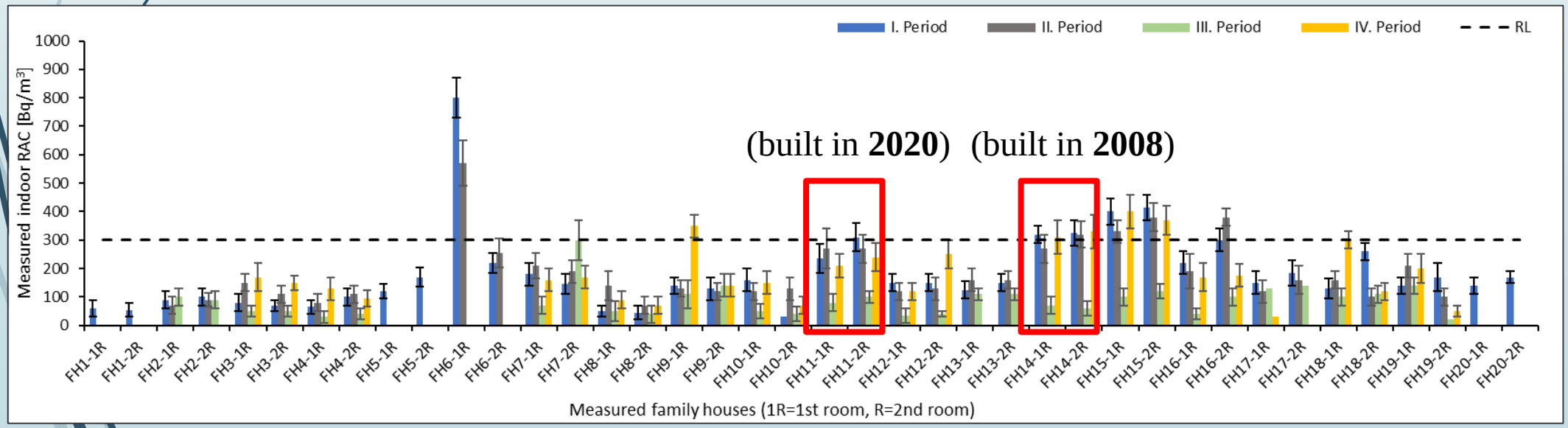
Rescaled RP map:



Rudná (district of the SR - Rožňava) → RP – Medium, High

Results of anual measurements

Rudná	Winter season December - February		Spring season March - May		Summer season June - August		Autumn season September - January	
	all rooms	**contact with subsoil**	**all rooms**	**contact with subs.**	**all rooms**	**contact with subs.**	**all rooms**	**contact with subs.**
Number of rooms	38	20	34	20	26	17	26	17
Average RAC [Bq/m³]	187 ± 141	213 ± 165	188 ± 110	208 ± 119	80 ± 57	82 ± 62	192 ± 99	195 ± 94
Median	150	170	145	175	65	70	170	173
MAX	**800**	**800**	**570**	**570**	**300**	**300**	**400**	**350**
MIN	45	45	70	70	20	20	50	50
above RL [%]	**18 %**	**25 %**	**15 %**	**15 %**	**4 %**	**6 %**	**19 %**	**18 %**
75. percentile – RAC [Bq/m³]	220	270	210	270	100	100	248	263

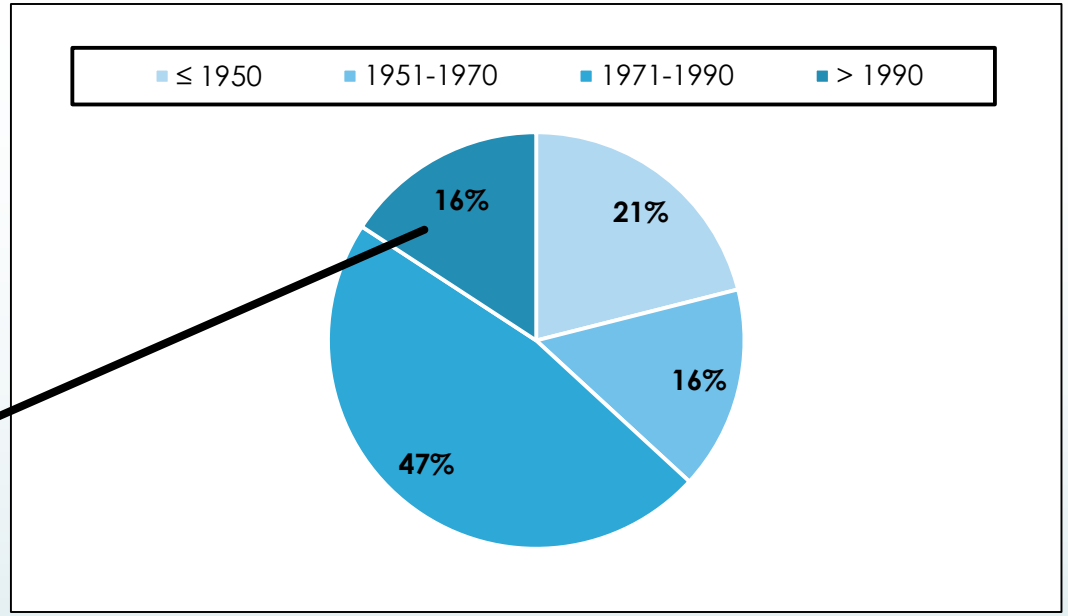


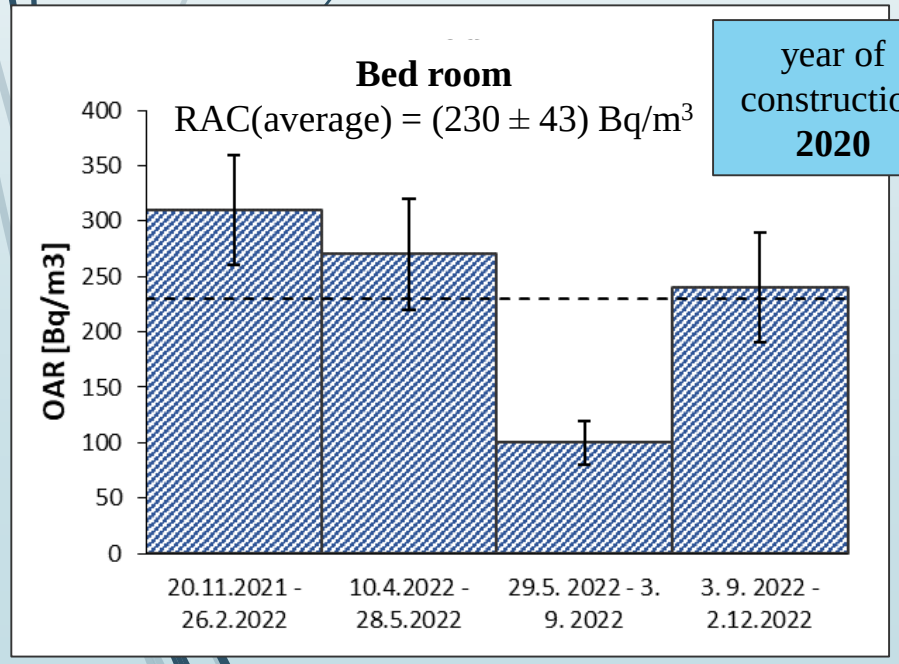
Other results

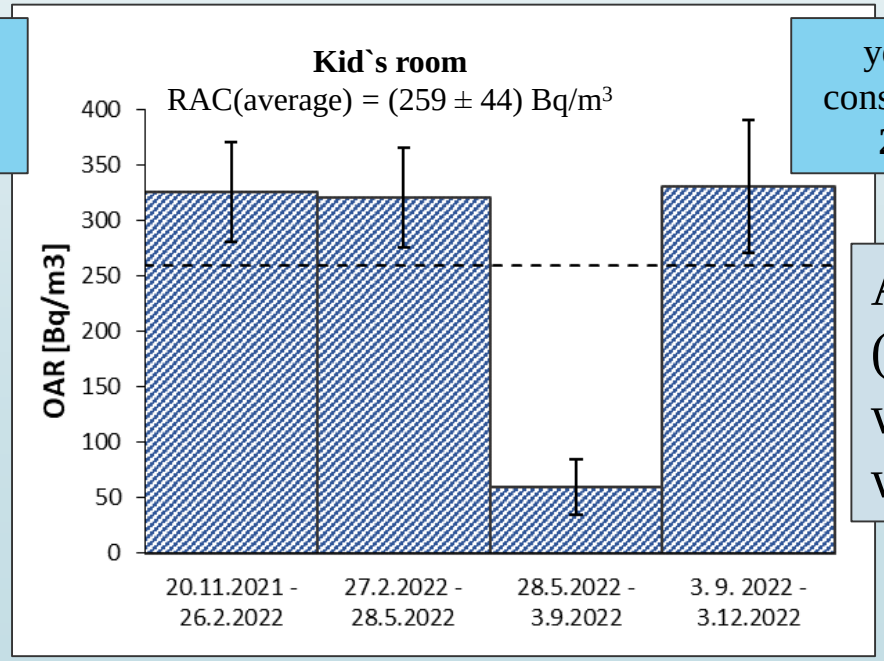
Percentage of houses by year of their construction

Y. of construction	Percentage of houses	Percentage of houses with RAC above RL
≤ 1950	21 %	25 %
1951-1970	16 %	33 %
1971-1990	47 %	11 %
> 1990	16 %	**67 %**

Winter season:







Also new houses (**year of construction > 2008**) with indoor RAC above RL in winter season (**2 from 3**)

Conclusion

- Rescaling the RP scale ⟶ searching for **radon-prone areas** (NARP SR)
- 99 municipalities (**RPAs**) in Slovak Republic

Preferred measurements of indoor RAC

Approach **more efficient** than

nationwide survey

↓

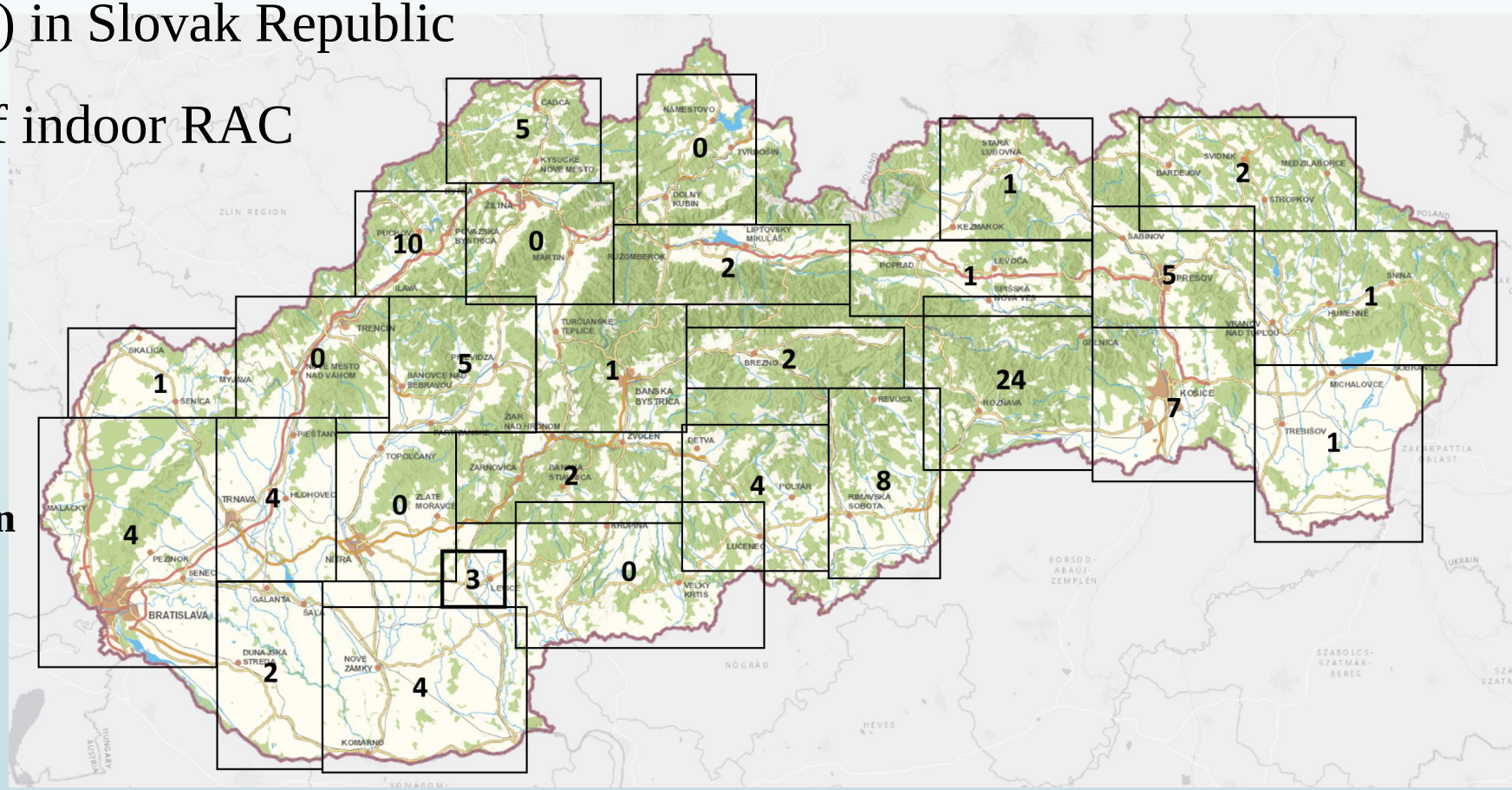
Measured RAC above RL

Result consistent with RPAs definition

↓

Radiation protection

of the population



Thank you for your attention!

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