Employing a multi-method approach consisting of soil radon deficit, resistivity, and induced polarization measurements to track NAPL pollution in two regions in Italy and India.

Paola Tuccimei [1], _Mauro Castelluccio_ [1], _Sudha Agrahari_ [2], _Gabriele De Simone_ [1], _Francesca Pompili_ [1], _Carlo Lucchetti_ [1], _Debashish Sengupta_ [2], _Gianfranco Galli_ [3], _Pierluigi Friello_ [4], _Pierpaolo Curatolo_ [5], _Riccardo Giorgi_ [5]

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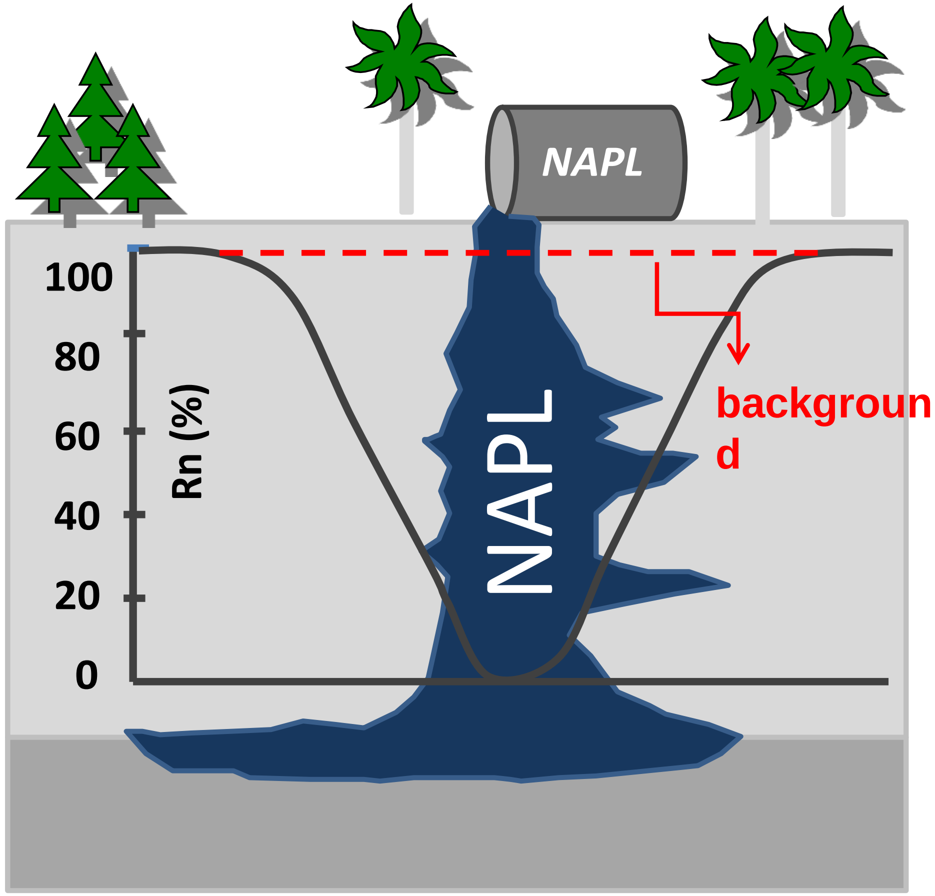
17° GARRM – Prague, September 16 – 18, 2025

Presentation outline

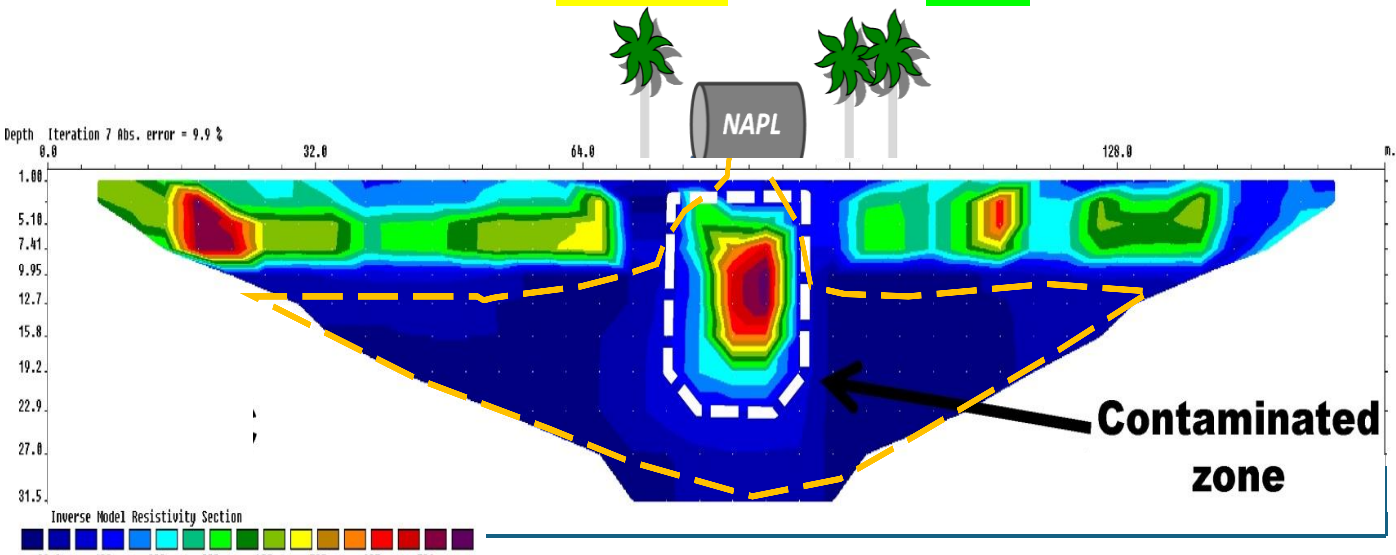
- Introduction
- Study areas
- Methods
- Results Rn
- Results Geophysics
- Discussion
- Conclusions

Radon deficit



Modified after Schubert et al. (2002)

ERT and IP



Red and yellow indicate areas of high resistivity (ERT) and induced polarization (IP) where non-polar NAPLs are located.

Low values (blue, green) of ERT and IP show areas without NAPLs or where groundwater is placed.

Introduction

CALCULATION

Equation 1 correlates soil radon activity concentration (**C_∞**) with NAPL fraction of total fluid saturation (**X_{NAPL}**) in the pore space:

$$C_\infty = \varepsilon \, A_{Ra} \, \rho_d \, / \, n \, (1 - S_F + K_{W/SG} \, S_F \, (1 - X_{NAPL}) + K_{NAPL/SG} \, X_{NAPL} \, S_F)$$

Eq. (1)

where

C_∞ : Radon concentration in the soil pore space (Bq/m^3)

ε : Emanation coefficient

A_{Ra} : ^{226}Ra activity concentration of the mineral matrix (Bq/kg)

ρ_d : Bulk density of the mineral matrix (kg/m^3)

n : Porosity of the mineral matrix

S_F: Total fluid saturation of the pore space

X_{NAPL} : NAPL fraction of SF

$K_{W/SG}$: Radon partition coefficient between water and soil gas, quantified by Weigel (1978) *Schubert (2015)*

$K_{NAPL/SG}$: Radon partition coefficient between NAPL and soil gas

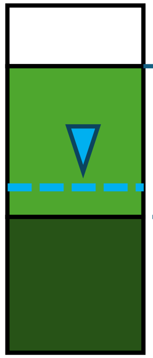
Introduction

De Simone et al. (2017) developed a new calculation, Eq. (2), to quantify the residual fraction of NAPL ($NAPL_{Pi}$) in the subsoil (unsaturated part of the aquifer)

$$NAPL_{Pi} = \frac{-J \pm \sqrt{J^2 - 4CH}}{2H} \quad \text{Eq. (2)}$$

where
J, C, H: site-specific polynomials whose explanation is provided in the De Simone et al., 2017.

Central Italy (RM) - Site 1



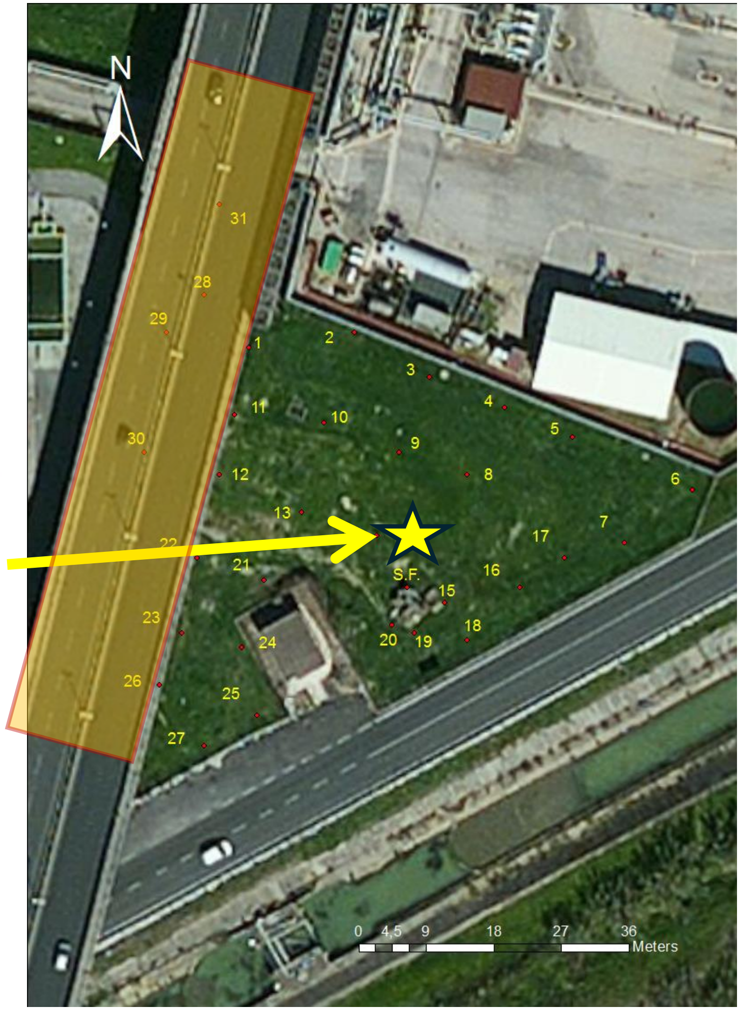
0.5 m of backfills

2.5 m of medium grained sands

3 m of medium-fine grained sands

The water table fluctuates in the range 0.5–2.5 m below the ground

Permanent sensors of temperature and humidity at 30 and 80 cm depth

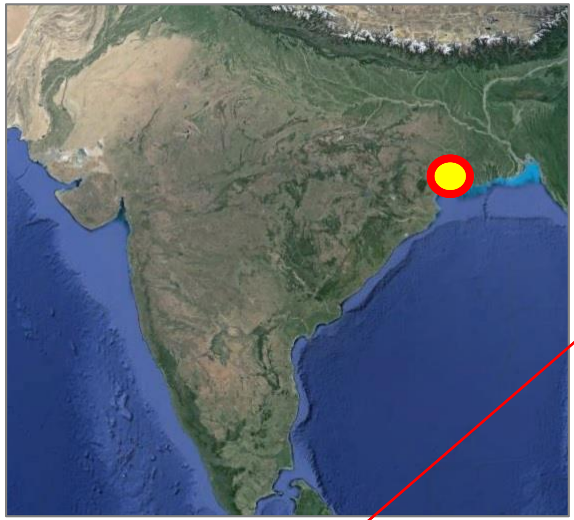


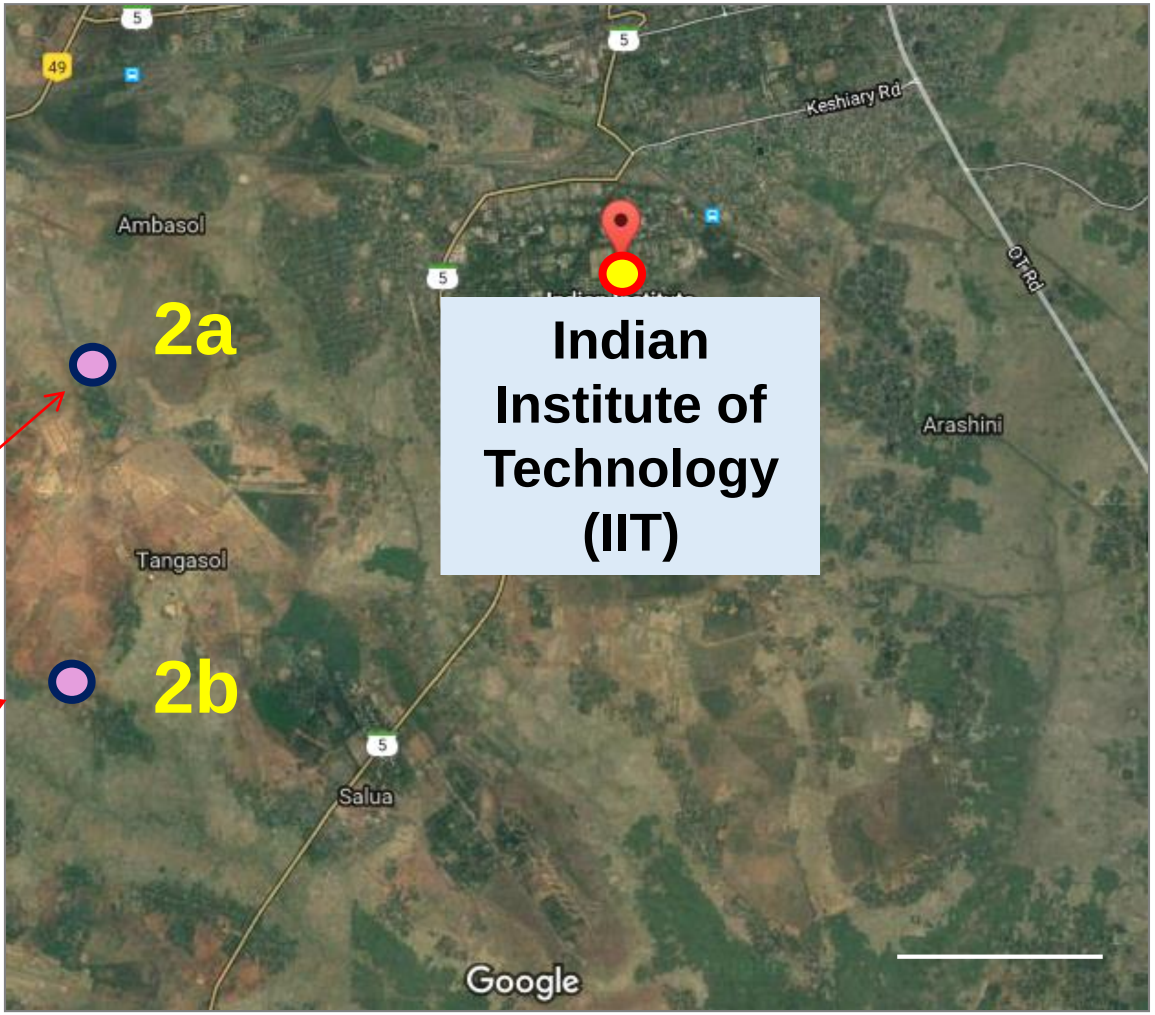
31 stations at 80 cm depth, to measure the concentrations of ^{222}Rn and CO_2

This is an area of deep CO_2 degassing

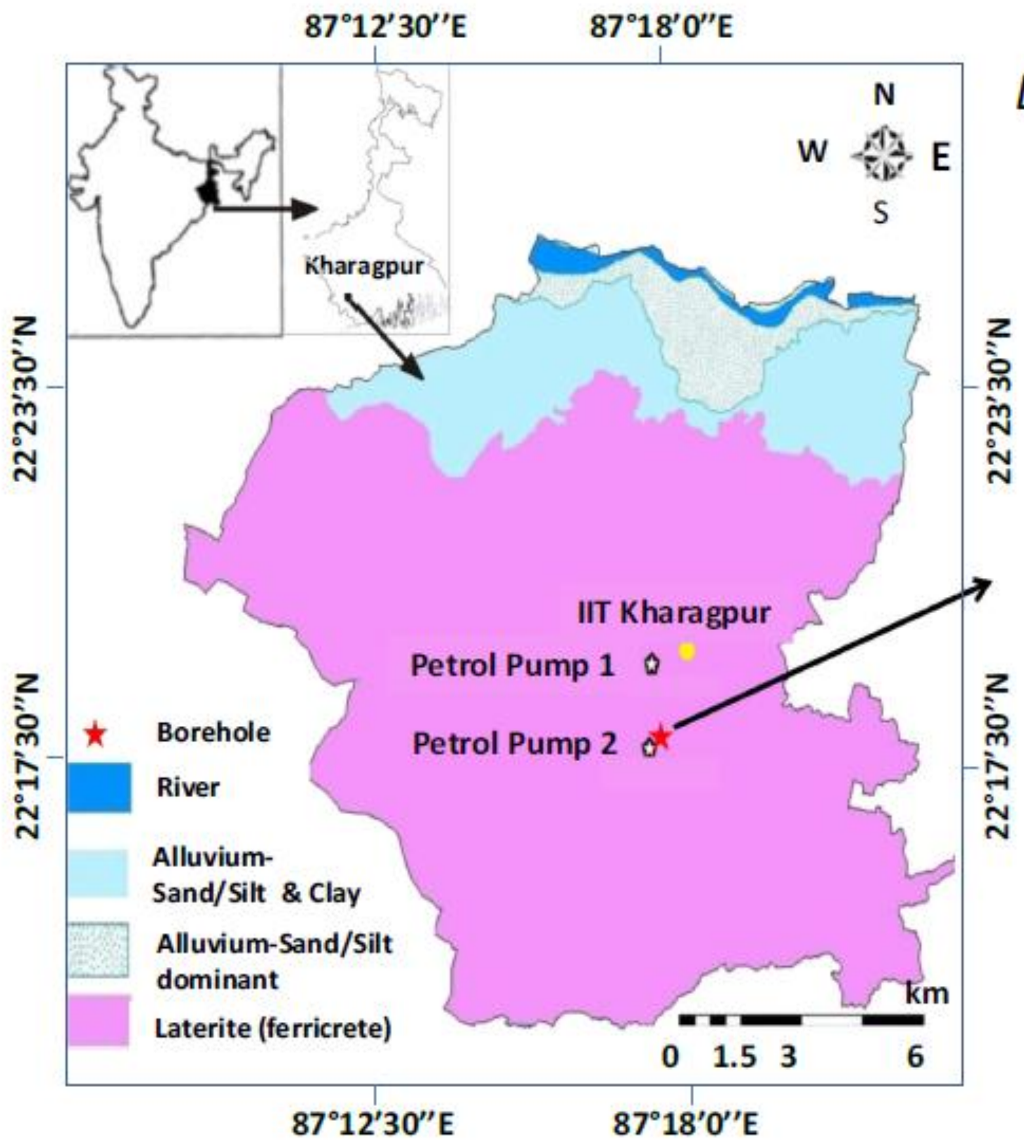
Tuccimei et al., 2014

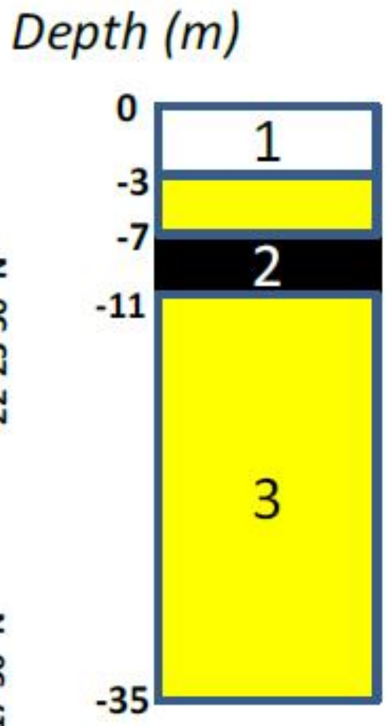
Kharagpur, West Bengal (India) Site 2a and 2b





Two working petrol stations

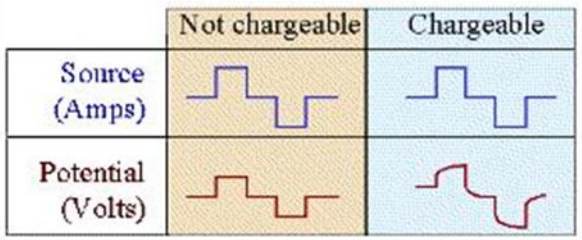


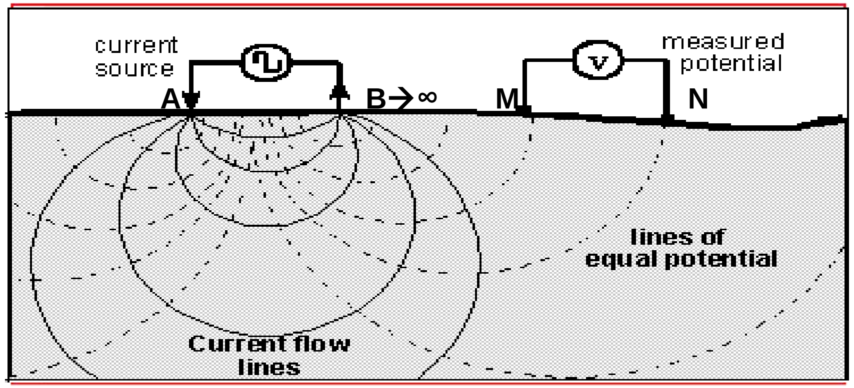


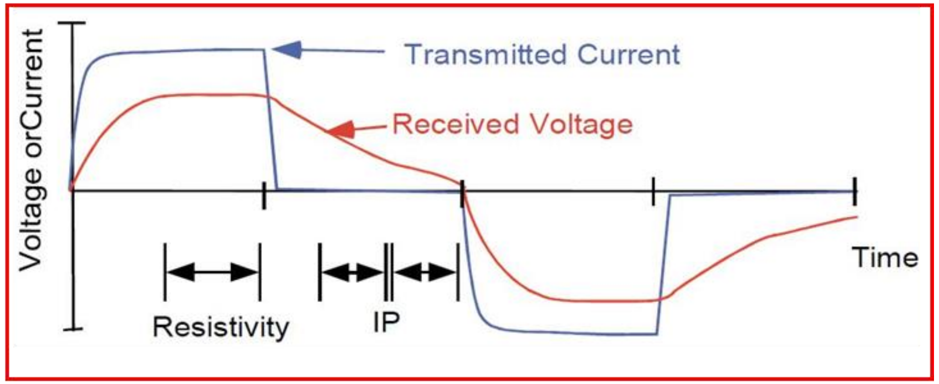
Simplified lithological map of Kharagpur area

1 Soil + murrum (lateritic bauxite)
2 Coarse + medium sand
3 Coarse + medium to fine sands

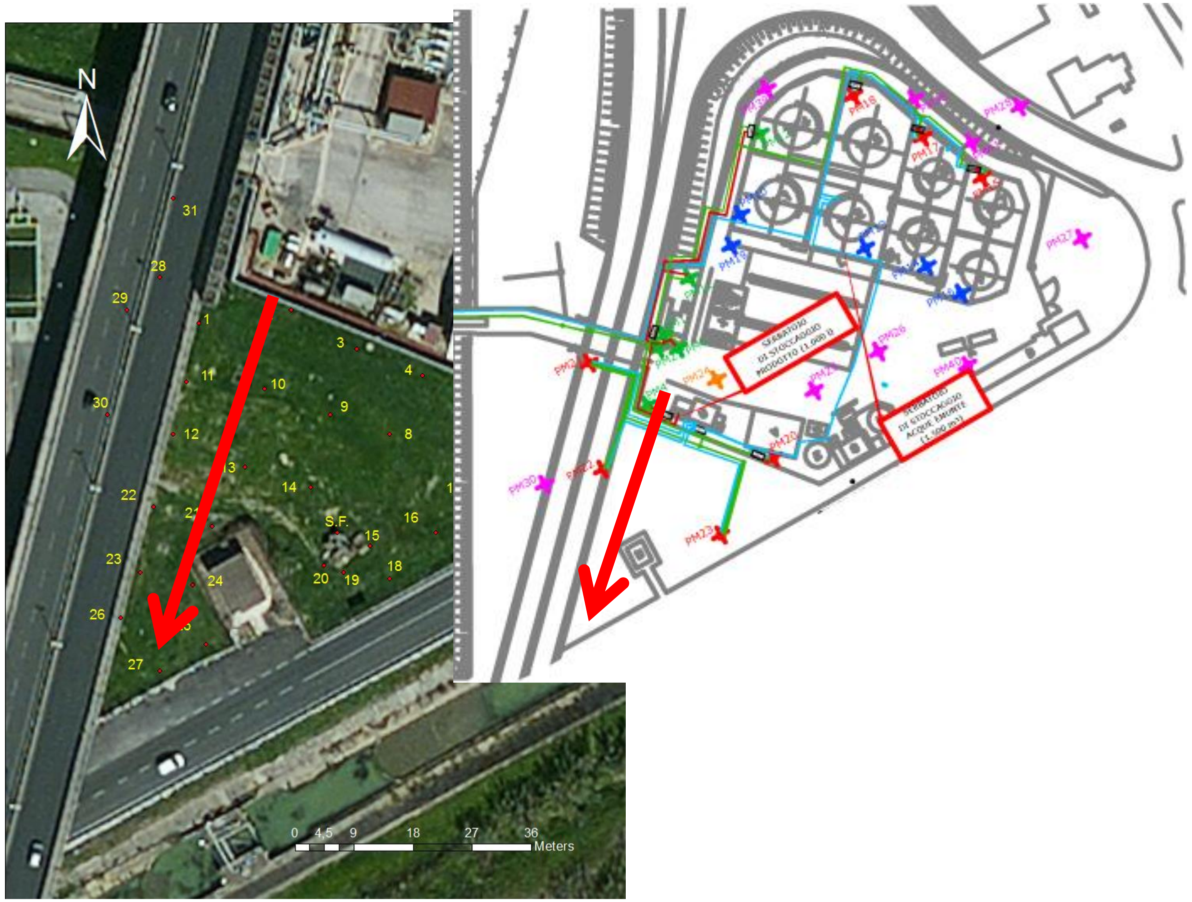
- RESISTIVITY: $\rho = \frac{k\Delta V}{i}$
- CHARGEABILITY : M= $\frac{1}{V_0}\int_{t_1}^{t_2} V(t)\,dt$

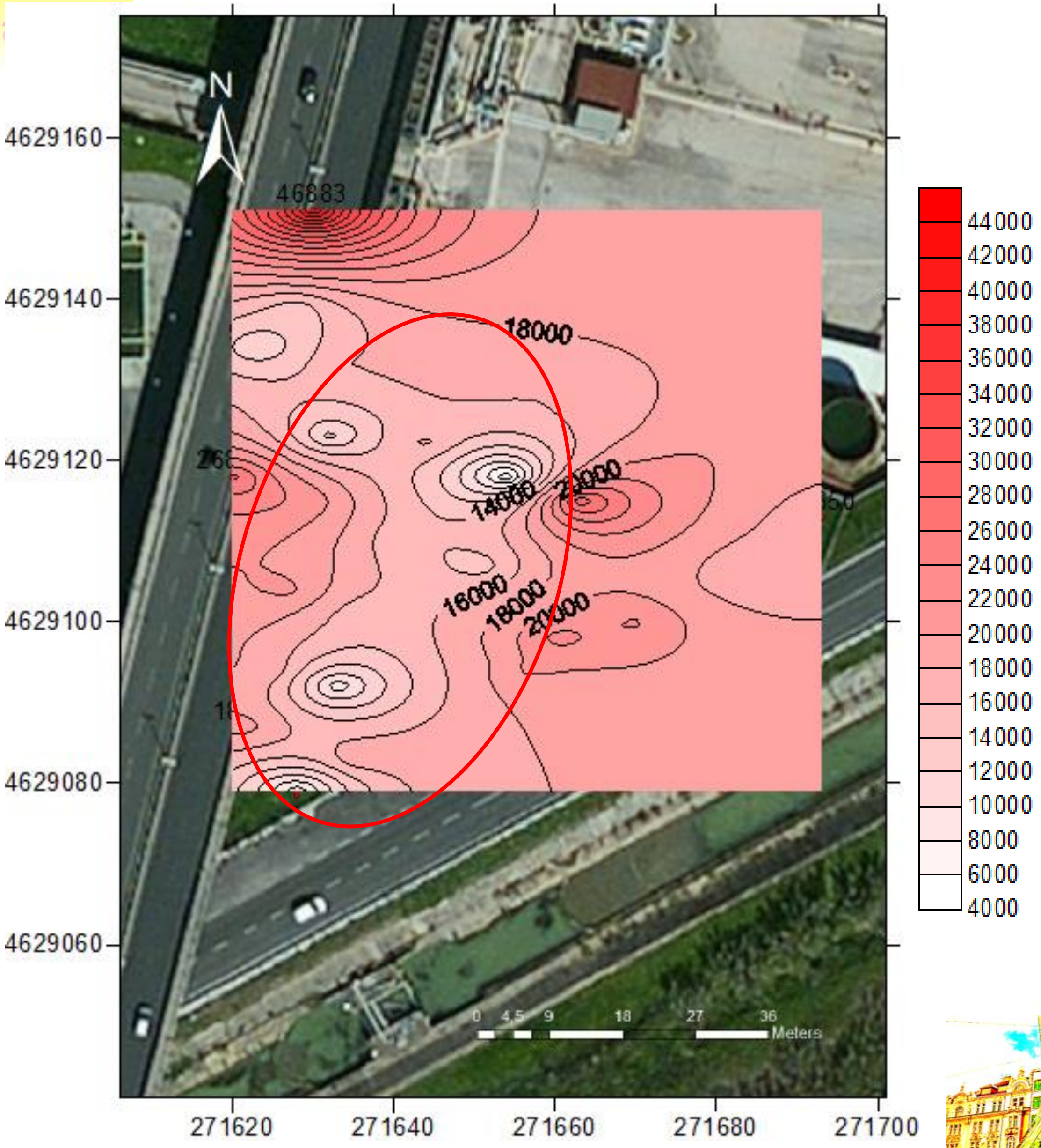


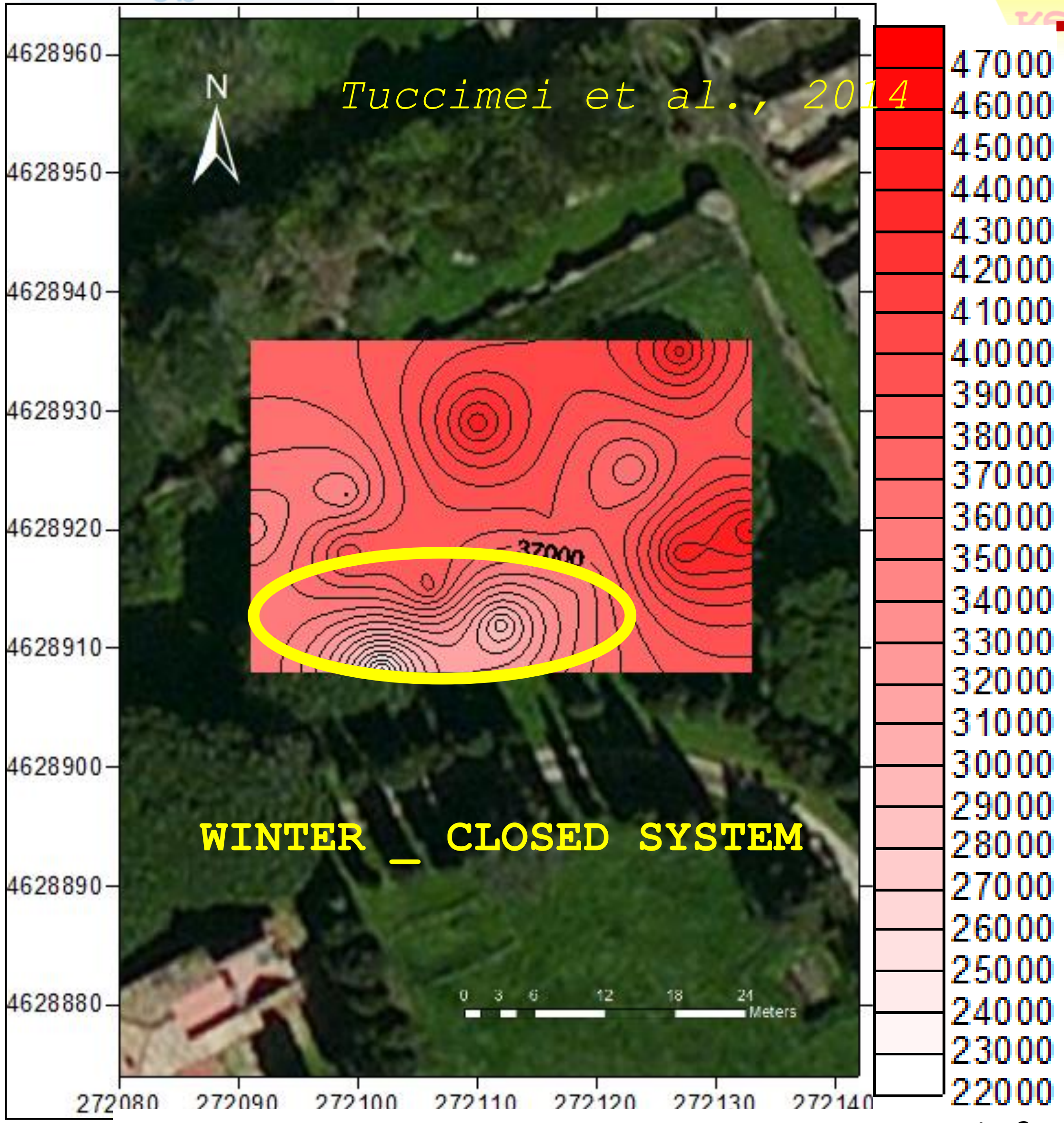




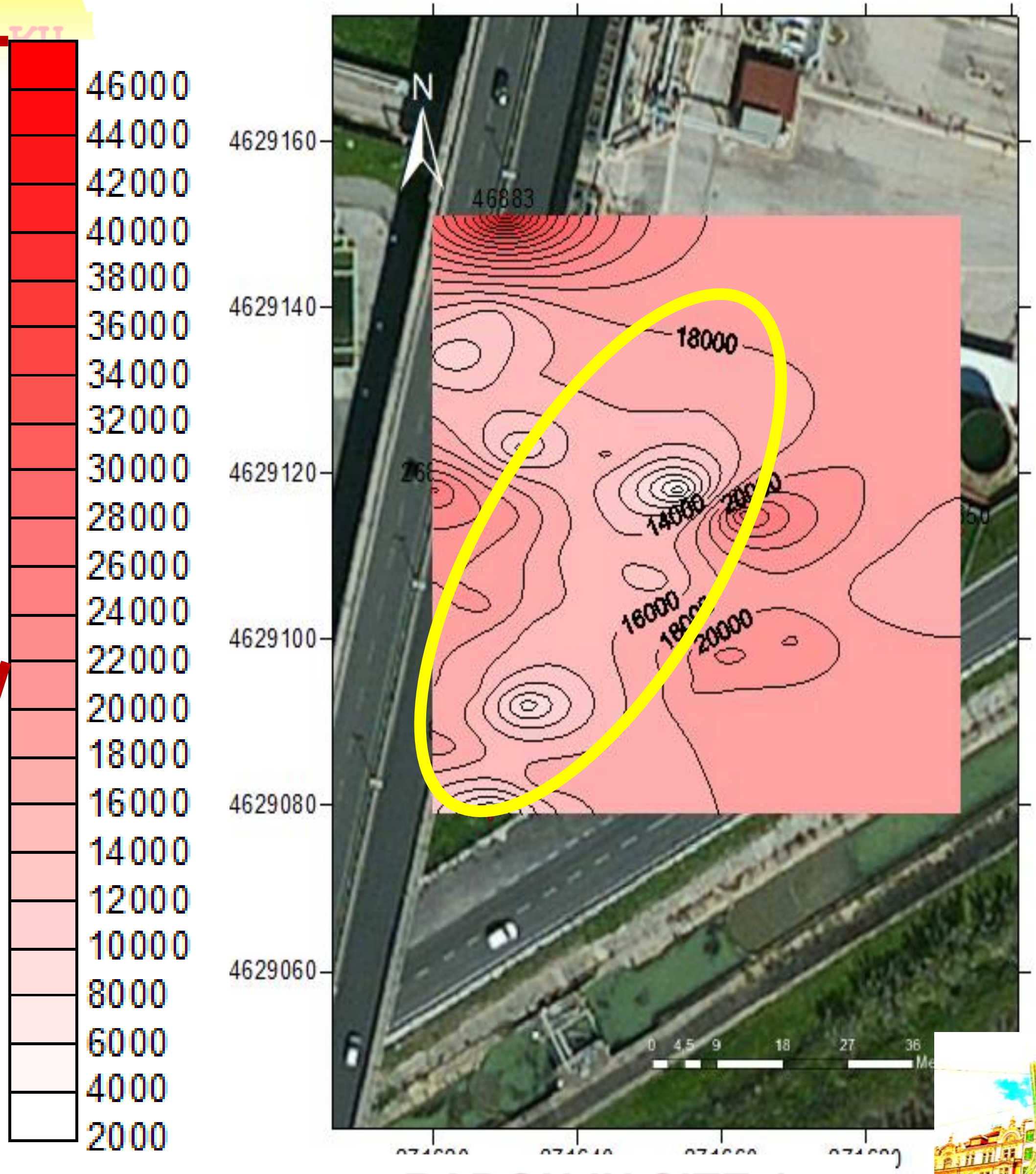
Radon map in site 1



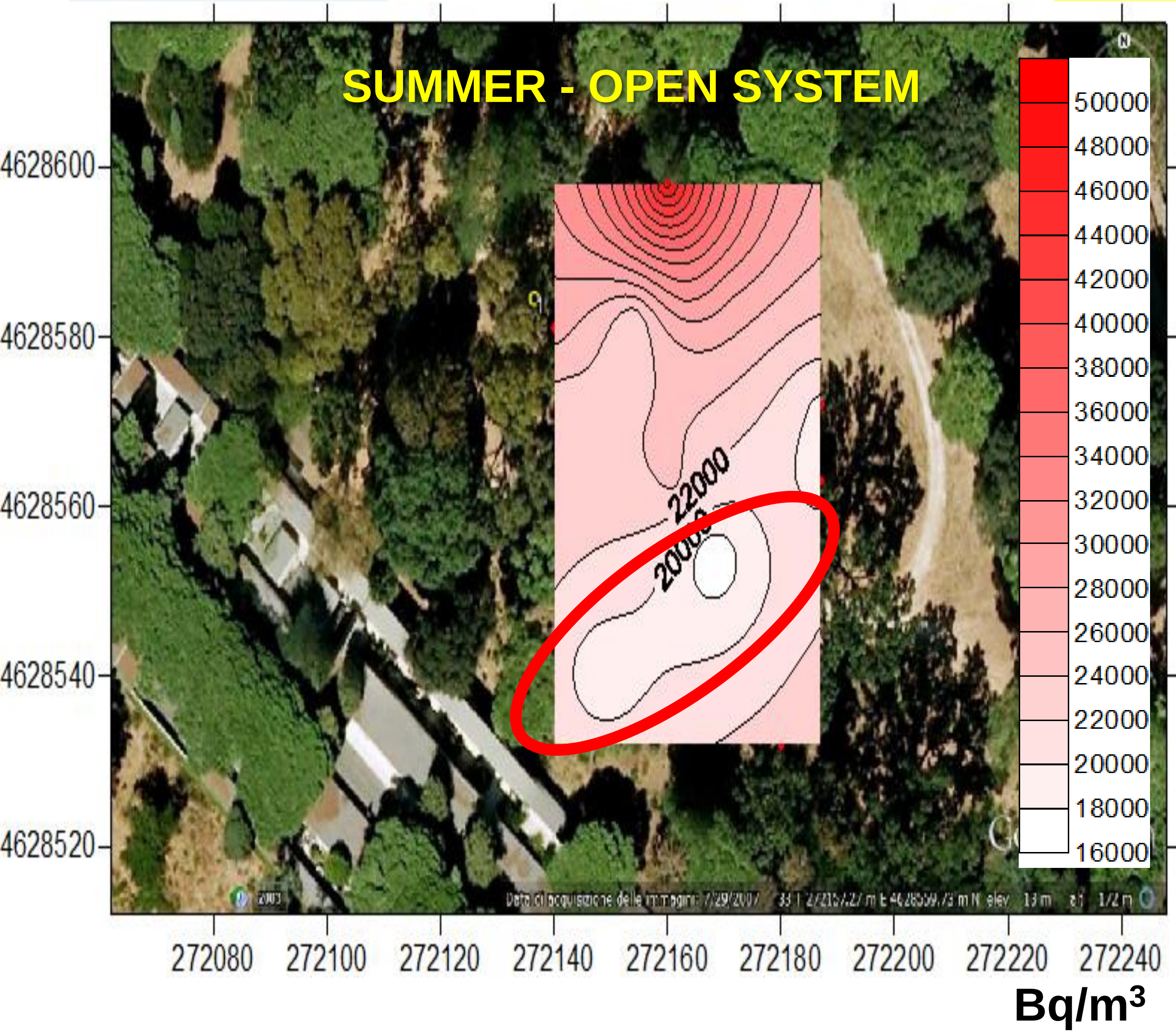


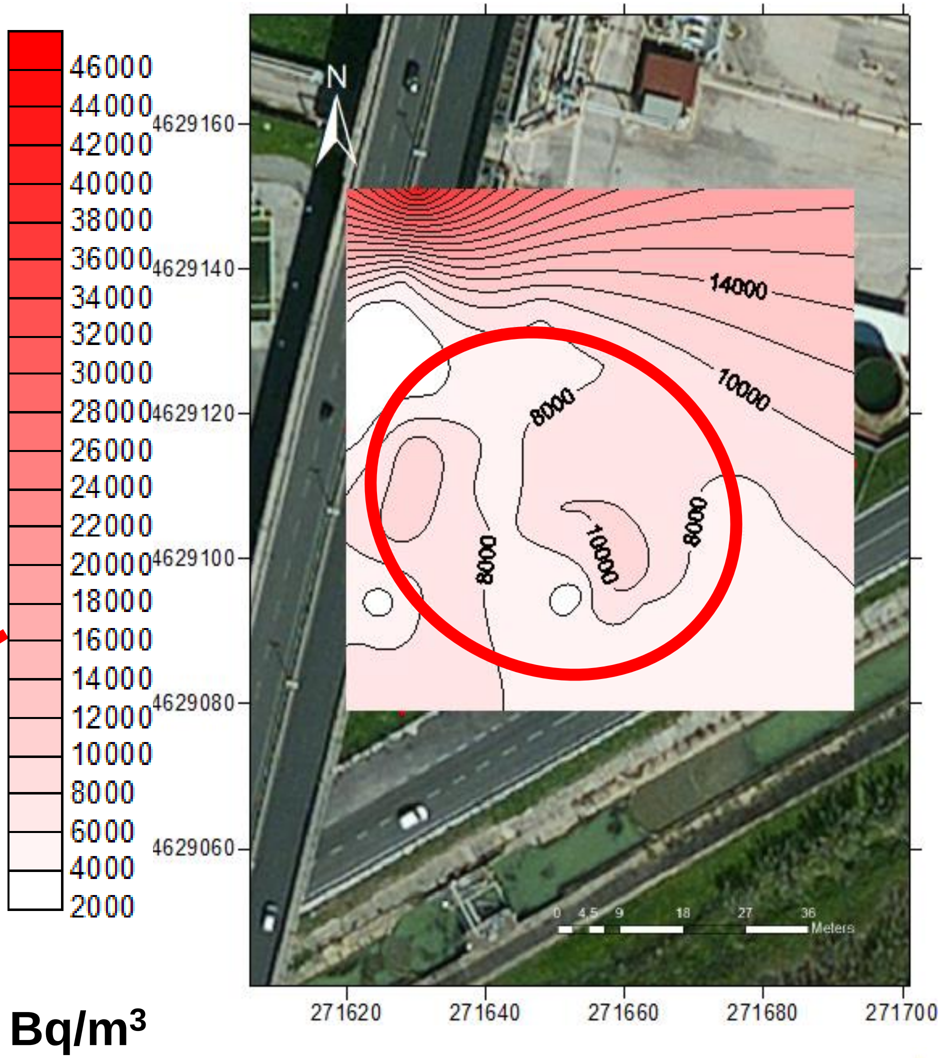


RADON IN THE BACKGROUND



RADON IN SITE 1

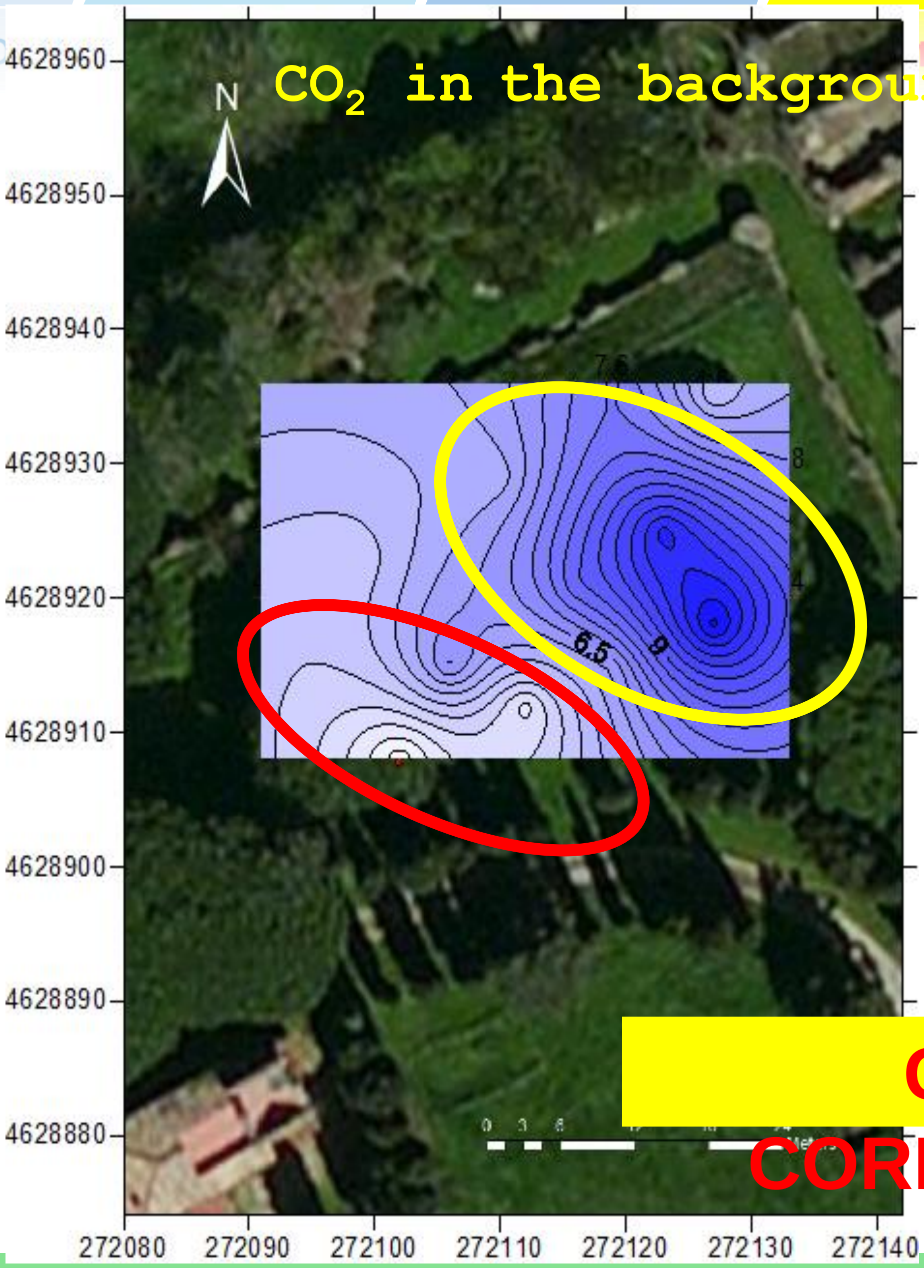


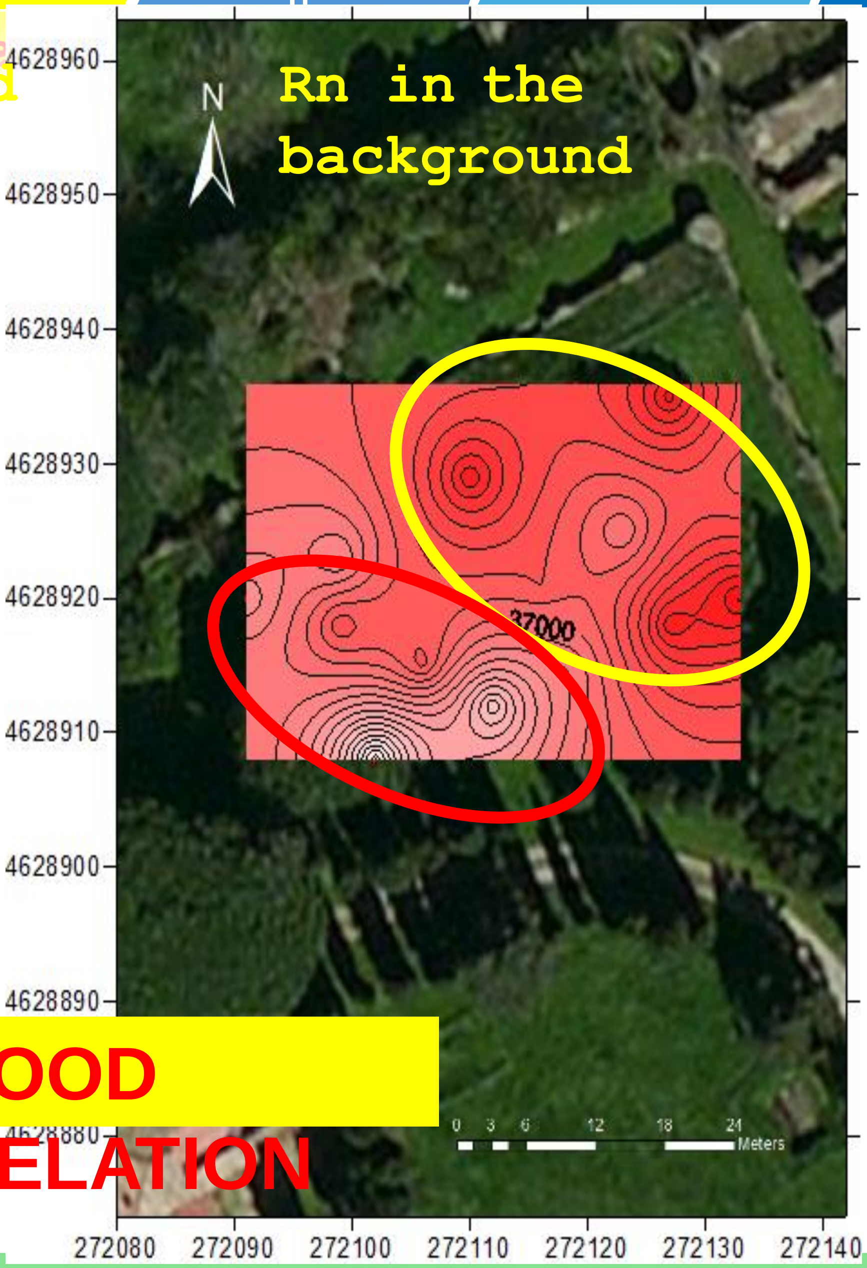


RADON IN THE BACKGROUND

RADON IN SITE 1

W I N T E R

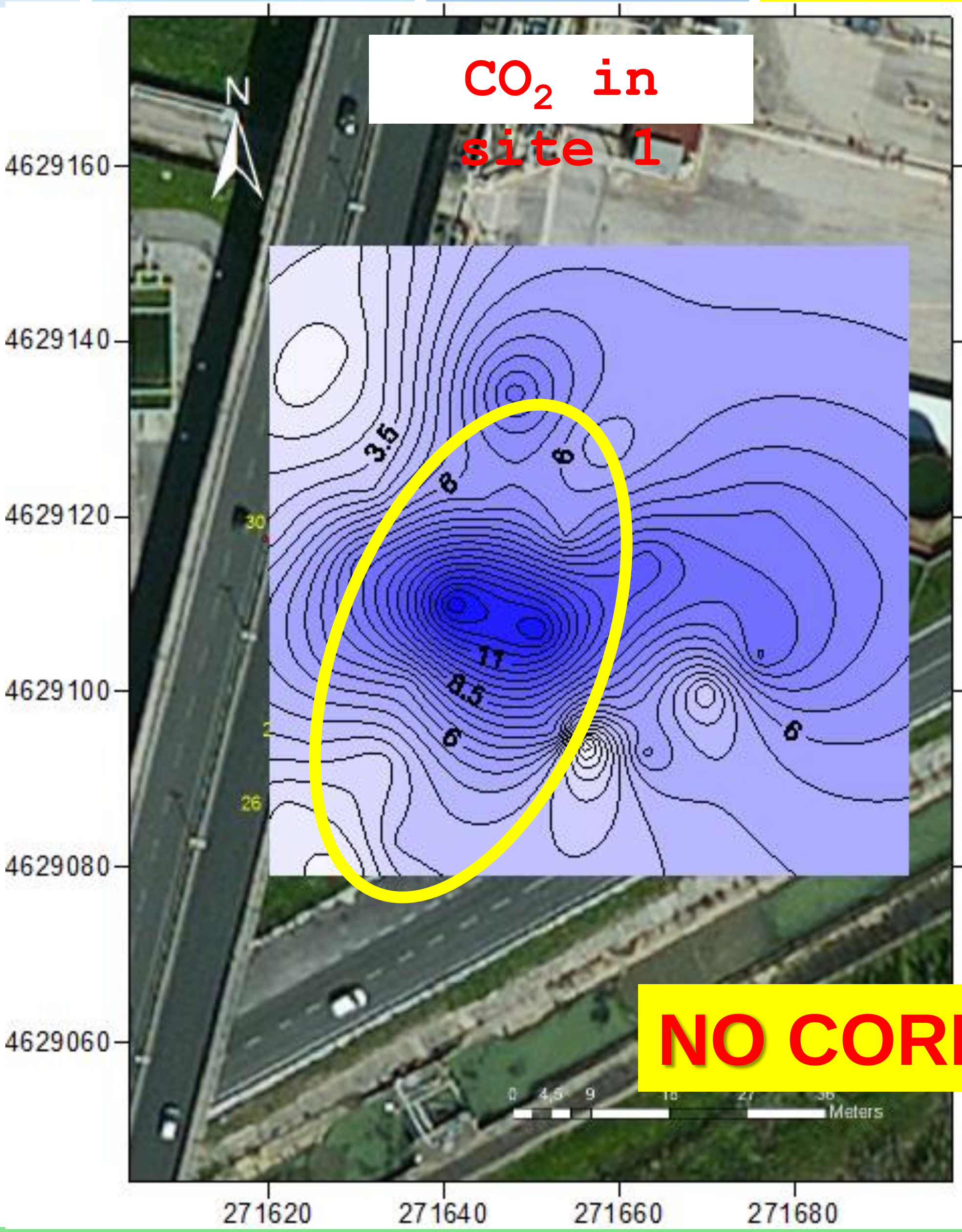


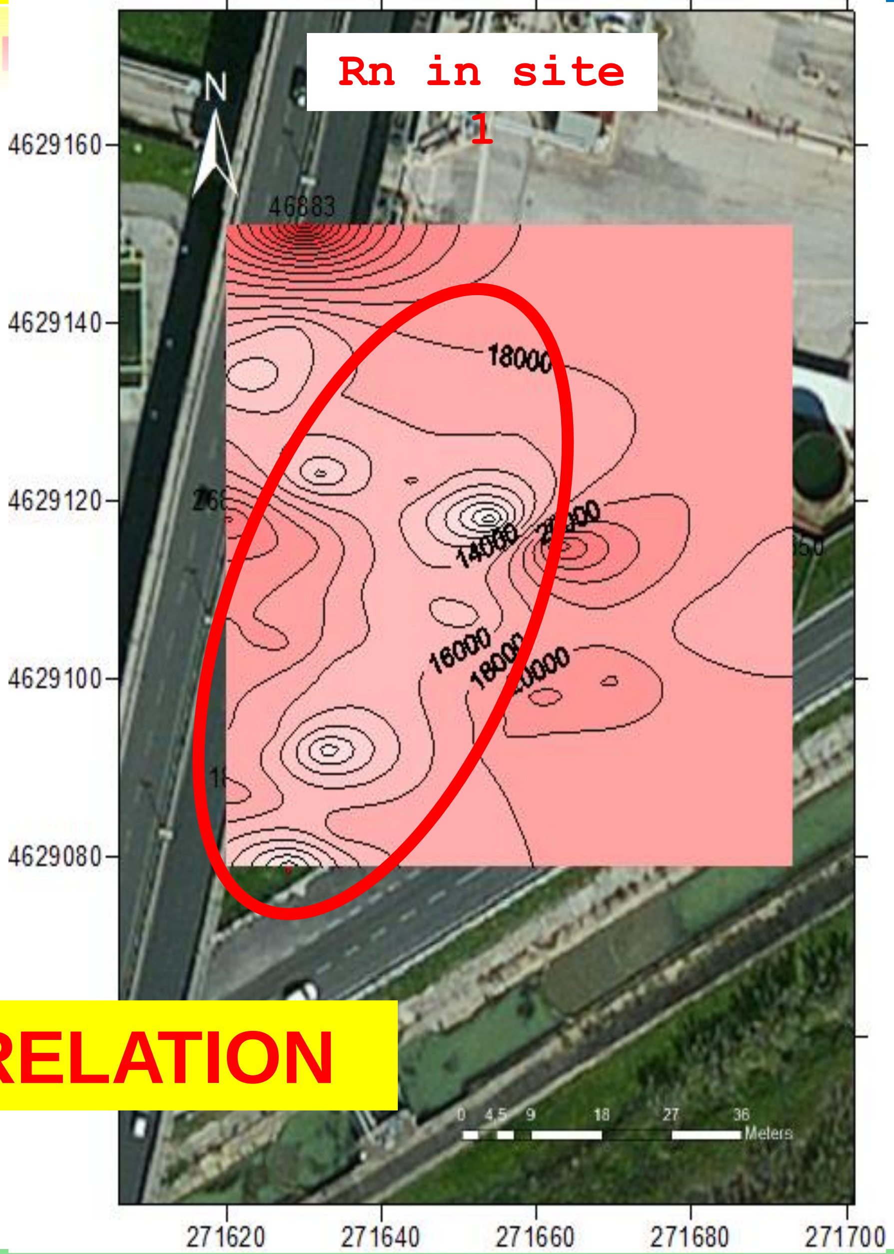


GOOD CORRELATION

Tuccimei et al., 2014

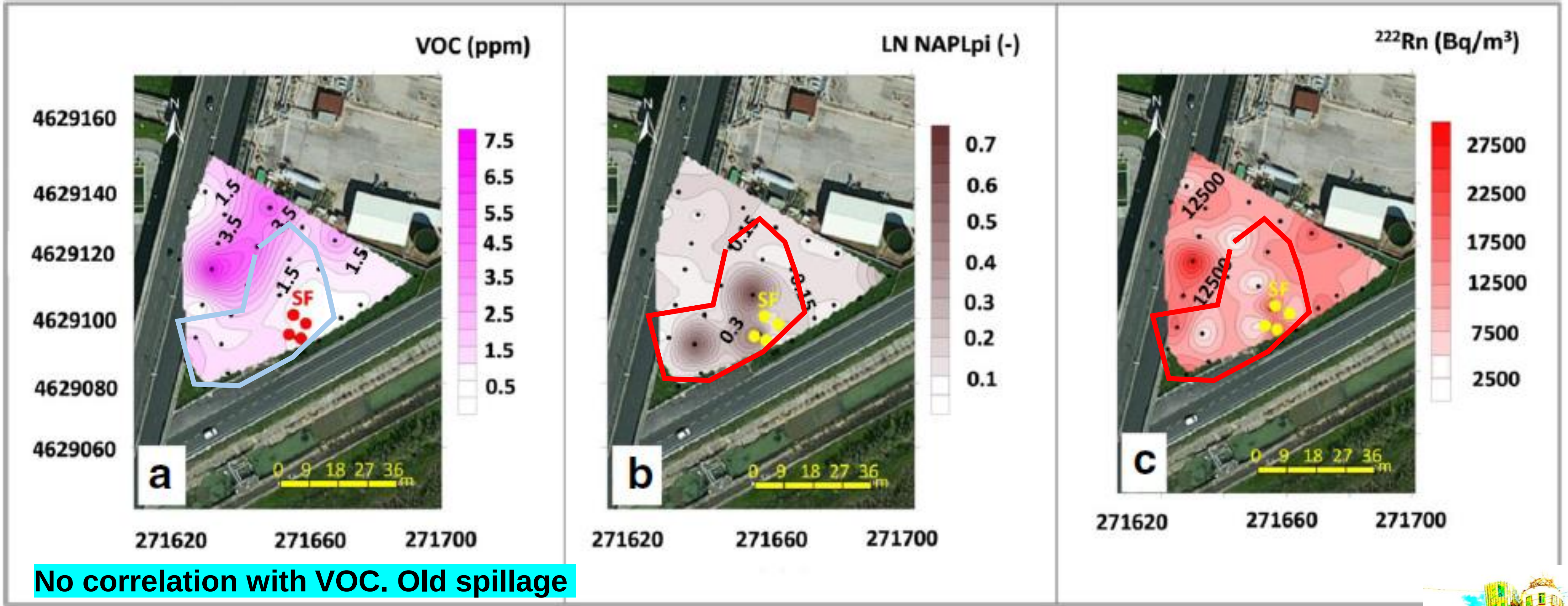
S U M M E R





NO CORRELATION

SITE 1



No correlation with VOC. Old spillage

Calculated by applying Equation 2

Introduction
Results Rn

Recent gasoline spillages

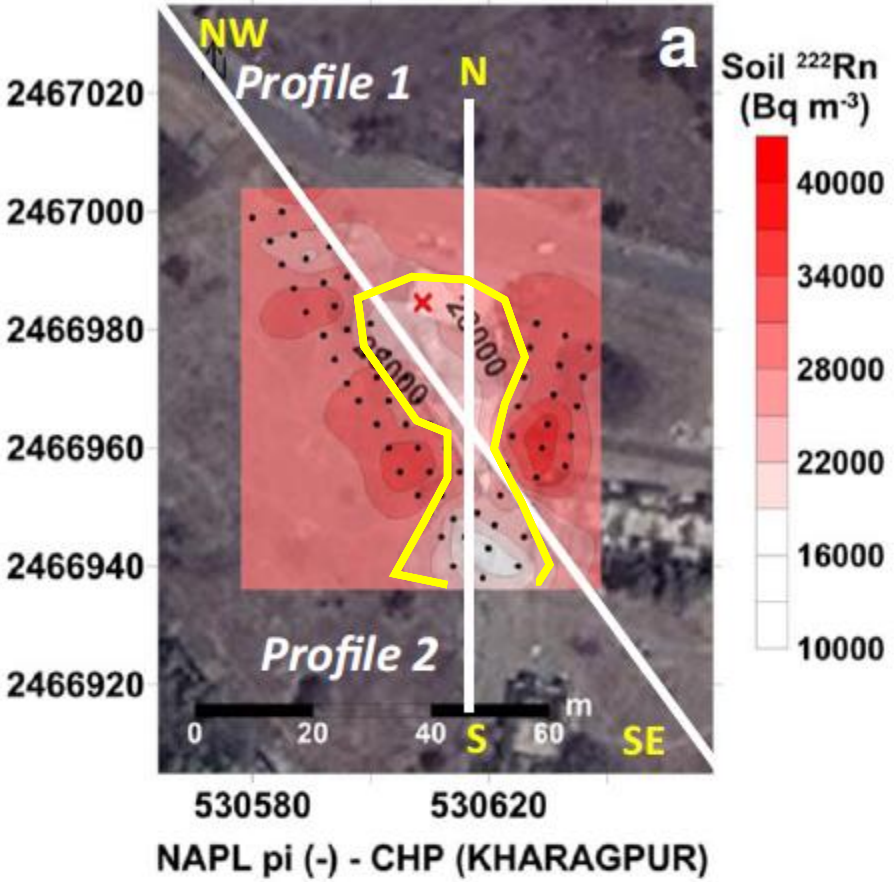


Site 2a

Site 2b



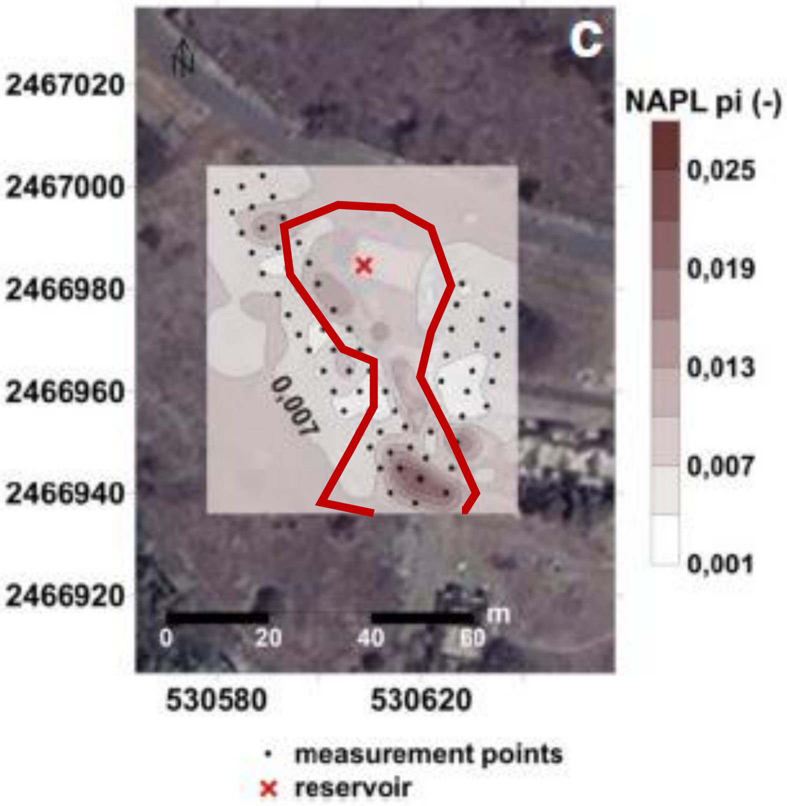
SITE 2a



SOIL RADON

SITE 2a

Calculated by applying Equation 2



NAPL SATURATION

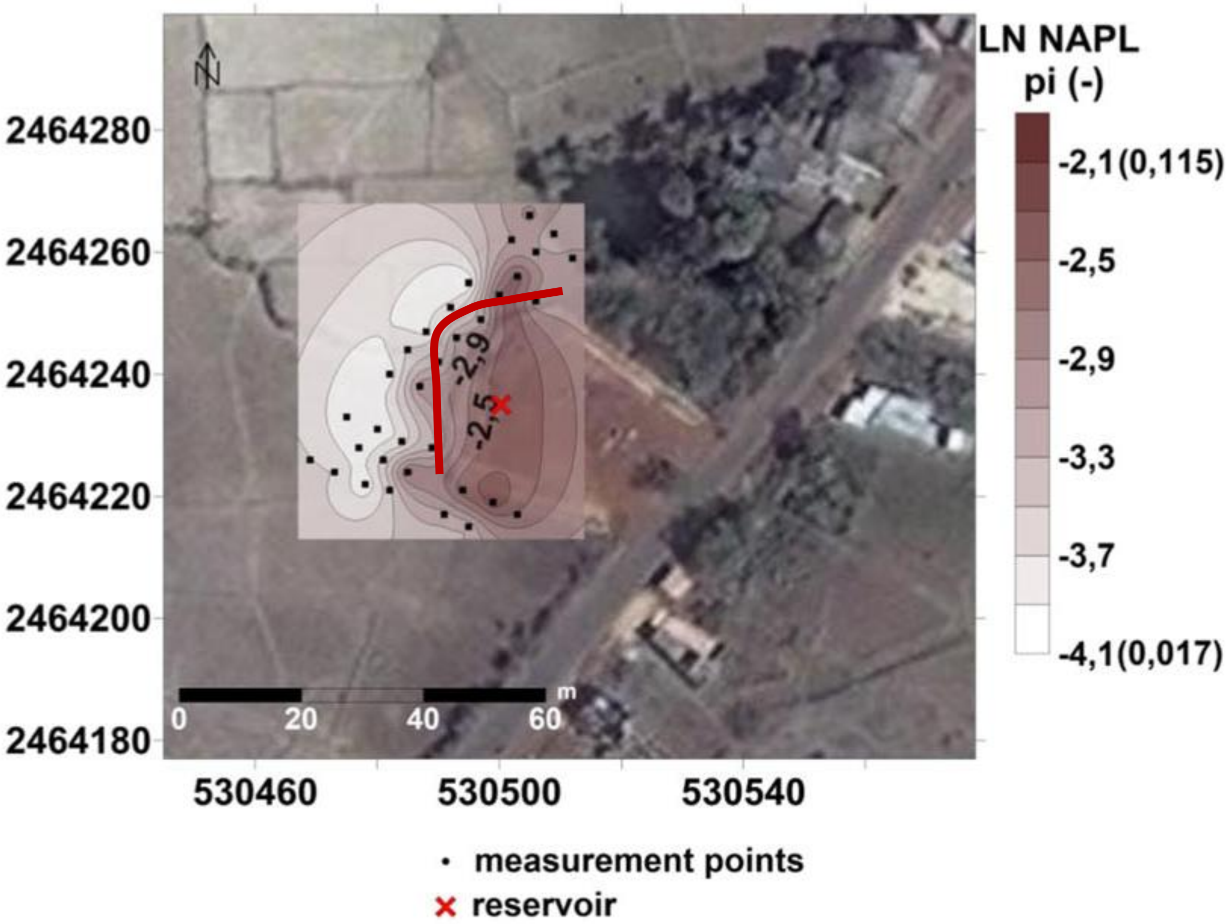
SITE 2b

RADON MAP - SIO (KHARAGPUR)

SOIL RADON

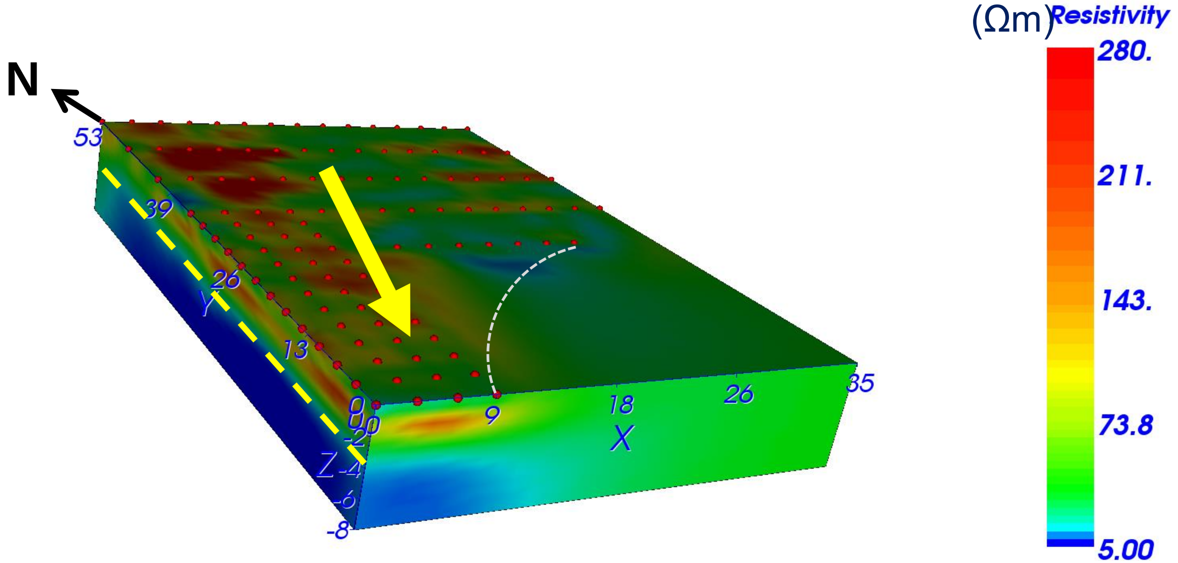
SITE 2b

NAPL pi (-) - SIO (KHARAGPUR)

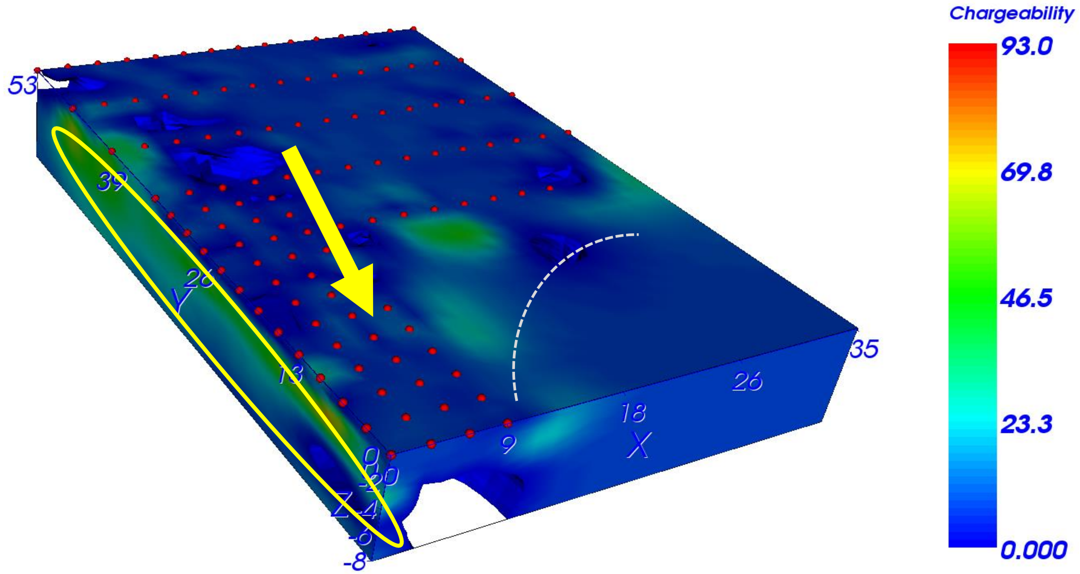


NAPL SATURATION

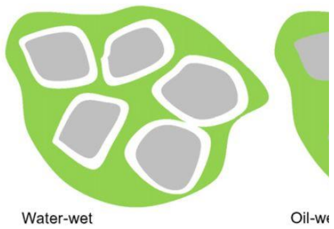
ERT


N
(Ωm)
Resistivity
280.
211.
143.
73.8
5.00
53
39
26
13
Y
0
9
18
26
35
X
Z
-8

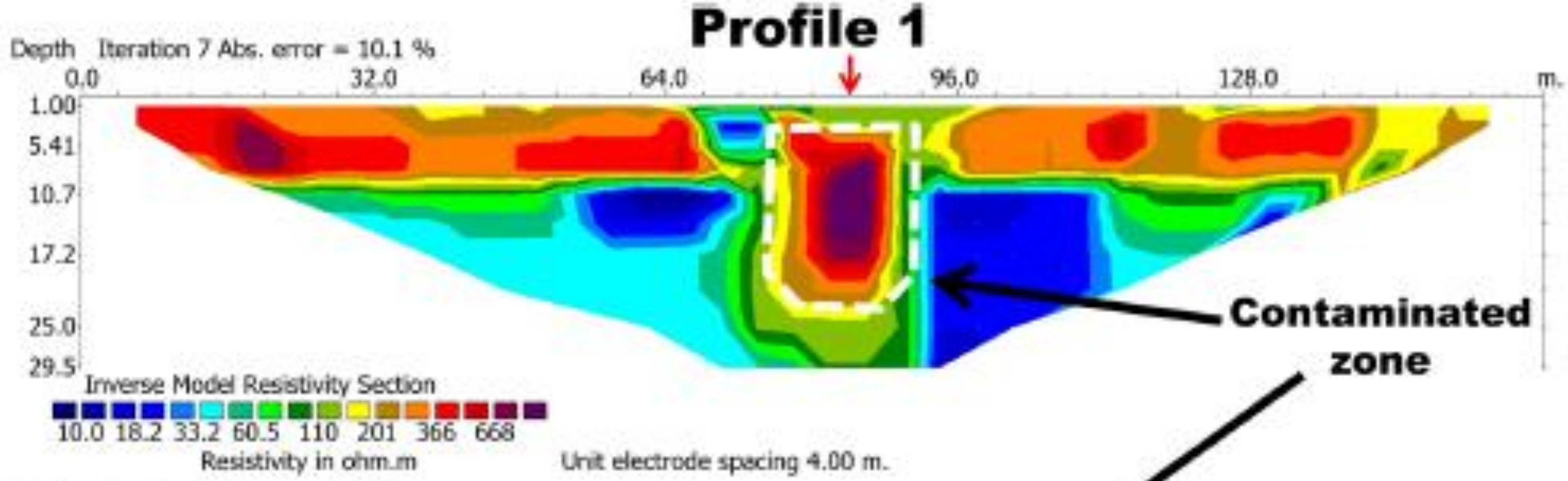
IP


Chargeability
93.0
69.8
46.5
23.3
0.000
53
39
26
13
Y
9
18
26
35
X
Z
-8

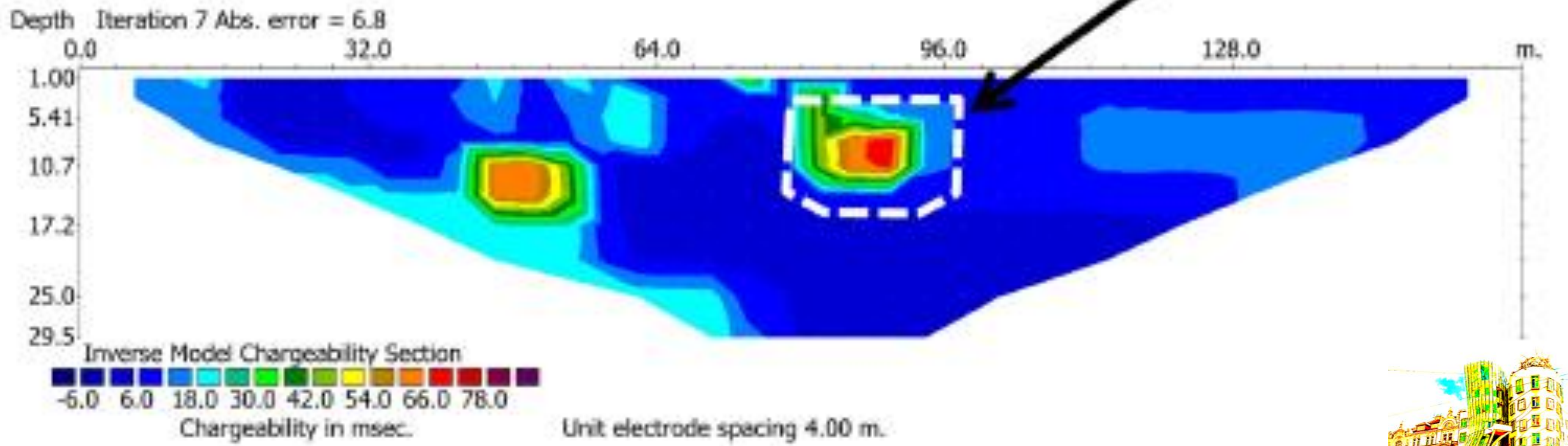
SITE 1


Water-wet

ERT


Profile 1
Depth Iteration 7 Abs. error = 10.1 %
0.0 32.0 64.0 96.0 128.0 m.
1.00
5.41
10.7
17.2
25.0
29.5
Contaminated zone
Inverse Model Resistivity Section
10.0 18.2 33.2 60.5 110 201 366 668
Resistivity in ohm.m
Unit electrode spacing 4.00 m.

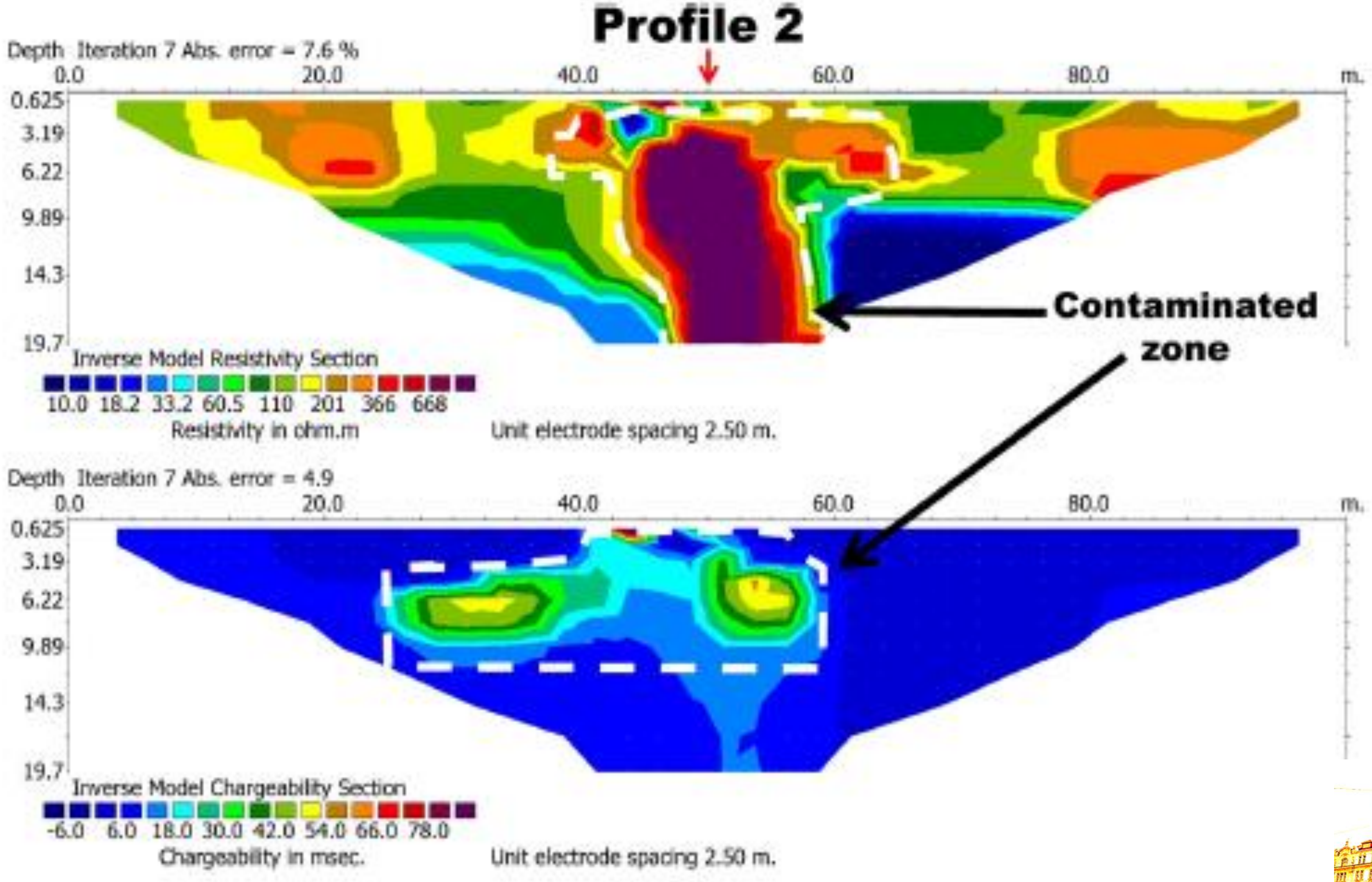
IP


Depth Iteration 7 Abs. error = 6.8
0.0 32.0 64.0 96.0 128.0 m.
1.00
5.41
10.7
17.2
25.0
29.5
Inverse Model Chargeability Section
-6.0 6.0 18.0 30.0 42.0 54.0 66.0 78.0
Chargeability in msec.
Unit electrode spacing 4.00 m.

SITE 2

ERT

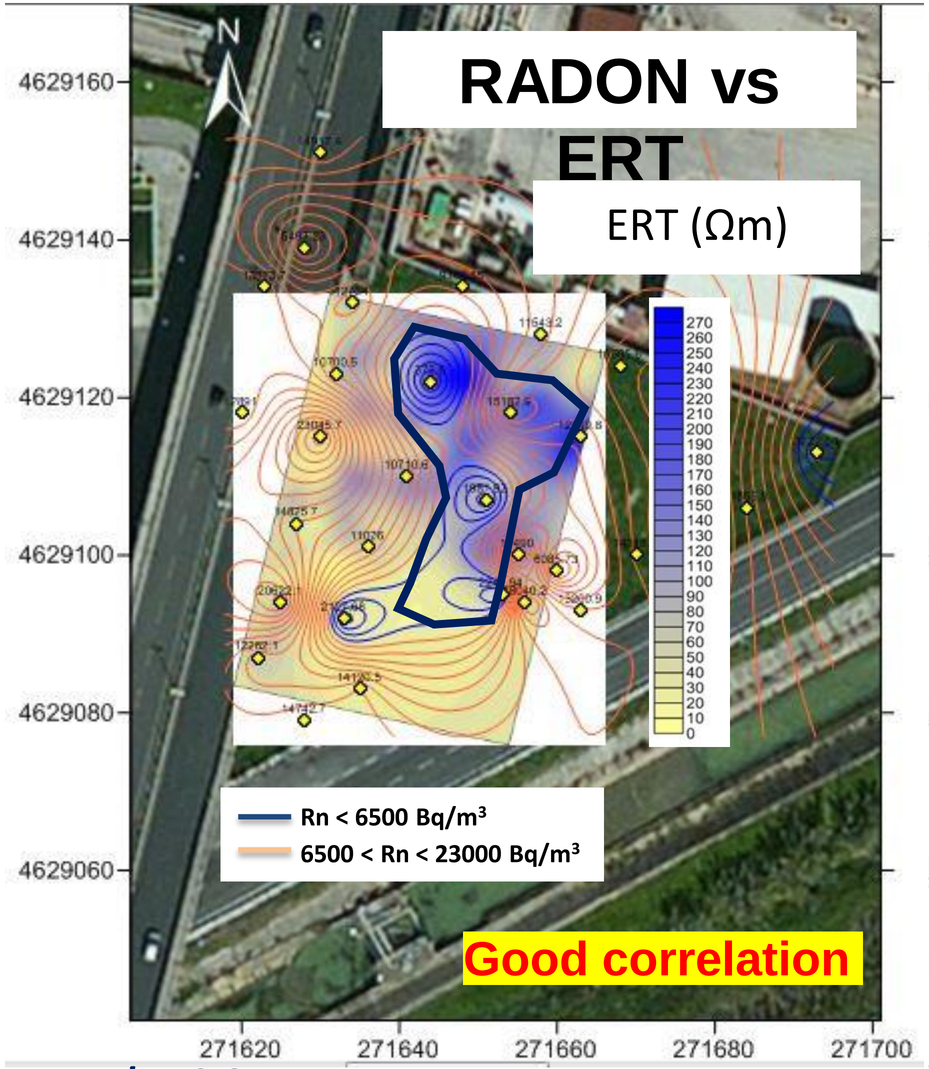
IP

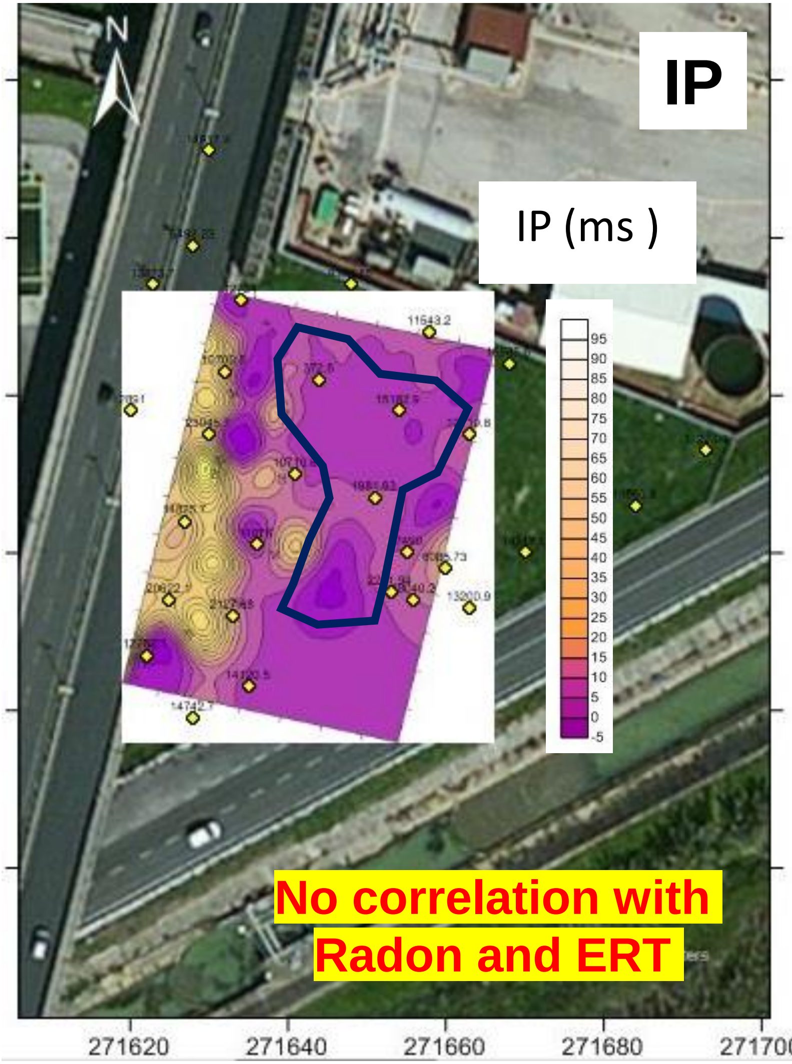


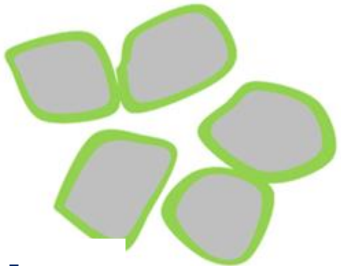
SITE 2b

SITE 1

21 L (17 Kg) of residual kerosene per cubic meter of terrain were calculated with equation 2



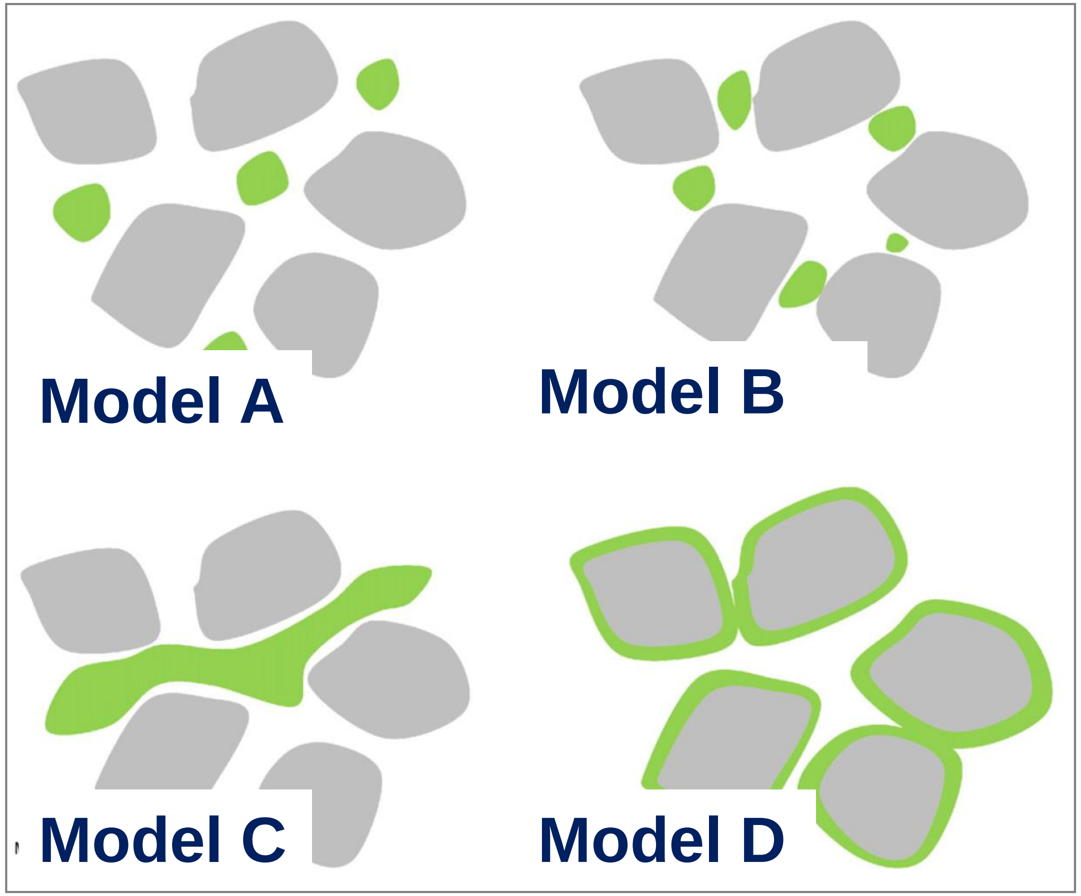




Model D

Johansson et al., 2015

IP



Johansson et al., 2015

Model A: the NAPL is distributed as isolated droplets in the pores.

Model B: the NAPL droplets are trapped in the pore throats.

Model C: the NAPL forms a continuous phase through several pores.

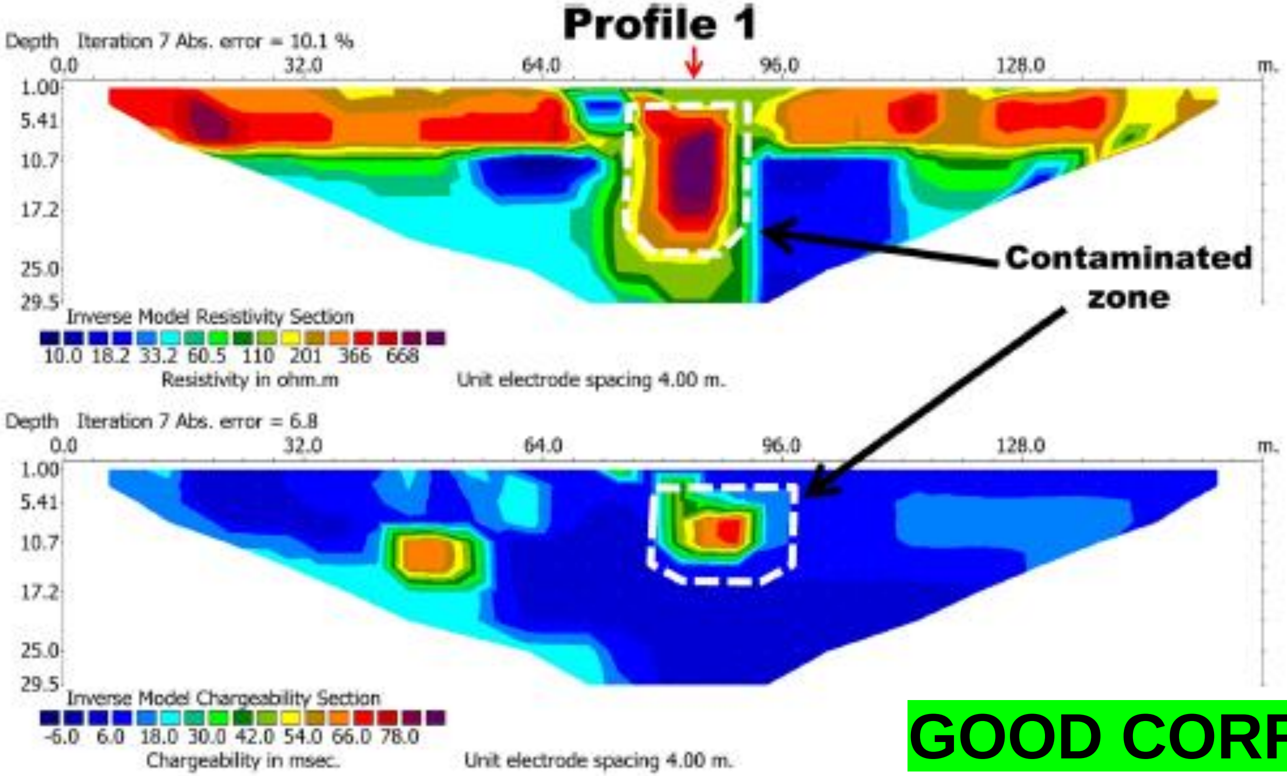
Model D: the NAPL is coating the grains (it prevents from transmitting the charge to the soil matrix, resulting in a low or absent IP response).

SITE 2a

1.5 kg of gasoline per cubic meter of terrain were estimated with equation 2


Model A
Model B

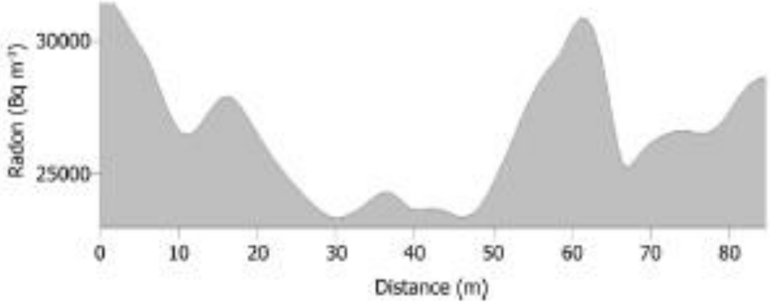
Model C



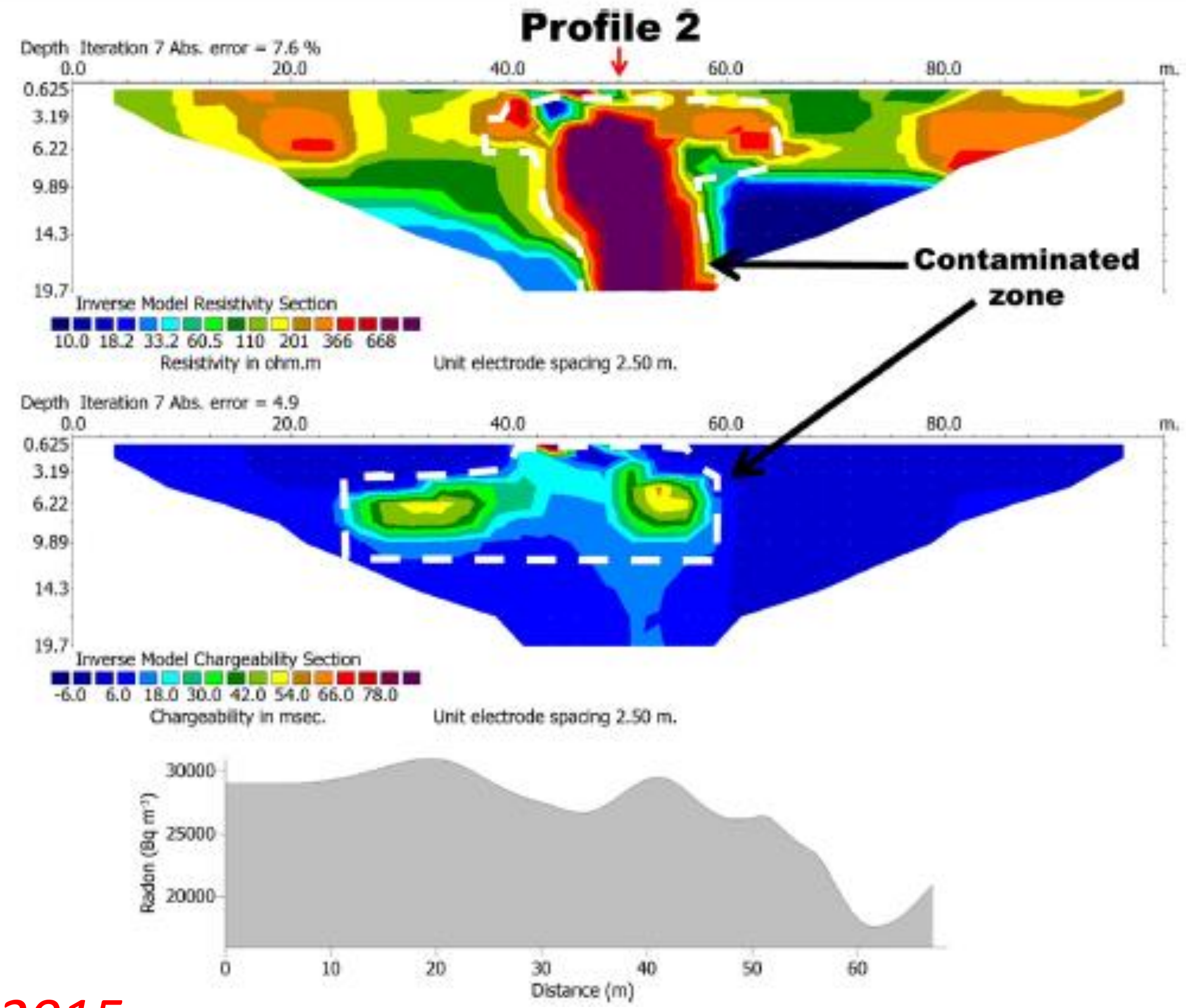
ERT

IP

GOOD CORRELATION



SITE 2a



In site 2a we suppose that the LNAPL is present in the pore spaces or in the pore throats (model A, B or C).

Johansson et al., 2015

Introduction Conclusions

- **Radon-deficit technique shows the location of residual NAPLs in the soil**

- **An evaluation of the fraction of residual NAPL in the soil can be obtained using equation 2**

- **Better results are obtained in winter or at middle latitude locations (such as central Italy) compared with low-latitude sites (such as West Bengal, India) with tropical climate, because both soil radon and volatile organic compounds (such as NAPLs) are more easily released at high temperature, reducing the sensitivity of the radon-deficit technique.**

- **A direct correlation between radon deficit at shallow depth and highest electrical resistivity at greater depth could be used as proxy for the presence of the contaminant in the aquifer.**

- **A progressive reduction of radon deficit over time (corrected for seasonal-induced variations), coupled to a reduction of electrical resistivity and a change of correlation with chargeability, could be used to evaluate the progress of remedial actions such as soil venting or dual-phase extraction. Further research is needed to explore this.**


THANK
YOU