On wellhead protection assessment methods and a case-study application in Montemor-o-Novo, Portugal

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WELLHEAD PROTECTION AREA (WHPA)

Surface and subsurface area around a well, the limits of which are defined to assure that potential contaminants, after reaching groundwater inside or outside protection zones, become **harmless** before reaching the well

Groundwater resources polluting activities are **prohibited** or **restricted** inside the WHPA

Portuguese law (*Decreto-Lei* 382/99, September 22nd)

✓ **Zone of *imediate* protection**

Area around the well in which **all** activities are prohibited, except those for conservation, maintenance or better exploration of the aquifer

✓ Zone of *intermediate* protection

Area around the zone of immediate protection, in which the objective is to protect groundwater resources from microbiological pollution. Installations or activities susceptible of polluting groundwater resources are prohibited or restricted; this includes infiltrating pollutants or favouring the infiltration in the zone close to the well

(*e.g.* agricultural use or cattle rising, main roads and railways, industrial units, sanitary landfills, garages and gas stations).

✓ *Extended* zone of protection

Area around the zone of intermediate protection, in which activities are prohibited or restricted regarding installations capable of polluting groundwater resources with **persistent** pollutants, like organic compounds, radioactive substances, heavy metals, hydrocarbons and nitrates.

(*e.g.* application of persistent pesticides, cemeteries, transport of hydrocarbons, radioactive materials or other hazardous substances, deposits of radioactive materials, chemical industries and refineries).

✓ *Special* protection zones

- Can be set up in the case of karstic or fractured aquifers where preferential flowpaths exist.
- These zones limit areas located outside the WHPA, characterized by hydraulic connection with the well due to the existence of fractures or fissures.
- Restrictions are similar to those applied inside the zone of immediate protection

✓ *Saltwater intrusion* protection zones

- Can be defined in coastal regions.
- Inside them, extraction rates that might lead to an eventual degradation of groundwater quality, by favouring saltwater intrusion, are limited.
- The construction or exploitation of new wells can be limited and the exploitation regime can also be conditioned

- **All** groundwater extraction wells designed for public water supply shall have a zone of ***immediate*** protection.

- Wells extracting water for public supply with a discharge **above 100 m³/day** or serving **more than 500 inhabitants** shall have **three protection zones** (immediate, intermediate and extended).

- Considers six **types of aquifer systems**:

- confined porous (Type 1)
- unconfined porous (Type 2)
- semi-confined porous (Type 3)
- limestone (Type 4)
- igneous or metamorphic fissured formations (Type 5)
- igneous or metamorphic poorly fissured formations (Type 6)

Presents **minimum values** for the dimension of the required protection zones

Type of aquifer system	Immediate zone	Intermediate Zone	Extended zone
Type 1	r = 20 m	r = largest value between 40m and r_1 (t =50 days)	r = largest value between 350m and r_1 (t =3500 days)
Type 2	r = 40 m	r = largest value between 60m and r_2 (t =50 days)	r = largest value between 500m and r_2 (t =3500 days)
Type 3	r = 30 m	r = largest value between 50m and r_3 (t =50 days)	r = largest value between 400m and r_3 (t =3500 days)
Type 4	r = 60 m	r = largest value between 280m and r_4 (t =50 days)	r = largest value between2400m and r_4 (t =3500 days)
Type 5	r = 60 m	r = largest value between 140m and r_5 (t =50 days)	r = largest value between 1200m and r_5 (t =3500 days)
Type 6	r = 40 m	r = largest value between 60m and r_6 (t =50 days)	r = largest value between 500m and r_6 (t =3500 days)

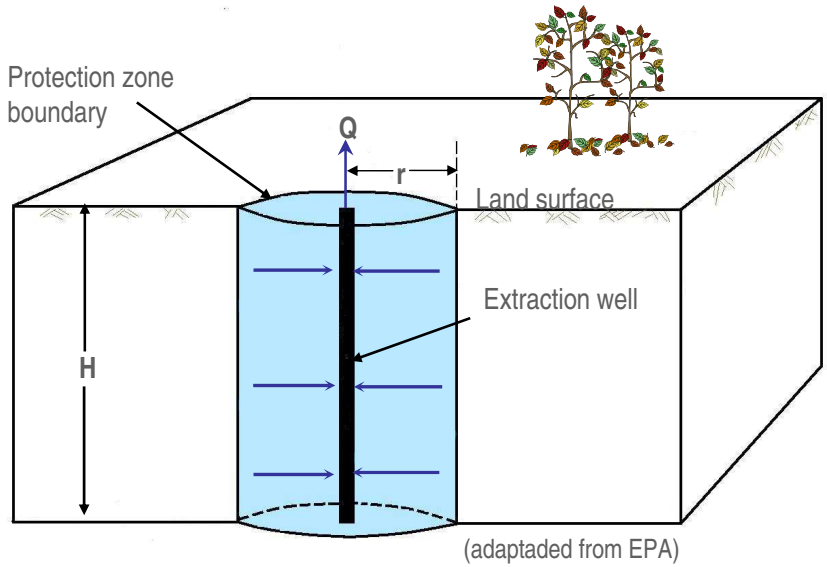
- Immediate zone: fixed values o *r*
- Intermediate zone: *r* is calculated using *t* = 50 days
- Extended zone: *r* is calculated using *t* = 3500 days

Method suggested by the law to calculate *r* :

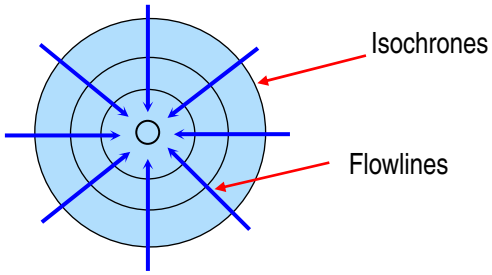
Calculated Fixed Radius (CFR)

- Analytical Methods Applied to the Case-Study Area -

- ***Calculated Fixed Radius (CFR)***



(adaptaded from EPA)



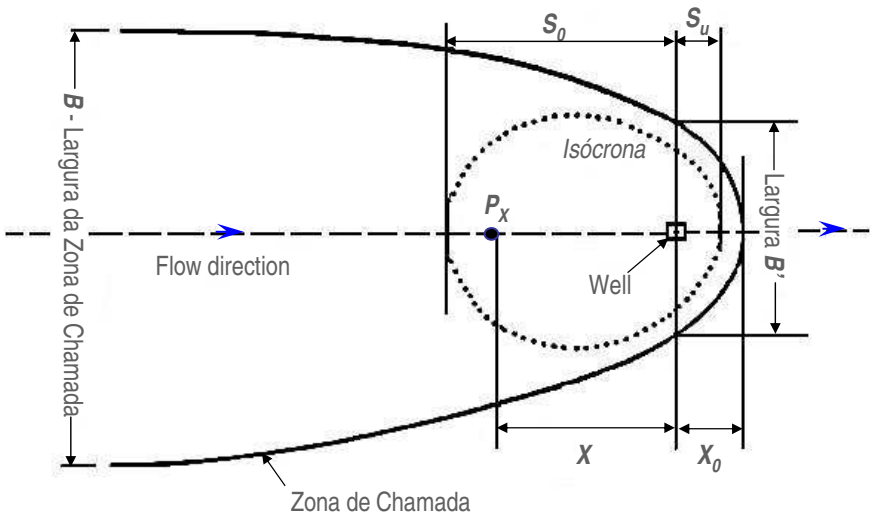
- Does not consider the existence of hydraulic gradient. **Effective porosity** (*n*) is the only hydrogeological parameter considered
- Only appliable when initial water table is (near) **horizontal**
- Cone of depression is a **circle** around the well

$$Q.t = n.\pi.H.r^2 \Leftrightarrow r = \sqrt{\frac{Q.t}{n.H.\pi}}$$

Q - extraction rate (m^3/d)
t – time of travel (d)
n – effective porosity
H – saturated thickness (m)
r – protection zone radius (m)

- Analytical Methods Applied to the Case-Study Area -

- ***Wyssling***



- Considers wells in extraction and the existence of a **sloping hydraulic gradient**
- Besides effective porosity (n), considers **hydraulic conductivity** (K) and **hydraulic gradient** (i)

$$S_0 = \frac{+l + \sqrt{l(l+8X_0)}}{2}$$

S_0 – upgradient protection distance (m)

$$S_u = \frac{-l + \sqrt{l(l+8X_0)}}{2}$$

S_u - downgradient protection distance (m)

$$X_0 = \frac{Q}{2.\pi.K.b.i}$$

$$v_e = \frac{K.i}{n}$$

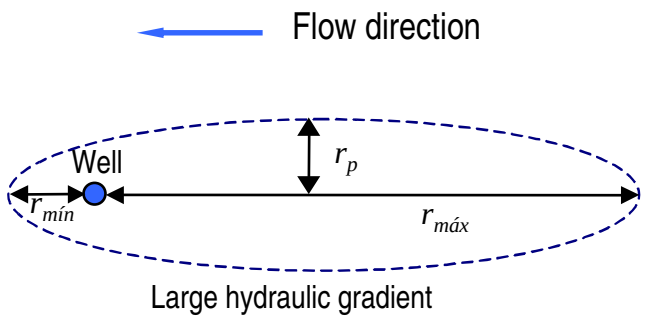
$$l = v_e.t$$

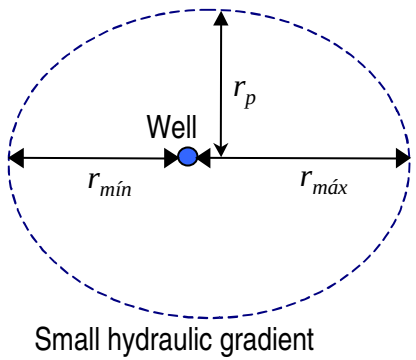
- Analytical Methods Applied to the Case-Study Area -

Krijgsman and Lobo Ferreira method (KLF)

- Developed for the assessment of the **intermediate** protection zone (***t*** = **50 days**) and is an alternative to hydrogeological studies referred to in the Portuguese legislation

- Sloping hydraulic gradient (***i***) → intermediate protection zone is **elipse** shaped and more like a circle if hydraulic gradient is smaller





- Refers a safety minimum protection distance of **25 m**

- **Three** protection zones dimensions:

$$r_{máx} = \frac{(0{,}00002.x^5 - 0{,}00009.x^4 + 0{,}015.x^3 + 0{,}37.x^2 + x)}{F}$$

$$r_{mín} = \frac{(0{,}042x^3 - 0{,}37x^2 + 1{,}04x)}{F}$$

$$r_p = 4\sqrt{\frac{Q}{n\,b}}$$

$$x = 2.K.i.\sqrt{\frac{\pi.b.t}{Q.n}}$$

$$F = \frac{2.\pi.K.b.i}{Q}$$

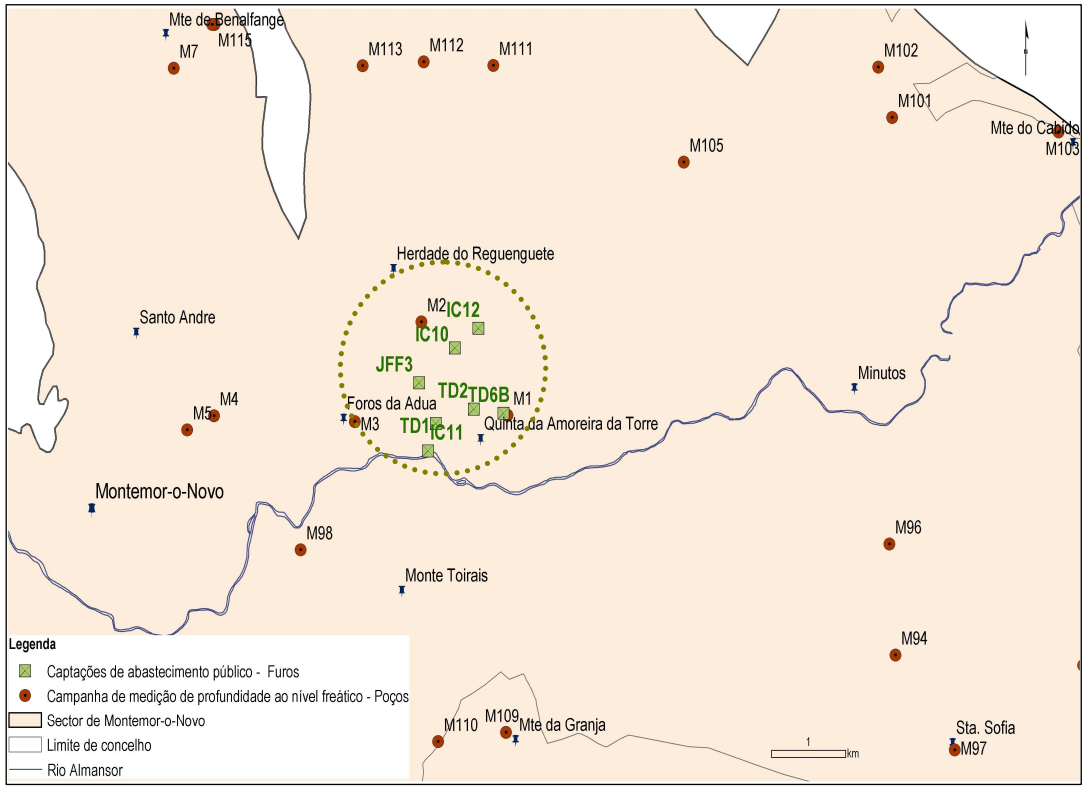
K = hydraulic condutivity (m/d)
n = effective porosity
i = hydraulic gradient
b = saturated thickness (m)
Q = extraction t (m^3/d)
t = travel time (d)

- Numerical Method Applied to the Case-Study Area -

- ***ASMWIN***

- Two dimensional groundwater flow and transport model. Includes a finite-difference flow model and a **particle tracking** module ASMPATH which allows the computation of flow paths and travel times.

- Wells selected as case study -



- Located in Portuguese Southern Region of **Alentejo**
- Belong to **Montemor-o-Novo aquifer**, located in Évora and Montemor-o-Novo municipalities and in **Tejo** and **Sado** river basins

- Montemor-o-Novo aquifer -

- **Igneous** and **metamorphic** constitution
- **Heterogeneous** medium where groundwater flows:

(1) in porous media, in the above altered part,

(2) in double porosity media, in the intermediate zone, and

(3) in fractured media, in the bottom, near the bedrock

- The weathered depth of the aquifer varies between **20 and 60 meters**
- The majority of the wells located in this region explore the **altered formations**
- Due the alteration degree, this **phreatic** aquifer presents **detritic characteristics** (clayey sand) with an effective porosity (*n*) of **10%** (minimum value to use in case of porous formations, according to portuguese legislation)

Wells characteristics (reports)

Furo	M (m)	P (m)	Cota do terreno (m)	Profundidade (m)	Profundidade do nível freático (m)	Profundidade da base do aquifero (m)	Espesssura saturada (m)	Data
TD1	197396	187822	234	31	0.8	22	21.2	12/10/1976
TD2	197910	188000	236	31	0.9	17	16.1	12/10/1976
TD6B	198310	187950	236	31	3.6	31	27.4	17/11/1977
JFF3	197169	188326	238	45	1.56	21	19.44	05/02/1996
IC10	197652	188754	244	49	4.3	-	-	14/02/2000
IC11	197292	187483	219	85	3	-	25	14/02/2000
IC12	197971	188998	250	65	5	-	-	14/02/2000

Hydraulic gradient

Well	Hydraulic gradient
TD1	**0.022**
TD2	**0.014**
TD6B	**0.013**
JFF3	**0.01**
IC10	**0.02**
IC11	**0.023**
IC12	**0.034**

Well	Rate (m^3/d)
TD1	200.8
TD2	278.8
TD6B	6.3
JFF3	25.3
IC10	252
IC11	252
IC12	252

Extraction rates

Hydraulic parameters

Well	T (m^2/d)	$K = T/b$ (m/d)
TD6B	173	6.3
JFF3	115	5.9
others	-	6

- Definition of WHPA using analytical methods -

Travel time values used in the calculations were:

- **24 hours**, for the **immediate** zone (according to ITGE, 1991), despite Portuguese legislation refers a fixed value for this zone radius,
- **50 days**, for the **intermediate** zone (according to Portuguese legislation),
- **3500 days**, for the **extended** zone (also according to Portuguese legislation).

Well	Immediate protection zone				
	CFR	Wyssling		Krijgsman and Lobo Ferreira	
		upgradient	downgradient	upgradient	downgradient
TD1	5.5	6.2	4.9	6.5	4.8
TD2	7.4	7.9	7	8	7.1
TD6B	0.9	1.4	0.5	1.5	0.4
JFF3	2	2.4	1.8	2.5	1.7
IC10	5.7	6.3	5.1	6.6	5
IC11	5.7	6.4	5	6.7	4.9
IC12	5.7	6.8	4.7	7.2	4.5

- Legislation fixes a value of **40 m** for the imediate protection zone radius

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Well	Intermediate protection zone					
	CFR	Wyssling		Krijgsman and Lobo Ferreira		
		upgradient	downgradient	upgradient	downgradient	perpendicular
TD1	38.8	84	18	93.1	25	38.9
TD2	52.5	77.6	35.6	85.4	29.2	52.6
TD6B	6.1	41.7	0.9	43.4	25	25
JFF3	14.4	35.4	5.9	39	25	25
IC10	40.1	80.1	20.1	88.9	25	40.2
IC11	40.1	86.5	18.6	95.9	25	40.2
IC12	40.1	115.9	13.9	126.8	25	40.2

- **CFR** - calculated values indicate eventual under protection on the upgradient side and over protection on the downgradient side when compared with other methods results
- **Upgradient** - values achieved with **Wyssling** and **KLF** methods are very similar
- **Downgradient** - main differences: wells TD6B and JFF3; extraction rates are very small and KLF method suggests a safety minimum protection distance of **25 meters**
- Legislation refers a value of **60 m** for the intermediate protection zone radius

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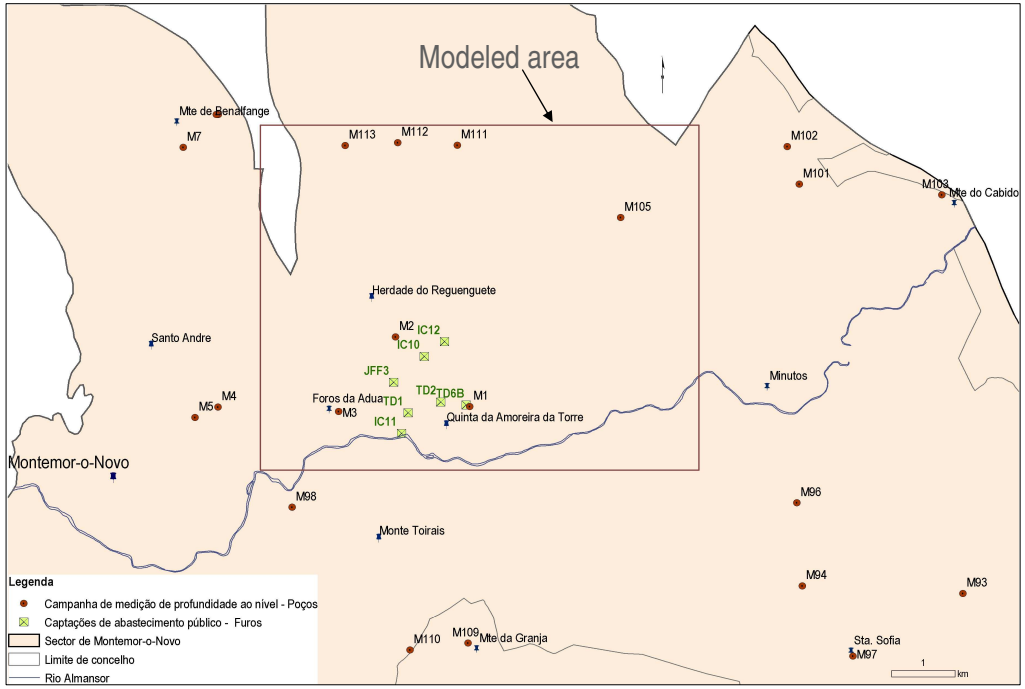
Well	Extended protection zone		
	CFR	Wyssling	
		upgradient	downgradient
TD1	324.9	4627.7	22.7
TD2	439.3	3004.2	64.2
TD6B	50.6	2857.4	0.9
JFF3	120.4	2072	7
IC10	335.2	4226.6	26.6
IC11	335.2	4777.1	23.5
IC12	335.2	7155.7	15.7

- **KLF** method was not appliable
- **CFR** - calculated values indicate eventual under protection on the upgradient side and over protection on the downgradient side when compared with Wyssling method results
- Legislation refers a value of **500 m** for the extended protection zone radius

- Definition of WHPA using numerical method -

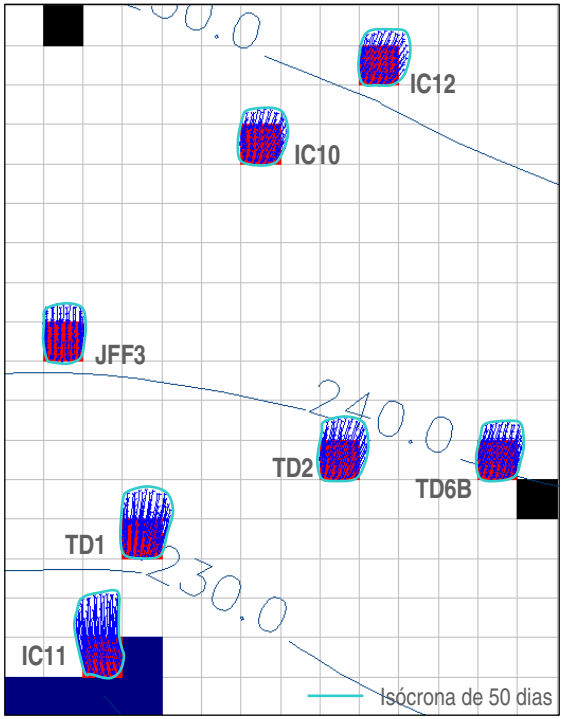


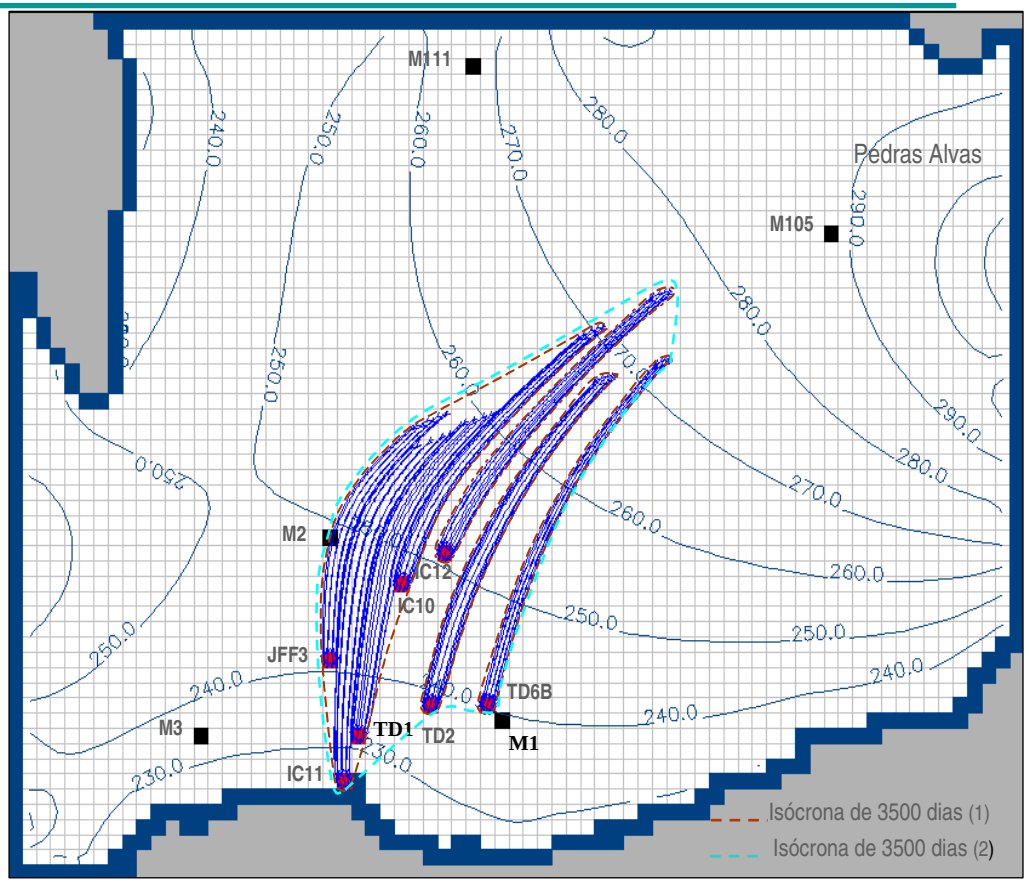
- Modelled area = 39 km^2
- **One** single layer with variable thickness representig the **phreatic** aquifer

Input data

- Initial water table: **DEM**
- Hydraulic conductivity: **6 m/d** in the whole area
- Effective porosity: **0,1**
- Extraction rates: values used in the application of analytical methods, (total extraction rate = **1268 m^3/d**)
- Recharge: **170 mm/year** = 0,0005 m/d (Oliveira, 2002)

ASMWIN - some results





Intermediate protection zone (***t*** = 50 d)

- Downgradient: confirms the small distances achieved with analytical methods

- Upgradient: in some wells similar to CFR; in other wells similar to Wyssling and KLF methods

Extended protection zone (***t*** = 3500 d)

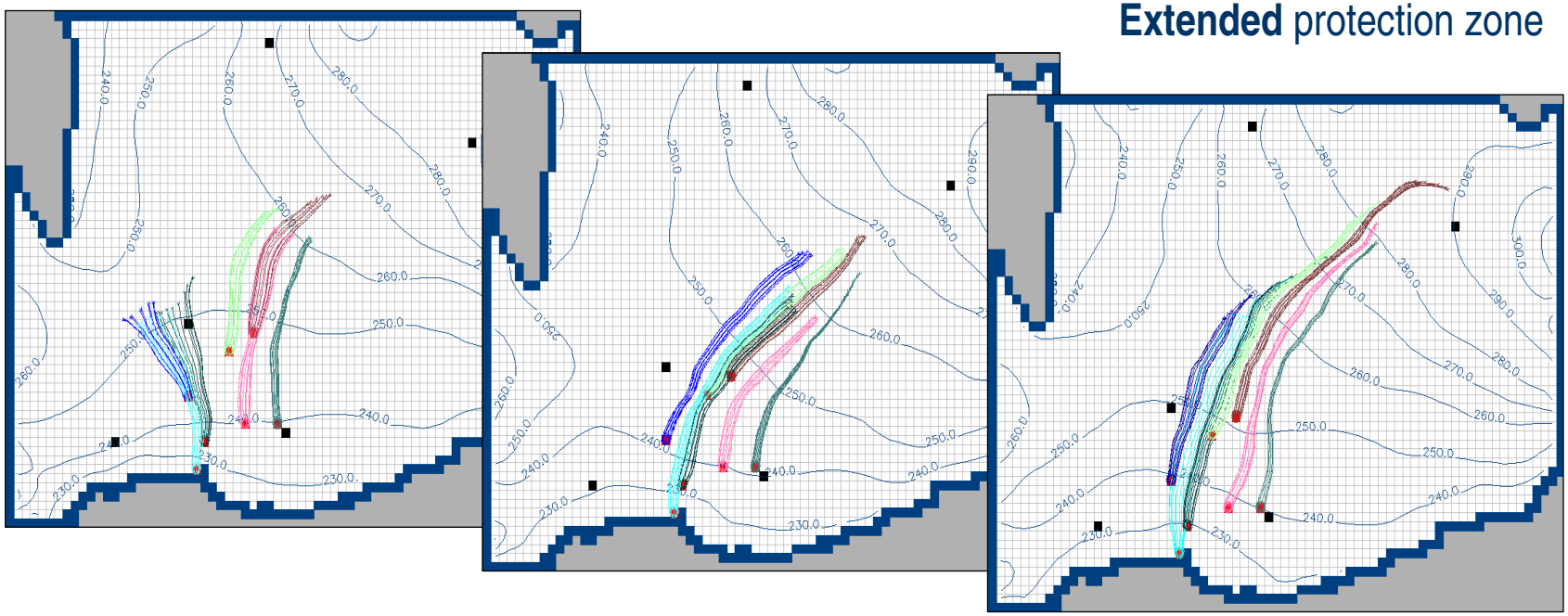
(Upgradient side)

CFR << *ASMWIN* << Wyssling

Stochastic simulations

- Different **heterogeneous** distributions of ***K*** were obtained and reused in ASMWIN and ASMPATH
- Show the **uncertainty** related to the distribution of hydraulic conductivity and the influence of this parameter in pathlines and travel times of pollutant particles.

Extended protection zone



- CONCLUSIONS -

- **Analytical** methods are **user friendly** and **easy** to be applied, and some of them, like Krijgsman and Lobo-Ferreira method, can give **solid solutions** and also more precision in the delineation of WHPA.

- **Numerical** models can also give **robust solutions** in the case of complex hydrogeologic systems but their use implies the availability of large amount of **complex information** and also **more expertise**, which makes their application more expensive.

- Numerical modelling results can be improved by the use of **stochastic** approaches, once they allow generating **heterogeneous distributions of *K***. The new WHPA can assume **different shapes** depending on ***K* spatial distribution**, highlighting the **uncertainty** related with the distribution of this parameter inside the aquifer and also its importance in the definition of WHPA.