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 immediate 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 \(100 \text{ m}^3/\text{day}\) 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.
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<table>
<thead>
<tr>
<th>Type of aquifer system</th>
<th>Immediate zone</th>
<th>Intermediate Zone</th>
<th>Extended zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>$r = 20,m$</td>
<td>$r = \text{largest value between } 40,m \text{ and } r_1$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 350,m \text{ and } r_1$ (t $= 3500,\text{days}$)</td>
</tr>
<tr>
<td>Type 2</td>
<td>$r = 40,m$</td>
<td>$r = \text{largest value between } 60,m \text{ and } r_2$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 500,m \text{ and } r_2$ (t $= 3500,\text{days}$)</td>
</tr>
<tr>
<td>Type 3</td>
<td>$r = 30,m$</td>
<td>$r = \text{largest value between } 50,m \text{ and } r_3$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 400,m \text{ and } r_3$ (t $= 3500,\text{days}$)</td>
</tr>
<tr>
<td>Type 4</td>
<td>$r = 60,m$</td>
<td>$r = \text{largest value between } 280,m \text{ and } r_4$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 2400,m \text{ and } r_4$ (t $= 3500,\text{days}$)</td>
</tr>
<tr>
<td>Type 5</td>
<td>$r = 60,m$</td>
<td>$r = \text{largest value between } 140,m \text{ and } r_5$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 1200,m \text{ and } r_5$ (t $= 3500,\text{days}$)</td>
</tr>
<tr>
<td>Type 6</td>
<td>$r = 40,m$</td>
<td>$r = \text{largest value between } 60,m \text{ and } r_6$ (t $= 50,\text{days}$)</td>
<td>$r = \text{largest value between } 500,m \text{ and } r_6$ (t $= 3500,\text{days}$)</td>
</tr>
</tbody>
</table>

- **Immediate zone**: fixed values of $r$
- **Intermediate zone**: $r$ is calculated using $t = 50\,\text{days}$
- **Extended zone**: $r$ is calculated using $t = 3500\,\text{days}$

### Method suggested by the law to calculate $r$:

**Calculated Fixed Radius (CFR)**
- Analytical Methods Applied to the Case-Study Area -

**Calculated Fixed Radius (CFR)**

- 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

\[
Qt = n \pi H r^2 \iff r = \sqrt{\frac{Qt}{nH\pi}}
\]

\[
\begin{align*}
Q & \quad \text{extraction rate} \ (m^3/d) \\
t & \quad \text{time of travel} \ (d) \\
n & \quad \text{effective porosity} \\
H & \quad \text{saturated thickness} \ (m) \\
r & \quad \text{protection zone radius} \ (m)
\end{align*}
\]
- 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)

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

\[
v_e = \frac{K . i}{n}
\]

\[
l = v_e . t
\]
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- **Analytical Methods Applied to the Case-Study Area** -

  - **Krijgsman and Lobo Ferreira method (KLF)**
    
    - Developed for the assessment of the intermediate protection zone \( t = 50 \text{ days} \) and is an alternative to hydrogeological studies referred to in the Portuguese legislation.
    
    - Sloping hydraulic gradient \( i \) indicates that the intermediate protection zone is elliptical shaped and more like a circle if hydraulic gradient is smaller.
    
    - Refers a safety minimum protection distance of **25 m**
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- Three protection zones dimensions:

\[ r_{\text{max}} = \frac{(0,00002 \cdot x^5 - 0,00009 \cdot x^4 + 0,015 \cdot x^3 + 0,37 \cdot x^2 + x)}{F} \]

\[ r_{\text{min}} = \frac{(0,042 \cdot x^3 - 0,37 \cdot x^2 + 1,04 \cdot x)}{F} \]

\[ r_p = 4 \sqrt{\frac{Q}{n \cdot b}} \]

- **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.

  

\[ x = 2 \cdot K \cdot i \cdot \frac{\pi \cdot b \cdot t}{Q \cdot n} \]

\[ F = \frac{2 \cdot \pi \cdot K \cdot b \cdot i}{Q} \]

- \( K = \) hydraulic conductivity (m/d)
- \( n = \) effective porosity
- \( i = \) hydraulic gradient
- \( b = \) saturated thickness (m)
- \( Q = \) extraction t (m³/d)
- \( t = \) travel time (d)
- 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)
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Wells characteristics (reports)

<table>
<thead>
<tr>
<th>Furo</th>
<th>M (m)</th>
<th>P (m)</th>
<th>Cota do terreno (m)</th>
<th>Profundidade (m)</th>
<th>Profundidade do nível freático (m)</th>
<th>Profundidade da base do aquífero (m)</th>
<th>Espessura saturada (m)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD1</td>
<td>197396</td>
<td>187822</td>
<td>234</td>
<td>31</td>
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<td>22</td>
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<tr>
<td>TD2</td>
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<td>188000</td>
<td>236</td>
<td>31</td>
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<td>17</td>
<td>16.1</td>
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<td>TD6B</td>
<td>198310</td>
<td>187950</td>
<td>236</td>
<td>31</td>
<td>3.6</td>
<td>31</td>
<td>27.4</td>
<td>17/11/1977</td>
</tr>
<tr>
<td>JFF3</td>
<td>197169</td>
<td>188326</td>
<td>238</td>
<td>45</td>
<td>1.56</td>
<td>21</td>
<td>19.44</td>
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<tr>
<td>IC10</td>
<td>197652</td>
<td>188754</td>
<td>244</td>
<td>49</td>
<td>4.3</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
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<td>188998</td>
<td>250</td>
<td>65</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>14/02/2000</td>
</tr>
</tbody>
</table>

Hydraulic parameters

<table>
<thead>
<tr>
<th>Well</th>
<th>$T$ (m²/d)</th>
<th>$K = \frac{T}{b}$ (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD6B</td>
<td>173</td>
<td>6.3</td>
</tr>
<tr>
<td>JFF3</td>
<td>115</td>
<td>5.9</td>
</tr>
<tr>
<td>others</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

Hydraulic gradient

<table>
<thead>
<tr>
<th>Well</th>
<th>Hydraulic gradient (m³/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD1</td>
<td>0.022</td>
</tr>
<tr>
<td>TD2</td>
<td>0.014</td>
</tr>
<tr>
<td>TD6B</td>
<td>0.013</td>
</tr>
<tr>
<td>JFF3</td>
<td>0.01</td>
</tr>
<tr>
<td>IC10</td>
<td>0.02</td>
</tr>
<tr>
<td>IC11</td>
<td>0.023</td>
</tr>
<tr>
<td>IC12</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Extraction rates
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- 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).

<table>
<thead>
<tr>
<th>Well</th>
<th>Immediate protection zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CFR</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>TD1</td>
<td>5.5</td>
</tr>
<tr>
<td>TD2</td>
<td>7.4</td>
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<td>JFF3</td>
<td>2</td>
</tr>
<tr>
<td>IC10</td>
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</tr>
<tr>
<td>IC11</td>
<td>5.7</td>
</tr>
<tr>
<td>IC12</td>
<td>5.7</td>
</tr>
</tbody>
</table>

- Legislation fixes a value of **40 m** for the immediate protection zone radius
### Intermediate protection zone

<table>
<thead>
<tr>
<th>Well</th>
<th>CFR</th>
<th>Wyssling</th>
<th>Krijgsman and Lobo Ferreira</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upgradient</td>
<td>downgradient</td>
</tr>
<tr>
<td>TD1</td>
<td>38.8</td>
<td>84</td>
<td>18</td>
</tr>
<tr>
<td>TD2</td>
<td>52.5</td>
<td>77.6</td>
<td>35.6</td>
</tr>
<tr>
<td>TD6B</td>
<td>6.1</td>
<td>41.7</td>
<td>0.9</td>
</tr>
<tr>
<td>JFF3</td>
<td>14.4</td>
<td>35.4</td>
<td>5.9</td>
</tr>
<tr>
<td>IC10</td>
<td>40.1</td>
<td>80.1</td>
<td>20.1</td>
</tr>
<tr>
<td>IC11</td>
<td>40.1</td>
<td>86.5</td>
<td>18.6</td>
</tr>
<tr>
<td>IC12</td>
<td>40.1</td>
<td>115.9</td>
<td>13.9</td>
</tr>
</tbody>
</table>

- **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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<table>
<thead>
<tr>
<th>Well</th>
<th>CFR</th>
<th>Wyssling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upgradient</td>
</tr>
<tr>
<td>TD1</td>
<td>324.9</td>
<td>4627.7</td>
</tr>
<tr>
<td>TD2</td>
<td>439.3</td>
<td>3004.2</td>
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<tr>
<td>TD6B</td>
<td>50.6</td>
<td>2857.4</td>
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<tr>
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<td>120.4</td>
<td>2072</td>
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<td>IC10</td>
<td>335.2</td>
<td>4226.6</td>
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<td>IC11</td>
<td>335.2</td>
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</tr>
<tr>
<td>IC12</td>
<td>335.2</td>
<td>7155.7</td>
</tr>
</tbody>
</table>

• **KLF** method was not applicable

• **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 -

**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 m³/d**)
- Recharge: **170 mm/year = 0.0005 m/d** (Oliveira, 2002)

- Modelled area = **39 km²**
- **One single layer with variable thickness** representig the phreatic aquifer
**ASMWIN - some results**

**Intermediate protection zone \( t = 50 \text{ d} \)**
- 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 \( t = 3500 \text{ d} \)**
(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.
- 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.