Assessment of groundwater vulnerability to pollution by pesticides in catchment scale

Ireneusz KAJEWSKI
Institute of Environmental Engineering, Agricultural University, Wroclaw

ABSTRACT

In the paper DRASTIC method and Attenuation Factor technique have been applied for assessment the groundwater vulnerability to pollution by pesticides within the small, typical agricultural catchment of Polish lowlands. According to DRASITC approach within the studied basin almost the entire catchment is high and very high susceptible to pollution by pesticides. According to Attenuation Factor method the risk of application of pesticides is relatively high at only less than 1% of studied basin. The studied example shows clearly that in assessments of groundwater vulnerability to pollution chemical properties of pesticides play extremely important role.

1. Introduction

Land productivity was, and still is, improved by using pesticides. Progress towards effective and, especially safe agrochemicals was very slow until the period after the Second World War. The number of pesticides, and their use have increased dramatically over the past four decades, revolutionizing agricultural practices and improving crop yields. Numerous surveys have stated that the yield and quality of crops would be very significantly reduced without the use of pesticides. In European Union an average consumption of pesticides exceeds currently 4.5 kg of active ingredients per hectare of agricultural land. Consumption of pesticides in Poland is much lower and reaches 0.5-0.6 kg of active ingredients per hectare, more then 60% of this amount are herbicides.

The widespread use of synthetic organic pesticides over the past 40 years has led to their frequent detection in groundwater and surface water (Barbash et al. 1999), the most often pesticides detected in shallow groundwater are herbicides.

The most of developed countries have legal regulations to control the use of pesticides as well as a number of criteria for pesticide levels in food and water bodies. For example, the European Union Council Directive 98/83/EC of 3 November 1998 limits the concentration of any single pesticide in drinking water to a level of 0.1 μg/l (with four exceptions: for aldrin, dieldrin,heptachlor and heptachlor epoxide the parametric value is 0.03 μg/l) and for total pesticides 0.5 μg/l.

According to Polish Ministry of Environment (1999) the share of groundwater for total water intake is 14.2% This number increases though to about 40% when cooling waters are subtracted. After adding the intake from individual house wells not measured by statistics, the share of groundwater grew to about 45%. About 50% of city inhabitants and 95% of rural inhabitants, (more than 25 million people) use groundwater. About 4.0 to 5.5 million of these people use water from shallow, often dug wells, so analysis of assessment groundwater vulnerability to pollution by pesticides should be an important part of hydrogeological practice.

2. Main factors affecting the transfer of pesticides to groundwater

The fate of pesticides in unsaturated and saturated zone is a complex process influenced by compound physical and chemical properties, management practices, climatic conditions, soil and groundwater properties Assessment of potential for water contamination by a chemical and decisions regarding its application should not be based only on the intrinsic product properties. Movement of contaminants strongly depends also on local soil, hydrogeologic and weather conditions.

3. Methods of assessment groundwater vulnerability to pollution

Because of very complicated nature of pesticides migration through the vadose zone a variety of criteria and indices have been used to identify pesticides and land regions where potential exists for pesticide residues to enter groundwater table.

Simple methods (indices) of assessment groundwater vulnerability to pollution by pesticides which are based on chemical properties of these compounds only are reviewed by Rao et al. (1985). In these methods such properties of pesticides are taken into account as solubility in water, susceptibility to sorption by organic carbon, vapor pressure and half-life time in the soil environment. Such methods are designated for pesticide ranking only and are useless for assessment at larger – aquifer or basin scales, where large heterogeneity of soil properties, and other factors exists.

3.1 DRASTIC index

DRASTIC method was developed in US Environmental Protection Agency (Aller et al. 1984). This technique relies on readily available information for a studied site, catchment or region. The acronym DRASTIC refers to the seven factors utilized in rating system:

- depth to groundwater table
- recharge rate of the aquifer
- aquifer media
- soil media
- topography (slope of the soil surface)
- impact of vadose zone
- hydraulic conductivity of the aquifer

Each of factors is assigned a value based on a rating system, Tables 1-7 (Aller et al. 1984).

Table 1. Ranges and ratings for depth to groundwater

Range of depth [m]	*Rating D_R*
0.0 – 1.5	10
1.5 – 4.5	9
4.5 – 9.0	7
9.0 – 15.0	5
15.0 – 22.0	3
22.0 – 30.0	2
> 30	1

Table 2. Ranges and ratings for net recharge

Range of recharge [mm/year]	*Rating R_R*
0 – 50	1
50 – 100	3
100 – 180	6
180 – 250	8
> 250	9

Table 3. Ranges and ratings for aquifer media

Aquifer types	*Rating range A_R*	*Typical rating A_R*
Massive shale	1 – 3	2
Metamorphic/Igneous	2 – 5	3
Weathered Metamorphic/Igneous	3 – 5	4
Glacial till	4 – 6	5
Bedded sandstone, limestone, and shale sequences	5 – 9	6
Massive sandstone	4 – 9	6
Massive limestone	4 – 9	6
Sand and gravel	4 – 9	8
Basalt	2 – 10	9
Karst limestone	9 – 10	10

Table 4. Ranges and ratings for soil media

Soil types	*Rating S_R*
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Nonshrinking and nonaggragated clay	1

Table 5. Ranges and ratings for topography

Soil surface slope [%]	*Rating T_R*
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
> 18	1

Table 6. Ranges and ratings for impact of vadose zone

Media type	*Rating range I_R*	*Typical rating I_R*
Confining layer	1	1
Silt/clay	2 – 6	3
Shale	2 – 5	3
Limestone	2 – 7	6
Sandstone	4 – 8	6
Bedded sandstone, limestone, and shale sequences	4 – 8	6
Sand and gravel with significant silt and clay	4 – 8	6
Metamorphic/igneous	2 – 8	4
Sand and gravel	6 – 9	8
Basalt	2 – 10	9
Karst limestone	8 – 10	10

Table 7. Ranges and ratings for hydraulic conductivity

Hydraulic conductivity [cm/s]	*Rating C_R*
$5.0 \times 10^{-5} - 5.0 \times 10^{-3}$	1
$5.0 \times 10^{-3} - 1.5 \times 10^{-2}$	2
$1.5 \times 10^{-2} - 3.3 \times 10^{-2}$	4
$3.3 \times 10^{-2} - 5.0 \times 10^{-2}$	6
$5.0 \times 10^{-2} - 1.0 \times 10^{-1}$	8
$> 1.0 \times 10^{-1}$	10

Factors listed in Tables 1-7 are adjusted by a weighting factors, see Table 8, and summed to calculate DRASTIC index:

$$DRASTIC = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W \qquad (1)$$

where the subscripts R and W refers to the rating and weighting factors respectively.

Table 8. Weighting factors for pesticide DRASTIC

DRASTIC factor	*Weighting factor*
Depth to groundwater table	5
Net recharge	4
Aquifer media	3
Soil media	5
Topography	3
Impact of the vadose zone	4
Hydraulic conductivity	2

To utilize the DRASTIC method, the studied region must be divided into smaller subregions based on available hydrogeological data, in which the factors considered can be regarded as homogeneous. A grid cell subdivision is very often used and thus raster GIS modeling is well suited for performing DRASTIC analyses. Next, for each subregion (cell) pesticide DRASTIC index, Equation (1), is calculated and the map of spatial distribution of the index can be generated. Interpretation of such map is performed on a relative scale. The site where DRASTIC index is higher is more susceptible to pollution by pesticides than others. According to Engel & Navulur (1998), areas, where pesticide DRAS-

TIC index is in the range 141-200 are regarded as high vulnerable to pollution. Regions with the index > 200 are very high susceptible to contamination.

Pesticide DRASTIC index is used to prioritize various areas with respect to their vulnerability to pollution by pesticides. It should be noted that the DRASTIC scheme does not explicitly take into account the pesticide properties. For this reason, comparison can only be made between each area susceptibility to the pesticides as general, not between various pesticides.

3.2 Attenuation Factor approach

Rao et al. (1985) developed another vulnerability assessment technique which takes into account chemical properties of the pesticides as well as some natural properties of the assessed site. The technique utilizes an attenuation factor (AF) as a quantitative index for ranking organic contaminants based on their potential for migrating from soil surface to the groundwater table. Attenuation factor represents the fraction of the compound remaining after it has traveled through vadose zone to water table.

The AF is calculated by:

$$AF = \exp\left(-\frac{0.693\, l\, RF\, \theta_{FC}}{q\, t_{1/2}} \right) \tag{2}$$

where l = distance from the soil surface to groundwater table [L]; θ_{FC} = soil-water content at field capacity [-]; q = net annual groundwater recharge [L/T]; $t_{1/2}$ = half-live time of compound in soil [T], and retardation factor (*RF)*:

$$RF = 1 + \frac{\rho_b\, f_{oc}\, K_{oc}}{\theta_{FC}} + \frac{n_a\, K_H}{\theta_{FC}} \tag{3}$$

where ρ_b = dry soil bulk density [M/L^3]; f_{oc} = organic carbon content in the soil expressed as mass fraction [-]; K_{oc} = pesticide sorption coefficient [L^3/M]; n_a = air content in the soil expressed as volume fraction [-]; K_H = air-water partitioning coefficient (Henry's Law constant) [-]. Chemical properties of pesticides one can find in relevant literature (Samiullah 1990, Rao et al. 1985).

The AF accounts for the most important migration processes – advection, sorption, volatilization and biochemical transformation (decay). The processes of sorption an volatilization of the compound are accounted by the retardation factor RF, given by Equation (3). Equation (2) for AF accounts for biotransformation (a first-order decay relationship) and stationary advective water flow through unsaturated zone.

Rubin et al. (1998), recommends some qualitative numerical values for interpretation of the results of AF analysis, given in the Table 9.

Table 9. Qualitative designations for Attenuation Factor (AF)

Ranges of Attenuation Factor	*Probability of groundwater contamination*
$< 1.0\ 10^{-4}$	Very unlikely
$1.0 \times 10^{-4} - 1.0 \times 10^{-2}$	Unlikely
$1.0 \times 10^{-2} - 1.0 \times 10^{-1}$	Moderately likely
$1.0 \times 10^{-1} - 2.5 \times 10^{-1}$	Likely
$2.5 \times 10^{-1} - 1.0$	Very likely

Similarly as in the case of DRASTIC analyses, also Attenuation Factor analysis can be easily conducted using raster GIS modeling

4. Characteristics of studied catchment

Example catchment “Ciesielska Woda” is typical small agricultural basin of Lower Silesia. The area of the catchment is 33 km^2, nearly 77% of its area is utilized as an arable lands and about 9% as grasslands.

All necessary data for calculations of pesticide DRASTIC index and Attenuation Factor index were obtained from multidisciplinary (hydrological, pedological and climatological) field studies and are stored in the form of ArcInfo coverages.

The surface of the catchment is relatively flat, 80% of the area has soil surface slopes in the range from 0 to 2%. Groundwater depth ranges from less than 0.5 m to more than 10 meters. The aquifer is composed mainly from medium and coarse sand. There were distinguished 9 main soil types over the investigated area, from sand and gravel to loamy soils. The organic carbon in the soils is connected with soil type and varies from 0.1% to 1.6%.

All necessary analyses, presented in the next chapter were done with ArcView GIS system using grid maps of uniform cell size 10×10 meters.

5. Results of assessments

Figure 1 shows the distribution of pesticide DRASTIC index over the studied region. According to the numerical analysis of the map it was stated that 38 % of the area has DRASTIC index in the range from 140 to 180 and 61 % in the range from 180 to 200. Nearly entire area has DRASTIC index value more than 140, it means that the risk of application of pesticides varies, according to Engel & Navulur (1998) from high to very high.

The results of analyses of groundwater vulnerability to contamination by pesticides using DRASTIC method seems to be over assessed and it should be noted again, that according this method groundwater vulnerability to pollution is the same for each compound.

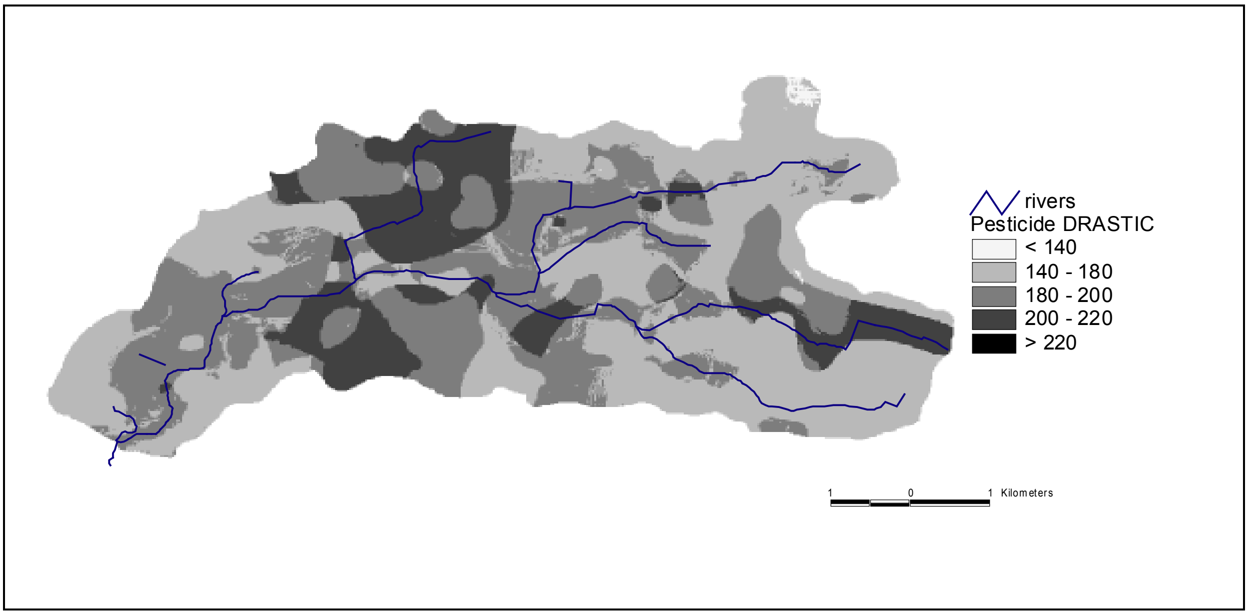

Figure 1. Groundwater pollution vulnerability as determined by DRASTIC analysis

For the analyses with Attenuation Factor method, as example pesticide atrazine was chosen. The following chemical properties of this herbicide were adopted, according to data published by Rubin et al. (1998):

- sorption coefficient by organic carbon $K_{oc} = 0.16\ m^3/kg$,
- dimensionless Henry's law constant $K_H = 2.5 \times 10^{-7}$
- half-life time in the soil $t_{1/2} = 70$ days

Spatial distribution of AF over the catchment shows Figure 2.

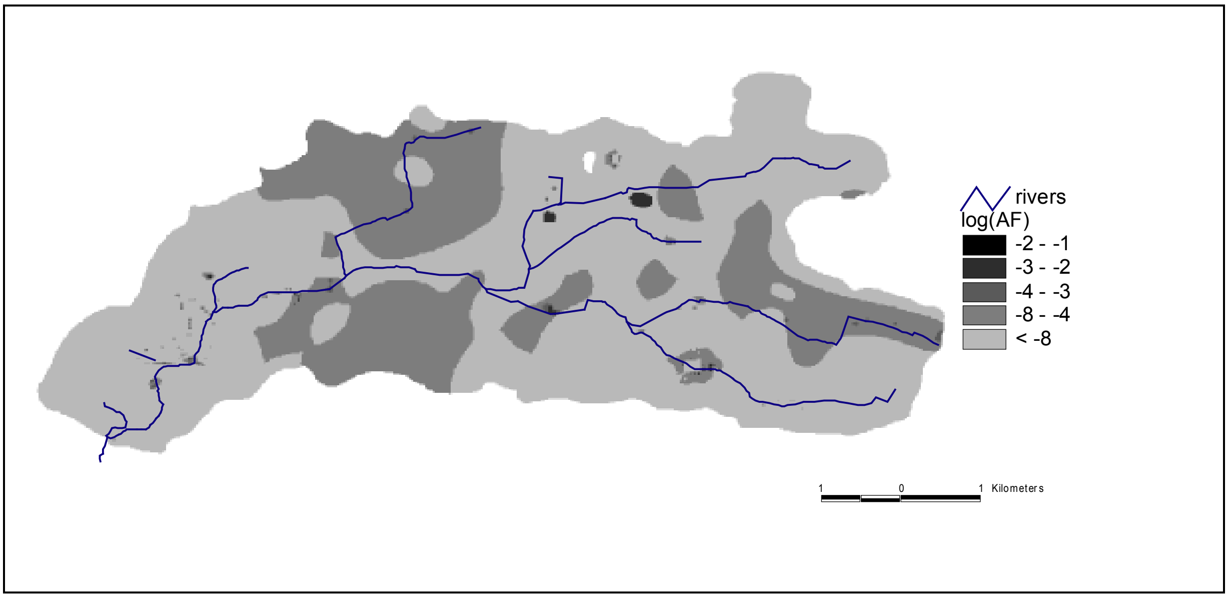

Figure 2. Groundwater pollution vulnerability as determined by Attenuation factor analysis

According to numerical analysis of the map 99.4% of the catchment area possess very low value of AF (< 10^{-4}), it means, that probability of contamination of groundwater can be regarded as extremely low.

6. Conclusions

Two methods of assessment are very easy to perform using GIS-based analysis, but it requires very detailed maps of studied region with high resolution.

The results of assessments groundwater vulnerability to pollution by pesticides obtained using DRASTIC and AF method differs very significantly. It seems, that results of DRASTIC analysis are over assessed, ranges proposed by Engel & Navulur (1998) should be reviewed and verified. AF method seems to be much closer to reality, because it utilizes not only hydrological characteristics of the studied site but also chemical properties of pesticides.

7. References

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