

Assessing aquifer vulnerability to pollution in the Piana Campana

By:

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Summary

This exercise deals with the assessment of aquifer vulnerability to pollution in the Piana Campana, southern Italy. Maps of aquifer vulnerability to pollution are becoming more and more in demand because, on the one hand groundwater represents the main source of drinking water, and on the other hand high concentrations of human/economic activities, e.g. industrial, agricultural, cattle-breeding, represent real or potential sources of groundwater contamination.

In such a context, pollution vulnerability maps are useful either for land use planning or groundwater quality monitoring. For the former, those maps provide information to law-makers, land use planners and developers as to the spatial distribution of areas which are more or less vulnerable to pollution. For the latter, groundwater vulnerability maps can be used for identifying areas that need more detailed analyses and assessment.

Getting started

The data for this case study are stored on the ILWIS 2.1 CD-ROM in the directory d:\appguide\chap13. If you have already installed the data on your hard-disk, you should start up ILWIS and change to the subdirectory where the data files for this chapter are stored, c:\ilwis21\data\appguide\chap13. If you did not install the data for this case study yet, please run the ILWIS installation program (see ILWIS Installation Guide).



- Double-click the ILWIS program icon in the ILWIS program group.
- Change the working drive and the working directory until you are in the directory c:\ilwis21\data\appguide\chap13.

13.1 Objectives

The main objectives of this case study are:

- to show how to obtain a pollution vulnerability map of the Piana Campana using the DRASTIC method
- to show how the data layers used for the analysis are obtained from raw data
- to show how a GIS can be used as a powerful tool for validation of the results and for a critical approach to the analysis.

13.2 Background information

13.2.1 General setting

The Piana Campana, southern Italy, is an alluvial plain with interbedded pyroclastic deposits. This area is strongly vulnerable to pollution due to the presence of agricultural intensive activity and industries. Increasing groundwater demand makes the protection of the aquifer from pollution crucial. Physical and hydrogeological characteristics make the aquifer susceptible to pollution in different ways.

The study area is approximately 410 km² and covers the south-east part of the Piana Campana, to the north of Naples, southern Italy. The Piana Campana is traversed by the lower part of the Volturno River and by the Regi Lagni that are artificial canals built for land reclamation. Elevation ranges between 0 and 80 m a.s.l.



- Display the map `Pianacam`, the band 5 of a Landsat TM image.
- Overlay the boundary of the study area masking the polygon map `Mask` (boundary only) and the segment map `Drain` containing the main drainage lines (use `Single color: Blue`).
- Display on the map also the location of the main municipalities, adding the point map `Cities` and selecting the text option to display the names of the cities.

13.2.2 Geologic and hydrogeological setting

The Piana Campana is a large Quaternary basin in southern Italy, delimited by the Tyrrhenian Sea, the Vesuvius Volcano and by limestone Mesozoic relief, dislocated during the Pleistocene tectonic activity. The graben, created during such an activity, continued to deepen during the Quaternary, reaching a vertical dislocation of 3 to 5 km. The graben was filled by alluvial deposits interbedded with

pyroclastics derived from the Vesuvius and Flegrean Fields activities. The geological setting of this area is very complex: see references in Napolitano (1995) for more information on it.

The lithology of the area can be described as a succession of three groups of units (from the top): (1) sands, clay-sands and pyroclastics, sometimes absent or thin; (2) tuffs (the “Campanian Ignimbrite” - thickness between 0 and 70 meters); and (3) thick layers of pyroclastic and sedimentary deposits of variable grain size (thickness 70-100 m).

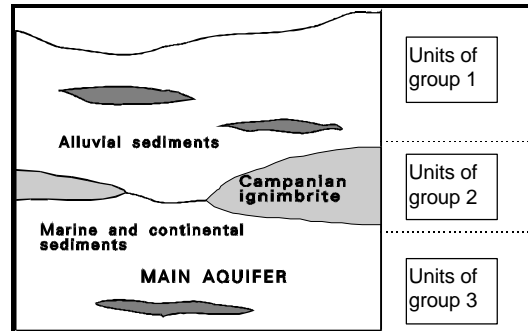


Figure 13.1: Lithology of the area

The main aquifer is located in the units below the Campanian Ignimbrite and the hydrogeological setting is strongly related to the thickness and to the physical characteristics of the “Campanian Ignimbrite”, which plays the role of confining or semi-confining bed. Groundwater circulation takes place mainly in the levels with gravel grain size, but the aquifer can be considered a single continuous body. The aquifer is fed by the rainfall and the limestone mountains; the global flow is directed by SW.

13.3 Methodology

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against the natural impacts, especially with regard to contaminants entering the subsurface environment. Consequently, some land areas are more vulnerable to groundwater contamination than others. Indeed, the ultimate goal of vulnerability maps is a subdivision of an area into several units which have different levels of vulnerability.

Aquifer pollution vulnerability can be assessed using several approaches. In general, the selection of assessment methods and data requirements depends on the purpose of the assessment and on the criteria given by the map user. An exhaustive discussion on groundwater vulnerability mapping can be found in Vrba & Zaporozec (1994).

In this case study we use DRASTIC (Aller et al., 1987), a standardised system for evaluating groundwater pollution potential, that has been broadly used in many countries. One of the reasons of its success is the fact that the inputs required for its

application are generally available or easy to obtain from public agencies. Indeed, DRASTIC is based on seven factors, corresponding to seven base maps to be produced as input to modelling. The acronym DRASTIC corresponds to the initials of the seven layers: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity.

Each of those parameters is mapped and classified either into ranges or into significant media types which have an impact on pollution potential. The range for each factor has been assigned a subjective rating which varies between 1 and 10. Weight multipliers are then used for each factor to balance and enhance its importance. The final vertical vulnerability, the DRASTIC index (Di) is computed as the weighted sum overlay of the seven layers:

$$D_i = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad [13.1]$$

where D, R, A, S, T, I, and C are the seven parameters, r is the rating value and w is the weight associated to each parameter. For a critical review of the DRASTIC method see Merchant (1994).

The figure below is a simplified scheme that uses only three parameters to illustrate how the DRASTIC index is computed for one pixel.

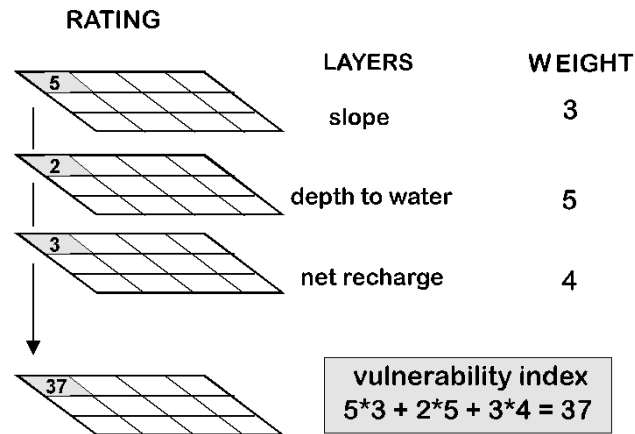


Figure 13.2: DRASTIC index computation

13.4 Available data

The data for this exercise were kindly provided by the Institute of Applied Geology, University of Naples, Italy, and were used by Napolitano (1995). The original dataset used here has been modified for the purpose of this exercise. The author is not responsible for the reliability of the data if they are used for purposes other than the exercise.

In this exercise, first you will use raw data to obtain two of the layers used to compute the vulnerability index:

Piezo.pn*	a point map containing the position of the piezometers
Piezo.tb*	the attribute table of Piezo containing the value of the piezometric level and the height a.s.l.
Dem	a raster map of the digital elevation model.
Mask	a polygon map with the area boundary.

Then, you will use two data layers to assign them the DRASTIC ratings:

Recharge	a raster map of the net recharge
Soil	a raster map of the soil media.

Furthermore, you will use the seven base maps and their attribute tables to compute the vulnerability index:

d	a classified raster map of the depth to water
r	a classified raster map of the net recharge
a	a classified raster map of the aquifer media
s	a classified raster map of the soil media
t	a classified raster map of the topography
i	a classified raster map of the impact of the vadose zone
c	a classified raster map of the hydraulic conductivity.

Finally, you will add some data layers and annotation to the vulnerability map, to create a view that can be used for a final report:

Drain	a segment map of the main drainage
Cities	a point map with the location of the main municipalities.

13.5 Preparing the data layers

In this exercise you will see how the data layers are obtained from raw data. In particular, we deal with two of them: Depth to water and Topography.

13.5.1 Depth to water

Depth to water, the first of the seven data layers, represents the depth of the water table from the topographic surface and gives an idea of the minimum distance that a pollutant has to travel to reach the saturated zone.

In this exercise you will use field data representing the piezometric level as measured in sample wells. By interpolating the point data, you obtain the map that represents the piezometric level; then, you have to subtract this map from the DEM in order to obtain the map of the Depth to water.



- Display the image `Pianacam` and the point map `Piezo`. Have a look at the distribution of the points.
- Display the attribute table `Piezo` and take note of the properties of column `Piezolev` (pay attention to the domain, min and max values, and range).
- Create the raster map `Piezole` by interpolating the point map `Piezo`: use the attribute column `Piezolev` of table `Piezo`, with the **Moving average** method, select the **Linear Decrease** method, and weight 1; use georeference `Dem` and precision 0.1.

(Please, notice that this interpolation takes a long time. Therefore you can find the map `Pilevel` already available in the data set).

- Display the raster map `Pilevel` (or the map `Piezolev` if you calculated it) and add the point map `Piezo`. Use `PixelInfo` to check the result visually.
- Mask the map `Piezole`:

```
Piezolev:=iff(isundef(Dem),Dem,Piezole)↓
```



The moving average is not an exact interpolation method, because each point is obtained as the mean of more points, you will not get exactly the same value as the input at the position of each point.

Once you have obtained the piezometric surface, you can compute “Depth to water” as the difference between `Dem` and `Piezo`.



- Create the map:
`Depth=Dem-Pilevel`↓
creating the value domain `Depth`. The precision is 0.1.
Create and edit the representation `Depth`, assigning colours ranging from light blue to dark blue.
- Display the raster map `Depth` and use `PixelInfo` to check if the result is correct.

At the present, the hydrogeological setting in the Piana Campana is more complex because the main aquifer can be considered sometimes as confined, semiconfined or unconfined. As suggested by Aller *et al.* (1987), depth to water is equal to the piezometric depth when the aquifer is unconfined or semi-confined, and to the depth of the bottom of the confining bed when the aquifer is confined.

13.5.2 Topography

Topography is represented by steepness. Areas with low slope tend to retain water longer. This allows a greater infiltration of recharge water and a greater potential for contaminant migration. Areas with steep slopes, having large amounts of run-off and smaller amounts of infiltration, are less vulnerable to groundwater contamination.

In this exercise you will use the map `Dem` to obtain the map `Slope` that represents the topography layer. The slope is computed as percentage. You can refer back to the *User's Guide* manual for more detailed information on the creation of a slope map using a digital elevation model.



- Create the gradient maps `Demdx` and `Demdy` using the filters `Dfdx` and `Dfdy`, respectively.
- Type the following formula:
$$\text{Slope} = (\text{hyp}(\text{Demdx}, \text{Demdy}) / 30) * 100$$

Create the domain `Slope` (type `Value` and precision `0.1`) and the representation `Slope`.
- Edit the representation `Slope` using the following limits: 0, 1, 2, 3, 5, 10.
- Display the map using representation `Slope`.

13.6 Computing the vulnerability

Once the seven data layers are ready, it is possible to compute the vulnerability index by weighted sum overlay.

The first step is to assign the ratings to the data layers. The ratings are provided by Aller *et al.* (1987) both in form of tables and graphs. In this exercise we use tables, although the use of functions obtained from the graphs would give a more precise result.

Among the seven layers some are represented by continuous values that are classified into ranges (e.g. depth to water and slope), others are represented by significant media types that are assigned typical ratings (e.g. soil media and impact of the vadose zone).

In the next exercise you will assign the ratings to the map `Soil` (using typical ratings) and to the net recharge (using ranges).

13.6.1 Assigning the ratings to the soil media

Soil media is the portion of the unsaturated zone characterised by significant biological activity. The characteristics of the soil influence the amount of recharge infiltrating the ground surface, the amount of potential dispersion, the purifying process of contaminants, etc.

The soil map is represented by significant media types. In this exercise you have to assign the ratings to each soil type.



- Display the raster map `Soil` using the attribute `Texture`.
- Close the map and open the attribute table `Soil`.
- Create a new column and call it `Rating`, creating the new domain `Rate` (type: `Value`; range 0-10; precision 1).
- Enter the following values into the column `Rating`:

	<u>Rating</u>
thin or absent	10
sand	9
loamy sand	7
sandy loam	6
loam	5
clay	1

- Create the representation `Rate` and assign gradual colours for `Rate` ranging from 0 to 10.
- Display the map `Soil` using the attribute `Rating` and the representation `Rate`.

(Hint: change the properties of the map `Soil`).

13.6.2 Assigning the ratings to net recharge

Net recharge provides information about the amount of water that reaches the saturated zone. It is important because the infiltration water is a pollutant transport vector and because a greater recharge gives a higher degree of saturation and thus a higher value of permeability of the unsaturated zone.

In this exercise you will assign the ratings to the net recharge layer. Because that map contains continuous values, first you have to group these values into ranges, and then you can assign the ratings to the group classes.



- Display the raster map Recharge.
- Create the map Rechclas slicing the map Recharge. To do so, create the class Group domain Rechcl assigning the following ranges:

<u>Class</u>	<u>Range (mm)</u>
1	0 - 50.8
2	50.8 - 101.6
3	101.6 - 177.8
4	177.8 - 254.0
5	> 254.0

- Create the table Rechclas using the domain Rechcl and add the column Rechclas containing the items of the domain typing the following expression in the command line:

Rechclas=%K

- Create the column Rating with the same domain Rate as from the previous exercise.
- Assign the following values to the column Rating:

<u>class</u>	<u>rating</u>
1	1
2	3
3	6
4	8
5	9

- Add the attribute table Rechclas to the Properties of the raster map Rechclas.
- Display the raster map Rechclas using the attribute Rating and the representation Rate.

! Check the properties of map Recharge: the minimum value is 173 and the maximum 592. Therefore, it would have been enough to create only classes 3, 4, and 5 in domain Rechcl. In this case we preferred to create a domain containing all the classes as provided by the method DRASTIC.

! The calculated maps Soil.Rating and Recharge.Rating correspond to the maps r.Rating and s.Rating that will be used in the next exercise. Check!

13.6.3 Computing the vulnerability index

Finally, when the seven layers are ready we can compute the vulnerability index as the weighted sum of the seven data layers using the formula 13.1.

The ratings for each data layer are stored in the attribute table in the column Rating. The weights have been assigned by the authors to each DRASTIC factor in order to determine the relative importance of each factor. The relative weights range between 5 (the most significant factors) and 1 (the least significant). DRASTIC uses two weight classifications, the “normal” and the “agricultural DRASTIC”. The last one is used for areas with strong agricultural activity to give more importance to the usage of herbicides and pesticides. In a specific study area only one weight scale can be used. In the study area the “normal” weights were used. The two weight classes are provided in Table 13.1.

Table 13.1: Two weight classes.

Layers	Normal DRASTIC	Agricultural DRASTIC
D	5	5
R	4	4
A	3	3
S	2	5
T	1	3
I	5	4
C	3	2



- Use the MapCalc window to compute the vulnerability index, typing the following formula:

$$\text{Vuln} = d.\text{Rating} * 5 + r.\text{Rating} * 4 + a.\text{Rating} * 3 + s.\text{Rating} * 2 + t.\text{Rating} * 1 + i.\text{Rating} * 5 + c.\text{Rating} * 3$$

Create the value domain Vuln, with range 10–230 and precision 1.

- Create and edit the representation Vuln, using the following limits: 25, 50, 75, 100, 125, 150, 175, 200 and 225. Select colours that give an idea of the increasing degree of vulnerability with highest values.
- Display the raster map Vuln, open the PixelInfo window and the seven input maps to check if your result is correct.

13.7 Creating a map view

In this exercise you create a view of the vulnerability map, that can be used for a printed report.



- Open the raster map `Vuln`.
- Add the segment map `Drain`, using single colour blue.
- Add the point map `Cities` displaying the names of the municipalities.
- Add annotation: title, legend, north arrow, scalebar.
- Save the view as `Vulnmap`.

13.8 Some considerations on the vulnerability map

Subjectivity is unavoidably associated to the selection of the ratings and weights that have to be assigned to the seven base maps which represent the seven parameters. Such a selection can strongly affect the result of the final vulnerability map. The aim of the following exercise is to show how the variations in the input values sometimes can affect significantly the output, sometimes they do not. Answer to the following questions:

- ! Does the vulnerability index give you any information about the values of the single parameters that contributed to obtain it?



- Use `PixelInfo` to display the values of the seven input maps and of their attribute `Rating`.
- Browse with the mouse and write down the values corresponding to the pixels indicated below.

Row	Col	D	R	A	S	T	I	C	Vuln
265	185								
493	477								

- ! Imagine that another scientist does not agree with the ratings that you have assigned to the input maps. Does the vulnerability index change if you use different ratings for some units? Do you have the same variation for the whole area?



- Once again use PixelInfo to check the input values for the pixel (459, 627) and write them down.
- Compute manually the vulnerability index assigning different values to the parameters D and T, as indicated below.

Row	Col	D	R	A	S	T	I	C	Vuln
459	627								
459	627	6							
459	627					5			



If you change the boundaries of the classes, does it affect the final vulnerability index?



- Create the map Rechcla1 in the same way you have done to calculate the map Rechclas, but use slightly different ranges.
- Assign the ratings to these ranges and compute again the vulnerability map.



Now suppose that you don't agree to assign the "normal DRASTIC" weights, and you want to compute the vulnerability index using the "agricultural DRASTIC" weights. Does the vulnerability change significantly?



- Compute the vulnerability index using the "agricultural" weights. Call Vuln1 the output map.

$$\text{Vuln1} = d.\text{Rating} * 5 + r.\text{Rating} * 4 + a.\text{Rating} * 3 + s.\text{Rating} * 5 + t.\text{Rating} * 3 + i.\text{Rating} * 4 + c.\text{Rating} * 2$$

- Display the raster map Vuln1. Use PixelInfo to display also the values of the map Vuln.
- Create the raster map Diff, that shows the differences between the vulnerability computed using the two different weight classes. Type the following expression from the command line:

$$\text{Diff} = \text{Vuln} - \text{Vuln1}$$

- Display the map `Diff` and make your consideration on it.

Given the fact that at present it is not possible to avoid subjectivity, the way to deal with it is performing a sensitivity analysis which characterises the distribution of both, individual variables and input parameters, on the resultant output of an analytical model. From a practical point of view, as vulnerability maps are tools used by planners for socio-economical decisions, sensitivity analysis is useful for validation and consistency evaluation of the analytical result and for a correct interpretation of the vulnerability map.

13.9 An example of sensitivity analysis

Sensitivity analysis studies the contribution of individual variables and of input parameters on the resultant output of an analytical model. Many factors influence the result such as the type of overlay operation performed, the value of the weights, the number of data layers and of map units in each layer, the error or uncertainty associated to each map unit, and so on.

In this exercise we deal only with those aspects related to the influence of ratings assigned to the single parameters. The procedure consists in creating unique condition subareas and then performing the single-parameter sensitivity analysis on each subarea. More detailed information on sensitivity analysis and the complete procedure illustrated here can be found in Napolitano & Fabbri (1996).

13.9.1 Creating the unique condition subareas

A “unique condition subarea” is defined as a set of one or more areas consisting of pixels with a unique combination of D_i , R_i , A_i , S_i , T_i , I_i , and C_i , where D_i , R_i , A_i , S_i , T_i , I_i , and C_i , are the rating values of the seven layers used to compute the vulnerability index, and $1 \leq i \leq 10$. The unique condition subareas are obtained by crossing the seven layers, two at a time. This operation yields a map of the subareas and an associated cross table. In the final cross table, each record represents a unique combination of the D_i , R_i , A_i , S_i , T_i , I_i , and C_i layers. The figure below shows a simplified scheme of unique condition subareas obtained crossing three layers.

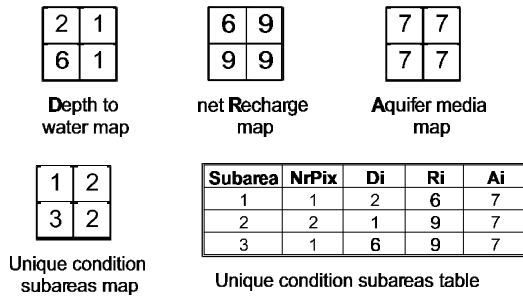


Figure 13.3: Example to obtain unique condition subareas

The attribute maps containing the attribute rating for the seven layers have to be created in first place. Next we will use a trick: as in the next exercise we need to know the exact position of each character of the column created during the cross operation, we substitute the rating 10 with the new value 0. Later on, we will assign back the original value.



- Open the table D and type the following expression in the command line of the table window:

```
Newrat=iff(Rating=10,0,Rating)↵
```

Select domain Rating.

- Click the map D with the right button of the mouse and activate the context sensitive menu. Select **Raster Operations, Attribute map**.
- Create the output map D_i using the attribute Newrat.
- Repeat the same operation to create the attribute maps for the other six layers. Call them R_i, A_i, S_i, T_i, I_i, and C_i.

Now the crossing between the layers, two at a time, can be done. First we cross the maps D_i and R_i, then the result of this cross with the map A_i, and so on.



- Click on the **CROSS** icon on the operations list. Select D_i as first map, and R_i as second map. Calculate the output table and the output map D_r.
- Show the cross table D_r. You can notice that the columns D_i and R_i contain the information of the ratings of the two input layers.
- Repeat the cross operation using as first map D_r and second map A_i. Call the output table and map D_ra.
- Repeat the same operation crossing the output map with the other layers one by one. After the last crossing the output table and map should be called D_ra*s*t*i*c.
- Display the cross table D_ra*s*t*i*c.

As you can see, the column D_ra*s*t*i*c contains all the information related to the ratings of the first six layers for each unique subarea. Column C_i contains the value of the rating for the last layer. Now we need to use this information for calculation, therefore the ratings for each parameters should be copied into new separate columns with a value domain.

- ! The analysis will be performed now using the cross tables. You don't need anymore the cross maps, except the last one *Drastic*, that is used for displaying the final result. You can **Edit Properties** for those maps and click on the **Release Disk Space** button in order to save space on the disk.
-



- On the command line of the table window type the following formula:
`Ndrasti=Drasti`
Select domain *String*. Check the properties of the new column.
- Create the column *Di* containing the ratings of the first layer, typing the following formula:
`Di=sub(Ndrasti,1,1)`
Select domain *Rating*. Column *Di* returns a substring of column *Ndrasti*, starting at position 1, and 1 character long.
- Type the following expression:
`D:=iff(Di=0,10,Di)`
Select domain *Rating*.
- Use the mouse to check the position of the rating of the second parameter in column *Ndrasti*.
- Create the column *Ri* containing the ratings of the second layer, typing the following formula:
`Ri=sub(Ndrasti,5,1)`
Select domain *Rating*. Column *Ri* returns a substring of column *Ndrasti*, starting at position 5, and 1 character long.
- Type the following:
`R:=iff(Ri=0,10,Ri)`
Select domain *Rating*.
- Repeat the same procedure to create columns *Ai*, *Si*, *Ti*, and *Ii*.
- Copy the column *Ci*, table-owned, into the new column *C* with domain *Rating*, typing the following:
`C:=Ci`

Now the table is ready to perform the sensitivity analysis.

13.9.2 Single-parameter sensitivity analysis

This procedure evaluates the “effective” or “real” weight that each parameter has in each subarea. Indeed, it depends not only on the “theoretical weight” assigned by the Drastic method, but also on the “value” of the single parameter in the “context” of the values of the other parameters.

The effective weight W_{pi} (in %) for each subarea is computed as follows:

$$W_{pi} = \frac{P_{Ri} P_{Wi}}{vuln_i} * 100 \quad [13.2]$$

where P_{Ri} and P_{Wi} are the ratings and the weights respectively of the layer P assigned to the subarea i , and $vuln_i$ is the vulnerability index as computed in expression (13.1).



- Compute the vulnerability index for each subarea, typing the following formula on the command line of the table window:
 $Vuln = D * 5 + R * 4 + A * 3 + S * 2 + T * 1 + I * 5 + C * 3$
Use the value domain `Vuln`
- Compute the “effective” weight for depth to water typing the following formula on the command line of the table window:
 $W_D = 100 * ((5 * d) / vuln)$
Use the predefined domain `Perc` with precision 1.
- Repeat the same operation to compute the “effective” weight for the other six Drastic parameters.
- Display the map `Drastic` using the attribute column `WD`.
- Add the data layer `Drainage`, open `PixellInfo` and add the maps `Vuln` and `Drastic`. Browse with the mouse and make your considerations on the result obtained.
- Display also the other attributes.

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