HOVER
GeoERA
GROUNDWATER

Hydrogeological processes and geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystem

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Deliverable D.7-3

Results of the vulnerability assessment of the upper aquifer to pollution at pilot areas scale: statistics and sensitivity analysis

Version: 28-05-2021

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data		
Deliverable number	D.7-3	
Dissemination level	Public	
Deliverable name	Report	
Work package	WP7, Harmonized vulnerability to pollution mapping of the upper aquifer	
Lead WP/Deliverable beneficiary	BGR	
Deliverable Status		
Submitted (Author(s))	28/05/2021	All WP7 partners
Verified (WP leader)	28/05/2021	Broda, S.
Approved (Coordinator)	28/05/2021	Gourcy, L.

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1 INTRODUCTION

This deliverable is part of work package (WP) 7 in the overall project HOVER - Hydrogeological processes and Geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystems.

It has been promoted by the ERA-NET GeoERA (Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe). In this European project, led by the German Geological Survey (BGR), 16 geological services from 13 different countries participate. It focuses on the harmonized vulnerability to pollution assessment and mapping of the upper aquifer at both pan-European scale and national/cross-border and regional scale in 12 pilot areas.

Deliverable D.7-3 is the third report of the following four HOVER-WP7 deliverables:

- DeliverableD.7-1. Comparison of internationally commonly applied index methodologies for assessing the vulnerability of the upper aquifer to pollution. (Broda et al., 2019).
- Deliverable D.7-2. Compilation of the examination results of the data sets of input data for the respective methodologies assessing vulnerability of the upper aquifer to pollution. (Broda et al., 2020).
- Deliverable D.7-3. Results of the vulnerability assessment of the upper aquifer to pollution at pilot areas scale: statistics and sensitivity analysis (Arnó et al., 2021).
- Deliverable D.7-4. Delivering of cross sections and maps of extend of selected aquifers in specific national pilot areas. (Pulido et al., 2020).

Deliverable D.7-3 describes the workflow and methodologies used to first obtain the final DRASTIC and COP vulnerability indexes which are comparable between pilots and also with the pan-European DRASTIC map and second to analyze, from a numerical point of view, the results by computing main statistical parameters and by performing a sensitivity analysis of the 7 DRASTIC parameters indexes.

The sources of the input data used for the vulnerability assessment in the individual pilot areas are documented in deliverable D.7-2.

This D.7-3 PDF report is complemented and needs to be visualized jointly with the dashboard report made in PowerBI application which is available here. It permits to create interactive visualizations and filters which allow end users to create their own reports and visualizations.

Appendix A includes the final DRASTIC and COP indexes assessments (A1 for DRASTIC and A2 for COP) and Appendix B shows the spatial distributions of the sensitivity and the effective weight indexes computed. Appendix C shows the screenshots of the D.7-3 powerBI dashboard report. Appendix D describes the meaning of the DRASTIC vulnerability classes.

2 WORKFLOW AND METHODOLOGIES

In a previous step (Broda et al., 2019) two index methods were identified from a set of proposed approaches to evaluate the intrinsic groundwater vulnerability. The DRASTIC method (Aller et al., 1987) was used for the continent-wide evaluation and for non-karstic regions in the pilot areas. In those parts of the pilot regions with karstic features dominating groundwater flow, the COP approach (Vías et al., 2006) was applied.

For the application of both methods a set of spatially distributed input data were required. Documentation of the input data/input layers that were used for the pan-European and the pilot scale vulnerability assessments and pilot areas geological and hydrogeological descriptions are included in Broda et al. (2020).

As input DRASTIC and COP layers were prepared based on the same ratings and weights of source datasets according to given classification schemes, DRASTIC and COP indexes values were calculated obtaining comparable results between each pilot and also with the pan-EU DRASTIC map.

The vulnerability maps obtained are important tools for groundwater management, through which specific high vulnerability areas can be identified and preventive or corrective actions can be taken at different scales for their protection. In HOVER WP7 pilot area scales range from 1:10.000 up to 1:250.000.

At this point DRASTIC and COP vulnerability assessments maps of the 12 pilot areas were analyzed from a statistical point of view. Furthermore, for the vulnerability DRASTIC assessment, a map single parameter removal sensitivity analysis has also been performed to study the contribution of each individual variables.

It should be pointed out that the two intrinsic vulnerability assessment methods only consider the natural intrinsic factors and are independent to the source of contamination. For this reason, the vulnerability maps depend mainly on the hydrodynamic characteristics of each region and it is not easy to establish a validation method that considers the specificities of each site.

Some validation tests have been carried out in the framework of HOVER WP7 project considering the land use spatial distribution maps of some pilots and nitrate concentrations data. Correlation obtained with the vulnerability assessment maps (DRASTIC and COP) was very low. Contaminant loading for many years (in some areas mor than 30) and local and regional hydrogeological conditions determine that the actual distribution of nitrates concentrations in groundwater is related with many other processes.

2.1 DRASTIC and COP vulnerability index assessment

After obtaining the input data, DRASTIC and COP vulnerability indexes were calculated according to the two original methods selected (Broda et al., 2020) by geoprocessing data based on GIS techniques.

DRASTIC vulnerability index (DVI) is an index methodology based on the natural characteristics of media. It contemplates seven different parameters: depth to groundwater level (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), hydraulic conductivity of the aquifer (C). Every parameter has a weight and a rating depending on their relative impact to potential contamination as follows:

$$DVI = 5D \times 4R \times 3A \times 2S \times 1T \times 5I \times 3C$$

The COP method is a parametric model specifically developed for karstic systems that takes into account the kind of preferent flow, concentrated or diffusive (C factor), the unsaturated zone of the overlying layers (O factor) and the different climatic conditions (Precipitation, P factor).

To obtain comparable results between pilot areas, DRASTIC index spatial representation considers five classes which are the maximum value of DRASTIC methodology (230) minus the minimum value of DRASTIC methodology (23) divided by 5. For the COP index, the original method (Vías et al., 2006), also five classes of vulnerability are proposed (see Figure 1).

COP index - (vulnerability classess)	DRASTIC index - (vulnerability classess)
Very high vulnerability (0 - 0,5)	Very high vulnerability (189 - 230)
High vulnerability (0,5 - 1)	High vulnerability (148 - 188)
Moderate vulnerability (1- 2)	Moderate vulnerability (106 - 147)
Low vulnerability (2 - 4)	Low vulnerability (65 - 105)
Very low vulnerability (4 - 15)	Very low vulnerability (23 - 64)
Surface water	Surface water

Figure 1: Classification of vulnerability indexes for the DRASTIC and COP methods.

The results are shown in Appendix A1 (for DRASTIC) and A2 (for COP). They are also available at the EGDI platform. A definition of the meaning of the individual vulnerability classes, along with suggested action plans and required protection measures can be found in Appendix D.

2.2 *Statistical analysis of DRASTIC and COP results*

To get a general overview of the vulnerability assessment made in each pilot and to have numerical comparable results between them, a GIS computation was used to obtain the mean, median, minimum (Min), maximum (Max) values, the standard deviation (σ_V) and the variation coefficient (Cv) for each pilot and for both the final vulnerability DRASTIC and COP indexes. Statistics were also computed for each input parameter indexes.

DRASTIC and COP index (V)	DRASTIC and COP input parameters indexes (P)
mean ($\overline{V}$)	mean ($\overline{P}$)
median ($\tilde{V}$)	median ($\tilde{P}$)
minimum (V_{min})	minimum (P_{min})
maximum (V_{max})	maximum (P_{max})
standard deviation (σ_v)	standard deviation (σ_p)
variation coefficient (VC_v)	variation coefficient (PC_v)

Figure 2: Main statistical parameters calculated for the vulnerability indexes (DRASTIC and COP methods) and also for the corresponding parameters indexes of each method.

The variation coefficient (Cv) is defined as:

$$VC_v=\left(\frac{\sigma_v}{\overline{V}}\right)100\ (\%) \qquad \text{and} \qquad PC_v=\left(\frac{\sigma_p}{\overline{P}}\right)100\ (\%)$$

Where $\overline{V}$ is the mean value of the vulnerability index and $\overline{P}$ the mean value of the parameter index considered.

Cv indicates, in a relative way, the degree of values variability so for Cv<80% the dataset could be classified as homogeneous and the mean values representative while for Cv>80% mean values could be considered not representative enough as dataset is classified as heterogeneous. The higher variability of the parameters implies a greater contribution toward the variation of the vulnerability index and reverse.

Table 1: Main statistics of the DRASTIC and COP vulnerability indexes for each pilot.

Pilot area	Country	Participant	Area (km^2)	Cell size (m)	Scale	Parameter	Mean	STD	Cv (%)
Atalanti alluvial aquifer	Greece	HSGME	54	50	1:10K	DRASTIC	112	14	12
Boyne	Ireland	GSI	2.627	10	-	DRASTIC	125	26	21
Catalunya	Spain	ICGC	32.112	50	1:100K	DRASTIC	99	30	30
						COP	2	2	81
Cobadin-Mangalia	Romania	IGR	2.192	50	1:200K	DRASTIC	100	16	16
						COP	3	1	39
Finland	Finland	GTK	338.440	200	1:200K	DRASTIC	124	24	19
Lower Oder/Odra river German part	Germany	BGR-LBGR	4.553	200	1:250K	DRASTIC	120	23	19
Lower Oder/Odra river Polish part	Poland	PIG-PIB	2.821	200	1:250K	DRASTIC	127	34	27
Rockingham	Ireland	GSI	15	10	-	COP	1	1	115
Slovenia	Slovenia	GeoZS	20.273	100	1:250K	DRASTIC	130	31	23
						COP	1	1	105
Tønder	Denmark	GEUS	293	100	1:25K	DRASTIC	139	15	11
Traun-Enns-Platte	Austria	GBA	810	100	1:100K	DRASTIC	135	30	22
Upper Guadiana Basin	Spain	IGME	14.093	100	1:50K	DRASTIC	103	22	22
						COP	3	2	57

2.3 Map single-parameter removal sensitivity analysis for the DRASTIC method

Input layers of each pilot area have been generated according to available and/or accessible data sources. This suggests the results analysis or interpretation that can be done for a region or pilot area cannot be extrapolate to other areas as they have different hydrogeological conditions and source data.

In order to establish the relationship between the vulnerability obtained and the parameters considered a map single-parameter removal sensitivity analysis was performed. The method, based on Lodwick et al. (1990), Napolitano et al. (1996) and Adeyinka (2020), was developed for weighted sum intersection overlays and can be easily applied to the DRASTIC expression (not valid for the COP method).

This sensitivity analysis allows to study the contribution of individual variables (input parameters) one by one, on the resultant output of an analytical model. Two parameters were calculated:

The sensitivity index (S) for each parameter: it is usually used to determine if all the parameters contribute equally and sometimes it is analysed jointly with the Pairwise correlation matrix between the analysed parameters (see Figure 3*Figure 1*):

a) The effective parameter weight (W) which allows to compare the real weight that each parameter had in each pilot area with the theoretical weight assigned by the DRASTIC method.

Sensitivity parameter index (S)	Effective parameter weight (W)
Identifies the sensitivity of the vulnerability towards removing one or more maps from the vulnerability analysis. It is computed as follows:	Contribution of each parameter in the final DRASTIC vulnerability index (effective weight). It is computed as follows:
$S = \left(\frac{\left\| \frac{V}{N} - \frac{V'}{n} \right\|}{V} \right) \times 100$	$W = 100 P_r P_w / V$
S; sensitivity index measure expressed as variation index (for each parameter) V and V'; unperturbed and perturbed vulnerability N and n; number of parameters used to compute V and V' respectively	W; effective weight of each parameter P_r and P_w ; ratings and weight values of each parameter respectively V; the overall vulnerability index

Figure 3: Sensitivity analysis index (S) and effective parameter weight (W) definitions and formulas to perform the map single-parameter removal sensitivity analysis.

At the end 7 maps (one by each DRASTIC parameter) and their main statistics were computed for the "S" index (Sd, Sr, Sa, Ss, St, Si, Sc) and 7 maps (one by each DRASTIC parameter) and their main statistics were computed for the "W" index (Wd, Wr, Wa, Ws, Wt, Wi, Wc).

To complement the statistical analysis, pairwise correlations between the 7 parameters for each pilot were calculated. The correlation matrix for each pilot area (square table that shows the correlation coefficients between several pairwise combination of variables) are included in the PowerBI report and show the relationship between the seven DRASTIC parameters between each other. Values meaning are:

- -1 indicates a perfectly negative linear correlation between two variables.
- 0 indicates no linear correlation between two variables.
- 1 indicates a perfectly positive linear correlation between two variables.
- NaN values correspond to correlations which one or both variables are constant within the pilot area.

The further away the correlation coefficient is from zero, the stronger the relationship between the two variables.

3 RESULTS

Once the analysis has been completed, all the information acquired has been processed with the PowerBI Desktop Application, which enables data for a further exploration and visualization.

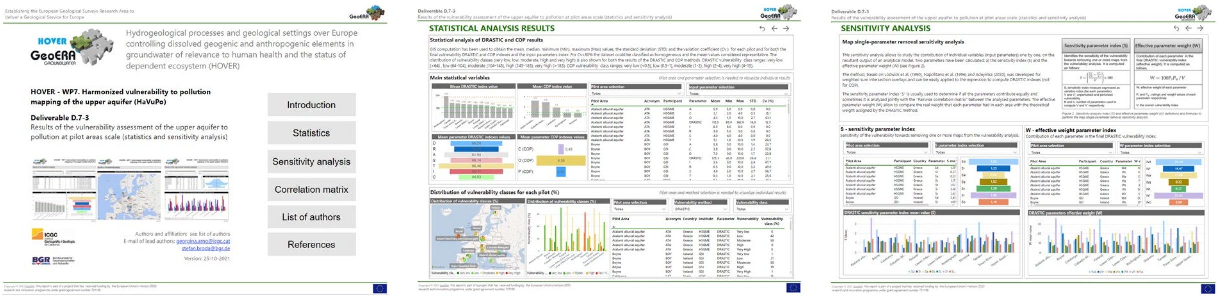

Figure 4: Screenshots of the PowerBI report of D.7-3.

Users can use interactive graphs, filters and maps to visualize local or global results and to create an overall or detailed report. This way, the application turns into a management tool of the project information which can be used for decision-making, both at environmental protection actions and the improvement / optimization of input data.

It contains six pages or dashboards. The first one “Get started” has an interactive index to move within the PowerBI report, and the second one “Introduction” describes the framework and main goals of HOVER - WP7 project. The “Statistical analysis”, “Sensitivity analysis” and the “Pairwise correlation matrix” pages summarize the obtained results from a numerical point of view. Finally, the “List of authors” and “References” are listed in the PowerBI.

For one or more pilot areas the distribution of vulnerability classes (%) and the mean, minimum, maximum, the standard deviation and the variation coefficient values of the vulnerability indexes and parameters considered can be visualized.

The Sensitivity analysis jointly with the Pairwise correlation matrix gives a general idea of which are the most significant parameters in each pilot depending on the hydrogeological settings and the available input data. Thus, the trend of S and W parameter indexes (from the highest to the lowest values) are different from one pilot to another so conclusions have to be drawn from a detailed hydrogeological knowledge of each site. For instance, the D (depth to water table) could have a great impact on the final DVI indicating that having available groundwater level measurements could be critical to enhance the results or to necessary to take improvement actions in critical areas / subareas or to concentrate on obtaining higher quality information about some characteristic or parameter of the system. In summary, it gives an idea about where to focus future efforts in a more efficient way.

The effective parameter weight (W) informs about the real weight of each of the DRASTIC parameters which can be compared with the theorical weight assigned by the DRASTIC method.

It should be noted that the effective weight obtained vary according to the pilot area. The reason is that the weight of them dependent not only on the value of the parameter but also on the value of the rest of them (which can be different in each context or area).

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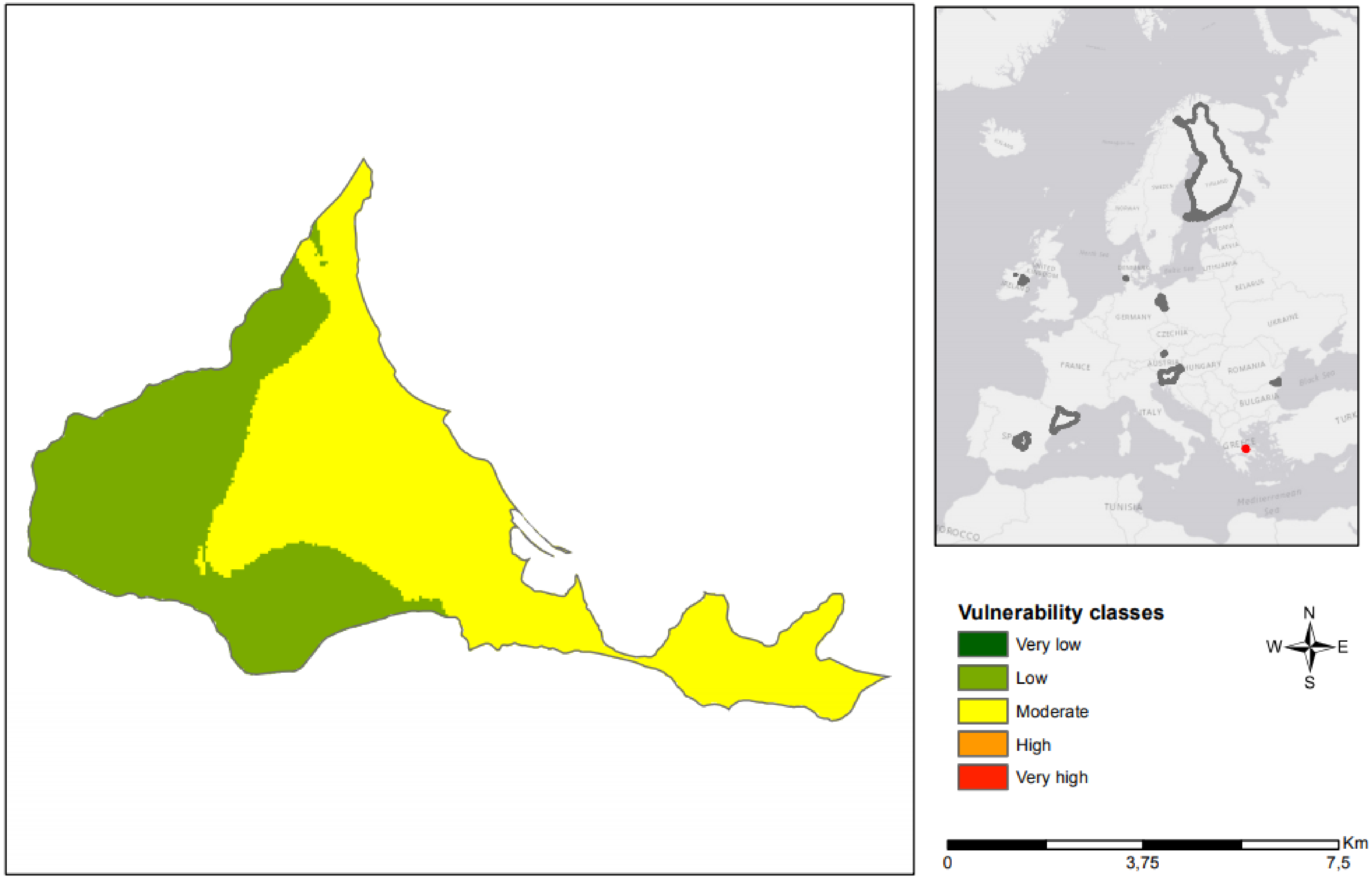
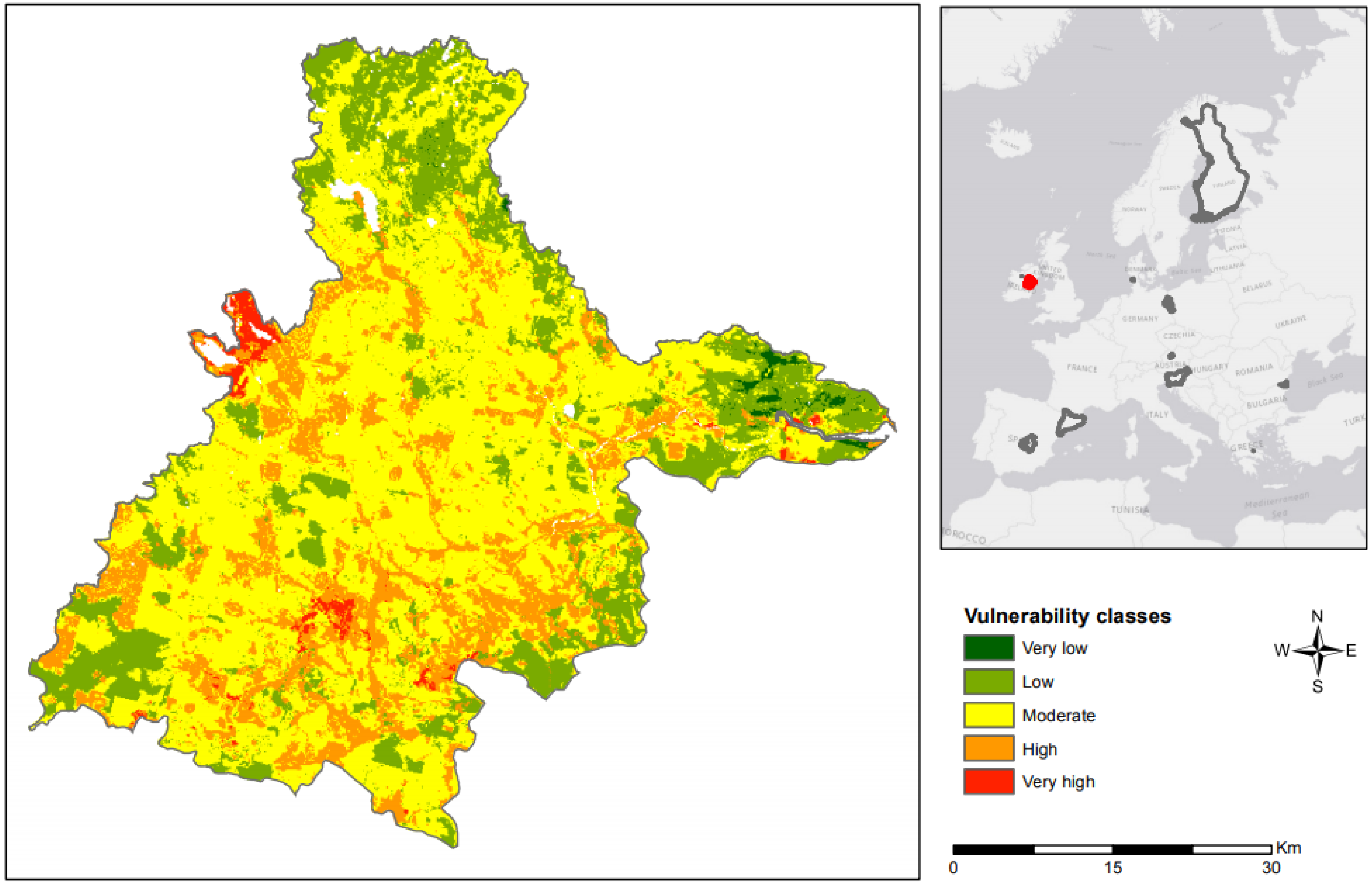
APPENDIX A1: VULNERABILITY INDEXES .DRASTIC ASSESSMENTS

Pilot area Atalanti alluvial aquifer (Greece) - HSGME

DRASTIC vulnerability index spatial distribution

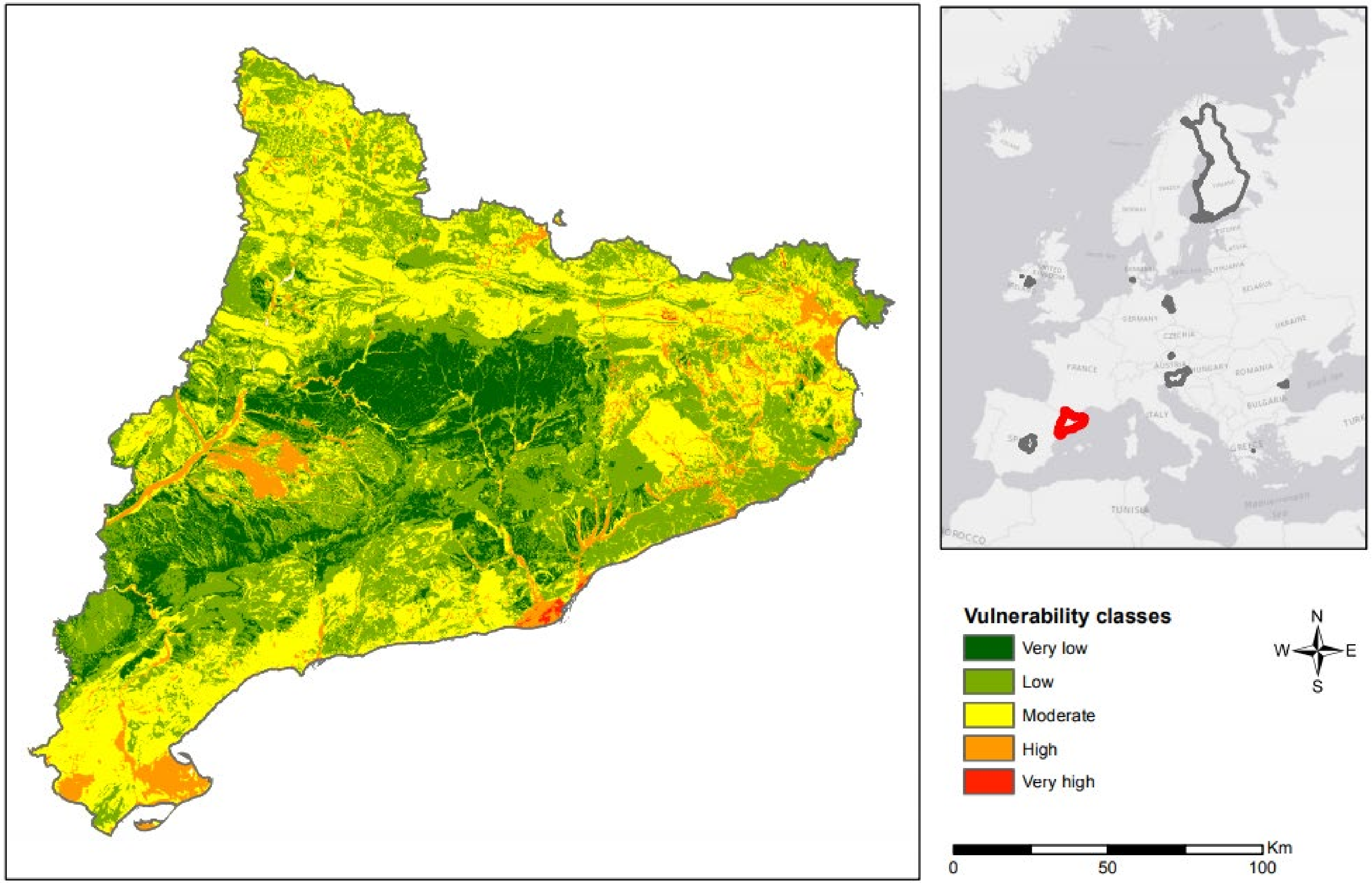


Pilot area Boyne (Ireland) - GSI
DRASTIC vulnerability index spatial distribution



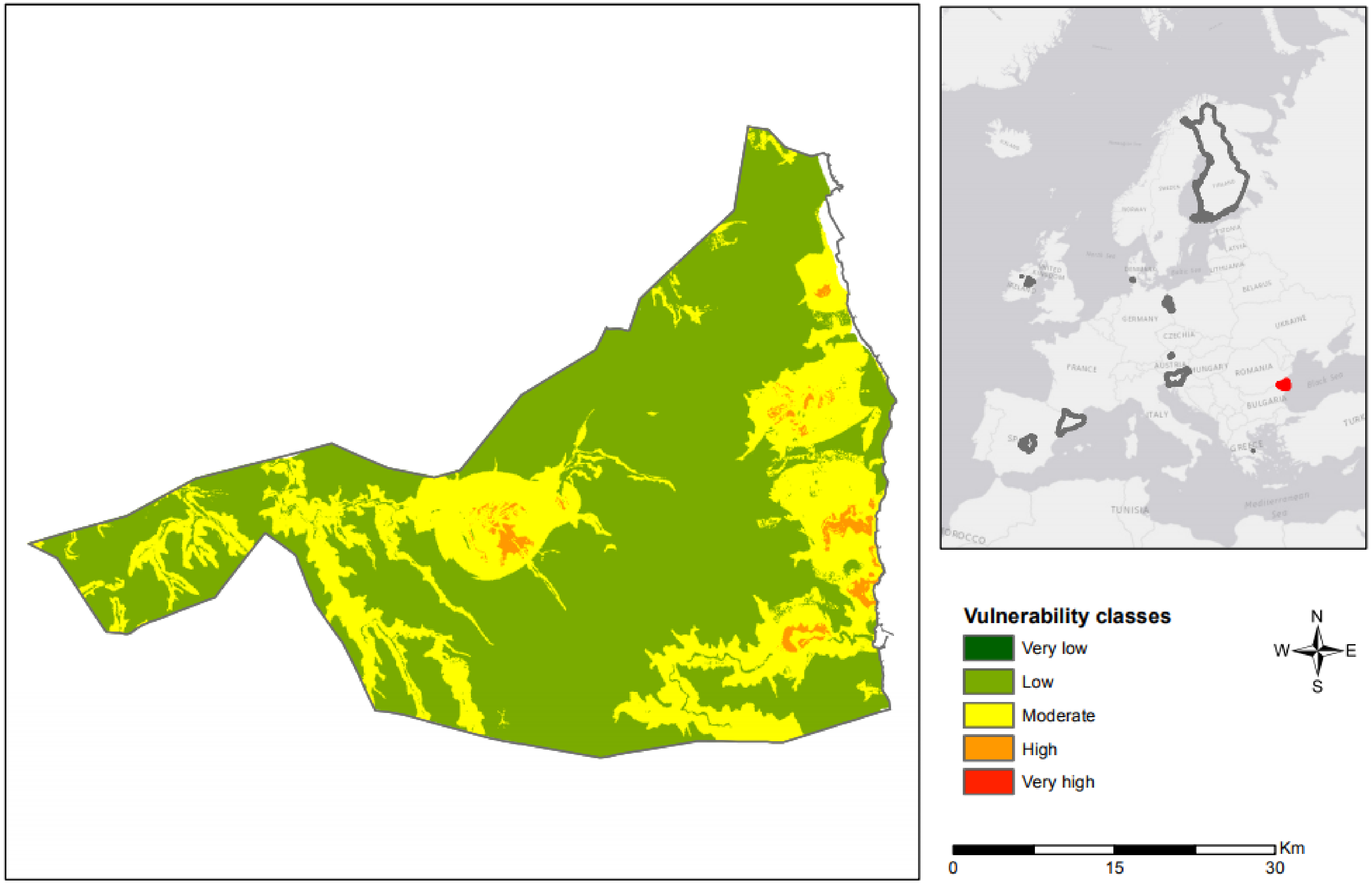
Pilot area Catalonia (Spain) - ICGC

DRASTIC vulnerability index spatial distribution

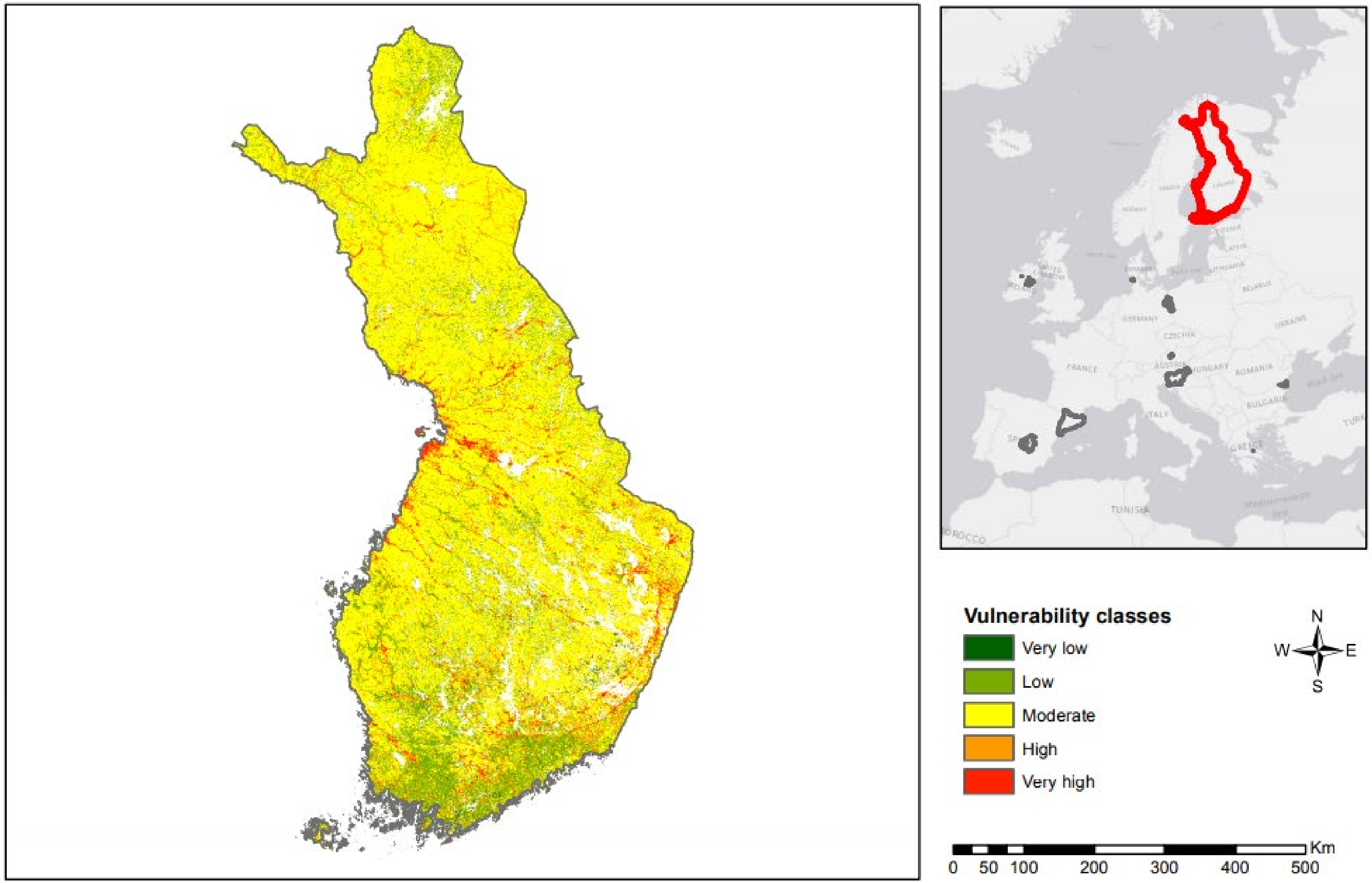


Pilot area Cobadin-Mangalia (Romania) - IGR

DRASTIC vulnerability index spatial distribution

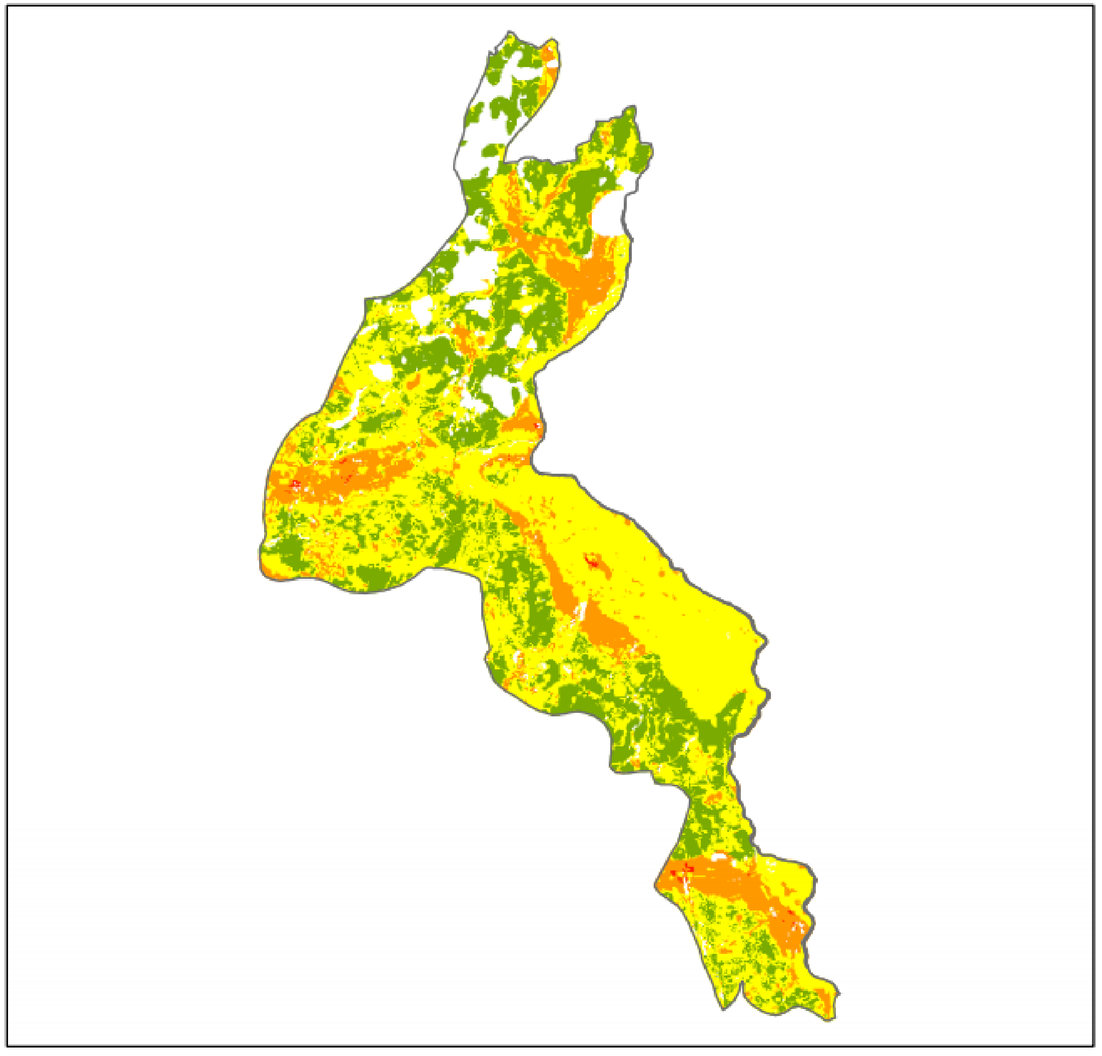


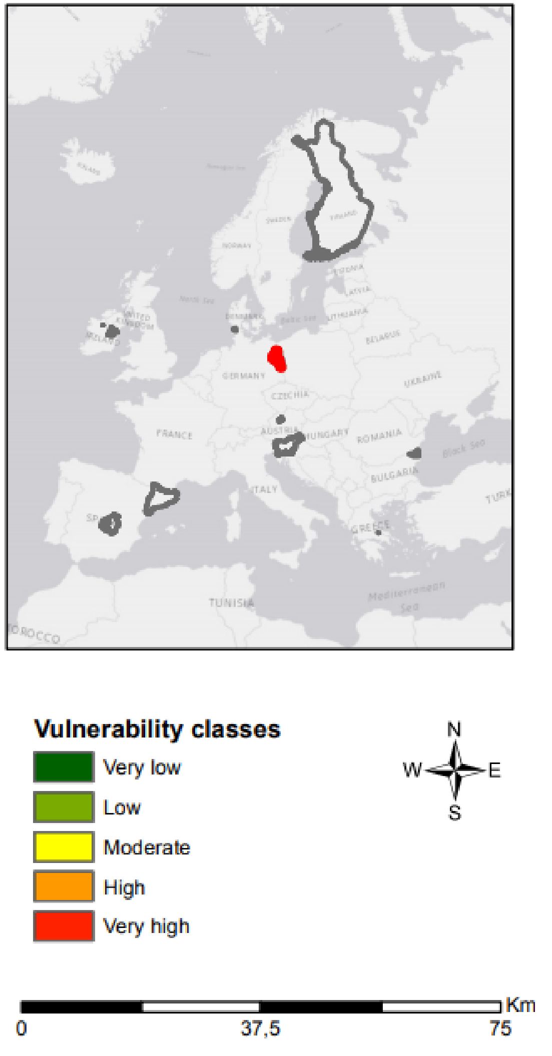
Pilot area Finland (Finland) – GTK
DRASTIC vulnerability index spatial distribution



Pilot area Middle and Lower Oder/Odra river (German part) – PGI/LBGR/BGR

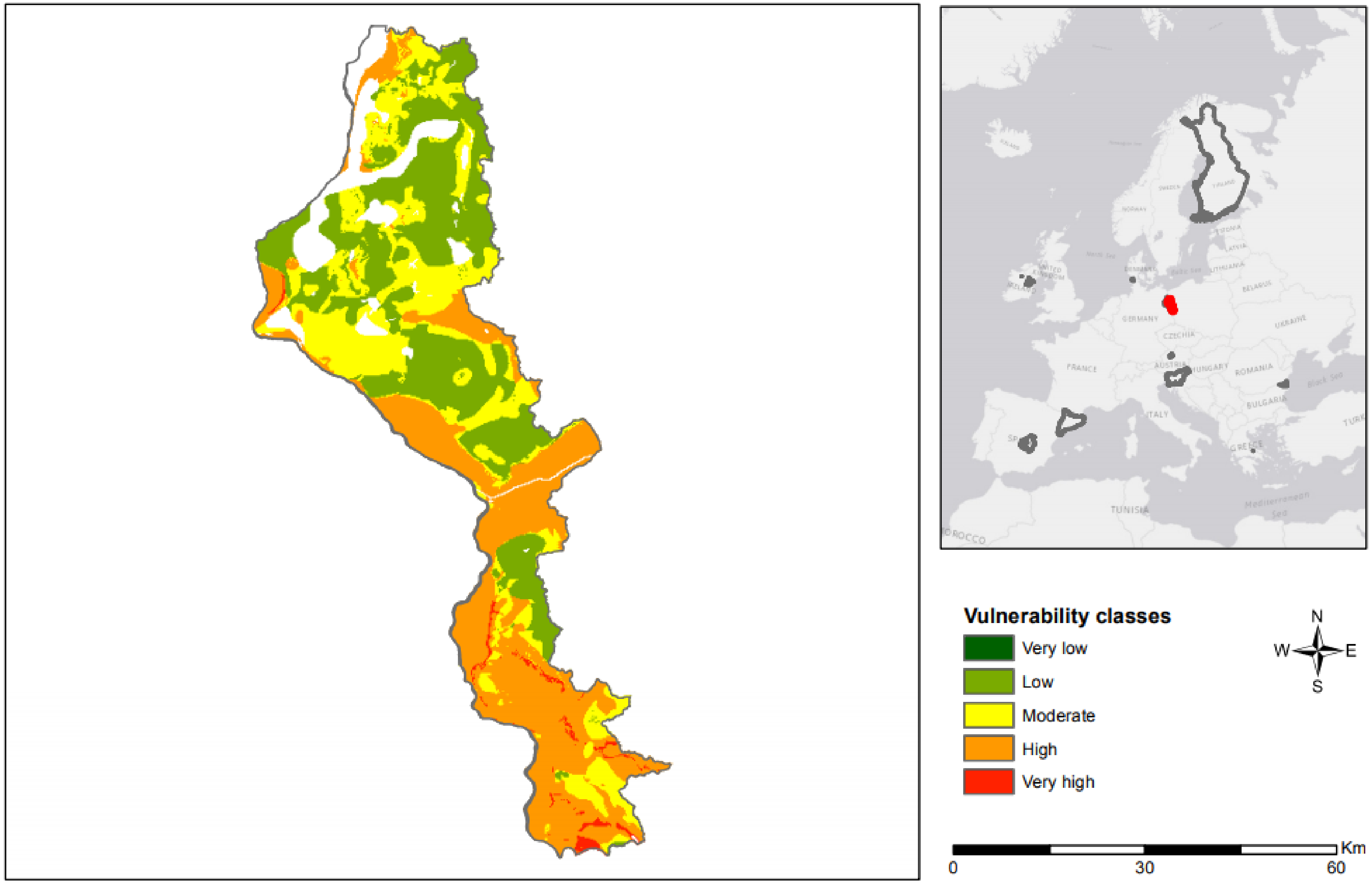
DRASTIC vulnerability index spatial distribution





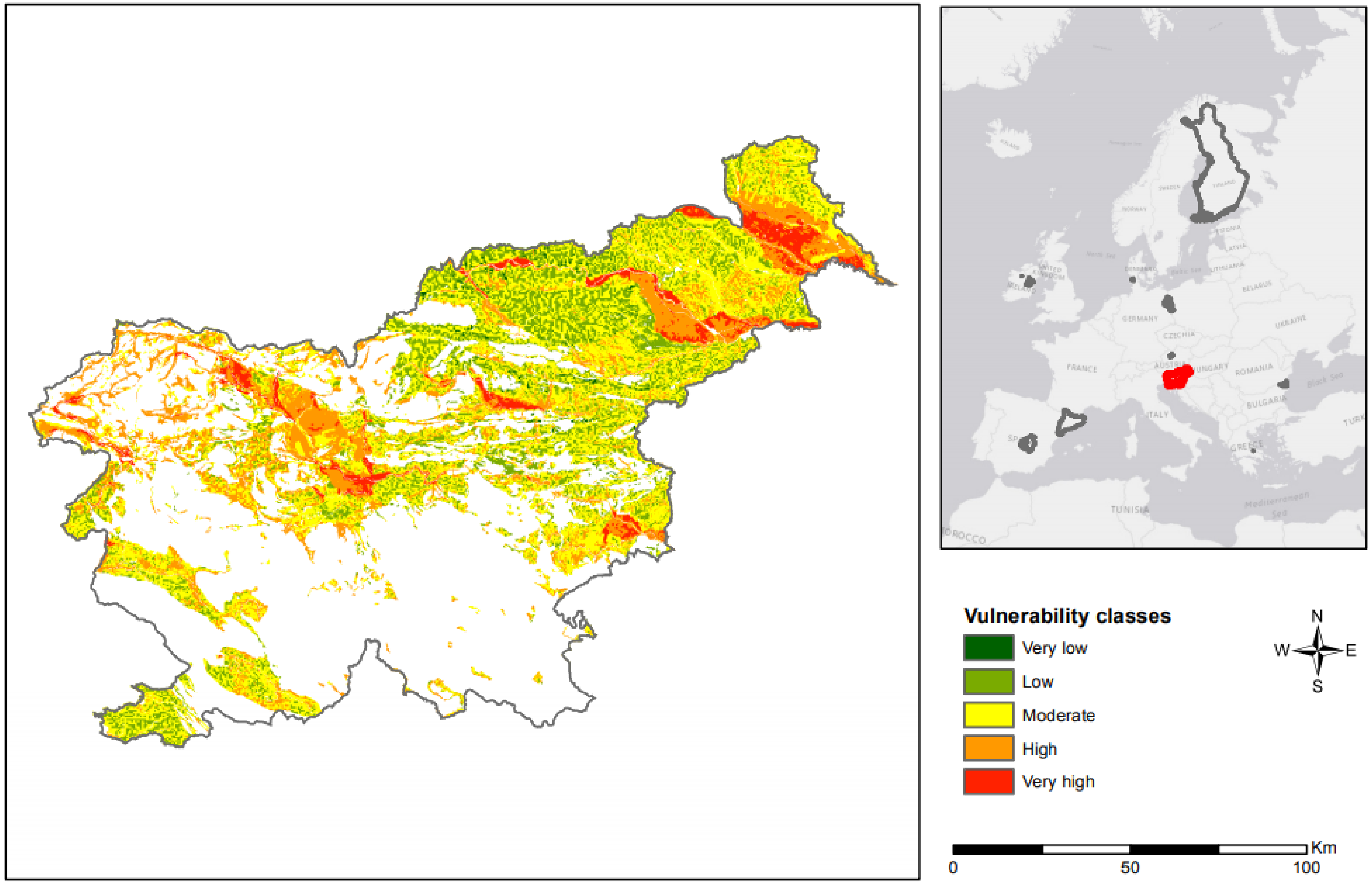
Pilot area Middle and Lower Oder/Odra river (Polish part) – PGI/LBGR/BGR

DRASTIC vulnerability index spatial distribution



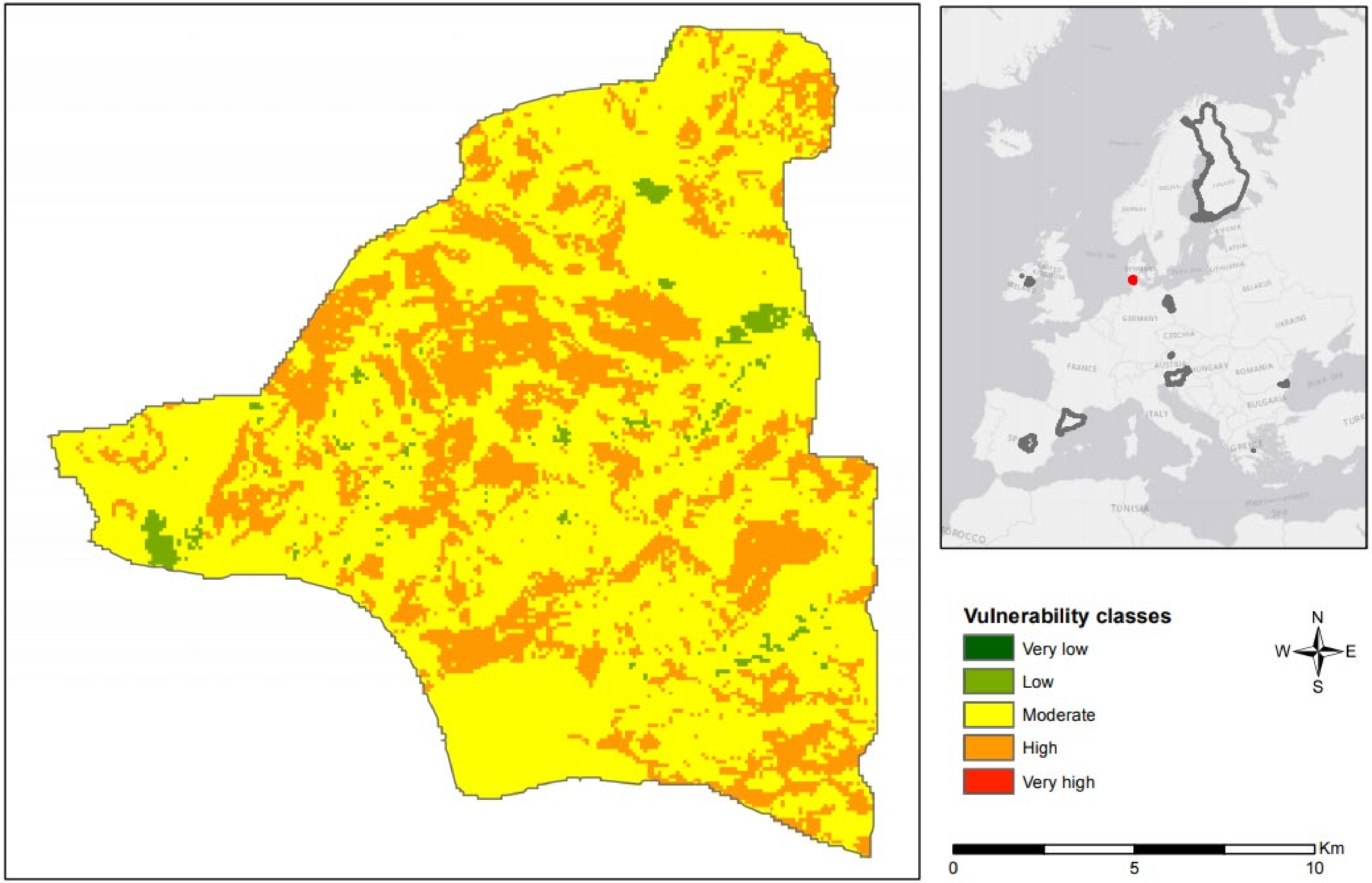
Pilot area Slovenia (Slovenia) – GeoZS

DRASTIC vulnerability index spatial distribution

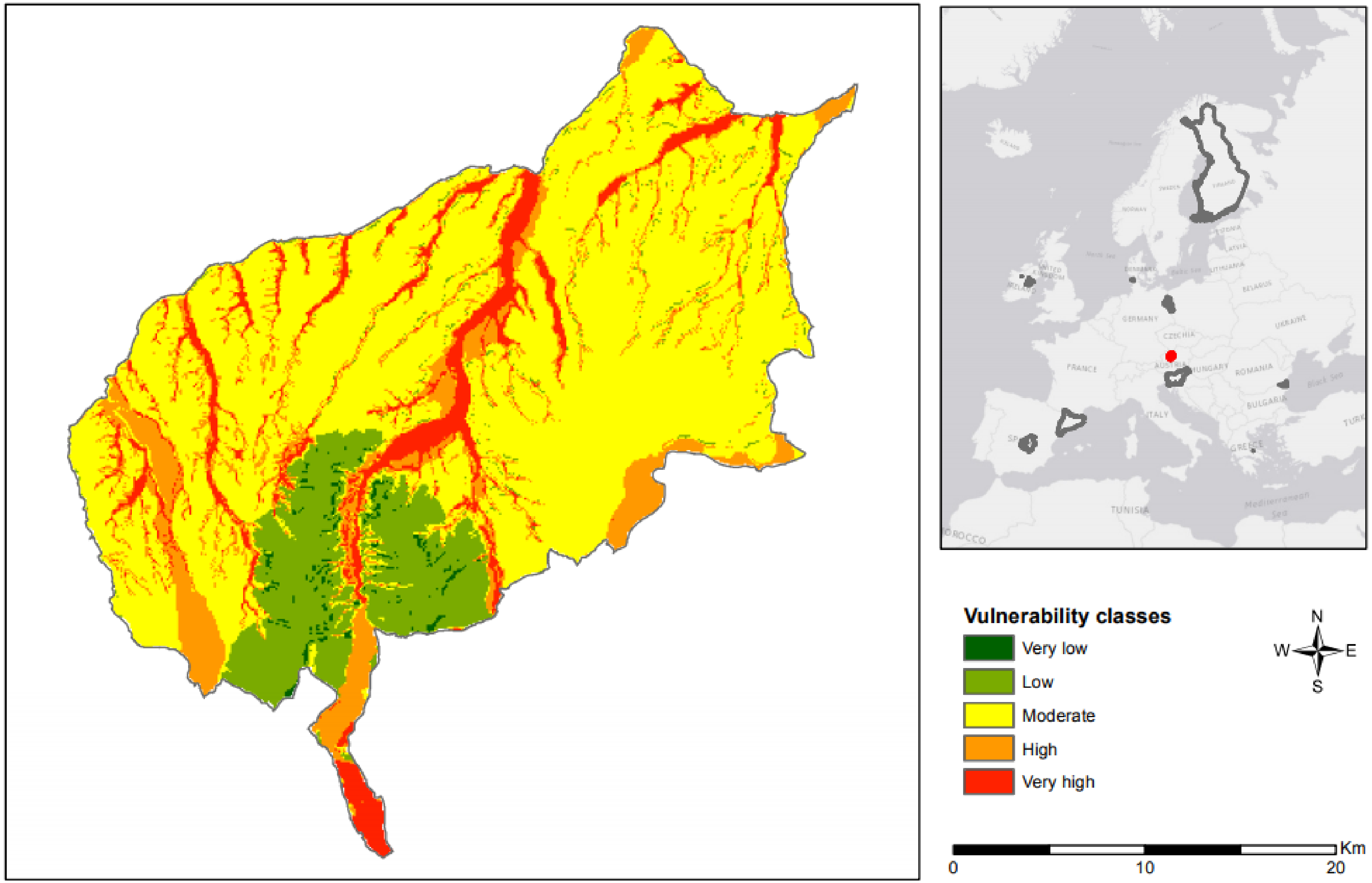


Pilot area Tønder (Denmark) – GEUS

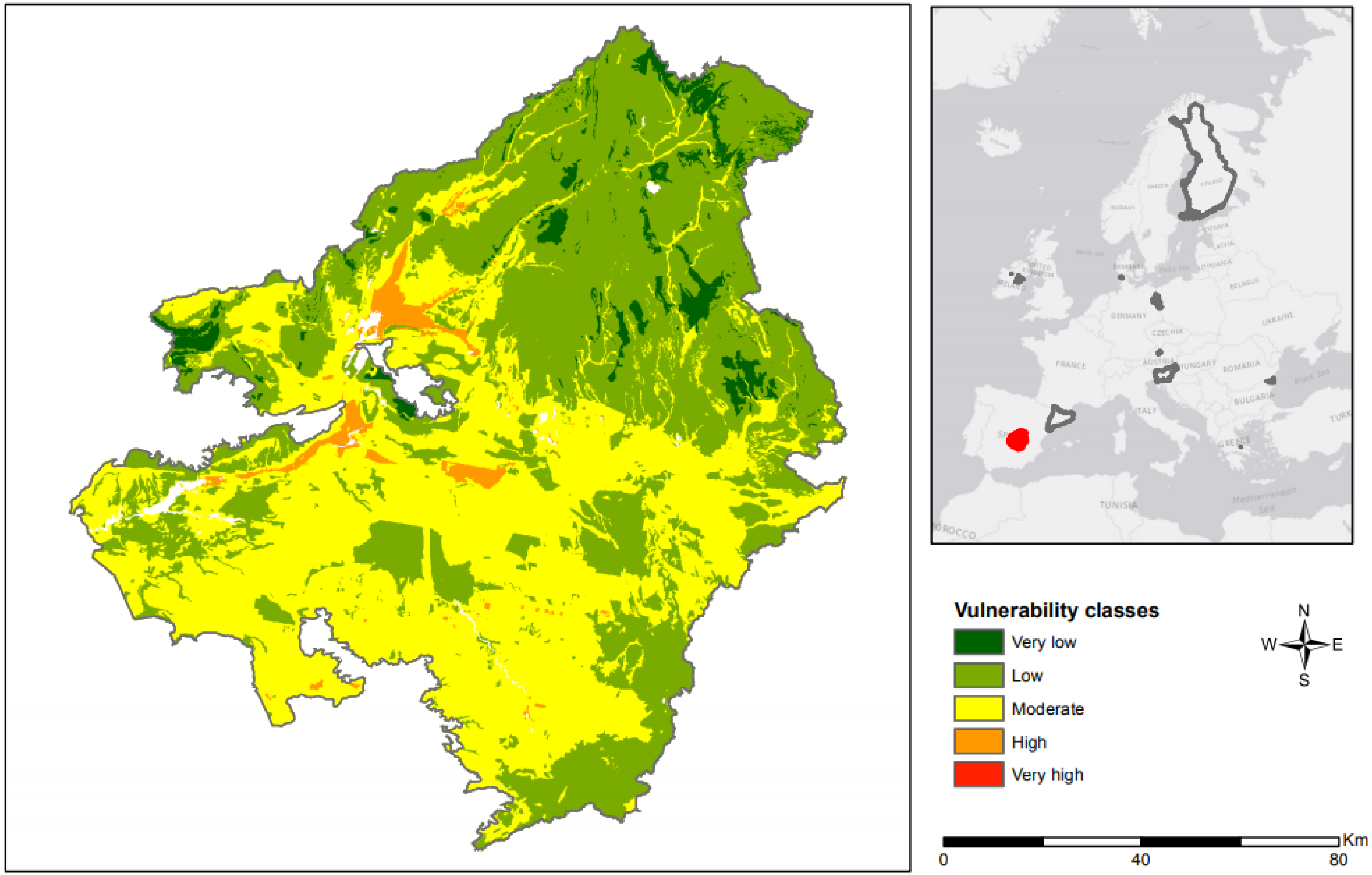
DRASTIC vulnerability index spatial distribution



Pilot area Traun-Enns-Platte (Austria) – GBA
DRASTIC vulnerability index spatial distribution



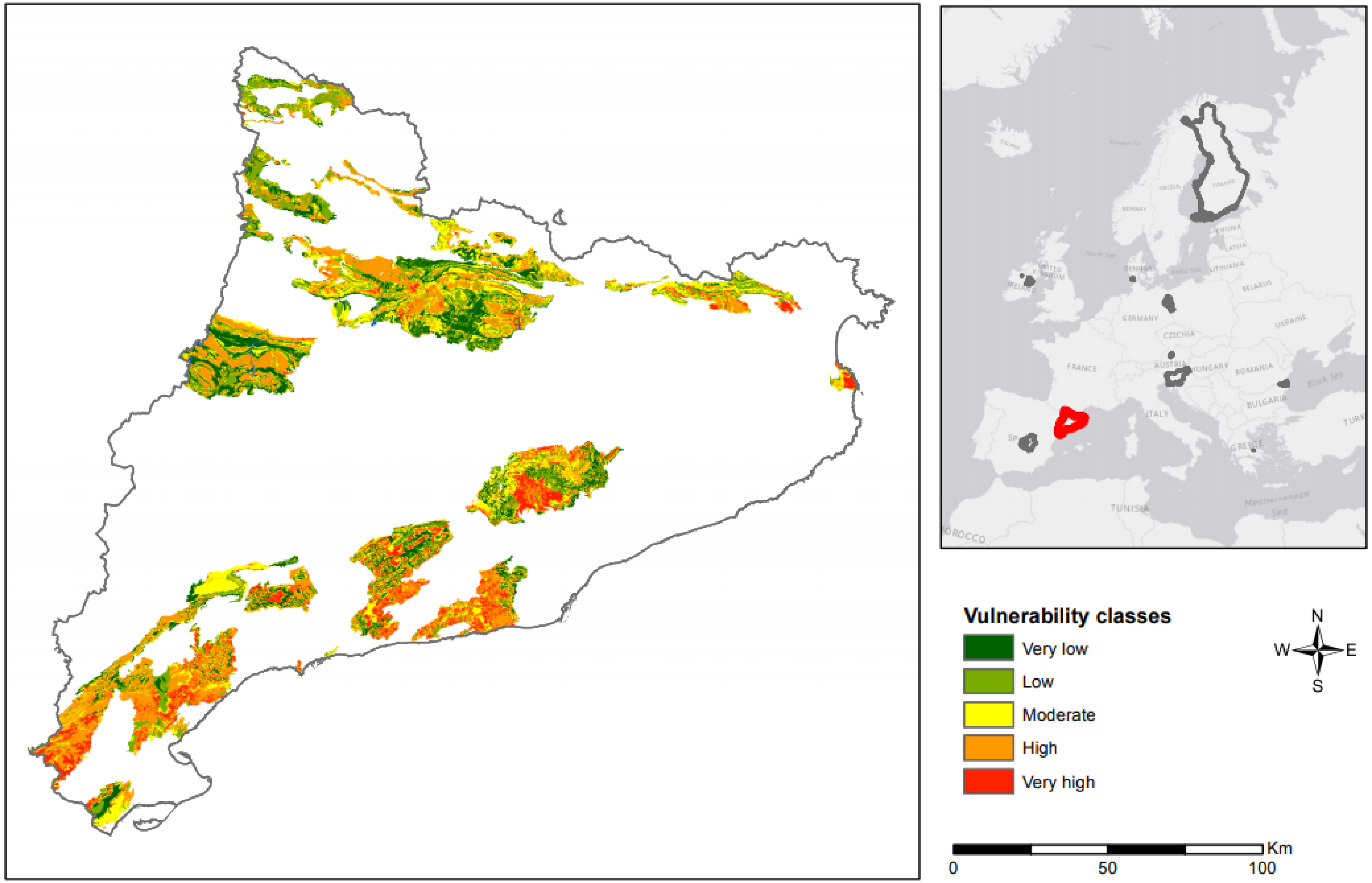
Pilot area Upper Guadiana Basin (Spain) – IGME
DRASTIC vulnerability index spatial distribution



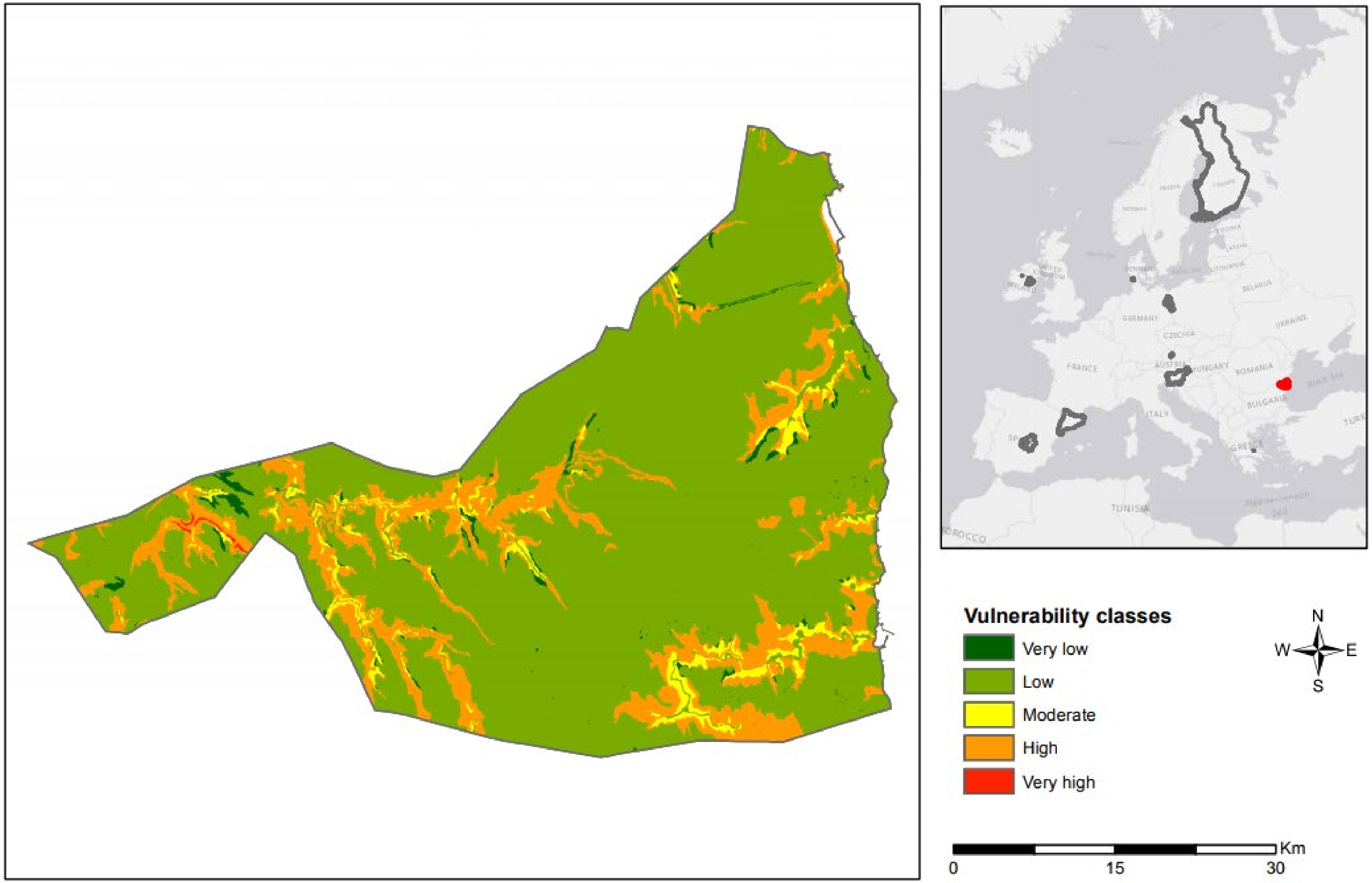
APPENDIX A2: VULNERABILITY INDEXES .COP ASSESSMENTS

Pilot area Catalonia (Spain) - ICGC

COP vulnerability index spatial distribution

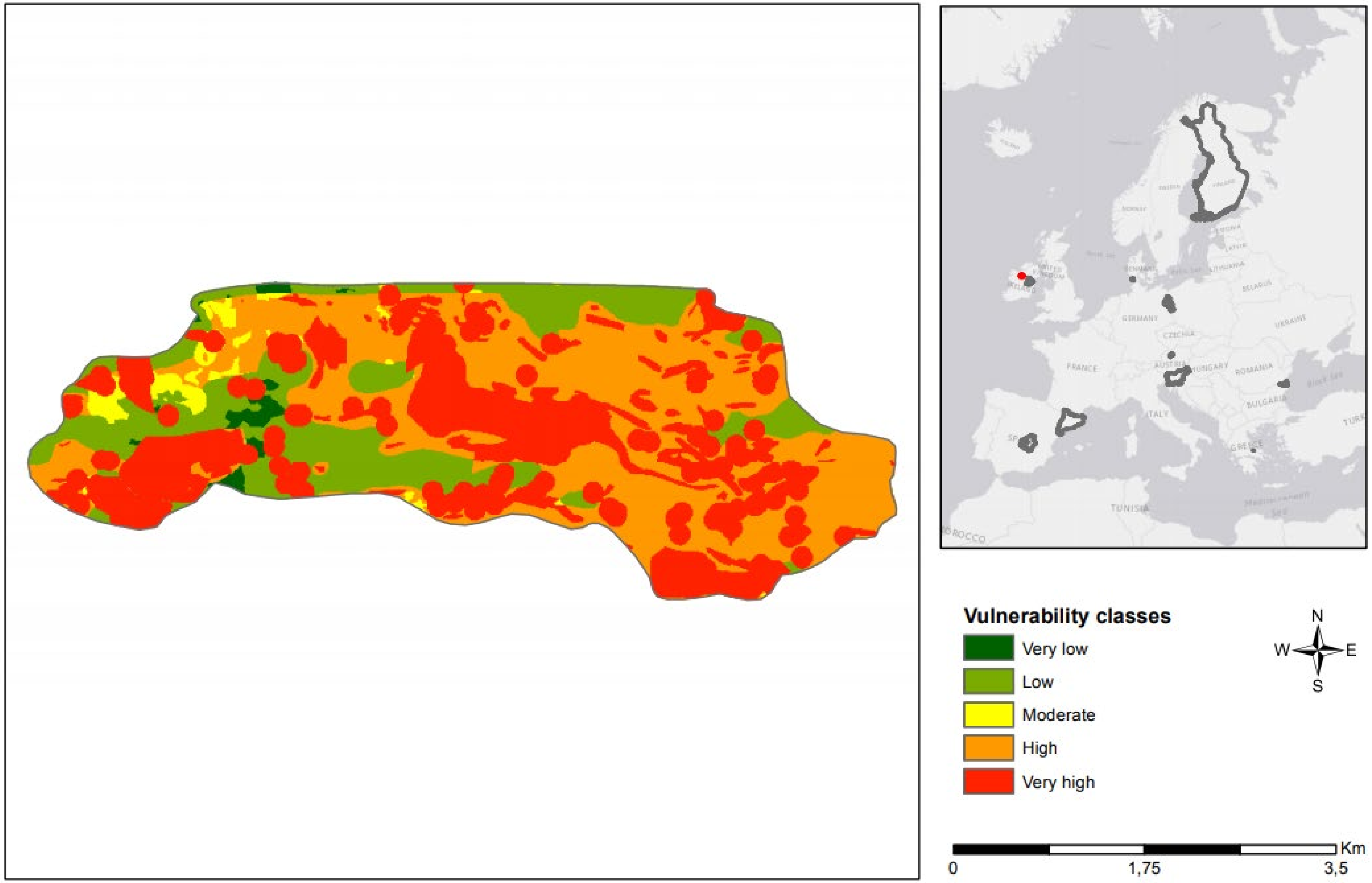


Pilot area Cobadin-Mangalia (Romania) - IGR
COP vulnerability index spatial distribution



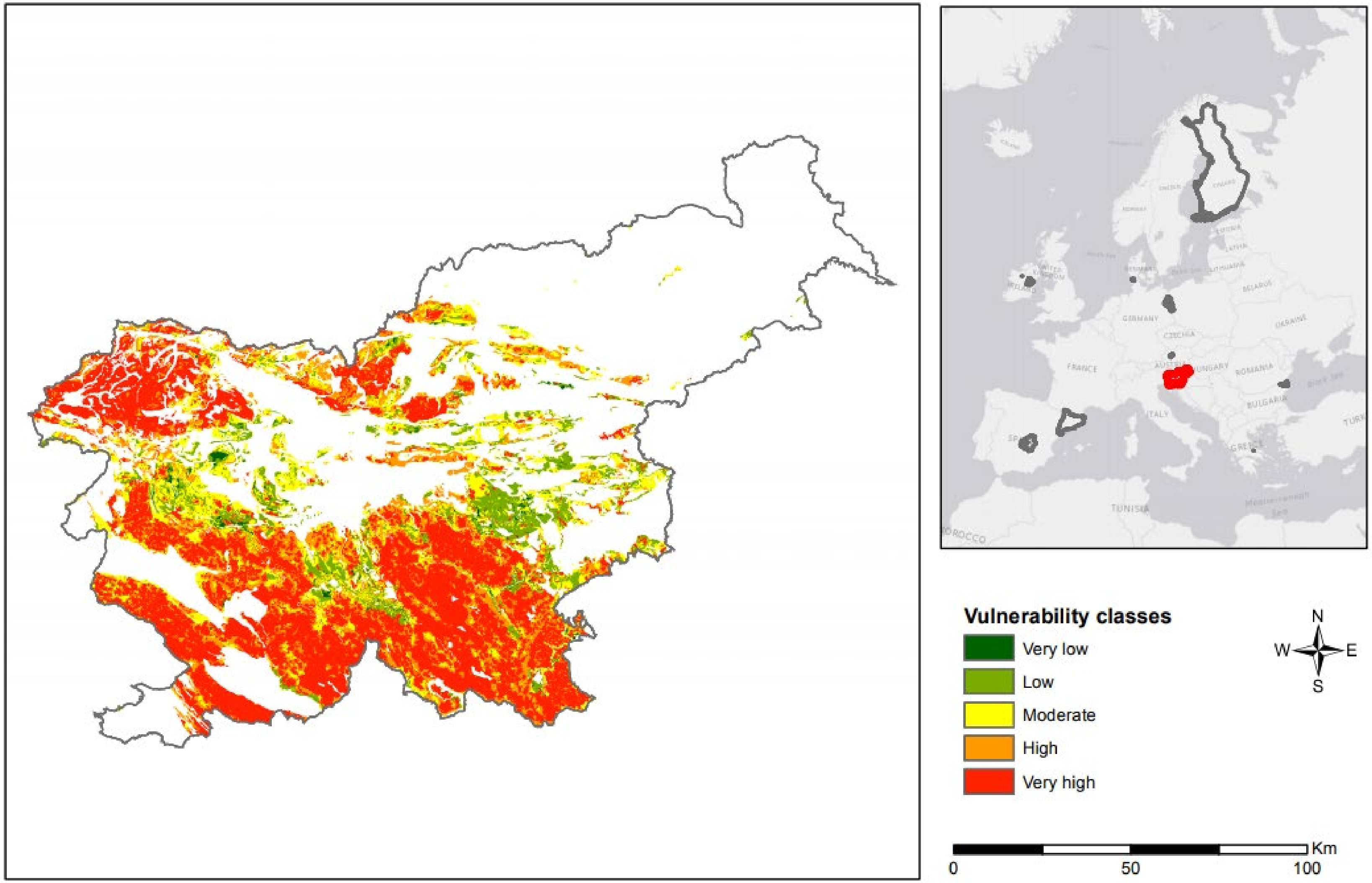
Pilot area Rockingham (Ireland) - GSI

COP vulnerability index spatial distribution



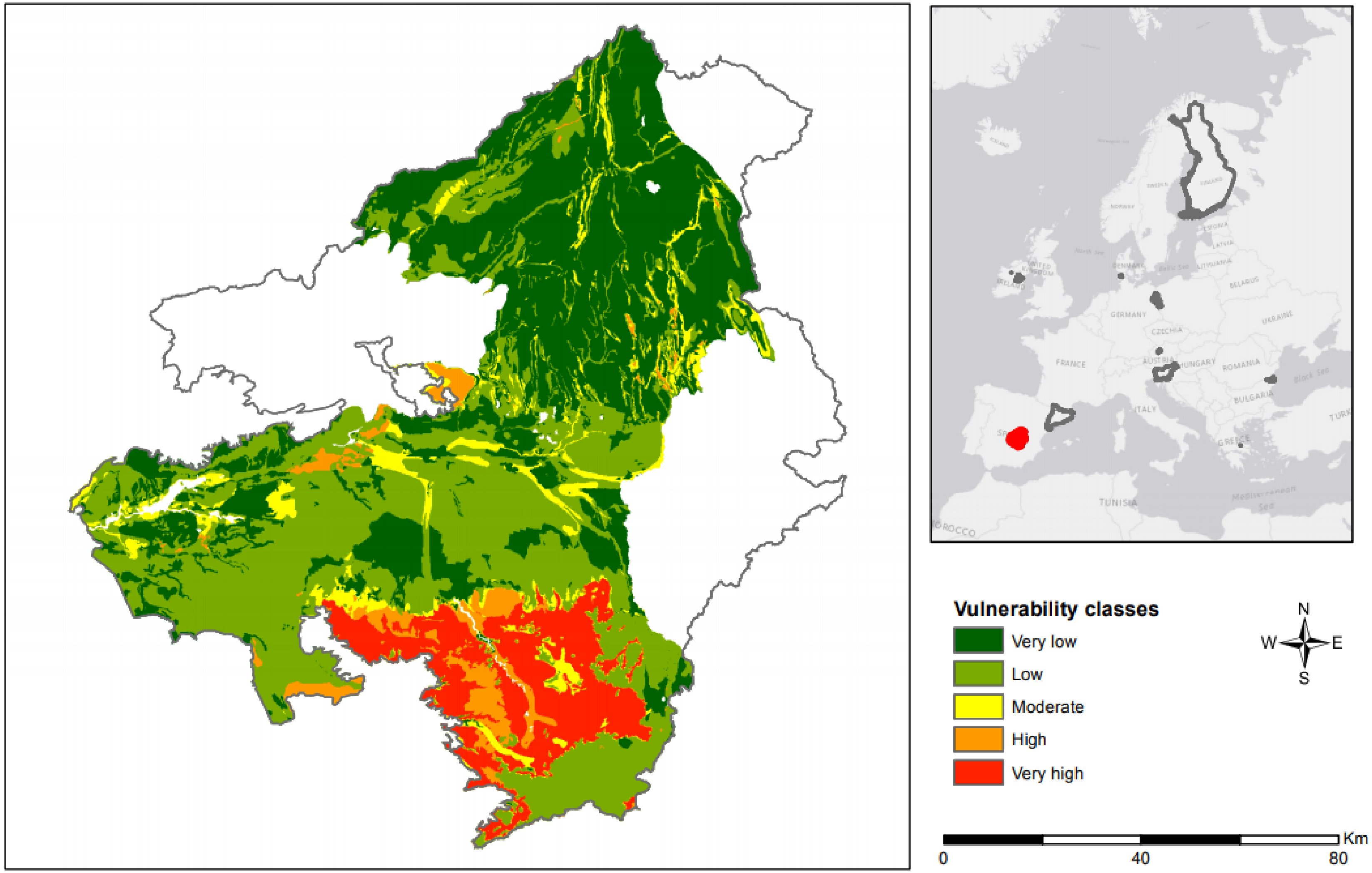
Pilot area Slovenia (Slovenia) – GeoZS

COP vulnerability index spatial distribution



Pilot area Upper Guadiana Basin (Spain) – IGME

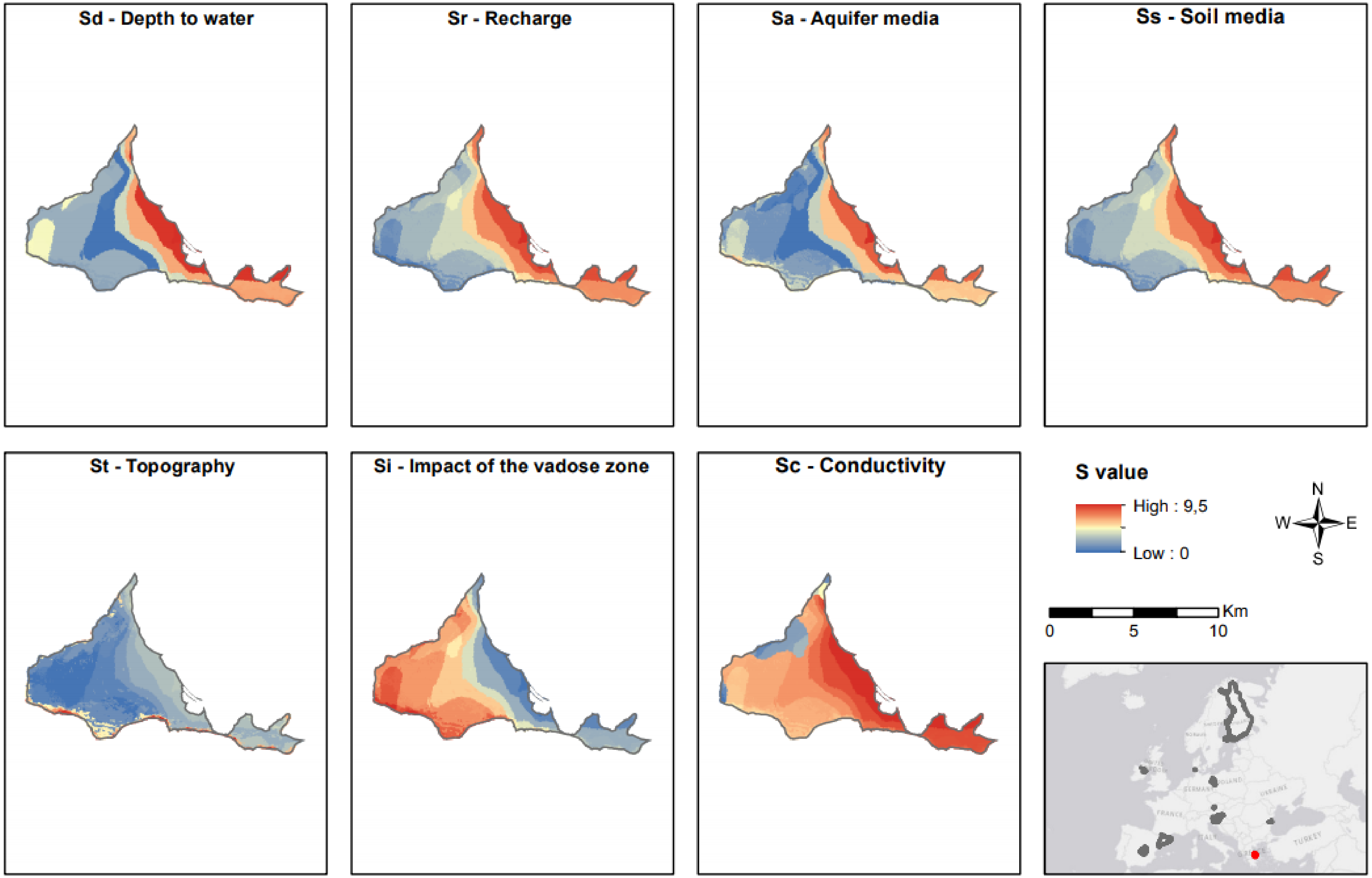
COP vulnerability index spatial distribution



APPENDIX B1: SPATIAL DISTRIBUTION OF THE SENSITIVITY INDEX (S)

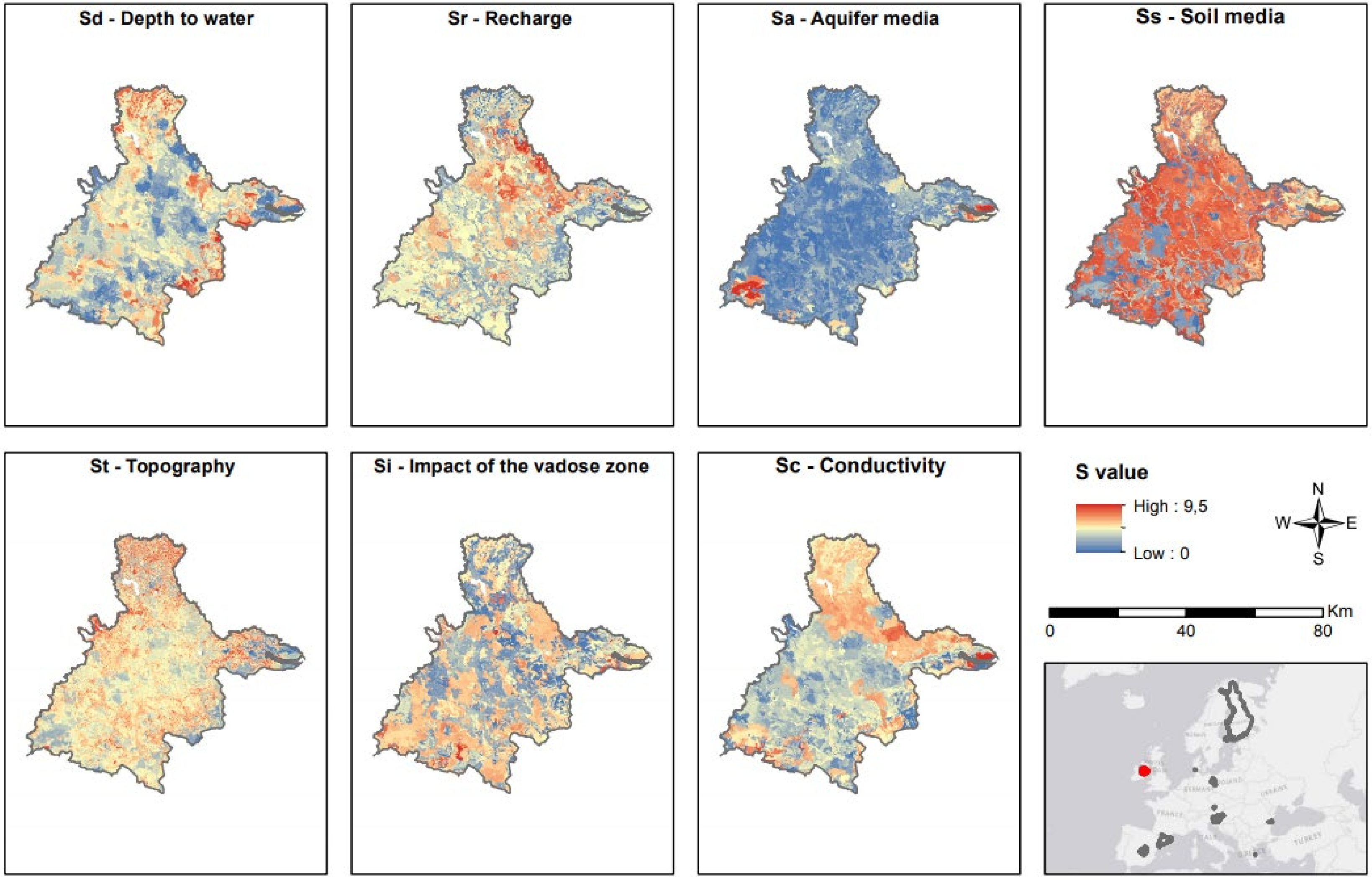
Pilot area Atalanti alluvial aquifer (Greece) - HSGME

Spatial distribution of the Sensitivity index (S)



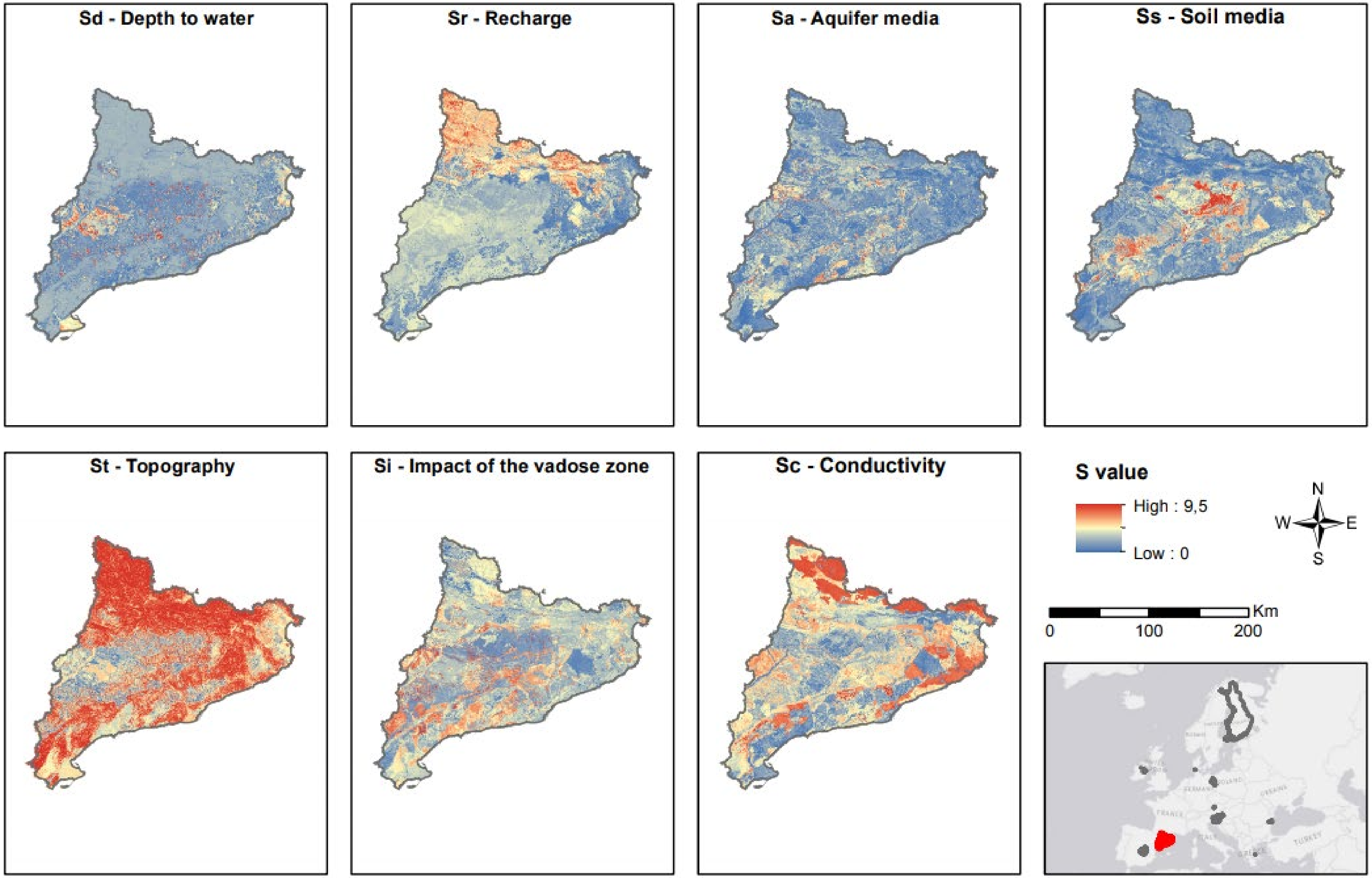
Pilot area Boyne (Ireland) - GSI

Spatial distribution of the Sensitivity index (S)



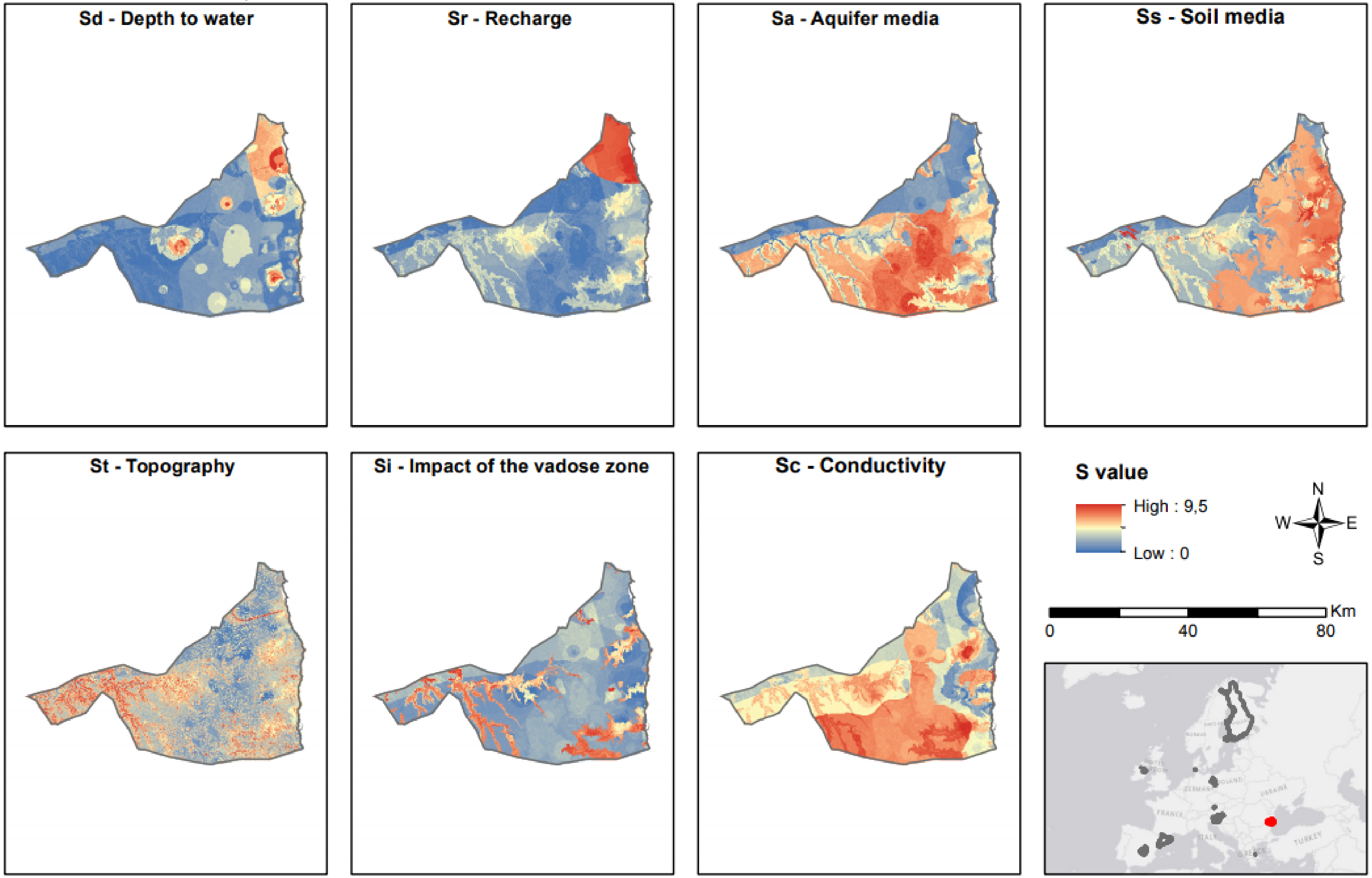
Pilot area Catalonia (Spain) - ICGC

Spatial distribution of the Sensitivity index (S)



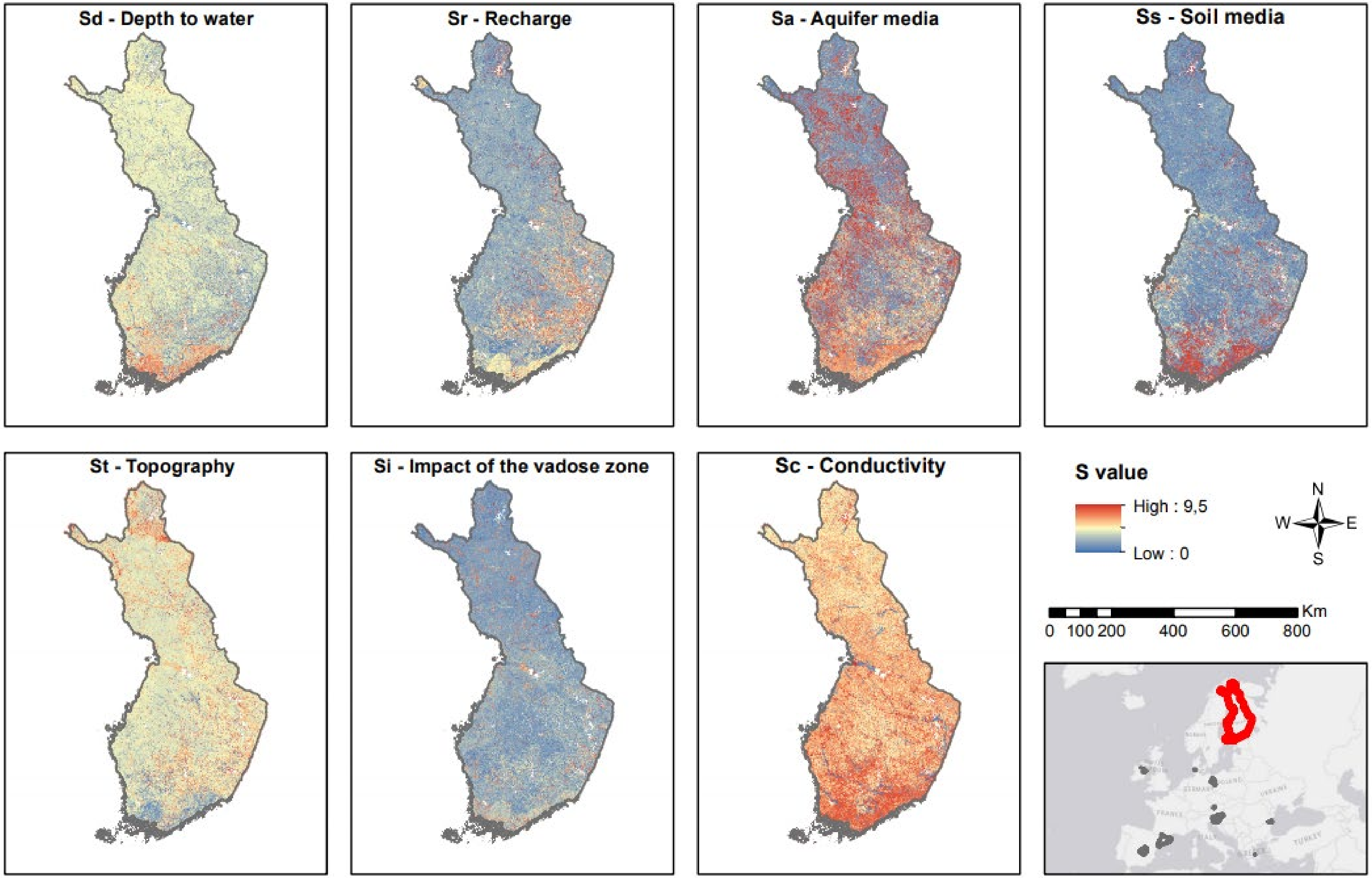
Pilot area Cobadin-Mangalia (Romania) - IGR

Spatial distribution of the Sensitivity index (S)



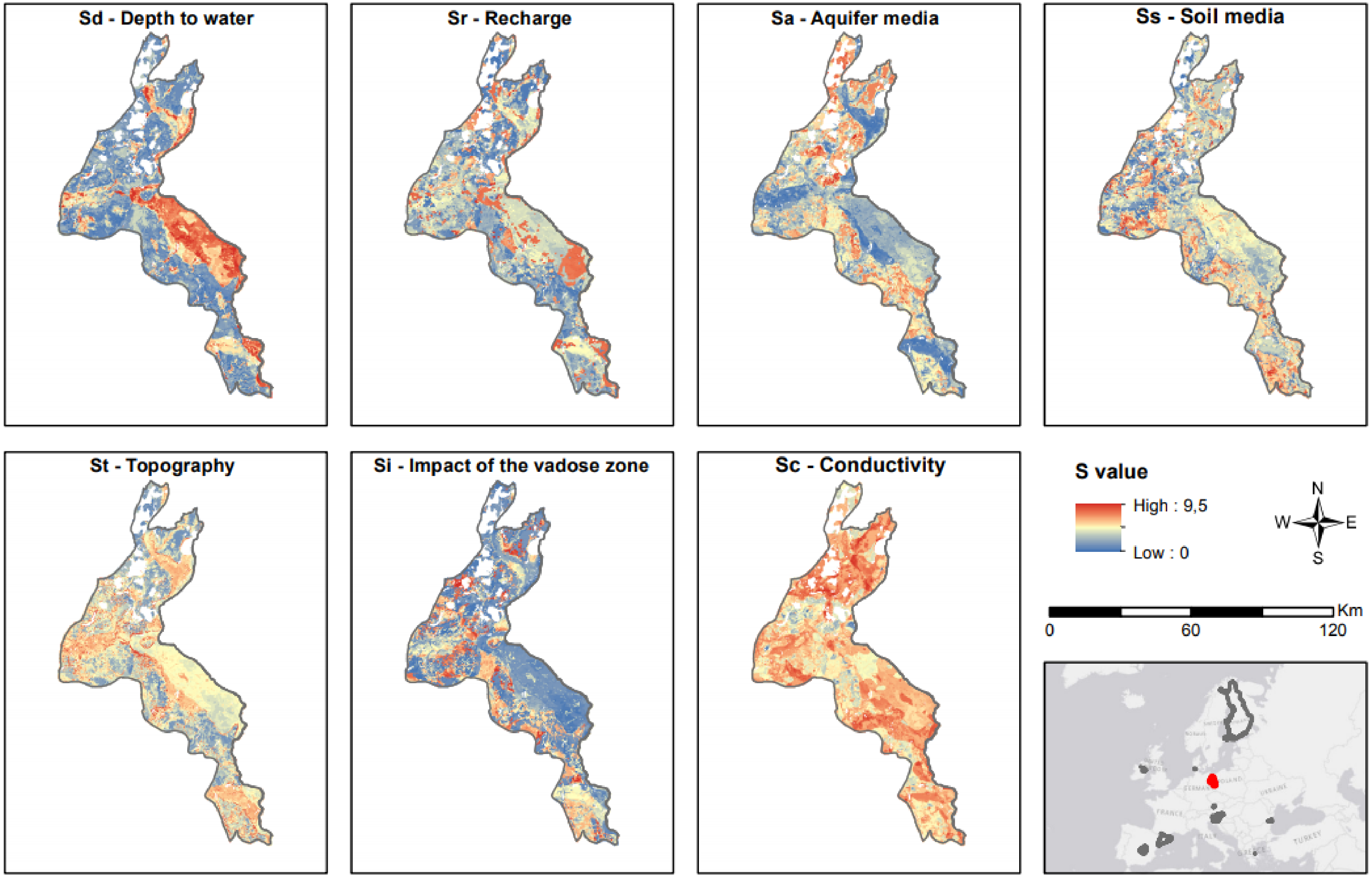
Pilot area Finland (Finland) – GTK

Spatial distribution of the Sensitivity index (S)



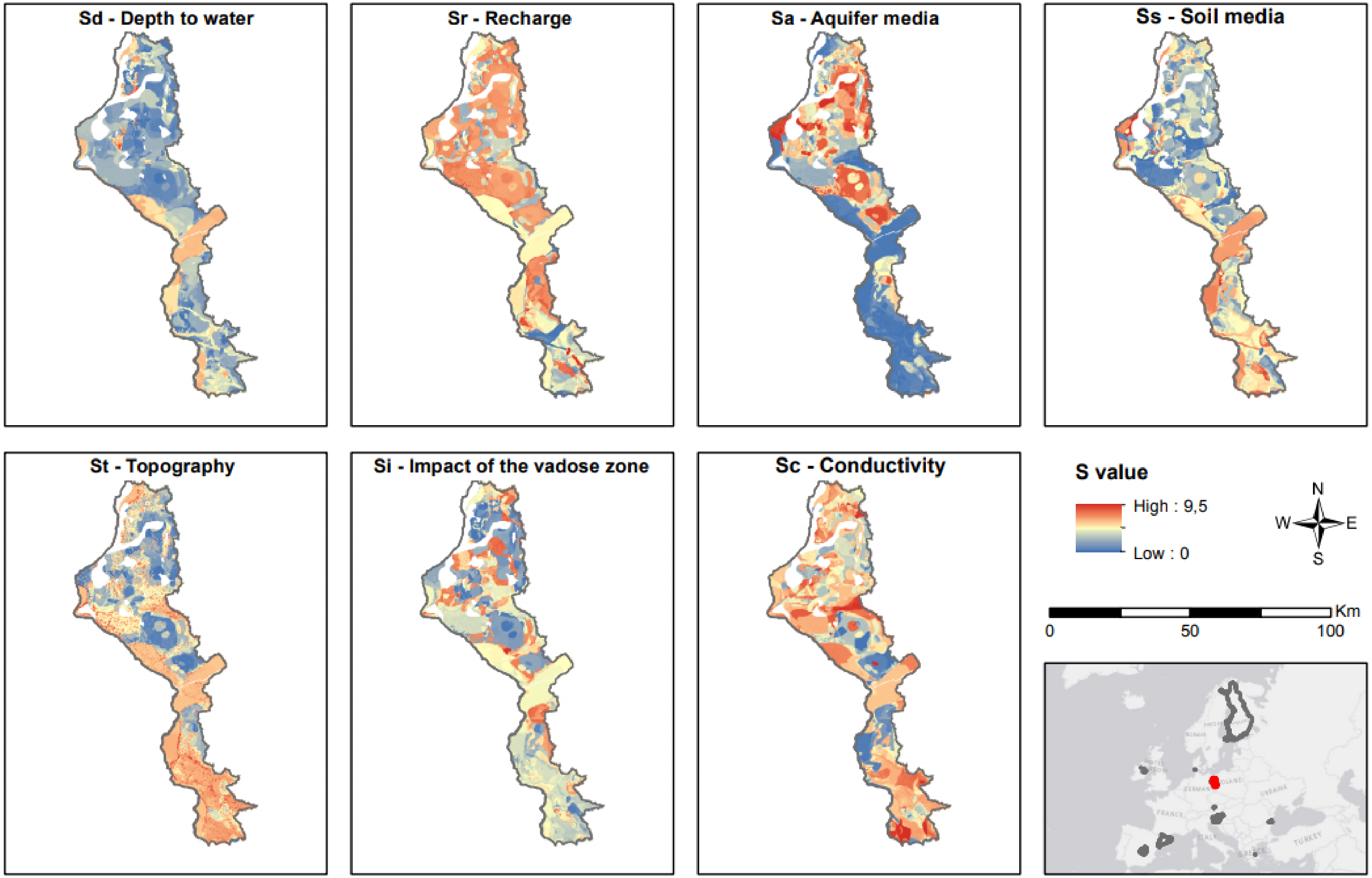
Pilot area Middle and Lower Oder/Odra river (German part) – PGI/LBGR/BGR

Spatial distribution of the Sensitivity index (S)



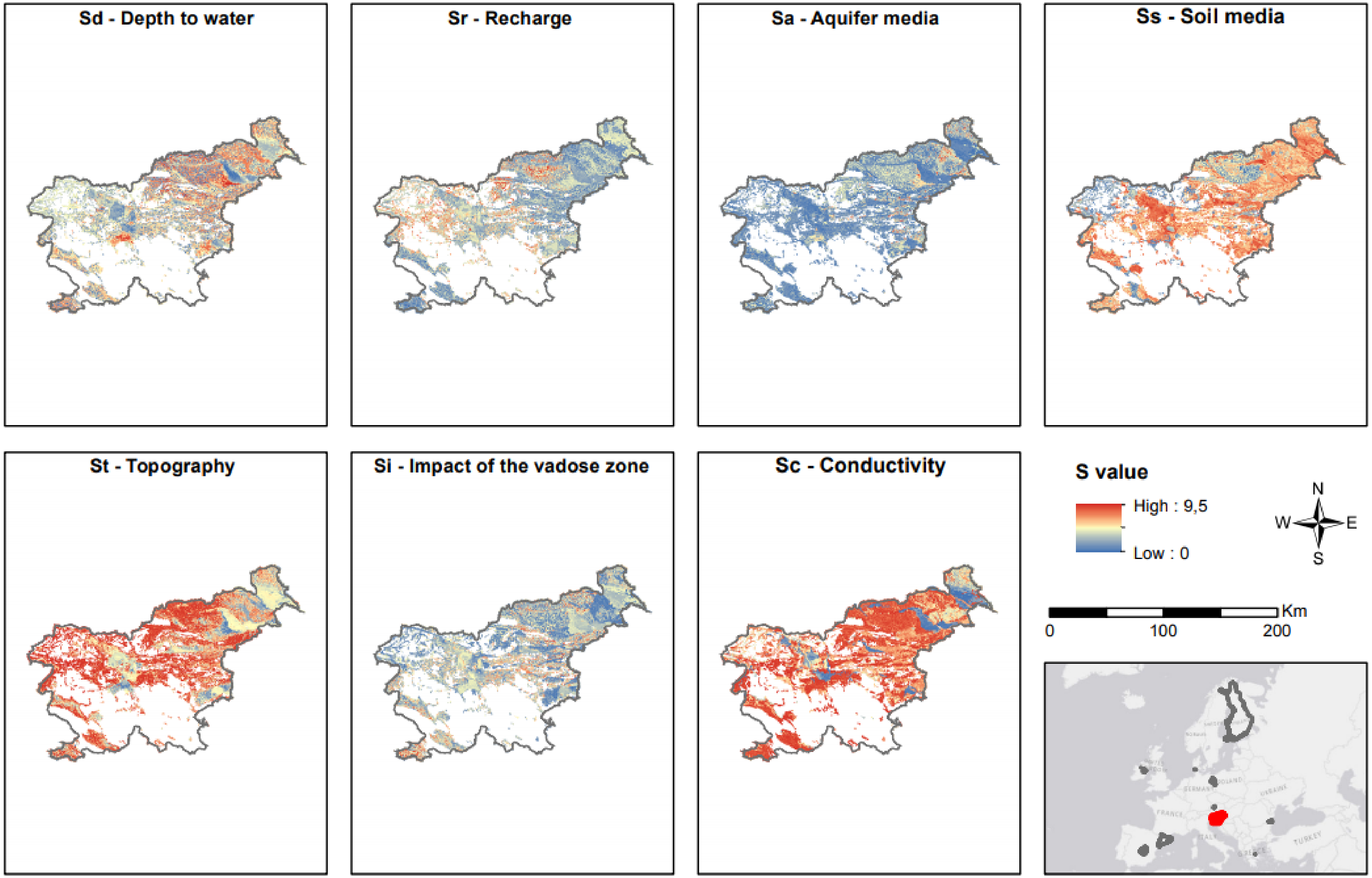
Pilot area Middle and Lower Oder/Odra river (Polish part) – PGI/LBGR/BGR

Spatial distribution of the Sensitivity index (S)



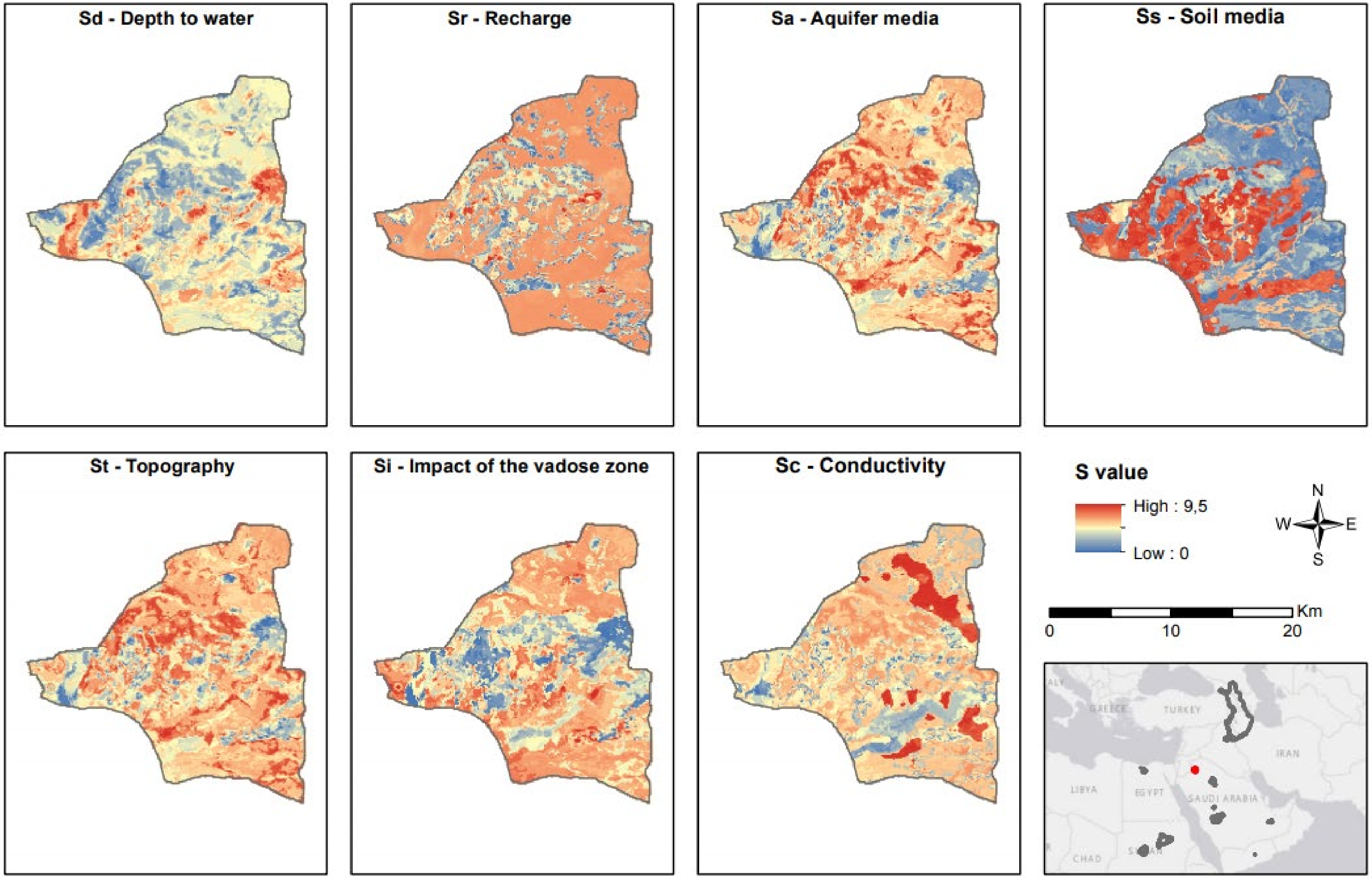
Pilot area Slovenia (Slovenia) – GeoZS

Spatial distribution of the Sensitivity index (S)



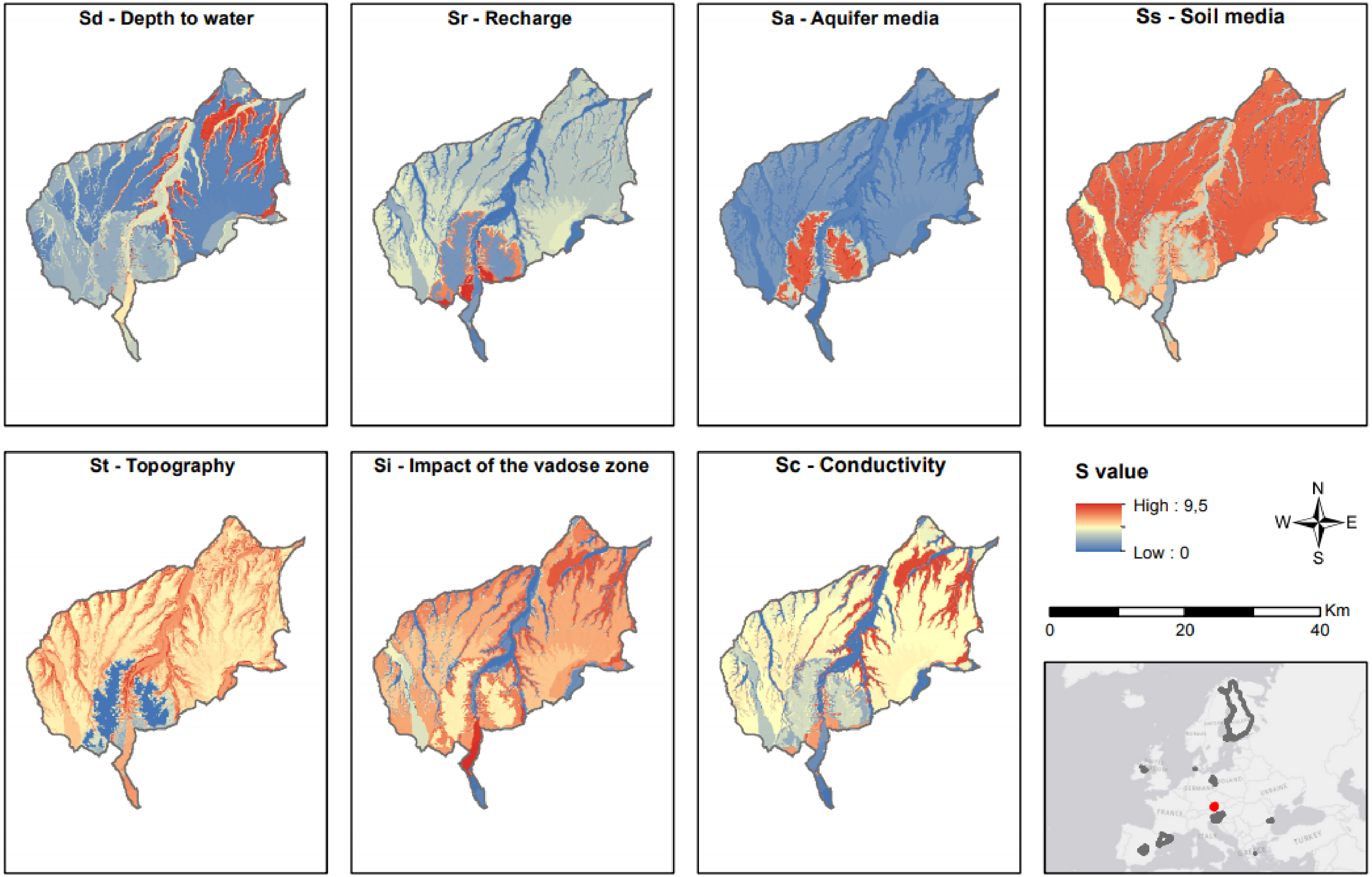
Pilot area Tønder (Denmark) – GEUS

Spatial distribution of the Sensitivity index (S)



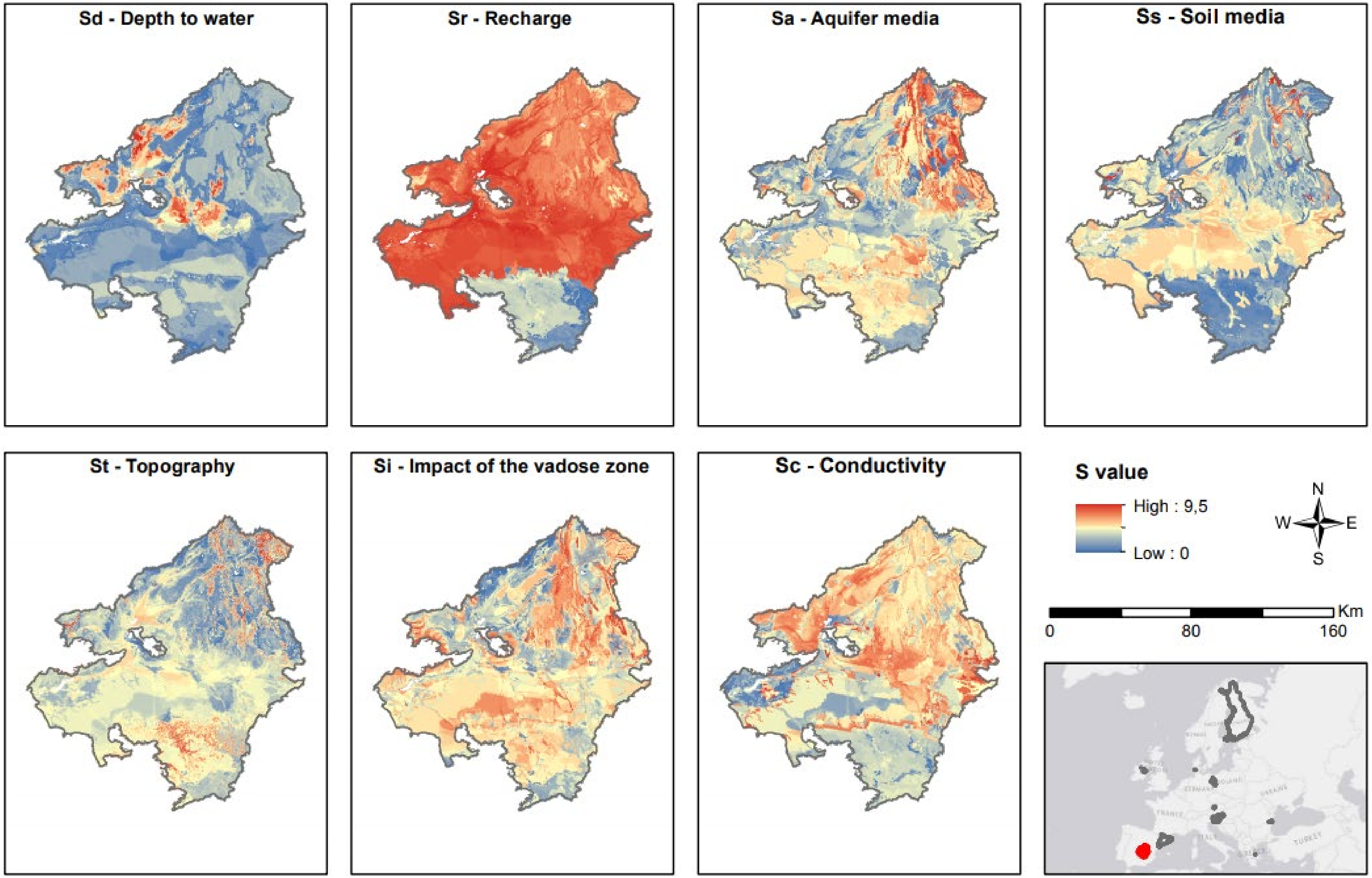
Pilot area Traun-Enns-Platte (Austria) – GBA

Spatial distribution of the Sensitivity index (S)



Pilot area Upper Guadiana Basin (Spain) – IGME

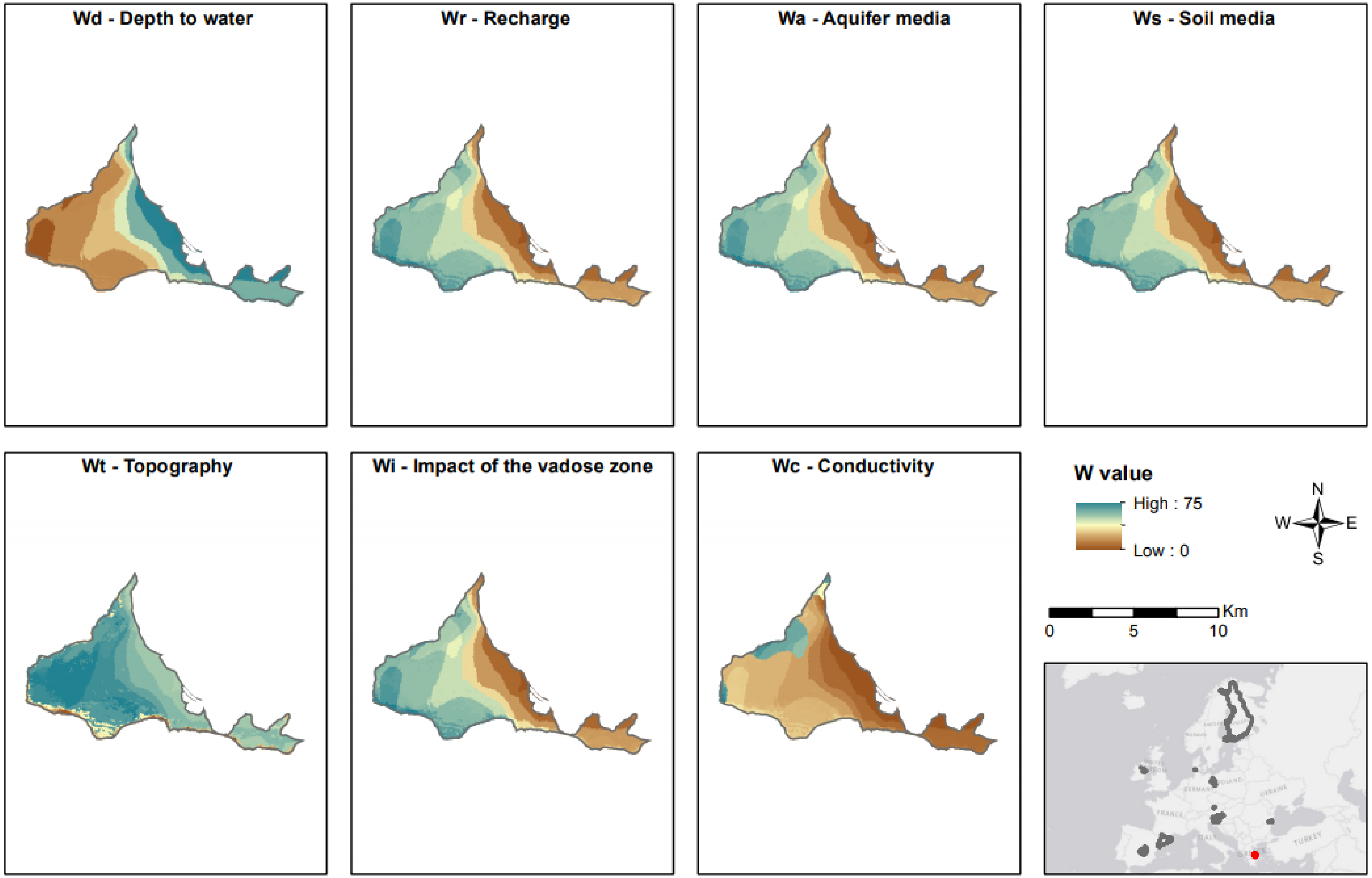
Spatial distribution of the Sensitivity index (S)



APPENDIX B2: SPATIAL DISTRIBUTION OF THE EFFECTIVE WEIGHT INDEX (W)

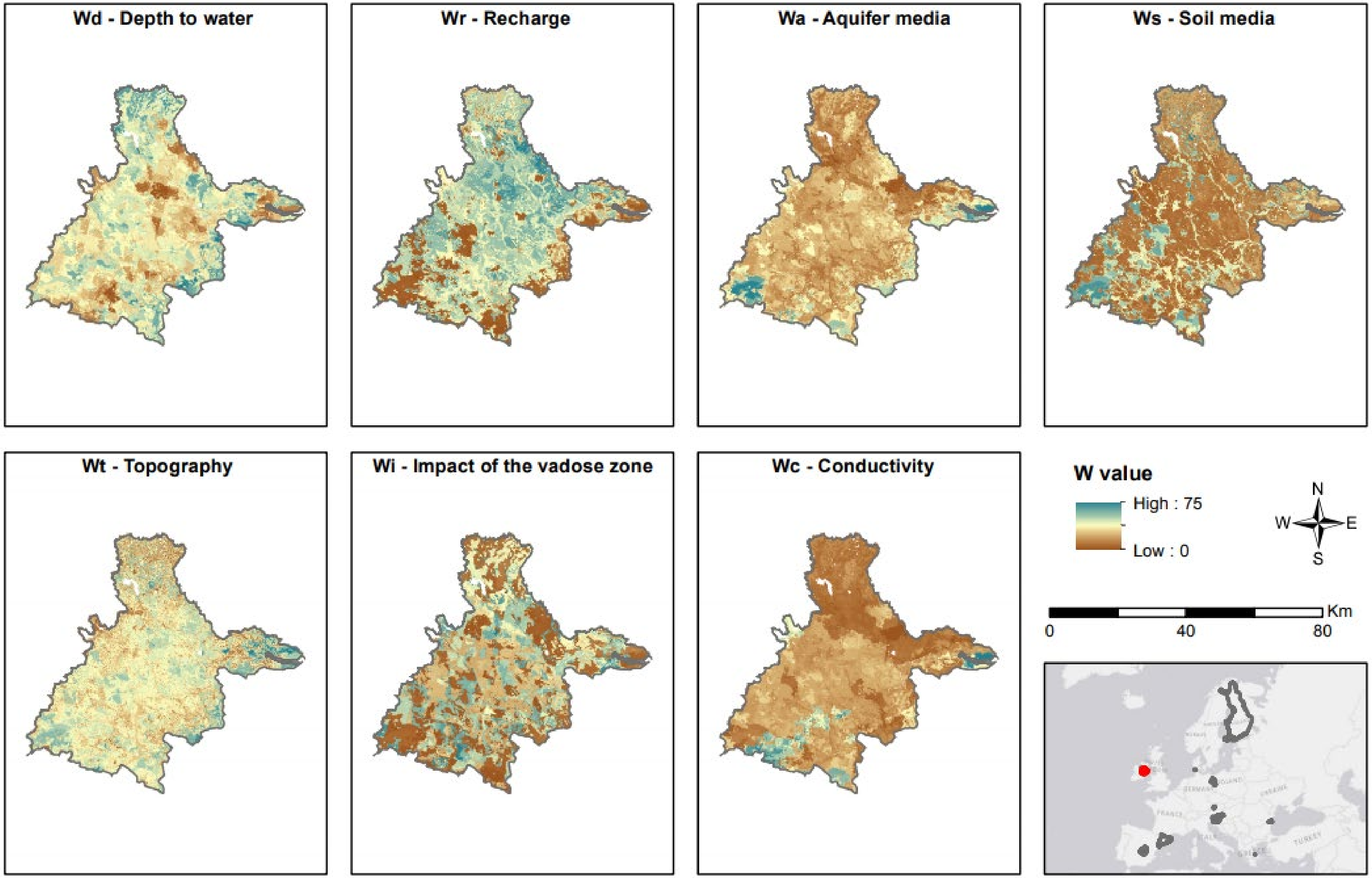
Pilot area Atalanti alluvial aquifer (Greece) - HSGME

Spatial distribution of the effective Weight index (W)



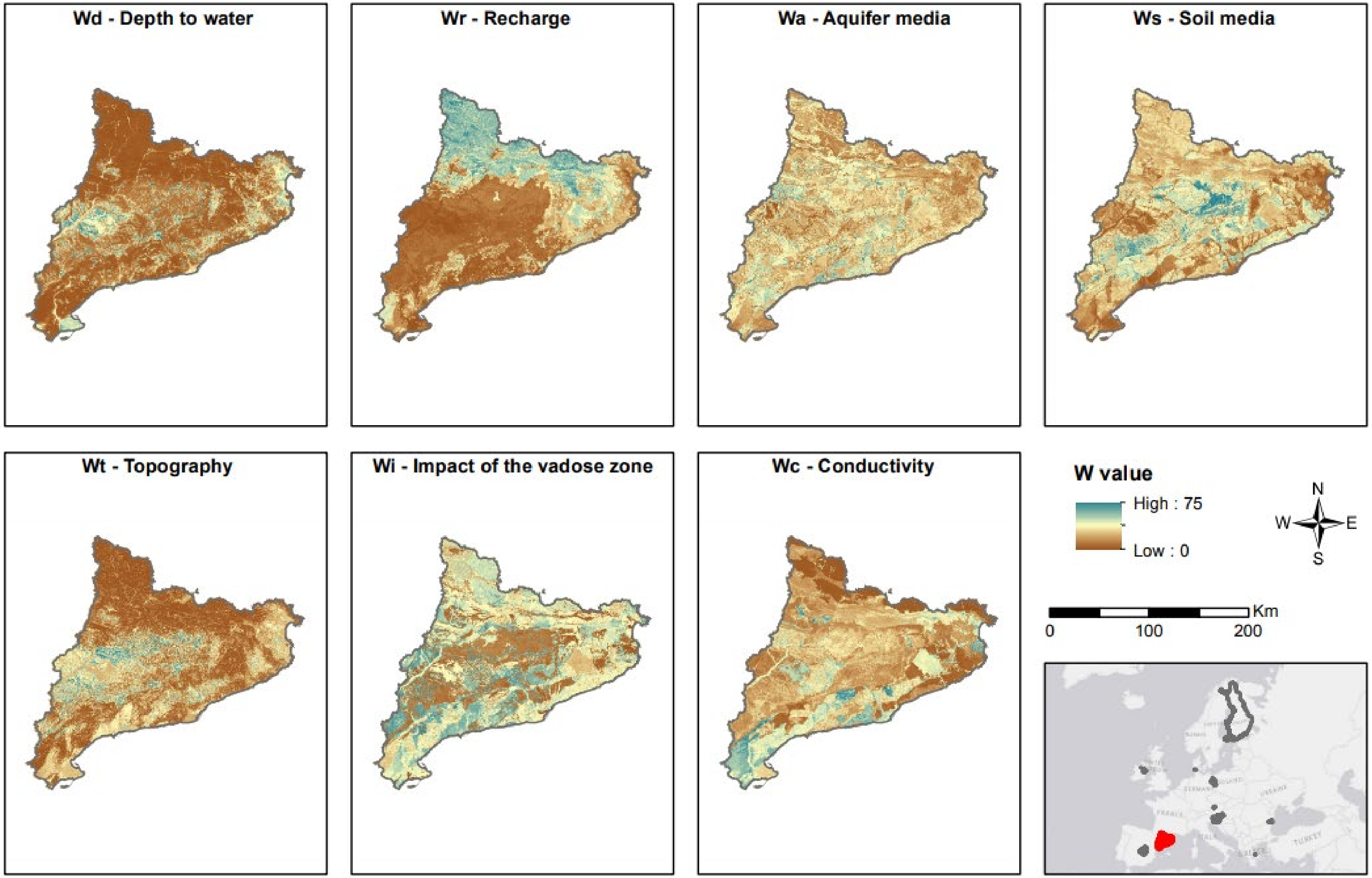
Pilot area Boyne (Ireland) - GSI

Spatial distribution of the effective Weight index (W)



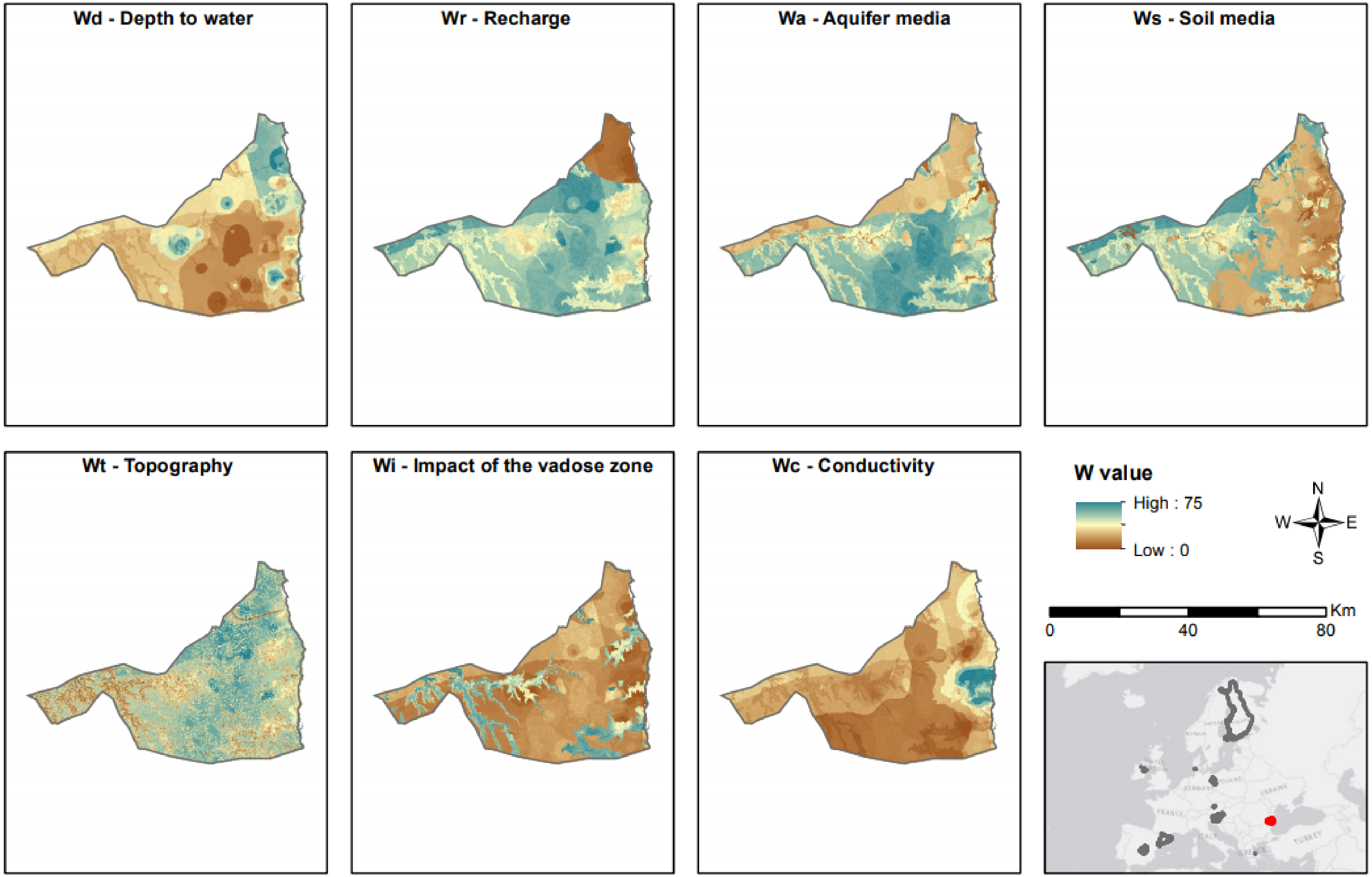
Pilot area Catalonia (Spain) - ICGC

Spatial distribution of the effective Weight index (W)



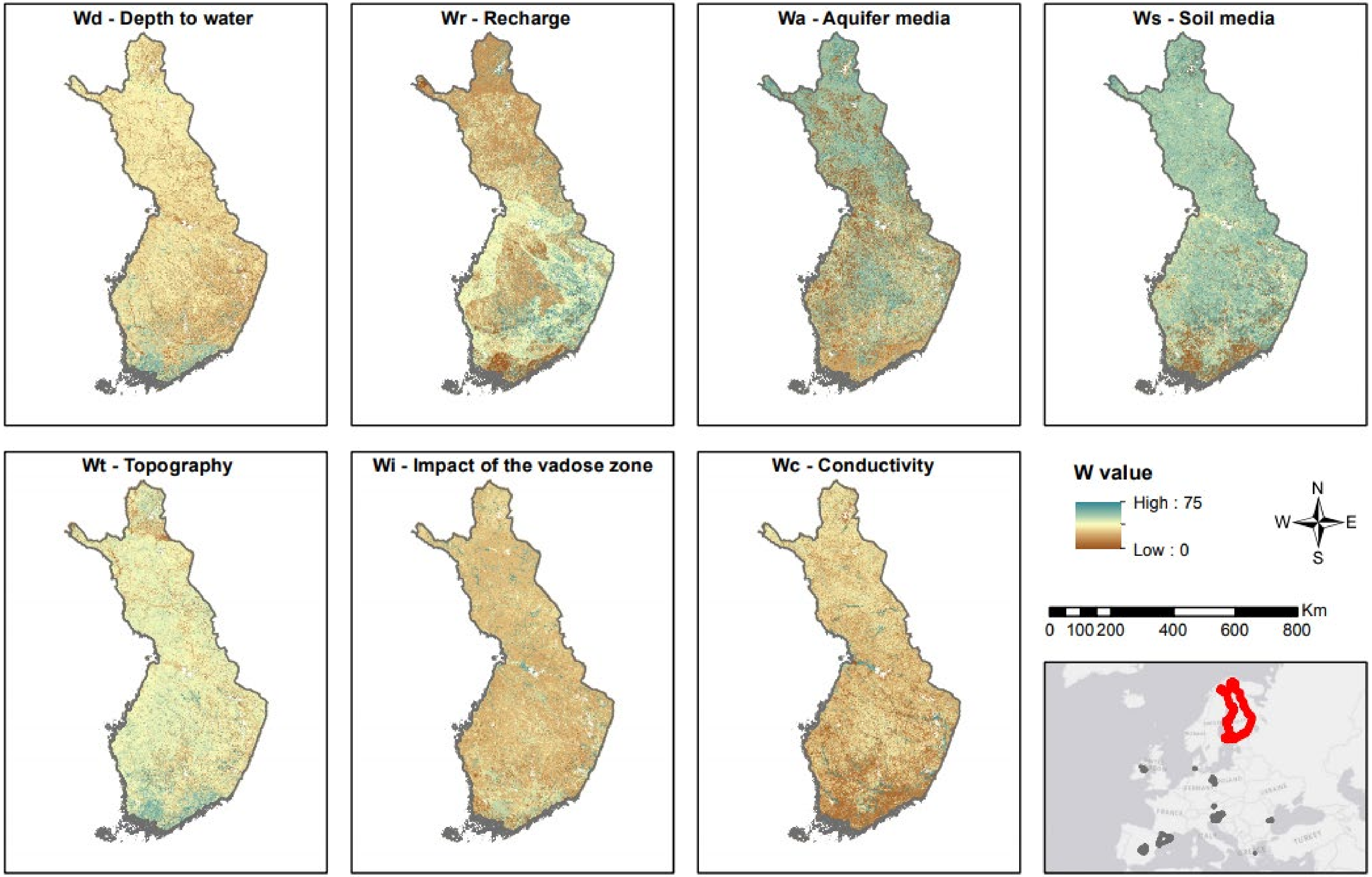
Pilot area Cobadin-Mangalia (Romania) - IGR

Spatial distribution of the effective Weight index (W)



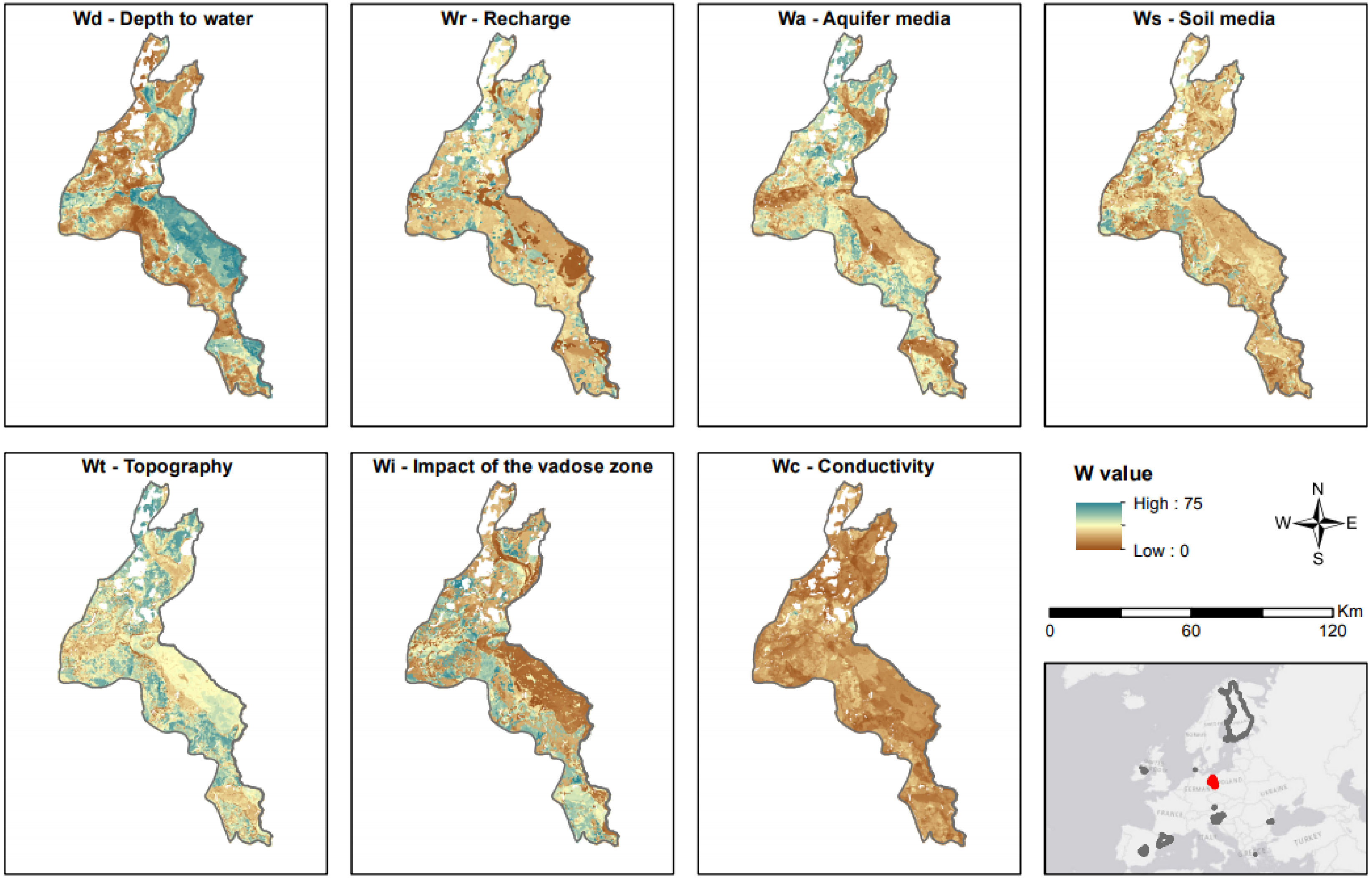
Pilot area Finland (Finland) – GTK

Spatial distribution of the effective Weight index (W)



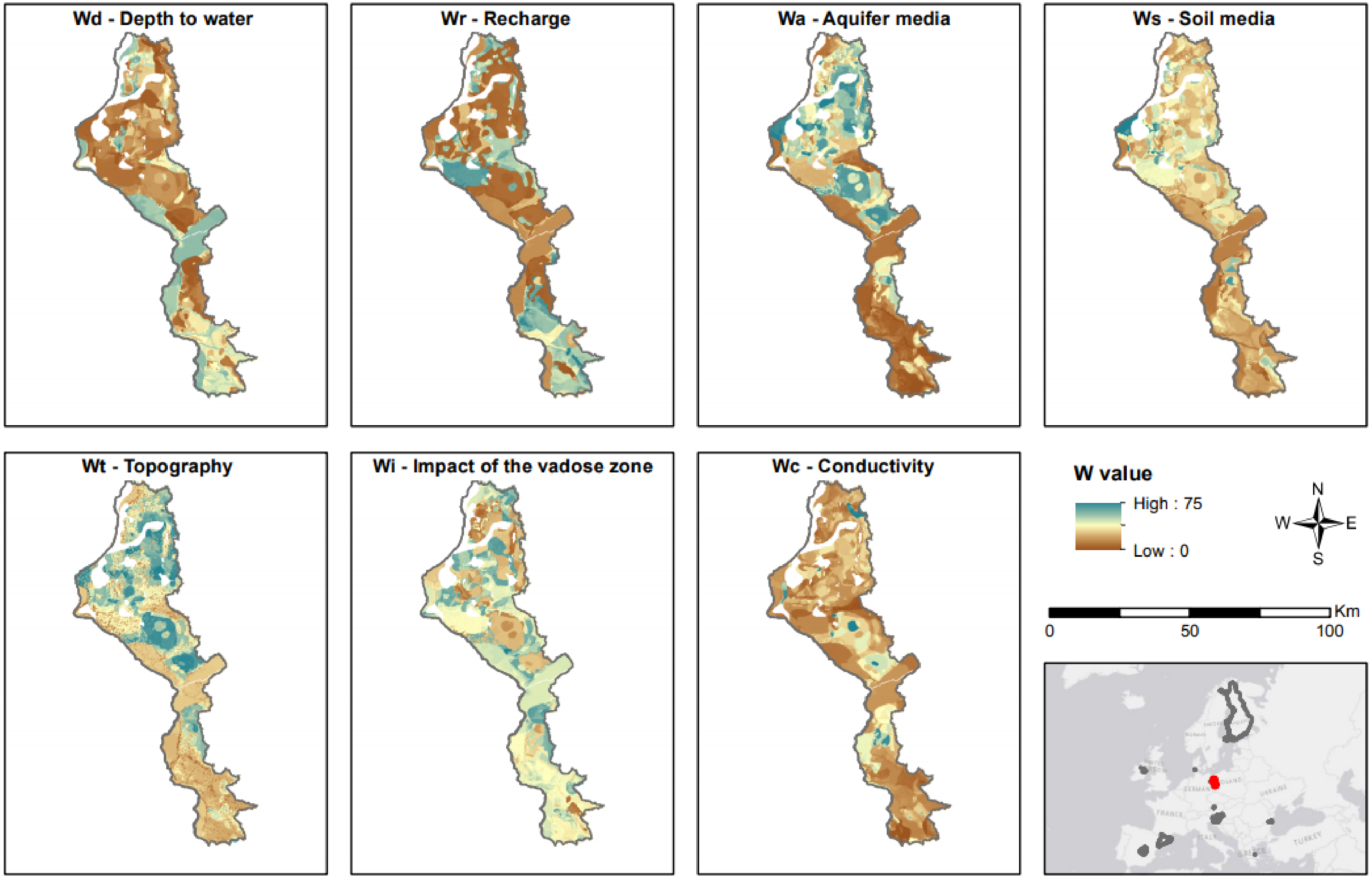
Pilot area Middle and Lower Oder/Odra river (German part) – PGI/LBGR/BGR

Spatial distribution of the effective Weight index (W)



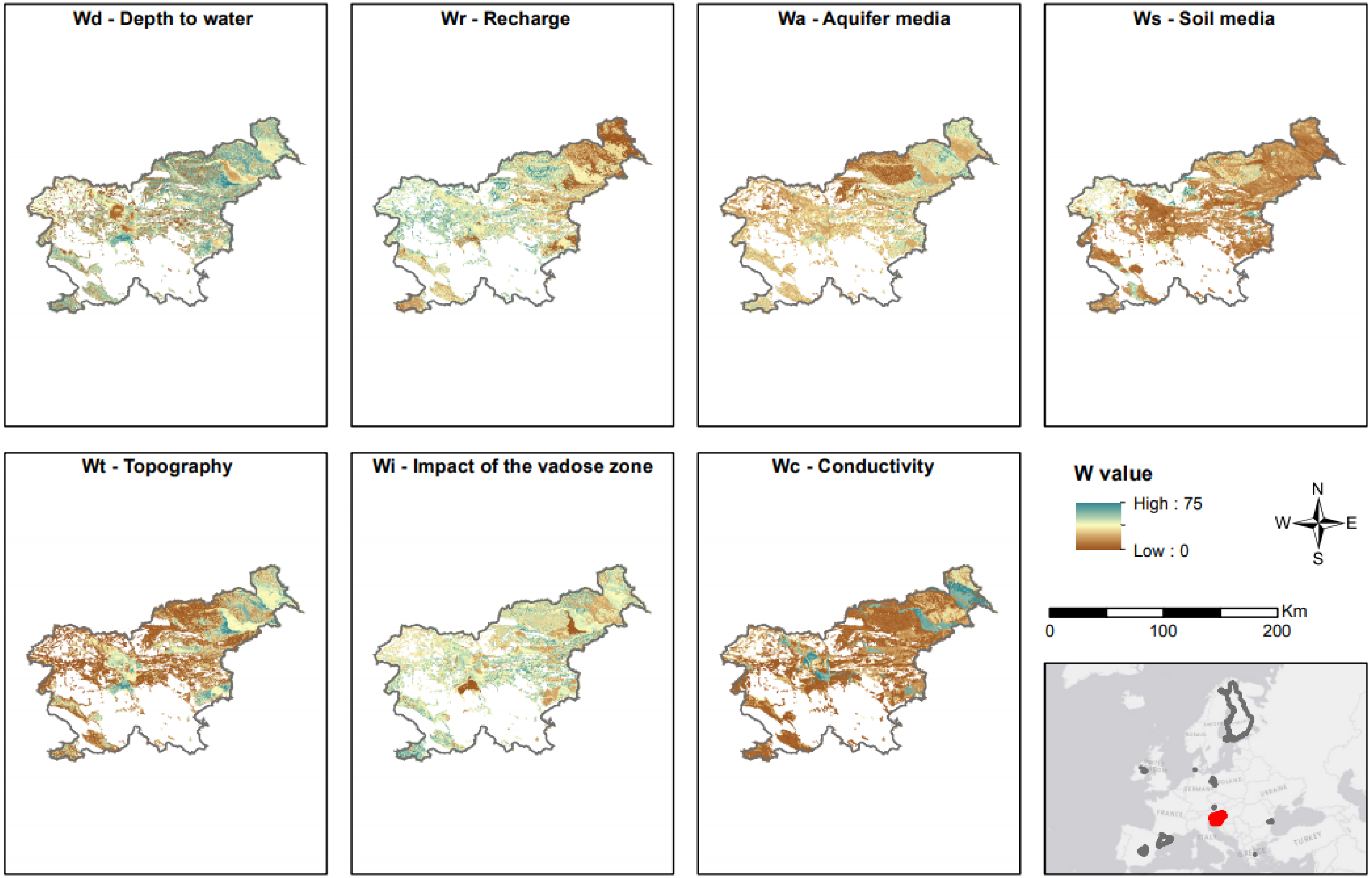
Pilot area Middle and Lower Oder/Odra river (Polish part) – PGI/LBGR/BGR

Spatial distribution of the effective Weight index (W)



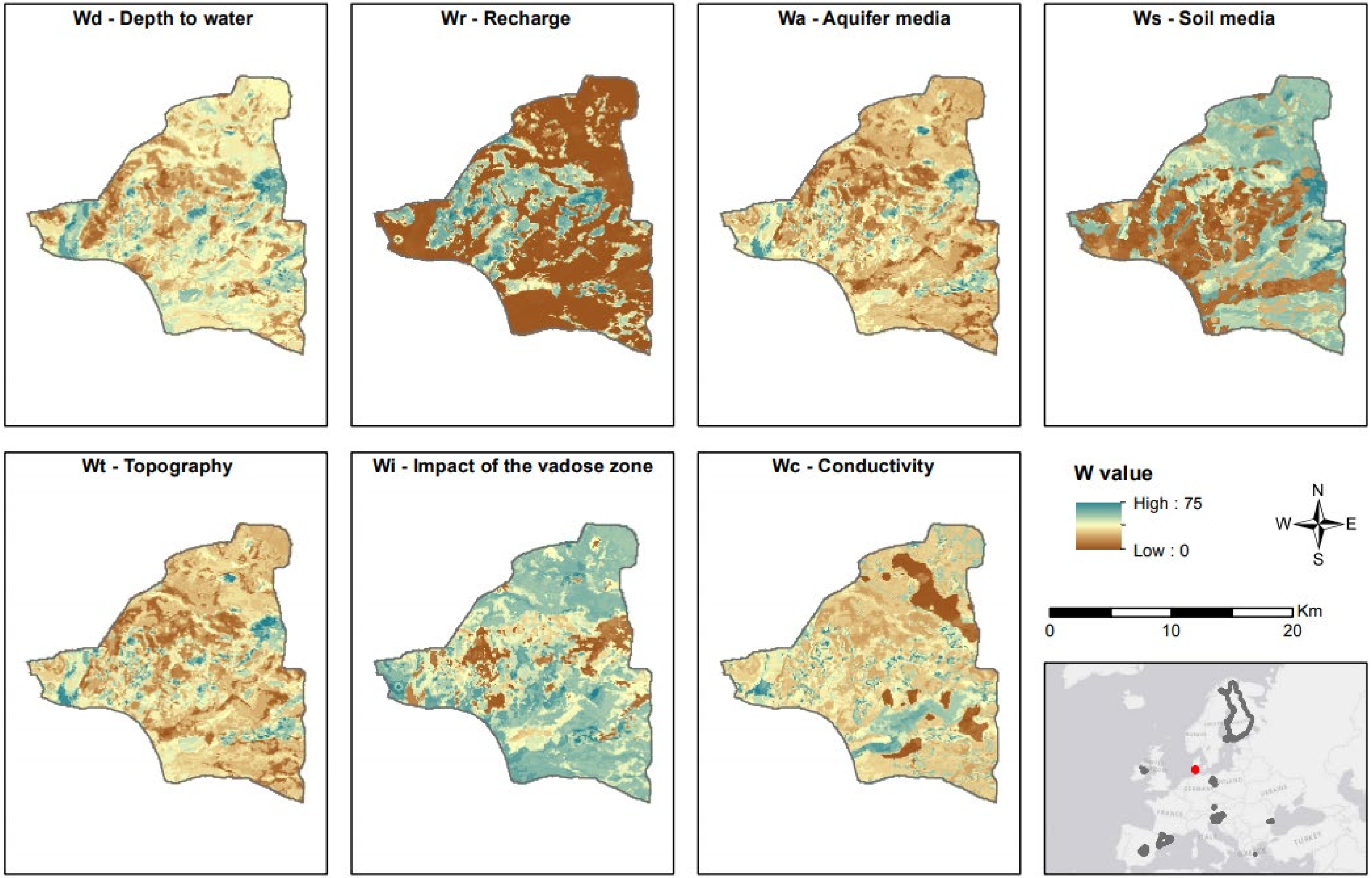
Pilot area Slovenia (Slovenia) – GeoZS

Spatial distribution of the effective Weight index (W)



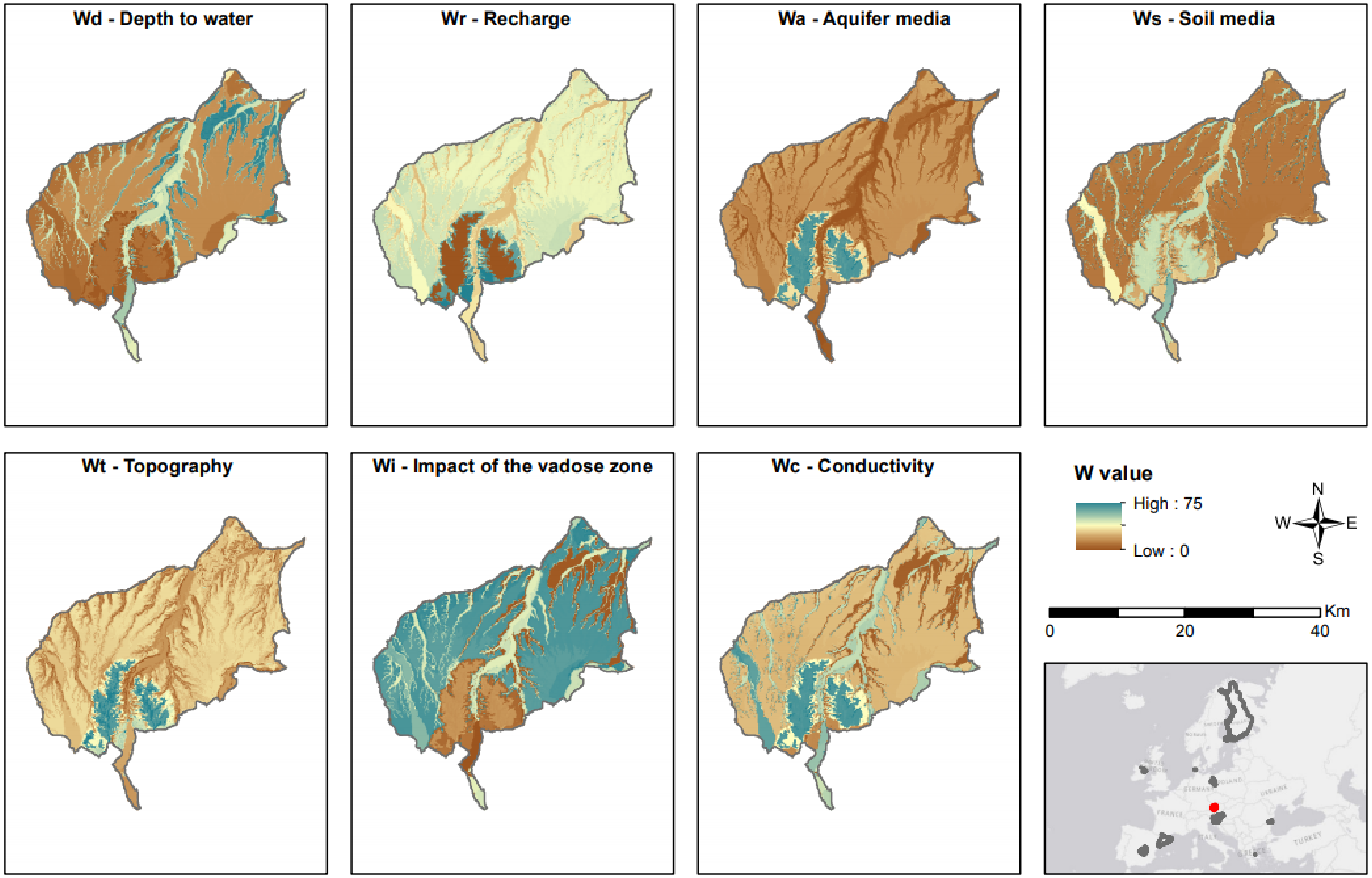
Pilot area Tønder (Denmark) – GEUS

Spatial distribution of the effective Weight index (W)



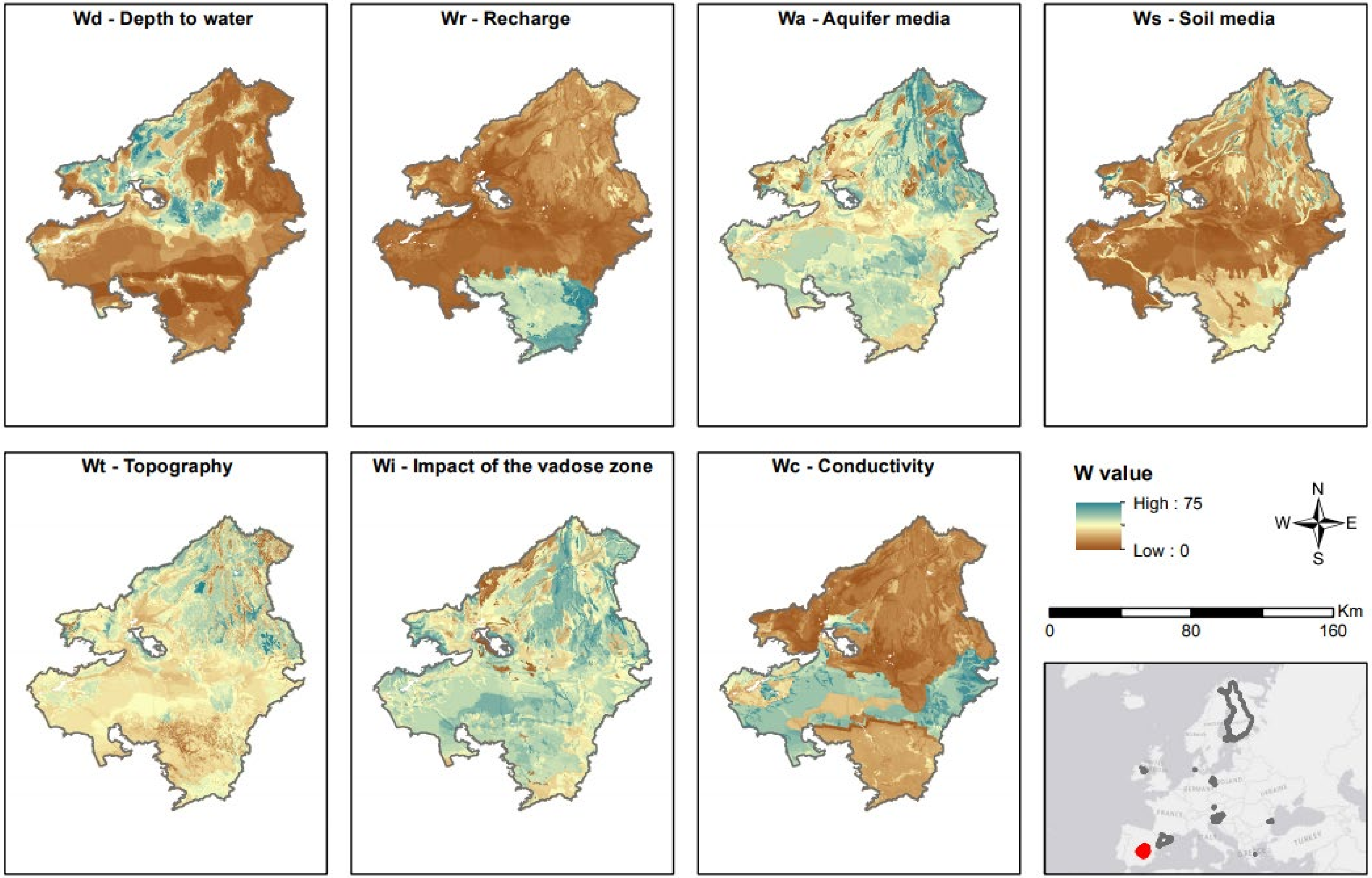
Pilot area Traun-Enns-Platte (Austria) – GBA

Spatial distribution of the effective Weight index (W)

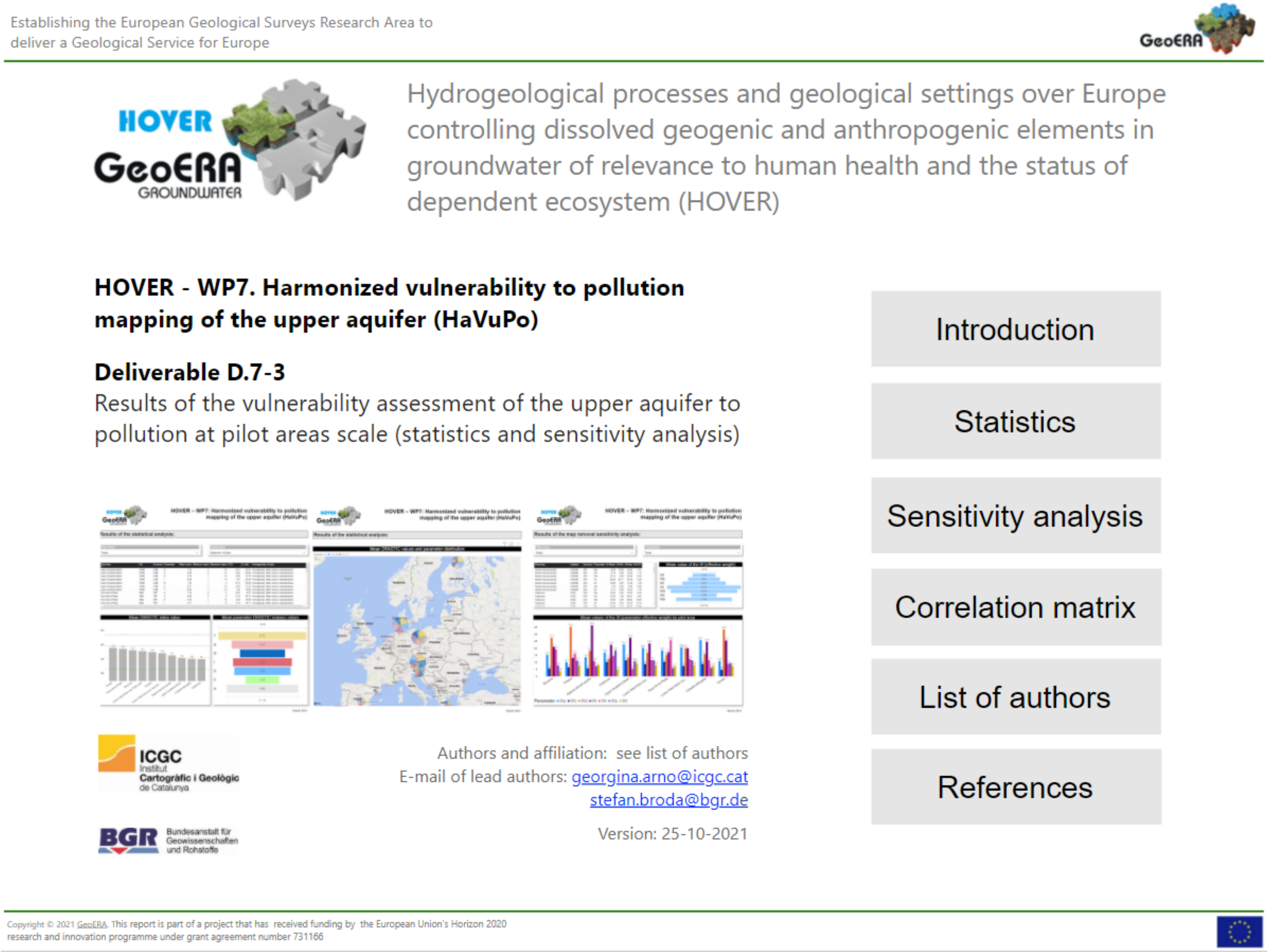


Pilot area Upper Guadiana Basin (Spain) – IGME

Spatial distribution of the effective Weight index (W)



APPENDIX C: POWERBI REPORT SCREENSHOTS



INTRODUCTION

Project framework

This deliverable 7.3 is part of work package (WP) 7 named **Harmonized vulnerability to pollution mapping of the upper aquifer (HaVuPo)** in the overall project HOVER (**H**ydrogeological processes and Geological settings **over** Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystems).

It was promoted by the ERA-NET GeoERA (Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe). In this European project, led by the German Geological Survey (BGR), 16 geological services from 13 different countries participated.

Click here for more information about the HOVER project and access the reports deliverables D.7-1, D.7-2 and D.7-4

Main goals

- WP7 of the GeoERA HOVER project deals with groundwater vulnerability assessment to pollution of the shallow upper aquifer
- Vulnerability across Europe was assessed applying the DRASTIC method (Aller, L., 1987) in 11 pilot areas and the COP method (Vías J.M., 2006) for karst systems in 5 pilot areas (see Figure 1). DRASTIC was also applied for the vulnerability assessment at a small scale to obtain a pan-European overview (not included in this D.7-3).
- Obtain comparable results for which input DRASTIC and COP layers were prepared based on the same ratings and weights.

Input layers and vulnerability index maps are available at the EGDI plataform webside

Figure 1: HOVER WP7 partners and demonstration pilot areas indicating the vulnerability assessment methods applied (D = DRASTIC and COP).

PILOT AREA	PARTICIPANT	COUNTRY	AREA [km2]	CELL SIZE [m]	DRASTIC	COP
Alluvial aquifer Atalanti	HSGME	Greece	54	50	X	-
Boyne	GSI	Ireland	2627	10	X	-
Catalonia	ICGC	Spain	32112	50	X	X
Cobadin-Mangalia	IGR	Romania	2192	50	X	X
Finland	GTK	Finland	338440	200	X	-
Lower Oder/Odra river German part	BGR-LBGR	Germany	4553	200	X	-
Lower Oder/Odra river Polish part	PIG-PIB	Poland	2821	200	X	-
Rockingham	GSI	Ireland	15	10	X	X
Slovenia	GeoZS	Slovenia	20273	100	X	X
Tønder	GEUS	Denmark	293	100	X	-
Traun-Enns-Platte	GBA	Austria	810	100	X	-
Upper Guadiana basin	IGME	Spain	14093	100	X	X
Total			**418283**			

Deliverable D.7-3 contents

- Results of the DRASTIC and COP methods are presented by performing a simple statistical analysis of the input data and the final vulnerability indexes for each pilot.
- For the vulnerability DRASTIC assessment, the results of a map single parameter removal sensitivity analysis are also shown to study the contribution of individual variables.
- Using PowerBI Desktop Application, results are shown in three dashboards (statistical analysis, sensitivity analysis and Pairwise correlation matrix) by using interactive visualizations and filters which allow end users to create their own reports and visualizations.

STATISTICAL ANALYSIS RESULTS

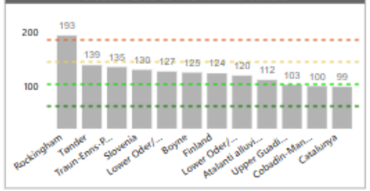
Statistical analysis of DRASTIC and COP results

GIS computation has been used to obtain the mean, median, minimum (Min), maximum (Max) values, the standard deviation (STD) and the variation coefficient (Cv) for each pilot and for both the final vulnerability DRASTIC and COP indexes and the input parameters index. For Cv<80% the dataset could be classified as homogeneous and the mean values considered representative. The distribution of vulnerability classes (very low, low, moderate, high and very high) is also shown for both the results of the DRASTIC and COP methods. DRASTIC vulnerability class ranges: very low (<64) , low (64-104), moderate (104-145), high (145-185), very high (>185). COP vulnerability class ranges: very low (<0.5), low (0.5-1), moderate (1-2), high (2-4), very high (4-15).

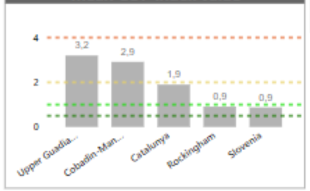
Main statistical variables

Pilot area and parameter selection is needed to visualize individual results

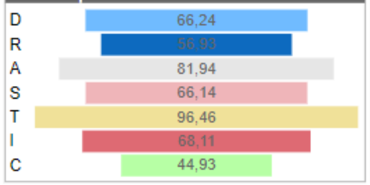
Mean DRASTIC index value



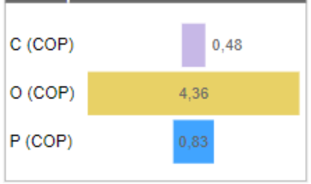
Mean COP index value



Mean parameter DRASTIC indexes values



Mean parameter COP indexes values



Pilot area selection: Todas

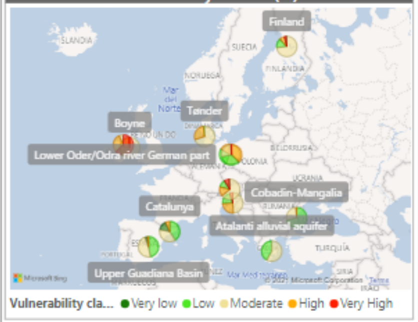
Input parameter selection: Todas

Pilot Area	Acronym	Participant	Parameter	Mean	Min	Max	STD	Cv (%)
Atalanti alluvial aquifer	ATA	HSGME	A	5,0	5,0	5,0	0,0	0,0
Atalanti alluvial aquifer	ATA	HSGME	C	2,1	2,0	4,0	0,3	15,1
Atalanti alluvial aquifer	ATA	HSGME	D	4,3	1,0	10,0	2,7	63,1
Atalanti alluvial aquifer	ATA	HSGME	DRASTIC	112,0	89,0	142,0	14,0	12,5
Atalanti alluvial aquifer	ATA	HSGME	I	8,0	8,0	8,0	0,0	0,0
Atalanti alluvial aquifer	ATA	HSGME	R	3,0	3,0	3,0	0,0	0,0
Atalanti alluvial aquifer	ATA	HSGME	S	4,0	4,0	4,0	0,0	0,0
Atalanti alluvial aquifer	ATA	HSGME	T	9,1	1,0	10,0	1,9	20,5
Boyne	BOY	GSI	A	5,8	0,0	10,0	1,4	23,7
Boyne	BOY	GSI	C	3,8	0,0	10,0	2,2	57,6
Boyne	BOY	GSI	D	7,0	0,0	10,0	1,7	23,9
Boyne	BOY	GSI	DRASTIC	125,3	43,0	220,0	26,4	21,1
Boyne	BOY	GSI	I	3,6	0,0	10,0	2,4	67,7
Boyne	BOY	GSI	R	6,5	0,0	10,0	3,2	49,0
Boyne	BOY	GSI	S	4,8	3,0	10,0	2,7	56,7
Boyne	BOY	GSI	T	8,3	1,0	10,0	2,1	25,6

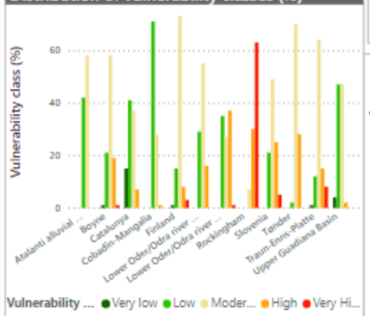
Distribution of vulnerability classes for each pilot (%)

Pilot area and method selection is needed to visualize individual results

Distribution of vulnerabilty classes (%)



Distribution of vulnerability classes (%)



Pilot area selection: Todas

Vulnerability method: DRASTIC

Vulnerability class: Todas

Pilot Area	Acronym	Country	Institute	Parameter	Vulnerability	Vulnreability class (%)
Atalanti alluvial aquifer	ATA	Greece	HSGME	DRASTIC	Very low	0
Atalanti alluvial aquifer	ATA	Greece	HSGME	DRASTIC	Low	42
Atalanti alluvial aquifer	ATA	Greece	HSGME	DRASTIC	Moderate	58
Atalanti alluvial aquifer	ATA	Greece	HSGME	DRASTIC	High	0
Atalanti alluvial aquifer	ATA	Greece	HSGME	DRASTIC	Very High	0
Boyne	BOY	Ireland	GSI	DRASTIC	Very low	1
Boyne	BOY	Ireland	GSI	DRASTIC	Low	21
Boyne	BOY	Ireland	GSI	DRASTIC	Moderate	58
Boyne	BOY	Ireland	GSI	DRASTIC	High	19
Boyne	BOY	Ireland	GSI	DRASTIC	Very High	1

SENSITIVITY ANALYSIS

Map single-parameter removal sensitivity analysis

This sensitivity analysis allows to study the contribution of individual variables (input parameters) one by one, on the resultant output of an analytical model. Two parameters have been calculated: a) the sensitivity index (S) and the effective parameter weight (W) (see Figure 2).

The method, based on Lodwick et al. (1990), Napolitano et al. (1996) and Adeyinka (2020), was developed for weighted sum intersection overlays and can be easily applied to the expression to compute DRASTIC indexes (not for COP).

The sensitivity parameter index "S" is usually used to determine if all the parameters contribute equally and sometimes it is analyzed jointly with the "Pairwise correlation matrix" between the analysed parameters. The effective parameter weight (W) allow to compare the real weight that each parameter had in each area with the theoretical weight assigned by the DRASTIC method.

Sensitivity parameter index (S)	Effective parameter weight (W)
Identifies the sensitivity of the vulnerability towards removing one or more maps from the vulnerability analysis. It is computed as follows:	Contribution of each parameter in the final DRASTIC vulnerability index (effective weight). It is computed as follows:
$S = \left(\frac{\left| \frac{V}{N} - \frac{V'}{n} \right|}{V} \right) \times 100$	$W = 100 P_r P_w / V$
S; sensitivity index measure expressed as variation index (for each parameter) V and V'; unperturbed and perturbed vulnerability N and n; number of parameters used to compute V and V' respectively	W; effective weight of each parameter P_r and P_w ; ratings and weight values of each parameter respectively V; the overall vulnerability index

Figure 2: Sensitivity analysis index (S) and effective parameter weight (W) definitions and formulas to perform the map single-parameter removal sensitivity analysis.

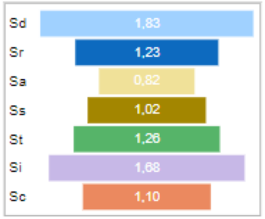
S - sensitivity parameter index

Sensitivity of the vulnerability towards removing one or more maps from the vulnerability analysis.

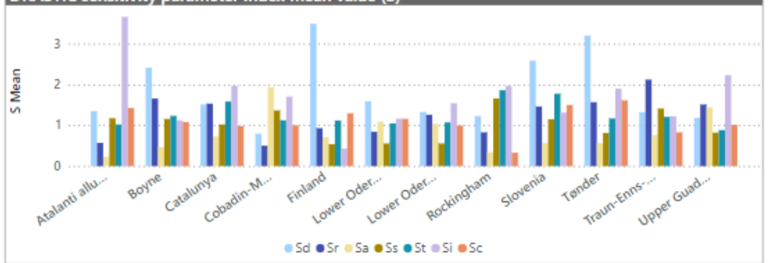
Pilot area selection: Todas

S parameter index selection: Todas

Pilot Area	Participant	Country	Parameter	S-me
Atalanti alluvial aquifer	HSGME	Greece	Sd	1,35
Atalanti alluvial aquifer	HSGME	Greece	Sr	0,57
Atalanti alluvial aquifer	HSGME	Greece	Sa	0,23
Atalanti alluvial aquifer	HSGME	Greece	Ss	1,17
Atalanti alluvial aquifer	HSGME	Greece	St	1,02
Atalanti alluvial aquifer	HSGME	Greece	Si	3,66
Atalanti alluvial aquifer	HSGME	Greece	Sc	1,43
Boyne	GSI	Ireland	Sd	2,41
Boyne	GSI	Ireland	Sr	1,66



DRASTIC sensitivity parameter index mean value (S)



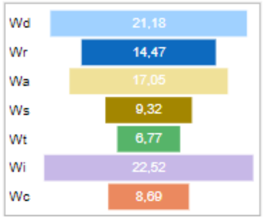
W - effective weight parameter index

Contribution of each parameter in the final DRASTIC vulnerability index.

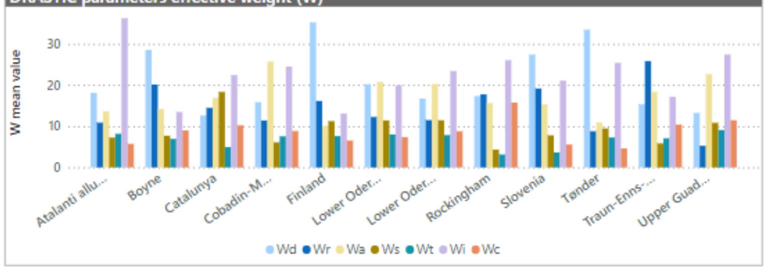
Pilot area selection: Todas

W parameter index selection: Todas

Pilot Area	Participant	Country	Parameter	W-r
Atalanti alluvial aquifer	HSGME	Greece	Wd	18
Atalanti alluvial aquifer	HSGME	Greece	Wr	10
Atalanti alluvial aquifer	HSGME	Greece	Wa	13
Atalanti alluvial aquifer	HSGME	Greece	Ws	7
Atalanti alluvial aquifer	HSGME	Greece	Wt	8
Atalanti alluvial aquifer	HSGME	Greece	Wi	36
Atalanti alluvial aquifer	HSGME	Greece	Wc	5
Boyne	GSI	Ireland	Wd	28
Boyne	GSI	Ireland	Wr	20



DRASTIC parameters effective weight (W)



PAIRWISE CORRELATION MATRIX

Pairwise DRASTIC parameters correlation matrix

The Pairwise correlation matrix measures the strength of the relationship between two variables (i.e. DRASTIC input parameters). Positive values indicates positive linear correlation between two variables, whereas negative values indicates negative linear correlation. The correlation is high if values approach 1.0 and -1.0. NaN values correspond to correlations which one or both variables are constant within the pilot area.

Pilot area selection
Todas

Pilot Area	Acronym	Participant	Country	Parameter	D	R	A	S	T	I	C
Atalanti alluvial aquifer	ATA	HSGME	Greece	D	1,00						
Atalanti alluvial aquifer	ATA	HSGME	Greece	R	NaN	1,00					
Atalanti alluvial aquifer	ATA	HSGME	Greece	A	NaN	NaN	1,00				
Atalanti alluvial aquifer	ATA	HSGME	Greece	S	NaN	NaN	NaN	1,00			
Atalanti alluvial aquifer	ATA	HSGME	Greece	T	0,17	NaN	NaN	NaN	1,00		
Atalanti alluvial aquifer	ATA	HSGME	Greece	I	NaN	NaN	NaN	NaN	NaN	1,00	
Atalanti alluvial aquifer	ATA	HSGME	Greece	C	-0,18	NaN	NaN	NaN	-0,04	NaN	1,00
Boyne	BOY	GSI	Ireland	D	1,00						
Boyne	BOY	GSI	Ireland	R	0,06	1,00					
Boyne	BOY	GSI	Ireland	A	-0,01	-0,10	1,00				
Boyne	BOY	GSI	Ireland	S	0,07	-0,15	0,12	1,00			
Boyne	BOY	GSI	Ireland	T	0,07	-0,07	0,24	0,02	1,00		
Boyne	BOY	GSI	Ireland	I	0,03	0,36	0,12	0,36	-0,04	1,00	
Boyne	BOY	GSI	Ireland	C	-0,02	-0,01	0,58	0,10	0,16	0,08	1,00
Catalunya	CAT	ICGC	Spain	D	1,00						
Catalunya	CAT	ICGC	Spain	R	-0,23	1,00					
Catalunya	CAT	ICGC	Spain	A	0,08	0,26	1,00				
Catalunya	CAT	ICGC	Spain	S	-0,39	0,36	0,08	1,00			
Catalunya	CAT	ICGC	Spain	T	0,49	-0,40	0,00	-0,58	1,00		
Catalunya	CAT	ICGC	Spain	I	0,13	0,15	0,31	-0,01	0,12	1,00	
Catalunya	CAT	ICGC	Spain	C	0,26	0,01	0,44	-0,18	0,26	0,30	1,00
Cobadin-Mangalia	COB	IGR	Romania	D	1,00						
Cobadin-Mangalia	COB	IGR	Romania	R	-0,40	1,00					
Cobadin-Mangalia	COB	IGR	Romania	A	-0,23	0,35	1,00				
Cobadin-Mangalia	COB	IGR	Romania	S	0,08	0,11	0,06	1,00			
Cobadin-Mangalia	COB	IGR	Romania	T	0,00	-0,09	-0,04	-0,16	1,00		
Cobadin-Mangalia	COB	IGR	Romania	I	0,19	0,11	0,08	0,17	-0,17	1,00	
Cobadin-Mangalia	COB	IGR	Romania	C	0,24	-0,12	-0,05	-0,15	0,03	-0,01	1,00
Finland	FIN	GTK	Finland	D	1,00						
Finland	FIN	GTK	Finland	R	0,02	1,00					

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APPENDIX D: DRASTIC VULNERABILITY CLASSES DEFINITIONS

Vulnerability class	Example of definition (Based on Foster et al., 2002 & 2013)	Suggested Action Plan (Based on Büyükdemirci, 2012)	Protection measures required /Activities (Based on Foster et al., 2013)
Very High	Indicates that the area is vulnerable to most pollutants, with a relatively rapid impact in many pollution scenarios	An immediate action plan is required including above. Any risk containing activity to groundwater is not allowed by the responsible authority	Presumption that all potentially polluting activities will be prohibited or only permitted at low intensity with exceptional and expensive containment, detailed monitoring and inspection
High	Indicates that the area is vulnerable to many pollutants, except those highly adsorbed or immediately transformed, in many pollution scenarios	Need to search for design factors for protecting groundwater. A feasibility plan with on-going monitoring should be considered	Presumption that many potentially polluting activities will be prohibited or subject to detailed controls and considerable additional expense in terms of design, inspection and monitoring
Moderate	Indicates that the area is vulnerable to some pollutants, especially when continuously and widely discharged or leached	"Detailed site investigation and monitoring: Requires more detailed site investigation including ongoing monitoring and protection	(Not defined)
Low	Indicates that the area is only vulnerable to conservative pollutants in the long term when continuously and widely discharged or leached	design factors (e.g., natural attenuation, physical barriers) in addition to requirements above	Presumption that most development activities will be permitted and only subject to normal design conditions, except those that involve unlined lagoons or soak away drainage and/or handling groundwater-hazardous chemicals
Very low	Typical of areas with confining beds without significant vertical groundwater flow (leakage)	Site investigation with monitoring: Requires limited site investigation, groundwater monitoring, testing, and delineation of flow system in addition to desk study	Presumption that all development activities will be allowed and only subject to normal design conditions

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