MARSOL
Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought

Candidate areas for artificial recharge
Contents:

EXECUTIVE SUMMARY 

1 Introduction ........................................................................................................................................... 5
   1.1 Objective ........................................................................................................................................ 5
   1.2 Outline .......................................................................................................................................... 5

2 Aspects influencing delineation of candidate areas ........................................................................... 6
   2.1 Site selection: A multidisciplinary approach .................................................................................. 6
   2.2 The use of integrated approaches ................................................................................................. 8
   2.3 GIS based approaches ................................................................................................................... 9

3 The MARSOL Demo Sites .................................................................................................................. 11
   3.1 Lavrion (Greece) ........................................................................................................................ 11
   3.2 Algarve (Portugal) ....................................................................................................................... 11
   3.3 Los Arenales (Spain) .................................................................................................................. 13
   3.4 Llobregat (Spain) ......................................................................................................................... 13
   3.5 Brenta River (Italy) ..................................................................................................................... 14
   3.6 Serchio River (Italy) .................................................................................................................... 14
   3.7 Menashe (Israel) ......................................................................................................................... 15
   3.8 South Malta ................................................................................................................................... 16

4 Vulnerability Index as a proxy for MAR suitability ............................................................................ 17
   4.1 Introduction ...................................................................................................................................... 17
   4.2 The DRASTIC Index ....................................................................................................................... 17

5 An evolution of the DRASTIC index to incorporate natural variability ........................................... 20
   5.1 Introduction ...................................................................................................................................... 20
   5.2 Methodological approach: problem statement and uncertainty assessment ............................... 20
   5.3 Best delineation of spatially variable individual parameters ........................................................ 22

6 Example of application of the new developed index ........................................................................ 27
   6.1 Study area: geological and hydrogeological settings ................................................................. 27
   6.2 The individual DRASTIC layers ................................................................................................... 28
   6.3 The overall DRASTIC index map ................................................................................................. 35

Appendix .................................................................................................................................................. 35
Figure captions

Figure 5.1. Suggested methods for mapping individual DRASTIC parameters, allowing uncertainty evaluation, depending on amount and type of data................................. 23

Figure 6.1. Location of the study area. ........................................................................................................................................... 27

Figure 6.2. Depth to water table for two different scenarios: (a) median – 50% confidence, and (b) conservative – 80% confidence (see the text for the definition of the two scenarios)................................................................................................................................................ 30

Figure 6.3. Ternary diagram (labeled according to the USDA soil texture class) for $\alpha = 0$ (a); $\alpha = 1$ (b); and $\alpha = 3$ (c) and the resulting S layers in DRASTIC. ................................................................. 32

Figure 6.4. Net recharge, Aquifer Media, impact to the vadose zone, Topography and Hydraulic Conductivity layers......................................................................................................................... 34
EXECUTIVE SUMMARY

WP Technology Assessment and Risk (WP16) deals with proper methodologies to assess the potential risk associated to a MAR facility. Deliverable 16.2 tackles the methodologies existing to select the best location to place infiltration basins for MAR activities. Optimal location of potential candidate areas to place such facilities within a given water basin must be based on a multidisciplinary approach involving a number of aspects, including: natural characteristics of the aquifer system, availability of water for recharge, quality of recharge water, social impact, as well as legal, and economic issues. Such different issues should be combined in an integrated framework, and this can only be done by a combination of simplified indices integrated in a GIS framework.

The wide variability in the reasons for site selection is illustrated by means of the eight MARSOL Demo Sites, each one located based on the prioritization of a number of different aspects. Yet, the geological setup involving the trinomial soil–vadose zone–aquifer is most significant for site location in all cases. Optimal site location in terms of infiltration capacity can be directly linked to the concept of aquifer vulnerability. Thus, any Vulnerability Index existing in the literature can be used as a proxy for the suitability of placing a MAR facility, by performing a number of modifications that include the desired degree of conservatism.

For this reason, an evolution of the DRASTIC index to incorporate natural variability is developed, with emphasis in the quantitative evaluation of uncertainty. The method could be extended to any other index existing in the literature. The system starts by finding the best approach to delineate each of the layers involved in the methodology as a function of data type, source (errors), and density, and then combining all indices into a final one. All the methodologies are synthesized in Figure 5.1, providing a detailed description of the optimal methods depending on data sources (direct or indirect, obtained from the field or from models), data nature (numerical, categorical or percentual), amount (from very few to dense or even extensive), and type of data.

The approach allows performing a number of modifications that include the desired degree of conservatism in each of the layers involved in the index. The methodology is illustrated with the analysis of an area in NE Spain that is now being considered for future implementation of MAR.
1 Introduction

1.1 Objective

This is the second deliverable in **WP Technology Assessment and Risk**. The main objective of Deliverable 16.2 is to provide information about the methods that are traditionally used to delineate the best potential areas for placing a MAR facility using a multidisciplinary approach.

1.2 Outline

The document incorporates different chapters. In Chapter 2, we present a compilation of the different aspects that might influence the delineation of candidate areas for MAR in a given basin. Chapter 3 is devoted to the analysis of the individual MARSOL Demo Sites as a way to compile how the sites are selected according to a subset of the aspects explained in the previous chapter.

Among the different methodologies, a most significant one is the suitability of the site for infiltration in quantitative terms. This topic can be easily related to the hydrogeological concept of vulnerability. In Chapter 4 we contend that a well-defined Vulnerability Index can be used as a proxy for MAR suitability of a given location. Finally, adopting the previous conjecture, in Chapter 5 we analyse existing vulnerability indices and suggest yet another one, this one properly considering the uncertainty in the different subindices caused by either subsampling or else from the inherent heterogeneity of all natural variables and parameters involved in the definition of vulnerability indices. Chapter 6 shows an application of the new methodology to an area in NE Spain where MAR is being explored.
2 Aspects influencing delineation of candidate areas

2.1 Site selection: A multidisciplinary approach

Potential candidate areas to place a MAR facility within a given basin must be based on a number of aspects, here including:

- natural characteristics of the aquifer system

Here we are interested in the existence of a geological setup that is capable of infiltrating a large water flow for a long time, without compromising the quality of the resulting fluid. This involves the proper combination of the trinomial soil (surface) - vadose zone - aquifer, so that the combination of the geological substratum and the morphology of the topographic surface, presents the most favourable conditions for water recharge.

Regardless of the methodology used it is obvious that a number of parameters can be used as proxies for favourable conditions. As an example, in any approach dealing with the suitability of a site for MAR practices we should assess the vertical hydraulic conductivity of the vadose zone, as it limits the maximum infiltration rate, as well as the transmissivity of the aquifer, being the main parameter controlling the amount of water that the aquifer may accept.

- social impact

For this analysis it is important to be aware that in a democratic and participative society, actors and citizens should have a great influence on the decision of project of this type.

The best area for the construction of artificial recharge facilities is the one that has the smallest better impact on the population while having the bigger beneficiaries for the all community.

An interesting example of the application of the analysis of social acceptability of MAR practices was presented by Rawluk et al. (2013). This case involved the potential implementation of MAR using water from large floods in a major
groundwater irrigation region in Australia, and the acceptability of such practices amongst groundwater license holders. The authors carried out a survey amongst farmers (210 answers from 447 property owners) involving the following questions (directly extracted from Rawluk et al., 2013):

1) Aquifer storage and recovery (MAR) appears to be a good idea.

2) If public funds were used to develop the infrastructure for MAR, I would be prepared to invest in technology to improve the water-use efficiency on my farm.

3) I would be prepared to invest, along with others, to develop MAR in my water sharing plan (WSP) area without public funding.

4) I am interested in learning more about the interception of large floods to implement MAR in my WSP area.

Questions were answered in a code ranging from “Strongly Disagree” to “Strongly agree”. Most of the respondents to the survey agreed that MAR has merit: however, some of them were concerned about the impact of recharge on groundwater quality and the possibility that MAR would be another intervention leading to over-exploitation of a scarce resource.

We should notice anyway that Australia has a long tradition on the use of MAR, and that the results of this survey cannot be directly extrapolated to the Mediterranean area. Yet, it is also relevant to point out how knowledge of the technology (even if only partial) leads to a high acceptance rate.

- availability of water for recharge

Water can be diverted to MAR facilities from different sources, including reclaimed water, river water, storm water, or opportunity water (e.g., excess from desalination).

Quality of water recharged is highly dependent on its source
- social and legal aspects

For individual projects, whether demonstration or large-scale, the following issues must be considered: (1) who will finance the project; (2) who will benefit for the storage of water; (3) what organizations/agencies have the authority to construct and operate the project; (4) should recharge water be integrated with surface water; (5) what are the rights and duties of entities storing water; (6) is the required land available and affordable; (7) what will be the impacts of the projects on interstate compacts that deal with water allocation and flood control; (8) impacts on land use, population and the local economy.

A large body of legislation is applicable to MAR facilities, from European legislation (mainly the Water Framework Directive) to those at the national or regional level.

- economic issues

Each MAR project should be evaluated to determine its impact, effectiveness and benefit/cost ratio. The economic analysis should considered the following issues:

1- Expenditures for land and easements including land availability
2- Engineering and construction of facilities
3- Transportation of the water from the water source to the artificial recharge area
4- Water or right to water
5- Operation and maintenance of the artificial recharge facilities.

2.2 The use of integrated approaches

Regarding the integrated methods, members of the MARSOL group developed some years ago the GABA-IFI index (Oliveira et al., 2008). This index results from the classification of the natural characteristics of the aquifer system, the economic aspects and the social impact of its construction, and can be used as
a first approach to geographically locate the best areas to perform artificial recharge.

2.3 GIS based approaches

There is not a single unified method to integrate all indicators in a simple way. A most widely used method is GIS based maps based on exclusion of areas that do not satisfy one or more of the requirements.

When only the first one of the aspects is considered, the corresponding analysis can be directly linked to the concept of vulnerability. Thus, a vulnerable area is also an area suited for natural or induced recharge. When more aspects are considered there is a need to either integrate several concepts together or else to use all indices in a binary type of GIS model that provides a Y/N code at each location, and then using Boolean algebra to delineate the best potential locations.

When such a simple delineation method is used, emphasis is placed in the careful delineation of the most significant (and spatially variable) item. This is indeed the natural characteristics of the aquifer. Several authors use deterministic type approaches that assign a single number to each location (pixel) in the map, without even considering the uncertainty associated to such a deterministic value. Then, optimal location areas are based on a relative classification of such values, mapping all points that exceed a given pre-specified threshold. Examples of this approach are those based on vulnerability indicators such as the well-known DRASTIC method (explained later, section 4.2). While much more involved in terms of parameters involved, this same methodology is used to map areas by means of the GABA-IFI index.

One of the most important uncertainties in the site-selection process using GIS is finite ranges or intervals resulting from data classification. In order to reduce these uncertainties, Malekmohammadi et al. (2012) developed a method
involving the integration of Multi-Criteria Decision Making, GIS, and a Fuzzy Inference System.

A different, quite sophisticated approach was presented by Rahman et al. (2012). The authors developed a software tool for selecting suitable sites for MAR systems. The tool combines multi-criteria evaluation methods (non-compensatory screening, criteria standardization and weighting) with decision analysis techniques such as Analytical Hierarchy Process, Weighted Linear Combination, and Ordered Weighted Averaging methods.

In any case, there is a need to find simplified approaches that could be directly use by stakeholders.
3 The MARSOL Demo Sites

Different strategies were used to select the location of the Demo Sites, involving a subset of the elements considered in the previous section. Here we analyse each of the sites individually, writing in each one of them the individual methodology used.

3.1 Lavrion (Greece)

The Lavrion Demo Site involves surface infiltration to increase available groundwater resources by means of a Soil-Aquifer-Treatment (SAT) system and to control seawater intrusion. The site location was mostly driven by the following considerations:

- Hydrogeological setup, the main objective of the site is to act as a hydraulic barrier, strongly conditioning the optimal location of the MAR facility. Additional objectives, such as combatting water scarcity are not so restrictive.
- Geological considerations, the combination of alluvial and karstified aquifer layers is strongly favourable for recharge practices.
- Political support, the MAR activities are fully supported by the Region of Attica, General Directorate for Development Planning and Infrastructure.

3.2 Algarve (Portugal)

Three sites are considered here. Site selection was based on the application of the GABA-IFI methodology, involving the combination of three issues: geological suitability, legal implications, and economic issues. We hereby analyse all three subsites individually.
1) Rio Seco and Campina de Faro aquifer system. The MAR facility was located based on a number of considerations:

- Environmental conditions, associated with a need to remediate a relevant environmental quality problem.
- Legal considerations, as the zone was declared as “vulnerable to nitrates” in the framework of the transposition of the EU Directive 91/676 to the Portuguese legislation, which aimed at water protection from diffuse pollution caused by nitrates of agricultural sources.
- Economic reasons, based on the existence of a number of infrastructures, and a suite of experiments performed in the site to assess the infiltration rates from surface water surpluses.

2) Querença-Silves aquifer. The MARSOL site was selected based on the following background considerations and advantages:

- Water availability, due to the characteristics of the Mediterranean climate, during wet years a large water surplus can be expected.
- Infrastructures, presence of two dams interconnected by a channel eventually connected to the Alcantarilha WWTP. Additional existing infrastructures (two pumping wells) are available for MARSOL activities.
- Economic and opportunity, a relevant amount of surface and groundwater data, including water budget and recharge estimations is available.
- Social issues, including the implication of Águas do Algarve.

3) Melides watershed and lagoon study area, selected based on:

- Environmental restrictions, an area polluted by nitrate and pesticides caused by agriculture practices, eventually reaching the Melides coastal lagoon.
- Economic reasons, since a very significant amount of surface and groundwater data, including climate change water budget and groundwater recharge estimations is available.
- Implication of water actors, APA Ambiente (water agency) is supporting the activities in the site.
### 3.3 Los Arenales (Spain)

The concept of the Los Arenales Demo Site is based on river water infiltration to increase the water resources and raise groundwater levels for their use in agricultural practices. The most significant elements for site location are:

- Social awareness, public participation and a deep education of the farmer groups involved in the irrigation communities. Municipalities play also an important role in MAR management, and Public Private Partnership (PPP) schemes are being implemented.
- Geological setup, the Los Arenales aquifer origin is polygenic with a predominance of Quaternary sand dunes system facies, filling a complex substrate from the Miocene, notably sandy and clayey, with large thickness. This is a very favourable geological setup for infiltration.

### 3.4 Llobregat (Spain)

The Sant Vicenç dels Horts (Llobregat River) Demo Site is based on river water infiltration to increase the water resources and rise groundwater levels. Significant elements for site location are:

- Geological setup, the sedimentary basin of the Lower Valley is formed by a layer of high transmissivity sands with variable thickness, very favourable for infiltration.
- Political implication, of both the Water Catalan Agency (ACA) and the Water Users Community (CUADLL).
- Land availability, the lower valley is very narrow and surrounded by transport infrastructures (railway and two highways), leading very little space for MAR activities.
3.5 Brenta River (Italy)

The concept of the Demo Site is a forested infiltration area for aquifer storage and recovery. It is located close to an agricultural area in Schiavon municipality (province of Vicenza). The topic tackled is rural water management, specifically water scarcity and conflicts with other water users in the irrigation season. The site location was mostly driven by:

- Ecological considerations, the NE Alpine system is extremely vulnerable in relation to the present and future water resource management. In the last years the water table has slowly but progressively declined, causing numerous wetlands to desiccate. MAR practices aim at reverting this problem.
- Water availability, the nearby presence of a Forested Infiltration Area that uses a system of furrows that are fed by drainage channels connected to the irrigation ditch of the local irrigation network for ensuring infiltration into the aquifer.
- Political and social support, the responsible partner is the Alto Adriatico River Basin Authority (AAWA), which is also the responsible for the implementation of the River Basin Management Plans for the Eastern Alps District in light of the objectives of Water Framework Directive 2000/60/CE and Directive 2007/60/EC on the assessment and management of flood risks. The Irrigation Consortium of Brenta-Bacchiglione rivers is also involved directly in the project.

3.6 Serchio River (Italy)

The main concept of this Demo Site is that of river bank infiltration. The actual location of the site is driven by the following considerations:

- Water availability, in dry periods the Serchio River flow may be as low as 3 m³/s. During these periods, the volume abstracted by the river bank process is approximately 30% of the river flow.
- Existing infrastructures, a small barrier across the river flow is used to rise the river head and consequently to increase bank infiltration.
- Political considerations, Provincia di Lucca has been directly involved during all the process.

3.7 Menashe (Israel)

The Demo site is located in the vicinity of Hadera, and it is dedicated to the topic of managed aquifer recharge of surplus desalinated seawater. Location is based on the following considerations:

- Availability of infrastructures and water, the nearby (~4 km) presence of the Hadera-seawater-desalination plant. Surpluses from the desalination plant sometimes cannot be distributed directly to consumers and this water is diverted toward the MAR facility for infiltration to the Israeli coastal aquifer by means of an infiltration basin.
- Geological setup, the coastal aquifer has been extensively used for artificial groundwater recharge practices, due to the favourable characteristics of the aquifer for infiltration. The aquifer consists of interlayered sandstone, calcareous sandstone, siltstone, and red loam, which alternate with continental and marine clays of Pleistocene age, and its upper part behaves as phreatic, with very large infiltration rates.
- Political/economic considerations, implying the lack of economic implication of government capital, leading to the involvement of the private sector. In these contracts the governments is obliged to buy a fix volume of desalinated water of fixed quality at a fixed price for a long period (~ 25 years), leading to periodic periods of water surplus.
3.8 South Malta

The objective of the MAR facility is to create a seawater intrusion barrier using water from the Malta South wastewater treatment plant (WWTP). The main reasons for site location were:

- Water availability, the site is located close to the main WWTP of the island. It is envisaged that the production of treated wastewater at the plant will exceed the demand of the agricultural sector in the region, making water available for aquifer management purposes. The quality of the recharging water will be ensured by a tertiary treatment.

- Hydrogeological setup, the location presents the typical characteristics of a coastal “floating-lens” aquifer system, in direct lateral and vertical contact with sea-water. The fate of this freshwater lens is highly sensitive to the location of the recharge area, heavily conditioning the potential valid locations.

- Geological considerations, the creation of a sea-water intrusion barrier is an effective method to reduce the outward flow of freshwater from the central regions of the island and thus increase the availability of groundwater in the region, and also improve the quality of the regional groundwater body.

- Social/political considerations, the Malta Resources Authority (MRA) is the official partner responsible for the coordination and operation of the MAR pilot project, closely supported by the Water Services Corporation (WSC), the main public utility of the Maltese islands, which is the operator of the Maltese WWTPs.

- Legal considerations, the implementation of the EU’s Waste Water Treatment Directive has seen the increased availability of treated sewage effluents in coastal regions, which are currently being discharged into the sea and could be incorporated back to an integrated water resources scheme.
4 Vulnerability Index as a proxy for MAR suitability

4.1 Introduction

The concept of aquifer vulnerability exists for more than forty years, but no consensus has been reached regarding its definition. The word “vulnerability” is used in a number of geosciences problems, such as the potential of a pumping well to get either dry or polluted (e.g., Starn et al., 2010; Hunt et al., 2010), or for the reduction of water reserves in a given aquifer (Chattopadhyay and Singh, 2013).

But the definition that has had more impact is the one made by Foster (1987). It considers vulnerability to contamination of an aquifer in terms of the inherent characteristics of the three strata separating the saturated zone from the ground surface: the soil, the vadose zone and the aquifer itself. In practice, mapping vulnerability involves the production of two-dimensional maps where at each point different characteristics of the aquifer (amount and quality of available data, budget and time constraints, difficulty to transfer the results into actual policies, etc.) are combined to obtain an indicator of whether some hazardous activity taking place at the surface could eventually result in aquifer pollution assuming vertical infiltration.

This said, it is quite direct to find an analogy between a “vulnerable” point within an aquifer and a point where the location of a surface MAR facility is expected to provide satisfactory results. That is, if a point in the aquifer is easily accessible to a potentially polluting activity located at the surface, it is an indication that a high infiltration rate can be expected from a MAR facility (eventually the system can be clogged due to continuous water infiltration).

4.2 The DRASTIC Index

One of the most widely used methods for mapping water vulnerability worldwide is DRASTIC (Aller et al., 1987). It was developed within an EPA (Environmental
Protection Agency, USA) project, with the aim of assisting planners, managers and water administrators. The method involves assessing values for seven hydrogeological and physical parameters, combining quantitative and categorical values. DRASTIC is an acronym for the variables involved: Depth to water, Recharge, Aquifer media, Soil media, Topographic slope, Impact of the vadose zone, and hydraulic Conductivity. Any DRASTIC index map involves finding a global indicator ($DI$) at each point $(x, y)$ in the surface given by

$$DI (x, y) = \sum_{i=1}^{7} w_i l_i (x, y), \quad (4.1)$$

where $w_i$ and $l_i$ are respectively the weight and the rating of the individual indices. Weights were fixed values ranging from 1 to 5 and assigned by an expert panel (Aller et al., 1987). Ratings span between 1 to 10. Overall, the final DRASTIC index varies from 23 (lowest vulnerability) to a maximum of 226. Variations of the method exist covering different ranges. The $DI$ valid range can be further partitioned into descriptive vulnerability categories (“very low”, “low”, …, “very high”) so that each point in the map can be classified by a descriptor. More than 130 papers in Science Citation Index and countless reports have been published where DRASTIC is used for mapping vulnerability, due to its easy implementation. According to Rosen (1994) the use of numerous (and partially correlated) parameters in DRASTIC decreases the probability of misjudgment of a single parameter and enhances the accuracy of the resulting maps.

Other methods for vulnerability mapping based on combination of indices have been proposed in the literature, with tens of papers presenting applications of GOD (Foster and Hirata, 1988), AVI (Stempvoort et al., 1993), EPIK (Doerfliger and Zwahlen, 1995), SINTACS (Civita and De Maio, 1997), amongst many others; all such names are acronyms referring to a number of hydrogeological parameters affecting vulnerability. None of these methods can actually provide a scientific approach to vulnerability. As a consequence, when different methods are applied to the same hydrological system, the results can differ radically (e.g., Gogu et al., 2003).
The simplicity of the DRASTIC method is a clear strength, but also a weakness. It has been shown that there is little connection between the DRASTIC index and actual observed concentrations. We contend that this misfit is caused by a number of reasons: (1) the presence of only sparse and scattered field data (associated to time and cost constraints in gathering data); (2) the deterministic approach related to the non-inclusion of uncertainties in the estimations; (3) the use of zonation instead of dealing with continuous variables; and (4) the presence of correlations between variables.
5 An evolution of the DRASTIC index to incorporate natural variability

5.1 Introduction

There is still room for producing new simplified methods for aquifer vulnerability assessment that could eventually be used to assess the most convenient areas to locate MAR facilities. Such improvements can be framed in a geostatistical framework in order to combine producing the best estimates plus a measure of uncertainty for each of the parameters used to define vulnerability, eventually producing risk maps that allow policy-makers to take informed decisions. Geostatistical approaches have been extensively used in groundwater pollution applications, mostly as a way to evaluate the probability of exceeding regulatory thresholds (Assaf and Saadeh, 2009). Only recently, some works have applied a geostatistical framework for vulnerability assessment (Chen et al. 2013).

We develop here a methodological approach for aquifer vulnerability that directly incorporates uncertainty, and that by extension can be used to locate the best areas for the location of new MAR facilities. It is formulated as an extension of DRASTIC, and it aims at selecting the proper (geostatistical) method that can be used to map each of the seven DRASTIC parameters as a function of available data. We also show how the selection of the degree of confidence in the data, as applied to the different estimation tools, might be included in the maps of the corresponding estimated indices in a formal mathematical framework.

5.2 Methodological approach and uncertainty assessment

DRASTIC involves defining at each point in the two-dimensional space a value for seven different parameters or variables that can be grouped into the three elements in a geological vertical section. For the soil, the driving variables are Net Recharge (parameter R, with a weight of \( w_R = 4 \)), Soil Media (S; \( w_S = 2 \)), and Topography (T; \( w_T = 1 \)), altogether combining to a weight of 7/23, meaning that
30% of total weight in the method is assigned to the element soil; the vadose zone, involving two parameters, Depth to Water Table (D; \( w_D = 5 \)) and Impact of the Vadose Zone Media (I; \( w_I = 5 \)), combining to a weight of 10 (44% of total weight), and finally the aquifer, involving two parameters, Aquifer Media (A; \( w_A = 3 \)) and Hydraulic Conductivity (C; \( w_C = 3 \)), adding up to 6 (26% of the weight). Only in some particular field studies researchers have used variations of these weights to accommodate to local geological settings or climate conditions (e.g., Shirazi et al., 2012).

Actually, all parameters and variables in geosciences are highly uncertain, and thus amenable of being treated as random spatial functions. DRASTIC involves a weighted combination of parameters, transmitting the individual uncertainties into the final index. Thus, it is questionable whether a deterministic approach to vulnerability mapping can be considered adequate at all. Uncertainty and measurement errors combined limit the use of vulnerability maps for proper management strategies. Hence the importance of properly quantifying the uncertainty associated to vulnerability indices, accounting for several items:

- All parameters and variables involved in map delineation are variable in space and maybe in time. Parameters are sparsely sampled, and may include sampling errors.
- Parameters in unsampled areas are obtained by either interpolation or extrapolation tools. Best tools should be considered for each variable and should account for a measure of uncertainty in the estimation process.
- Estimation methodologies should adapt to the different sampling densities and the presence of continuous and discontinuous variables combined.
- Vulnerability maps do not use dimensionless parameters, and furthermore, there is a need to combine variables that can span widely different range of values.
- Categorical and numerical variables are combined into global indices.
- Several methods for vulnerability mapping involve the estimation of different parameters that are not completely independent from each other.
5.3 Best delineation of spatially variable individual parameters

The seven DRASTIC parameters and the required data to define each one of them are analyzed individually. This allows defining the best approaches depending on available data (type and amount). The overall description has been compiled into Figure 5.1.

Depth to water table (D)

Parameter D can be reproduced from field data obtained from hydraulic head measurements, data loggers or available hydrogeological reports. The variable is time dependent. The amount of data available is sparse and may vary from a few points per basin to a high-density sampling network, and each sampling point is sampled with an individual time regime. Alternatively, groundwater levels, and then depths to water table can be obtained from flow models combined with Digital Elevation Models (DEM).

The best method for mapping depth is data dependent. When an extensive data set is available, direct mapping is the simplest option. A single deterministic mapping would not allow for uncertainty evaluation that can only be obtained if the modeling effort involves a geostatistical inverse problems or a Monte Carlo approach. An alternative is to use interpolation methods, not directly, but rather obtained by subtracting the hydraulic head interpolated map to the exhaustive DEM. If a large amount of data distributed along the aquifer is accessible, Ordinary or Universal Kriging could be employed depending whether the mean is considered constant in space or not. If a trend is visible, it is possible to use other methods such as Kriging with an external drift (Desbarats et al., 2002).

When data is sparse along the territory and if the aquifer is unconfined, an option would be to perform cokriging of the phreatic surface with topography (Hoeksema et al., 1989). An alternative way of using data from a secondary variable (such as topography) to improve the estimation of a sparcely-sampled variable could be Collocated cokriging (Deutsch and Journel, 1998). Finally, if data is really scarce it may be possible to first translate all depth data into categories (very deep, deep, shallow,...) and then use indicator kriging.
Figure 5.1. Suggested methods for mapping individual DRASTIC parameters, allowing uncertainty evaluation, depending on amount and type of data.
All the methods suggested here being in the Kriging family (Ordinary, Universal, with external drift, indicator or cokriging) by definition include uncertainty estimation in their methodology, so it is possible to attach a map of uncertainty (e.g., kriging variance) in the estimates for D.

A note of caution; in unconfined aquifers depths are time dependent. To be on the conservative side, minimum depths (largest heads) should be used.

Recharge (R)

This is a very complex parameters to evaluate, with a high variety of data available from different sources and a large number of existing evaluation methods. These include soil/basin water balance, Cl⁻ ion balance, infiltration tests, environmental tracers, empirical correlations with precipitation, or spring hydrographs. The only direct measurement is coming from a lysimeter, but each data point would only represent the local area surrounding the device, far from the scale needed for vulnerability mapping.

Estimation of parameter R is driven by meteorological data, but also related to soil and vadose zone parameters. The information needed could be acquired from water supply agencies, agriculture departments, national weather services, or hydrogeologic reports. Regardless the sources, the data amount and type makes mapping R amenable for a geostatistical approach. Universal Kriging can be used as the default method. Nonetheless, in unconfined aquifers in wet climate zones with sparse data, (collocated) cokriging with precipitation is arguably the best option. In the rare cases where a large amount of information about recharge is available, ordinary or universal kriging could be an alternative. Again, all methods belonging to the kriging family, uncertainty in the evaluation of point R values can be directly estimated and mapped.

Aquifer Media (A)

Contrarily to the numerical nature of D and R, Aquifer Media data are mostly of a categorical nature. Aquifer litological information can be found in geological maps, borehole log descriptions, or geological/hydrogeological reports. Notice
that DRASTIC works with 2D mapping, and thus it is necessary to integrate along the vertical the 3D information if existing.

The methodology we propose is based on the concept of facies reconstruction. From single points classified into categories (hydrogeological facies), there are a suite of methods that allow facies reconstruction: nearest-neighbor classification, support vector machines, or kernel regression methods. Only this last one embeds directly the evaluation of uncertainty. An alternative is working with lithological data directly in an Indicator Kriging framework (Isaaks and Srivastava, 1989).

Soil Media (S)

The Soil Media (S) is constructed from categorical data based in direct field measurements or specific soil maps. Two alternatives exist depending whether data is given as soil classification or else as percentages of sand, silt, and clay.

In the former case a single indicator is given at each point (e.g., based on the USDA soil classification), and mapping by means of Indicator Kriging is a valid approach. Whenever percentage of sand, silt and clay are available, the method should acknowledge the fact that the three percentages must add up to one. Thus, a solution must be sought using the framework of compositional data, and we suggest using Cokriging of log-transformed proportions (Aitchison, 1982).

Topography (T)

Topography (T) index is calculated based on a DEM or a topographic map. DEM can be transformed to a layer of local slopes using GIS tools. Depending on the DEM resolution, or in very flat areas, a filter may be used to avoid a noisy map. Uncertainty in this layer is very low and is usually neglected.

Impact of the vadose zone (I)

Methodology for mapping indicator I is similar to that of A, since data type is also categorical and sources are similar. Existing 3D data must be transferred to 2D maps. Thus, the methodology to be used should belong to the facies
reconstruction family: nearest-neighbor classification, support vector machines, kernel regression methods, or indicator kriging, depending on data available.

**Conductivity (C)**

Hydraulic conductivity is the variable displaying the largest amount of heterogeneity from all those included in DRASTIC. In any given aquifer local values may span several orders of magnitude within a given study area. When upscaled to a 2D map the variable of interest is transmissivity.

Transmissivity data can be obtained at the point scale (slug-tests) or at different intermediate or large scales, from a suite of hydraulic tests (pumping, recovery, or specific capacity). Indirect data could be obtained from litological or geological mapping or borehole logs. Finally, in most cases a full map can be obtained from calibrated numerical models. In the latter case, mapping is unnecessary because transmissivity values are available at all points in the mesh, and should only be converted into categories based on the thresholds provided by Aller et al. (1987). A single deterministic model would not allow for uncertainty evaluation; this could only be obtained if the modeling effort had already been performed in a geostatistical framework.

Whenever data is not coming from a modelling effort, just a small number of points and/or areas are known and some interpolation method should be employed. Depending on the number of data and the potential existence of a spatial trend, Ordinary or Universal Kriging may be used. If transmissivity values are first translated to categorical terms, indicator kriging is a reasonable option. Again, all kriging methods include the estimation of uncertainty in their methodology.
6 Example of application of the new developed index

We applied the variation of the DRASTIC index explained in the previous Chapter incorporating different degrees of uncertainty in a real case in Spain where MAR activities are being considered.

6.1 Study area

The Onyar river basin, with an area of 295 km², is located in NE Spain (Figure 6.1). According to Folch et al. (2011) this depression displays three hydrogeological units: (1) the granite bedrock, outcropping outside the basin and affected by regional faults; (2) the multilayered Neogene aquifer, consisting of alternating silt, sands, and gravels with low clay content; and (3) the alluvial aquifers linked to the main water courses, composed of fine sands with a high content of silt and clay.

![Figure 6.1. Location of the study area.](image)
6.2 The individual DRASTIC layers

Layer 1: Depth to water table

Depth to the water table information was obtained from five field campaigns carried out in 2000-2003 (Menció, 2006), comprising 83 wells. Average (in time) depths were classified according to the range values suggested in Table 6.1.

The Indicator Kriging (IK) method was chosen due to the spatial distribution and the amount of data available. The continuous variable at every point \( x \) is transformed into a series of binary values (one for each value of \( z_l \)) by means of indicator functions. While in general Depth is not an appropriate regionalized variable, if the topographic surface does not display sudden changes, it is an admissible simplification.

The limits of the ranges in DRASTIC (Table 1) are chosen as the four \( z_l \) thresholds (1.5, 4.6, 9.1, and 22.9 m for \( z_1 \) to \( z_4 \), respectively). IK is performed at each point \( x_0 \), for the four thresholds, and as the method preserves order, the following result holds: \( 0 \leq \bar{I}_1(x; z_1) \leq \bar{I}_2(x; z_2) \leq \bar{I}_3(x; z_3) \leq \bar{I}_4(x; z_4) \leq 1 \). Here the overbar indicates the indicator kriging function, that is the probability that the actual value lies below the corresponding threshold (the higher the threshold the higher the probability). Thus, by substracting the values for two succesive functions we get the probability that each point is assigned to a particular range and associated the corresponding index in the DRASTIC layer.

Since now depth is a discrete variable a choice must be made in order to select the index corresponding to each individual point. Here it is possible to include the concept of degree of confidence. One choice could be to get the value corresponding to the “median”; i.e., selecting the range where we will find the 50% probability of non-exceedance. However, other issues can be considered when selected this value. If improvement of water quality by the capability of the vadose zone to degrade some contaminants wants to be considered, higher values of vadose zone thickness should be included in the approach. In that case a higher cut-off value should be selected. A more or less conservative scenario would be obtained by selecting a different cut-off value. For example,
we define a cutoff of 0.8, we would look at the range in Table 1 where we have the 80% probability of depth being lower than the corresponding threshold, rather than that obtained with a cutoff of 0.5, eventually resulting in a higher vulnerability index.

Table 1: Ranges, ratings of depth to water table and the relative frequency.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>Rating</th>
<th>( f_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.5</td>
<td>10</td>
<td>0.024</td>
</tr>
<tr>
<td>1.5-4.6</td>
<td>9</td>
<td>0.301</td>
</tr>
<tr>
<td>4.6-9.1</td>
<td>7</td>
<td>0.277</td>
</tr>
<tr>
<td>9.1-22.9</td>
<td>5</td>
<td>0.241</td>
</tr>
<tr>
<td>22.9-30</td>
<td>2</td>
<td>0.157</td>
</tr>
<tr>
<td>&gt;30</td>
<td>1</td>
<td>0.000</td>
</tr>
</tbody>
</table>

An illustrative example is presented in Figure 6.2, where we developed the two maps corresponding to the 0.5 and 0.8 cutoffs. The 0.5 scenario would be somewhat similar to the (standard) deterministic DRASTIC approach. A more conservative approach (0.8 cutoff), would be equivalent to run a number of Monte Carlo realizations in the continuous variable, and then finding the value with 80% probability of being exceeded, and finally convert into a class and assign an index from Table 1. This approach would result at each point in an index that is larger or equal to that obtained in the median map, equivalent to state a more stringent policy in order to assure the water quality of the recharged water and/or the aquifer.

In the example of Figure 6.2, for the “median” map a rating equal to 7 represents 61.3% of the total area, while a rating of 9 is present in 18.6 % of it (equivalent to 56.16 km²). These values change in the “conservative” map, where almost the whole area is classified with a rating of 9 (79.6%). Also in the 50% map there is a 20.1% area associated to rating 5, mostly non-existing in the map corresponding to 80%.
Figure 6.2. Depth to water table for two different scenarios: (a) median – 50% confidence, and (b) conservative – 80% confidence (see the text for the definition of the two scenarios).

Layer 2: Soil Media

In the same basin, the layer representing Soil Media (S) was determined from 27 soil samples displaying the percentages of silt, clay, and sand (Ros, 1997). In this case data treatment is based in the framework of compositional data, as a
way to ensure that at every point the percentages of silt, clay, and sand add to one. Aitchison (1982) introduced the additive-log-ratio (alr) transformation to deal with kriging of compositional data; when applied, compositions are termed “coordinates” and the sample space is the simplex, where data is projected or mapped onto non-orthogonal axes. The composition consists of d elements, $z = [Z_1, Z_2, ..., Z_d]^T$, where $Z_i > 0 \forall i = 1, ..., d$ and $\sum_{i=1}^{d} z_i = 1$. The alr transform of z gives the variable y, mapped in a d-1 dimensional system

$$y = alr(z) = \left( \ln \frac{z_1}{z_d}, \ln \frac{z_2}{z_d}, ..., \ln \frac{z_{d-1}}{z_d} \right), \quad (6.1)$$

Writing a w vector (dimension d) as $w = [y^T, 0]^T$ allows writing the inverse of the alr transform in terms of a vector j, of length d (Lark and Bishop, 2006).

$$z = \frac{\exp(w)}{j^T \exp(w)}, \quad (6.2)$$

In the Case Study silt percentages were used as the denominator ($Z_d$), and then cokriging was applied. The semivariograms of $Z_{\text{clay}}$ and $Z_{\text{sand}}$ as well as the cross-variogram were first computed from the transformed (alr) coordinates, and a Gaussian model was fitted. Afterwards cokriging provided the best estimates of $Z_{\text{clay}}$ and $Z_{\text{sand}}$. Coordinates are then back-transformed using (6.1) to obtain the expected values of clay, sand, and silt for all points. Uncertainty is assessed from the standard deviation of the variables. Therefore,

$$z_{\text{clay}} = z_{\text{cok}} - \alpha \sigma_{\text{clay}} \quad (6.3)$$

$$z_{\text{sand}} = z_{\text{cok}} + \alpha \sigma_{\text{sand}} \quad (6.4)$$

where $z_{\text{cok}}$ is the cokriged value, $\sigma$ is the standard deviation and $\alpha$ is a positive coefficient, set by the user, and representing the degree of confidence involved in the estimation. If $\alpha$ is 0, then $z_{\text{clay}} = z_{\text{cok}}$, while the higher the $\alpha$ coefficient, the higher the DRASTIC rating. Notice that in (6.3) a negative sign is involved, since the smaller the value, the larger the vulnerability rating. Contrarily, in (6.4) the positive sign accounts for the increase in vulnerability associated to the large estimated percentage of sand.
Results for three $\alpha$ values representing different degrees of confidence are represented as ternary diagrams and the resulting DRASTIC ratings (Figure 6.3), corresponding to $\alpha=0$, 1 and 3. Positive $\alpha$ values is the most conservative when evaluating vulnerability, but it would be non-conservative in terms of best locating future MAR facilities. Using a negative value would favor the presence of clay/silt at the surface reducing the potential for infiltration (being on the conservative side for MAR facility location). In all cases the NE and SW part of the basin involves sandy sediments while in the rest of the basin clays and silts are mostly found. Changing the coefficient $\alpha$ varies the contact limits between the sandy and the clayey-silty soils. The outermost part of the basin is the one with more variance, thus more affected by the choice of the $\alpha$ coefficient.

![Figure 6.3. Ternary diagram (labeled according to the USDA soil texture class) for $\alpha = 0$ (a); $\alpha = 1$ (b); and $\alpha = 3$ (c) and the resulting S layers in DRASTIC.](image)

From the ternary diagrams it is found that an increase in $\alpha$ results in a substantial increase in the area defined as sandy (i.e., most vulnerable) soils.
The difference of using $\alpha=0$ and $\alpha=1$ is to move points that were originally classified as silty clay, and clay, thus located in the upper and right side, towards the center of the ternary diagram, thus classified as clay loam and loam. Moreover, textures with a high sand content (sandy clay loam) become sandy loam or loamy sand. The subsequent increase from $\alpha=1$ to $\alpha=3$ mostly increases the points classified as sand (in about 30%).

**Layer 3: Net Recharge**

Net recharge (R) layer was obtained by performing a water balance in the soil. Soil infiltration and retention parameters were validated with head levels in a representative well and data from a gauging station. Rainfall data were obtained from a single meteorological station, so that it was not possible to delineate a spatially variable recharge map. Estimates involving different degrees of confidence resulted always in recharge estimates in the range 100-180 mm/y, thus providing a unique map with a DRASTIC index of 6 (Figure 6.4, top left).

**Layer 4: Topography**

Whenever a high resolution DEM is available, this layer can be obtained from tools embedded in GIS to obtain the topographic gradient at each point. Being a high resolution result, this layer can be treated as deterministic. The resulting map can be seen in Figure 6.4 (bottom, left). Notice the high degree of detail in the plot as compared to the remaining plots in the same figure.

**Layers 5 to 7: Aquifer Media, Impact of the Vadose Zone and Hydraulic Conductivity**

The remaining 3 layers in DRASTIC have been treated as deterministic, showing the potential of the method proposed to consider heterogeneity in each layer independently, depending on the amount and type of data available.

Aquifer Media and Impact of the Vadose Zone layers were directly exported from the geological map (1:50000) of the Environment Department website of the Government of Catalonia (www.gencat.cat). Since no additional information
was available, uncertainty could not be evaluated. The resulting maps are presented in Figure 6.4 (center and top right). Finally, data for the Hydraulic Conductivity layer were taken from an existing deterministic groundwater numerical model (ACA, 2009), implying the impossibility of including uncertainty. The final map of the C layer is included in Figure 6.4 (bottom, right).

The use of these three layers (A, I, C) as deterministic is not a limitation of the approach. Notice that they have been evaluated as the standard way it would be done in a DRASTIC approach, thus conveying the same information. It would definitely be possible to create a version of such layers including uncertainty, e.g., building a model embedded within a geostatistical framework for layer C, or generating a new geological model by updating the existing one with information from boreholes for layers A and I.

![Maps of Net Recharge, Aquifer Media, Impact to the Vadose Zone, Topography and Hydraulic Conductivity](image)

Figure 6.4. Net recharge, Aquifer Media, impact to the vadose zone, Topography and Hydraulic Conductivity layers.
6.3 The overall DRASTIC index map

In the example presented we have shown how the degree of conservatism can be included in the layers. DRASTIC maps can combine the different layers, each one with a different approach. This results in a large number of maps that can be used by policy makers to different degree.

We present here only the average final map (Figure 6.5), where all layers have been treated either deterministically, or else presenting only the median values. The most vulnerable zones match with high Impact to the Vadose Zone rating, corresponding to the presence of schist, calix and sandstone formations located in the N, NW and S. On the contrary the same zones show low rating on the Aquifer Media layer (2 to 3). This disagreement is due to the greater weight of the Impact to the Vadose Zone parameter based on overweighting the infiltration capacity with respect to the storage capacity of the aquifer.

![Figure 6.5. Final DRASTIC index for the Onyar basin, all layers including the median scenario.](image)

Appendix

A.1 Kriging concepts

Kriging is an interpolation technique developed in the field of geostatistics. This technique observes the underlying process in the space using representative
variables and computes unknown values of the variable using the values sampled in a limited set of locations. The interpolated values are based on data values, the semivariogram function, and the potential presence of a spatial trend.

The name of kriging involves a family of groups all sharing the same principles, but varying in the type of data involved and in the presence of additional information regarding spatial trends.

In general kriging involves obtaining a linear estimator based on data that has the properties of unbiasedness and a minimum estimation error. That is, \( Z^* = \sum_i \lambda_i Z_i \), with \( Z^* \) is the estimated value and \( Z_i \) the actual measurement of the variable at a measurement point. The weights, \( \lambda \), are obtained by solving a system of equations that depends on the kriging method adopted.

Finally, kriging allows the evaluation of the estimation variance at each point.

### A.2 Kriging methods

**Ordinary Kriging (OK)** assumes that the mean of the regionalized variable is unknown but equal at all points. The resulting system of equations to solve is

\[
\begin{pmatrix}
0 & y_{12} & \cdots & y_{1n} & 1 \\
y_{21} & 0 & \cdots & y_{2n} & 1 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
y_{n1} & y_{n2} & \cdots & 0 & 1 \\
1 & 1 & \cdots & 1 & 0
\end{pmatrix}
\begin{pmatrix}
\lambda_1 \\
\lambda_2 \\
\vdots \\
\lambda_n \\
\mu
\end{pmatrix}
=
\begin{pmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n \\
1
\end{pmatrix}
\]

\[ A \cdot \lambda = b \rightarrow \lambda = A^{-1} \cdot b \tag{A.1} \]

where \( y_{ij} = y[x_i - x_j] \) indicates the variogram associated to the distance between two measurement points, while \( y_i = y[x_i - x] \) is that associated between a sampling point and the point where estimation is being performed. In short, if there are \( n \) measured points, the system in (A.1) involves \( n+1 \) equations with \( n+1 \) unknowns.

Moreover, once the system has been solved and the weights are obtained, the estimation error variance at each point is obtained from

\[
\sigma_k^2 = -\sum_i \sum_j \lambda_i \lambda_j y[x_i - x_j] + \sum_i \lambda_i y(x_i - x) \tag{A.2}
\]
Indicator kriging (IK) is very similar to OK, method with the only difference that all the data points are either 0 or 1. Also the variograms involved in the system of equations used to estimate the kriging weights are indicator variograms.

Modification of OK allow the inclusion of a non-constant mean. When this mean is known (e.g., associated to an external variable) the method is known as kriging with an external drift (ED); when it is unknown and should be estimated from the data, the method is known as Universal kriging (UK).

Cokriging (CK) is a variation of the methods of the kriging family that involves two variables, instead of one. The method uses two semivariograms (one per variable) plus a cross-variogram in order to obtain the kriging weights.

References


