Unit 5 – Vulnerability Mapping

Dirk De Ketelaere

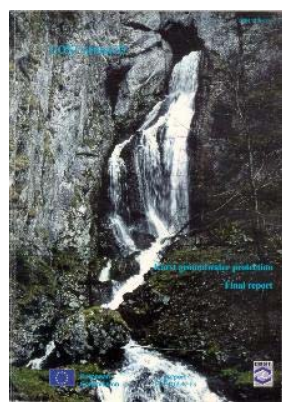
Preamble: This final unit provides a detailed assessment of a vulnerability map produced for the Island of Gozo which resulted from a joint research effort with colleagues in Turkey and Lebanon. First, a brief overview is presented of recent research projects on the vulnerability of karst environments.

> Given the particular sensitivity of karst aquifers to human impacts, both in terms of pollution and over-exploitation, it is remarkable that the drinking water supply of most countries in Europe depends extensively on karst groundwaters.
>
> (Zwahlen Ed., 2004)

The Special Vulnerability of Karst Environments

All over the world, karst landscapes are arguably among the most vulnerable environments because of the close interconnectedness between the geological, geomorphological, biological, and most importantly, hydrological processes affecting these landscapes. The underground solution channels and conduits commonly provide a direct hydraulic link between the surface and the underground aquifers. This causes the hydraulic behaviour of karst areas to be very complex. This can be illustrated by the fact that it is common in karst environments for the impact of an accidental spillage to be transmitted through the underground path flows to a point which may be far removed from the initial point of impact. This is a distinctive characteristic of a karst environment, with its hydrological processes that operate underground and, unfortunately, out of sight of many policy makers (Urich, 2002).

Also the underground aquifers themselves demonstrate a very heterogeneous behaviour which makes them appear as complicated and unpredictable aquifers. Detailed scientific investigations coupled with a high degree of hydrogeological knowledge of karst aquifers, must be considered a basic prerequisite for any action related to their consideration as a resource, particularly where their protection is concerned (Final Report, Cost Action 65, 1995).



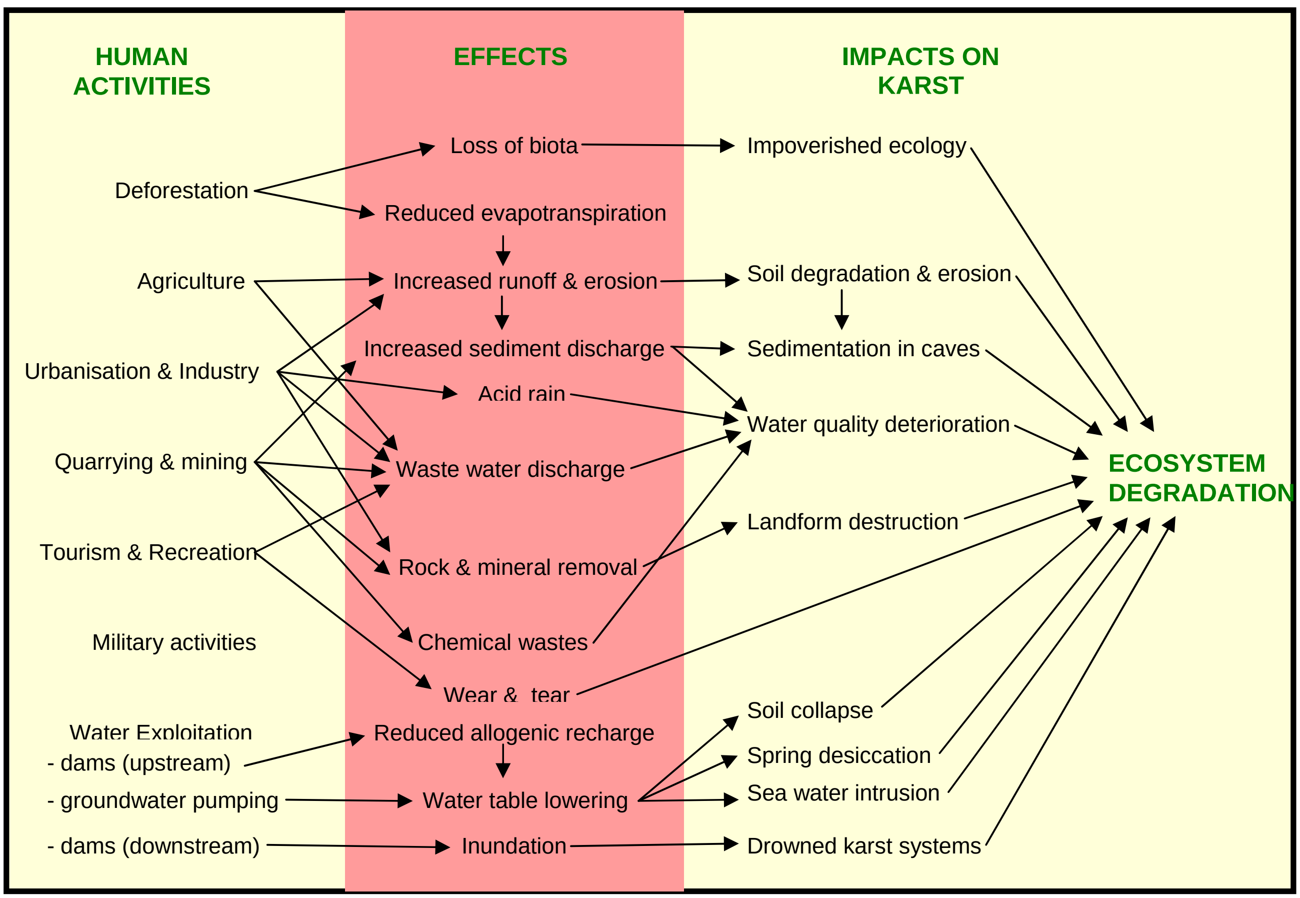
Final Report, Cost Action 65, 1995 (cover)

Human activities at the surface result in the generation of numerous sources of water-borne contaminants. A general classification of the land use distinguishes between three main types of activities, i.e. infrastructural, industrial and agricultural activities. As highlighted in Unit 3 Water Resources, the highly fissured nature of the limestone makes karstic aquifers particularly vulnerable to contamination. The natural self-treatment capacity found in non-karst environments is rendered relatively ineffective by the conductive nature of karst terrains. Therefore, the probability of spreading contaminated water through karst is high and potentially serious.

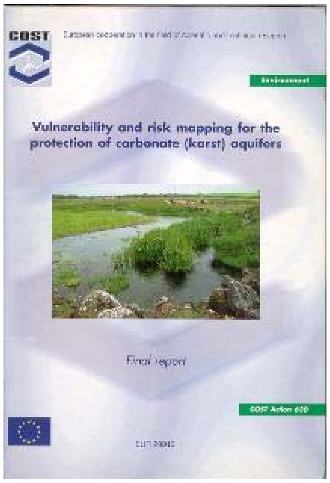
Derek Ford (1989) lists a number of reasons why karst terrains are ineffective in treating the infiltrating contaminated water reaching the aquifers:

- Rapid infiltration into karst reduces the opportunity for evapotranspiration, a mechanism that is important in the elimination of highly volatile organic compounds such as solvents and pesticides.
- Physical filtration is relatively ineffective in typically thin karst soils and through rocks with large secondary voids; thus sediment and microorganisms are readily transported into karst aquifers.
- Time-dependent elimination mechanisms (of bacteria and viruses for example) are curtailed in effectiveness because of rapid flow through times in conduits

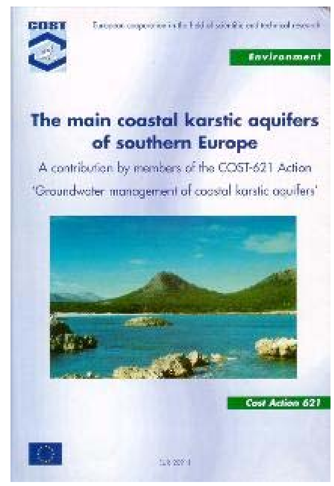
Schematic overview of the effects of human activities and their impacts on karst (adapted from Urich, 2002)



Research on vulnerability, hazard and risk mapping

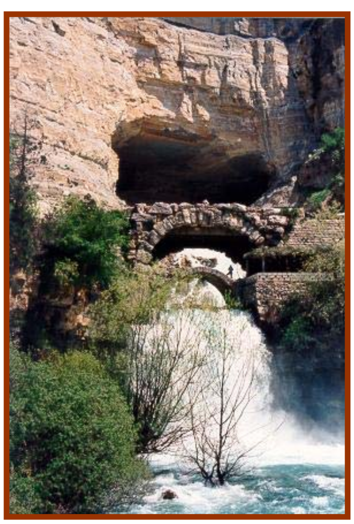


Within the context of the Water Framework Directive, a European-wide research project, 'Cost Action 620' sought to develop a common 'European Approach' for mapping the vulnerability, hazards and risk of karst aquifers. The Final Report acknowledges that the objective proved difficult to achieve, not least due to the (different) regulations and practices carried out in the 15 participating countries and the varying points of view of the numerous experts (Zwahlen, Chairman, Cost Action 620, 2004).



In a parallel research effort, 'Cost Action 621' focused on coastal karst aquifers in the southern Mediterranean region. In coastal conditions, the aquifer is open towards the sea and overexploitation creates a progressive salinisation due to seawater intrusion. Coastal karst aquifers are particularly sensitive to this phenomenon, because the underground conduits which are normally feeding submarine springs become easy ways for the inland penetration of seawater when the aquifer is overexploited. (Tulipano, Chairman, Cost Action 621, 2004)

While our active participation in both, European-wide, research projects on karst proved an immensely enriching experience, our efforts to apply the new methodologies that emerged to the local context were hampered by a general lack of detailed hydrogeological data on the aquifers in the Maltese Islands. This became particularly evident for the island of Gozo.



The EU-sponsored International Cooperation (INCO) Project entitled 'Resource Management in Karstic Areas of Coastal Regions of the Mediterranean' (*ResManMed*), enabled us to join forces with the **International Research and Application Centre for Karst Water Resources** at Hacettepe University in Ankara, Turkey and the **National Centre for Remote Sensing** in Beirut, Lebanon. Within the overall context of the research, each of us was responsible for mapping the vulnerability of a 'study area'. For Turkey, the study area consisted of a National Park in the close vicinity of Antalya, while in Lebanon the selected area included the littoral north of Beirut and extended inland up into the mountains at elevations exceeding 2600m. The island of Gozo was chosen for the purpose of our 'study area'.

Karstic spring at Aqfa, Lebanon

The initial phase of the *ResManMed* project had the objective to produce maps depicting the state and use of the 'environmental resources' in the respective study areas. The environmental resources that were mapped included the geology, soil, water, forest, karst heritage and biodiversity. Soon, each of us was faced by an acute lack of raw data, particularly for the purpose of mapping the state of the 'water resources'. The original idea to resolve this by means of computer simulation was abandoned in recognition of the difficulty to model water flows through karstic systems. However, at a joint project meeting in Beirut, an alternative solution emerged and was agreed upon and was coined the SCI map, i.e. '***Surficial Cover Infiltration***' map.

Water Resources Vulnerability Map for Gozo

The production of a water resources vulnerability map for the island of Gozo featured as one of the innovative outputs achieved from the research carried out under the EU funded *ResManMed* project. The map provides a qualitative assessment of the **relative infiltration ability** (i.e. in terms of low, medium, high or very high infiltration).

Developed by the Mediterranean partners in the consortium, the '*Surficial Cover Infiltratrion'* method considers the combined appraisal of four hydrogeological factors: i.e. the surface lithology, faults, karst features and Surface Drainage Density. The method consists of rating each of the hydrological factors which have been assigned with an appropriate weighting coefficient to arrive at the **Surface Cover Infiltration (SCI) index**.

Below, a detailed explanation on the method is given which is then followed by a discussion on the application of the method to the island of Gozo. It is deemed important however, to underline the scope of the method in terms of the output that is obtained, i.e. the method provides a measure of the relative infiltration ability based on the calculation of a SCI index.

Relative infiltration ability

The SCI method does not intend to assess the actual infiltration in a quantitative manner, as this would require the consideration of a much wider range of parameters such as rainfall, evapotranspiration, slope or gradient of the terrain etc. By eliminating these meteorological and topographical parameters, the focus is on obtaining the relative ability of the surface cover to permit water to seep through to the subsurface, hence the reference to a 'relative infiltration ability'.

SCI index

A grid is placed over the study area and, in each cell of the grid, the ratings for the four factors are determined. Thus, in each cell of the grid a SCI index is obtained. For the Island of Gozo, the SCI indices have been mapped according a grid made up of 200 by 200m square elements. It was considered appropriate not to produce the vulnerability map at a denser scale since the method does not replace the need for detailed hydrogeological investigations to be made e.g. when preparing an Environmental Impact Assessment to determine the impact of a proposed development on the underlying water resources at a(ny) specific location.

Surface Lithology (SL)

Generally, the surface lithology can be classified according to either the permeability or the hydraulic conductivity. In both instances, literature (e.g. Bear, 1979; Cherry and Freeze, 1979) provides abundant data about the range of possible permeability and hydraulic conductivity values. However, as explained above, the SCI method is concerned only with a '**relative infiltration ability**' assessment.

To this effect, the SCI method simply considers that the surface lithology is divided into three distinct classes: Pervious, Semipervious and Impervious, and are assigned with a rating of 2, 1 and 0 respectively. Evidently the 'relative infiltration ability' is expected to decrease with decreasing perviousness.

In their intact form, limestone and dolomite are impervious. When they are fissured or fractured, their infiltration ability increases and they become semi-pervious. Fractures enlarged by karstification processes are highly permeable. For the island of Gozo, the highest rating has been assigned to the Upper Coralline Limestone, while the lowest rating has been assigned to the Blue Clay. It is recalled that the latter follows from the observation that the Blue Clay acts as 'a barrier' to the deeper infiltration of water.

Relative ratings assigned to the Surface Lithology

Hydrogeological Character	Rating	Application to Gozo Study Area
Pervious	2	Upper Coralline Limestone
Semipervious	1	Lower Coralline and Globigerina Limestone
Impervious	0	Blue Clay

Thus, the geology map of the Island of Gozo was discretized into 200x200m cells and the rating in each of the cells was determined according to the relationship shown in the table above. Obviously, it is possible to find more than one of the above 'surface lithologies' in a single cell. In this case, the rating in the cell is found by calculating the weighted average.

For example, if we have a cell which is %20 impervious, %15 semipervious and %65 pervious, then the rating assigned to the Surface Lithology of this particular cell will be:

SL = (0.2*0)+(0.15*1)+(0.65*2)=1.45

Faults (F)

Fault lines play an important role in the infiltration process. Aerial photographs combined with surface mapping of the area enables to distinguish between different types of faults or fractures. Since the SCI method does not intend to give a numerical figure for the infiltration, the method is only concerned with solving a difficulty that is related to the density of the grid, i.e. the working scale, selected for the specific study area.

This difficulty is overcome by applying the following method which is based on the statistical analysis of the fault density. Each fault line is divided into sections with a pre-defined length **f** (e.g. division of each fault into sections of one centimetre as measured on the geology map, in which case **f**=1cm) and one counts the number of **f** centimetre long (fault) sections found in each cell of the grid.

The difference between the maximum and the minimum number of **f** centimetre long sections found in the grid is divided by three to find the classes defining the fault density factor as shown in the table below.

$$\mathbf{F} = \frac{(\text{Max number of } \mathbf{f} \text{ cm long sections}) - (\text{Min number of } \mathbf{f} \text{ cm long sections})}{3}$$

Relative ratings assigned to Faults (**F**)

Effect on SCI	Fault density	Rating
Low	Less than **F**	1
Medium	Between **F** and 2**F**	2
High	Greater than 2**F**	3

Thus, the effect of the working scale has been normalized. Note that it is possible to speculate about the direction of the water circulation if also the azimuth of the **f** centimetre long, part of the lineament, is measured and presented statistically as a rosette for the 10° increment classes as suggested by Milanovic (1981).

Karst Features (KF)

Karstification produces many specific surficial and subsurface landforms which are extremely important from the standpoint of both recharge regime (infiltration ability) and groundwater circulation.

Dealing solely with the infiltration ability, the SCI method considers the karstification in the assessment of the SCI index, by measuring the area covered by karst depressions. For the island of Gozo, the dolines have been considered together with the deep incisions into the landscape which appear as gorges.

A density factor (**KF**) similar to F for the fault density is defined in order to normalize the scale effect. First, the total area of the karstic depressions located within the grid is measured and recorded as a percentage of the grid area. Then the rating obtained for each individual cell of the grid is obtained according to the 'karst feature' intensity as shown in the table below. Note that the rating '0' is assigned whenever the Surface Lithology is considered impervious!

Relative ratings assigned to Karst Features (**KF**)

Effect on SCI	Karstic Feature Intensity	Rating
Nil	No effect if Surface Lithology (SL) is impervious	0
Low	**KF**<10%	1
Medium	10%<**KF**<30%	2
High	**KF**>30%	3

Surface Drainage Density (SSDD)

The study of the drainage (stream) network on a topographical map can provide useful hints about the hydrogeological conditions. For example, areas that show a very dense drainage network can typically be associated with the existence of impervious formations beneath the surface cover. Thus, a higher Surface Drainage Density is linked to lower infiltration ability. Of course, it should be kept in mind that a dense drainage pattern may form also in areas receiving relatively high rainfall. However, if the whole study area is governed by the same rainfall regime, the rainfall regime does not affect the description of the classes according to the Surface Drainage Density in this SCI method.

The Surface Drainage Density is measured similarly to the density of faults. First, the study area is again discretized into square cells. Then, each drainage element (stream) is divided into a pre-defined length **d** (e.g. 1 centimetre as measured on the topography map) and one counts the number of **d** centimetre long (stream) sections found in each cell of the grid. The difference between the maximum and the minimum number of **d** centimetre long sections found in the grid is divided by three to find the classes defined in the table below.

$$\mathbf{SDD} = \frac{\text{(Max number of } \mathbf{d} \text{ cm long sections) - (Min number of } \mathbf{d} \text{ cm long sections)}}{3}$$

Relative ratings assigned to Surface Drainage Density (**SDD**)

Characterization	Surface Drainage Density	Rating
Low Surface Drainage Density	Less than **SDD**	3
Medium Surface Drainage Density	Between **SDD** and 2**SDD**	2
High Surface Drainage Density	Greater than 2**SDD**	1

Calculation of the SCI Index

In each cell of the grid, the SCI index is then calculated on the basis of the ratings obtained for each of the individual factors. The four factors have been assigned with a 'weight' which represents their relative importance on the infiltration phenomenon.

Factor	Weight (%)
1- Surface Lithology	35
2- Faults	20
3- Karst Features	30
4- Surface Drainage Density	15

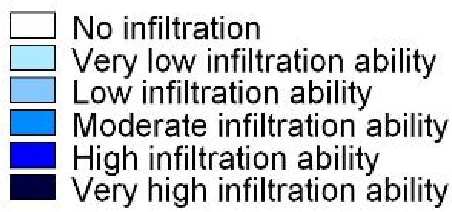
Thus, the SCI Index in any given cell of the grid is obtained as follows:

SCI index = 0.35x(rating Surface Lithology) + 0.20x(rating Faults) + 0.30x(rating Karst Features) + 0.15x(rating Surface Drainage Density)

The SCI index values are interpreted according to the following classification and colour legend.

SCI INDEX

<0.40
0.41-0.85
0.86-1.30
1.31-1.75
1.76-2.20
> 2.20

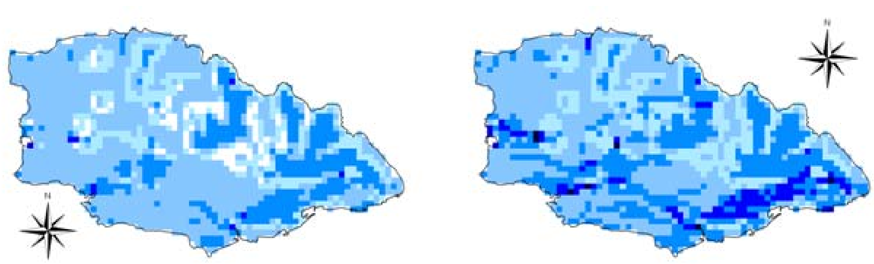


SCI Map for Gozo Island: an in-depth assessment

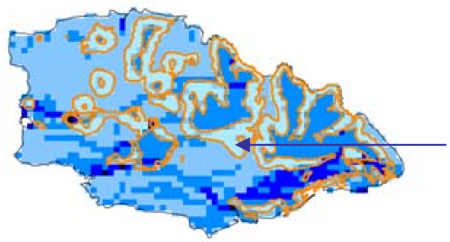
A detailed assessment of the SCI Map obtained from the above described method, revealed that while the Surface Lithology and Karst Features were duly taken into consideration, the contribution of the Fault Density and the Surface Drainage Density factors to the infiltration ability did not prove to be represented in a satisfactory manner for the island of Gozo.

The figure below shows the initial Surficial Cover Infiltration (SCI) Map obtained from the direct application of the above described method, as well as the revised SCI Map which resulted from an in-depth assessment of the method.

Initial SCI Map (left) and Revised SCI Map (right)



Assessment of the Surface Lithology Factor



As expected, the infiltration ability is reduced, particularly in those areas where the Blue Clay forms the outcropping formation.

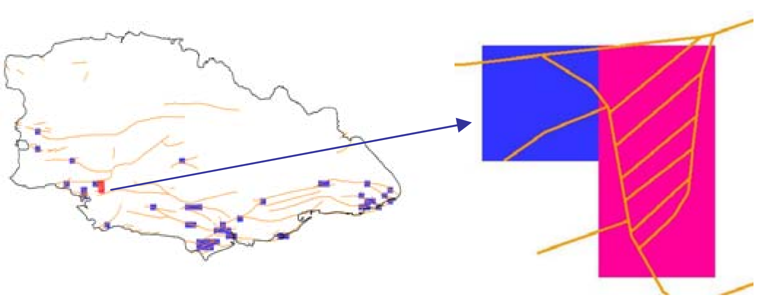
The areas where the Blue Clay outcrops (delineated by the orange contours) coincide with areas that have been assigned with 'Very low infiltration ability' in the revised SCI map.

Assessment of the Faults / Fault Density Factor

The maximum length of the faults in a grid of 200x200m was found to be 930m, and a minimum length equal to 0m. According to the SCI method, this defines F=310m and the classes as shown in the first column of the table below.

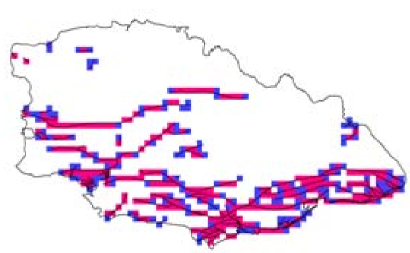
Contribution of Faults

Fault density classes according to SCI method	Revised Fault density classes	Rating
Less than **310**m	Less than **50**m	1
Between **310** and **620**m	Between **50** and **250**m	2
Greater than **620**m	Greater than **250**m	3



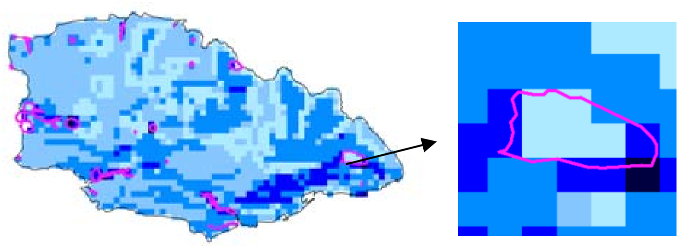
With F=310m, the method assigns the highest rating in only 2 cells of the grid, and it is noted that the contribution of the faults is underestimated as a result of the classification proposed by in the SCI method.

The revised fault density classes consider the fault lengths in terms of a frequency distribution. As a result, the contribution of the faults is much more significant, and is now in conformity with the understanding that fault lines play an important role in the infiltration process. Cells marked in red are assigned with the highest rating (=3), cells marked in blue with the rating=2, and all other cells with a rating=1.



Assessment of Karst Density Factor

The karst features which affect the relative infiltration ability for the island of Gozo include dolines as well as a series of gorge shaped valleys, which appear as deep incisions into the landscape, e.g. at Mgarr ix-Xini (see also Unit 4 Karst Heritage). According to the SCI method, the cells that contain karst features are assigned with a higher infiltration rating.

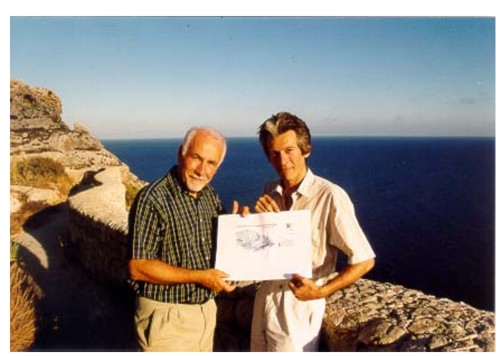


One of the largest dolines is found in the south-eastern part of the island, however its location coincides with a Blue Clay outcrop. The latter represents an impervious surface lithology. Thus, in agreement with the method, this particular doline is considered to have no effect on the infiltration ability.

Assessment of Surface Drainage Density Factor

The assessment considered that the Surface Drainage Density factor had been incorporated in the SCI method because in many cases it is not so easy to decide on the surface lithology rating. For example not all limestone areas are composed of limestone only. Thin interlayers may change the permeability of the lithology as a whole. If the lithological unit is really of pervious character, then the Surface Drainage Density is expected to be low (due to the higher infiltration ability of the lithological unit). In this case, according to the proposed methodology, it can be decided to consider the lithology as pervious limestone with a rating of 3, whether it contains relatively impervious layers or not. For if these impervious layers are present, the Surface Drainage Density factor will adjust for this by decreasing its SCI value.

However, for the Gozo study area, the Surface Drainage Density is quite uniformly distributed over its respective catchments. Moreover, the Surface Drainage Density values are consistently 'low'. This led to the understanding that the Surface Drainage Density factor should not be used to 'fine tune' the SCI index for the Gozo Study area. The revised SCI map considers the Surface Drainage Density to be uniform and low, and thus with a maximum rating of 3 for the whole island.



Discussing the Gozo SCI Map with Prof. Dr. Heinz Hotzl Chairman Karst Commission International Association of Hydrogeologists

Thematic Map and Information Layers for Unit 5

The Thematic Map associated with Unit 5 in the WebGIS is made up of the following information layers:

Gozo SCI Map: raster map showing the relative infiltration ability based on the SCI method

Gozo Blue Clay Outcrop: polygon map showing the Blue Clay outcrops

Gozo Karst Features: polygon map showing the distribution of karst features at the surface, including dolines and gorges

Gozo Faults: segment map of the island's main faults

Layers	Type	Visible	Selectable	Attribute data (short name)	Attribute data (description in full)
Gozo SCI Map	Raster	Yes	Yes		
Gozo Blue Clay Outcrop	Polygon	Yes	Yes		
Gozo Karst Features	Polygon	Yes	Yes		
Gozo Faults	Segment	Yes	Yes		

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