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MAPPING FROST RISK IN FRUIT TREES USING GIS-BASED ANALYSIS: A CASE STUDY IN THE PROVINCE OF ALICANTE (SPAIN)

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ABSTRACT

Agricultural activity is exposed to the effects of global warming, which implies socioeconomic and environmental impacts. This research presents a methodology to facilitate the management of daily temperature time series for climate risk analysis. GIS-based analysis has allowed us to generate climate and relief models, along with other land-use suitability data, integrating information to map frost risk in fruit trees. The calculation was made using open official repositories of massive meteorological and geographic data. Finally, the proposed methodology has been verified by applying it to the risk map of the almond growing areas of the province of Alicante, due to its socio-economic importance and being the first fruit tree to flower with high exposure to the risk of frost. Docker technology has played a fundamental role in automating the process of daily minimum temperature data, which will facilitate the requirements for the reproducibility and application of the research to other areas of study and fruit species.

Keywords: GIS; spatial analysis; almond tree cultivation, *Docker technology*; open data; frost risk; risk mapping.

CARTOGRAFÍA DE RIESGO DE HELADAS EN ALMENDROS MEDIANTE SIG: CASO DE ESTUDIO EN LA PROVINCIA DE ALICANTE (ESPAÑA)

RESUMEN

La actividad agropecuaria está expuesta a los efectos del calentamiento global, lo que implica impactos socioeconómicos y ambientales. Esta investigación presenta una metodología para facilitar la gestión de series temporales diarias de temperatura para el análisis de riesgos climáticos. El análisis basado en SIG nos ha permitido generar modelos climáticos y de relieve, junto con otros datos de

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idoneidad de uso de la tierra, integrando información para mapear el riesgo de heladas en árboles frutales. El cálculo se realizó utilizando repositorios oficiales abiertos de datos meteorológicos y geográficos masivos. Finalmente, se ha verificado la metodología propuesta aplicándola al mapa de riesgos de las zonas de cultivo de almendro de la provincia de Alicante, debido a su importancia socioeconómica y a ser el primer frutal en florecer con alta exposición al riesgo de heladas. La tecnología *Docker* ha jugado un papel fundamental en la automatización del proceso de datos diarios de temperatura mínima, lo que facilitará los requisitos para la reproducibilidad y aplicación de la investigación a otras áreas de estudio y especies frutales.

Palabras clave: SIG; análisis espacial; cultivo de almendro, *tecnología contenerización Docker*; datos abiertos; riesgo de heladas; cartografía de riesgos.

1. Introduction

Irregular thermal behavior and its possible aggravation caused by global warming introduce changes in the phenological stages of crops. Since 1970, fruit trees have been blooming earlier in Europe, an average of 2.5 days per decade (Menzel *et al*. 2006), leading to increased exposure to frost in late winter and early spring. The climatic diversity in the Mediterranean regions favors the frequency of atmospheric risks and for this reason, the climate change policy of the Valencian Govern indicates that the increase in frosts, among other extreme phenomena such as aridity or the advance of desertification, require a correct adaptation strategy that anticipates and minimize the effects on agricultural, livestock and fishing productivity, in order to avoid economic and social problems (*Valencian Strategy for Climate Change and Energy 2030*, 2018).

The main objective of this paper is to demonstrate how geographic information technologies and standardized and open data sources contribute to facilitating the application of methodologies for frost risk analysis in crops at the provincial or regional scale. In addition, the territorial approach and the cartographic aspect of the results are decisive for their use in climate change adaptation planning. To do this, it is necessary to make use of techniques that facilitate its reproducibility by other analysts or researchers, as well as its application to other areas of study and to other species of fruit trees in any part of the Iberian Peninsula. In the proposed case study, spring irradiation frosts have been analyzed, as they are the most frequent and easiest to predict. We start from three main assumptions, namely: *Assumption A*.- the higher the annual probability of critical thermal records for the crop analyzed, the greater the danger of frost, *Assumption B*.- the greater the land-use capacity for agriculture, the greater the spatial concentration of these crops, and therefore, the greater the exposure to possible frosts, and finally Assumption *C*.- the greater the slope and the appearance towards noon, the lower the vulnerability to frost by irradiation.

1.1 Brief literature review

As for the precedents of the object of our research and case study, we can highlight some cartographic works of the first frost risk map (Zaragoza Adriaensens *et al.* 1989), prepared because of the frost of January 1985, which produced the greatest economic damage for Valencian agriculture. On the other hand, the phenological and climate studies on the risk of frost in the almond tree of the Region of Murcia (Erena *et al*. 1992) stands out, in which the effect on flowering in a great diversity of varieties in the area affected by the frosts of March 1977 and February 1978 is analyzed. In 2010, the Food and Agriculture Organization of the United Nations (FAO) published the book A Practical Guide to Frost Protection, which defines the concepts of probability and risk of frost damage very well and includes algorithms that simplify the calculations and favor their application (Snyder *et al.* 2010).

There are more and more studies on natural hazards and their impact on agricultural activities, in part, thanks to an open data policy from official bodies, access to spatial data infrastructures (SDI) and the widespread use of geographic information technologies, mainly Remote Sensing & GIS. Despite this, it is important to highlight the lack of specific references on the application of *Geothecnologies* to analyze frost risk factors in the proposed study area, although there are recent studies on frost risk in crops in nearby geographical areas, such as the demarcation of the Segura River Basin (Pérez Morales

2016, Erena *et al.* 2017, Espín Sánchez 2021). This article does not methodologically consist of a GIS-based MCA in the strict sense (Gómez Delgado & Barredo Cano 2005), but our methodology based on GIS-based spatial analysis has been inspired by work of this type. The multicriteria analysis has helped us to partially define our methodological proposal, by quantitatively integrating an assessment of factors in the estimation of risk (Van Westen & Greiving 2017), such is the case of its concrete application to the study of frost risks, with studies as interesting as that of Li *et al*. (2018) in tea cultivation in Zhejiang Province (China). We have also been able to verify the application of these techniques in thematic and geographical areas closer to our case study, applied to the consequences of climate change on natural hazards on traditional crops in areas of Turkey (Bilgilioğlu 2021).

The ease of reproducibility of the research has been another of the objectives of this research, especially to provide an effective solution to the difficulty involved in processing large volumes of daily temperature data. Containers are quickly becoming another tool for *GIS scientists* and researchers to efficiently conduct and share analyses, a good example for our field of study is the work of Zaragozí *et al* (2017). For this reason, an optimized geodatabase with Docker containerization technology has been used, as it has already demonstrated its effectiveness in other works on natural hazards and the processing of voluminous geographic data, as is the case of its application to hydrological calculation (Landa *et al.* 2017) or in the study of landslide risks (Strauch *et al.* 2018) and even for the determination of exposure to forest fires (Navarro-Carrión *et al.* 2021). The experience and effectiveness demonstrated by container technologies in *GIS science* in publications of this type has made us opt for this type of solution.

2. Materials and methods

2.1 The case study

From a geographical point of view, the relief of the province of Alicante (Valencian Community) is one of the physical factors that most influences the local variability of the Mediterranean climate, characterized by mild temperatures throughout the year, due to the influence of the sea. However, in interior of the province isolated by relief, the effect of continentality and greater exposure to the North and Northeast flows lead to less thermal comfort. Over the last quarter of a century, more than 20 frosts have been recorded in these areas, with detrimental effects on agriculture, with very serious consequences for the cultivation of almond trees, which demonstrates a high exposure of this species to frost, with an economic impact of more than 42 million euros, according to Valencian Agricultural Sector 2000 to 2021 Report, Ministry of Agriculture (Valencian Government).

The cultivation of almond trees appears in all the agricultural regions of Alicante, occupying a total area of 21 370 ha, highlighting the agricultural region of Vinalopó with 65 % of the provincial area of almond trees, 9 340 ha in cultivation of almond trees in cultivation rainfed and about 4 458 ha irrigated (SIGPAC 2022).

In recent years, the cultivation area has undergone a double transformation process: the emergence of new intensive plantations of late varieties in irrigated areas and the introduction of organic farms in rainfed areas. This new process of surface growth implies an increase in exposure to frost, as the cultivation area expands to increasingly colder areas, avoiding the effects of thermophilic pests, such as *Xylella fastidiosa,* detected in the study area since 2017 (Gutiérrez & García 2018, Pérez Moreno 2022) and considered one of the most dangerous plant pathogenic bacteria in the world (Wells *et al*. 1987) that affects numerous species of agricultural interest and of great economic and landscape importance.

Finally, it is worth mentioning the importance of almond trees in areas with a high risk of erosion, such as the rainfed slopes of the interior and the mountains of Alicante, forming a fundamental agroforestry mosaic from the point of view of food production, biodiversity and forest fire prevention (Wolpert *et al*. 2022). All this, without forgetting its role as a woody species in the capture of atmospheric CO_2, and therefore in its contribution to mitigating the effects of climate change.

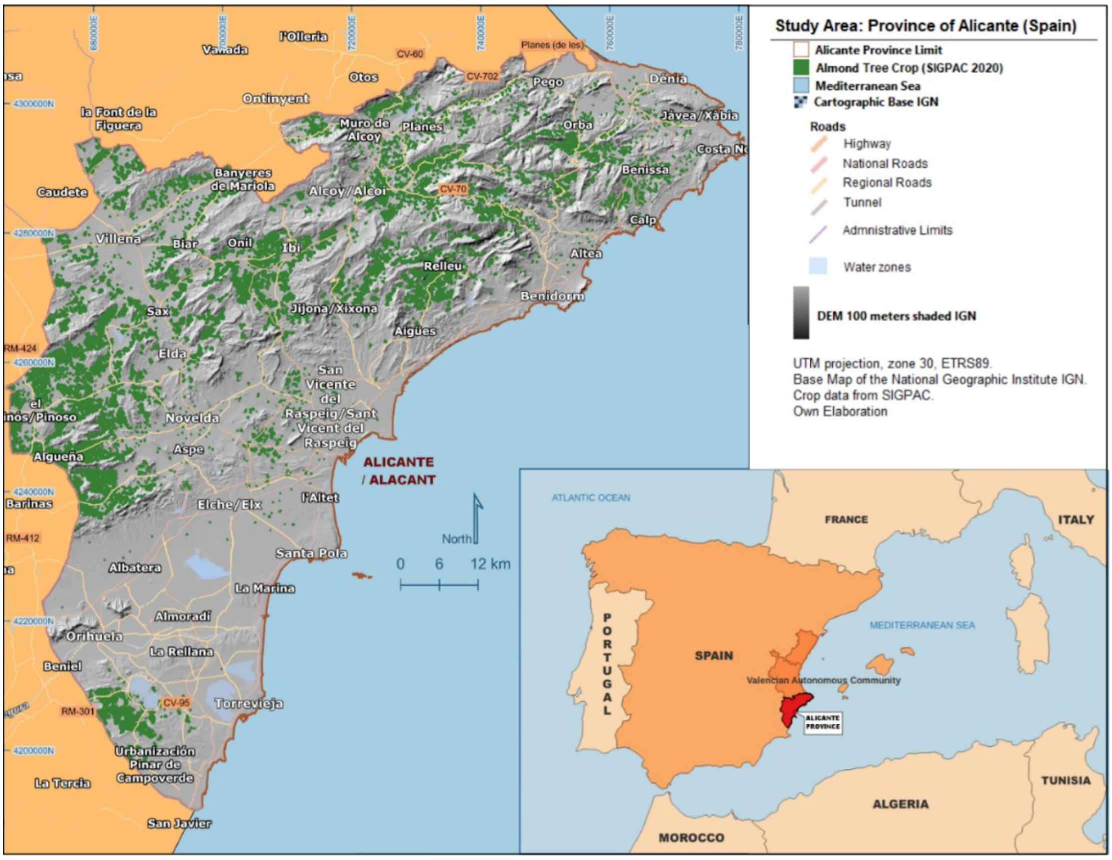

Figure 1. Location map of the study area (province of Alicante - Spain).

Source: National Geographic Institute (IGN) and Geographic Information System for Agricultural Plots (SIGPAC). Own elaboration.

2.2. Data sources and open geo-data

Two types of climatic data have been collected with different time scales, to obtain the minimum daily temperature variable that implies hazardousness. An information group is made up of the data observed in meteorological stations of the networks of observatories of the State Meteorological Agency (AEMET) and the Valencian Institute of Agricultural Research (IVIA), which manages the network of the Agroclimatic Information System for Irrigation (SIAR). This group of data will be referred to as *observed data*, as it is obtained directly in the field. On the other hand, we have a massive set of data interpolated and projected in a daily grid by AEMET modeling, designed for the study of Climate Change scenarios. For this reason, we will refer to this data as *projected data from now on*.

The data from the SIAR stations have the advantage of having been obtained from a network of observatories located in rural areas, next to agricultural holdings, although the number of stations is more limited than the AEMET observation network and the time series are shorter and incomplete, for this reason the integration of both sources has been carried out. In addition, the data observed by the AEMET and SIAR networks have forced us to generate the corresponding interpolation models for application at the scale of analysis, while those projected in the form of an AEMET grid offer a great starting advantage, since they are the result of a validated interpolation model with a pixel spatial resolution of 5 km, obtained from homogeneous series of greater temporal length than the rest of the series obtained from the network of meteorological stations (observed data). In addition, these projected data are appropriate for the scale of analysis of this study, although their large volume makes it difficult to process. Projected data can be downloaded in a format that makes it easy to view in a desktop GIS (ASCII or NetCDF) but makes it difficult to process in a database or spreadsheet directly.

For the analysis of the frost exposure factor, the vector layer of Land Use Capacity *for* the Valencian Community, published by the Spatial Data Infrastructure of the Valenciana Govern (IDEV) of the Valencian Institute of Cartography (ICV), will be used, according to the method of Sánchez *et al*. (1984), modified by Antolín *et al.* (1997) which, from a territorial perspective, leaves aside the socioeconomic and environmental components to simplify the analysis, in the absence of more specific bibliographic references.

For the modelling of the vulnerability factor, relief data from the National Center for Geographic Information of the National Geographic Institute (CNIG-IGN) with a spatial resolution of 200 m were used. From the data of the DEM lidar of the CNIG we have calculated the corresponding digital models of slopes and aspects, applying the method of the *Sobel Operator,* which offers the results closest to reality for the scale of analysis and the object of the analysis. This is because other calculation models can introduce undesirable variations in the valuation of agricultural and forestry activities (Castillejo *et al*. 2006).

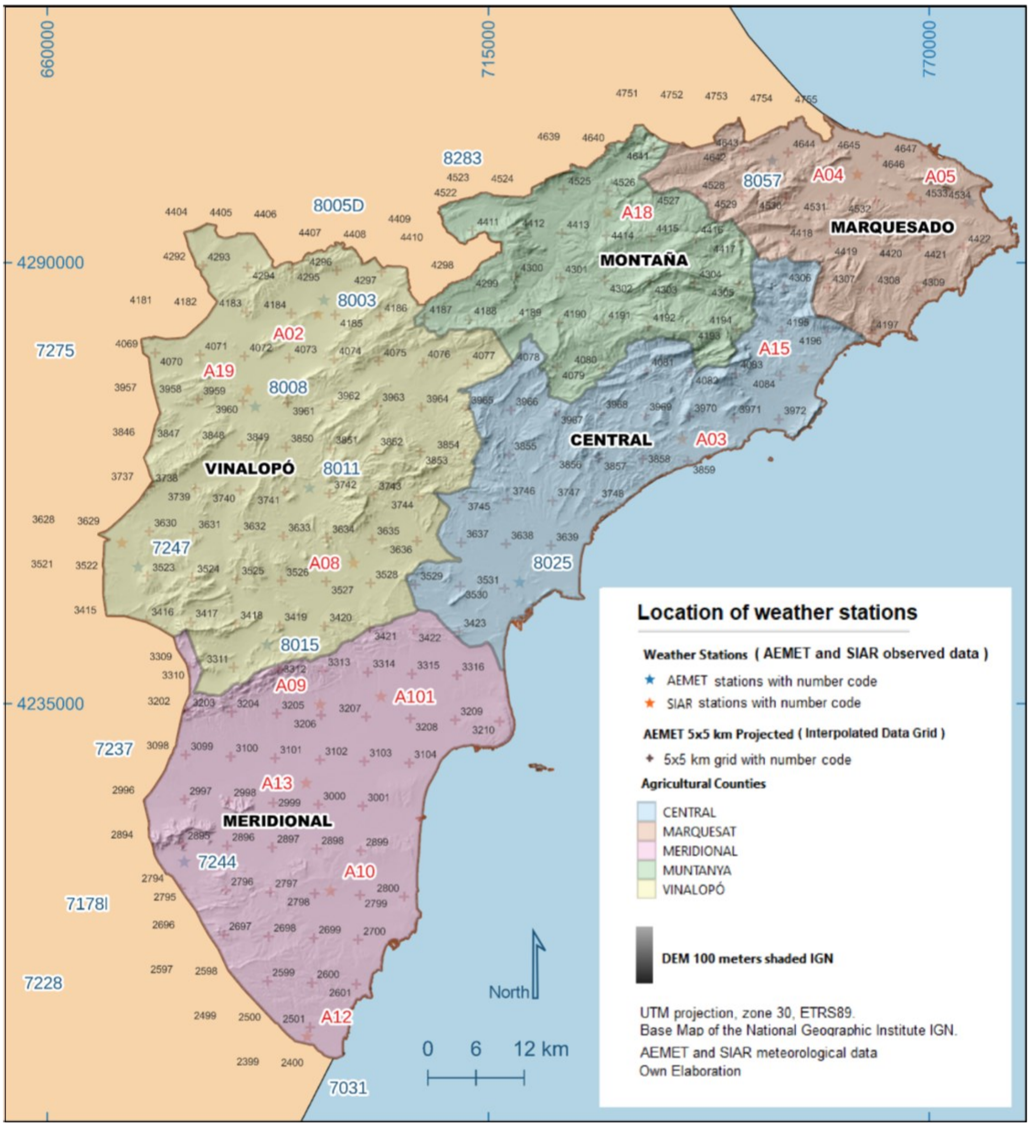

Figure 2: Spatial distribution of the **network of meteorological stations used to obtain a time series of daily minimum temperature in the study area**.
Source: AEMET 5 km x 5 km grid Projected data and observed data SIAR - AEMET Meteorological Network. Own elaboration.

To evaluate the different factors of frost risk in almond tree cultivation, a vector layer of production areas of this crop in Alicante will be obtained from the GIS of the agricultural parcel

(SIGPAC) for the year 2022. To verify the suitability of the results obtained in this research, our results have been compared with the time series of the climatic index of frost days and the *Risk Maps: Frost and Cold Hours in Peninsular Spain (*Period 2002 - 2012) of the AEMET (2015). Finally, the results of the final risk maps were checked with damage data provided by the *Spanish Association of Insurance Entities of Combined Agricultural Insurance, S.A.* (*Agroseguro*).

2.3. Methodology: GIS-based spatial analysis and Docker geotechnologies

The methodology chosen for the development of a spatial model of frost risk in fruit trees is based on the elaboration of digital raster models, based on the factors that make up the risk: hazard, exposure and vulnerability, computing in *PostGIS*, *SAGA* and *QGIS* a spatial analysis based on different assessments carried out using a combination method based on the general risk formula (Varnes 1984), adopted by the UNDRR (United Nations Office for Disaster Risk Reduction).

GIS-based spatial analysis is an analytical process that allows you to evaluate and compare different objective values that integrate multiple thematic criteria, but the most important thing is their geolocation. The methodological objective is to identify geographical areas from the point of view of a natural hazard, so the spatial analysis approach is inspired by multi-criteria analysis, although we have not followed a GIS-based MCA method in the *strict sense*, there is a quantitative and geospatial categorization that allows the risk of frost to be identified in fruit trees with a geographical and cartographic dimension. The effort dedicated to the processing of geographic information is aimed at the production of multi-scale thematic maps for regional and provincial studies that identify the most critical situations, where measures must be taken to mitigate risk or reorient agricultural policy, following the guidelines set out in the agronomic map defined in the Law on Agricultural Structures of the Valencian Community (Law 5/2019 of the Valencian Govern), to improve crop management and increase efficiency in the management of agroclimatic risks of the agricultural insurance system.

To meet the objective of proposing a methodology that can be easily reproduced by third parties, both researchers and technicians from companies or public administrations, we have used geotechnologies that are easy to apply with the free and open geographic software FOSS4G (Jamal-Uddeen 2014). The data computed in the spatial analysis have been weighted to fit the values of the information layers used between pre-established maximum and minimum limits (Aznar & Guijarro 2012, Eastman *et al*. 1995), because it is a very intuitive criterion, simple to implement and validated in most of the revised precedents of GIS application to multi-criteria territorial analysis (Santos 1997). Simplifying the process of downloading and processing large amounts of daily minimum temperature data has been another methodological challenge.

The voluminous management of hundreds of observatories was a considerable problem, and the NetCDF raster format was not easy to process on a desktop GIS such as *QGIS* or *SAGA*. Although NetCDF is a standardized format that facilitates the representation of data of this type through a temporal and visual dimension, our purpose was to use this information for mathematical and geostatistical calculation. The solution required facilitating the download and conversion of these ASCII or NetCDF formats to data tables from a *PostGIS* geodatabase.

Docker geotechnologies have helped to solve these problems, facilitating the reproducibility and automation of the download and database integration processes, as they allow the creation of isolated and portable virtual containers that can be run on different platforms. This means that a Docker *container can be created* in a file that contains all the tools needed to process and analyze daily temperature statistics data, regardless of software compatibility between different operating systems or hardware configurations.

The factor corresponding to the hazard by probability of frost has been calculated according to the internationally standardized probabilistic method, developed by Haan in 1979 (Snyder *et al.* 2010), which is based on the variable of daily absolute minimum temperature, for which there is a spreadsheet that already incorporates the formulation and graphing of the projected and observed data, this is the *TempRisk* spreadsheet, published by the FAO and developed by the University of California, where it obtained good results for minimum temperature data using a probability density function of extreme value type I, expressed in the formula of this cumulative curve:

$$P(T < T_c) = 1 - exp\left[-exp\left(\frac{T_c - \beta}{\alpha}\right)\right]$$

Where $\alpha = \sigma/1.283$, $\beta = \mu + 0.45\alpha$; and μ is the mean minimum temperature and σ is the standard deviation of the minimum temperatures in the recorded years.

Temprisk calculates the probability of the temperature falling below the critical temperature of the crop and determines the certainty of frost occurrence at least once during the time series analyzed. This is the fundamental reason for deriving the calculation from the database to the formula established by this spreadsheet, to reproduce the usual handling of many users, since it is a common and well-known tool among agricultural technicians and specialists.

3. Development of the case study research

3.1. Calculation of the hazard model

As already explained in the previous point, the fundamental source of information for frost danger is the minimum daily temperature, obtained from two sources of information with different time scales: the *observed* data (from meteorological stations of the AEMET networks and the SIAR network) and the *projected data* (resulting from the of the 5 km x 5 km grid interpolation model of AEMET's daily minimum temperature data), as seen in the map in Figure 2. This 5 km x 5 km grid is updated until December 2020 and has been created with the HIRLAM numerical prediction model, operational in AEMET as initial information or first estimate (HIRLAM-5, 2002), subsequently corrected by the observed data. These data are in NetCDF and ASCII format for free download from the AEMET open data portal (2020), with proven solvency for this type of climate analysis (Amblar-Francés *et al.* 2020), although they require pre-processing to be transformed into formats suitable for analysis in computer environments such as a spreadsheet, *R program*, *PostgreSQL, PostGIS*, *SQLite* or *SpatialLite* databases (Figure 3).

After downloading the data in ASCII format, a single minimum temperature file was obtained for the whole period, with 25 568 records, corresponding to each day of the 70 years of the available series (since 1950), sorted by the date of estimation of the minimum temperature data without geolocation information, as you can see in the example in Figure 4. To complete this data series, an ASCII file of records called '*master*' has been created, each record consisting of four fixed-width fields *(point identifier, longitude, latitude, and altitude* in a non-projected angular coordinate system). This *master file* has 16 156 records, sorted by an identifier field, as you can see in the example in Figure 5. The identifier is an integer in the interval [1,16156] that allows the geolocation of the centroid of each of the grids with minimum temperature data.

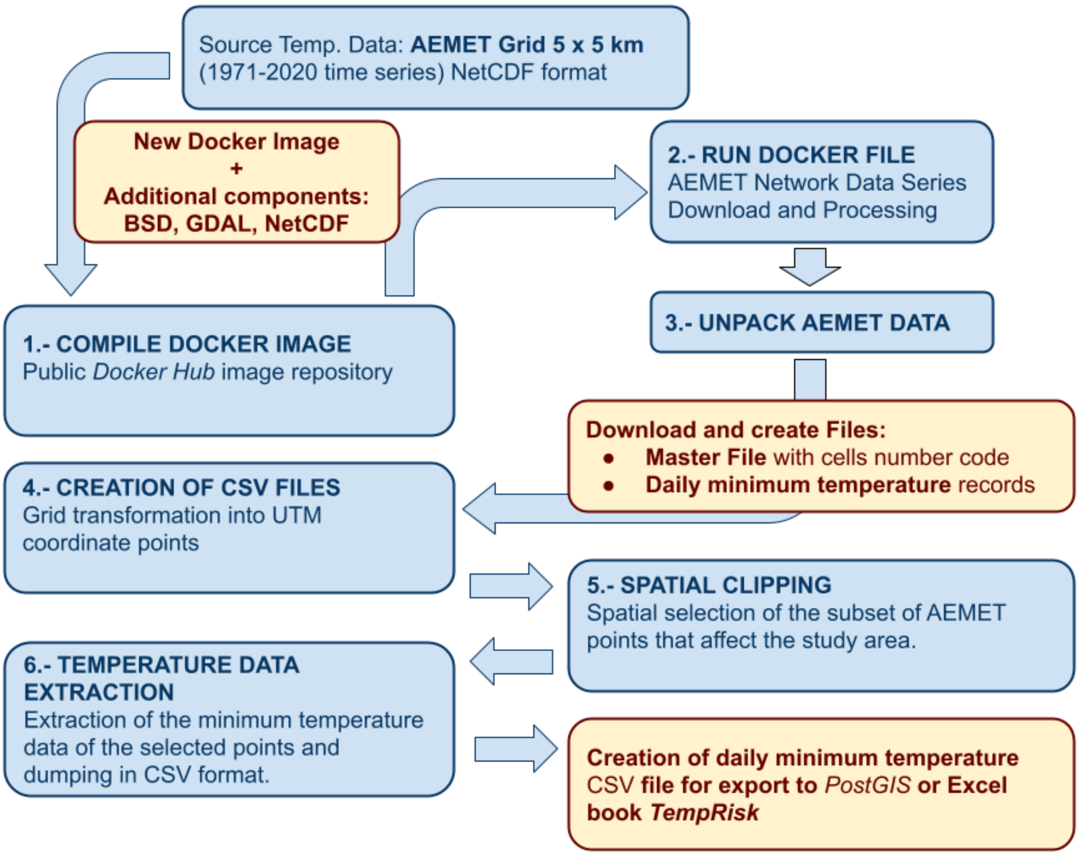

Figure 3. Diagram of extraction and transformation of daily temperature from AEMET data with *Docker Tech*.
Source: own elaboration.

A

19510101	5.62	8.71	7.75	7.59	.....
19510102	8.35	10.82	10.01	9.79	.....
19510103	7.55	8.80	7.67	7.52	.....
.....					
20200630	21.37	19.86	20.00	19.66	.....

B

1	-2.948	35.307	102.
2	-5.323	35.898	58.
3	-5.630	36.049	124.
4	-5.568	36.049	186.
	......		
16156	-7.520	43.740	1.

Figure 4. (a) ASCII Daily Minimum Temperature File Sample: ***COORD_red_hr_tmin.txt*. B) Example of ASCII master file *maestro_red_hr_tmin.txt*.**
Source: AEMET. Authors' own elaboration (2022).

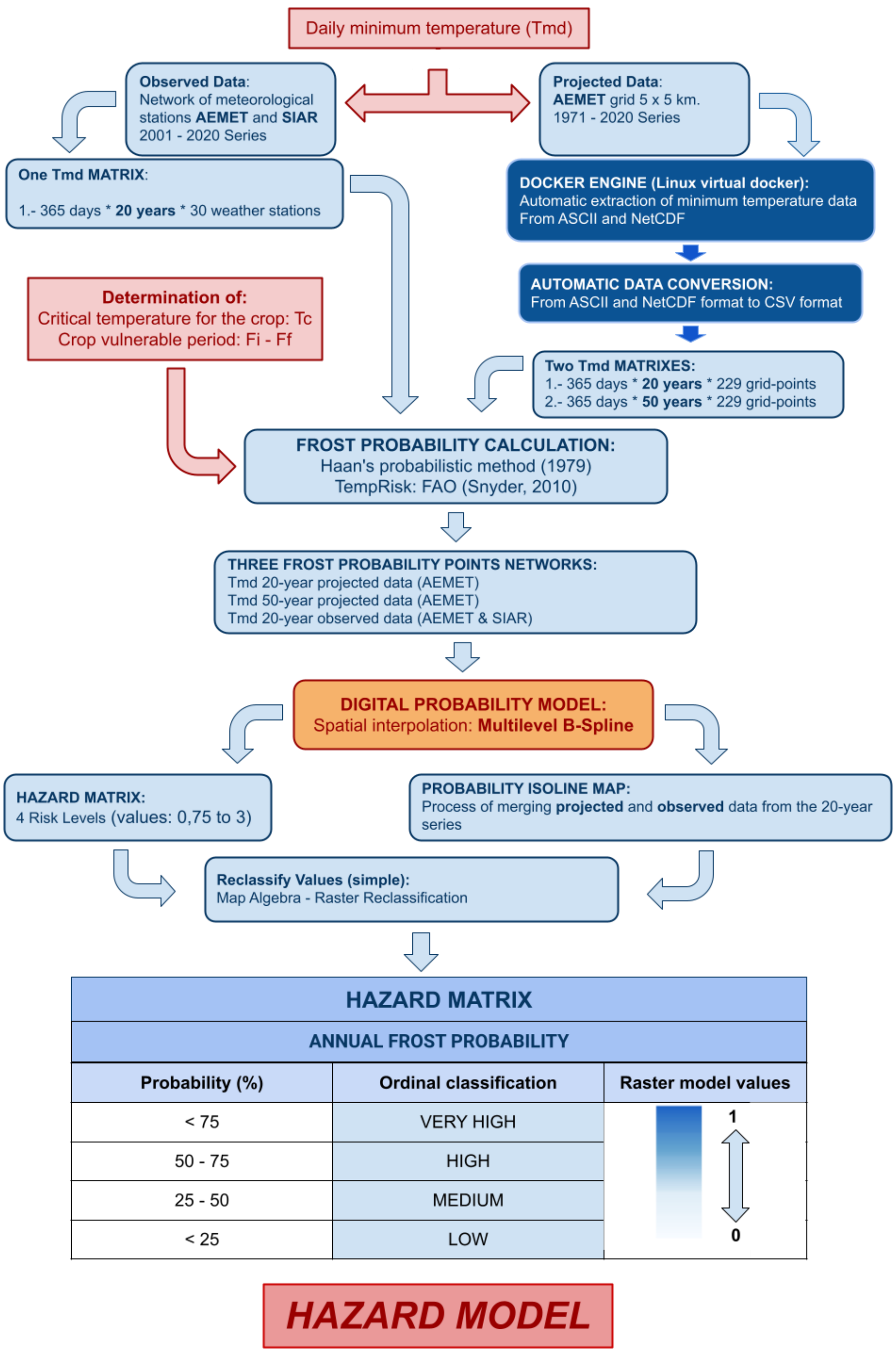

Figure 5. Conceptual diagram for the frost risk calculation in almond trees.
Source: Own elaboration and Pérez (2022)

One of the main objectives of the proposed methodology has been to facilitate the calculation of the risk of frost in fruit trees for the agents involved in the agricultural sector, i.e. farmers, technical specialists or technicians from the public administration. For this reason, the formulation contained in the *TempRisk spreadsheet* (Snyder *et al.* 2010), according to the probabilistic method of (Haan 1979), recommended by the FAO, which facilitates the obtaining of the percentage of probability that the temperature will fall below a threshold critical value for the crop analyzed, according to its sensitivity to damage due to low temperatures. The determination of this critical temperature threshold and the period of dates of interest to be considered in the calculation are carried out according to the characteristics of the study area and the crop. In our case of application, the main varieties of almond trees are sensitive from a thermal threshold of -1 ºC, between January 20 and March 31 for the province of Alicante, according to frost sensitivity data in almond trees (Muncharaz 2017) and *the Agricultural Situation Reports* 2020 of the Ministry of Agriculture. Valencian Government (see Figures 6 and 7).

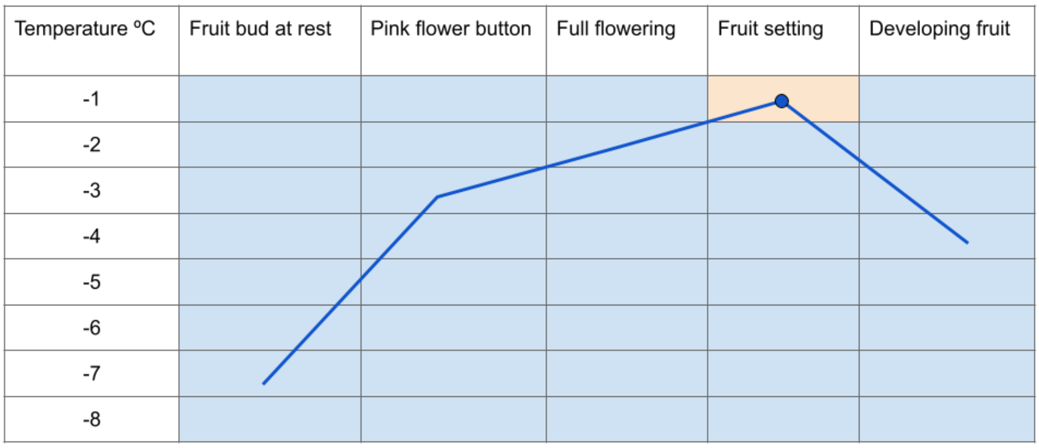

Figure 6. Frost sensitivity according to the development of the almond tree.
Source: Muncharaz (2017). Own elaboration.

Almond tree phenology in Alicante year 2020										
Agricultural County	Variety Type	January			February			March		
VINALOPÓ	Extra - Early			F						
	Early			F		G				
	Late					F				
CENTRAL	Early			F						
	Late					F	G-H			I
MARQUESADO	Early			F			I			I
	Late			B			G-H			I
Most vulnerable phenological stage				Period increased vulnerability to frost						

Phenological stage B: swollen buds
Phenological stage F: flower open
Phenological stage G: petals falling off
Phenological stage H: fruit set.
Phenological stage I: young fruit

Figure 7. Phenology of the almond tree in Alicante.
Source: 2020 Agricultural Situation Reports. Ministry of Agriculture. Generalitat Valenciana. Own elaboration.

To calculate the danger of frost with *TempRisk*, it has been necessary to carry out a pre-treatment from a database (*PostGis-PostgreSQL*), to create materialized views with the points or weather stations of the study area, by means of the corresponding SQL statements, for each of these analyzed stations. The fields are each of the years that make up the analyzed data series, the records are each of the 365 or 366 days that make up those years of the analyzed time series, as can be seen in Figures 8A and 8B.

Once AEMET's ASCII data was adapted for the calculation, Docker data containerization technology was used to automate and facilitate the automation of these processes, using a virtual container for Linux (*dockerfile*) that simplifies the extraction, transformation, and massive processing of daily temperature of open repositories of climate data, such as those of the State Meteorological Agency. This facilitates the reproducibility of the method and its possible application to the extraction of any study area in Spain (Navarro, 2023), starting from the definition of the study area with a pair of geographical coordinates, the download of the data in ASCII format and its integration into a *PostGIS* database with the minimum temperature data necessary for the research (Figure 8, A sample).

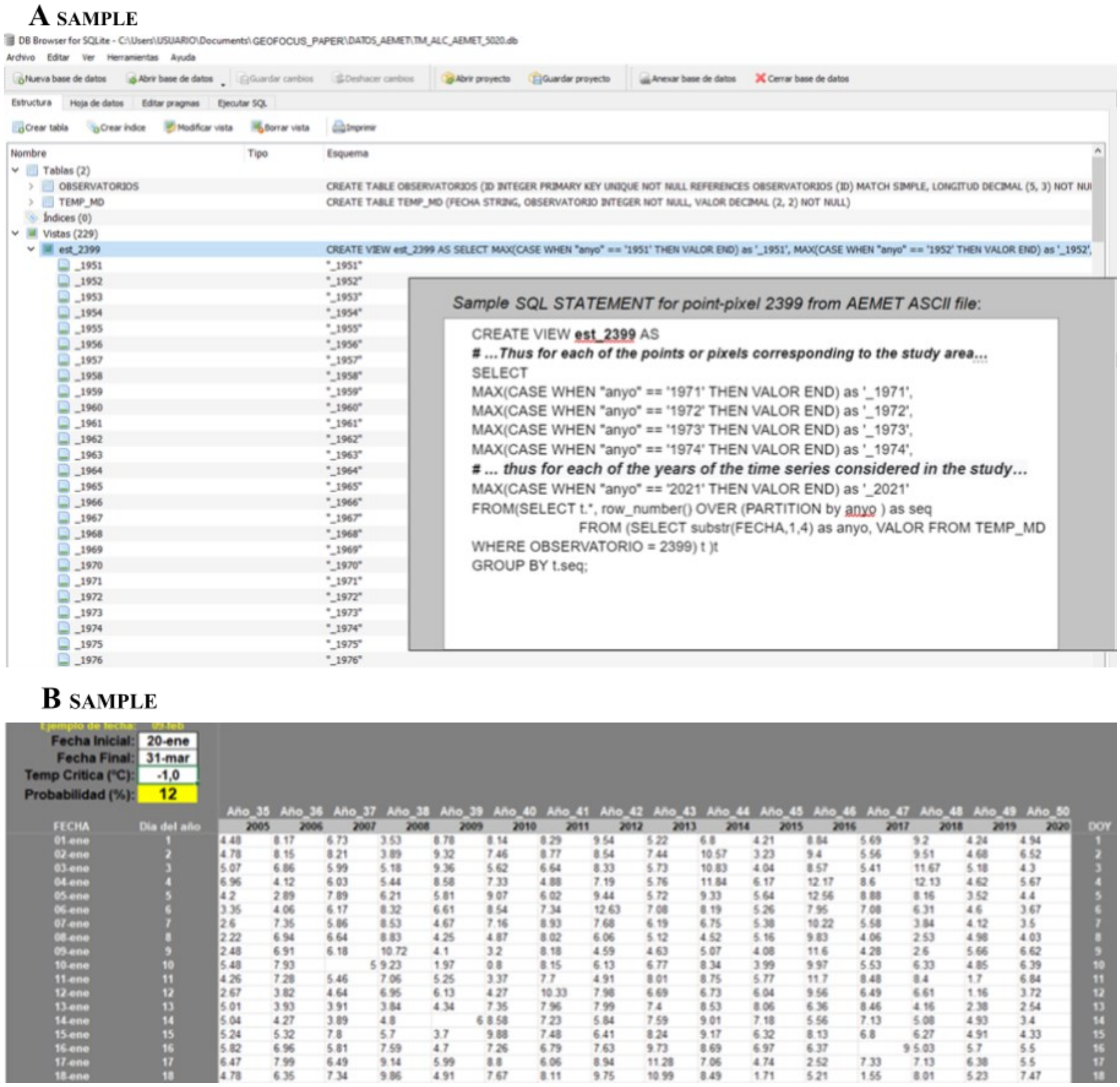

Figure 8. (a) Sample of SQL statements to process the temperature data for pixel # 2399. (PostGIS view #299). B) Sample TempRisk spreadsheet with data imported from this SQL View.
Source: own elaboration.

Once the projected data from the AEMET daily grid were obtained and adapted, it was possible to calculate the probability of frost using the probabilistic method (Haan, 1979), with the variable of daily absolute minimum temperature (*Tmd*) from the projected and observed data. The use of a long series of years is frequently associated with greater accuracy of the probability estimate, although a minimum of 20 years of daily data is required for reliable analysis. Therefore, the probability of frost was calculated for the study area with two different time periods: 20 or 50 years, to check the difference in the results. This was done with the data projected in grids of the daily AEMET network, from which 229 *stations* (locations) were obtained, completing 50 years with complete and uniform data. The temperatures of the AEMET and SIAR meteorological stations (observed data) only allowed the completion of 30 stations (the real stations), with only 20 years of observation, from the available data series. Finally, the dates of the period to be evaluated (January 20 to March 31) and the critical temperature (-1 ºC) are the parameters that were used in *TempRisk*, as can be seen at the top of Figure 8, B sample.

The results of the frost probability calculation were geolocated from CSV delimited text files, with geographic coordinate values for each pixel or weather station in the study area. In addition, an assessment was made of the different hazard interpolation models obtained, according to the temporal duration of the series analyzed or the origin of the data processed with QGIS-SAGA: 20 and 50 years of AEMET and the series of 20 years observed of the (SIAR/AEMET), as can be seen in tables 1, 2 and 3. The objective was to compare the three frost probability models, in order to obtain the most suitable model, as can be seen in Figures 11 and 12 of the research results section.

Table 1. Annual probability of frost based on projected daily minimum temperature series data for a 20-year period.

VALUES	WEATHER STATIONS (AEMET CODE)	ANNUAL PROBABILITY (t<-1°C)	AGRICULTURAL COUNTIES	MUNICIPALITY
Minimun	2800	3 %	Meridional	Torrevieja
	2601			Orihuela
Maximun	4187	**94 %**	Montaña	Alcoi

Table 2. Annual probability of frost based on projected data from daily minimum temperature series for a 50-year period. Source: AEMET and Pérez (2022)

VALUES	WEATHER STATIONS (AEMET CODE)	ANNUAL PROBABILITY (t<-1°C)	AGRICULTURAL COUNTIES	MUNICIPALITY
Minimun	2800	2 %	Meridional	Torrevieja
	2601			Orihuela
Maximun	4187	**95 %**	Montaña	Alcoi

Table 3: Annual probability of frost based on observed data from daily minimum temperature series for a 20-year period. Source: AEMET, SIAR and Pérez (2022)

VALUES	WEATHER STATIONS (AEMET/SIAR CODE)	ANNUAL PROBABILITY (t<-1°C)	AGRICULTURAL COUNTIES	MUNICIPALITY
Minimun	A 15	3 %	Marquesado	Altea
	A 12		Meridional	Pilar de la Horadada
Maximun	8008 - A 19	**96 %**	Vinalopó	Villena

Source: AEMET and Pérez (2022).

3.2. Calculation of the exposure model

The Valencian Cartographic Institute and the Regional Ministry of Territory of the Valencian Government have been in charge of developing and maintaining an open geodatabase with the classification in decreasing classes of land use capacity, resulting from the evaluation of limiting factors for agriculture, such as erosion, slope, effective thickness of the soil, rocky outcrops, stoniness, salinity, physicochemical properties and hydro-morphism (Antolín *et al.* 1997, Sanchez 1998).

This assessment of the agrological productivity capacity has allowed us to establish the zoning of the most suitable areas for the potential development of almond cultivation, establishing 5 levels ordered from highest to lowest capacity (see Figure 9). The starting assumption is that the greater the agrological capacity of the land use, the greater the potential presence of almond trees and, therefore, the greater the exposure to frost risk in these areas. The modelling was obtained by downloading the open data on land use capacity, converting it into a raster layer for the study area, and then reclassifying it according to the values shown in the table in Figure 9, with the exposure matrix, which translates the ordinal values to numerical values. between 0 and 1, with 5 exposure levels, suitable for use in the analysis process in QGIS and SAGA.

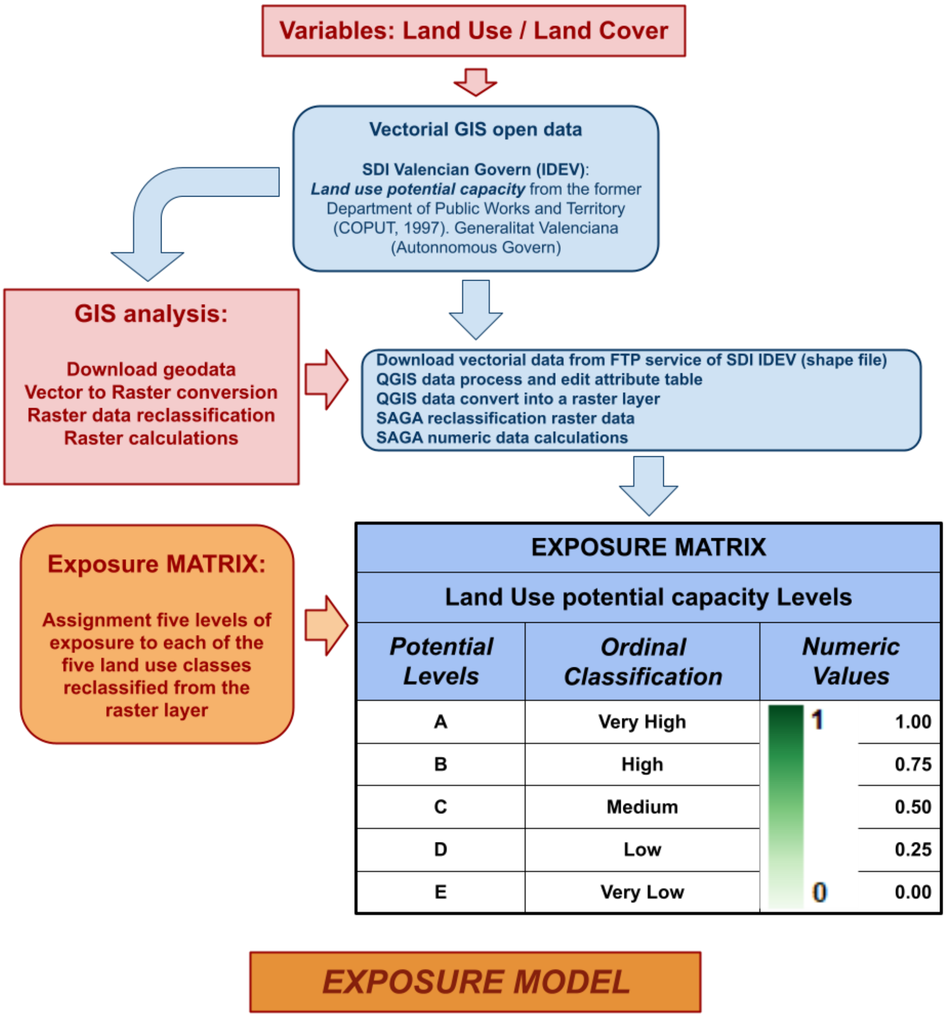

Figure 9. Exposure modelling scheme with reclassification matrix table.
Source: own elaboration.

3.3. Calculation of the vulnerability model

There are hardly any specific references or background on the application of GIS-based analysis to the frost vulnerability of almond trees (Pérez Morales 2016 and Espín Sánchez 2021). For this reason, physiographic factors derived from slopes and guidelines for vulnerability assessment have been considered, as in the few reference studies on vulnerability (Pérez Morales 2016 and Espín Sánchez 2021). An intuitive and easy-to-implement valuation method has been sought, as we have been able to confirm in many bibliographic references (Rivera *et al*. 2013, Simbaña 2014).

The slope and aspect data used to obtain the vulnerability have been calculated from a DEM with a spatial resolution of 200 meters, adapted to the regional and provincial scale of the objectives of the study, based on the official geodata of the National Center for Geographic Information of the National Geographic Institute (CNIG-IGN), prepared from the thematic class of the *terrain,* derived from the lidar point cloud obtained in the flight of the second coverage of the National Aerial Orthophotography Plan (PNOA).

The slope can be essential when establishing almond plantations, because cold, denser air tends to occupy the lower levels of the relief. This means that the steeper the slope, the lower the frost vulnerability (value 0), while in areas with low slopes, the accumulation of cold air increases vulnerability (value 1). Finally, to calculate and assess the slopes, an interpolator based on the *Horn or Sobel Operator Method has been made*, as it is the most versatile application (Castillejo *et al*. 2006).

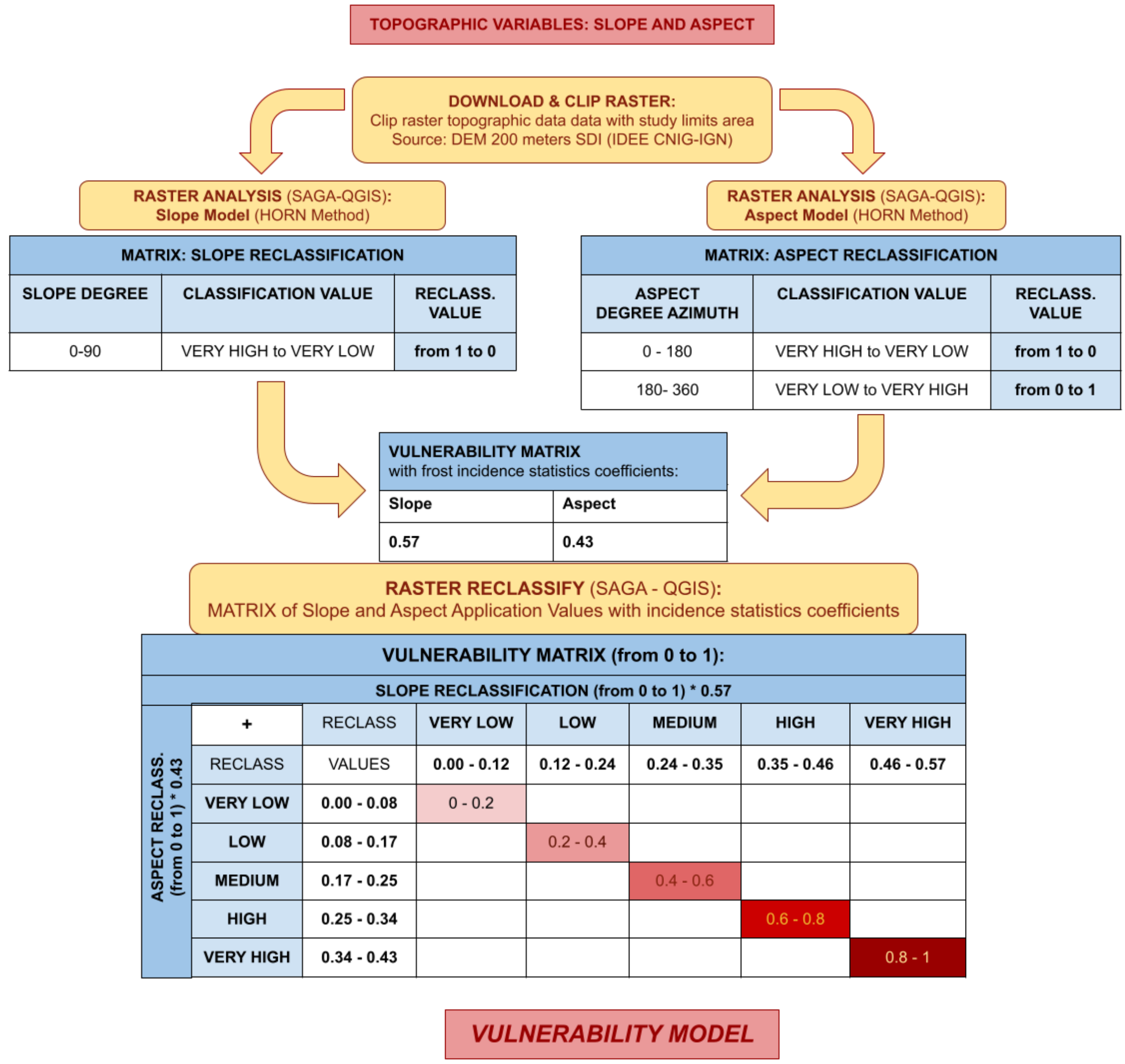

Figure 10. Conceptual scheme for the calculation of frost vulnerability according to the influence of topographic factors.
Source: own elaboration.

Aspect is also an important factor influencing frost vulnerability. In general, south-facing plots are less vulnerable to frost, as they will receive more solar radiation during the day. Therefore, it is assumed that a north orientation (*shady*) is more vulnerable to frost than a south orientation (*sunny*). For the calculation of aspect, the same *Horn method* has also been used, resulting in values from 0 to 360 degrees. The aspect model has been reclassified following the previous assumption, valuing the north-facing slopes as more vulnerable to frost (value 1), while the lowest vulnerability (value 0) corresponds to those facing south, as can be seen in the table corresponding to the aspect assessment matrix in Figure 10.

As no references were found on the determination of weights for these physiographic values in this study area, a statistical coefficient based on the incidence of topographic factors in frost events in almond trees registered in the province has been used. For this purpose, a percentage calculation has been made of the incidence of these two variables (slope and aspect) as a function of a climatic index of the frequency of the average number of days of frost per year of the AEMET stations analyzed located in these areas, if there is at least one day of frost per year. In stations with more than 1 day of frost per year, the result was a slope incidence factor of **0.57** and **0.43** for aspect. According to the criteria analyzed, as can be seen in tables 4 and 5, the two factors do not have the same weight, with the influence of slope being more important than aspect, with a total difference of 14 percentage points, as shown in the table with the priority matrix in Figure 10.

Table 4. Index of annual frost days in AEMET meteorological stations with very high susceptibility to frost according to slope.

WEATHER STATION CODE	LOCATION NAME	ALTITUDE	UTM LONGITUDE COORDINATES	UTM LATITUDE COORDINATES	NUMBER OF FROST DAYS PER YEAR
8021A	AGOST ESCUELA NACIONAL	306	706079	4256846	8
8025	ALICANTE	81	718904	4250120	1
8019	ALICANTE-ELCHE/AEROPUERTO	43	712468	4239983	1
8003A	BENEIXAMA CASA CRESPO	661	694493	4285275	40
8036B	**BENIDORM (AQUAGEST)**	**70**	**749812**	**4270925**	**0**
8043	BENISSA CONVENTO	275	764807	4289402	1
8027A	CASTALLA ALFAS	612	706274	4273756	34
8018A	**ELCHE**	**95**	**701719**	**4238104**	**0**
8018	ELCHE CAMPO D AGRICOLA	63	701604	4235880	1
8011A	ELDA (AYUNTAMIENTO)	410	692687	4261881	13
8048E	GATA DE GORGOS	79	768344	4296405	1
8050E	JAVEA AYUNTAMIENTO	15	775167	4297534	8
8013X	NOVELDA	230	695835	4251099	1
7244X	ORIHUELA DESAMPARADOS	26	677074	4215260	5
8057A	**PEGO CONVENTO**	**70**	**750412**	**4302639**	**0**
7247	PINOSO C H SEGURA	575	671237	4252574	19
7247E	PINOSO IES	575	671322	4251990	34
8008A	VILLENA	486	685931	4271992	61
8006I	VILLENA (LA VEREDA)	533	681084	4284959	48

Source: Pérez (2022)

Table 5. Index of annual frost days in AEMET meteorological stations with very high susceptibility to frost according to aspect.

WEATHER STATION CODE	LOCATION NAME	ALTITUDE	UTM LONGITUDE COORDINATES	UTM LATITUDE COORDINATES	NUMBER OF FROST DAYS PER YEAR
8041I	BENIMANTELL POLIDEPORTIVO (1)	615	742430	4284183	23
8043G	**CALP PEÑON DE IFAC**	**60**	**767575**	**4281161**	**0**
8011A	ELDA (AYUNTAMIENTO)	410	692687	4261881	13
8057A	**PEGO CONVENTO**	**70**	**750412**	**4302639**	**0**
7247E	PINOSO IES	575	671322	4251990	34
7261I	ROJALES EL MOLINO	31	700365	4218051	0,7
8056C	VALL DE LA GALLINERA-PATRO (2)	450	737791	4300152	6

Source: Pérez (2022)

4. Results: mapping risk model

4.1 Digital Hazard Model

Obtaining the hazard model, as explained in the research development section, offers several possibilities, depending on the time series applied or the network of observatories chosen, as shown in Figure 11. If we look at the results of the extreme values, there are practically no significant differences, as can also be seen in the data in Tables 1 and 2. Despite this, there is a slight trend towards polarization over the 50-year series, with an increase in the probability of frost in continental and colder areas, while it tends to decrease in the southern, more coastal and warmer areas (see table 2). However, there are hardly any noticeable differences between the use of 20- and 50-year series (see maps A and B in Figure 11).

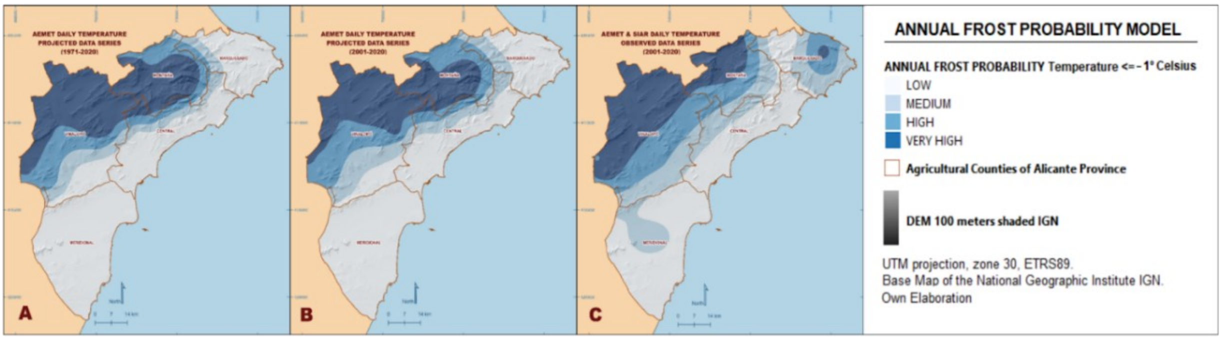

Figure 11. Annual comparative frost probability models.
Source: A) 50-year series of projected daily temperature data from AEMET (1971-2020); B) 20-year series of projected daily temperature data from AEMET (2001-2020) and C) 20-year series of observed daily temperature data from AEMET & SIAR (2001-2020). Own elaboration.

Comparing the projected data (AEMET grid) with the observed data (AEMET/SIAR network), the results of the range and the maximum and minimum extreme values are very similar, indicating that there is consistency between the data from the different sources, but important anomalies are detected in areas conditioned by relief. with the appearance of areas of high probability of frost that do not appear in the HIRLAM predictive interpolation models of the projected AEMET data (Map C in Figure 11). In fact, the model obtained from the observed data from AEMET/SIAR offers two frost danger zones in the valley of the river Segura and in the coastal plain of Denia (see the maps of frost probability isolines of the maps in Figure 11, especially the differences between map C and maps A and B.

In conclusion, the projected data offer us a greater coverage and a better definition in the isoline models, while the observed data provide a greater correction on the variations imposed by the physiography of the land, due to its location closer to the cultivation areas (especially the network of SIAR stations), with the identification of zones probability of frosts clearly caused by orographic influence, so we proceeded to combine the 20-year series of projected and observed data to obtain the most complete scenario capable of representing the most adverse situation with respect to frost danger. The map in Figure 12 represents the result of this fusion of the observed and projected data from the 20-year series to model frost danger, as it is considered the most appropriate and realistic option.

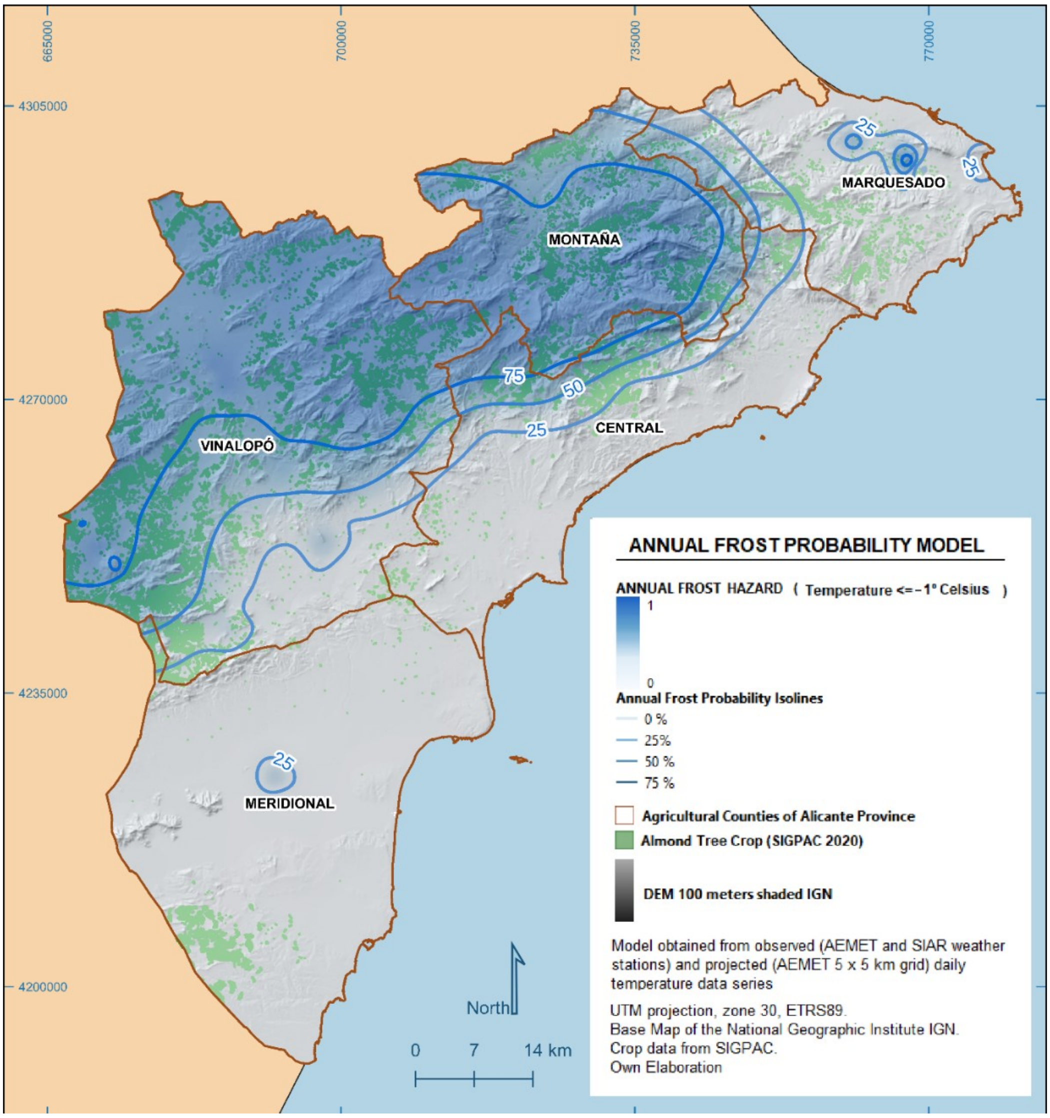

Figure 12. Annual frost probability model (daily temperature <= -1 ºC).
Source: observed data from the AEMET and SIAR network of meteorological stations and projected data from the AEMET network. (2001-2020). Authors' own elaboration.

4.2 Digital Exposure Model

The map in Figure 13 shows the result of the exposure model, according to the application of the potential exposure assessment criteria that have been calculated from the data on agricultural capacity for land use, as explained in the section corresponding to the development of the research, which is shown graphically in Figure 9. The exposure model obtained is a model of potential exposure to risk, as it does not only consider the current almond cultivation areas, as shown in Figure 1 on the study area in the introduction section. As can be seen in the map in Figure 13, in the Southern region there are large areas of potential exposure where almond trees are not currently grown, but there is nothing to prevent them from being able to dedicate themselves to this crop in the future.

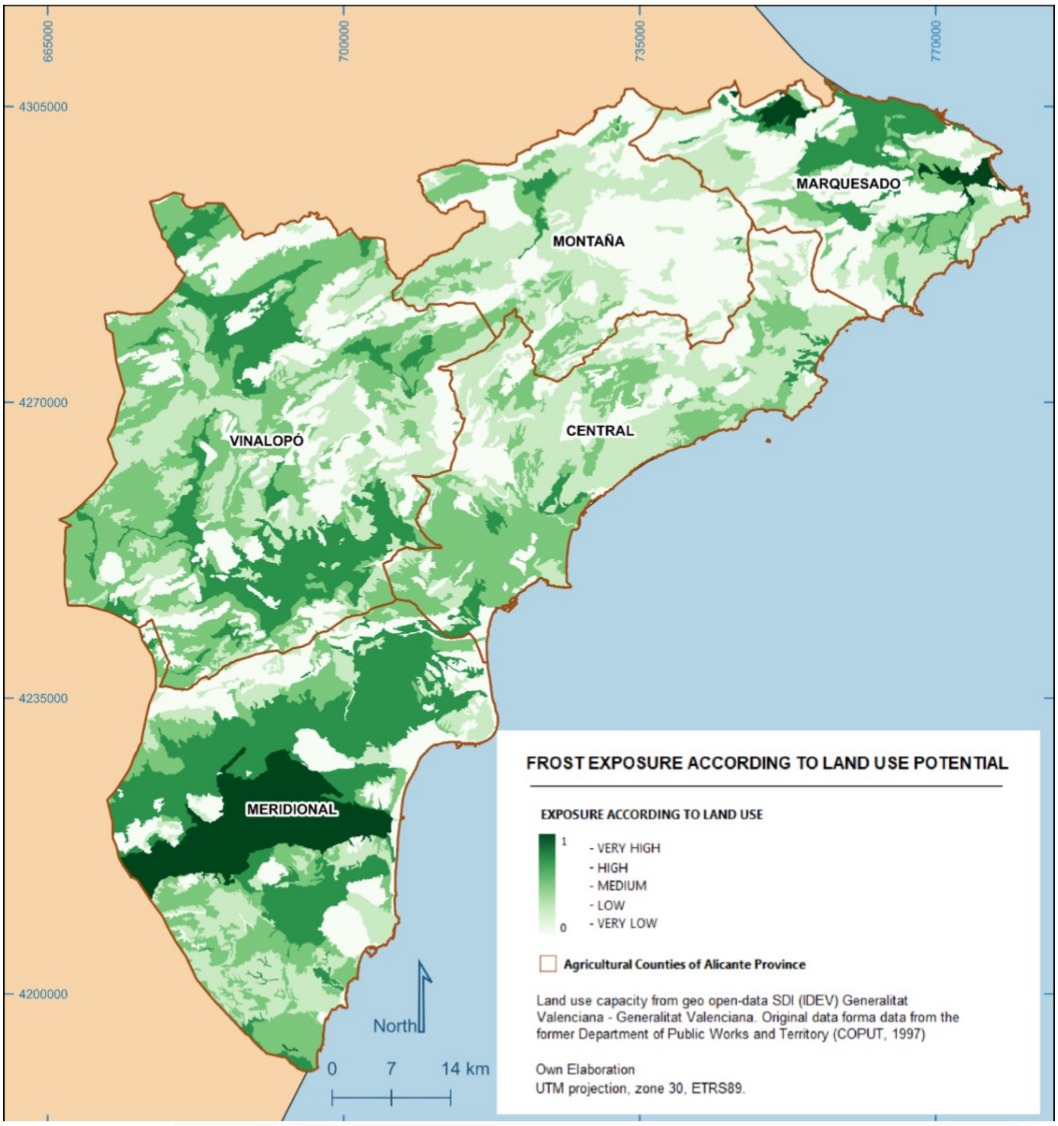

Figure 13. Map of frost exposure according to land use capacity by agrological productivity.
Source: own elaboration.

4.3 Vulnerability model

For the calculation of topographic vulnerability, the digital slope model has been reclassified with qualitative values from 0º - 90º to 1 - 0, applying the assumption that the steeper the slope, the lower the vulnerability to frost.

On the other hand, the digital aspect model has been reclassified according to the azimuth degrees of 0º - 360º, under the assumption of greater vulnerability to frost with a north orientations and less with a south orientations, that is, from 0º - 180º to 1 - 0 and from 180º - 360º to 0 - 1, as can be seen in the diagram of the Vulnerability Model in Figure 10 and in the maps corresponding to the vulnerability Based on the slope and aspect values in Figure 14.

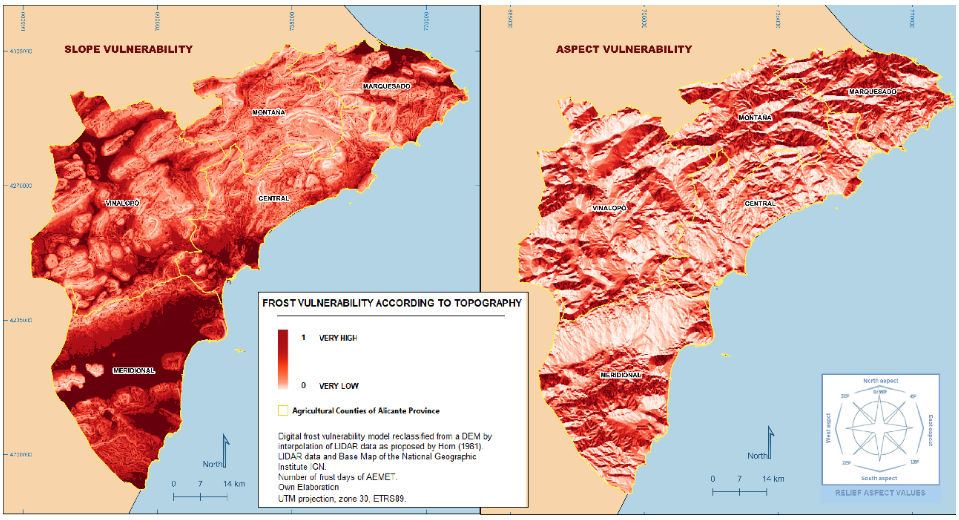

Figure 14: Frost vulnerability according to slope and aspect reclassification.
Source: lidar data from the IGN. Own elaboration.

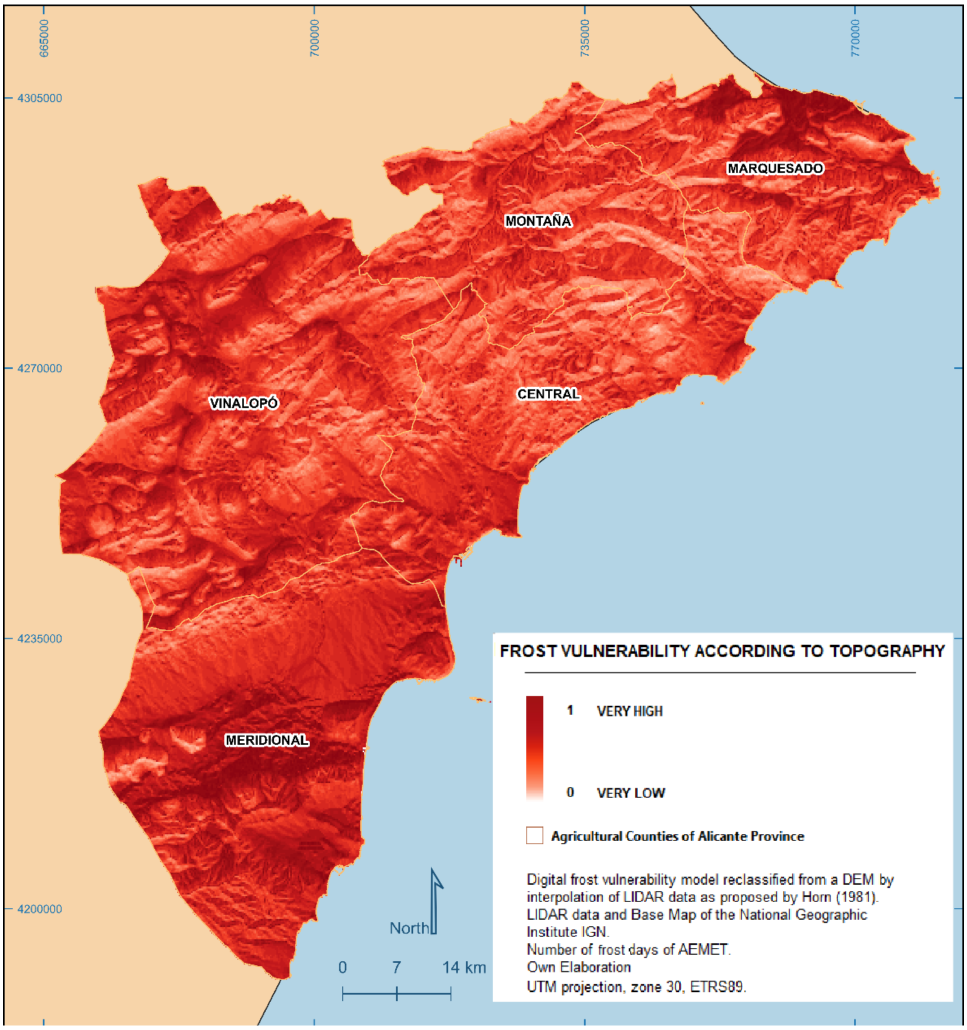

Figure 15. Frost vulnerability according to Relief and topographic conditions (slope and aspect).
Source: lidar data from the IGN. Own elaboration.

Once the digital models of slopes and aspects were obtained, GIS spatial analysis techniques were applied, reclassifying the digital vulnerability model (Figure 15), giving greater weight to the slope as a frost triggering factor with a weighting coefficient 0.57, compared to 0.43 in the aspects, according to the statistical weighting matrix, based on the frost episodes known from the network of meteorological observatories (Pérez, 2022). The weights established by the sum of the reclassified values of both criteria are shown in the vulnerability matrix table at the bottom of the vulnerability model calculation diagram in Figure 10.

4.4 Final Frost Risk Model Estimate

Once the raster models of hazard, exposure and vulnerability have been obtained with GIS-based spatial analysis, we use map algebra to integrate the analysis of the hazard of the hazard of the case. To calculate the Final Risk Model, a method of combining the results obtained in the different risk components in QGIS with the raster calculator has been used to integrate them into the final values of each pixel, as shown in Figure 16, following the example of other previous works close to our area of study (Espín 2021).

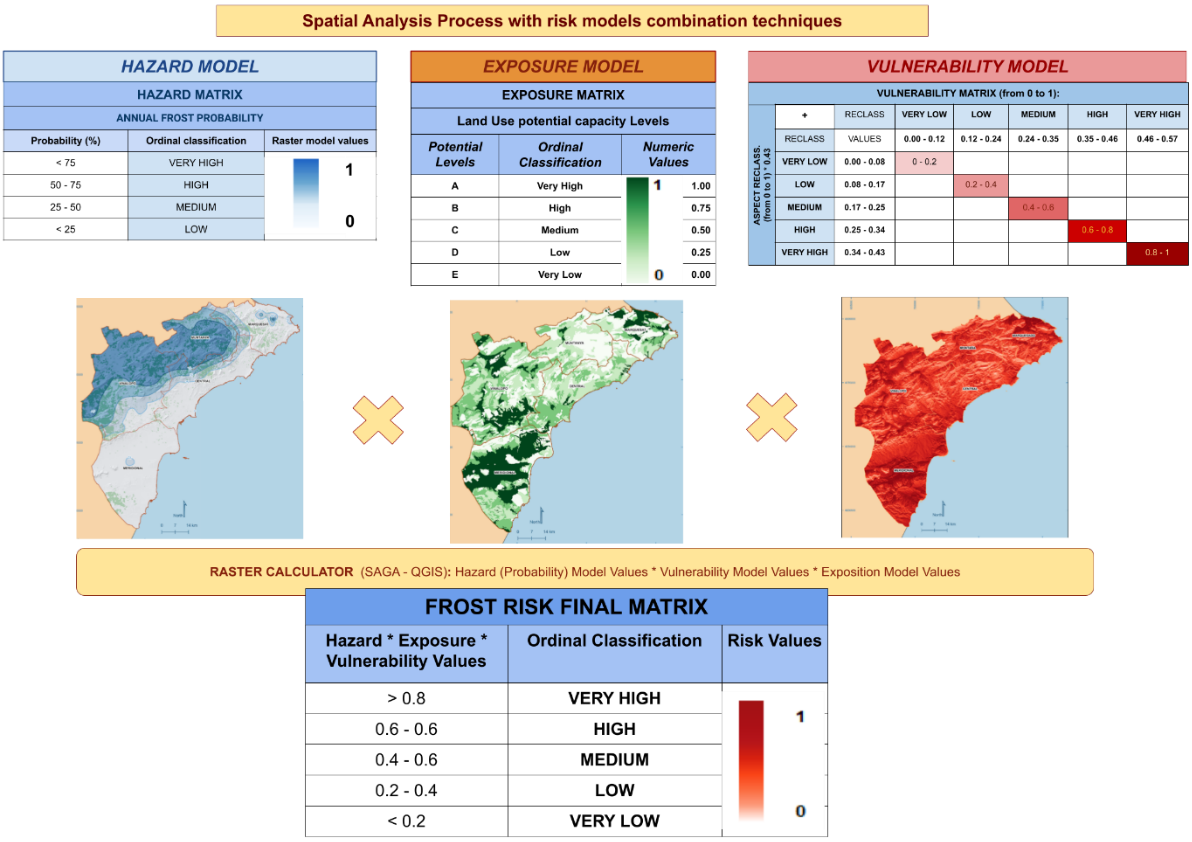

Figure 16. Conceptual scheme for the **calculation of the digital frost risk model.**
Source: own elaboration.

The final values were reclassified into 5 classes, to facilitate their thematic representation, if necessary, but in the map in Figure 17 the original resulting values have been preserved, without reclassification (from 0 to 1), according to the risk reclassification matrix in the scheme in Figure 16. A red ramp has been used for the map of the final risk model, with the most intense red color for the highest risk values, as shown in Figure 19. The result at the provincial level offers a general perspective of the study area at the provincial level, but it can also be useful at a regional and even municipal scale, if we take into account the characteristics of the geographic information sources used and the spatial resolution of the output raster model (50 meters), which allows a 1:50 000, i.e. suitable for the spatial planning of agricultural areas on a more detailed scale than the research objectives set (see the detailed map in Figure 17).

The Vinalopó region concentrates 65% of the almond cultivation area in the province of Alicante and the detailed map in Figure 17 corresponds to a specific area of this region, the surroundings of

Castalla, where we can check quite accurately the overlap of crop plots with frost risk areas with *High* or *Very High* value of the risk model. In view of the results, the maps obtained for the case study demonstrate its usefulness for planning and prioritizing the implementation of risk mitigation or prevention measures, such as the installation of frost protection systems, the use of more appropriate irrigation techniques, and even, the spatial selection for fruit tree varieties, according to their resistance to frost, as recommended by the Law on Agricultural Structures of the Valencian Community (Law 5/2019 of the Valencian Government) for the preparation of the Valencian Agronomic Map.

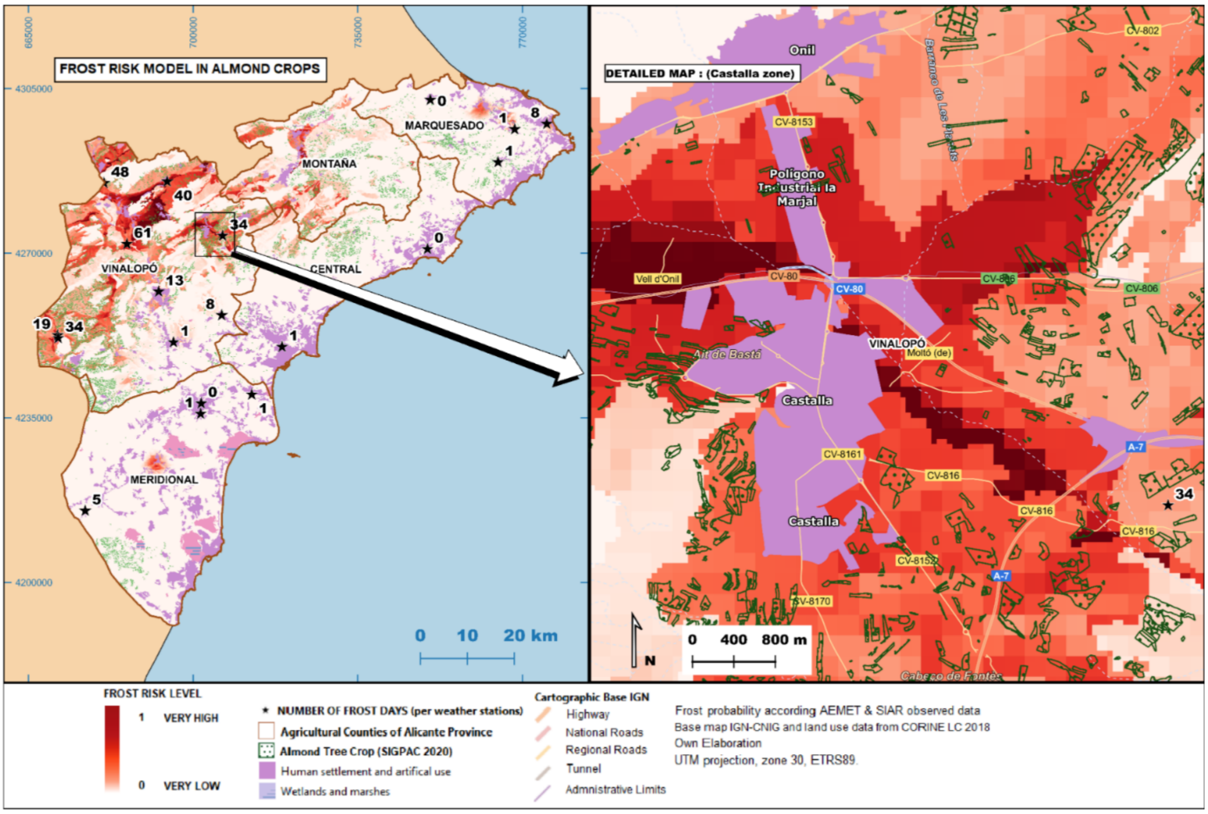

Figure 17: Results of the application of the proposed frost risk model to the almond crops of the province of Alicante and a detailed map of the risk model obtained for the town of Castalla.

Source: Own elaboration

5. Discussion

The effects of climate change seem to mark a trend to reduce frost in April, according to the records of the last 20 years, which has led to an intensification of almond cultivation with the spread of almond cultivation of new plantations in areas of intensive irrigation with late varieties to avoid frost. However, these thermal trends are causing an earlier flowering, which also affects the traditional late varieties, while the climatic data also show a greater intensity of the frosts in February and March, coinciding with the phenological stage H (*freshly set fruit* in Figure 7) with greater sensitivity to cold.

The minimum daily temperatures of the years analysed for this study area show a reduction in the probability of frost, but an intensification of this for cold areas of the interior, as in the case of those shown in the map in Figure 17, with the consequent increase in significant economic losses. The validity of the model obtained (Figure 17) has been carried out in the most affected agricultural region (Vinalopó) and in the municipalities most damaged by frost from 2011 to 2022, according to data from *Agroseguro* (2011-2019) and the Department of Agriculture of the Valencian Government (year 2022). In the validation, historical data have been used on the percentage of municipal area affected by frost with guaranteed production losses since 2011 or area damaged in the 2022 frost (see table 6), demonstrating a high coincidence between the areas in which the final model indicates the highest risk value and the losses caused by frost in the period analysed with these sources. The plots of farms affected by frost could not be included in this study, as they did not have authorization from *Agroseguro* for their publication, they have only allowed the use of data on the area affected by municipalities. In this sense, validation methods can and should be improved in the future, using other data sources and fieldwork, but the current results already show a risky trend of agricultural policy with respect to this crop that would be very necessary to prevent.

Obtaining a digital frost risk model in fruit trees, based on a very complete factorial consideration of hazard, exposure, and vulnerability, offers us a rather unprecedented approach in studies on agriculture and climate risks in this geographical area, considering the previous work of Espín (2021) or Snyder *et al.* (2010), which establish calculations of the probability of frost in crops or that apply methods to obtain frost hazard maps for citrus fruits in the neighboring Region of Murcia using GIS techniques (Erena *et al*. 2017). These references have been very useful for the definition of our digital frost risk model, so we have tried to innovate in the methodology by combining open, official, varied, voluminous and complex data sources. A good example are the daily series of minimum temperature based on the data observed in the meteorological stations of the AEMET and SIAR networks, on the one hand, and the data projected in the daily networks by AEMET that are used for the Climate Change scenarios.

Table 6: Validation of the frost risk model with municipal data in the Vinalopó region (2011-2022). Sources: *Agroseguro* and Valencian Department of Agricultura. Own elaboration

RISK MODEL VALIDATION IN THE VINALOPÓ COUNTY				
Municipality	Almond crops surface (ha)	1 - Production damage (2011 - 2019) %	2 - Crop surface damage (2022) %	3 - Municipal surface with Frost Risk % (model value > 0.75 = *HIGH or VERY HIGH* risk)
SALINAS	866.32	60.31	91	75
BIAR	309.90	68.54	100	80
ONIL	313.00	68.62	100	84
CASTALLA	916.00	76.80	86	88
BENEJAMA	121.92	85.05	100	87

1 - Data source from Agroseguro, years 2011 to 2019.
2 - Data source from Department of Agriculture of the Valencian government (year 2022)
3 - Percentage of surface with *high risk value*, according to the frost risk model obtained in the research

Source: *Agroseguro* and Valencian Department of Agricultura. Own elaboration

The innovative aspect of the processing of these voluminous data sources solves problems of temporal and spatial length of the observed data, which has allowed us to obtain digital frost risk models with a spatial resolution very suitable for crop management studies at the county, regional or national scale. Therefore, the cartographic product resulting in this article is adapted to the needs of the future *Agronomic Map* contemplated in the Law on Agricultural Structures of the Valencian Community (Law 5/2019, of 28 February), as it appears in Chapter I, with Title II on *Sectoral planning and its tools tags*. However, the use of daily minimum temperature data (projected *grid data*) has posed a methodological challenge for its processing in the *TempRisk program*, due to the characteristics of the ASCII and NetCDF source formats, for a very large time series (50 years) and many of observatories nationwide (16,156 points). To this end, *Docker technology* has simplified the management of the most complex and voluminous data, facilitating the download by determining a geographical boundary, and automating the process of obtaining and converting virtual data tables from a *PostGIS* geodatabase, for calculation with *TempRisk*, as has been done in similar studies (Erena, M. *et al*. 2017). Therefore, the next step in this line of research should be to automate the calculation of the *TempRisk* application by including it in the processes of the geodatabase implemented in the *Dockerfile*.

The B-Spline multilevel *interpolation method* used to obtain the digital frost probability model has offered good results for the case study, respecting the original temperature values, and avoiding the need to cross-validate the resulting data. From this point of view, it should be noted that, thanks to the model obtained with the observed data, two danger zones have been differentiated that did not appear in the modelling carried out from the projected data, which has justified the calculation of the probability of frost with the union of the series of years of projected and observed data. Figures 11 and 12 show how increasing altitude and continentality lead to an increased probability of frost in the analyzed area. This result coincides with that of the annual frost probability map (AEMET, 2015) made with the temperature data available in the National Climatological Data Bank of AEMET, using an interpolation made with Universal Kriging with external drift, in which altitude and distance from the coast were considered as external variables (Martínez et *al.*,2014). In the case study, it has been very interesting to include data from the IVIA-SIAR meteorological observation network in the calculation of frost probability, since it is a network of observatories with a geographical location closer to agricultural production areas.

The variables considered to model vulnerability, such as slope and aspect, have been used to obtain a useful model, despite the scarcity of bibliographic references in this regard. It is true that the weighting of these variables (slope and aspect) can be studied in greater depth, which is why we have chosen to give a vulnerability assessment based on the percentage of the number of annual frost events applied to the study area. A climatic index has been created of the incidence of each of these topographic factors on the average number of annual frost days (AEMET) in the areas with the highest risk of frost (where at least one frost occurs per year). In this sense, the difference of 14 percent points in favor of the slope variable importance, has made it possible to establish a weighting coefficient for these factors of the vulnerability model. Thus, in areas where there is a discrepancy between the projected and observed data, this model confirms that there is a greater correlation between the orography assessed as vulnerability and the probability of frost calculated with the observed AEMET-SIAR data (see maps in Figures 11 C and 15). The conflict areas are located below the level of 200 m and relatively close to the sea, but do not offer a low probability of frost, because a low topographic level and a north orientation expose them to the accumulation of cold air, as occurs in the depressions of Catral. or in the exposed foothills to the north of Denia, Ondara or Jávea.

When selecting the information resources for the development of the exposure model, it was decided to simplify the analysis by using criteria based on official and open sources, which has helped to facilitate its reproduction and application to other geographical areas or crops. In this sense, the absence of bibliographic references for the case of application forced us to select information on the current use of the soil for this crop and the consideration of the most suitable soil areas, in view of the prospect of a future increase in the area to be cultivated. However, the criteria could have been expanded to include other economic variables, differentiating between irrigated and non-irrigated areas, productivity, or varietal differences of the crop under analysis. To do this, it would be necessary to start from an exhaustive knowledge of the influence of these factors, so it was considered to model the study area considering only this factor of suitability for cultivation, since it is standardized, open, official, and easily available information for the study area.

5. Conclusions

The methodology used for the development of the digital frost risk model based on GIS spatial analysis, with Docker containerization techniques, has allowed an analysis for the territorial identification and mapping of the risk applied to the almond tree crop in Alicante, thanks to the ability to integrate in a simple way different information resources and thematic criteria that integrate the necessary components in this type of study: hazard, exposure and vulnerability. Thanks to this, the spatial intersection of risk areas with almond growing areas has provided a quantitative assessment of the potential impact of frost risk, demonstrating its applicability to other fruit crops and its usefulness in improving the management of fruit crops threatened by low temperatures in a scenario of adaptation to the consequences of climate change. In this sense, the results of the application to this case study could demonstrate its usefulness for improving efficiency in risk management, facilitating the optimization of financial support measures, such as the justified introduction of tax improvements or improved agricultural insurance coverage (Pérez 2022).

The consistency of the results obtained in the case study has been verified through a double comparison with the data from the main almond producing areas, using historical series on the percentage of areas with frost losses in almond trees. provided by the insurance companies and public institutions involved. However, to validate and improve the methodology, it will be necessary to apply it to other geographical areas, other crops and improve the validation criteria with cartographic and field data. For this reason, it would be very useful to create an open spatial database on a peninsular scale, with data on the probability of frost, according to the crops most sensitive to this type of climate risk, as part of a line of research and dissemination aimed at the creation of interpolation models with greater spatial resolution (Miró 2013).

In the methodology applied, the critical data of temperature and sensitive period are the only ones specific to the almond crop in the hazard calculation carried out with *TempRisk,* the rest of the criteria used to calculate the digital vulnerability and exposure models could be used to Extend the study to other fruit trees. Thanks to the automation of the dockerfile for the calculation of the probability of frost, the development of these hazard models will be facilitated for other fruit trees of interest such as citrus, avocado trees, cherry trees, peach trees and apricot trees, even for other areas at the national level.

This study demonstrates the virtuality of geographic information analysis to improve the management of climate risks in a global warming scenario, as a strategic aspect for reducing its impact on agricultural activity. The open data platforms of official bodies, RFIs and the widespread use of GIS - OSGEO (free open-source GIS) are boosting the usefulness of geoinformation in different thematic and geographical contexts. In the case of application of this article, the ability to analyze frost risk is demonstrated through the integration of geoinformation on hazard, exposure and vulnerability factors, as well as its application in the development of risk mapping, one of the most important objectives of this research. In addition, the second main objective is also met, to facilitate the reproducibility of the methodology applied in the processing of the information, for its application to other fruit trees or areas to be analyzed, thanks to the automation of the processes carried out by Docker Technology.

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