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Role of Integrated Approaches in Water Resources Management: Antofagasta Region, Chile

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Abstract: Water is essential for the survival of all living beings and plays a significant role in the growth of any country's economy. At present, water depletion and pollution are a serious challenge due to anthropogenic, geogenic and climate change activities worldwide, including in Chile. The Antofagasta region is located in northern Chile and is the heart of its mining industry, playing a significant role in the country's economy. The Antofagasta region's main challenge is water shortage and contamination. Due to it, the region's local population is facing major difficulties in obtaining the necessary water for domestic, industrial, irrigation, and other uses. Therefore, a water resources management plan is essential for the region to maintain a sustainable environment. Considering the above points, significant parameters, such as slope, aspect, elevation, hillshade, drainage, drainage density and river basin—maps of the Antofagasta region prepared using the digital elevation model (DEM) data in geographic information system (GIS) environment. Besides, a pollution risk level assessment of the study area's cities/villages done using GIS application. The important created maps and the identification of pollution risk of cities/villages of the present study could provide significant information to policymakers and help them make a suitable water management plan for the area.

Keywords: hydrology; thematic maps; DEM; mines; pollution risk; GIS

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1. Introduction

Chile is an important country in South America for a total covered area approximately equal to 2,919,299 square miles (7,560,950 square km). Located in the southwest of South America, Chile is a narrow strip of land between the Andes to the east and the Pacific Ocean, to the west. Chile has a boundary with Peru in the north, Bolivia in the northeast, Argentina in east, and the Pacific Ocean in the west. Chile is divided into 16 regions and has a diverse climate, such as northern region belongs to world's driest desert with a semi-arid climate, the center region of the country belongs to a Mediterranean climate, Easter Island has humid subtropical climate and east and south regions including alpine tundra and glaciers are belong to oceanic climate [1]. Chile has four significant seasons, summer from January to March, autumn during the April to June, winter during the July to September, and spring during the October to December. Mining, products manufacturing, and agriculture sectors are the main contributor to the Chilean economy. In the Chilean economy, the mining sector is a major contributor, with around a 10% of de GDP [2], and most of the mining areas are in the northern region of the country. In another aspect, the mining and related activities threatens the quality of environmental matrix, including water scarcity in the northern region of Chile [3]. Use of huge volumes of water during the mining and its related processes cause threatens to the supply for water resources for other important uses in life [4]. Consumption of water in the mining industry is estimated to rise in all territory due to an increase in mining developments and a decline in ore concentration,

causing greater processing needs [5]. In 2014, estimated water consumption was 14.8 m^3/s in the copper mining industry, while forecasts showing that it will be increased to around 24.6 m^3/s by 2025 [5]. In addition, the natural and anthropogenic (rapid urbanization, mining, extensive agriculture, domestic disposal etc.) factors are responsible for water scarcity [3,6]. In Chile, the sparsely populated southern region has an abundance of water as compared to the densely populated central and northern regions [7].

A combined approach of remote sensing (RS) data and geographic information system (GIS) can play an essential role in hazard monitoring, natural resources exploration, heritage management, sustainable management of resources etc. [8–12]. Furthermore, integrated RS and GIS application play a significant role in managing water resources, such as groundwater recharge zones identification, water quality monitoring, flood-prone area mapping, and watershed management, among others [9–18]. Therefore, in the recent era, the RS and GIS approach is essentially required to because it can provide essential information to policymakers for taking quick decisions for water resources management of any area.

In the Antofagasta region, water shortage and contamination are a significant problem. Due to them, the region's local habitat faces serious challenges in obtaining water for drinking, industrial, irrigation, and other uses [3,19,20]. A desalination practice has been recognized as a secure source of water to fulfil the water necessity of different uses (DGA in Spanish, Direccion General de Aguas). However, water shortage and contamination are still key concerns, and to achieve this goal, many primary and secondary data information is required. Therefore, the present study's objective encompasses (i) to provide important information on essential hydrogeological parameters derived from a DEM using GIS and (ii) identification of pollution level risk of cities/villages of the Antofagasta region, Chile. The present study could play a significant role in sustainable water resources protection and management in the area.

2. Material and Methods

2.1. Study Area

In Chile, the Antofagasta region is one of the most important administrative division in the sixteen administrative regions and second-largest region of the country with having more than 126,000 km^2 geographical area (Figure 1). The region has three provinces, Antofagasta, El Loa and Tocopilla. It has a border with the Tarapacá region in the north and with the Atacama region in the south and borders Bolivia and Argentina to the east. The region has a population of 402,669 as per the 2015 census. Antofagasta has an average annual temperature of 16.8 °C and July is the coldest month, with an average low temperature of 11.8 °C, and an average high temperature of 16.5 °C [1]. In Chile, the Antofagasta region is called the mining industry's heart, generating 53% of the mining output, led by copper and followed by potassium nitrate, gold, iodine, and lithium in the area.

2.2. Significant Maps Creations

The digital elevation model (DEM) was developed by Shuttle Radar Topography Mission (SRTM), an international research effort, SRTM model was downloaded from the United States Geological Survey (USGC) to create the significant hydrological maps in a geographic information system (GIS) platform. Use of the DEM data in a GIS environment is faster to create many significant features. Therefore, in the present research, DEM data used in a GIS environment to create some important features, such as aspect, elevation, hillshade, slope, basin and stream network and drainage density of the Antofagasta region, Chile (Figure 2). Moreover, Chile's geological map has been collected from the National Geology and Mining Service, Santiago, Chile, and the Antofagasta region's geological map was acquired using GIS.

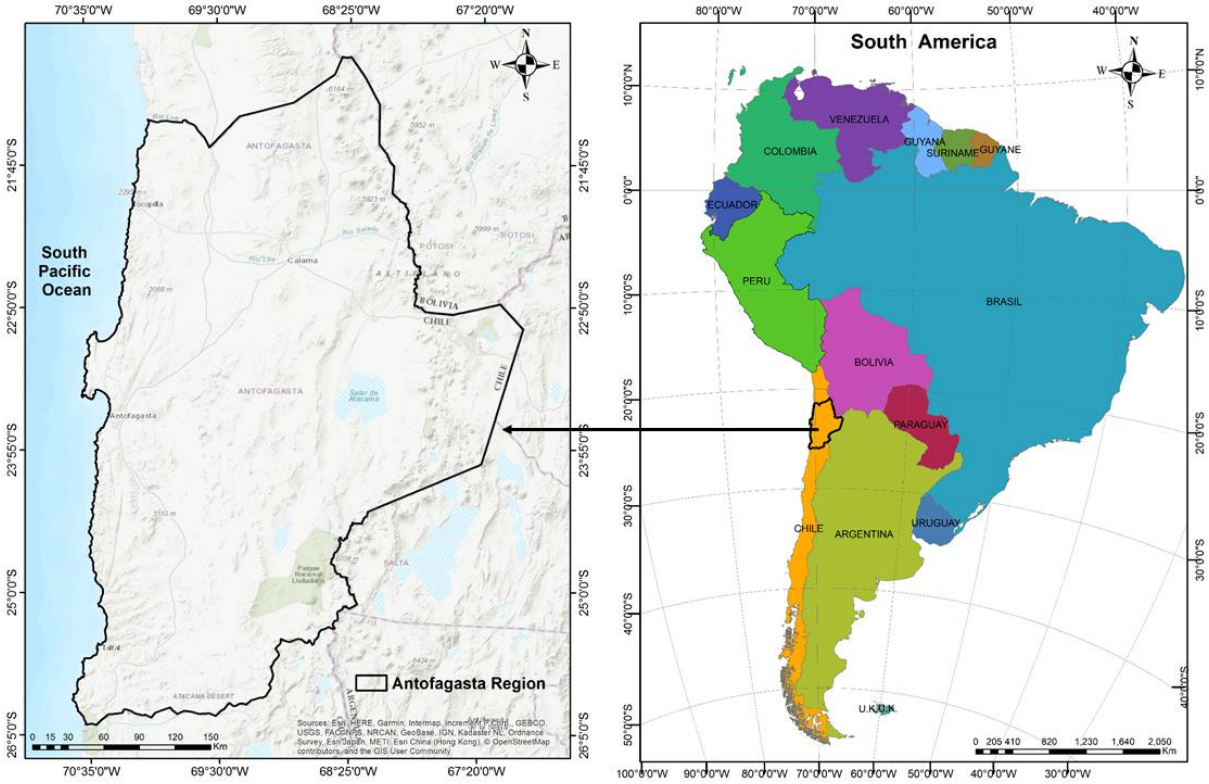

Figure 1. Location map of the Antofagasta region, Chile.

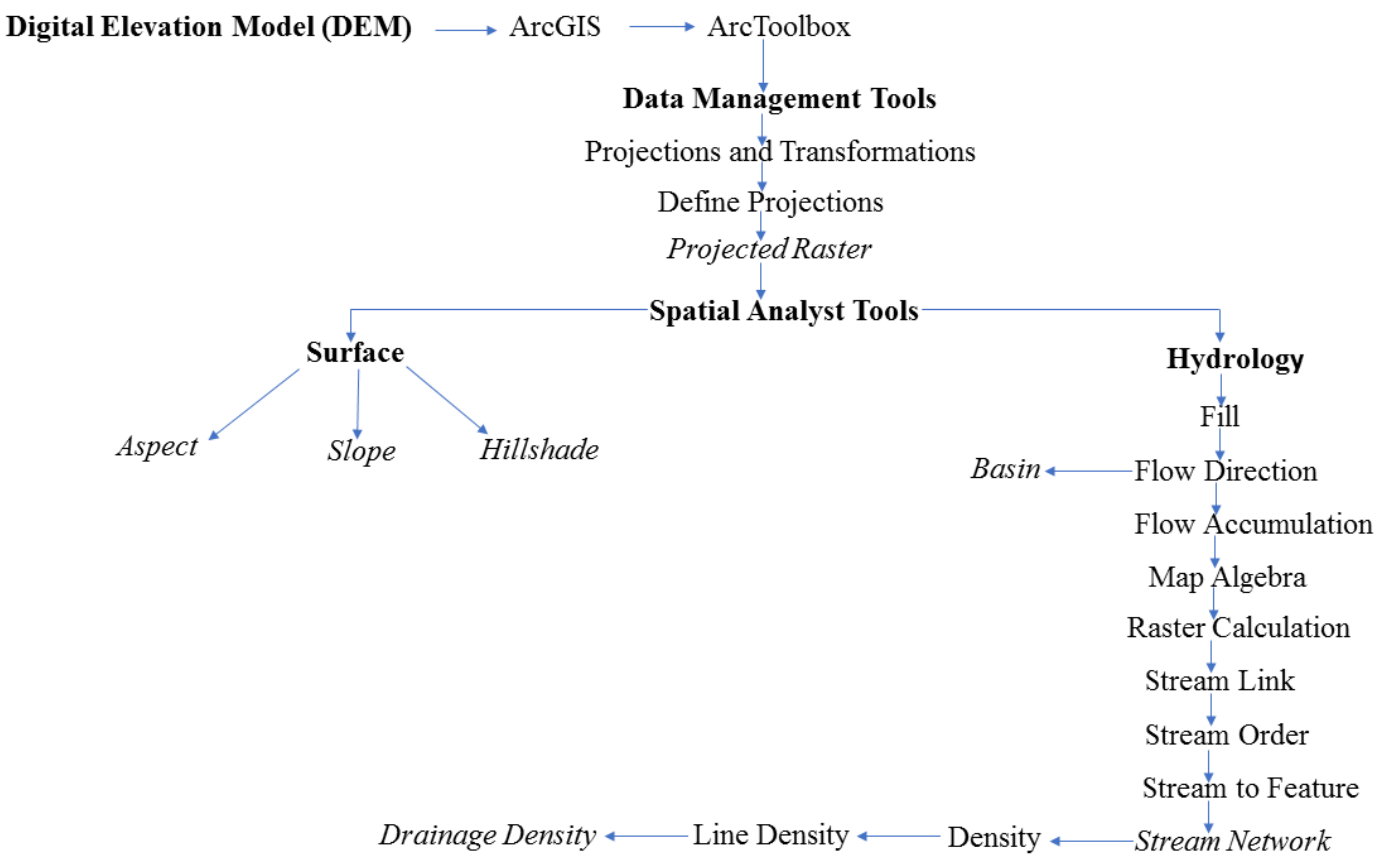

Figure 2. Methodology flow chart.

2.2.1. Elevation

The elevation defined as height elevated above a reference point, which usually means sea level. The elevation is an important parameter that provides an essential role in managing water resources [21–24]. For example, in groundwater recharge, the regions with lower elevation are considered a good recharge zone and the areas with higher elevation considered a less potential recharge zone [25]. In the study area, elevation classified in five classes, such as <500 masl (metres above sea level), 701–1500 masl, 1501–3000 masl, 3001–4500 masl and >4500 masl based on the values (Figure 3). Around two-third area (75.5%) of the Antofagasta region has a high to a very high elevation, while 2.4% coast area has elevation less than 500 masl and 22.1% of the area has an elevation between 501–1500 masl, respectively (Table 1, Figure 3).

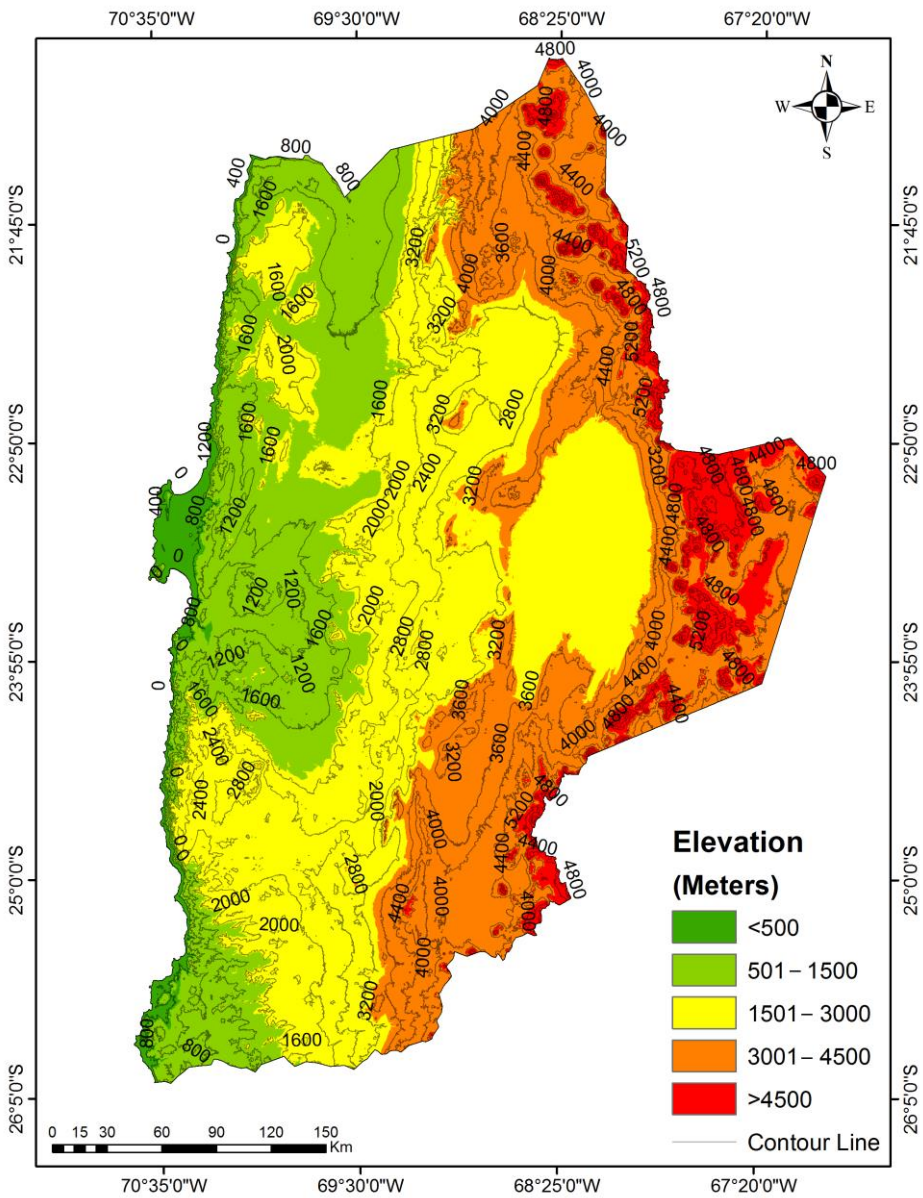

Figure 3. Elevation map of the Antofagasta region.

Table 1. Area and percentage distribution of elevation, slope, aspect, basin and drainage density of the Antofagasta region, Chile.

Parameter	Area (km^2)	Percentage (%)
Elevation (masl)		
<500	2973	2.4
501–1500	27,948	22.1
1501–3000	50,888	40.3
3001–4500	36,346	28.8
>4500	8099	6.4
Slope (degree)		
<5	63,007	50.0
5.1–10	32,294	25.6
10.1–15	14,028	11.1
15.1–20	7566	6.0
>20	9358	7.4
Aspect (degree)		
Flat	15,085	12
North	7383	5.8
Northeast	11,652	9.2
East	10,233	8.1
Southeast	10,657	8.4
South	13,350	10.6
Southwest	16,970	13.4
West	17,831	14.1
Northwest	16,278	13
North	6814	5.4
River Basin		
Loa River	27,148	21.5
Frontier Michincha Salt Field-Loa River	2676	2.1
Coastal Loa River-Caracoles Ravine	8367	6.6
Atacama Salt Field	15,572	12.4
Caracoles Ravine	18,293	14.5
Frontier Atacama and Socompa Salt Fields	4052	3.2
Endorreic between Frontier y Atacama Salt Field	5311	4.2
Endorreic Atacama Salt Field-Pacifico Stream	14,439	11.5
La Negra Ravine	11,342	9.0
Coastal between La Negra and Pan de Azucar Ravines	16,853	13.4
Coastal Pan de Azucar Ravine and Salado River	1949	1.5
Drainage Density (Km/Km^2)		
0–0.14	40,773	32.3
0.15–0.26	40,115	31.8
0.27–0.41	27,637	21.9
0.42–0.61	12,849	10.2
0.62–1.1	4879	3.9

2.2.2. Slope

The slope is an important parameter in hydrology, and it has its own significance in affecting the run-off, movement of surface water and potential infiltration [26]. In the case of groundwater resources management, slope plays a significant role in the movement of

water and permitting the infiltration of water into the aquifer system [27,28]. The slope can be calculated in percent (0–100%) or in degree from horizontal (0–90°), and the velocity of water directly associated with the angle of slope and depth. Information about the slope category is essential in the study of groundwater recharge mapping. An area with flat slopes has a very good capability for recharging groundwater and followed by moderate slopes. In contrast, the area with steeper slopes has poor recharging capacity. In the Antofagasta region, half (50%) of the area has a slope of less than 5 degrees and 25.6% of the area between slope 5 to 10 degrees (Table 1; Figure 4). However, the rest of the area of the Antofagasta region has slope above 15 degrees (Table 1)

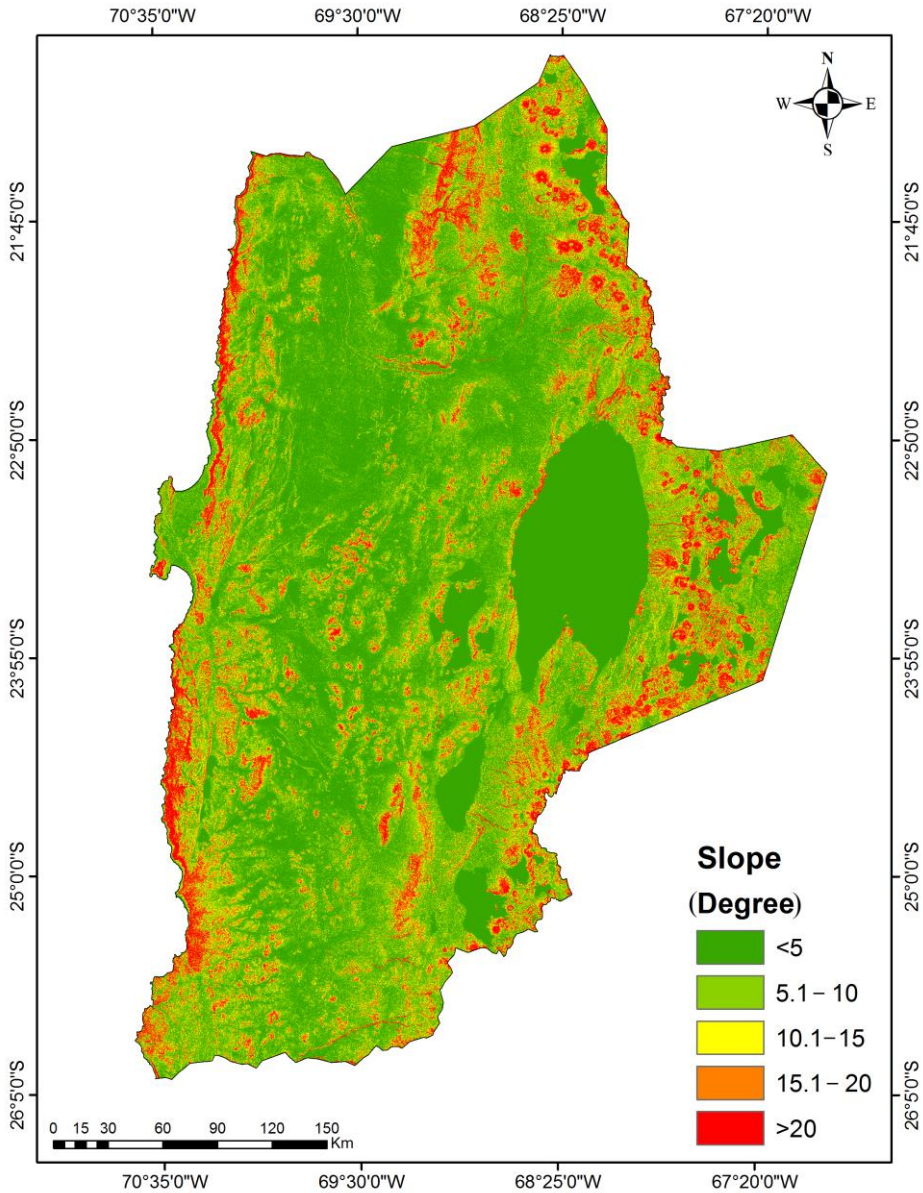

Figure 4. Slope map of the Antofagasta region.

2.2.3. Hillshade

A hillshade is a 3D image (grayscale) of the surface, by the sun's relative position considered for shading the image. This event uses the properties of altitude and azimuth to indicate the position of the sun, in this case, the standard value (Azimuth 315° and Altitude 45°) [29]. The sun altitude is 45°, and the sun azimuths are 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° in the hillside map [30]. It provided important information to

researchers to consider for the management of environmental matrices, such as landslide, groundwater potential mapping and others [29–32]. Figure 5 shows that the hillshade image of the Antofagasta region of Chile.

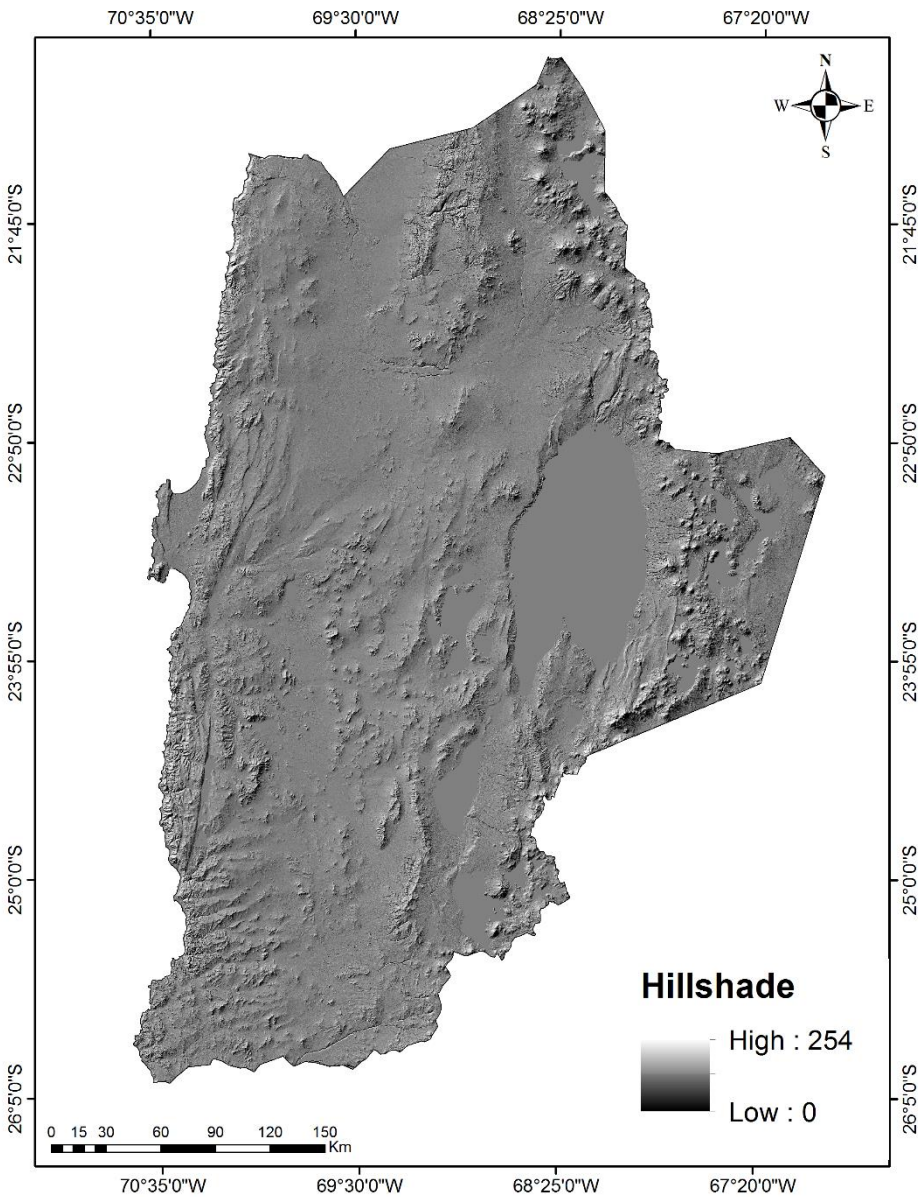

Figure 5. Hillshade map of the Antofagasta region.

2.2.4. Aspect

Aspect is the horizontal direction of the highest slope (i.e., the facing direction). It can convey as the actual number of the direction or can expressed as one of the nine key compass directions, such as flat, north (N), north-east (NE), east (E), south-east (SE), south (S), south-west (SW), west (W), and north-west (NW) [33]. Aspect is measured clockwise in degrees to 360 from the north. For environmental management, aspect can play an important role. Singh et al., [34] have considered aspect as a significant parameter to identify the potential groundwater recharge zones in New Zealand. Singh et al., [34] have described that the flat terrain receives less solar radiation than elevations with a northerly aspect and more than elevations with a southerly aspect. Due to this reason, flat terrain oblations a similar volume of solar radiation to elevations by a westerly and easterly aspect.

Thereby, a southern aspect contributes most to percolation in the recharging of groundwater as compared to the northern aspect. Because northern slopes are considered to contribute minimum to recharge due to higher evapotranspiration that reduces the amount of water for percolation [34]. The Antofagasta region has 14.1% of the area in the west direction, 8.1% of the area in the east direction and 12% of the area is flat, while 33.4% of the area has north, northeast and northwest direction and has 32.4% of the area with south, southeast and southwest direction, respectively (Table 1, Figure 6).

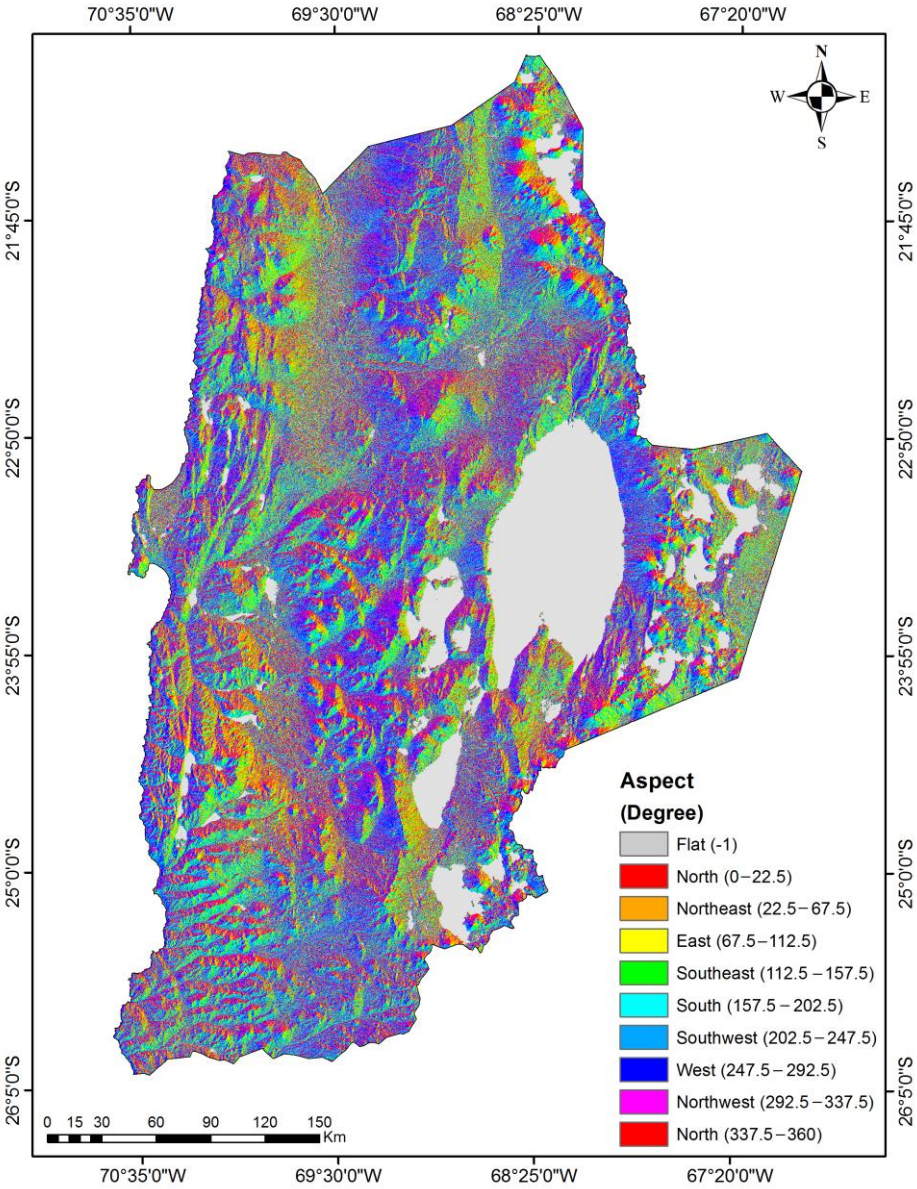

Figure 6. Aspect map of the Antofagasta region.

2.2.5. River Basin

A region of land drained by a river and its tributaries is called a river basin and it has some typical characteristics, such as a watershed, confluence, starting source of the river among others. To make a proper decision for water resources use, planning, and management within the river basin, information on the river's hydrological system is essential [35]. Furthermore, the river basin study plays an important role to make a strong scientific decision for environmental management in the different research fields. The Antofagasta region has 11 important major and minor river basin system in the area

(Figure 7). Around 21.5% of the area has covered by the Loa river basin of the region and followed by the Caracoles basin (14.5%), La Negra and Pan de Azucar Ravine (13.4%), and the Endorreic Atacama Salt Field-Pacifico Stream basin (11.5%). Moreover, other basins in the region have covered the rest of the area, respectively (Table 1).

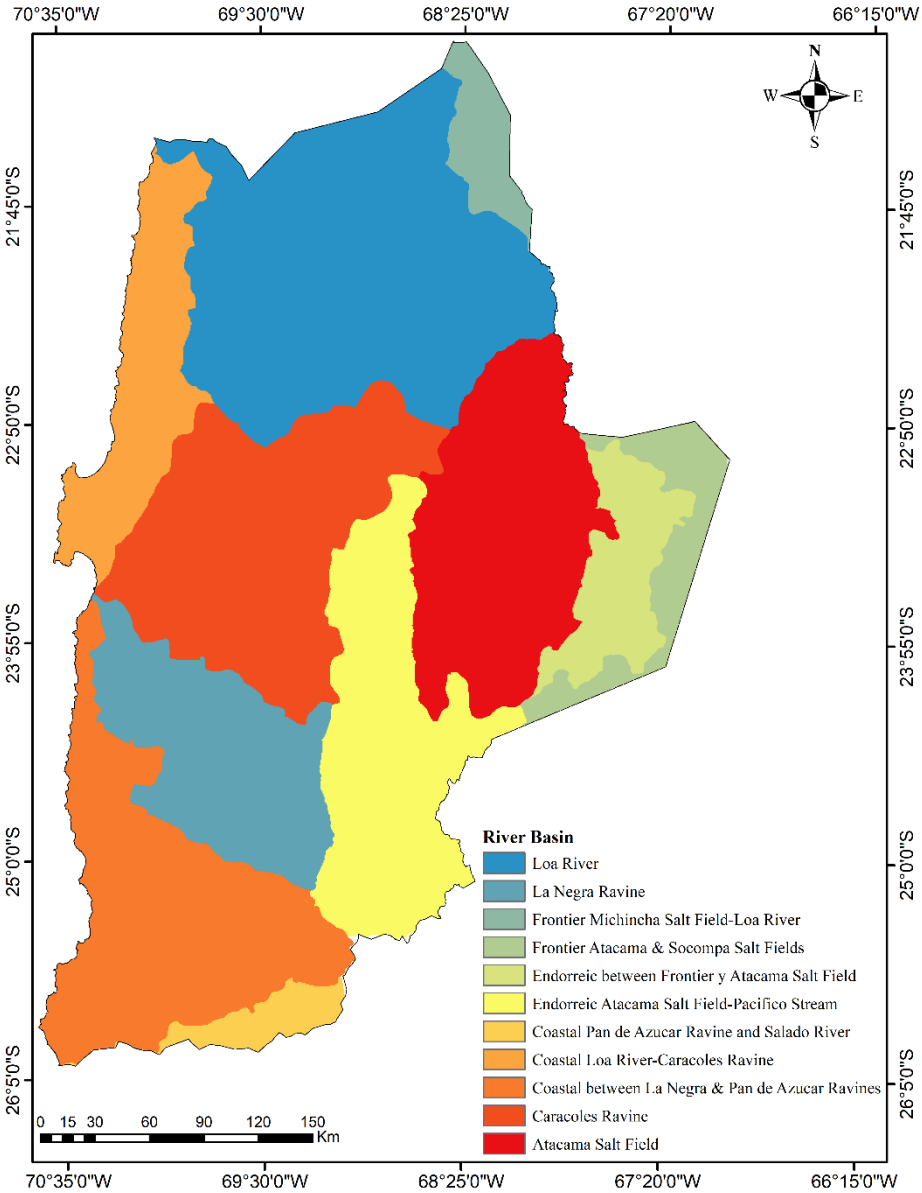

Figure 7. River basin map of the Antofagasta region.

2.2.6. Drainage Systems

Drainage systems are an essential part of the geomorphology and formed by the rivers, streams and lakes in a specific drainage basin. Drainage systems also well-known as river systems and controlled by the topography and gradient of the land. Drainage systems can fall into one of the numerous types recognized as drainage patterns. Drainage patterns are categorized based on their form and texture. Their pattern builds in response to the subsurface geology and local topography of the basin. Zernitz et al., [36] has described details about drainage patterns and their significance importance. Drainage can play a significant role in any area′s water resources management [21,37,38]. Chowdhury et al., [39] suggested that drainage density can indirectly reveal the suitability for groundwater recharge of any area due to its association by surface runoff and permeability. Hence,

drainage density can be considered one of the important factors for identifying artificial groundwater recharge zones. Lower drainage density is considered a good recharge category compared to the high drainage density. The region of Antofagasta mostly has a dendritic drainage pattern (Figure 8). Furthermore, the region's drainage density varied from 0.0 to 1.1 Km/Km^2 and more than half (64.1%) of the area between 0.0—0.26 Km/Km^2 and the rest of the region has a value above the 0.26 Km/Km^2 (Table 1).

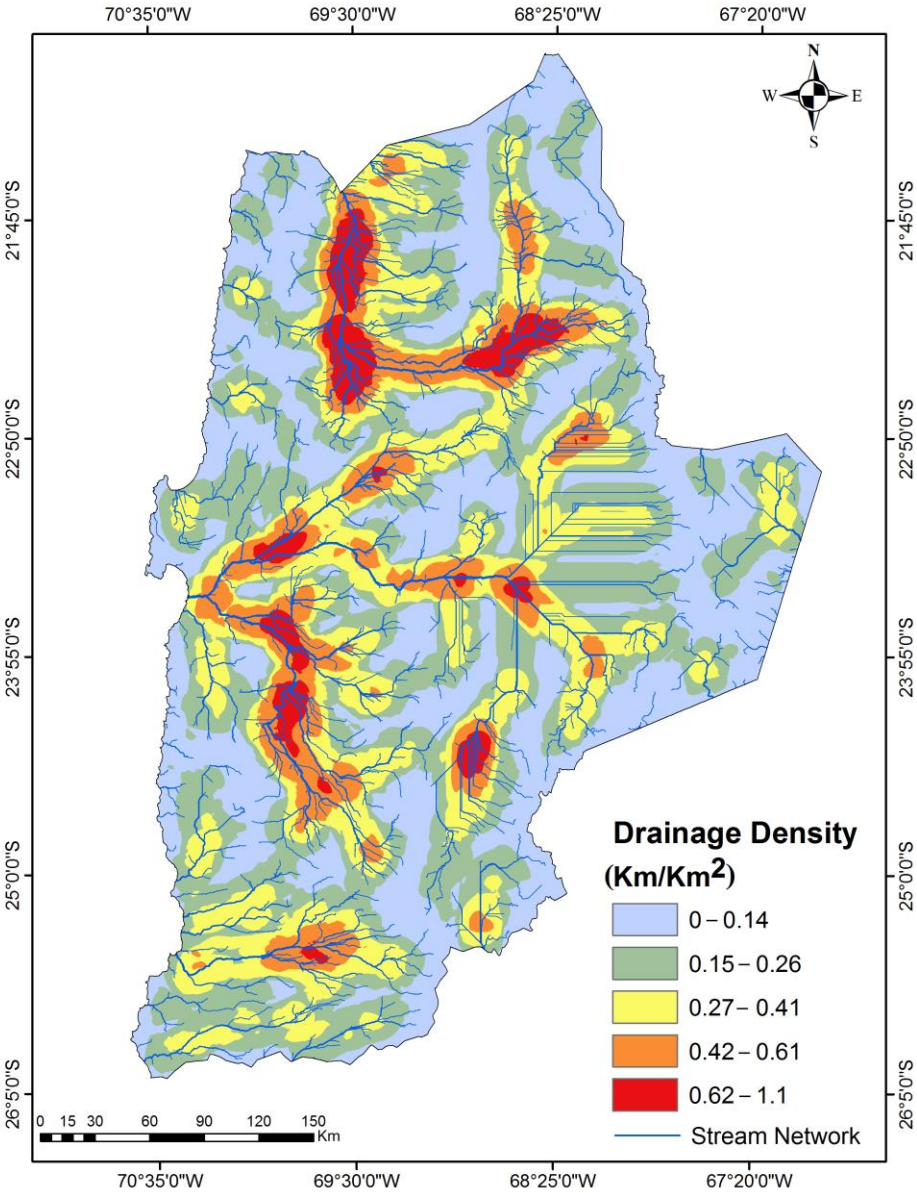

Figure 8. Drainage density and pattern map of the Antofagasta region.

2.2.7. Geology

Special attention is needed to protect recharge areas in dense urban, agricultural and heavy industrial areas [40]. Furthermore, [40] has suggested that the protection can depend on the aquifer types and its geological cover. The geological formations are having a significant relationship with the recharging of aquifers. In the present study, the Antofagasta region has complex geology with several geological environments (Supplementary Figure S1). Therefore, complex geology of the study area has divided into four eras and nine periods (Figure 9). The three geological environments, such as the clastic sedimentary sequences of piedmont, alluvial, colluvial or fluvial (MP1c), the alluvial deposits,

subordinately colluvial or lacustrine (Qa) and the sedimentary sequences of an alluvial, pediment or fluvial fans (M1c) are coved more than 40% of the area of the Antofagasta region (Supplementary Figure S1).

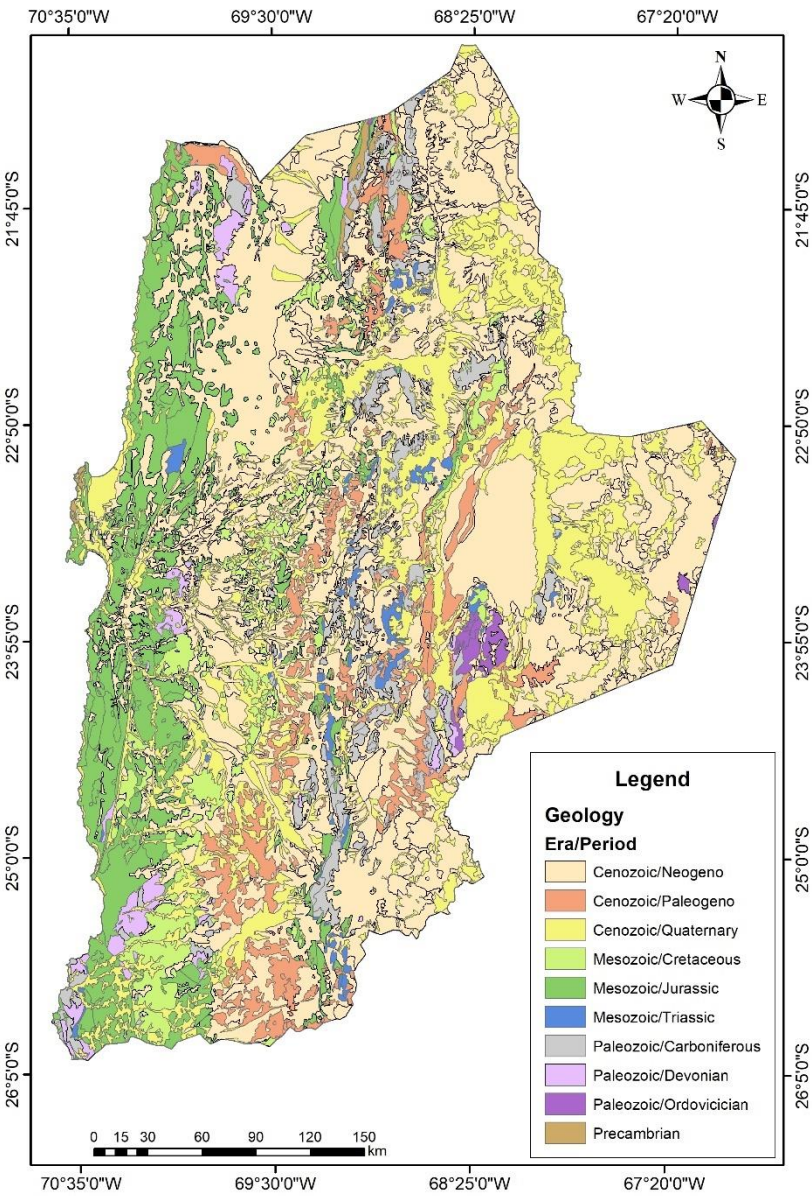

Figure 9. Geological map of the Antofagasta region.

2.3. Pollution Level Risk Identification

Starting from the previous data and adding the pollution factors (mines) and the elements at risk (cities and villages), it will be possible to identify which areas need a priority study in the case of water resource management. With the proposed methodology, which derives from the use of different techniques of watercourses and aquifer vulnerability analysis as DRASTIC [41], SINTACS [42], GOD [43], it is possible to investigate the different river stretches and how they may contaminate both underground water and be a potential risk factor for population and crops. At the end of the procedure, it will be possible to understand which cities have the most critical conditions indicated by colors ranging from green to red, as well as which stretches of river have the greatest probability of polluting the underlying aquifer. The infiltration recharge is an important parameter that plays a significant role in assessing aquifer vulnerability because it helps transport the

pollutant to the aquifer [42]. Therefore, a part of the SINTACS method (infiltration recharge calculation) was applied in a GIS environment to achieve the present research's second objective (Figure 10). Detail about the role and important of SINTACS parameters in aquifer vulnerability assessment are described elsewhere [42]. In the present study, the potential infiltration index was assigned based on the area's bibliography and geological reports. The potential infiltration index was used in the SINTACS method to estimate net recharge of the area, through the inverse water budget [44–47]. The potential infiltration coefficient X_R (that can assume values between 0 and 1) was estimated on the surface lithology of the hydrogeological complex, and other parameters that depend on different lithology characteristics [48]. Each lithological formation represented by era and period in Figure 11 has been divided by type of complex and a potential infiltration coefficient has been assigned to each one. Therefore, the final potential infiltration index for each lithology was assigned based on the type of complex, the average value of the complex derived by the bibliography [49], and the area's geological era.

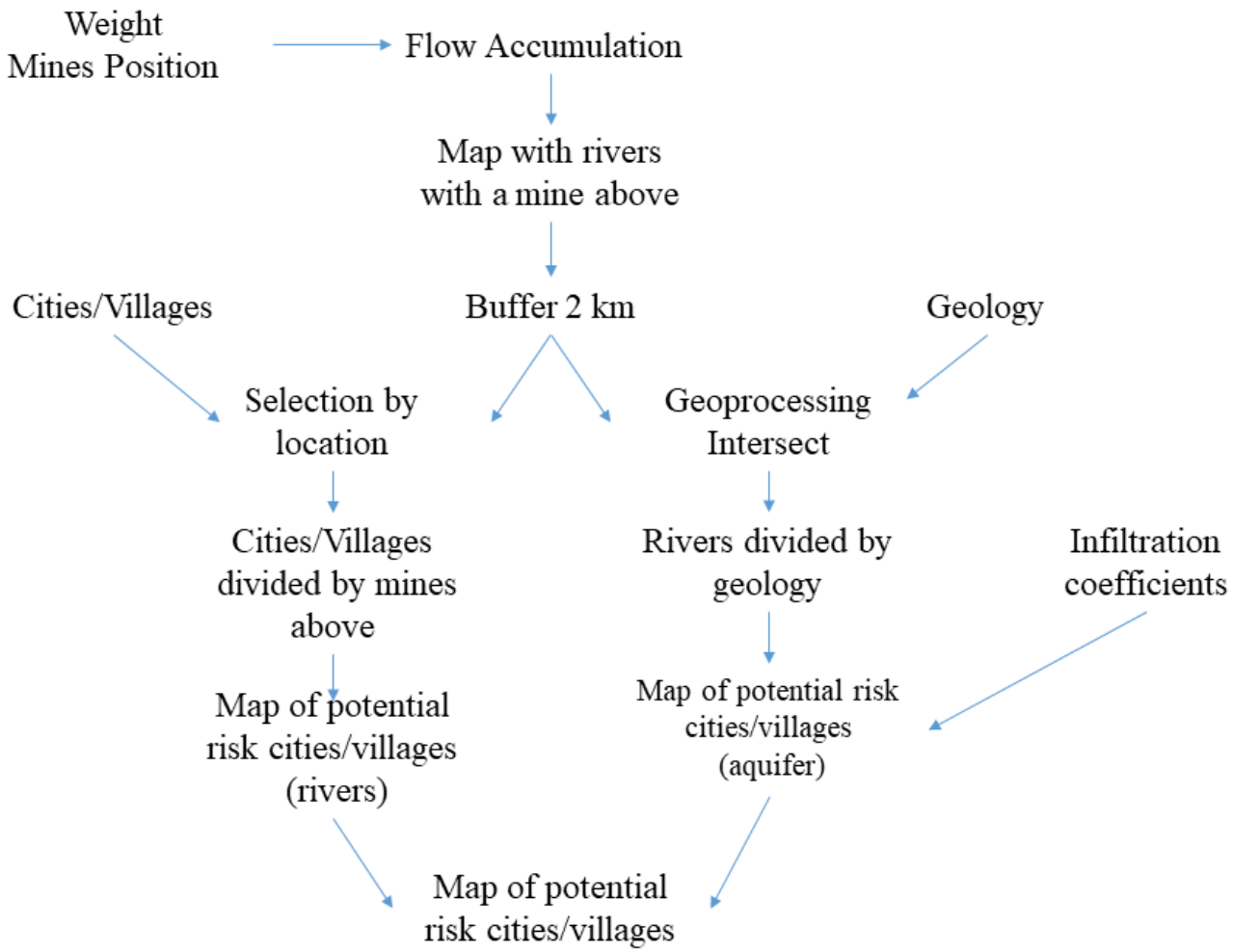

Figure 10. Methodology flowchart for pollution risk identification.

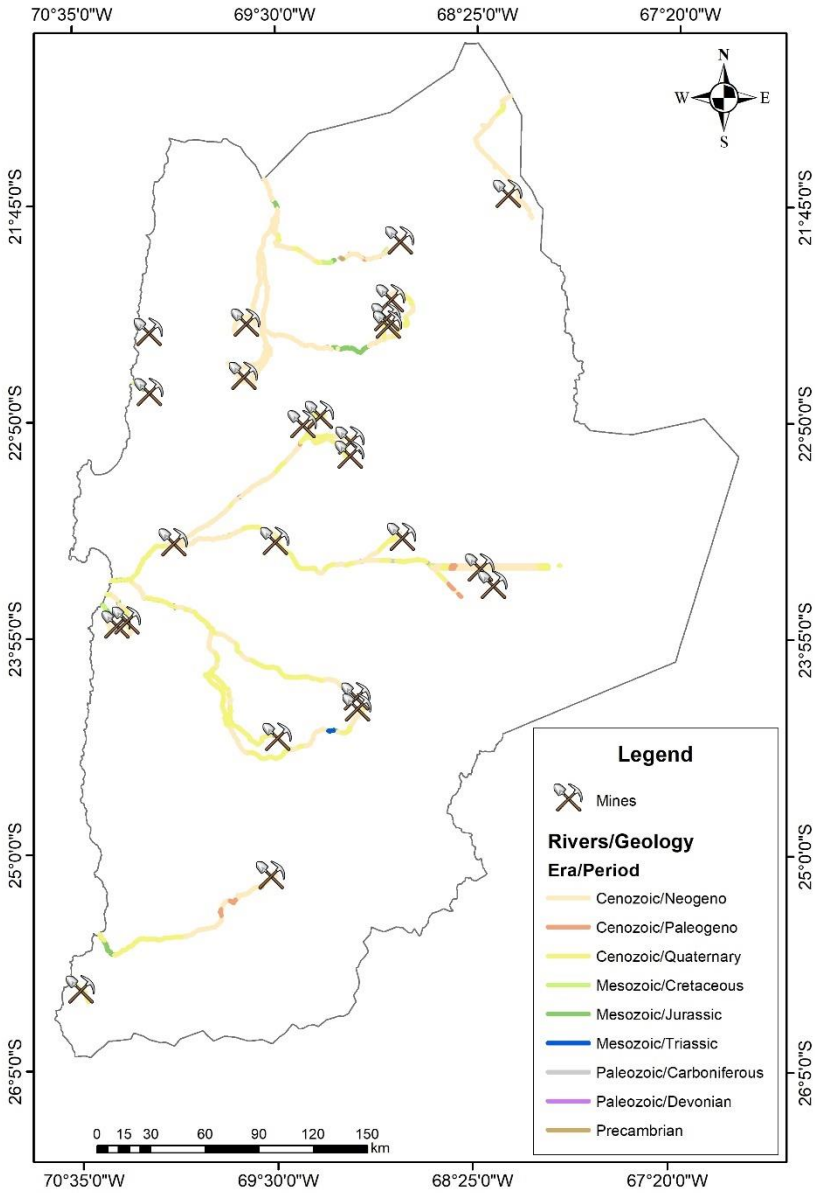

Figure 11. Map of mines and river divided by geological era/period.

3. Results and Discussions

Much of the drinking water in the Antofagasta region comes from treatment plants. As a result, much of the water from the mines have to be treated to be made drinkable. However, irrigation systems pump water directly from the aquifer that is fed by rivers. Therefore, it is necessary to analyze the main watercourses in relation to the cities served by the number of upstream mines and the geological era/period of the study area (Figure 11). Moreover, detail about the upstream mines and the lithology in which they have their beds is shown in Supplementary Figure S2. This expeditious methodology made it possible to identify which areas could be a source of aquifer recharge and which cities/villages were more at risk if they had to use the water from the rivers/stream for different purposes.

Starting from the identification of the rivers previously carried out by ArcHydro, it has been gone to extrapolate all the rivers that are downstream of a mine and all the cities/villages that are at a maximum distance of 2 km from the river itself. Each section of the river was then subdivided according to the geological era/period (Figure 11) and lithology crossed (Supplementary Figure S2). Moreover, by carrying out an in-depth study of the

geolithological map and by using a parameter of SINTACS method (recharge parameter "I") was possible to define an infiltration coefficient for each lithology (Figures 12 and 13).

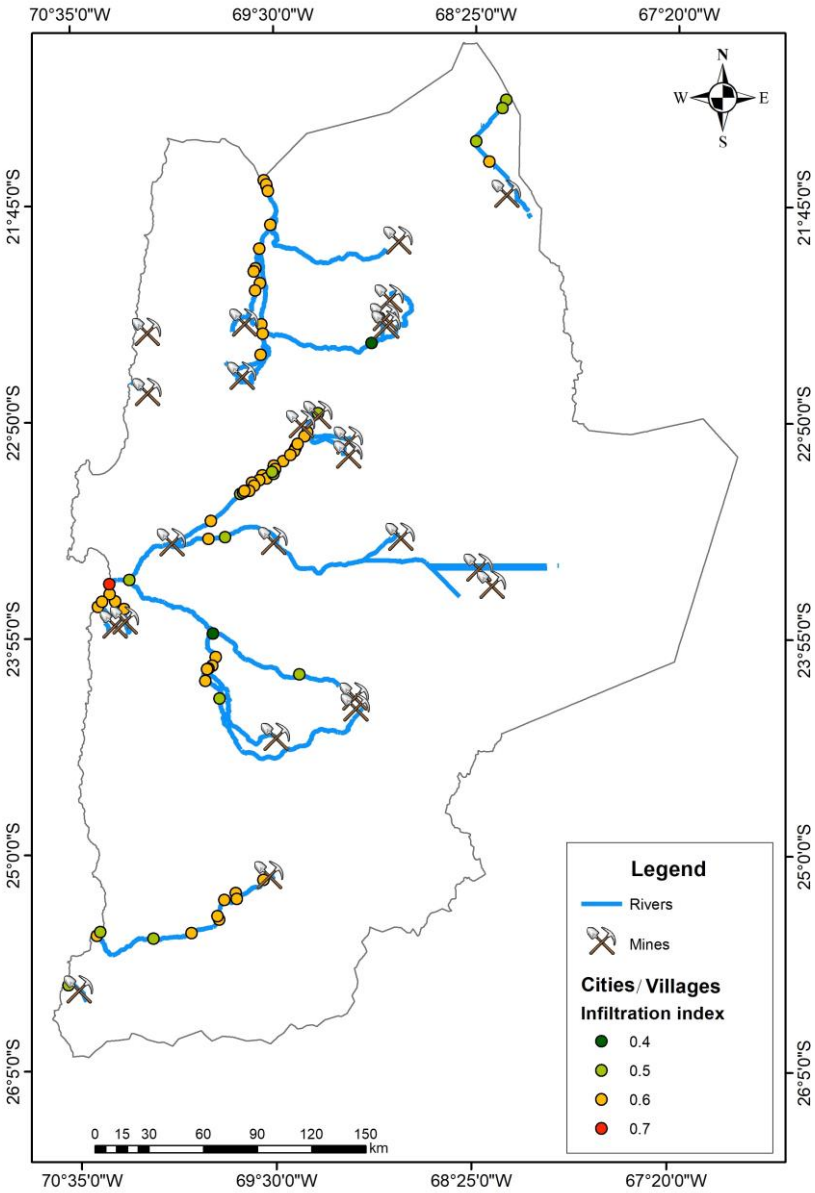

Figure 12. Map of cities/villages infiltration index.

Using the recharge part of the SINTACS method, it is possible to quickly identify which sections are most vulnerable to the pollutants because the river flows through a more permeable lithology. On the other hand, by observing the cities/villages, it is easier to identify those that may have a greater possibility of using contaminated water, if it is extracted from the aquifer due to their location. At the same time, using again the ArcHydro tool and specifically the flow accumulation a binary weight raster was added where 1 equals a mine and 0 the remaining territory.

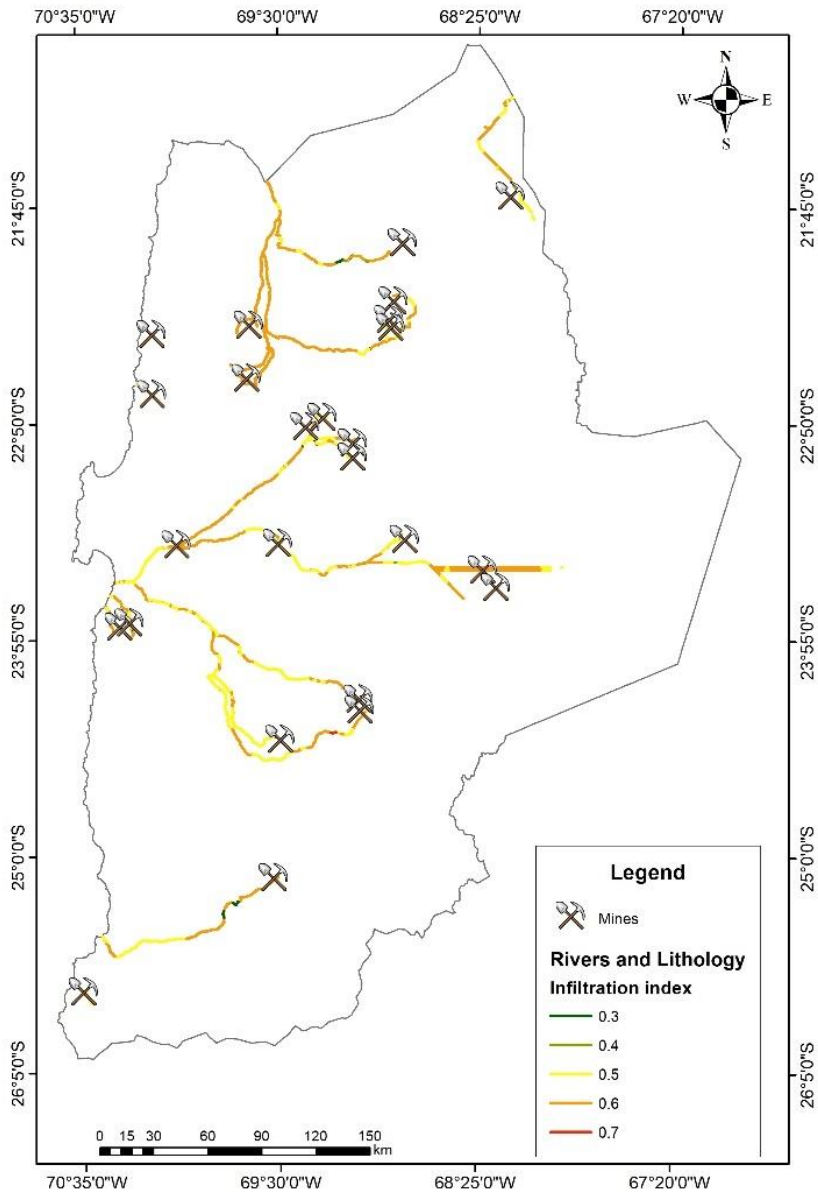

Figure 13. Map of river and lithology infiltration index.

The result is a new representation, colored on the map from green to red (Figures 14 and 15) which represents starting from mountain (green section) the number of mines that the river meets along its path or the tributaries that in turn are fed by water from mines until they reach the sea or the regional border (Figure 15). The number of upstream mines was represented not only in a punctual form to see which town was most at risk of possible pollution but also along the river's course. It is possible that along some sections, there are crops and that therefore the use of polluted water could impact the crops and secondarily on the people who eat the food produced in those plots. This classification is a method derived from Strahler [50] to identify and classify types of streams based on their numbers of tributaries.

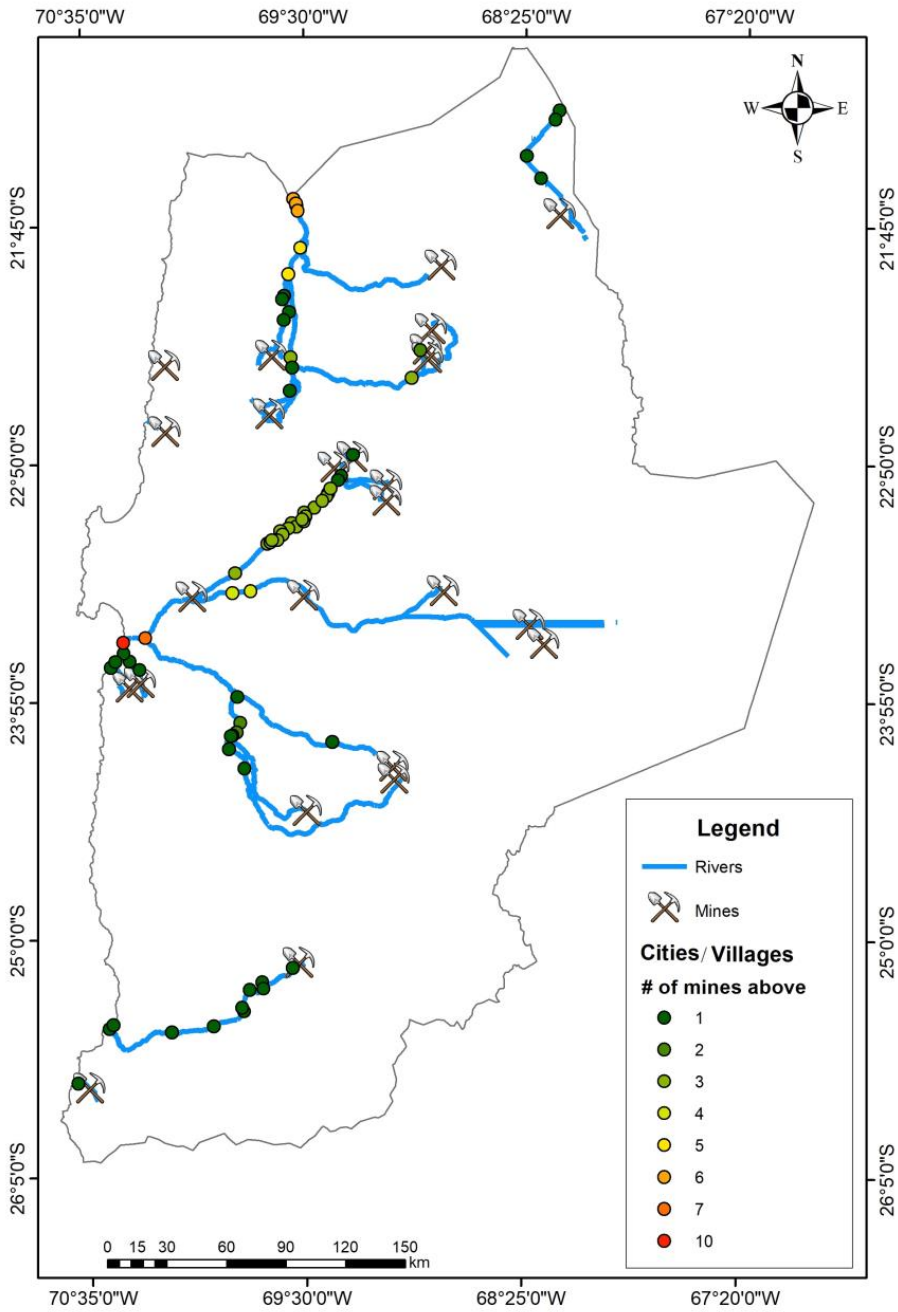

Figure 14. Map of cities/villages divided by the number of mines above.

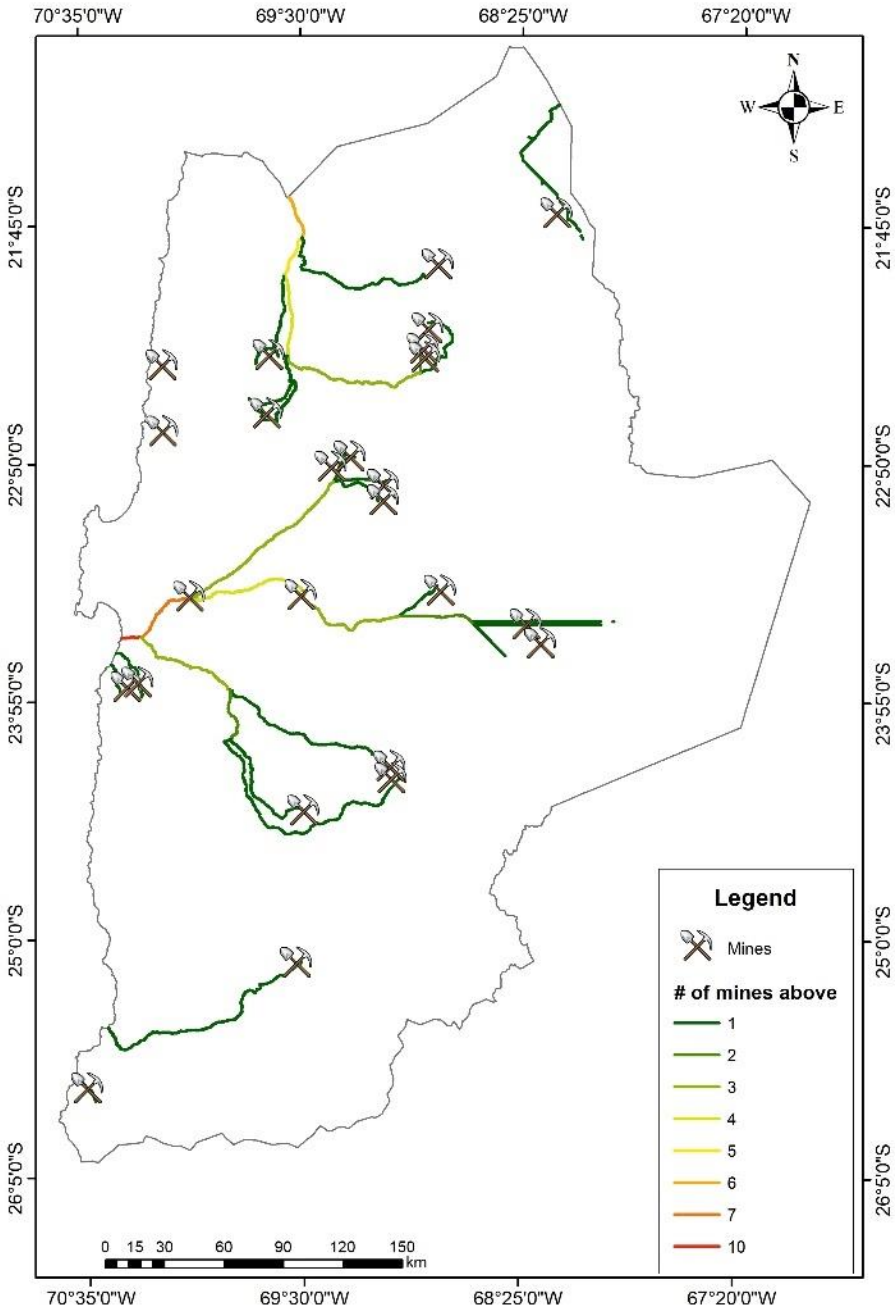

Figure 15. Map of river sections divided by the number of mines above.

By integrating these two data and using the cities/villages as an observation point, it has been possible to identify a pollution risk index (Figure 16). This assessment based on the simplification that cities/villages derive their water from rivers. The aquifer from which the water collected is recharge by the infiltration of the river/stream. Using this methodology, it is easier to identify the areas that most need to be safeguarded, and by further integrating the information with chemical sample data, it would be possible to further discretize the different areas.

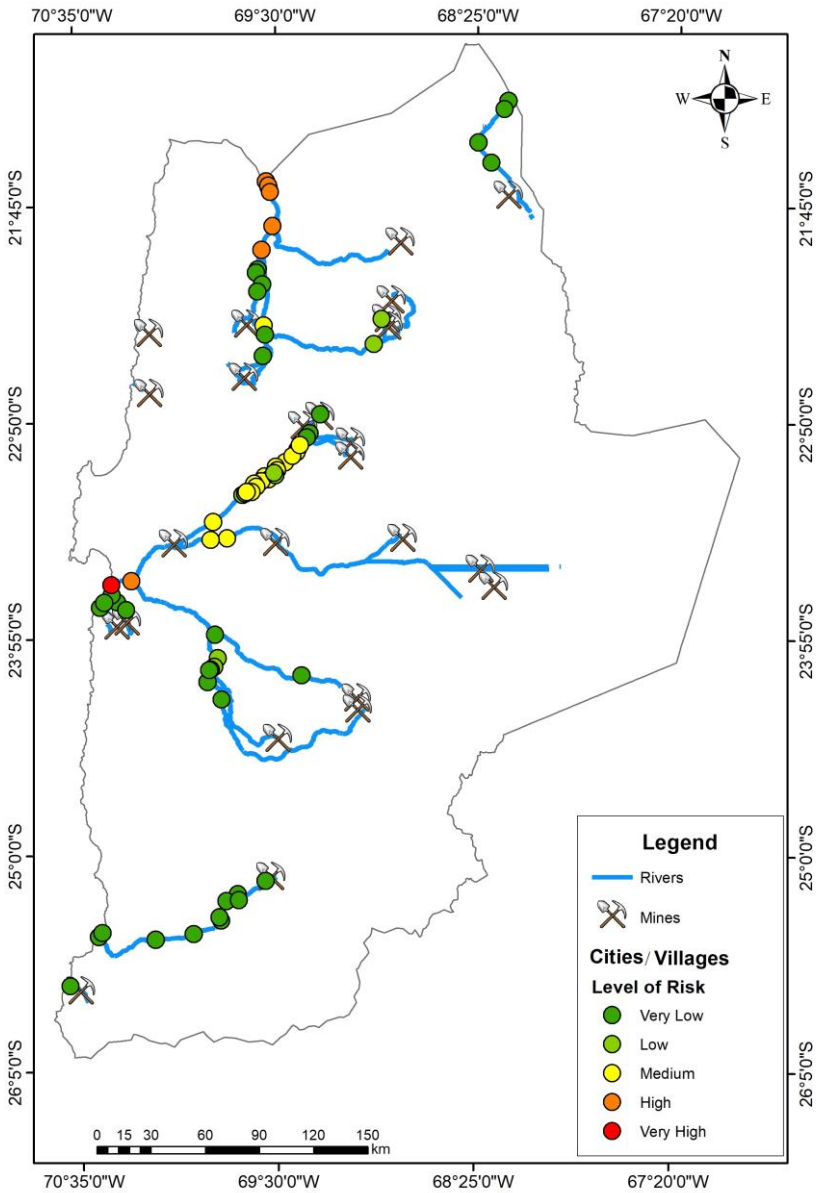

Figure 16. Cities/villages divided by risk value.

4. Conclusions

To achieve the present study's first objective, DEM data used in a GIS environment to create some important maps of the Antofagasta Region, Chile. A total of six significant maps (elevation, slope, hillshade, aspect, river basin and drainage network and density) of the study area created using DEM data in a GIS environment. Furthermore, a geological map of the Antofagasta region also developed using the GIS platform. These seven parameters are very important in the field of hydrology. On the other hand, to succeed the second objective of the study, a part of the SINTACS method applied in GIS to identify the level of pollution risk of the cities/villages in the Antofagasta region of Chile. The result suggested the cities/villages in the region had a lower to a high pollution risk. Some of the cities/villages were at a high and medium risk pollution level in the Loa river basin, while in the Caracoles Ravine basin, most of the cities/villages were at a medium pollution risk level and one city/village at a very high and high pollution risk. However, the cities/villages from the southern region of the study area were under very low to low pollution risk levels. The outcome of the present research is providing baseline information that could help researchers, local and national government, mining authorities etc. to

develop a plan for the sustainable management of water resources in the region at the current and future scenario.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/3/1297/s1, Figure S1: Geological map of the Antofagasta region, Figure S2: Map of mines and river divided by geological unit.

Author Contributions: A.K.T. collected essential information of the study area, designed the research and drafted the present manuscript. The manuscript was read and revised by A.K.T., E.S., C.S. and M.Z. Late M.D.M. provided software support and helped during the preparation of the manuscript at the initial phase. E.S. calculated the PR index and handled software with A.K.T. The current project supervised by M.Z. and C.S. All authors have read and agreed to the published version of the manuscript.

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