

# Comparison of Methods for Nitrate Interpolation in Wells in Aguascalientes, Mexico

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## Abstract

The accuracy of interpolation models applied to groundwater depends, among other factors, on the interpolation method chosen. Therefore, it is necessary to compare different approaches. For this, different methods of interpolation of nitrate concentrations were contrasted in sixty-seven wells in an aquifer in Aguascalientes, Mexico. Four general interpolation methods were used in ArcGIS 10.5 to make the maps: IDW, Kriging, Natural Neighbor and Spline. In the modeling, only method type was varied. The input parameters (location, temporality, and nitrate concentration) were the same in the four interpolations; despite this, different maximum and minimum values were obtained for each interpolation method: for IDW, 0.2 to 22.0 mg/l, for Kriging, 3.5 to 16.5 mg/l, for Natural Neighbor, 0.3 to 21.7 mg/l and for Spline –30.8 to 37.2 mg/l. Finally, an assessment of the maps obtained was conducted by comparing them with the Official Mexican Standard (OMS), where 24 of the 67 wells were found outside the 10 mg/l that the OMS establishes as maximum permissible limit for human consumption. Taking as a starting point the measured values of nitrates (0.25 to 22.12 mg/l), as well as the spatial distribution of the interpolated values, it was determined that the Kriging method best fitted the data measured in the wells within the studied aquifer.

## Keywords

Interpolation, Nitrates, Hydrogeology, GIS, Mexico

## 1. Introduction

In the 21st century, the world population will exceed 10,000 million human beings (United Nations, 2022). Considering this scenario, an increase in water re-

sources demand at global level is expected. This scenario becomes more complex if we add factors such as hydrological cycle modification, climate change, surface and groundwater contamination, inadequate management of water resources at different scales, and anthropogenic demand increases. In general terms, water is used in four activities: agricultural use, public supply, industrial use, and electricity generation (CONAGUA, 2019). However, these uses bring challenges related to both surface water and groundwater.

One of the main challenges with surface water is its easy contamination, since liquid (wastewater, runoff, acid rain) or solid (garbage, sediment) discharges can be conducted. Another challenge is incorrect management that can generate alterations to surface basins, such as modifications to the quantity of water (negative water balance, increase in evaporation, drying of wetlands, desertification), to water quality (increase in nutrients, pollutants, eutrophication, among others) or to the environment (disappearance of native species, interruption of migratory cycles, health deterioration or alteration of the food web, etc.).

In relation to groundwater, one of the biggest challenges is that in many aquifers, extraction exceeds natural recharge. Given this situation, various adverse effects arise, such as a decrease in groundwater levels, land subsidence, progressive deterioration of the quality of the liquid and an increase in extraction costs due to an increase in the dynamic pumping load (Bouwer, 2002). On the other hand, among the thirty-four largest aquifers in the world, at least twenty-one are in a negative water storage trend (Richey et al., 2015). Likewise, there are documented cases of adverse situations related to intensive exploitation, as occurs in Iran (Ghayoumian et al., 2007), India (Singh et al., 2013), China (Liu & Zhu, 2011), United States (Virat, 2001) and Mexico (CONAGUA, 2015).

Nitrogen occurs in various forms in nature, such as nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ), gaseous nitrogen ( $\text{N}_2$ ), ammonium ( $\text{NH}_4^+$ ) and cyanide ( $\text{CN}^-$ ). It also constitutes organic matter (amino acids), and a large part of the earth's atmosphere (78%) (Fetter, 2018).

Atmospheric nitrogen is converted into nitrate by cyanobacteria (lakes and oceans) and by bacteria living in the roots of plants (legumes and lichens). Atmospheric nitrogen is converted into oxidized and reduced forms by fertilizer production and heating it to elevated temperatures. Rainwater contains dissolved nitrate and ammonia, and nitrogen is released into the ground from sewage, animal waste and fertilizers.

In soil and aquifers, microorganisms conduct nitrogen oxidation and reduction. Under oxidizing conditions, ammonia is converted to nitrite, which is then converted to nitrate. Nitrite is a reactive ion and is immediately converted to nitrate, so little nitrite is found in the environment. Under reducing conditions, nitrate is converted to nitrogen gas (denitrification). Organic matter will decompose into ammonia under reducing conditions. The effluent from a septic tank, for example, has high concentrations of ammonia and little nitrate. If the receiving groundwater is reduced, nitrogen will remain as ammonia. If oxidized, bacteria will convert ammonia to nitrate (Fetter, 2014, 2018).

Nitrate is chemically inert, can be mobile in the underground environment, and high concentrations of nitrate in drinking water are most often associated with shallow wells. Since the 20th century, health concerns and regulatory standards for nitrogen in aquifers have focused on childhood methemoglobinemia (“*blue baby disease*”). The high gastric pH of infants and their large fluid intake in relation to body weight contribute to the internal bacterial reduction of ingested nitrate to nitrite, and the nitrite generated inhibits the function of blood hemoglobin in oxygen transport (Fetter, 2018).

Nitrate contamination of groundwater has been documented in many areas. Huang studied the distribution of nitrate in groundwater of a shallow aquifer in Zhangye basin, northwest of China, finding that groundwater has high concentrations of nitrates and these affect crops like lettuce (Huang, 2013). Fallahzadeh found that nitrate content of groundwater in Yazd city, Iran, is approximately 17.6 mg/l, which is higher than the limit allowed by the EPA (Fallahzadeh et al., 2016). In Mexico, the maximum allowable limit is 10 mg/l according to the Official Mexican Standard (hereinafter, OMS) (DOF, 1995).

Given the complex panorama of water challenges, scientists working in various areas of hydrology must offer viable alternatives that provide solutions, or at least mitigate the challenges. Among the alternatives proposed as viable solutions, GIS has emerged, which is “*an environment to collect, manage and analyze data using geography and cartography*” (Chang, 2022). Thus, the objective of this work is to conduct a comparison of four interpolation methods using nitrate values in sixty-seven wells in Aguascalientes, Mexico, using GIS.

## 2. Description of the Study Area

### 2.1. Ubication

The Chicalote Valley aquifer is located 45 km northeast of the capital of Aguascalientes State. It has an area of 657 km<sup>2</sup>, an elongated shape and a north-east-southwest orientation (Figure 1). Its limits are to the north and northeast by the Loreto Valley, in Zacatecas State; to the west by Sierra de Tepezalá; to the east and south by hills; to the east and south it borders by the El Llano plateau and the Aguascalientes Valley (CONAGUA, 2024). The aquifer includes municipality of Asientos, a small portion of San Francisco de los Romo and Aguascalientes municipalities, and borders Zacatecas State. According to CONAGUA, it is estimated that there are 39,805 habitants in the area (CONAGUA, 2024).

### 2.2. Clime

The climate of the study area is semi-dry, with a maximum temperature of 21.7°C and a minimum of 12°C. The average annual temperature is 17°C to 18°C. The average annual precipitation is 494.5 mm in summer, with average monthly precipitation of 100 mm in July and August, and less than 20 mm from November to May. The average annual evaporation is 2082 mm for the entire aquifer, which exceeds the precipitation values for the entire year (INEGI, 1991).

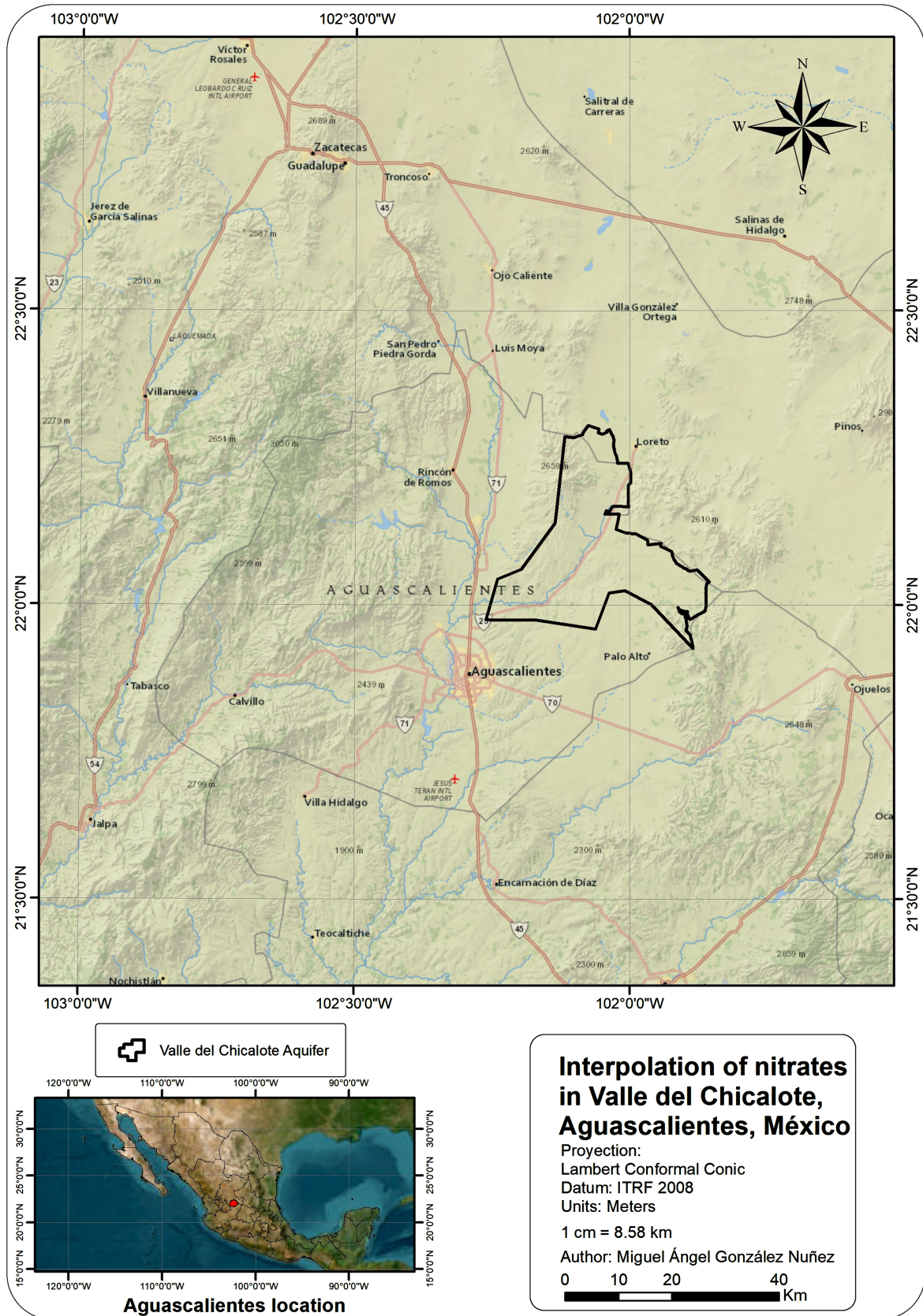


Figure 1. Study zone location.

### 2.3. Hydrography

The aquifer is in Hydrological Region 12 Lerma-Chapala-Santiago, Alto Santiago subregion, Río Verde basin, Río Chicalote subbasin. The main watercourse is the Chicalote River, which originates outside the state. Its route in the study area begins north of Villa Juárez, fed by multiple storage facilities that have been built along the river to take advantage of its flow. The surface lithological composition of the aquifer consists of poorly permeable rocks, as evidenced by the substantial number of creeks that exist in the area. The surface basins show a sub-parallel dendritic drainage pattern, controlled by the geomorphological conditions of the area (SPP, 1979).

### 2.4. Geology

The aquifer is in the Meseta Central physiographic province. It borders north and east with the Sierra Madre Oriental, west with Sierra Madre Occidental and south with Eje Volcánico Transmexicano. It presents plains interrupted by volcano-sedimentary mountain ranges with basalts, andesites and rhyolites that give rise to volcanic structures with a high degree of erosion, as well as mountain ranges and valleys made up of clastic materials from the Tertiary and Quaternary, with thicknesses of 450 m. in the Chicalote valley (SPP, 1979). The Sierra de Tepezalá separates Aguascalientes and Chicalote valleys (North-South and Northeast-Southwest orientation), formed by marine sedimentary rocks. The valley is divided to the northwest by the Tepezalá mountain range with altitudes greater than 2400 meters above sea level. In contrast, the Tepezalá mountain range shows a physiography with heights that do not exceed 2400 m., with a northeast-southeast orientation (SGM, 1998).

The Chicalote Valley is an extension of the Tierra Blanca plain in Zacatecas State. It is delimited to the west by Sierra de Tepezalá, made up of clayey limestones, which are intruded by granites or diorites; In some places they are correspondingly covered by sandstone, shale, or sand. This valley is semi-closed in the northern portion by rhyolite spills, and to the east and south it is limited by hills. The study area corresponds to a basin of tectonic origin, made up of tuff sands and alluvial deposits from the Quaternary, with thicknesses greater than 250 m at the center of the valley, which overlie a conglomerate of rhyolitic composition, clayey materials, and rhyolitic rocks from the Tertiary (SGM, 1998).

### 2.5. Hydrogeology

#### 2.5.1. Aquifer Characteristics

The aquifer is made up of a basement of igneous rocks, identified in different wells of the zone. The valley favors the development of depressions that have been filled with tuffaceous sands and fluvial deposits that constitute the main aquifer of the region, with thicknesses of up to 250 m that decrease towards the sides of the valley and increase towards the center. The northwest and south flanks of the valley are permeable, communicating with the Aguascalientes valley

to the West through sandstones and conglomerates; with El Llano, to the South, it is communicated through tuff sands. Within the hydrogeological units, the alluvial deposits and tuffs that fill the valley stand out, which, due to their high permeability, extension, and thickness, form the most important aquifer in the region. In relation to the rhyolitic sequence, although these make up an aquifer of moderate potential, its exploitation is not as intense as in the fill deposits, even though there is hydraulic communication between the two in several places in the valley.

### 2.5.2. Hydraulic Behavior

The static level depth varies from 20 to 80 m (CONAGUA, 2024). The shallowest levels are in Villa Juárez, in the central part of the aquifer, while the deepest levels are in the northern portion of the Valley. The behavior of the levels obeys the exploitation conditions since topography forms a plateau with a flat surface and elevations of 2000 meters above sea level in the entire valley area. In relation to water level configuration, hydraulic load varies regionally between 1970 and 1880 meters above sea level, with a decreasing behavior from the northern limit of the aquifer to the south-west part in Jaltomate. The highest values were recorded on the border with Zacatecas State near Asientos, northeast of the valley, with elevations of 1900 m, while the lowest values have been recorded in José Maria Morales town.

Based on geohydrological studies (CONAGUA, 2024; SGM, 1998, 2001; SPP, 1979), the underground flow takes place through the Chicalote River channel and expands upon reaching Aguascalientes Valley, passing a part through sandstones and conglomerates that outcrop south of Chiquihuites. The other part of the flow heads south towards El Llano, through permeable tuff sands, delimited to the west by Sierra de Tepezalá and to the North, East and South by hills.

## 3. Materials and Methods

### 3.1. Data Analysis

Hydrogeological investigations were conducted in the Chicalote Valley aquifer and throughout Aguascalientes State; the regular distribution of the sixty-seven wells in the study area made it optimal for the analysis. Likewise, satellite images of Aguascalientes were used along with land use, hydrology, climatology, and vegetation maps for the comparative analysis of various methodologies. Regarding the wells, the energy source is electric, the type of pump is submersible, and the water use is for public-urban and agricultural supply. Most of the wells belong to the sodium-bicarbonate or calcium-sodium-bicarbonate family, and the lowest nitrate values are 0.25 mg/l and the highest are 22.12 mg/l (Table 1).

### 3.2. Spatial Interpolation

Spatial interpolation calculates values from unsampled zones in an area surrounded by sampled zones. Ideally, there should be recorded values for each study area; However, most often this is not the case, and the data are found in:

**Table 1.** Well water quality data.

#	DATE	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	SO <sub>4</sub> (mg/l)	NO <sub>3</sub> (mg/l)
1	19/08/2021	120.81	11.45	32.46	13.46	173.2	<b>0.25</b>
2	31/08/2021	74.84	2.59	139.32	29.64	80.21	<b>2.11</b>
3	31/08/2021	61.26	2.12	128.65	34.59	79.73	<b>2.23</b>
4	01/09/2021	72.81	2.16	144.69	31.88	80.21	<b>2.35</b>
5	31/08/2021	73.65	2.28	137.98	38.24	84.53	<b>2.97</b>
6	01/09/2021	46.63	2	53.85	26.8	38.42	<b>3.22</b>
7	19/08/2021	6.56	0.31	26.53	9.02	5.65	<b>3.35</b>
8	31/08/2021	64.03	9.88	98.31	24.08	51.87	<b>3.41</b>
9	20/08/2021	74.4	0.35	113.53	33.41	57.6	<b>3.53</b>
10	16/08/2021	53.11	27.48	31.06	11.72	61.73	<b>3.66</b>
11	27/08/2021	14.78	0.41	40.06	16.17	24.98	<b>3.84</b>
12	20/08/2021	35.21	8.31	58.09	19.93	29.35	<b>4.28</b>
13	31/08/2021	43.18	5.72	51.37	26.87	29.78	<b>4.28</b>
14	31/08/2021	40.7	1.76	69.41	22.12	36.5	<b>4.4</b>
15	30/08/2021	70.21	2.8	77.84	10.82	13.45	<b>4.59</b>
16	19/08/2021	48.5	7.26	72.42	23.38	67.83	<b>5.14</b>
17	25/08/2021	15.35	0.06	56.98	7.38	15.37	<b>5.14</b>
18	20/08/2021	50.24	7.93	66.75	24.89	40.87	<b>5.27</b>
19	01/09/2021	63.61	1.86	43.79	14.96	20.17	<b>5.39</b>
20	01/09/2021	51.18	1.16	98.24	17.97	41.79	<b>5.58</b>
21	25/08/2021	38.96	0.54	32.27	11.62	11.66	<b>5.58</b>
22	19/08/2021	59.09	8.6	73.84	26.78	26.76	<b>5.76</b>
23	26/08/2021	58.84	2.29	83.57	30.56	94.62	<b>6.2</b>
24	27/08/2021	23.89	1.16	88.22	20.5	42.27	<b>6.51</b>
25	25/08/2021	40.54	0.42	24.63	4.5	13.2	<b>6.75</b>
26	25/08/2021	22.55	0.5	48.24	18.76	26.42	<b>6.88</b>
27	30/08/2021	12.01	1.1	29.54	11.43	14.41	<b>7.06</b>
28	01/09/2021	35.22	0.56	45.19	13.3	19.69	<b>7.13</b>
29	27/08/2021	38.25	1.58	67.29	33.43	54.27	<b>7.19</b>
30	16/08/2021	35.6	5.77	52.74	12.89	38.86	<b>7.37</b>
31	01/09/2021	34.42	2.19	43.09	13.01	25.46	<b>7.44</b>
32	17/08/2021	40.96	7.99	36.94	16.59	34.55	<b>7.5</b>
33	27/08/2021	41.66	2.79	104.83	15.58	41.79	<b>7.68</b>

**Continued**

34	27/08/2021	28.37	0.91	52.08	42.89	34.1	<b>8.12</b>
35	25/08/2021	47.23	0.41	149	10.8	33.14	<b>8.12</b>
36	27/08/2021	38.99	3.61	61.76	27.56	51.87	<b>8.43</b>
37	31/08/2021	45.37	2.15	64.63	25.32	28.34	<b>8.49</b>
38	27/08/2021	32.47	4.26	48.29	21	40.83	<b>8.68</b>
39	01/09/2021	38.8	0.92	57.18	18.11	41.31	<b>9.23</b>
40	20/08/2021	32.56	1.1	70.44	10.83	41.22	<b>9.3</b>
41	27/08/2021	34.67	4.31	56.25	27.32	56.68	<b>9.48</b>
42	25/08/2021	24.16	0.26	42.93	9.87	12.81	<b>9.67</b>
43	25/08/2021	23.34	0.14	51.01	12.16	24.63	<b>9.92</b>
44	19/08/2021	46.69	6.86	88.01	29.29	55.4	<b>10.16</b>
45	26/08/2021	61.32	2.04	72.91	28.79	72.04	<b>10.16</b>
46	19/08/2021	44.44	1.51	68.01	22.54	37.54	<b>10.29</b>
47	17/08/2021	37.53	1.39	92.37	13.19	84.56	<b>11.22</b>
48	27/08/2021	50.17	1.21	71.08	26.53	89.82	<b>11.22</b>
49	17/08/2021	34.85	1.64	94.63	18.3	96.6	<b>11.77</b>
50	26/08/2021	70.04	8.45	73.82	31.82	129.2	<b>11.96</b>
51	30/08/2021	38.22	0.45	59.96	28.88	43.71	<b>12.7</b>
52	18/08/2021	45.98	8.57	63.4	25.15	51.32	<b>13.26</b>
53	18/08/2021	55.19	10.35	100.97	30.88	125.05	<b>13.51</b>
54	26/08/2021	55.64	2.07	83.12	31.67	93.66	<b>13.7</b>
55	17/08/2021	30.24	0.73	58.44	13.19	39.74	<b>14.38</b>
56	18/08/2021	53.63	13.14	136.02	15.01	157.08	<b>14.56</b>
57	20/08/2021	25.32	0.51	78.03	8.23	37.4	<b>14.69</b>
58	16/08/2021	42.15	6.91	51.2	15.23	31.98	<b>15</b>
59	18/08/2021	58.22	10.71	79.13	24.42	76.8	<b>15.55</b>
60	27/08/2021	46.17	9.96	61.83	29.14	68.68	<b>15.8</b>
61	26/08/2021	42.82	5.69	68.05	24.44	61.96	<b>15.93</b>
62	18/08/2021	38.37	8.56	76.05	23.75	62.34	<b>17.48</b>
63	17/08/2021	35.16	3.6	47.23	33.5	46.99	<b>17.66</b>
64	26/08/2021	60.65	1.33	55.22	32.83	48.51	<b>18.9</b>
65	17/08/2021	20.99	0.99	81.15	8.77	28.04	<b>19.71</b>
66	26/08/2021	39.45	1.78	53.58	25.66	47.07	<b>20.88</b>
67	20/08/2021	65.02	6.86	92.9	24.33	78.54	<b>22.12</b>

1) regularly sampled areas that do not cover every spatial location, 2) irregularly sampled areas at specific locations, 3) random areas throughout the area of study (Heywood et al., 2010). For these reasons, spatial interpolation is used since it generates information in the spaces between observed data points. Below is a classification of interpolation methods to choose the appropriate method for a particular data set (Heywood et al., 2010).

1) *Global or local*. Global interpolation uses a mathematical function for all observed data points and predicts values for unknown points. Local interpolation repeatedly applies a mathematical function to small subsets of data points to generate predictions of a particular point, and then connects these regional surfaces to form a composite surface that spans the entire study area. These methods make it easy to evaluate and eliminate global variations caused by physical trends in the data.

2) *Exact or approximate*. Exact interpolation respects all available observed data points, meaning that the generated surface passes exactly through those points without smoothing or altering their values. On the other hand, approximate interpolation does not require to respect the observed data points and can smooth or modify them to fit a general trend, being more suitable when there is uncertainty in the measurements of the sample points.

3) *Gradual or abrupt*. Gradual methods produce a smooth surface between sample points, while abrupt methods create surfaces with a stepped appearance. Both approaches are often needed, as it is necessary to represent both gradual changes between observed points (valleys) and abrupt changes (mountains).

4) *Deterministic or stochastic*. Deterministic interpolation is used when there is sufficient knowledge about the geographic surface being modeled, allowing its character to be described with a mathematical function. However, this is rarely the case on surfaces that represent real-world features. To address this uncertainty, stochastic (random) models are used that incorporate random variation in the interpolated surface.

Different interpolation methods applied on the same data sources can give different results and, therefore, it is necessary to evaluate the comparative suitability of these techniques. Below are the results of applying four different interpolation techniques on the same nitrate values in sixty-seven wells from an aquifer in Aguascalientes, Mexico.

### 3.2.1. Kriging

The Kriging method is a geostatistical interpolation that uses a variogram that depends on the spatial distribution of the data rather than the actual values. Kriging weights are derived using a data-driven weighting function to reduce bias towards input values and provide the best interpolation when good variogram models are available (Slocum et al., 2023).

For the Chicalote Valley aquifer, according to the Kriging method, the lowest concentrations of nitrates were found towards the east of the study area (3.5 mg/l), and the highest concentrations were found to the northwest (16.5 mg/l) (Figure 2).

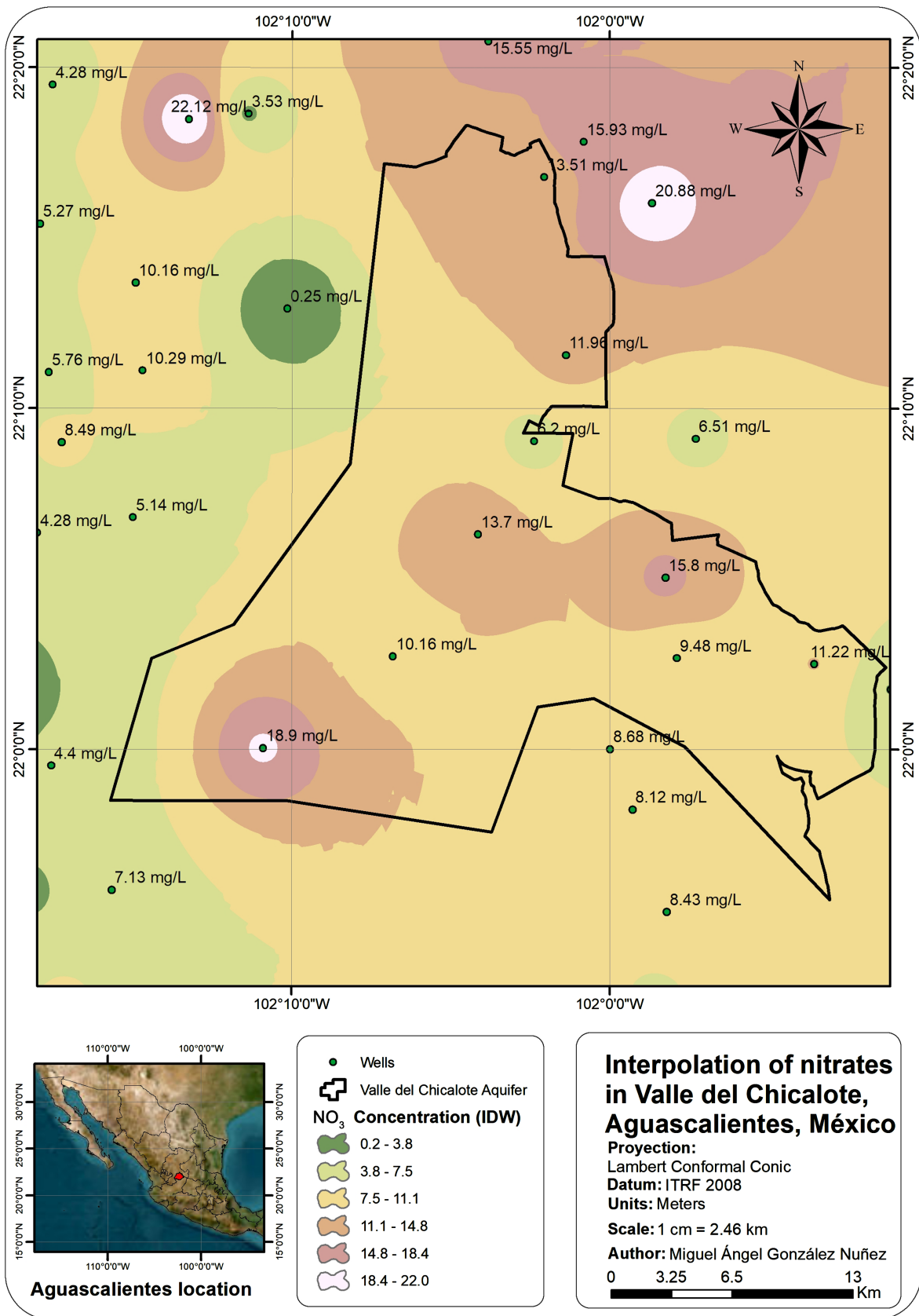


Figure 2. Nitrate interpolation (method: Kriging).

### 3.2.2. IDW

The IDW (Inverse Distance Weighting) method is an interpolation that imposes the condition that the estimated value of a point is more influenced by nearby known points than by more distant ones. The change in values is greater near the known points and stabilizes away from them. When using the IDW method, all predicted values will be within the range of maximum and minimum values of the known points. The IDW method is a local deterministic interpolation that calculates the value as a distance-weighted average of sampled points in a defined neighborhood. It weights the sample points with the inverse of their distance from the required point (Slocum et al., 2023).

For the Chicalote Valley aquifer, according to the IDW method, the lowest concentrations of nitrates were found towards the northeast of the study area (0.2 mg/l), and the highest concentrations were found in the center-north (22.0 mg/l) (Figure 3).

### 3.2.3. Natural Neighbor

The natural neighbor interpolation method finds the closest subset of input samples to a query point and applies proportional area-based weights to them. It is a local deterministic method, and the interpolated heights are guaranteed to be within the range of the samples used. It does not produce peaks, dips, ridges, or valleys that are not already present in the input samples and adapts locally to the structure of the input data. It requires no user intervention and works equally well for regularly and irregularly distributed data (Chang, 2022).

For the Chicalote Valley aquifer, according to the Natural Neighbor method, the lowest concentrations of nitrates were found towards the northwest of the study area (0.3 mg/l), and the highest concentrations were found to the northwest. (21.7 mg/l) (Figure 4).

### 3.2.4. Spline

The Spline interpolation method uses mathematical functions to minimize surface curvature and produces a smooth surface that conforms to the input points. This method creates a surface that passes through the control points and has the smallest possible change in slope at all points. In other words, Splines fit control points with a minimum surface curvature. Unlike the IDW method, the values predicted from the Spline method are not limited within the range of maximum and minimum values of the known points. In fact, a major problem with Spline is steep gradients in data-sparse areas, often called overshoots. Different methods have been proposed to correct the excesses, which belong to a diverse group called radial basis functions (RBF).

For the Chicalote Valley aquifer, according to the Spline method, the lowest concentrations of nitrates were found towards the north of the study area (−30.8 mg/l), and the highest concentrations were found in the center-north (37.2 mg/l) (Figure 5).

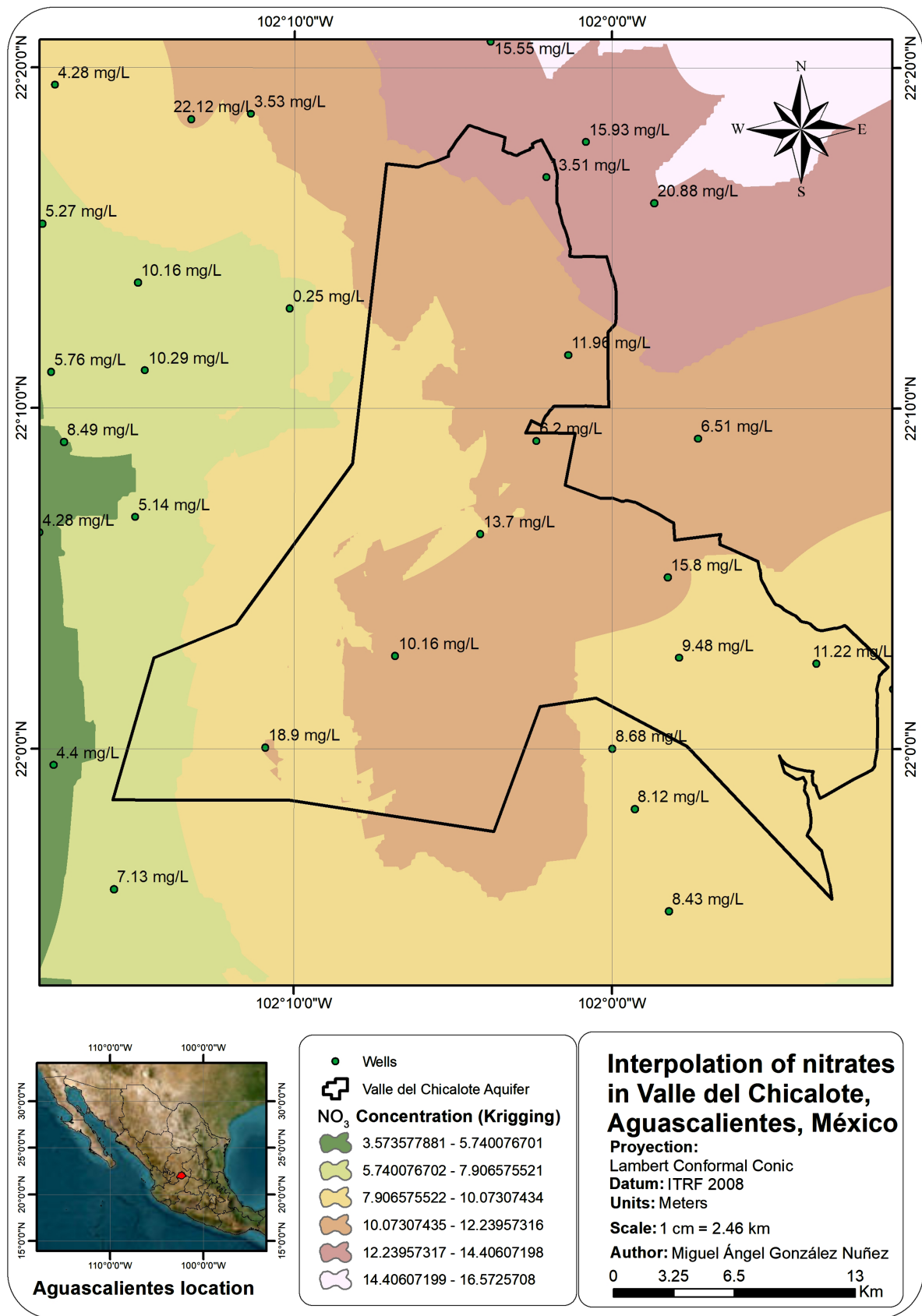


Figure 3. Nitrate interpolation (method: IDW).

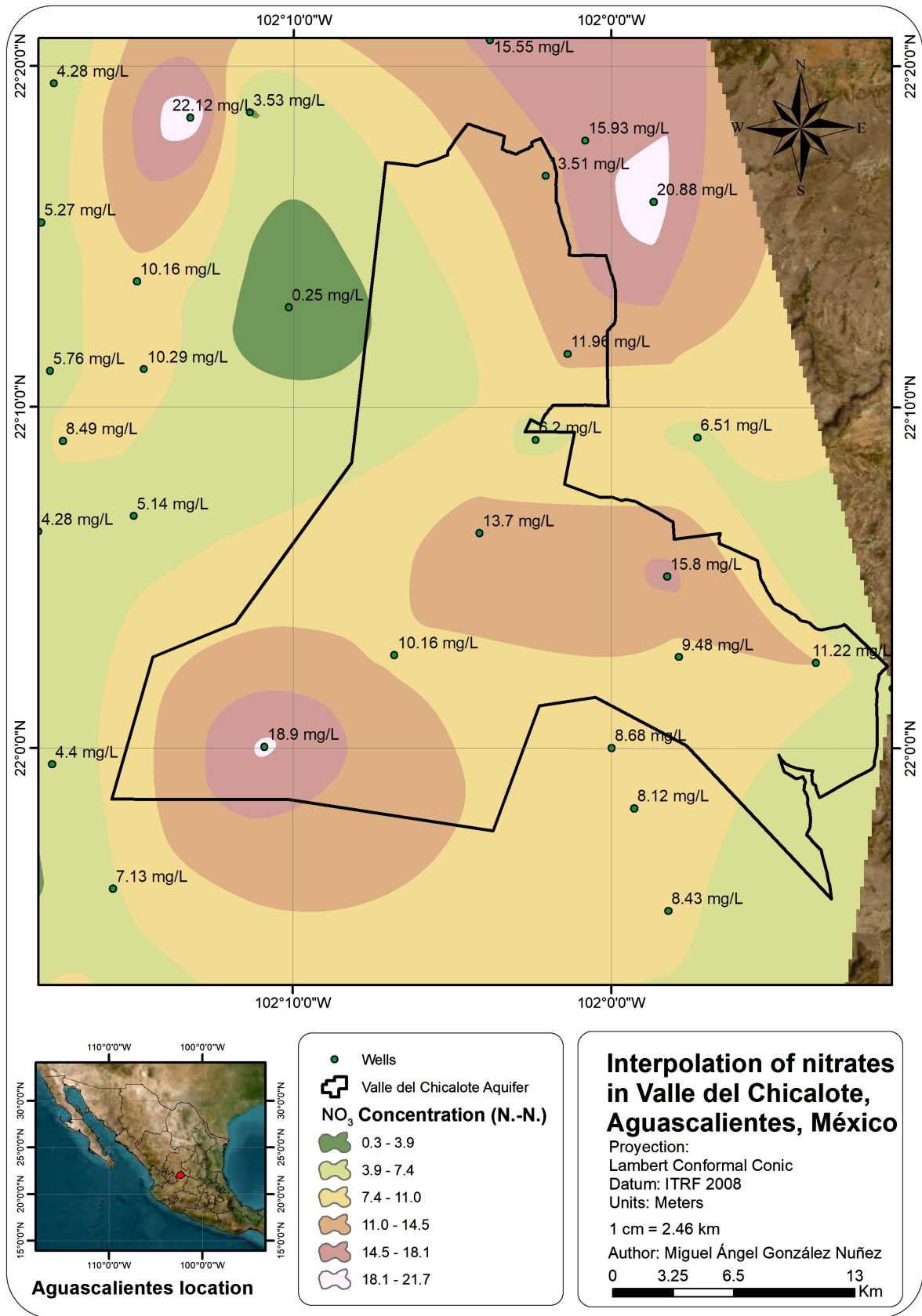


Figure 4. Nitrate interpolation (method: Natural Neighbor).

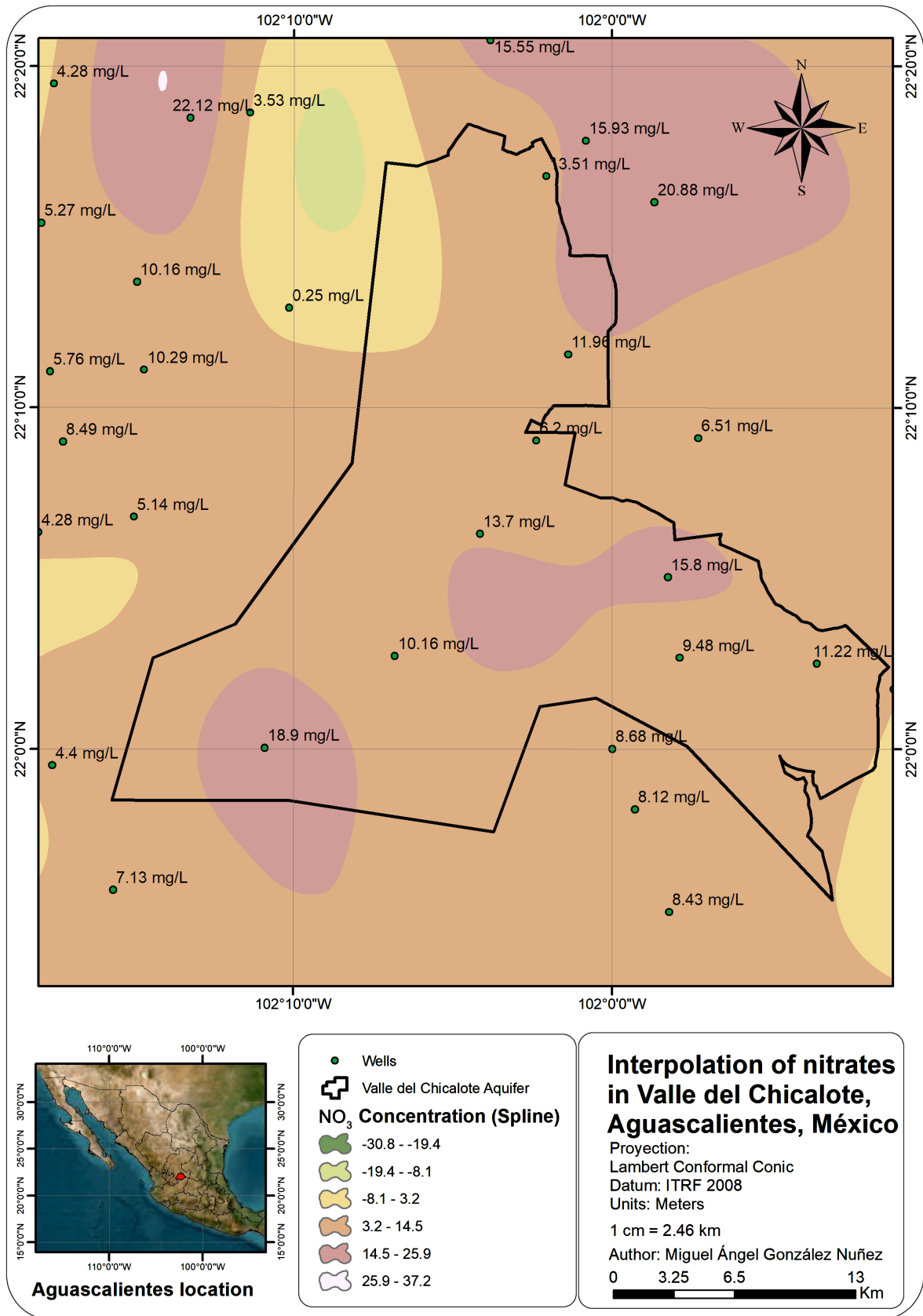


Figure 5. Nitrate interpolation (method: Spline).

## 4. Results and Discussion

Nitrate concentration was studied in sixty-seven wells of the Chicalote Valley aquifer, Aguascalientes, and in 2021, nitrate concentration in twenty-three wells was greater than 10 mg/l (**Table 1**), which is the limit maximum permissible according to OMS. Likewise, according to the interpolation methods used (IDW, Spline, Krigging and Natural Neighbor), it was found that the concentration of nitrates in northern, central, and southern region of the aquifer exceeds the limit allowed by OMS (10 mg/l).

Nitrate concentration in groundwater is influenced by factors such as wastewater, soil, geology, vegetation, topography, well depth and well structure. The lack of water quality control, the gradient flow from higher sites to the wells and the inadequate location of wells in plains are also factors that increase nitrate concentration in wells.

The nitrate concentrations that exceed OMS found in the twenty-three wells corresponding to north, center and south of the aquifer could be due to the presence of extensive agriculture in the area and therefore measures must be taken to mitigate this problem to avoid waterborne diseases related to nitrate intake. Mixing water with low nitrogen concentrations with regional water resources and installing adequate purification systems for drinking water are a couple of alternative solutions to reduce nitrate concentrations.

We must consider that the study primarily varies the interpolation method while keeping other parameters constant, which could potentially overlook other influential factors such as geology, climate, land use variations or temporal changes. This focus might lead to a limited understanding of the broader context that affects the wells being analyzed.

As a recommendation, a cross-validation method to evaluate the predictive accuracy of the interpolation should be used in the future to avoid concerns about the reliability of the results drawn. With these validation techniques, the study's findings may be more robust, as they would have the necessary checks to ensure that the results are accurate and applicable in different scenarios.

Furthermore, the study's focus on a limited geographical area (the Chicalote Valley aquifer), may restrict the generalizability of its findings. Regions with different geology, soil, climate and environmental conditions might not exhibit the same patterns or responses, which limits the applicability of the results to broader contexts. Additionally, while the sample size of sixty-seven wells is sufficient for this study, it could be considered limited for broader applications, potentially reducing the statistical power and the ability to detect smaller but significant trends.

Lastly, future works could benefit by including more recent advancements or alternative methods. Incorporating these could offer improved accuracy or applicability in similar studies, providing a more comprehensive understanding of the subject matter and enhancing the study's relevance to contemporary research.

## 5. Conclusion

In this study, the comparative suitability of different interpolation methods was evaluated based on their precision and sensitivity to variations in Nitrate concentration. According to the results obtained, the IDW method is more appropriate than Kriging, Spline and Natural Neighbor to estimate nitrate concentrations in Valle del Chicalote aquifer wells, since it considers the type of data and sampling pattern. This result is attributed to the ability of IDW to adjust to the spatial structure of the data. However, in other studies (Fallahzadeh et al., 2016; Tutmez & Hatipoglu, 2010), the Kriging method was found to be as accurate as IDW or even better, depending on the context and circumstances in which it is applied. The satellite images also contributed to obtaining a clearer picture of the aquifer in question.

It is undeniable that spatial interpolation methods have several disadvantages: the assumption that values are constant, human error, subjectivity and the amount of time required to interpolate a large amount of data. Despite the above, interpolation methods are a valuable tool to make a first approximation in areas where data is scarce. It should be considered that whatever the interpolation method used, the data obtained are an estimate of what the real values should be in the study area. Therefore, the quality of any analysis based on interpolated data is subject to some level of uncertainty. It is important to appreciate the limitations of interpolated data when using the results in subsequent analyses.

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## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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