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Determination of the sanitary protection zone, comparison of the NC1192:2017 and WhAEM methods, case study of supply sources in San Jose de la Lajas

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Abstract: In Cuba, the National Standardization Office established a calculation procedure for the delimitation of sanitary protection zones (ZPS), in force in NC 1192: 2017. In addition to this procedure, there are mathematical models that are applied worldwide as is the case of the mathematical model using the WhAEM program. These two methods were applied in four of the supply sources of San José de las Lajas. As a result, the two methods show favorable results, with a relationship between them of 99% accuracy, which justifies the use of the WhAEM program in areas where not all the hydrogeological data necessary for the use of the NC 1192: 2017 are available. This guarantees that all supply wells have the determination of ZPS.

Key words: polluting; water quality; WhAEM

1 Introduction

The quality of groundwater is nothing more than the quantity and nature of the different materials that have been incorporated into it during contact with the land through which it flows. Knowledge of these elements will make it possible to determine the possibilities of its use for industrial purposes, irrigation, human consumption and others, since it is the type of use that determines the quality requirements in each case and the necessary analyses, whether chemical, physical or bacteriological. Groundwater can be damaged directly when the contaminating substance is introduced directly into the aquifer by the discharge of water in cesspools or indirectly due to the extraction of water from a well or from the drainage of the area (Pérez, 1982).

The sources of pollution are the continuous activities of man on the environment, some of these sources are: domestic wastewater discharged into septic tanks or cesspools and leaks from sewage systems caused by the life of man in community, pollution by agricultural activity with the use of insecticides, fungicides and others, as they are harmful to humans and animals, also produced by industries such as heavy metals, inorganic and organic substances. Pollution control must begin by subjecting domestic and industrial wastewater to adequate treatment, which can affect both surface and groundwater, and by taking various preventive measures to avoid contamination from other sources. Preventive measures may range from the prohibition, regulation or regulation of certain activities in specific areas and the establishment of safety measures on potentially harmful activities to the creation of detection networks for possible polluting substances. For all protection measures to be effective, there must be detailed knowledge of the hydrogeological characteristics of the aquifer and an adequate water quality control system (Pérez, 1982).

The province of Mayabeque has several sources of contamination from sugar mills, plastic factories, paint factories, as well as from the communities themselves, which have solutions for the waste they cause, while others do not. San José de las Lajas is the capital of Mayabeque province, located in the central northern part of the province, with a surface area of 592.67 km^2 and a total of approximately 80,960 inhabitants who are supplied with drinking water by a total of 12 supply wells located in the territory. Knowing the influence or not of contaminating sources in each supply source is essential to guarantee the quality of the precious liquid. To determine the SPZs, two methods were selected: NC 1192:2017 and the mathematical model WhAEM, which will be applied in three wells in the study area, with the objective of determining if there is a correlation between these two methods and to apply the mathematical model in the wells that do not have all the hydrogeological data necessary to apply NC 1192: 2017.

2 Theoretical references

Groundwater has the ability to recharge and replenish itself. This can occur naturally when rain and snowmelt seep through cracks and crevices beneath the earth's surface, or artificially when people take steps to restore groundwater levels by redirecting water to be reabsorbed into the ground through canals, basins, or ponds (Hermann and Prunes, 2022).

The extraction of groundwater is being higher than its replenishment, which is why it is mandatory to make visible the importance of water resources and develop monitoring, review and follow-up processes and measures to manage the extraction of the resource. Some measures may include (Pérez, 1982):

- Establish protection perimeters.
- Correctly locate solid waste dumps and drains.
- Develop sustainable systems to eliminate polluting liquid compounds that are already within the aquifer zones.
- Improve irrigation and fertilization systems.

2.1 Water pollution

The problem of water pollution has been known since ancient times. With the increase in population and the emergence of industrial activity, the pollution of rivers, lakes and groundwater is constantly increasing. The World Health Organization defines freshwater pollution as follows:

"A water is considered polluted when its composition or state is altered in such a way that it no longer meets the conditions for one or other or all of the uses for which it would have been intended in its natural state".

There is always natural contamination caused by animal remains, plants, minerals and gaseous substances that dissolve when water bodies pass through different terrains (Rodríguez et al., 2011).

Organic materials are degraded to simpler substances through natural biological biodegradation processes involving aquatic decomposers (bacteria and fungi). In these processes, the amount of oxygen dissolved in the water is fundamental because the decomposers need it to live and to produce biodegradation (Ramíres, 2007).

Water pollution caused by human activities is an important environmental phenomenon. Industrial production processes require the use of large volumes of water for the transformation of raw materials, and the effluents of these production processes are discharged into natural watercourses (rivers, lakes) with polluting wastes. Water pollution is caused by the direct or indirect introduction of solid, liquid and gaseous substances, as well as heat energy, among others, into watercourses or aquifers. This pollution causes damage to living organisms in the aquatic environment and also represents a danger to the health of people and animals.

Pollution sources can be natural and anthropogenic, the latter including industrial pollution, urban discharges, pollution from shipping and from agricultural and livestock activities, with the industrial and urban sources being of greater importance for this work.

The quality of groundwater is of great importance since this water is a source of supply in the world, of rapid use and relatively low cost (Perez, 1982), so it is important that it be monitored since it is a renewable and limited resource. It supplies the population as well as industry and irrigation, and each of these activities determines the quality requirement demanded by the quality standards established for such use.

In order to protect water quality, sanitary protection zones are determined, which are nothing more than the territories created around the water supply sources to preserve their quality. These are divided into 3 zones: zone I is a fenced area around the supply well, where there are greater restrictions; in zone II the existence of any type of hazardous waste, industrial products or agricultural activities is not recommended; and in zone III some activities are allowed as long as the pertinent measures are complied with. These zones are located away from industrial companies and residual areas to protect the health of adjacent areas, providing an area for the safe disposal of hazardous industrial waste, adjusting their concentrations to current hygienic regulations, to protect the reserves and maintain adequate water quality.

2.2 Legislative framework

The National Standardization Office (NC) is the National Standardization Body of the Republic of Cuba that represents the country before International and Regional Standardization Organizations. NC 1192: 2017 establishes the calculation procedure for the determination of the sanitary protection zone, replacing NC 93-01-209: 1990 and adjusted to the new format established by the NC. The standard is applicable to all groundwater supply sources, which are studied by the system of the National Institute of Hydraulic Resources (INRH), or by any other private or State organization that is granted this responsibility. The same does not apply in those wells for domestic use, where no extraction permit is required. The user is responsible for monitoring the quality of the well water through the Ministry of Public Health.

3 Materials and methods

3.1 Geographical location

San José de las Lajas is the capital of the province of Mayabeque, located in the central northern part, with a surface area of 592.67 km², bordered to the north by the province of Havana and the municipality of Jaruco, to the south by the municipalities of Güines, Melena del Sur and Batabanó, to the east by the municipalities of Madruga and Güines, and to the west by the municipalities of Bejucal and Quivicán. The plain where this territory is located is bordered to the north by the heights of Habana-Matanzas and to the south by the heights of Bejucal-Madruga-Limonar. Geologically, the study area is characterized by the presence of rocks of the Colón Formation which is characterized by biogenic calcareous marls, biogenic clayey limestones, biogenic-detritic limestones and eventually sand lenses. Its color varies from mustard in the most altered portions, to yellowish cream at depth. The total thickness of the formation can reach about 80 meters. It rests discordant on the oldest rocks and in turn, it is covered concordantly by the Güines Formation and eventually by the Cojímar Formation, as occurs north of Limonar. This formation is aquiferous and all the wells in the study area are located in it.

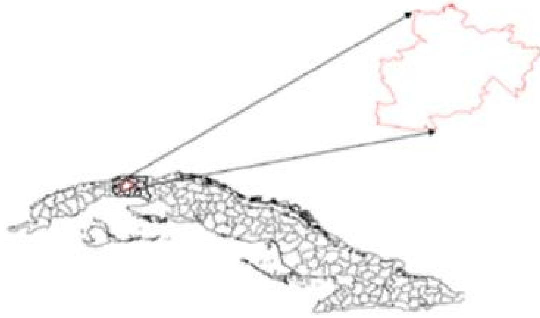

Figure 1. San José de las Lajas

The three supply wells selected to establish the comparison between the methods for determining the SPZ belong to INRH, which are distributed in the main area of the municipality of San José de las Lajas. The main purpose of these wells is to supply both the population and the main industries in the area. Table 1 shows the names of the sources and their geographic location, which can be seen in Figure 2:

Table 1. Sources of supply

No	Town or Village	Watershed	Station name	Coordinates	
				North	East
1	San José de Las Lajas (Consejo Popular Norte)	HAV-2	Ac. San José de Las Lajas No. 1	350 250	382 720
2	San José de las Lajas	HMJ-1	Ac. Las Parcelas	348 080	383 810
3	Pastorita y Vostok	HAV-2	Ac. Gran Panel	350 600	381 230

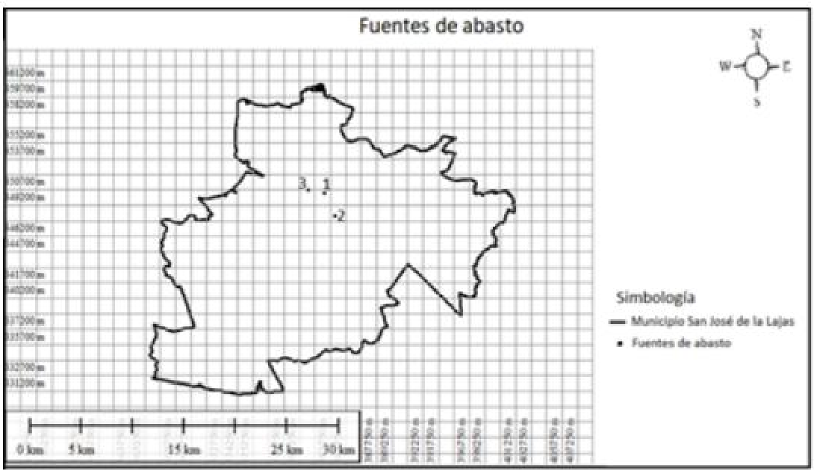

Figure 2. Location of water supply wells

Calculation procedure by NC: 1192: 2017.

To determine the ZPS by NC 1192: 2017 it is necessary to know and determine a group of parameters that will later be necessary to establish the representation of the zone. The values of the velocity in the main flow direction towards the well (Ux), is obtained by Equation 1 while the natural gradient will be determined by Equation 2, Equation 3

$$U_x = I_0 * kd \quad (1)$$

Where:

I_0: Natural gradient

$$I_0 = \frac{\Delta h}{L} \quad (2)$$

Where:

Δh: Height difference between equipotential lines (m).

L: Distance between equipotential lines with respect to each well (m).

Kd: Hydraulic conductivity (m/s).

$$k_d = \frac{T}{h_0} \quad (3)$$

Where:

T: Hydraulic transmissivity of the aquifer (m/s).

h_0: Saturated thickness.

$$h_0 = profundidad\ total - NE \quad (4)$$

Where:

NE: Static level

The stagnation point (Xo) is determined by the equation:

$$X_0 = -\frac{Q}{2\pi * k_d * h_0 * I_0} \quad (5)$$

Where:

Q: Source extraction flow rate (m^3/s).

The maximum horizontal extension (Y) is obtained by the equation:

$$Y = \pm \frac{Q}{2k_d * h_0 * I_0} \quad (6)$$

The sanitary protection distance (*DPS*) is calculated using the equation:

$$DPS = \sqrt{\frac{Q}{\pi * h_0 * \mu}} * t_d + X_p^{\ 2} \quad (7)$$

μ: Storage coefficient, whose value is obtained according to the geological formation where the supply source is located. In this case it is equal to 0.02, since the three wells are located in the Colón formation.

t_d: Bacteria survival time (d), takes values between 50 and 75 days.

Xp: Stagnation point (X_0).

The width of protection zone II at distance *DPS* (*DII*)

$$D_{II} = \frac{1}{3} DPS \quad (8)$$

After calculating X_0, Y, *DPS* and *DII* these values are multiplied by a safety factor, in this case 1.3, to be on the safe side.

Procedure for the calculation of the ZPS by the mathematical model WhAEM.

The WhAEM (Haitjema and Kraemer, 2018) is a numerical model used for environmental risk assessment and management of chemicals; it is used to calculate the dispersion of these substances in the atmosphere and determine the exposure levels to which humans and the environment are exposed. To calculate health protection zones, WhAEM uses a layered protection approach, which consists of three layers of protection designed to provide different levels of protection for different population groups.

The first layer is the exclusion zone, which is intended to protect the extraction sources from contamination. This zone is based on the danger to life and health of the chemicals, generally it will be in a radius of 30 to 100 meters from the contamination site.

The third layer is the long-term protection zone. This zone is intended to protect the well from low levels of chemicals. This zone is based on chronic toxicity criteria and can extend up to several kilometers from the contamination.

3.2 Base maps

WhAEM (Haitjema and Kraemer, 2018) is supported by several raster maps and vector graphics, which serve as the basis for the groundwater models to flow. All maps must be georeferenced, i.e., they must contain coordinate information in UTM, and can be either NAD 27 or NAD 83, in this case NAD 27 was used.

3.3 Aquifer parameters

WhAEM requires the user to specify four regional aquifer parameters which are done by clicking on the Model setting option, as shown in Figure 3.

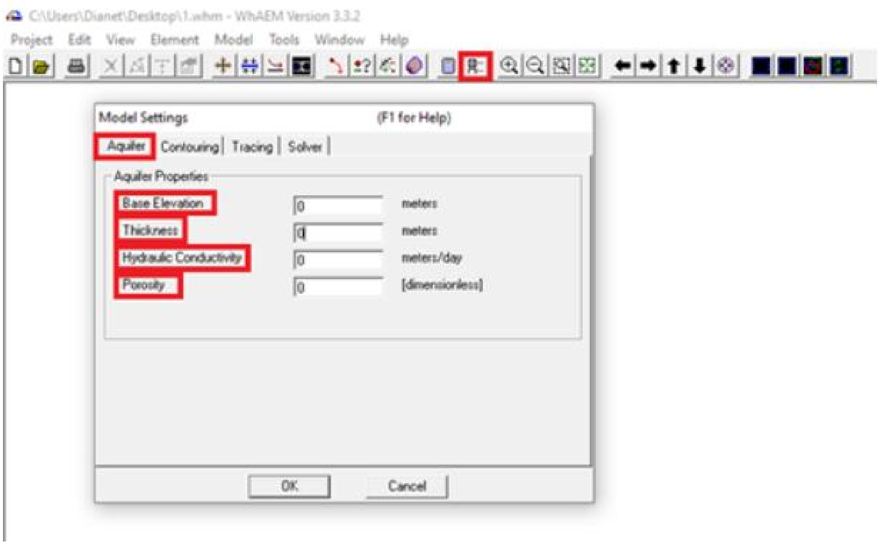

Figure 3. Aquifer configuration

The base elevation is in feet or meters above sea level. The base water table may be a layer of clay or stone surface that is normally not a perfect horizontal surface, and it is important that this base water table not be higher than the lowest water level.

Aquifer thickness is the actual thickness of the aquifer material above the bottom of the water table, regardless of how much it is saturated. If you want to ensure that conditions flow throughout the domain, regardless of groundwater elevation, you must set the aquifer thickness to a high value, large enough to ensure that the base elevation plus the aquifer thickness are above the water body.

The hydraulic conductivity is the regional value. A different hydraulic conductivity can be selected locally by defining one or more domains.

The porosity in WhAEM is an effective porosity which is the regional value. A different porosity can be selected locally by defining one or more domains, the porosity value is used to track the groundwater pathway.

3.4 Uniform flow

The uniform flow option (see Figure 4) allows regional flow planning without the introduction of surface water features into the model. This option should not be used in combination with other analytical elements, except for wells, so that protection zones are generated. Uniform flow is calculated based on a specified hydraulic gradient and regional aquifer properties.

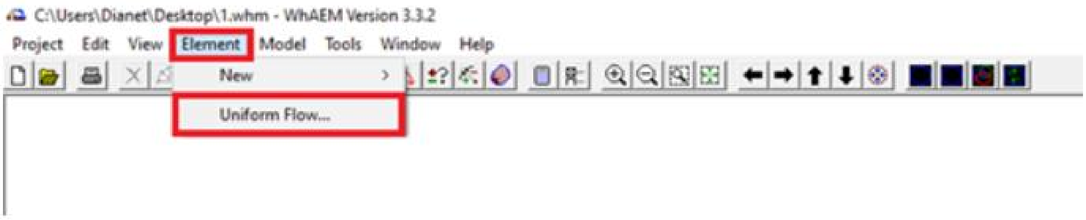

Figure 4. Configuration of the uniform flow option

3.5 Wells

To create a well, click on the Add well option in the menu (see Figure 5), place it in any zone and the options will be displayed where the well location can be adjusted by replacing the coordinates in the data box, then type the pumped flow rate in the discharge box and the radius of the well (never use commas in the numerical data).

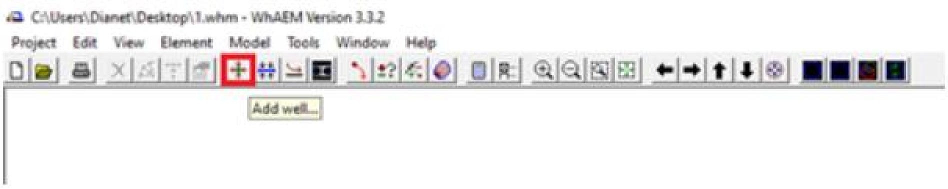

Figure 5. Add well option

3.6 Solver

The Run! button is pressed (see Figure 6), a black box appears with some indicators of the solver process. When the solver is done, the map reappears with a contour cover (blue lines) and the protection zone represented.

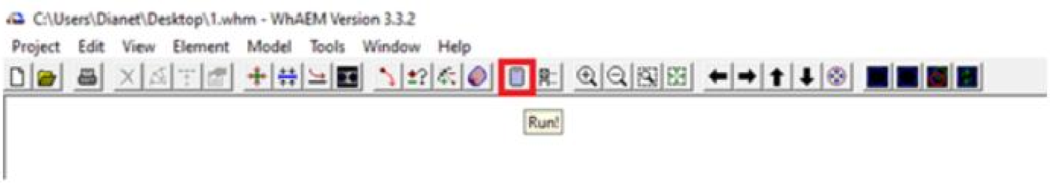

Figure 6. Run option

4 Results

The methodology described was applied in the three supply wells of the municipality of San José de las Lajas, the initial data for each of the wells: flow, total depth and static level are shown in Table 2. While Table 3 shows the calculated parameters, to determine the stagnation point (Xo), the maximum horizontal extension (Y), the sanitary protection distance (DPS) and the width of the same (D II) which are represented in Table 4, along with the parameters recalculated by the safety factor that according to NC 1192:2017 is 1/3 of the values obtained.

Table 2. Initial well data

No. Well	Q (m^3/d)	Total depth (m)	N.E.(m)
1	25	61	35,64
2	90	61	23
3	25	38	12,3

Table 3. Parameters for the calculation of Xo, Y, W, DPS and DII according to the Cuban standard

No. Well	Ho (m)	T (m/s)	Kd (m/d)	Δh (m)	L (m)	Io (adim)	Ux (m/d)
1	25,36	100	3,9432	20	15267	0,0013	0,0051
2	38	100	2,6316	20	6932	0,0029	0,0076
3	25,7	100	3,8911	20	16213	0,0012	0,0047

Table 4. Xo, Y, W, DPS and DII calculated and multiplied by the safety factor 1.3 according to Cuban standards

Calculated parameters						Parameters multiplied by the safety factor (1,3)				
No. Well	Xo (m)	Y (m)	W (m)	DPS (m)	DII (m)	1,3*Xo	1,3*Y	1,3*W	1,3*DPS	1,3*DII
1	-30,63	96,16	192,32	1215,47	405,16	-39,82	125,01	250,02	1580,12	526,71
2	-49,42	155,18	310,36	2872,11	957,37	-64,25	201,74	403,48	3733,75	1244,59
3	-33,18	104,17	208,34	1376,35	458,79	-43,14	135,43	270,86	1789,26	596,42

Table 5 shows the dimensions Xo, Y, W, DPS and DII of the protection zones obtained both by the calculation using the Cuban standard in force in our country, as well as those obtained using the mathematical model, where a correlation coefficient of 0.99 is observed; with a difference between the two methods ranging from 8m to 214 m in the extension of the DPS, being the WhAEM model (Haitjema and Kraemer, 2018) the one that behaves with a greater variation in the values with respect to the NC, as can be seen in Figure 7, Figure 8 and Figure 9, where the two methods are represented for the three wells studied.

Table 5. Dimensions of the sanitary protection zones according to both methods

Cuban Standard (with safety factor)						WhAEM					
No. Well	Xo (m)	Y(m)	W (m)	DPS (m)	DII (m)	Xo (m)	Y(m)	W (m)	DPS (m)	DII (m)	Correlation coefficient
1	-39,82	125,01	250,02	1580,12	526,71	-51,58	133,35	266,7	1638,7	571,73	0,99
2	-64,25	201,74	403,48	3733,75	1244,59	-68,12	264,53	529,06	3801,64	1030,09	0,99
3	-43,14	135,43	270,86	1789,26	596,42	-68,26	149,21	298,42	1952,77	459,33	0,99

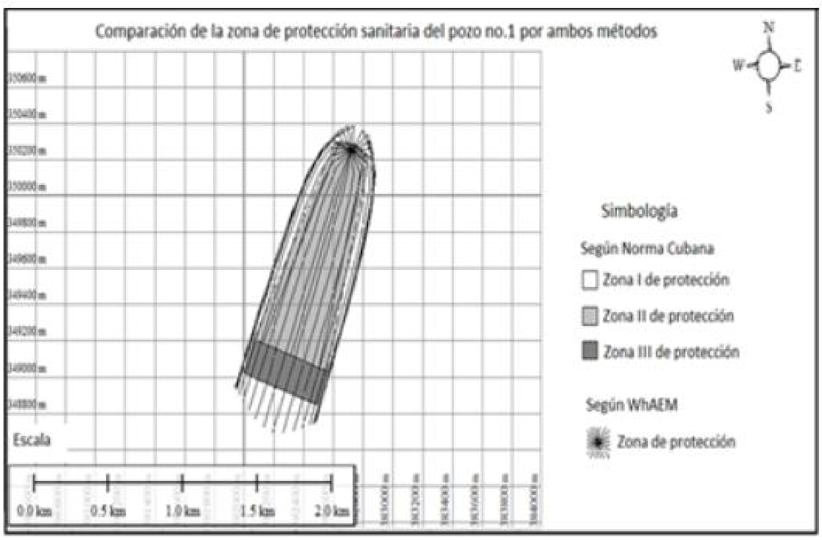

Figure 7. Comparison of the protection zones of well 1 according to both methods

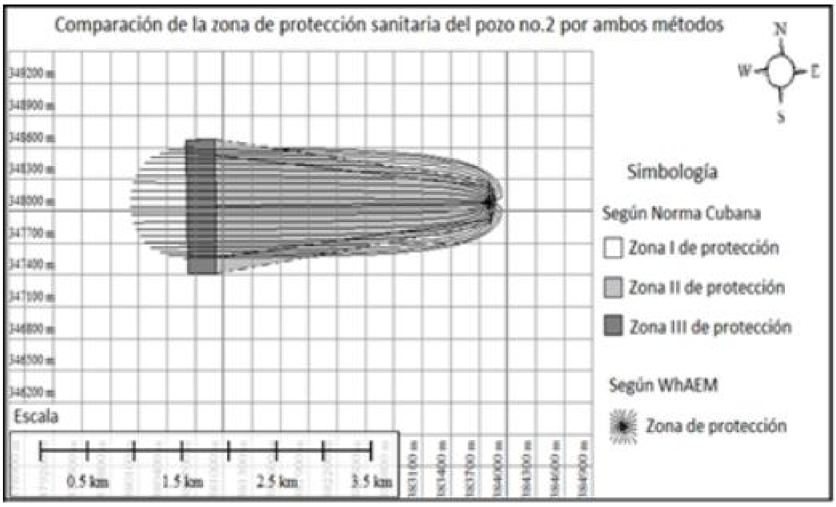

Figure 8. Comparison of the protection zones of well 2 according to the two methods

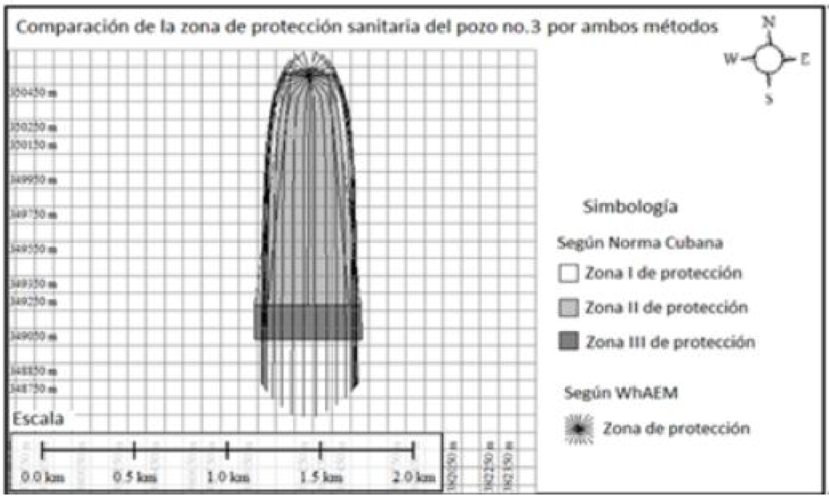

Figure 9. Comparison of the protection zones of well 3 according to both methods

The results achieved by the two methods allow us to positively evaluate the WhAEM model with respect to NC 1192: 2017, which allows the determination of the ZPS, in those wells that do not have complete hydrogeological data, making it easier to obtain the different zones, since in addition to giving values similar to the NC, the program provides us with a graphical output.

5 Conclusions

It was possible to determine and update the three sanitary protection zones of San José's water supply sources by the two selected methods, the current Cuban standard and the WhAEM mathematical model. The correlation between the two methods was 99%, which means that any of the two methods can be used to determine the SPZ.

Sanitary protection zones should be updated periodically to ensure that the latest findings on toxicity and other relevant factors are being taken into account.

Both methods have their limitations and can be improved through the use of more accurate data and more detailed studies of the effects of chemicals, these methods can be complementary and used in conjunction with each other depending on the situation and the degree of knowledge about the associated risks.

Conflicts of interest

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

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