Optimization of a groundwater quality campaign utilizing the NSGA-II with preference ordering algorithm, contamination risk maps and well availability

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Abstract

In Paraguay, the Patiño aquifer supplies water for 43% of the population covering the largest and most densely populated urban area of the country. A previous study [1] showed that 42% of the had a high risk of contamination by Nitrogen (TN) and Coliforms (TC). Most of the risk is due to the fact that there area more than 2800 deep wells that extract water from the subsoil with very little monitoring and that 93% of the houses in the aquifer area depend on septic tanks or blind wells for sewage disposal. Due to economic and practical constraints it is not possible to analyze all deep wells or monitor the aquifer continuously.

This work focused in selecting 70 wells to conduct a groundwater quality sampling campaign. The wells were selected using 4 objectis: contamination risk of NT and CT, the coverage area and the wells which are publicly accessible. A Multiobjective Optimization Problem was defined to obtain the possible selections, and the Nondominated Sorting Genetic Algorithm II [2]] with Preference Ordering [3] was implemented to solve it. The proposed solutions allowed the selection of 70 wells, 86% correspond to the wells which are publicly accessible, 70% of the wells are located in places with the high indices of contamination risk and cover 74% of the study area.

Based on the selection of wells a water quality sampling campaign was carried out in the selected wells. As of now there are 60 water quality results, performed in the laboratory. In total 21 parameters were analyzed such as: N-Ammoniacal, N-Nitrite, N-Nitrate, Total Alkalinity, Organic Matter, Conductivity, pH, Bicarbonate, Carbonate, Sulfate, Magnesium, Calcium, Sodium, Potassium, Chloride, Arsenic, Mercury, Manganese, Copper, Total Chromium and Fecal Coliforms.

Problem Statement

Of the more than 2800 wells, which wells should we choose to sample in a water quality campaign ?

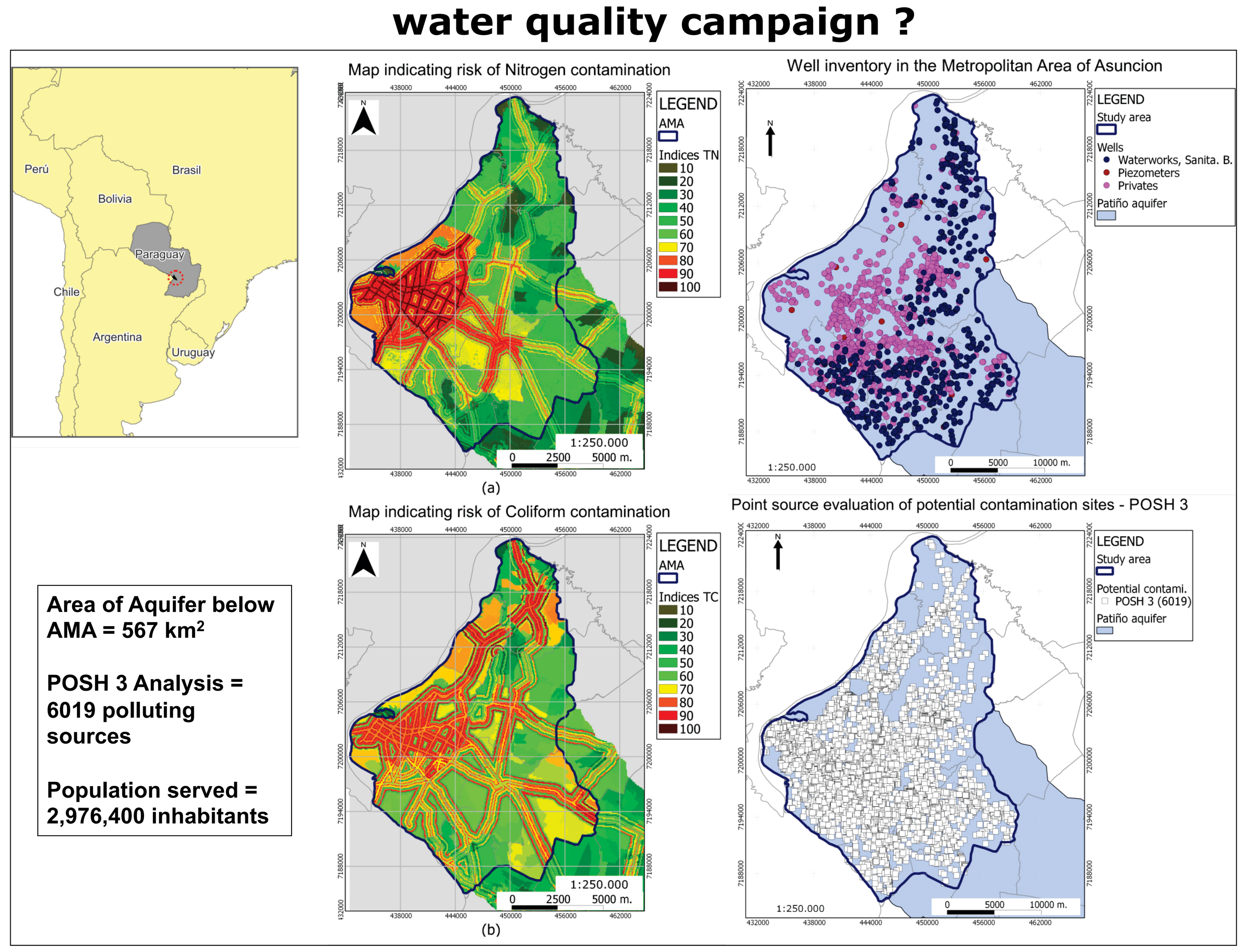


Fig. 1. Location of the Patiño aquifer with risk maps for contamination by NT and CT produced in [1]. The Metropolitan Area of Asuncion above the aquifer (567 km²), hosts more than 2800 deep wells and has more than 6000 potential sources of contamination based on a POSH analysis.

Research Objective

Select wells to carry out a water quality analysis campaign within the Metropolitan area of Asuncion (AMA), as a starting point to understand the state of the aquifer and to propose a permanent monitoring network.

Methods and Approach

The selection of wells was developed using NSGA-II [2] with Preference Ordering [3], combined with a GIS platform. The model considers maximizing **4 objective functions**:

$$maxITN_{acu} = \sum_{i=1}^{i=70} ITN_i \qquad (1)$$

where *ITNacu* is the cumulative contamination risk by Nitrogen concentration, and *ITN* is the individual contamination risk at a specific well site (80 m x 80 m cell).

$$maxITC_{acu} = \sum_{i=1}^{i=70} ITC_i \qquad (2)$$

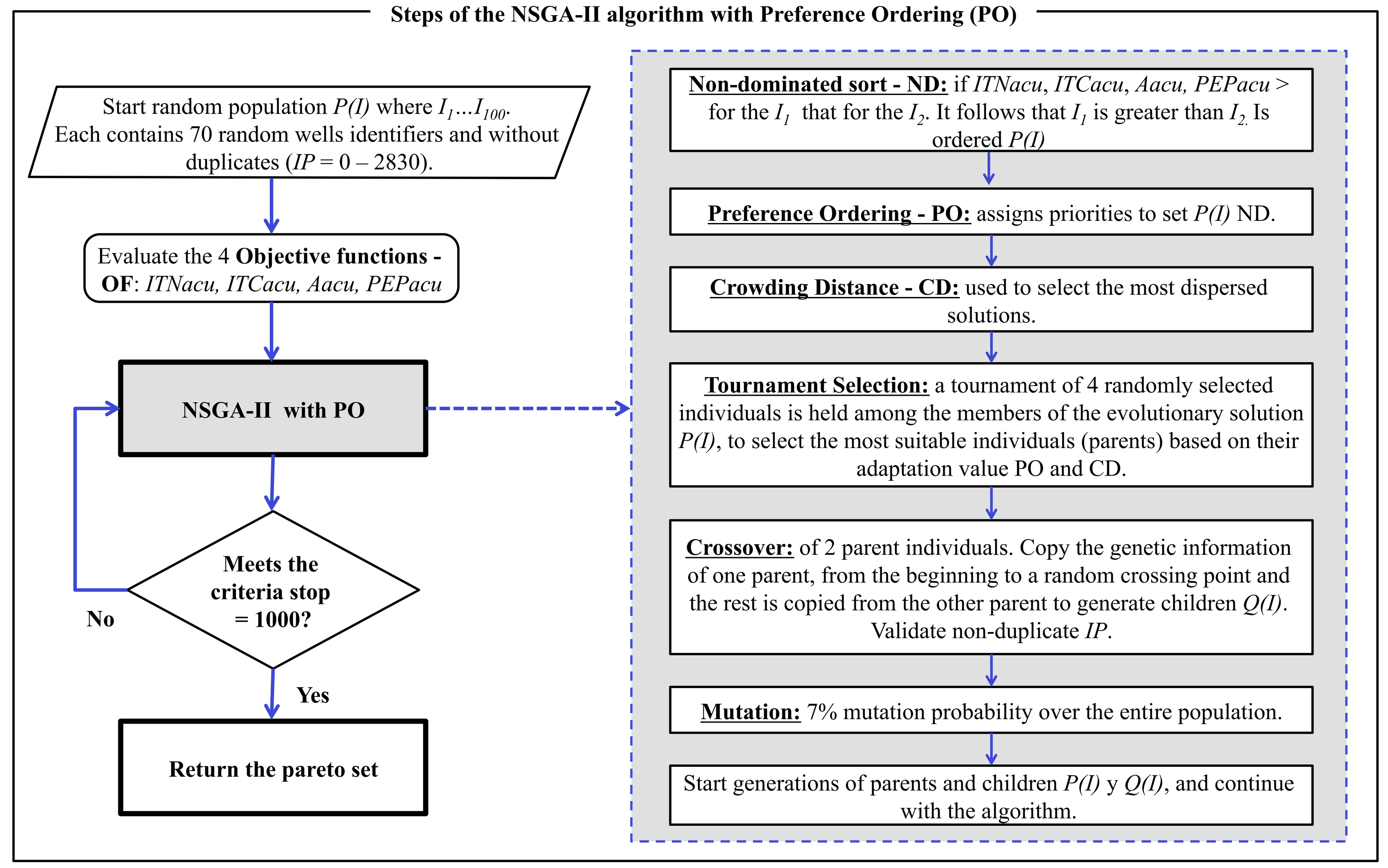
where *ITCacu* is the cumulative contamination risk by Coliforms, and *ITC* is the individual contamination risk at a specifc well site (80 m x 80 m cell).

$$maxA_{cob} = \sum_{i=1}^{i=70} A_i \qquad (3)$$

where *Acob* is the combined/total coverage area of the selected wells and *A* is the area of each well which is calculated utilizing the "buffer" function. Each well has a supposed coverage area of 1600 m.

$$maxPEP = \sum_{i=1}^{i=70} Ip_i \qquad Ip_i = \begin{cases} 1 \\ 0 \end{cases} \qquad (4)$$

where *PEPacu* is the number of total priority wells. Priority=1 for the wells which are publicly accessible (waterworks, sanitation boards and piezometers), priority=0 if it is a private residence well.



Results

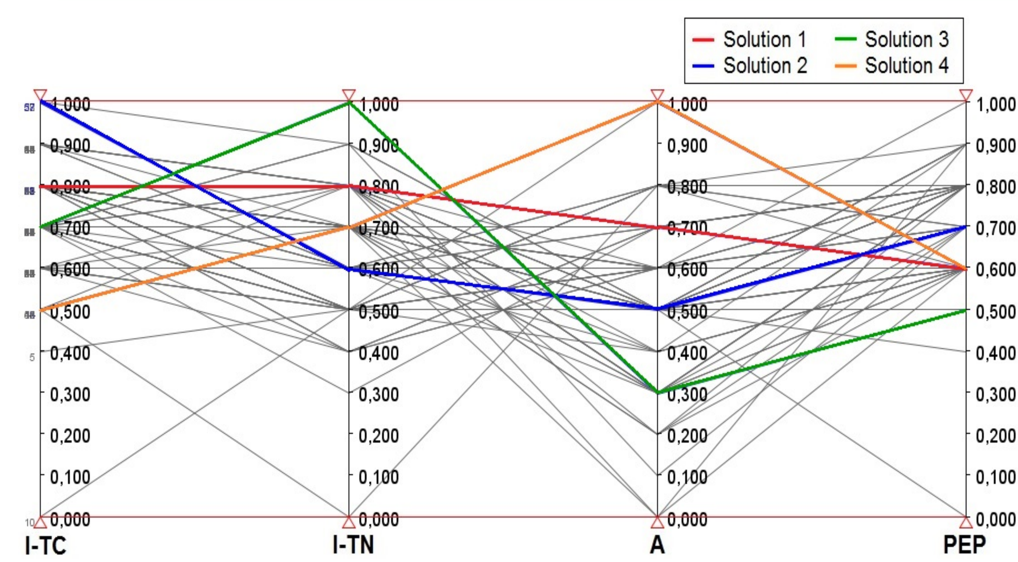


Figure 2. Parallel coordinates shows the optimal pareto front of the final 64 solutions – after executing the algorithm with 1000 generations. Solution 1: maximum value of the normalized sum of the four objectives. Solution 2: maximun I-TC risk. Solution 3: maximum I-TN risk. Solution 4: maximum coverage area.

I-TC – risk of contamination by Coliforms.
I-TN – risk of contamination by Nitrogen.
A – Coverage area of wells.
PEP – Publicly available wells.

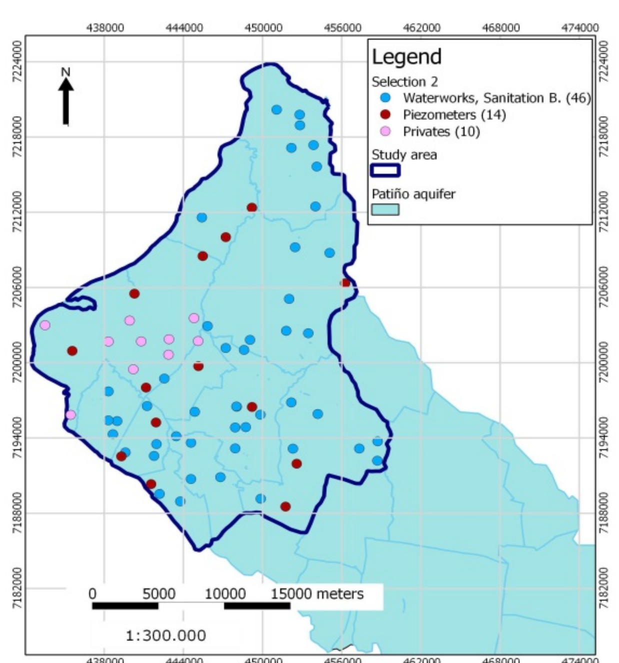


Fig. 3. Solution 2. Selection of 70 wells using NSGA-II with PO.

Table 1: Comparative summary of the pareto optimal fronts of NSGA-II with PO vs. Classic NSGA-II

	NSGA-II with PO	Classic NSGA-II
Pareto optimal front	64 options	88 options
High I-TN (70-100)	59% of the selected wells	59% of the selected wells
High I-TC (70-100)	70% of the selected wells	64% of the selected wells
Max. coverage area (%)	74% of Aquifer	68% of Aquifer
Max. well priority (%)	86% of all wells	69% of all wells

Equipment used in the groundwater quality sampling campaign.

More Results

Analysis of the 60 water quality results of the sampling campaign carried out between July and November 2018.

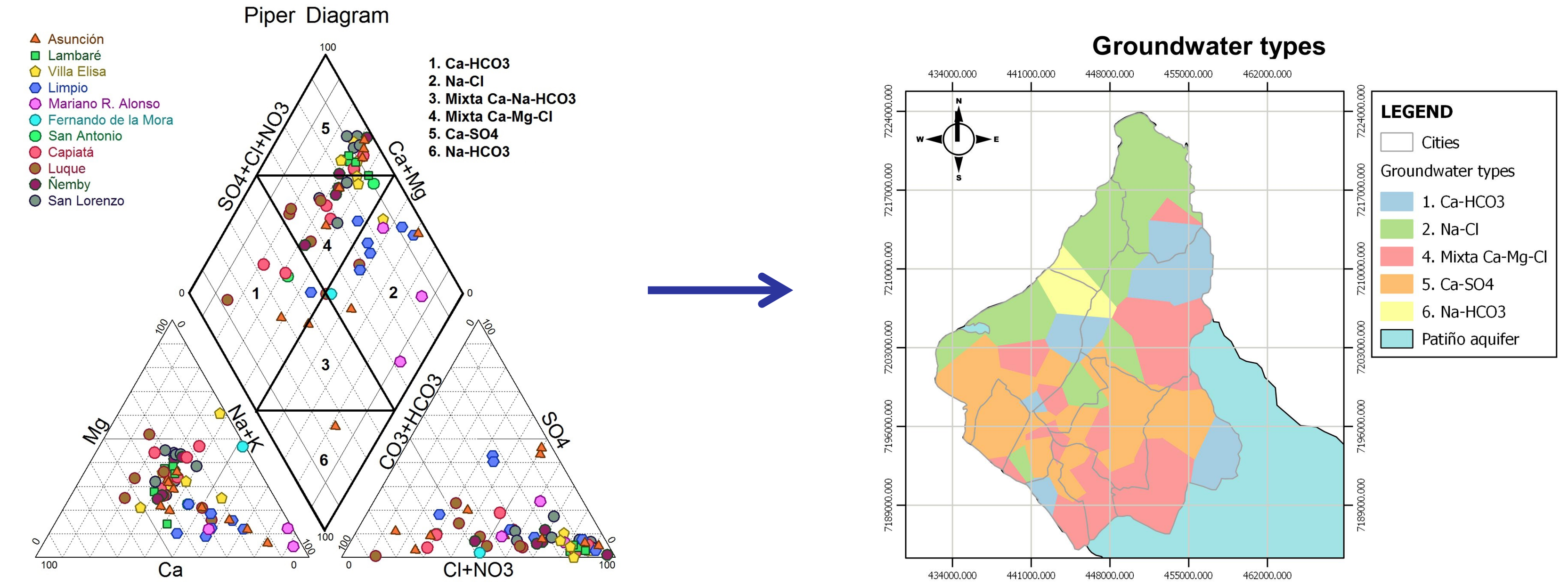


Fig. 4. The Piper diagram shows the types of water samples analyzed and the geochemical processes identified. Two predominant types of waters were determined: 33% of the sulphated calcium type (5) and 30% of the chlorinated calcium-magnesium mixed type (4). A lower percentage was also identified: 22% of the sodium chloride type (2), 13% the calcium-bicarbonate type (1) and 2% of the sodium bicarbonate type (6).

Critical areas

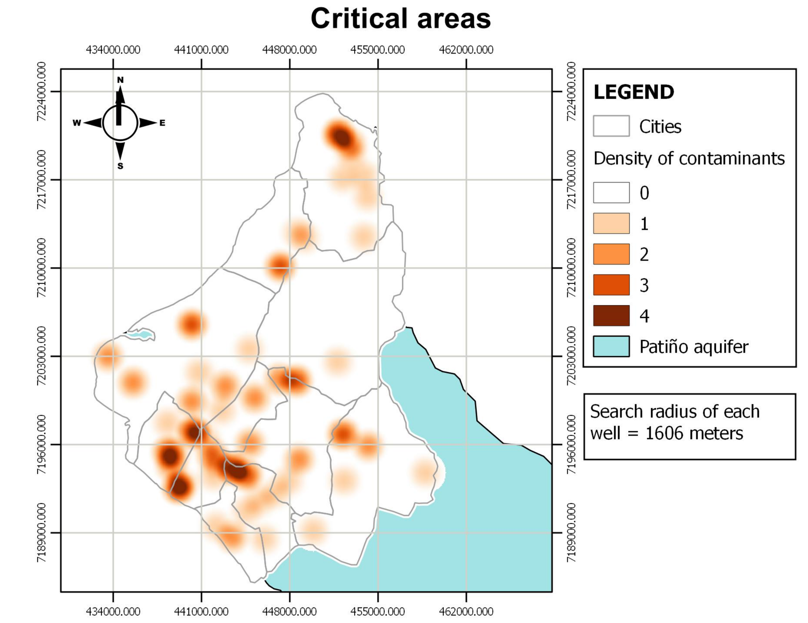


Fig. 5. Map of critical areas. Density of parameters outside legal standards per well over the AMA.

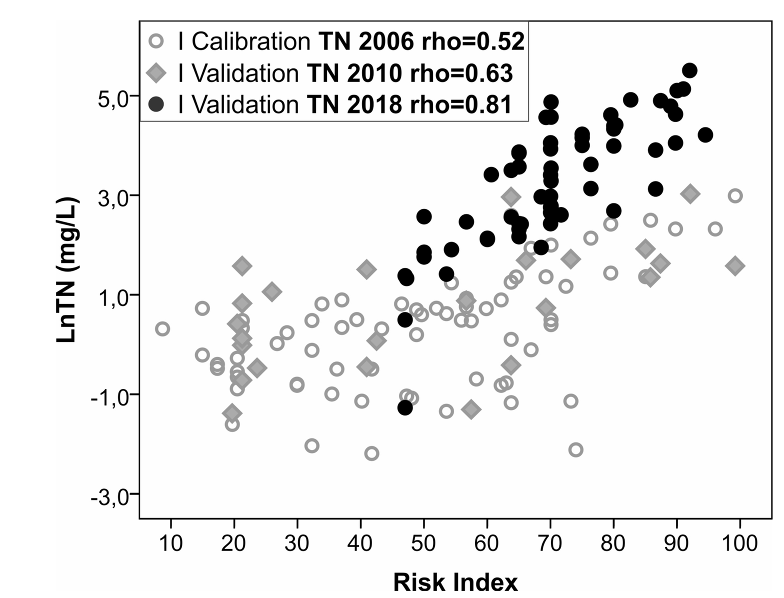


Fig. 6. Scatter of the TN concentrations of 2006, 2010 y 2018 vs. the pollution risk index model which was calibrated with NT of 2006 [1].

Conclusions

- The proposed algorithm allowed the selection of 70 wells to carry out a water quality sampling campaign. Based on the search algorithm, composed of four objectives, 59% of the wells were located in places with high risk of contamination (70-100) by nitrogen, and 74% of the wells were located in places with high risk of contamination by coliforms.
- Moreover, 70% of the selection correspond to wells which are publicly accessible and cover 74% of the study area.
- The measured nitrogen parameters had a high correlation (ρ = 0.81) with the risk indices produced by the a priori model developed in [1].
- Two predominant types of waters were determined: 33% of the sulphated calcium type and 30% of the chlorinated calcium-magnesium mixed type.
- The contaminants outside the admissible limit are: sodium (1), chloride (2), pH (32), conductivity (13), N-Ammonia (11), Fecal coli. (2), and N-Nitrate (25).

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