Multi-Objective Optimization for the Selection of Wells for a Water Monitoring Campaign of the Patiño Aquifer, Paraguay

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Introduction

Ensuring the quality of the drinking water supply is important for protecting the health and economy of urban populations (Masterson and Pope, 2016).

Groundwater is a widespread resource, but hidden and inaccessible and in contrast to surface water, changes in its quantity and quality are very slow processes that occur under the ground in large areas (Tuinhof et al., 2006).

Masterson, J.P., and Pope, J.P. (2016). Sustainability of groundwater supplies in the Northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Fact Sheet.

Tuinhof, A., Foster, S., Kemper, K., Garduño, H., and Nanni, M. (2006). Nota 9: Requerimentos de Monitoreo del Agua Subterránea. Gestión Sustentable del Agua Subterránea. Banco Mundial y GWP.

Patiño Acuifer

In Paraguay, a main source of groundwater is the Patiño aquifer (1173 km^2), used on a large scale for human consumption, and supplies 43% of the population (DGEEC, 2012), in an area, mainly urban, in addition to the commercial, industrial and agricultural sector.

Given its geographical location and its geological conditions, the aquifer runs the risk of constant contamination due to spillages on the water table and limited or no municipal sewerage coverage, with 93 % of households have cesspools (MOPC, 2010).

In this context, we want to know the state of the water quality of the Patiño aquifer, through a sampling campaign.

DGEEC. (2012). Encuesta Permanente de Hogares. Dirección General de Estadística Encuestas y Censos.

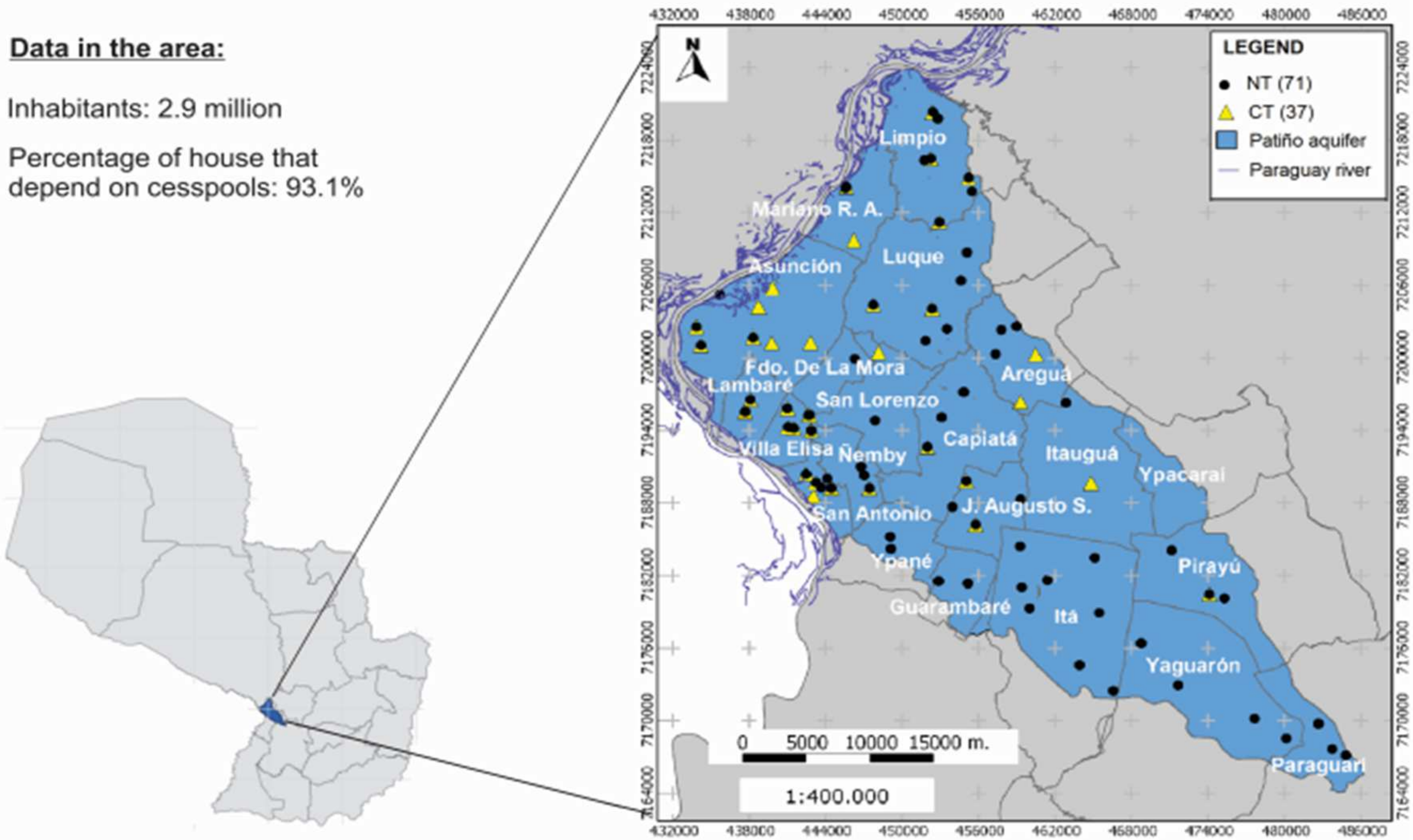
MOPC. (2010). Actualización del Análisis Sectorial de Agua Potable y Saneamiento de Paraguay. Ministerio de Obras Publicas y Comunicaciones.

Patiño Acuifer

Data in the area:

Inhabitants: 2.9 million

Percentage of house that depend on cesspools: 93.1%



Problem

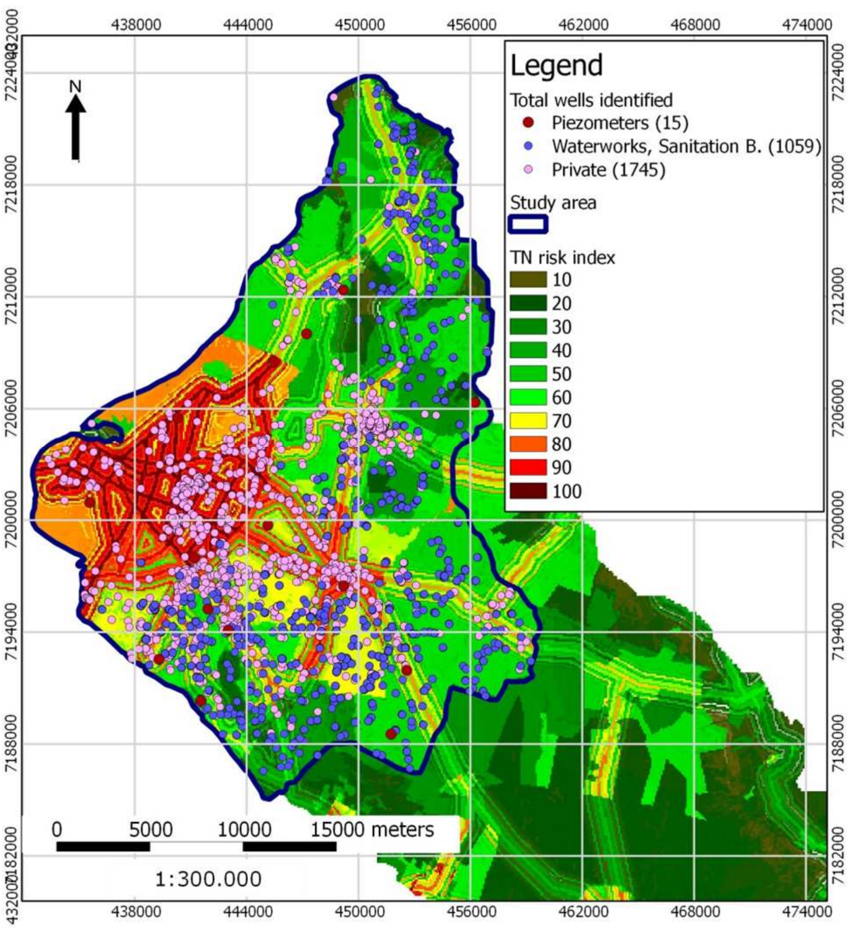
A previous work (Báez et al., 2014) identified the areas of greatest risk of contamination of the Patiño aquifer, by the concentrations of Total Nitrogen (NT) and Total Coliforms (TC), these present a risk index with values between 0 and 100, for each pollutant . The highest rates (70-100) were found within an area of 567 km2.

There also exists around 2800 deep wells that extract water from the subsoil, correspondig to waterworks, sanitation boards, piezometers and private wells, with very little sanitary treatment.

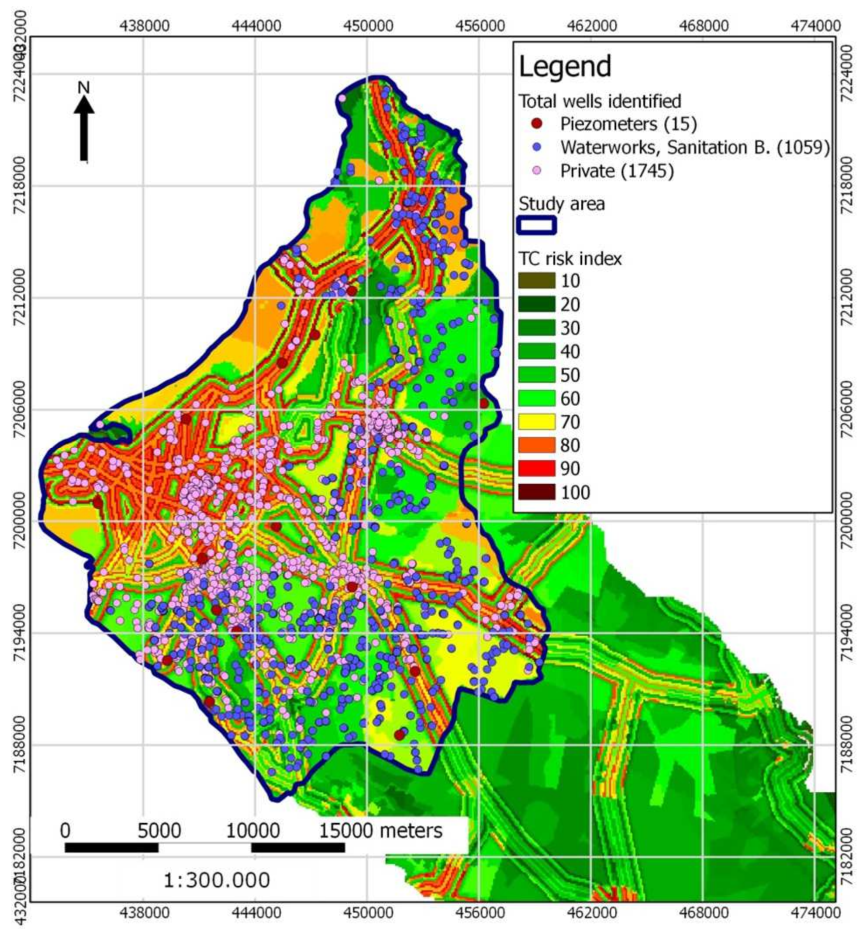
Baez, L., Villalba, C. and Nogues. J. P. (2014). Mapeo de la Vulnerabilidad y Riesgo de Contaminación del Agua Subterránea del Gran Asunción.

Problem

Total Wells Identified and the Total Nitrogen Risk Map



Total Wells Identified and the Total Coliforms Risk Map



Multi-Objective Optimization Problem

The uncertainty of this work lies in the fact that the wells to be evaluated are unknown in order to guarantee the representativeness of the samples to be made, which leads to a Multi-Objective Optimization Problem (MOP) for the optimal selection of wells.

Due to economic and practical constraints it is not possible to analyze all deep wells. Thus, this work aims to select 70 wells to conduct a groundwater quality sampling campaign considering to maximize four objective functions: contamination risk indices by concentrations of TN and TC, the coverage area and the wells which are publicly accessible.

A MOP was defined to obtain the possible selections, and the Nondominated Sorting Genetic Algorithm II (NSGA-II) proposed by Deb et al. (2002), was implemented to solve it.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T. A. M. T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6(2), 182-197.

Multi-Objective Optimization Problem

- Selection limited to 70 wells
- The area to monitor covers 567 km2
- Wells should cover as much area as possible
- The wells should be located in places with high risk of contamination by TN and TC
- Prioritize the selection of wells which are publicly accessible such as waterworks, sanitation boards and piezometers

Formal Representation of the Problem

1. Maximize the contamination risk indices:

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

where *ITNacu* is the cumulative contamination risk by the Total Nitrogen concentration, and *ITN* is the individual contamination risk at a specific well site.

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

where *ITCacu* is the cumulative contamination risk by the Total Coliforms concentration, and *ITC* is the individual contamination risk at a specifc well site.

Formal Representation of the Problem

2. Maximize the coverage area:

(3)

$$maxA_{cob} = \sum_{i=1}^{i=70} A_i$$

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.

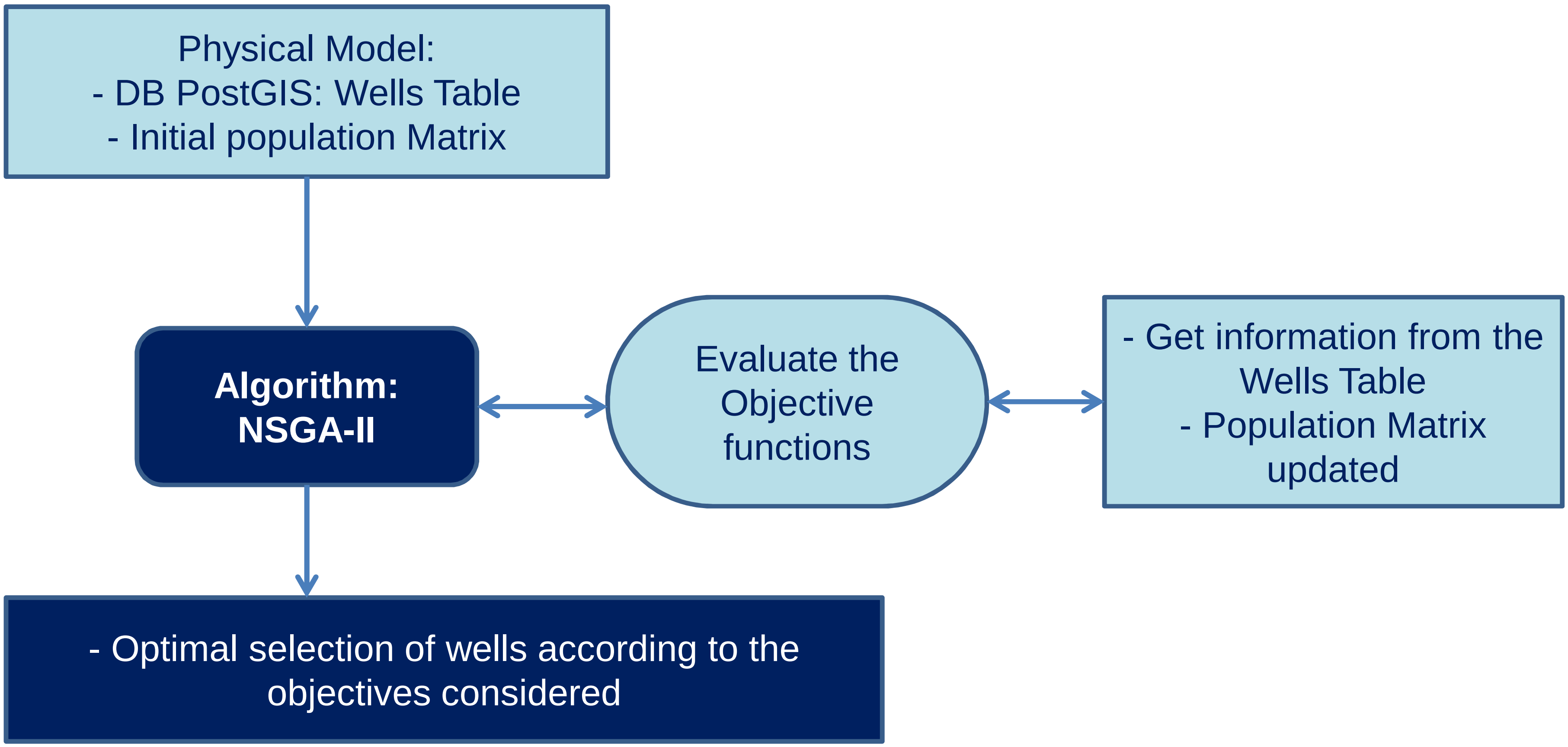
3. Prioritize the wells which are publicly accessible:

(4)

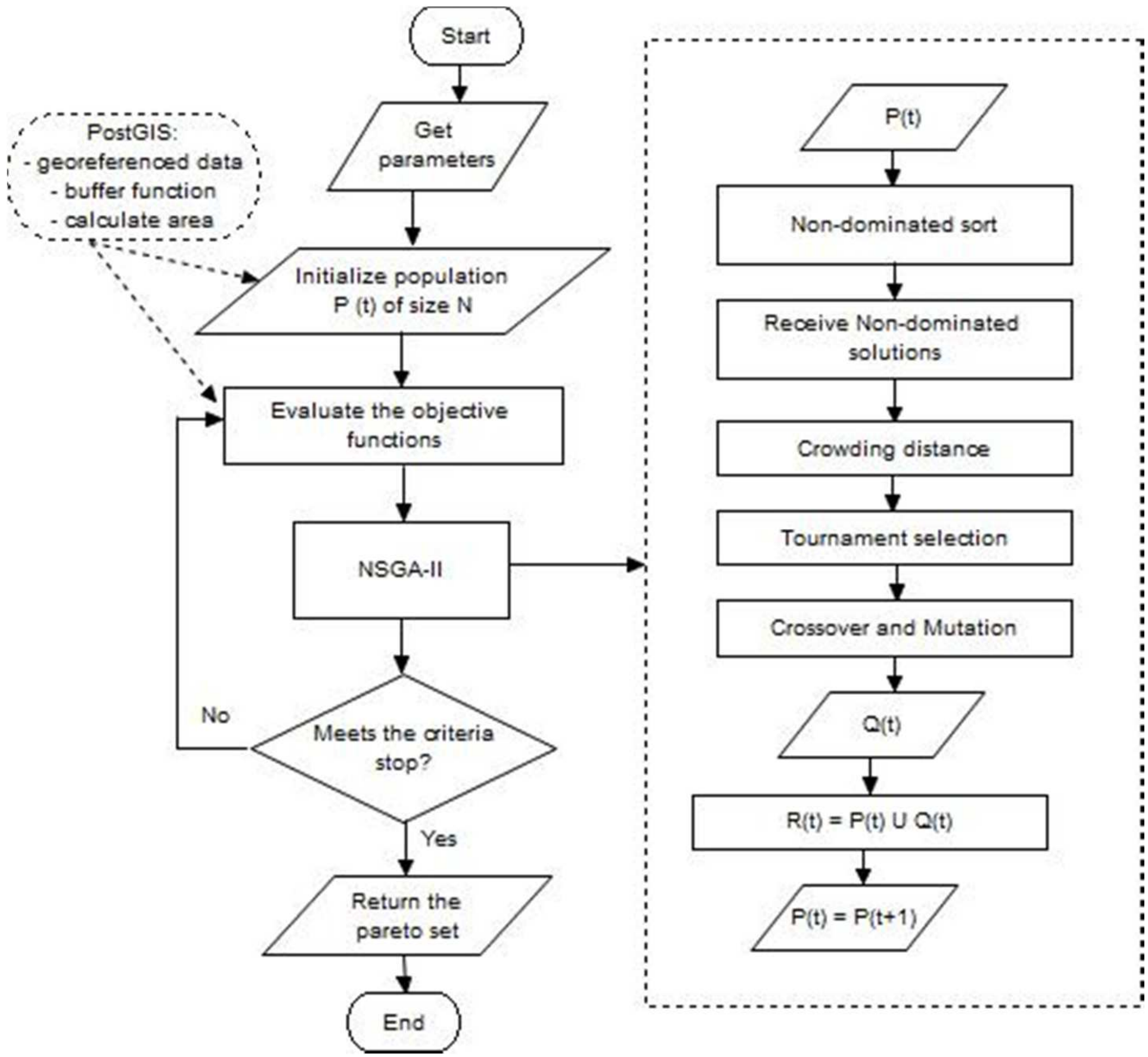
$$maxPEP = \sum_{i=1}^{i=70} Ip_i \qquad Ip_i = \begin{cases} 1 \\ 0 \end{cases}$$

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.

General Scheme of the Proposed Solution

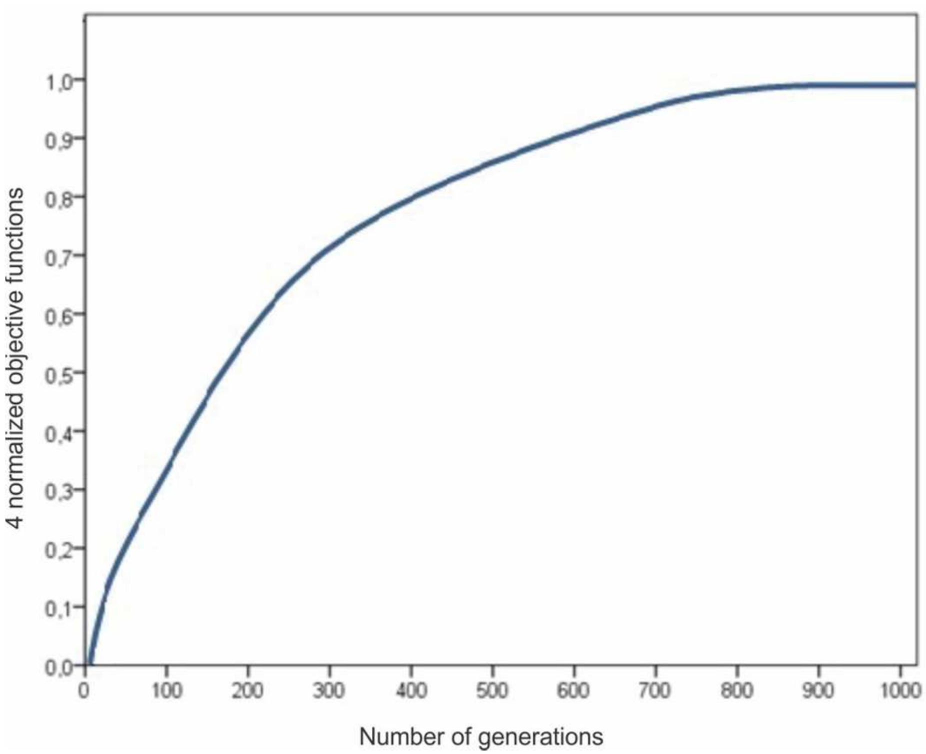


Flow Chart of the NSGA-II



Multiple runs of the algorithm were made. Initially, the model was executed with 100 generations. It was noted that there was an improvement in the front as the number of generations increased.

A total of 1000 generations were used in the final optimization model.

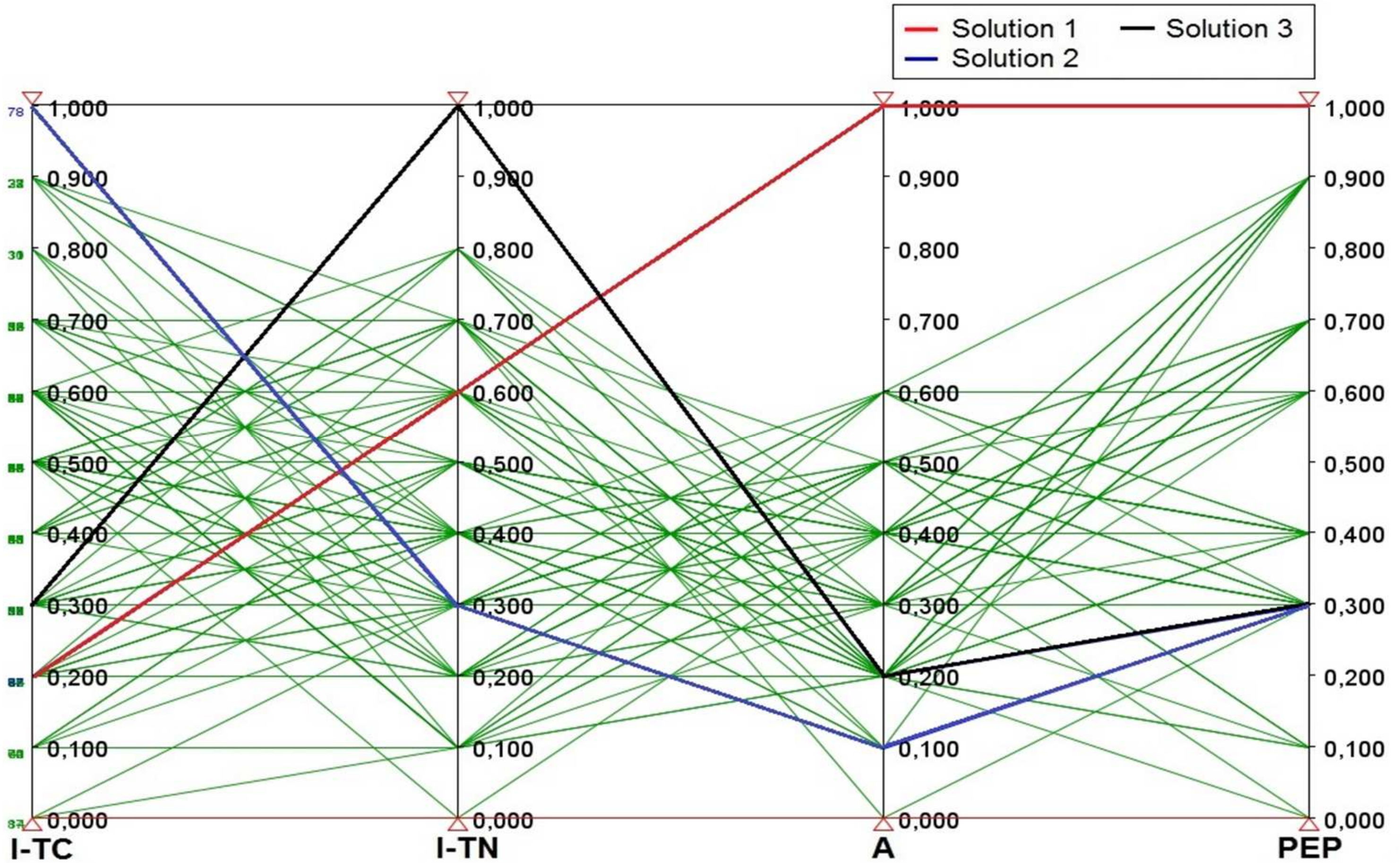


A population of psize = 100, number of wells = 70, mutate threshold = 0.7, criteria stop = 1000 generations were used.

The table with well information was also used.

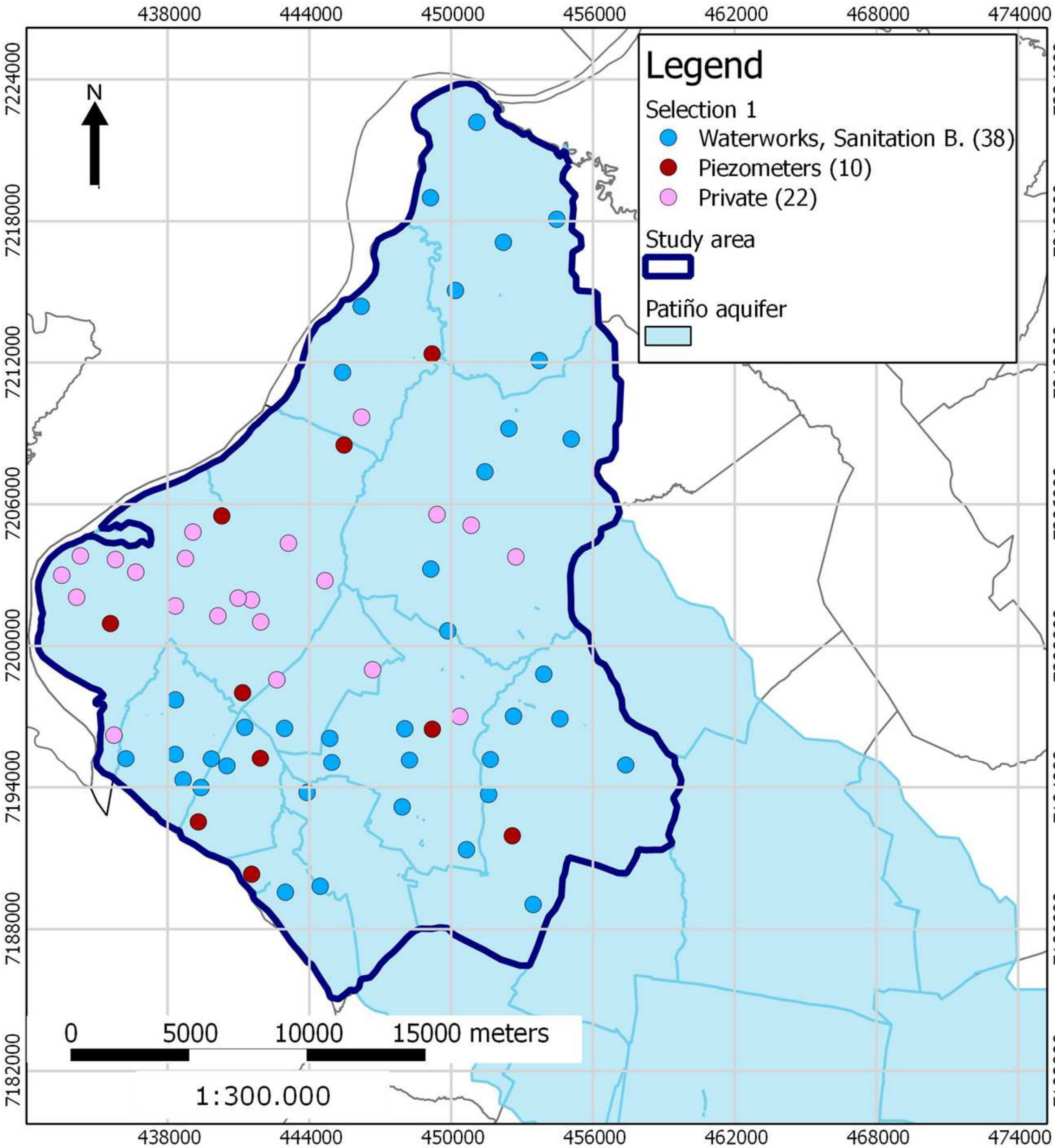
Experimental Results

To present the experimental results below, the pareto set obtained with 1000 generations was evaluated, identifying the farthest pareto optimal front from the origin, obtaining a set of 88 solutions. The Figure shows the parallel coordinates of the 4-dimensional chart.

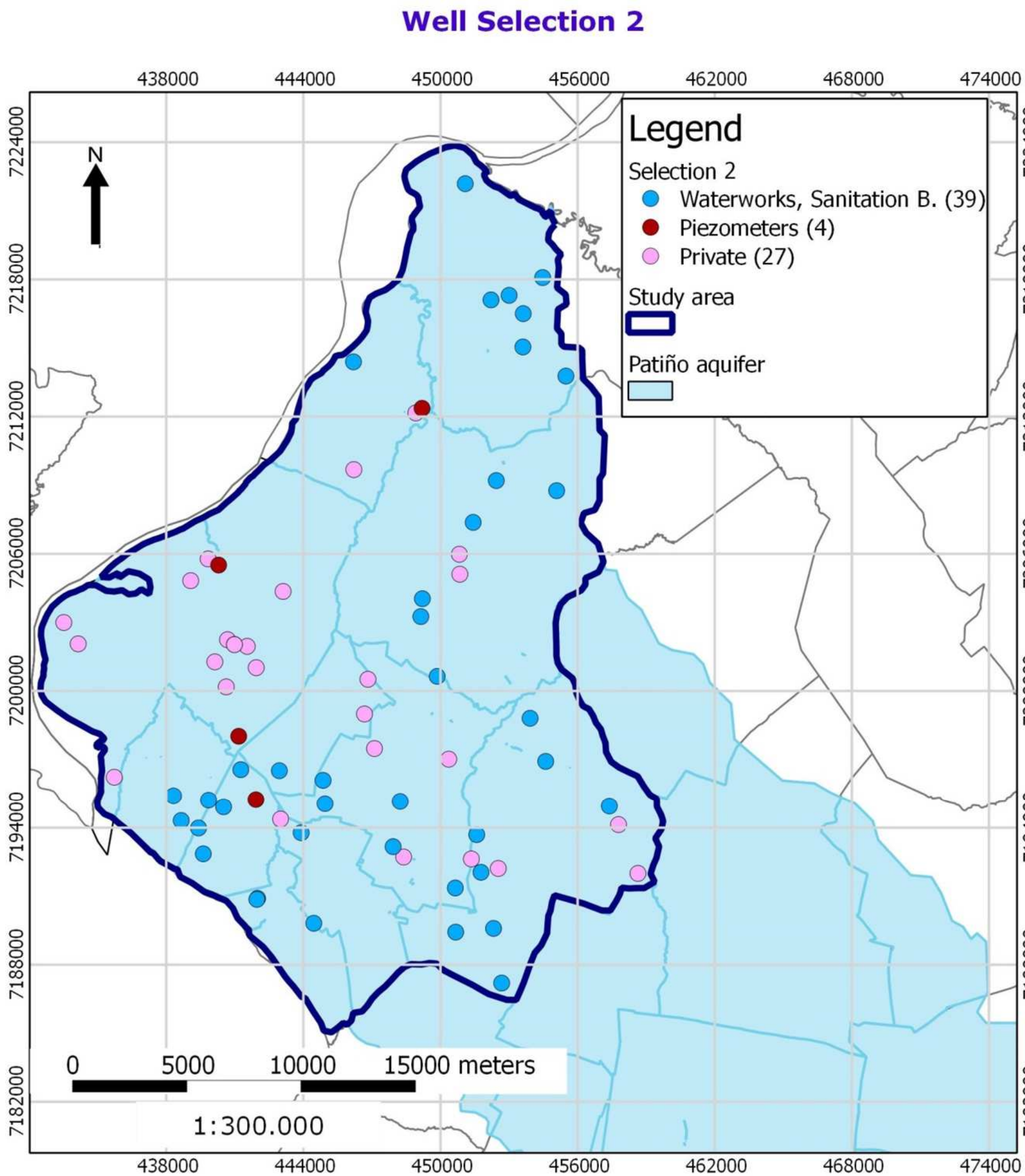


S1: maximum value of the normalized sum of the four objectives.
S2: maximun I-TC compared to the other objectives.
S3: maximun I-TN compared to the other objectives.

Well Selection 1

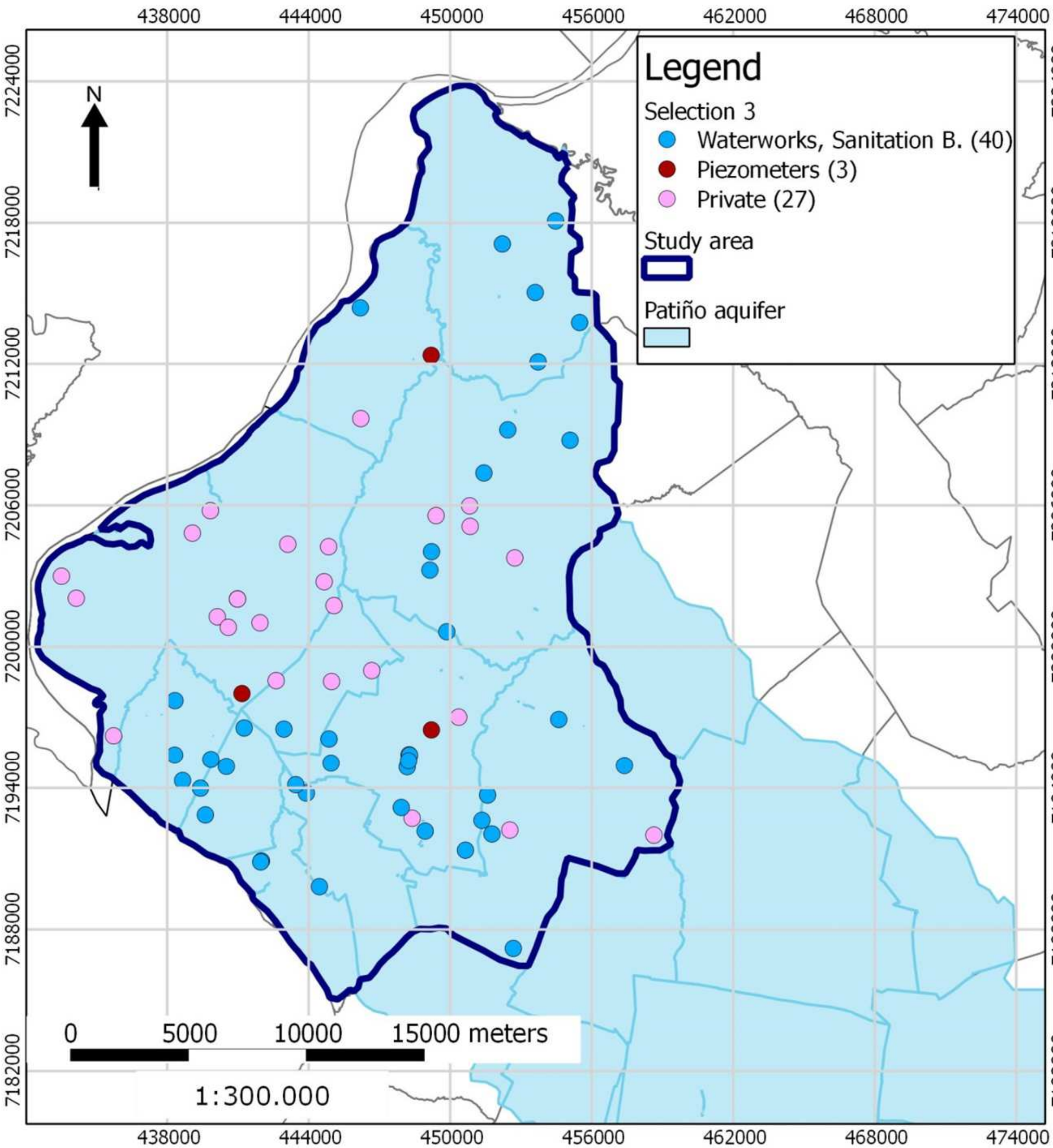


Solution 1 is the maximum value of the normalized sum of the four objective functions (2.8), with low rate of TC risk and high rate of TN risk, a coverage area above average (385 km2) and a well priority value of 48.



Solution 2 consider the result with maximum value of TC risk indices, with low rate of TN risk, an a coverage area of 339 km2 and a well priority value of 43.

Well Selection 3



Solution 3 consider the result with maximum value of TN risk indices, with low rate of TC risk, an a coverage area of 345 km2 and a well priority value of 43.

Conclusions

- The proposed solutions allowed the selection of 70 wells to carry out a water quality sampling campaign.
- A set of solutions was obtained, adjusted to the different characteristics of the problem, which will be analyzed by those responsible for making decisions.
- In the solution of the normalized sum of the four objectives, 60% of the wells are located in places with highest indices (70-100) of contamination risk with concentrations of CT and NT, 70% of the selection correspond to wells which are publicly accessible, such as waterworks, sanitation boards and piezometers, and cover 67% of the study area.