Delft University of Technology

Multi-disciplinary Project

Nitrate Pollution in the Northern Cartago Region

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April 11, 2023

Acknowledgements & Preface

This is the final report of the multi-disclipinary research of the TU Delft group which went to Costa Rica. It is the result of a three-month local investigation on the nitrate pollution in the region.

Before going to Costa Rica, we did not expect this research to become so relevant. Two weeks before we arrived, the water supply of two towns in the region, Cipreses and Llano Grande, were cut off due to the high concentration of fungicides. This gave our research more relevance for the villages that it affects and gave us a big motivation to do a thorough research.

We would like to thank our two TU Delft supervisors who gave us great advise and motivated us throughout our time in Costa Rica: Prof.dr.ir. L.C. (Luuk) Rietveld and Prof. Dr. Ir. Merle de Kreuk.

This report could not have been done without the help of all the people that helped us locally. Juan Carlos Porras helped us enormously with all his local knowledge and network. Furthermore, Luis Guillermo Romero Esquivel helped us with his knowledge about nitrate removal and his connections within the TEC (Figure 1).

Pacayas, April 11, 2023

Figure 1: Group photo before MDP

Abstract

Growing concerns about elevated nitrate levels in natural springs on the southern slope of the Irazu Volcano, Cartago province in Costa Rica, were the driving force for a multi-disciplinary study on the problem. The region is characterized by its high agricultural output and steep slopes. More than sixty springs located in the area are managed by a large number of local water authorities, ASADAS. The study focused on determining the main sources of nitrate pollution. Anthropological activities such as agricultural practices and domestic actions are found to contribute the most. A multivariate polynomial regression model was used with a large set of parameters. From the results it can be seen that human activities within the by law determined 200 meter radius protection zone around the springs, are most influential on high nitrate concentrations in the springs. Furthermore a stakeholder analysis, fieldwork, financial analysis of alternatives and farmer interviews were performed to produce a comprehensive list of recommendations for the various stakeholders. The recommendations are compiled to ensure a future with clean drinking water for all the citizens in the region.

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1 Introduction

Costa Rica is a nation that puts great emphasis on protecting its environment. The energy supply is virtually fully renewable and deforestation has been reduced to almost none Gallucci (2021). Nature is very well-preserved with over a quarter of the land's area considered protected. The average annual freshwater availability per capita in Costa Rica is one of the highest in the world according to the Biennial Report on Freshwater Resources (Gleick et al., 2011).

Recently, certain areas in the Northern Cartago region, in the center of Costa Rica, are having issues with contamination in the water supply. High concentrations of nitrate over 50 mg/L are being measured in natural springs and are causing health risks to the population supplied by these springs (AyA, 2021). Therefore, it is important to find out what is causing this pollution of the water bodies and which suitable measures can be taken to prevent this pollution.

In this report, the nitrate pollution is studied from different perspectives, including Environmental Engineering, Hydrology, Hydraulic Engineering, Water Resources, and Urban Water Management.

1.1 Research Relevance

Clean drinking water is of indisputable importance to human beings. The sixth goal of the United Nations' sustainable development goals is to ensure the availability and sustainable management of water and sanitation for all. Costa Rica scores well on freshwater withdrawal, but poorly on population using safely managed sanitation services. One of the pollutants in sanitation services is high concentrations of nitrate, which is why this research focuses on nitrate contamination (United Nations Publications, 2022).

When spring gets polluted with nitrate, clean drinking water cannot be guaranteed anymore and can get shut off due to health risks. Since water still needs to be provided to the citizens, in some cases trucks deliver potable water to the affected citizens (AyA, 2023).

This research is primarily relevant to the population that is dependent on the springs. Furthermore, it is relevant for water-providing organizations as it provides information on the main factors affecting nitrate concentrations in springs. Knowledge of critical areas and timely warning systems can improve their capabilities to ensure good water quality for the citizens.

1.2 Problem Statement

Inhabitants of central the region of Cartago rely on natural springs for their drinking water. Concentrations of pollutants in these springs are occasionally measured and when these concentrations exceed critical values, the consumers of these springs get strongly advised to stop drinking the water. In that case, other solutions must be found to supply the citizens with clean drinking water.

The pollutant considered in this research is nitrate. A high concentration of nitrate in drinking water causes health risks, as research has shown in the section on health and concerns for nitrate overdose. (Foster et al., 2002) Therefore, it is important to know where these pollutants come from and how to reduce them in the drinking water supply.

Often, an increase in nitrate concentration in water is caused by anthropological activities. Big contributors can be over-fertilization of agricultural land and polluted leakage of domestic wastewater. Lack of knowledge on fertilizer usage can be a reason for the problems, as well as flaws in the domestic discharge system. Septic tanks are often used, but the waste is not treated accordingly. The fertilizer contains ammonium, which will be converted into its more stable form, nitrate. Some fertilizers already have the nitrate compound in the form of ammonia nitrate (Gorbovskiy et al., 2017). This nitrate can run off to water bodies or leach into the ground and contaminate the groundwater in the aquifer. Another cause of the high nitrate concentrations can be the poor treatment of wastewater. This project aims to shed light on the nitrate pollution pathways and raise awareness of its related environmental impact.

1.3 Research Approach

The project is focused on identifying and quantifying the nitrate pollution sources and creating an ecosystem of information. Furthermore, it strives to make recommendations on mitigation strategies that can be used in the future for the water sources on the southern slope of the Irazú volcano. Alternative solutions such as utilizing neighbouring springs, treatment facilities and truck delivery are explored. Since it is a multidisciplinary project, the problem shall be addressed from different angles to achieve this goal.

Firstly, a database was built to categorize nitrate concentrations and nitrate measurements based on an older database provided by AyA (2021). The data points will be geo-referenced to get a clear understanding of where highly polluted areas are. A detailed map can be built by connecting these concentrations to geographical locations. Historical data from the AyA will be complemented with extra data from the Administrative Association of Communal Aqueduct and Sewerage Systems (ASADAS), municipalities, TEC studies, and information from SENARA (National Groundwater, Irrigation and Drainage Service) in addition to fieldwork trips and questionnaires with farmers. Combining this information will indicate what the main sources of nitrate pollution in the region are.

Secondly, the different factors contributing to the nitrate concentration that are found by answering the first research question will be modeled. With the help of QGIS, all different factors will be quantified. This data will be used as input for a multivariate polynomial model, in which the different factors will be related to the nitrate concentration.

Thirdly, mitigation and adaptation strategies to reduce nitrate contamination were analyzed through an extensive literature study. The most suitable strategies for the research area are then selected based on the literature study, economic analysis and acquired information from the various authorities.

It is important to note that this research aims to create a line of work. The complex problem spanning a large area with a multitude of communities cannot be fully solved in the time span of this project. An ecosystem of information will be one of the influential outcomes of the research. The ecosystem will be a database that holds all the acquired information from the ASADAS, SENARA, AyA, municipalities and various other sources. The goal is to facilitate future research groups by making the database freely available.

The entire problem will be challenged from different angles of disciplines. First of all, from the Environmental Engineering discipline, sustainable mitigation strategies will be analyzed. Secondly, from a hydrology perspective, nitrate pollution in the area poses a challenging problem. The water pathways in which the pollution gets transported are explored with limited data about the geo-hydrological situation. The role of precipitation, infiltration, inter-flow and overland flows are considered. Infiltration areas of the springs are established with a deterministic method following the topography. From a water management perspective, the economical and societal aspects of the project will be highlighted. This will be established by making a financial assessment, having conversations with all stakeholders and creating awareness within the communities. The hydraulic engineering expertise will be utilized by calculating flow speeds and the feasibility of several alternatives suggested and modelling in Python or Excel. The urban water management perspective is used by the analysis of the health effects of the contamination, the mitigation and end-of-pipe strategies associated with nitrate and in particular in the analysis of the breaching of the 200-meter radius around springs.

By combining these aspects of the multidisciplinary group, we aim to provide a report that can be used by governing bodies as well as local farmers to improve the current situation. Furthermore, a framework will be built so that future studies can continue and enhance the research that has been done here.

1.4 Research Questions

Main research question
With the aid of the problem statement, the research questions are drafted. The main question is formulated as follows:

What are the possible mitigation measures that can be taken to reduce the concentration of pollutants such as nitrate in drinking water supply sources in the Cartago region?

Sub-research questions
Subsequently, several sub-questions have been drafted in order to answer the main question and to divide the answer into smaller sections which make the writing more clear and manageable. The three main topics: nitrate pollution sources, impactful factors and mitigation strategies will be addressed with the following sub-questions:

1. What are the main factors in the region contributing to the input of nitrate in the hydrological system?
2. How can these factors be related to nitrate pollution?
3. What mitigation strategies can be implemented to reduce nitrate contamination in water bodies identified as critical?
4. What are the difficulties/obstacles to implementing these mitigation strategies?

1.5 Research Scope

The research area is defined in Figure 2. The research area includes villages on the side of Volcán Irazú: Llano Grande, Cot, Cervantes and Capellades. Recharge catchment areas from the springs within these borders have been researched. The area is on the southern side of the volcano and it has many steep slopes. A big portion of the land is used for agriculture. More than half of the farms in Costa Rica are located in the Cartago region (OECD, 2017a).

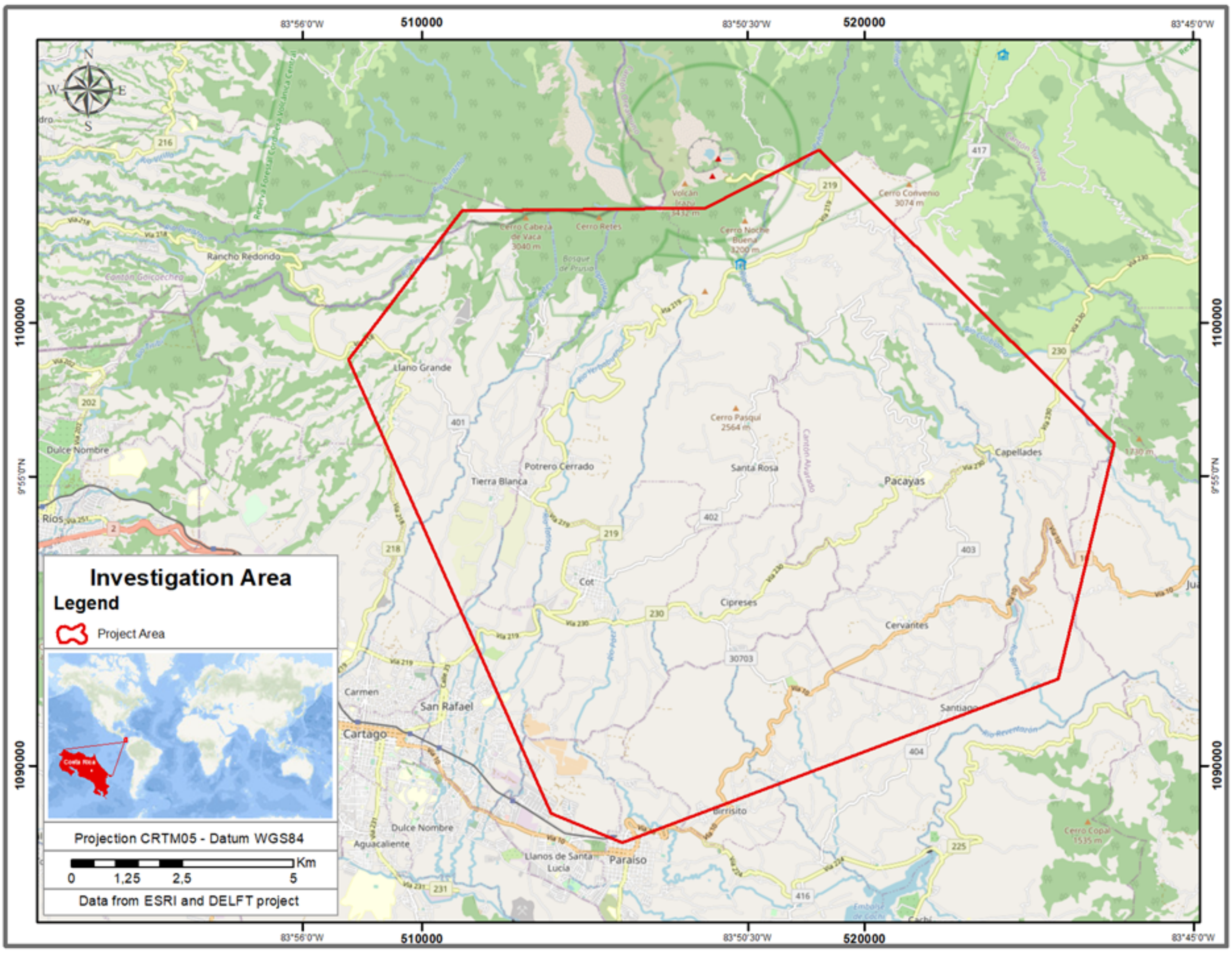

Figure 2: Northern Cartago Research Area

The focus of this project is on nitrate pollution. While the research area is afflicted by different polluting compounds, such as fungicides like Chlorothalonil, this research focuses specifically on nitrate. This choice has been made because of the lack of available measurements about these fungicides and the abundance of measurements on nitrate.

However the recommendations will - to a certain extent - be relevant in the prevention of contamination from other damaging compounds, it should be noted that our analyses and recommendations are solely on nitrate pollution. Some critical pollution compounds will be mentioned, but fall beyond the research scope and should be reviewed in future studies.

1.6 Report Outline

The research report consists of seven chapters in total. In the second chapter, the geological, hydrologic and socio-economic background of the research area is explored in the theoretical framework. Furthermore, a literature review on nitrate pollution in general and mitigation strategies is presented. In the third chapter, the research methodology of the stakeholder analysis, spatial analysis, modelling, interviews and fieldwork is shown. The results of these analyses are presented in the fourth chapter. In the fifth chapter, the results and limitations are discussed, after which conclusions are drawn in the sixth chapter. Lastly, recommendations are given to the stakeholders in the seventh chapter.

2 Theoretical Framework

Water problems are of increasing global concern; climate change, increased water demand, reduction of water availability, and management of water bodies are leading to major problems. Currently, 4 billion people face water scarcity for at least one month per year (Mekonnen & Hoekstra, 2016). The World Economic Forum has called a water resource crisis one of the biggest risks that humanity faces World Economic Forum (2022).

2.1 Background

2.1.1 Regional - Central America

In general, fresh water in Central America is abundant; the main problems in terms of water are therefore quality-related and not quantity-related. Agricultural pollution is of particular concern since agricultural activities are among the most important economic activities in the region (IICA, 2017). Agriculture is expected to grow by 14% over the next decade and the harvested area is expected to increase by 6.7% (OECD/FAO, 2022). This pollution has led to the occurrence of contaminant residues in water bodies, to the extent of representing a threat to humans and wildlife (IICA, 2017).

2.1.2 National - Costa Rica

General

Costa Rica has a total land surface area of 51,100 square kilometers, see Figure 3. As of 2021, the population of Costa Rica was assessed to be close to 5.1 million people according to the World Bank (World Bank, 2023). The capital of Costa Rica is San José, which is also its largest city. Other major cities in Costa Rica include Alajuela and Heredia. The majority of people live in the center of the country (Sawe, 2019).

Economy

Costa Rica's economy is characterized by a strong service sector, which accounted for about 66.86% of its gross domestic product (GDP) in 2021. The second-largest contributor to the country's GDP is the industrial sector, which accounted for 20,55% of the total, followed by the agricultural sector, which accounted for about 4.45% of the GDP (World Bank, 2022b). Poverty in the country is lower than in surrounding countries (World Bank, 2022a).

Overall, the economy of Costa Rica has been growing steadily between 3 and 4% in recent years, thanks to the strong performance of its service sector. However, the country still faces challenges such as a high level of public debt. Furthermore, unemployment rates more than doubled between 2017 and 2022 (World Bank, 2022b).

Figure 3: Overview map Costa Rica

Current legislative framework concerning groundwater protection

A brief description of relevant laws concerning spring pollution is listed here (Congreso Constitutional De La Republica De Costa Rica, 1997):

- Ley de Aguas 276, art. 31. Constitutes a protection zone around each public supply well and spring with a radius of 200 meters. Furthermore, forest areas that protect the source and are in the infiltration zone must be protected.
- Ley de Aguas 276, art 32. When there is a danger of contamination in a larger area than the one previously indicated, either in surface water or in underground water, the Executive Power,

through the Water Supply Section referred to in the following article, will take the necessary measures to prevent the danger of contamination in the area.

- Ley Forestal 7575, article 94. Bordering areas of permanent springs with a radius of 100 meters and recharge areas must be protected. The recharge areas are established by competent organizations chosen by the law on a case-by-case basis. The technical study will determine if certain land users should be expelled and/or bought out.

Climate and Hydrology

The climate in Costa Rica is typically tropical and warm, with temperatures averaging around 25 °C. Due to the equator's proximity, the temperature differences are small throughout the year. However, Costa Rica contains many microclimates, which have developed due to elevation differences and other climatic causes (Janzen, 1978). This makes predictions of the weather rather difficult.

During the rainy seasons, regions can experience temperatures up to 40 °C, while other regions can go down to 2 °C during the dry seasons. Since there is a big difference in elevation throughout the country, local temperature differences occur as well. The country experiences high levels of humidity, particularly in the coastal regions, which can make the air feel even warmer (Weather Spark, 2023).

Precipitation rates are high in Costa Rica, with the country receiving an average of 2,000-3,000 mm of rain per year. The wettest months are between May and November, with a peak in September and October; monthly precipitation in these months can surpass 600 mm. The regions with the highest precipitation are on the Pacific coast and around the volcanoes in the Central Valley (Capps, 2018).

The climate in Costa Rica is well-suited for agriculture, and the country is known for its production of coffee, bananas, sugarcane, and other crops. However, climate change can cause large issues in this capability. The increase in severe floods and droughts, rising temperatures, and heightened exposure to pests pose a threat to the continuity of the agricultural sector (OECD, 2017b).

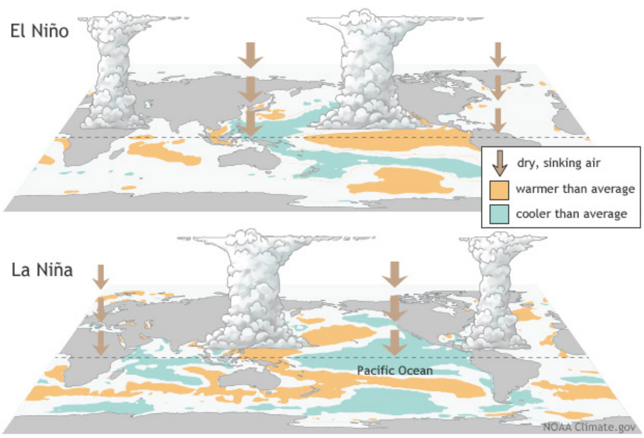

Figure 4: Figure of the El Nino/La Nina Oscillations (Climate.gov, 2022)

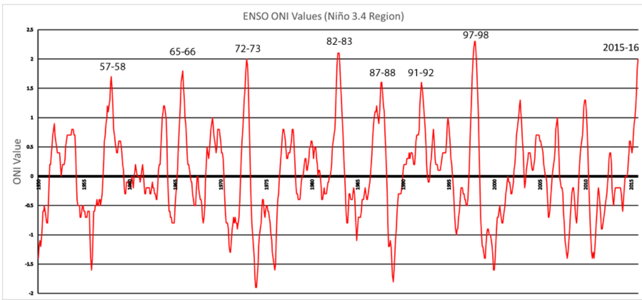

Figure 5: Historical ONI indices (Center, 2022)

El Niño and La Niña

Generally, trade winds blow from east to west and therefore take warm water from South America towards Asia causing cold water upwelling at the South American coastlines. This is visualized in Figure 4. During El Niño, trade winds weaken and therefore warm water is pushed back east to the South American coastline resulting in unusually warm water. This warmer water causes the Pacific Jet stream to shift towards the south resulting in wetter periods in Central America.

During La Niña, trade winds are stronger than usual resulting in more cold water upwelling on the West-American coast. This causes the jetstream to shift upwards resulting in a dryer area in Central America. El Niño and La Niña events occur every two to seven years, on average, but they don't occur on a regular schedule. Generally, El Niño occurs more frequently than La Niña (National Ocean Service, 2022).

Categorizing whether an El Niño or La Niña event has taken place is done by the Oceanic Niño Index (ONI). If the ONI value is high, it suggests an El Niño period. In the last 3 years (2020, 2021, 2022) there have been 3 La Niña events in the winter, this can be seen in Figure 5. In general, La Niña events cause more rainfall in central Costa Rica and therefore higher flood occurrences (Costa Rica Comisión Nacional de Prevención de Riesgos y Atención de Emergencias, 2014).

Because the events may have an impact on floods and increased overland flows, which results in the flushing of agricultural compounds on the land. That can increase the nitrate concentration in water, so it is important to consider its impact. In the case of Cartago, the precipitation over an extended period has been plotted against the nitrate concentration in Figure 36.

In general, the country is either in an El Niño year or a La Niña year. For Costa Rica, this is judged by the climate on the western coast of South America. Since the climate there is drier than usual, the local population calls it an El Niño period. In Costa Rica, the weather is judged to be drier than normal as well. During the La Niña periods, there would be much more precipitation and flows in the water bodies. Because there is little scientific support for this, we will not directly take this into consideration.

2.2 Geo-hydrological situation

Geological knowledge is relevant for understanding the aquifer recharge characteristics of the area. The type and permeability of the geology are important to understand before finding mitigation strategies. In 1972, the US geological survey by Krushensky (1973) conducted a study that included the research area of this study. The area is located on the deposits of the Irazú volcano, and therefore the geology is characterized by various volcanic rock types. The resulting map of this study clipped on the research area can be found in section 3.1.1, Figure 17.

2.2.1 Aquifers

Based on the geological surveys and lithological profiles of the wells in the area, it was determined that there must be at least 2 distinct aquifers (Hartig et al., 2012). One of the aquifers is situated in the fractured lava and breccia, whereas the other is porous and consists of ash tuffs and lapilli. With the data from the springs, Hartig et al. (2012) constructed equipotential and flow lines of the aquifer, as seen in Figure 6.

Aquifer depth and thickness studies have not been done at this point in time. Groundwater flows are in northeast-southwest and northwest-southeast directions between altitudes of 1,400 and 3,400 meters. The hydraulic gradient differs between 0.0106 and 0.734 (m/m) in the same direction as the groundwater flow. Observing sections of rivers, it can be concluded that it is an unconfined, contributing aquifer as it supplies water to surface water bodies.

Unconfined aquifers have a high vulnerability to contamination since there is no impermeable layer protecting them from diffusive nitrate (and other contaminants) sources. Confined aquifers are less prone to contamination since they are naturally protected from the surface by an impermeable layer.

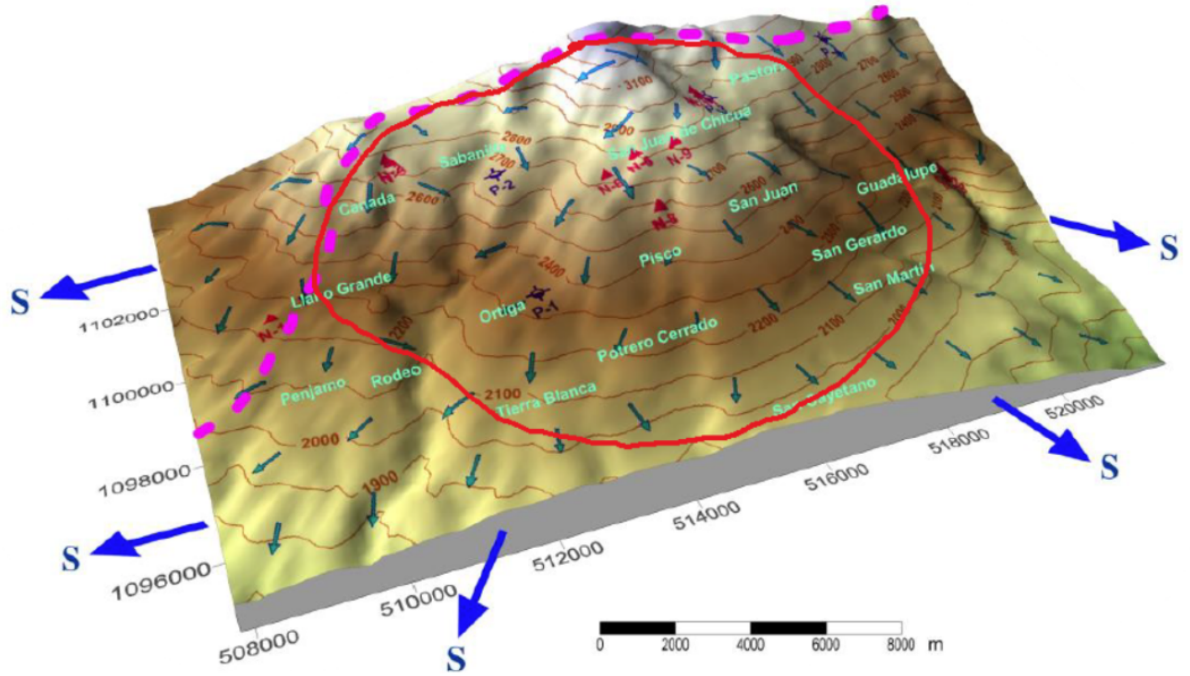

Figure 6: Groundwater flows in the area of interest. Adapted from Hartig et al. (2012)

Limited information about the aquifer composition is known, but three pumping studies in different springs provide insights into these particular locations. The double-ring Muntz infiltration test was used to obtain the hydraulic conductivity in the surrounding areas of the wells. However, all tests were performed in the northern part of the research area thus the representativity for the whole area is disputable.

The first test was done in the Sanatorio Durán spring. This test determined the presence of two aquifers, the upper was unconfined and the lower one was found to be confined. The second pumping test in the La Pastora area found a single, shallow, unconfined aquifer. The final pumping test in the Prusia area found a single, 21-meter thick, unconfined aquifer in the lava breccia geology, which is a common geology in the research area. A summary of the properties of the aquifers can be found in Table 1.

Table 1: Pumping test results (Hartig et al., 2012). *unconfined aquifer, **confined aquifer

Location pumping test	**Sanatorio Durán**			
	upper *	lower **	**La Pastora ***	**Prusia ***
Transmissivity (m2/d)	2.22	9.92	0.45	16.2
Hydraulic conductivity (m/d)	0.185	0.301	0.185	0.774
Storage coefficient	0.5	0.000048	N.D	N.D
Aquifer thickness (m)	12	33	12	21

Capture Zones & Recharge Areas

The capture zone of a natural spring is a three-dimensional region from which water flows into the spring. It represents the aquifer volume that is brought up by the spring. This area is determined by the geology and topography of the land and the location of the spring. It not only determines the amount of water available in the spring but is also important for the quality of the water, as the water from the surrounding land flows into the spring and can potentially contaminate it. The permeability and porosity of the soil, as well as the slope and groundwater flows, are factors influencing the size and shape of the capture zone.

Capture zones are often shown with various lines representing the capture zones for different time scales, this can be seen in the example of Figure 7.

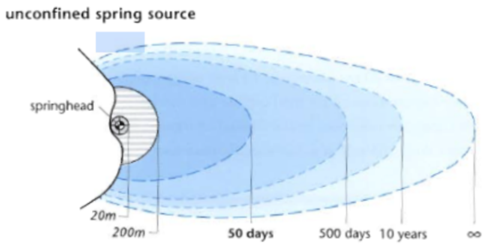

Figure 7: Capture zones, adapted from Foster et al. (2002)

Land use activities within the delineated capture zone are important, as the substances used on this land will show up in the spring. Once a capture zone is established, protection measures and regulations will have to be implemented to limit further contamination. Current national policy in Costa Rica established a 200-meter radius circle around each spring that is considered a protected area. Based on the steep topography, it is argued that a circle around the spring is not very effective and does not conform to the actual recharge area of the spring.

The circle shape does not correlate with the actual capture zone, especially not on the steep slopes of the Irazú volcano. This is visible for the Plantón spring in the Cipreses area in Figure 8. Here, the capture zone lines of 100 days and 5 years are visualized on a geological map. This has been done for a couple of wells for a study for the Cipreses ASADAS by various authorities (Hartig et al., 2014).

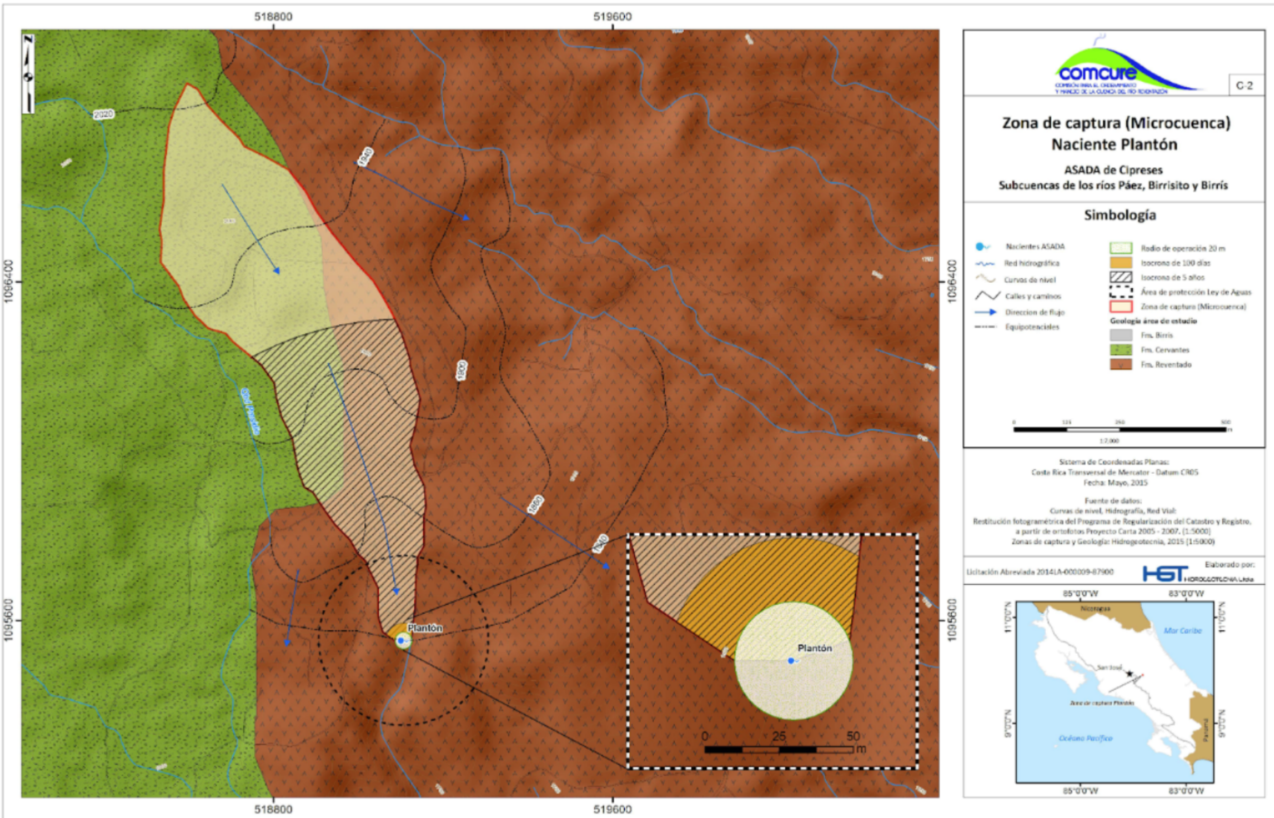

Figure 8: Geological map with Planton spring in the Cipreses area, retrieved from (Hartig et al., 2014). The black dotted circular line around the well is the national protection zone with a radius of 200 meters. The red outlined area is the actual capture zone of the well in which the striped area represents the 5-year capture zone and the yellow area the 100-day capture zone.

Soil Types

The soil type influences the infiltration rate. Information about the soil orders is publicly available from the Universidad de Costa Rica. In Figure 9, the different soil orders are mapped over the research area. The majority of the area is characterized as Andisol soil order, this type is formed from volcanic ash and is known to be very fertile. The suborders in this area are 70% Udands and 30% Ustands. This fertility makes the region exceptionally suitable for agriculture. The suborder Udands is according to the USDA soil taxonomy handbook a 'more or less well-drained Andisols of moist regions' (USDA, 1999). The South-Western area consists of the Ultisol soil order, suborder Humults. This order is defined as red clay soils and the suborder Humults are 'more or less freely drained, humus-rich Ultisols' (USDA, 1999).

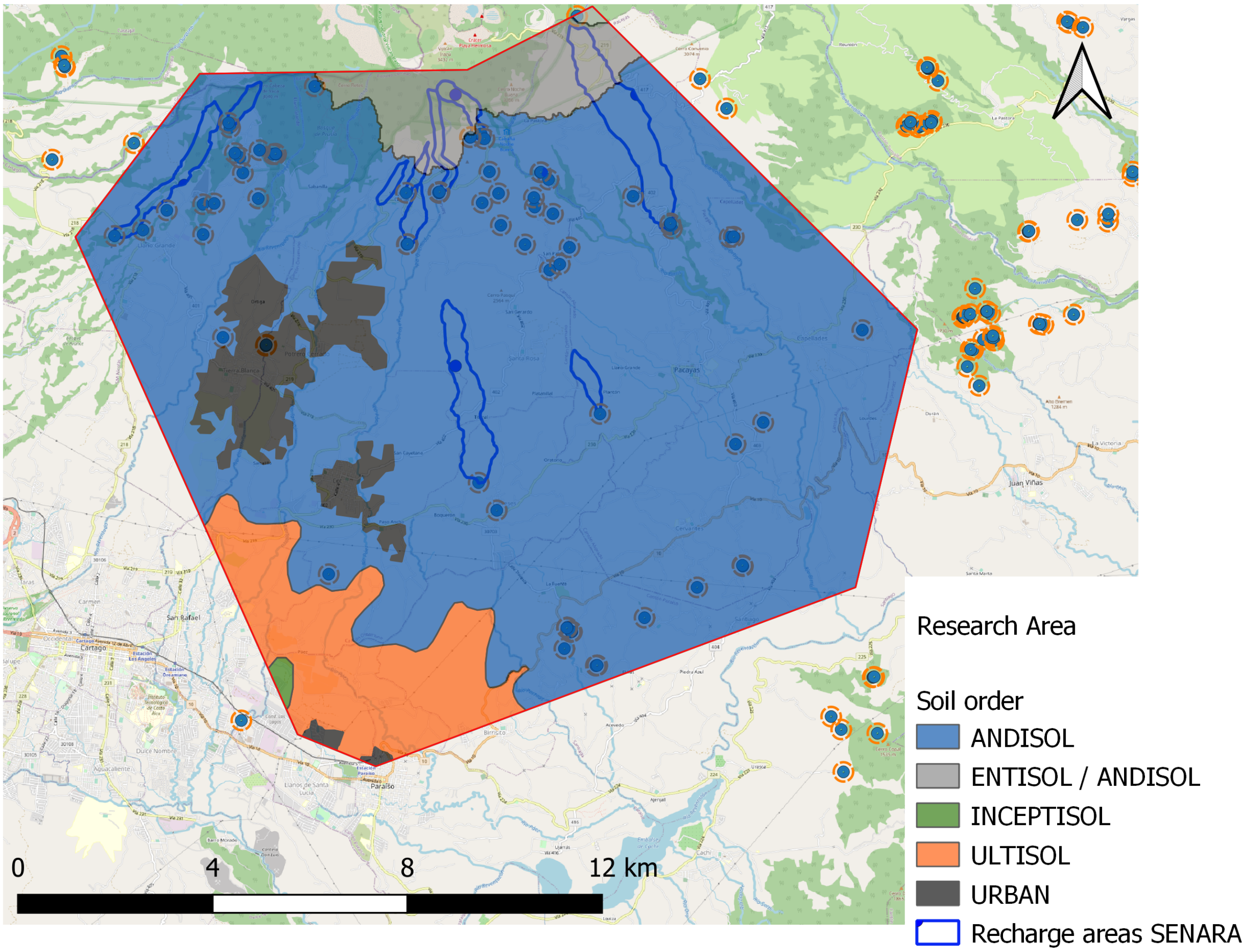

Figure 9: Soil order map of the research area, data retrieved from *Mapa de Suelos de Costa Rica | Centro de Investigaciones Agronómicas* (n.d.)

With this information, it is shown that the whole research area has good drainage characteristics, suggesting good aquifer recharge capabilities. However, Andisols, the dominant soil type in the area, exhibit variable charges and therefore can retain anions such as nitrate. It has been suggested that Andisols can retard nitrate leaching because of their charge (Tani et al., 2004; Reynolds Vargas et al., 1995). This important insight suggests that while the vast majority of the research area has good infiltration capacity, nitrate infiltration is limited and can be trapped in the soil. This fact might suggest that spring contamination is more intensely caused by overland flows than by aquifer flows.

Tani et al. (2004) conclude from their study of Japanese Andisols that the potential nitrate absorption capacity of Andisols should be accounted for in modelling groundwater contamination. Another study regarding Costa Rican Andisols by Ryan et al. (2001) found that from the two plots, one exhibited a much larger nitrate absorption capacity than the other plot, while both plots were in the same region and same Andisol soil. The study suggests that small changes in the mineral content of the soil have a large influence on retarding nitrate leaching. An older study performed on Andisols in Costa Rica by Reynolds-Vargas et al. (1994), showed that in the 5-month dry season, fertilizer-derived nitrate accumulation in the soil is highest. During the wet season, the nitrate content was significantly lower.

Based on this information, it can be assumed that at least some nitrate leaching is prevented by the Andisol, which would lead to more polluted overland flow that contaminates the springs. The magnitude of the effect is not possible to quantify in the heterogeneous research area and limited information about soil (mineral) composition. The retardation effect found in Andisols is much less pronounced in the Ultisol soil order found in the southern part of the research area.

2.3 Health concerns for nitrate overdose

Nitrate is a naturally occurring compound, however the majority of problems associated with nitrate have an anthropogenic origin. Nitrate cannot be detected by sight, smell or taste, but the abundance of nitrate can lead to harmful health effects and environmental dangers. Nitrate is the most stable oxidation state of the element nitrogen and therefore it is the most present in ground- and surface-water. Nitrate becomes a highly soluble salt when present in water, which makes removal difficult with standard water treatment practices.

The World Health Organization states that a maximum available daily intake (ADI) of 0-3,7 mg/kg body weight is advisory for nitrate ion (World Health Organization, 2003). The norms for drinking water are established at 50 mg/L for nitrate and 3 mg/L for nitrite. Furthermore, the sum of the ratios of the concentrations of nitrate and nitrite should not exceed 1; for instance, a nitrate concentration of 40 mg/L and a nitrate concentration of 1.5 mg/L would not be allowed as the sum of the ratios is 4050+1.53=1.3>1 (World Health Organization, 2011).

An acute overdose of nitrate is possible but unlikely caused by drinking water, as the lethal oral dose of potassium nitrate and sodium nitrate is in the order of 1-3 g/kg body weight. Overdosing with continuous intake of nitrate is improbable as well, as this requires an intake of around 15 mg/kg body weight per day.

Long-term risks which are caused by nitrate overdose are as follows:

- Methemoglobinemia: Nitrate ingested by infants under six months can be converted into nitrite and binds onto the methemoglobin of the infant. As methemoglobin is a carrier of oxygen and the nitrite takes the place of the oxygen, methemoglobinemia can be a life-threatening disease. There is an increased risk of methemoglobinemia when nitrate levels exceed 10 mg/L. When nitrate levels in drinking water exceed 50 mg/L, the risk of methemoglobinemia increases by 22% (Zeman et al., 2011)

- Adverse Pregnancy Outcomes: The consumption of polluted drinking water during pregnancy can be a threat to the fetus. Diseases that result from this intake are congenital heart defects , limb deficiencies, neural tube defects, oral cleft defects (Brender et al., 2013), premature rupture of membranes at term (Joyce et al., 2008), and small-for-gestational age (SGA) births (Migeot et al., 2013). These defects generally occur when nitrate in water drinking exceeds 5 mg/day.

- Cancer: increased cancer risk in the bladder, breast, colorectal, kidney, ovary, pancreas, stomach and thyroid is correlated with drinking water with a high nitrate content. The risk of cancer increases when the drinking water is higher than 1.7 mg/day (Stayner et al., 2017).

- Thyroid Disease: an increased risk of Thyroid Disease can be observed in communities with a drinking water source with a higher nitrate content, especially for children (Rádiková et al., 2008).

- Other: Other research shows a relation between nitrate in drinking water and type 1 diabetes, macular degeneration and lowering of blood pressure (Ward et al., 2018).

A high concentration of nitrate in water can bring health risks. As the norms of drinking water by both the WHO (World Health Organization, 2011) and the Costa Rican government (Mora-Alvarado et al., 2017) have been established at 50 mg/L of nitrate, this quantity will also be used as a norm in this report. Polluted sources with lower values will also be considered in this report.

2.4 Sources of nitrate pollution

Nitrate is introduced into the environment by various anthropogenic actions, which are summarized in Table 2. Agricultural activities are often seen as the main sources in rural areas. The compound nitrate is essential for agricultural production. Plants convert nitrate into proteins, which are necessary for the plant's growth. Humans and animals need protein in their diet and the ammonium-rich manure they eject is converted by surface bacteria back to nitrate. The conversion and pathways nitrogen takes from pastures to the aquifer are finely illustrated in Figure 10. Often nitrogen is applied in excessive quantities, which causes leaching in the surrounding surface waters and aquifers (Hansen et al., 2017). However, agriculture nitrogen use is surely not the only contributor to the contamination (Ford & Tellam, 2014). Domestic sources include improper discharge from septic tanks and other leakages. Various other potential sources are found in Table 2.

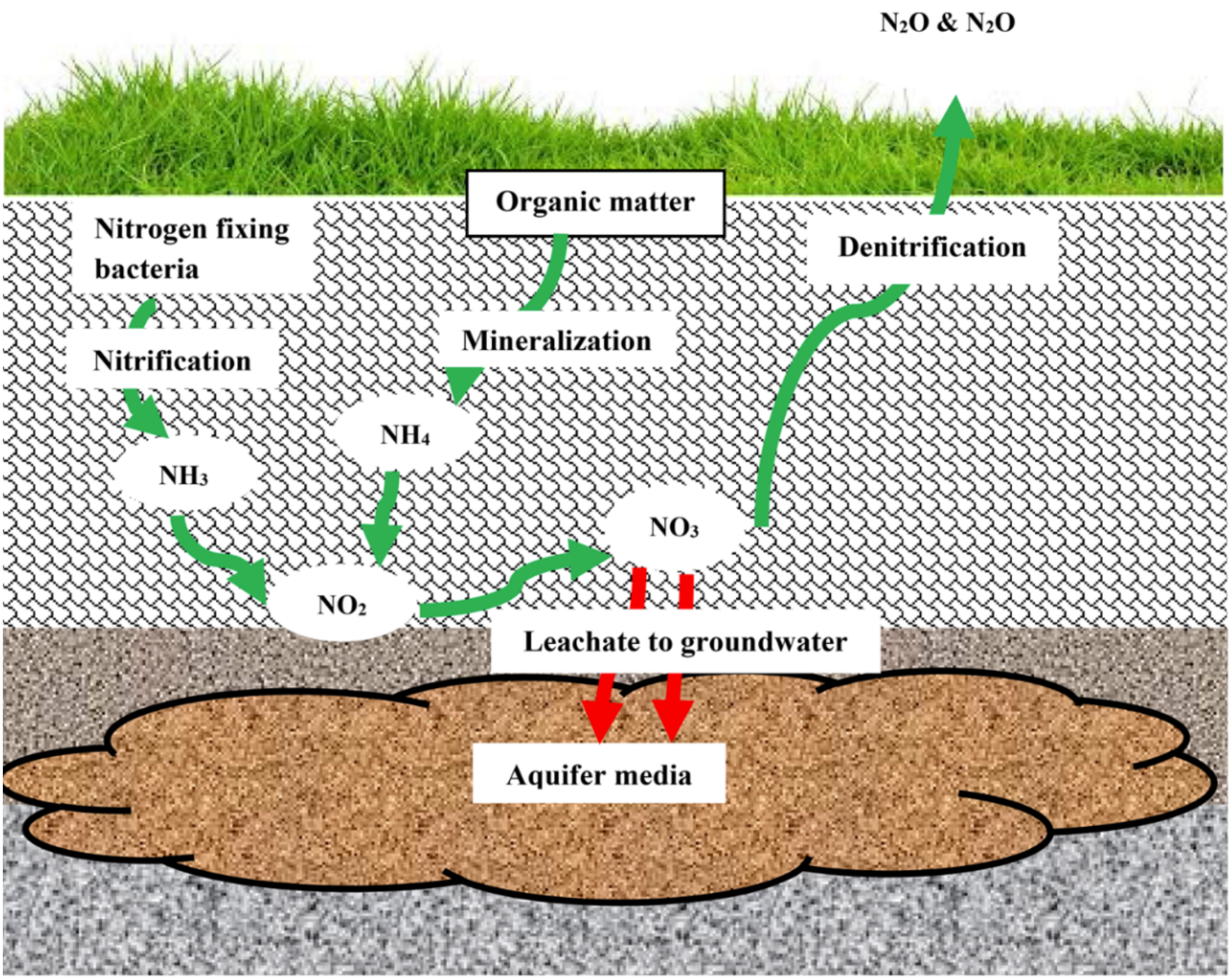

Figure 10: Nitrogens' journey from field to aquifer, retrieved from Huno et al. (2018)

Table 2: Overview of antropogenic nitrate sources, green;agricultural activities, orange; domestic systems, grey;industry

Anthropogenic Sources	Description	Impact & examples
Agriculture	- Use of organic fertilizer, manure and slurries - Use of synthetic nitrogen fertilizer - Over fertilization	Plants convert nitrate into proteins, which are necessary for the plant's growth. Often, non-organic fertilizers with a high concentration of N are used in agricultural sectors. In many cases, over-fertilization takes place which can cause excess nitrate to leach into the groundwater and surrounding waters. (Hansen et al., 2017)
Flushing	- Surface run off	If rainy events occur right after fertilization, there is a risk for that fertilizer getting flushed off with runoff
Livestock	- Manure - Improper discharge - Leaking from storage facilities - Excessive land application of manure	Organic waste components of livestock are decomposed by bacteria into ammonia, which subsequently is decomposed into nitrate and nitrate by nitrification. Because of this, the big potential nitrogen-leaching locations are manure storage, livestock yards and fields that receive the manure for fertilization. Via surface run off from farm buildings, improper discharge, leaking from storage facilities and excessive land application of waste, serious threats could be posed to groundwater (Sahoo et al., 2016).
Informal wells	- Open wells are often found on farms	These wells allow for exchange between polluted overland flows and the groundwater.
Leakage from sewage and lack of disposal networks	- Sewage leaks - Lack of sewage - Improper discharge	Leakage from sewerage and water supply networks provides the highest percentage of water recharge to aquifers underlying many cities throughout the world (Yang et al., 1999). Water supply mains and sewers with wastewater leak because of improper installation or deterioration through age, subsidence, earthquakes or other external factors.
Septic tank leakage	- Improper design - Poor maintenance and depth of watertable - Leakages of septic pipes	75% Of all households in Costa Rica are connected to a septic tank system (Hidrogeotecnia Costa Rica, 2020).The concentration of total nitrogen in effluents from a typical septic tank system ranges from 25 to 60 mg/L, with ammonia making up the vast majority of this total, 20–55 mg/L as ammonia and less than mg/L as nitrate (Canter, 2019). Ammonium from leaking septic tanks are nitrified into nitrate from which it can leach into the groundwater.
Industry	- Spillage of nitrate rich waste	Nitrogen compounds are used extensively in industrial processes. Some examples of industrial uses are plastic and metal treatments, raw materials for the textile industry, particleboard and plywood, household cleaning and the pharmaceutical industry (Potash Corporation of Saskatchewan, 2002). Therefore, it is expected that nitrogen compounds (e.g. nitric acid) from spillages will have a significant impact on groundwater quality in industrial zones.
Contaminated land	- Landfills - Gasworks sites - Abandonded industrial site	Landfills are considered a major source of pollutants and their impacts on groundwater quality have been extensively reported in the last four decades (Wakida & Lerner, 2005). Water, through precipitation or groundwater tributaries, percolates through the landfill and becomes contaminated, after which it forms leachate in the soils underneath (Vaverková, 2019).

2.5 State of the art - Mitigation strategies

In this section, possible mitigation strategies are discussed. Since these strategies can be generic, it is important to note which of these are applicable in the research area. The mitigation strategies are mostly focused on lowering the nitrate supply to the aquifers and on lowering the concentration in drinking water supplies. Table 3 shows an overview of mitigation strategies with benefits and downsides. Further explanation is given underneath.

Table 3: Brief overview of mitigation strategies from literature

Mitigation strategy	Description	Benefits	Downsides
Nitrogen application rates & timing	**- Optimize fertilization to the plant's needs** **- Careful planning**	**+ Efficient use of fertilizer** **+ Yield increase**	· Knowledge needed · Equipment
Tissue sampling and soil testing	· Getting feedback on fertilizer rates · Understanding soil nutrients	+ Better Understanding of the soil + Easier to plan fertilization strategies	· Intensive work · Knowledge needed
Use Residual Nitrogen	· Prevent nitrogen leaching by lifting it from the soil · Optimize fertilizer efficiency	+ Reduction of excess nitrate in the soil + Optimal use of fertilizer	· Lower yield than possible
Filtration and recovery	· Zero-valent iron filtration · Water treatment	+ Capture of resources + Cleaner water	· Costly investment · Maintenance
Filter beds	· Lift nitrate from runoff water · Fast-growing plants · Green manure filtration	+ Reduction of nitrate in water flows + Additional plant growth	· Suboptimal use of land · Financial incentive
Irrigation and fertilizer techniques	· *Drip irrigation* · *Side dressers*	· Optimal use of water and fertilizer · Increase in yield	- High Initial costs · Knowledge needed
Crop rotation	· *Switch shallow-rooted plants with deep-rooted*	· Healthier soil · Increase in yield	· Suboptimal financial incentive · Knowledge on different plants

2.5.1 Agriculture

Adjust nitrogen application rates

One of the biggest contributors to agricultural nitrate pollution is the flooding of land and washing the excess fertilizer away into the water stream. It is therefore important to minimize fertilization before, during or right after a high rainfall event. In addition, the amount of fertilizer should be carefully calculated. Previous research indicated that only 30-45% of the applied nitrate was used by the plants Bower (2014). That means that fertilizing it with only a third can already be sufficient. Existing research on efficient ways to reduce nitrogen fertilization and irrigation rates while sustaining crop yield and quality is presented here.

The first step is to make sure the nitrogen application is suitable for the specific crop and soil types, advice can be requested from agricultural organizations. The soil should be tested for existing nitrate concentrations before applying nitrogen fertilizer, preferably just before fertilizer application.The way N fertilizer is applied to the crops is of great influence; precision placement equipment can reduce the necessary amount of fertilizer by a great deal. Side dressers should be considered for direct application close to the crops. In addition, drip irrigation enables the precision application of fertiliser since nitrogen efficiency is strongly related to water use efficiency (Foley, 2011) .

Adjust nitrogen application timing

During the early growth stages of a crop's life, they tend not to absorb any amount of nitrogen, and therefore fertilizer should not be applied during the early stages. Fertilizer application should coincide with the growing stages of the plants when their nitrogen consumption is highest to prevent further nitrate leaching.

Use tissue sampling and soil testing

Incorporating tissue sampling into the farmer's routine can help the farmer understand if the plants are sufficiently provided with nitrogen. For example, for potato crops the sampling of the leaves is an accurate way of noticing a nitrogen shortage, nitrogen content in the leaves has been documented for various conditions and growing season progressions. (Lang, 2010).

Utilize residual nitrogen

Shallow-rooted plants like onions and potatoes leave excess nitrogen in the soil after they are harvested. The remaining nitrogen will slowly percolate in the soil. This lowered nitrogen content can be retrieved by deeper-rooted crops like corn or kinds of wheat. The alternation between shallow- and deep-rooted crops can increase nitrogen efficiency since the deep-rooted crops can utilize the remains of the shallow-rooted crops (Foley, 2011).

Filtration and recovery

Removing nitrate, a highly soluble salt, is challenging but in case the supply of nitrate cannot be lowered effectively, end-of-pipe solutions should be considered. There are multiple possibilities for filtering this nitrate out of the water. Apart from water treatment plants, more low-cost solutions for small areas are available. For example, filter beds could be located at the borders of agricultural land, where runoff often occurs. Here, the filters can capture the polluted water and filter it before discharging further. This mitigation strategy is not only applicable to agricultural sources but to other nitrate sources as well.

Nitrate filtration with zero-valent iron

Nitrate reduction to ammonium followed by ammonium capture is a compelling way to recycle nitrogen and apply the concept of circular economy to nitrogen since the ammonium can be used again as a fertilizer. A promising filter technique is the use of zero-valent iron (Figure 11). With this technique, nitrate in water is reduced to ammonium which then gets captured. This captured ammonium can then in turn be reused in new fertilizer. This technique presents a new pathway to recycle nitrogen, prevent pollution and save energy used in industrial ammonium production.

Lab tests performed by Florea et al. (2022) showed a conversion ratio of nitrate to ammonium of 70%, with nitrate removal of 82%. A big advantage was that high performance was recorded with short retention times of 35-45 minutes. Furthermore, there is almost 100% retention of ammonium, which enables the reuse of the recovered ammonium. The filters also have high efficiency at low temperatures. The cost of these filters can be high, with a calculated total cost of 35$/kg nitrogen reduced, but it should also be noted that the zero-valent iron technology is a perfect filter for trapping phosphorus. This phosphorus can be sold, just like the recovered nitrate, which can make this a cost-efficient strategy.(Copenhagen University, 2020)

Biological filter beds

Instead of mechanical filters, there is also the possibility of using plants in which nitrate gets converted to proteins. Fast-growing plants with a deep root system are very suitable for the prevention of nitrate leaching. For this particular purpose, mustard is an effective plant that already grows in many places in Cartago. It should be noted that these beds are not used to clean the polluted groundwater sources, because it will change the biological system. However, they are very useful as the first filter to make sure there is a decrease in nitrate pollution at the borders of agricultural fields. In lakes, plants can act as mechanical filters where nitrate gets converted to proteins. In lakes with many plants, the nitrate concentration in the water decreases (Briene, 2019).

Figure 11: A zero-valent filter system

Nitrate is one of the most important nourishment for plants. Plants suck it up through their roots and they convert the nitrate into protein that plants use to grow. Humans and animals need protein in their diet and the protein-rich manure they eject is converted by surface bacteria back to nitrate. The amount of nitrate is dependent on the species of plant, the soil, the amount of fertilization, climate circumstances and even the time of day during the harvest. When there is little fertilization, the plants will convert all the nitrate to protein without problems. However, if there is over-fertilization, the plant will have an excessive amount of nitrate.

In general, vegetables hold more nitrate than fruits, which means more is extracted from fertilization. Founded by measurements there has been a division in crops with high concentration and low concen-

Table 4: Flowers that are suitable for nitrate lifting

Name	**Characteristic**	**Flower**
Yellow Iris	Long vegetative period and easy to maintain	
Calamus	Consumption of phosphates is very high	
Spangranium erectum	Can grow in water up to 1 meter deep	
Veronica beccabunga	Creeping plant that consumes a lot of nitrate	
Watercress	Tolerates running water and has commercial value	
Lidsteng	Rapid growth in early stages, thus consumes nitrate early	
Mustard	Effective at leaching prevention and already common in Costa Rica	

trations of nitrate. Corps with a higher nitrate concentration than 1[g/kg] are endive, celery, lettuce (except iceberg lettuce), lamb's lettuce, spinach, radishes, parsley leaves and beetroot.
Plants with a lower concentration of nitrate are peppers, tomatoes, mushrooms, peas, apples, pears, oranges, peaches and grapes (FAVV, 2022).

Table 4 shows some alternatives of plants that can be used. Some plants have characteristics that are specifically good at filtering nitrate from water. These plants can be placed around fields with high nitrate pollution to reduce the concentration in the runoff. The plants themselves can be harvested and sold to keep the financial benefit of replacing cash crops with these nitrate-holding plants. However, it is hard to estimate the income these plants can generate.

Drip irrigation

Drip irrigation, also known as micro-irrigation, precise irrigation on trickle irrigation, is an irrigation technique that uses a network of pipes to carry a low flow of water under low pressure to plants. Water is applied frequently at low flow rates immediately above, on or below the surface of the soil with the goal of applying only the water that plants need. In areas with steep topography, drip irrigation is ideal since the slow rate of water addition is more likely to soak in before running off (Pramanik et al., 2016).

Often, irrigation is applied uniformly by sprat across the field. Every part of the soil gets the same amount of fertilizer and water. However, the soil is commonly not completely uniform. This means that parts of the field are under-irrigated and others are over-irrigated. Under-irrigation impacts crop yield and quality, whereas over-irrigation is a waste of water and fertilizer. Moreover, by keeping parts of the block more wet than necessary during the growing period, there is an increased risk of drainage and leaching when rainfall events occur (Wilson & Gardens, 2005).

With precise drip irrigation, the application of water and fertilizer can be adjusted so that it matches every soil requirement. That way, it can maximize crop response while simultaneously minimizing environmental impact. While using drip irrigation, the field is portioned into sub-units, where precise irrigation and fertilization can improve the efficiency of resource inputs. The spatial scale and timing of irrigation applications are therefore intended to improve yield and reduce the loss of fertilizer. In research done on drip irrigation in the United Kingdom, a benefit to the grower of crops was estimated to be typically around 30$/ha on fields that are over-irrigated (Daccache et al., 2015).

The cost of drip irrigation depends on multiple factors for example which kind of crop, type of terrain, water quality and quality of drip material. The drip irrigation system cost per acre of the vegetable crop will come to around 600-800/ha (Sawant, 2022).

Crop rotation

Often, only one type of crop is getting farmed. This makes sense since the farmers know much about this crop and are experts in the techniques of growing them. However, research suggests that the marketable yield increases with crop rotation. In addition to that, it reduces nitrate leaching. So by farming different crops with different root systems, less nitrate pollution will occur without risking the yield of the crop. (Jiang et al., 2022) Crop rotation can also significantly reduce nitrate pollution in livestock farms (Eriksen et al., 2015).

2.5.2 Livestock

Mitigation of nitrate because of livestock can be managed in many different segments of the livestock industry. Since springs are the main source of drinking water, livestock operations should be placed downstream from the wells to ensure as little infiltration in the well as possible. In addition, livestock facilities should be placed 100 to 120 meters away from houses and operations should be at least 30 meters from wells (Sahoo et al., 2016).

For site characterization, the soil permeability must be low. Clay and well-drained loam soils are appropriate locations for livestock applications. Shallow soils, soil with excessive drainage and high permeability or with a high water table are poor or unsuitable locations. If bedrock is close to the surface, it is helpful to pave the surface with concrete to reduce water contamination. Cleaning the area regularly will mitigate the manure in yard runoff and prevent leaching into the groundwater.

The application of buffer strips similar to agriculture can also help minimize pollutant leaching into the water bodies around the livestock area. The minimum separation distance between manure storages is preferred to be 100m. These manure storages must be positioned downstream from wells to make sure that runoff cannot drain into them. The distance between wells and manure storage should be at least 100m as well. Similar to manure storage, other livestock waste can easily contaminate groundwater thus hydrological characteristics of a site must be investigated to guarantee a suitable site for storage. If the groundwater is located close to the bottom of a storage facility, it must be paved with concrete to prevent seepage. In addition, manure storage facilities should include a compacted soil cover to seal the side. The reduction of oxygen contact will lessen aerobic decomposition and nitrification (Sahoo et al., 2016).

It is important to collect all the manure and soil mixtures from abandoned feedlots and yards and then spread them as fertilizer onto fields. Due to lack of use, the manure pack breaks up easily and rainwater can pass through the cracks and leach nitrate. Afterwards, planting fast-growing crops can drain the soil of excess nitrogen.

2.5.3 End of Pipe Solutions

Various methods do exist or are in an experimental state for the removal of nitrate from water. In this section, some technologies are discussed in Table 5. In addition to mechanical filters, conventional methods to remove nitrate are adsorption (for example by activated carbon), ion exchange, electrodialysis, reverse osmosis and biological denitrification in bioreactors.

Building wetlands

A way of reducing nitrate pollution by changing the architectural properties of the farmlands is by building wetlands. First of all, building wetlands in the Northern Cartago region is considered an option. In research of Bauwe et al. (2022a), Surface runoff engineered Wetlands (SFWs) are being utilized to reduce nitrate (NO3–N) loading in an agricultural watershed in Germany (2022). Results show that the basin-wide NO3–N loading could be reduced by 6.6%. However, it has to be noted that the watershed in Germany is entirely flat, which makes it an ideal location for these practices. In this research area, the hills on the Irazú volcano are relatively steep, which makes it extremely hard to recreate such effective SWFs. Since the water will not stay in one location but will make its way downstream, an SWF is not feasible to create in the research area.

Table 5: Overview and summary of the conventional end of pipe nitrate removal technologies

Nitrate Removal method	Mechanism	Examples	Downsides
Adsorption	Various materials have the ability to adsorb nitrate ions. It has fewer energy requirements from other processes and it has been shown to be efficient, low-cost and have a wide application (Huno et al., 2018). The high surface area of the adsorbents allows attraction of the dissolved nitrate ions. Other organic adsorbents also have potential.	Carbon-based sorbents have shown to effectively remove nitrate. Powdered and Granulated activated carbon (GAC) are partially promising as demonstrated by: (Khani & Mirzaei, 2008; Bhatnagar et al., 2008; Mehrabi et al., 2015)	Removal capacity can be sub-optimal
Ion Exchange	Negatively charge nitrate ions can be removed by ion-exchange. Feed water is passed over exchange resins containing either chloride or bicarbonate ions, the nitrate ions then replace the existing anions in the resin. When the resin is exhausted, it is rinsed with high salinity water to replenish the chloride and to be used again.	Chloride and bicarbonate containing resins are found to be most effective for nitrate replacement. As shown in studies like:(Matosic et al., 2000; Nujić et al., 2017)	Not suitable for high TDS feedwater
Electrodialysis	ED separates nitrate ions from feed water by using cation and anion exchange membranes that are subjected to a charge. The electric field drives the ions such as nitrate through the selective membrane.	ED used in Morocco for treating high nitrate groundwater (El Midaoui et al., 2002) Relatively high nitrate selectivity and 66 % nitrate removal rates achieved in full scale plant 25 years ago (Hell et al., 1998)	High complexity and energy demand
Reverse Osmosis	Water is forced through a multitude of semipermeable membranes. Ions such as nitrate and virtually all other compounds present in the feed water cannot pass through the membranes and are left behind. The feed water must be subjected to high pressures to overcome the osmotic pressures of the RO cells.	Useful example in rural setting, costs are around \$0.21/m3 in South Africa (Schoeman, 2009)	Expensive and high energy demand
Biological denitrification	The processes take place under anoxic conditions when either heterotrophic or autotrophic bacteria convert nitrate into nitrite to nitric oxide to dinitrogen oxide and eventually into harmless nitrogen gas. Various types of bioreactors are in existence. Biofilms containing bacteria are supplied with carbon sources such as ethanol or methanol.	Biological denitrification with alcohols for groundwater nitrate removal (Gómez et al., 2002) Biofilm–electrode reactor with both heterotrophic and autotrophic bacteria with 97% removal of nitrate (Zhao et al., 2011))	Complex and sensitive to changes

2.6 Measurement systems

Having a large quantity of and good quality measurements is pivotal when building a database. A higher amount of and higher accuracy measurements will make analyzing data easier and more impactful. There are multiple ways to increase these measurements, but the best is often the ease of measuring and the transfer of the data. Official measurements of nitrate concentration can be done by the cadmium reduction method which is a colorimetric method where nitrites react with other reagents to form a red color. The intensity of that color is proportional to the concentration of nitrate. This can then be measured by visual comparison or with an electronic spectrophotometer. Another method is the nitrate electrode method. With this, a nitrate electrode with a probe and a sensor is used to measure nitrate activity in water by the electric potential of a solution in the probe. *Standard Methods for the Examination of Water and Wastewater* (1925) These are complex and expensive methods, which means that many data points are not as easily obtained.

Citizen science

The easiest way to increase the number of measurements is by increasing the number of people that can perform these measurements. Implementing citizen science is therefore a very suitable alternative to having many people produce data. Data produced by citizens are considered to be less accurate and trustworthy, but with proper instructions and validation, it can prove to be very helpful. If citizen science is to be implemented, some principles have to be taken into account. Data collected by the public must be validated in some way, methods of data collection must be well-designed and standardized and volunteers must receive feedback on their contribution as a reward for participation (Edo et al., 2018).

Quick and dirty measurements for Nitrate concentration in water

During the project, it became apparent that having sufficient measurements often was a problem. One of the reasons for the lack of measurements is that it is hard to get to different locations where the springs are located. Another reason is that there is a lack of knowledge and people available to perform these measurements. Since roughly knowing the nitrate concentrations can be very valuable information, it would be interesting to research different ways to get those concentration measurements.

Figure 12: Example of a test-strip kit

One of the major areas where progression can be gained is with the local people. If they are provided with the right tools and information to carry out measurements themselves, it will greatly increase the database. Involving the local people in this citizen's science also increases the awareness of the problem and transparency of solutions.

In many cases, an indication of the nitrate concentration is enough. If the concentrations show critical values, AyA could perform more accurate measurements on these locations. So, as mentioned above, a cheap and quick way to measure the nitrate concentration should be provided by either the government or AyA to the local citizens. There are a number of possibilities.

One of the quickest and easiest ways is by using nitrate test strips (Figure12). These strips can be bought for less than 0.5$ per strip, which makes it a cheap option. By dipping the strip in the water sample, a quick measurement can be taken. The strips show in which range the concentration of nitrate is. A big advantage of this method is that it can be taught to people very easily and in consequence, it will greatly improve the number of measurements if it can be carried out by local people. The accuracy

Figure 13: Example of a Nitrate test kit

of nitrate concentration is dependent on visual recognition. The accuracy also depends on the test strips themselves. Most range from 0 to 100 with 8 steps. The accuracy could therefore be judged within 8mg/L. It has to be noted that this measurement is mostly for indication, so when nitrate levels reach critical levels, better measurements should be taken.(Bischoff et al., 1996).

Figure 14: Example of a Nitrate sensor

Another way could be by distributing nitrate test kits to the ASADAS(Figure 13). These kits can provide more accurate measurements, but they are also more expensive and slightly more complicated to use. Some nitrate kits have an accuracy of 2 mg/L, but it is still important to consider the ease of use. Especially if citizen science has to provide the measurements (API, 2023).

A third option could be the use of sensors or other pocket meters (Figure 14). These devices are much more expensive and therefore probably not a good alternative if the measurements should be carried out on large scales. An advantage is that the data is more accurate and can quickly be sent to interested parties since it is recorded digitally. The accuracy is within 0.1mg/L (Hach, 2023).

Monitoring wells

Literature suggests that groundwater quality should be monitored at least twice a year (Sahoo et al., 2016). During periods of exceeding nitrate levels, testing should be done more regularly.

While measuring directly in the springs is an option, purpose-built monitoring wells are the best option (Foster et al., 2002), as seen in Figure 15. These wells can be made very narrow (<5 cm diameter) with a screen length of only 2-5 meters. Gathering long-term, regular data allows for establishing relations between climate, land use and contamination better. As of now, qualitative data has been tested irregularly and too infrequently to establish hard relationships and conclusions between these factors.

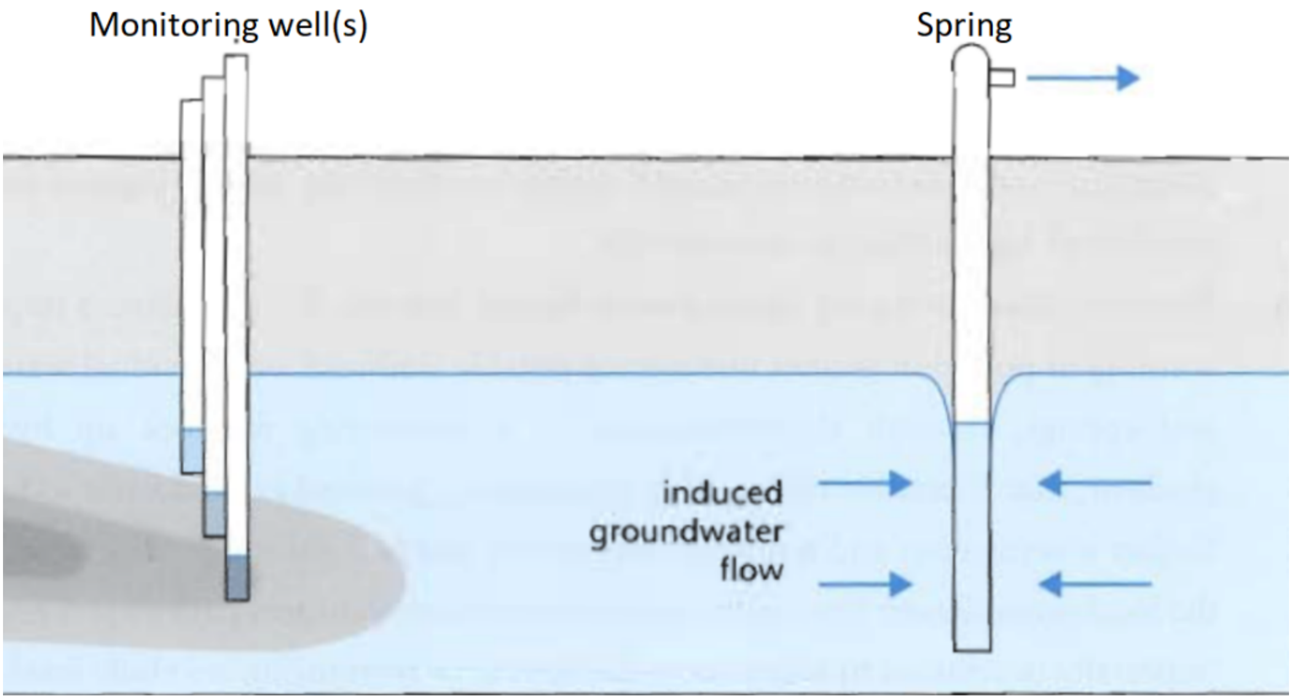

Figure 15: Example of a monitoring well, adapted from Foster et al. (2002)

3 Research Materials and Methodology

3.1 Obtaining data

One of the major tasks and opportunities of the project is to gather, organize and create an ecosystem of a wide variety of data. The structure in Costa Rica is set up in such a way that many different parties have valuable data points, however, mutual sharing is very limited. In the stakeholder analysis, it is explained who all these parties are. A collaboration between these parties is important, so transparency is needed to remove the existing barriers. Building up a database where all this data is available is essential for this project and future projects in the same area.

Retrieving this data is in most cases not straightforward. Oftentimes, data has been recorded online, but in some ASADAS the data was only recorded on notes. Visiting the ASADAS was necessary to receive all the data. On some occasions, building up the data points while the local ASADAS employees explained where these points were located. Many visits have been made, often together with a geographer, where maintenance personnel from the ASADAS pointed out the water distribution network on a projected map. Later, this information was processed in QGIS.

Next to obtaining the data from historic recordings, multiple field days were organized in order to complement the historic data set. An essential part of the field days was the performance of qualitative interviews. The exact completion of the content has been recorded in Appendix A.4.

3.1.1 Geo-hydrological situation

As mentioned in Section 2.2, the geological survey is shown here. All information has been gathered through literature studies and maps, which were then clipped to the particular research area. Geo(hydro)logical information is available through a study performed by a combination of various Costa Rican authorities led by SENARA (Hartig et al., 2012). During this study, characteristics of a limited number of springs in our area were measured and identified. This study provides many insights relevant to the aim of this project. Other local studies of various springs in the area were provided by AyA, specifically about the Boqueron, Cipreses and Santa Rosa springs. While the geological survey provides information about the types of rocks, the quantification of their characteristics such as permeability and porosity is not available for the majority of the region.

Geological formations
The results of the geological study by Krushensky (1973) were retrieved and shown over the research area.

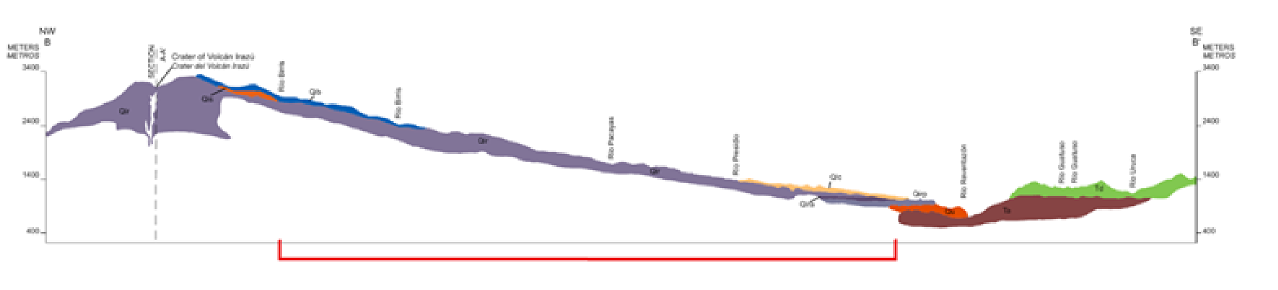

Figure 16: Cross-section with the research area indicated in red. Adapted from (Krushensky, 1973)

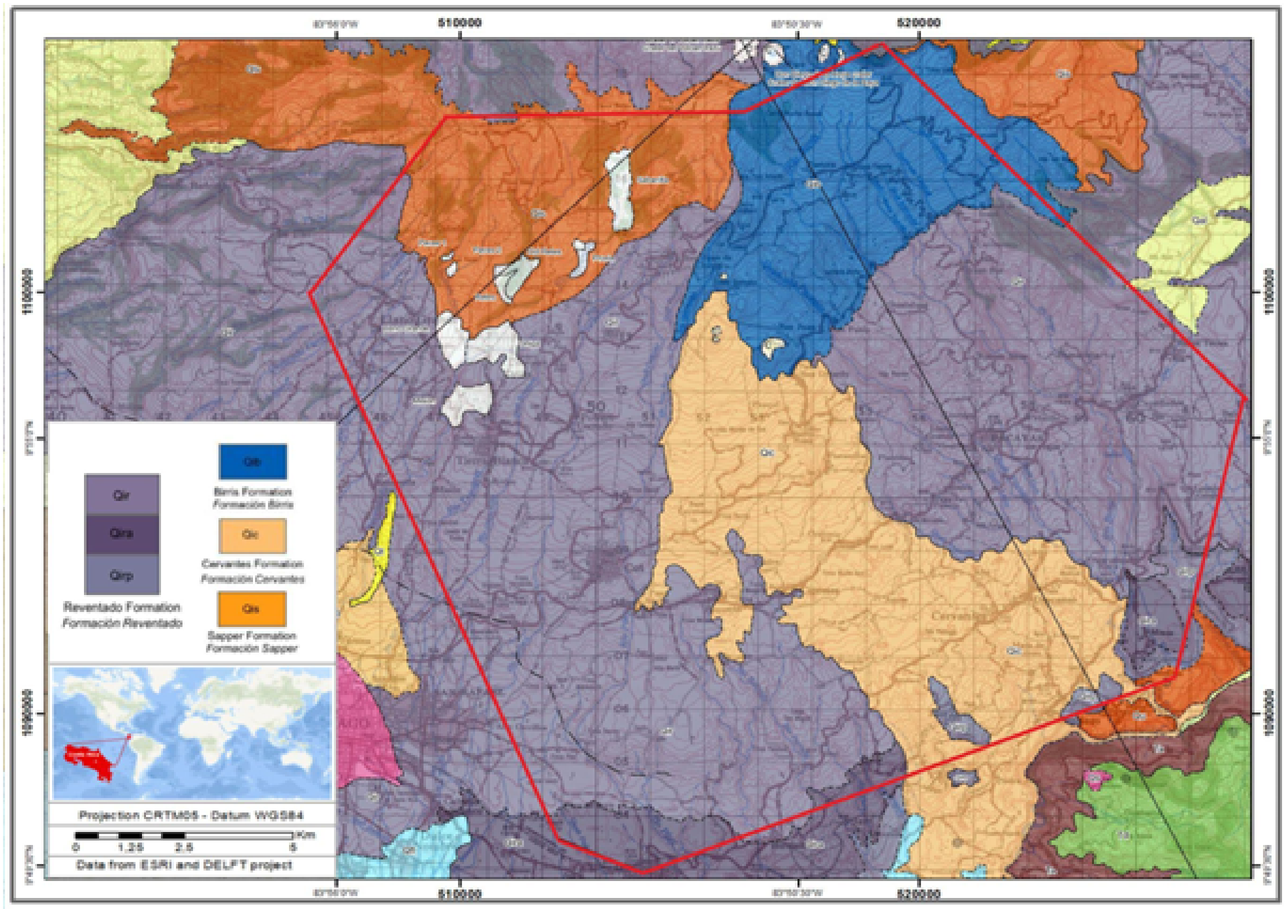

Figure 17: The geological map overlaid with the research area (red) and the springs (blue). Adapted from (Krushensky, 1973)

In Figures 17 and 16, it is observable that the majority of the area consists of Reventado formation (Purple). This is an Augite lava flow deposit which is locally vesicular. The whole area consists of mostly lava flows, with the only exception being the small dark orange area in the southeast which is the Ujarrás formation which consists of interbedded shale, siltstone, sandstone and conglomerate. The geological survey from 1972 mentions that the bottom meters of the 200-meter-thick Ujarrás formation holds an Artesian aquifer. The light orange area in the northwest is the Cervantes formation. Details about one source in this formation were available from AyA and mentioned that the Boqueron spring in Oreamuno originates from a phreatic aquifer that is formed in the lavas of the Cervantes formation. Here, the water flows through the volcanic rock fissures.

3.2 Data Cleaning and Analysis

Pre-analyses

In the early stages of the research, an extensive Excel was provided, including nitrate measurements that were executed by AyA in the period from 2009-2021 (AyA, 2021). The data-set was a combination of the measurements performed in the following sub-regions: Alvarado, Atenas, Canás, Cartago, Paraíso, El Guarco, Cañas, Desamparados, El Guarco, Escazú, Goicoechea, Jiménez, La Unión, Oreamuno, Payacas, Palmares, Poás, San Carlos, San Jose, Terrazú and Turrialba. After identification from the area, the following sub-regions were inside our project area: Cartago, Paraíso, Oreamuno and Alvarado.

The measurements were executed by a large variety of people giving rise to different notation methods. To equalize the notation methods and increase the workability, the data set was cleaned in Python. This was done by grouping the data points that were assumed to have similar notations, eliminating of invalid data points and creating sub-data-sets that were used in further data analysis. It is worth mentioning that the nitrate measurements in the AyA data set were not regular, some springs were tested once in the 12-year span of the data set while others were tested more regularly.

Identifying preliminary trends on the local level
The Python script was used to identify the following items:

- Identifying high-risk areas which demonstrated long-term trends in high values of nitrate pollution. The script is made in an interactive way to optimize workability in further research. Further research groups could use the script as a starting point for their analysis. The script is focused on analyzing local trends.
- Rolling yearly/monthly means in order to obtain long-term trends in nitrate pollution focused on Cartago, Paraíso, Alvarado and El Guarco.

Identifying preliminary trends on a regional level between precipitation and nitrate pollution
After obtaining the historical precipitation data from ICTR (ICTR, 2022) and visual crossing (Visual Crossing, 2022), a correlation could be drawn with the previously obtained historical pollution data. In Python, the following items are being created:

- Yearly and monthly precipitation means in the period between 2009-2021
- Yearly and monthly means from regional nitrate pollution in the period between 2009-2021.
- Visual representations from the combined trends
- Possible relationships between elevated regional nitrate pollutants and precipitation weather patterns. The quantification of the relationships is done by implementing the Pearson method.

3.3 QGIS

For the spatial analysis of this project, a research area had to be defined. This was done by firstly geo-referencing the chemical lab data received from the Laboratorio Nacional de Aguas from AyA. The spatial data were obtained by physically visiting the different ASADAS and municipalities in the region and obtaining data such as spring locations, storage tanks and chemical measurements. Often this was done by sitting down with experienced workers of the local ASADAS and having them point out on maps where pipes and other infrastructure were located, real documentation of this did not exist until now.

When both data-sets were obtained the chemical measurements were matched to their sample location in the different springs. This resulted in a map with a clear visualization of the nitrate spring contamination. From this map, a research area was identified, shown in Figure 18. Subsequently, the recharge areas of the springs were calculated in order to be able to do relevant spatial analysis. The parameters that were considered are the land use within these recharge areas, the slope and finally it was analyzed if the so-called ''protection area" (a circle with a radius of 200 meters around each spring according to the Ley de Aguas (Congreso Constitutional De La Republica De Costa Rica, 1997)) was breached by buildings.

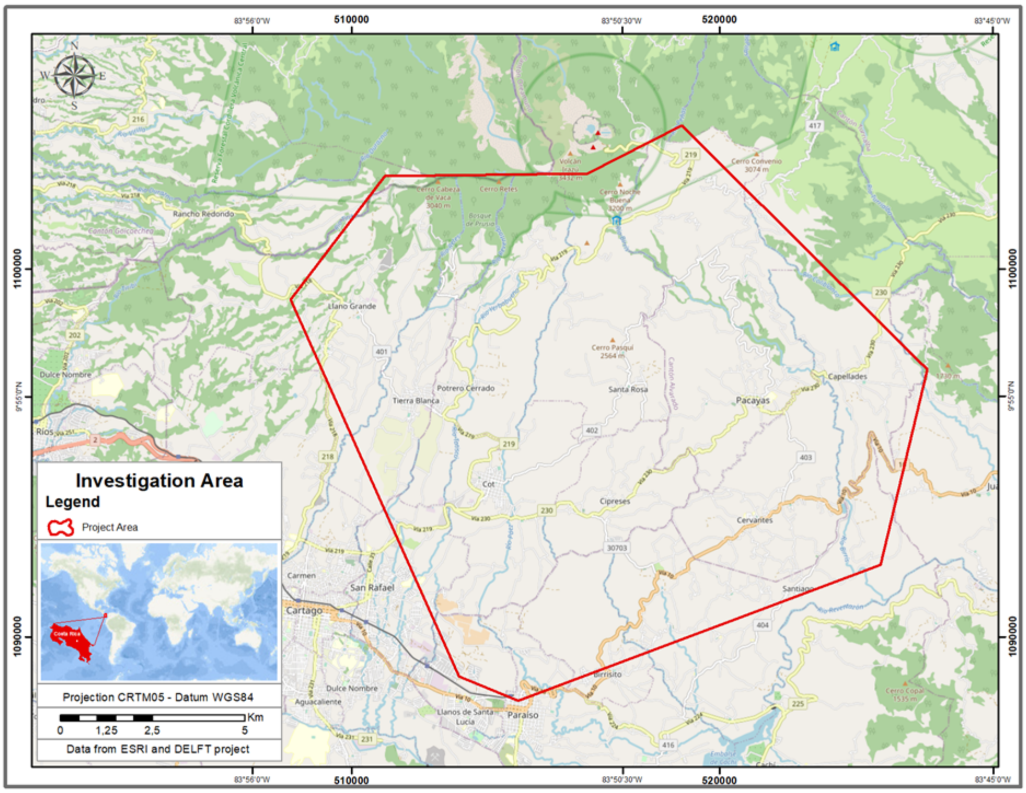

Figure 18: Project research area

3.3.1 Capture zone delineation method

The capture zone is here defined by the geographic area starting from the spring and ending at the tail end of the upstream branches. To correctly derive a capture zone for a spring, various factors should be known such as hydraulic conductivity, effective porosity, and hydraulic gradient. A multitude of analytical capture zone delineation methods is in existence varying from low to high complexity and accuracy. The simplest methods that work with very limited data are the fixed radius method and the uniform flow method.

For the scope of this project and because of the very limited data an indication of the capture zone based on elevation is sufficient. This model requires basic input which is beneficial since detailed aquifer and geological information is not available. Time constraints do not allow for taking soil samples, performing infiltration and penetration tests, or performing tracer experiments around 62 spring locations.

It is argued that this type of contributing area delineation is well-suited considering the reduced nitrate leaching of the Andisol soil order. Various studies have shown the possibility of a retardation capacity for nitrate leaching due to its variable charge characteristics (Tani et al., 2004; Reynolds Vargas et al., 1995; Ryan et al., 2001). The adsorption of nitrate in the soil could cause a more significant amount of nitrate to flow overland and through the unsaturated zone (interflow) to the springs instead of via infiltrating pathways to the groundwater. Therefore, topography largely determines the direction the nitrate contaminants take.

In order to be able to perform spatial analysis and link possible nitrate sources to nitrate pollution in the springs, the recharge areas of 24 springs are identified. These are generated using the D8 method in QGIS. The Digital Elevation Model (DEM) which was used for this algorithm is the dem10cr from the Atlas Digital de Costa Rica 2014. This data set was obtained from a CD at the library of the TEC Cartago. Before executing the algorithm the cells without data, the sinks, and the spikes of the DEM were smoothed using the ''fill no data" and the ''Wang Liu" tools provided by the SAGA plugin in QGIS (Wang & Liu, 2007).

After this geographical processing, the Strahler order was calculated. The Strahler order is a digit that defines every stream based on tributary hierarchy, with large main rivers resulting in a high Strahler number and small streams resulting in a low Strahler number (Strahler, 1952). After consulting the known recharge areas of the Mero, San Juan de Chicúa and Plantón (Viquez, Aurelia and Portilla, Luis E., 1993) springs a Strahler number of 4 was observed to have the best fit as a minimal value to define the recharge areas of the other springs.

Afterwards, the flow direction and the channels for the project area were calculated by the 'Channel network and drainage basins' tool from the SAGA plugin. This offered a clear insight into the hydrological system of the project area. Subsequently, making use of the coordinate capture tool from QGIS in combination with the 'Upslope Area' algorithm the corresponding sub-catchments were delineated for 24 springs, based on springs with the best available water quality data. This area was finally converted from a raster to a vector layer, to be able to do further spatial analysis on the recharge areas. The springs were selected based on the quality of the available data since some springs only had a few measurements which were also outdated.

3.3.2 Land Use

Different data sets are used for the different land use types and these are merged into one large data set. The land use in the region is classified into five different categories. These categories are classified according to the available data-sets of the Instituto Geográfico Nacional Instituto Geográfico Nacional (2017).

The land use types and their corresponding data sources follows in this list:

- **Buildings**: The urban environment in the research area. This includes houses, utility buildings and industrial buildings. Greenhouses are excluded from this data-set and added to the crops category.
- **Crops**: The agricultural area in the region. Greenhouses from the 'buildings' data-set are included in this category because they have the same impact potential as outdoor agriculture. The main crops in the region are carrots, potatoes, onions and cabbage.
- **Pastures**: The pastures in the region.
- **Forest**: The trees and woods in the region.
- **Other**: These are areas that are not represented in the earlier data-sets. Smaller patches of these areas can be found around buildings and in water bodies. Furthermore, at the top of the Irazú volcano, there are large sandy areas which fit into this category.

The geometries of all data-sets were fixed, after which everything was clipped to the research area with a margin to account for extent of recharge areas outside our project area. The data sets are then merged into one large data set and mapped. Results are given in Figure 19. The portions of each land use type in a capture area could then easily be calculated by taking each land use type area and dividing this by the sum of all land use types. A total of four land use parameters were used in modeling the contamination: portion of pastures, a portion of buildings, a portion of crops, and portion of woods.

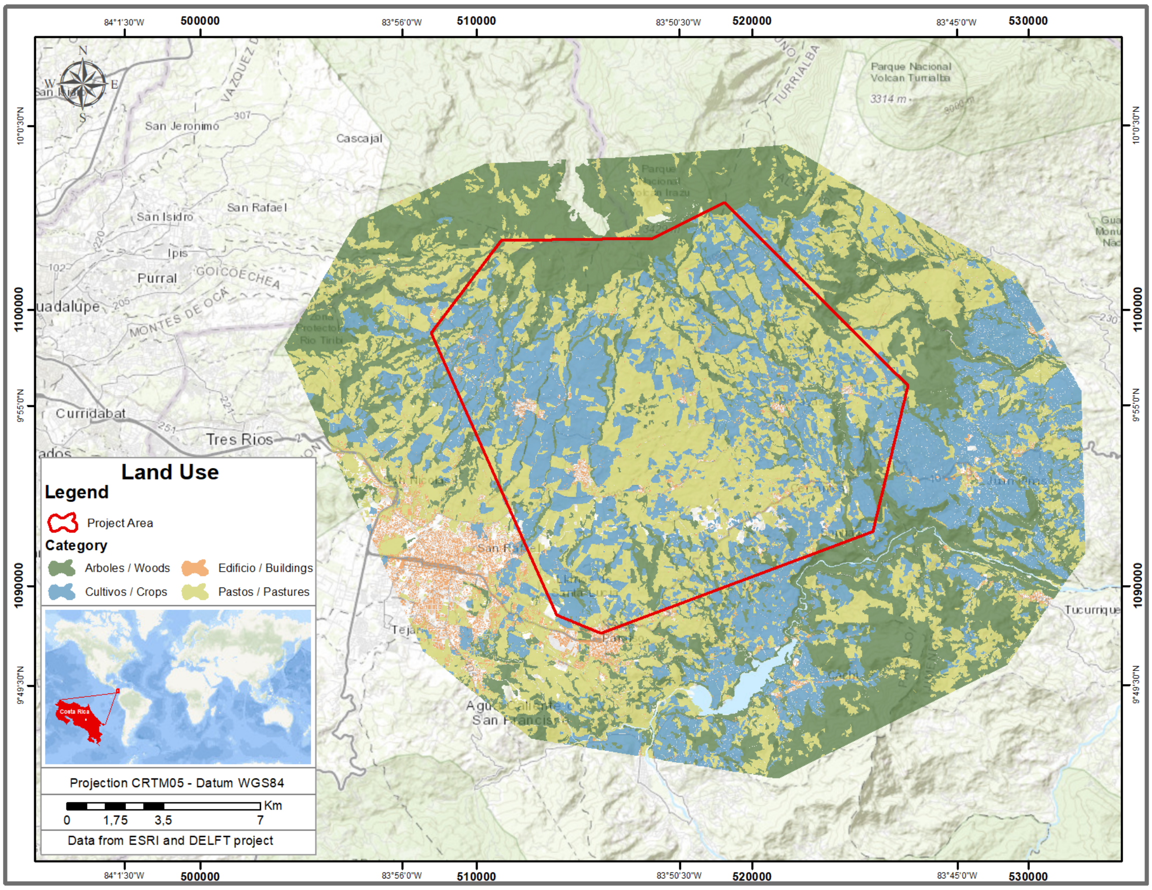

Figure 19: Land use in the project area

3.3.3 Slope

The second spatial parameter considered in this research is the slope. The complete research area is located on the southern slope of the Irazú volcano which results in an area with pronounced elevation differences. Sloping areas in agricultural areas have been known to positively contribute to input of contaminants from the agricultural industry in surface and groundwater (Dabrowski et al., 2002).

The slope was calculated using the Digital Elevation Model that was mentioned prior. For this calculation the slope tool from QGIS was used that calculates the inclination to the horizontal of each raster tile. The resulting map was then clipped by the recharge areas which finally returns the zonal statistics within each area. The selected spatial statistics chosen for further analysis were the minimum, maximum, mean and standard deviation of the slope. These were extracted and used as input parameters for the contamination model.

3.3.4 Protection Area Breach

The Ley de Aguas, law 276, art. 31 prescribes that there should be a radius of 200 meters around a spring with public water use in order to maintain water quality in this spring. From analyzing satellite imagery, visits to the spring, and stories from locals, it was found that this 200-meter radius was often not respected. Therefore, this was included in the research.
Each spring was given a score of 0, 0.5, or 1 to rank the magnitude of the breaching of the 200-meter radius. Defining whether buildings were present in the 200-meter radius was done using Google Satellite data. The scores were defined as follows:

- 0: No breaching of the spring. In the 200-meter radius around the spring, no buildings were found except for a protection shed of the spring itself.

- 0.5: Breaching of the spring with the low expected impact. Examples were springs with less than five buildings downstream in the 200-meter radius or a maximum one building upstream but not in the capture area of the spring.
- 1: Breaching of the spring with moderate to high expected impact. Examples were houses or buildings in the 200-meter radius and in the capture area. Also, some springs were surrounded by complete urban areas.

This ranking was used as input parameter to model the contamination in the springs.

3.4 Modeling of contamination

In order to search for relations and correlations in the data-set, Pearson analyses were made. A total of 174 measurements in 24 different springs were selected based on availability of the nitrate measurements. Different properties of the spring and its capture zone were compared with the contamination on different time frames.

Precipitation during measurement
The precipitation is also included in the model; it is assumed that there is no spatial difference between precipitation. Therefore, the average monthly precipitation data of the entire region is used. The average monthly precipitation data from ICTR and the visual crossing was calculated; spatial patterns were not considered due to ease of calculations. In the model, the measurement month was then coupled with the average monthly precipitation amount of that month.
An example: the Birris 1 spring was measured on the 29th of May, 2020. The average precipitation in May in the region is 237.2 mm. Therefore, 237.2 mm was linked to this measurement.

Contamination of the spring
From all the springs selected, nitrate measurements are available. These measurements include the spring where the measurement was done, the date of the measurement and the nitrate amount in mg/L.

3.4.1 Modeling nitrate contamination

All these parameters were assessed on their correlation with the nitrate concentration of the measurements using Excel. The assessment is two-folded: in the first part, a Pearson analysis was done on all parameters, their square roots and their squares. In the second part, a multivariate polynomial regression model is made to verify the parameters used.

Pearson analysis
A Pearson analysis was done as it is the most common and utilized way of finding correlations. For this analysis, the square and the square root of each parameter were calculated. This gave a total of 30 parameters. All parameters were then correlated to each other using a Pearson analysis and a correlation matrix was made. The following formula was used:

$$\rho = \frac{n(\Sigma xy) - (\Sigma y)(\Sigma x)}{\sqrt{[n\Sigma x^2 - \Sigma x^2][n\Sigma y^2 - \Sigma y^2]}}$$

Where:

- x,y: the parameters for which the correlation is calculated
- n: the total amount of measurements, in this model 174

Nitrate concentration model
Using the same parameters as used as the input of the Pearson analysis, the nitrate concentration in spring can be modeled using a regression model. Because the root and the square of a total of 10 parameters are used, the resulting model is a multivariate polynomial regression.

The model that is searched for is in reality a long single formula, with the following structure:

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + ... + b_kx_k + e_k$$

Where:

- b: the coefficient that corresponds with the parameter. This will be calculated later
- y: the modeled value of the nitrate concentration
- x: the observed value of a certain parameter, e.g. the precipitation, minimum slope, or the portion of woods in the recharge area. This can also be the square or the square root of one of these parameters, e.g. the square of the precipitation
- e: the error of the model
- k; the number of the parameter

The coefficients can then be calculated. In order to do so, first the A and H matrices have to be made using the following formula.

$$A = \begin{bmatrix} n & \Sigma x_1 & \Sigma x_2 & \Sigma x_3 \\ \Sigma x_1 & \Sigma x_1^2 & \Sigma x_1 x_2 & \Sigma x_1 x_k \\ \Sigma x_2 & \Sigma x_1 x_2 & \Sigma x_2^2 & \Sigma x_1 x_k \\ \Sigma x_k & \Sigma x_1 x_k & \Sigma x_2 x_k & \Sigma x_k^2 \end{bmatrix}, H = \begin{bmatrix} \Sigma y \\ \Sigma x_1 y \\ \Sigma x_2 y \\ \Sigma x_k y \end{bmatrix}$$

Furthermore, the $A_1, A_2, \ldots, A_k$ matrices are made. This is done by changing the (k+1)th column of the A matrix with the H matrix. In this example:

$$A_0 = \begin{bmatrix} \Sigma y & \Sigma x_1 & \Sigma x_2 & \Sigma x_3 \\ \Sigma x_1 y & \Sigma x_1^2 & \Sigma x_1 x_2 & \Sigma x_1 x_k \\ \Sigma x_2 y & \Sigma x_1 x_2 & \Sigma x_2^2 & \Sigma x_1 x_k \\ \Sigma x_k y & \Sigma x_1 x_k & \Sigma x_2 x_k & \Sigma x_k^2 \end{bmatrix}, A_k = \begin{bmatrix} n & \Sigma x_1 & \Sigma x_2 & \Sigma y \\ \Sigma x_1 & \Sigma x_1^2 & \Sigma x_1 x_2 & \Sigma x_1 y \\ \Sigma x_2 & \Sigma x_1 x_2 & \Sigma x_2^2 & \Sigma x_2 y \\ \Sigma x_k & \Sigma x_1 x_k & \Sigma x_2 x_k & \Sigma x_k y \end{bmatrix}, \text{etc.}$$

Now, the b values can be calculated using the following formula:

$$b_k = \frac{det[A_k]}{det[A]}$$

For simplification purposes, for this model, the Analysis ToolPak regression tool in Excel is used to calculate the parameters that correspond to the regression model. As it only allows 16 different parameters for regression analysis, an iterative method was used to find a R^2 value of the resulting model which was as high as possible. The resulting parameters are as follows:

- Precipitation
- Portion of forest

- Portion of pastures
- Portion of the urban area
- Mean slope
- Square root of mean slope
- Square of mean slope
- Max slope
- Square root of max slope
- Square of max slope
- Min slope
- Square root of min slope
- STD of slope
- Square root of STD slope
- Square root of STD slope
- Bufferzone respected (1, 0.5 or 0)

As can be seen, the portion of agriculture in the region is not considered directly. However, the sum of all portions of the other land uses is 1. If the portion of agriculture would also be included in the model, this would result in a coefficient corresponding to the portion of agriculture which would be equal to 0, as the determinant of A_k would also be 0. However, as the sum of the portions is 1, it is still indirectly included in the model.

The results of the regression analysis are given in Chapter 4.

For the precipitation in particular, more information on the spatial patterns can be found in section 3.4.2. Furthermore, a qualitative analysis of the relation between the precipitation and contamination levels can be found in Appendix A.3.1.

3.4.2 Spatial patterns in the precipitation

The following sub-chapter gives a further detailed analysis of the correlation between precipitation and nitrate concentration. The analysis is three-folded: the first part focuses on finding spatial differences between the precipitation based on measurement stations. The second part focuses on finding patterns in the whole AyA dataset in order to see whether the local spatial differences in our research area are decisive. The third part gives a qualitative analysis of the relation between the nitrate concentration and precipitation.

To find spatial patterns in the precipitation, the precipitation measurements from Visual Crossing (2022) and ICTR (2022) are mapped in the research area. The monthly average precipitation measurements are available; these values are interpolated on the whole research area. Results are given in Section 4.6.1.

The analysis of the whole AyA data set is not considered to be a core part of the research as it is not used in the final model. It can therefore be found in Appendix A.5, including the whole data set.

4 Results

In this chapter, the results will be presented in order to be able to draw sensible conclusions and answer the identified research questions. The nitrate pollution is mapped in Section 4.2, after which the recharge areas are mapped in Section 4.3. The recharge areas are spatially analyzed in Section 4.4. In Section 4.5, the results of the interviews are presented and the results of the models are in Section 4.6. Lastly, the results of the financial analysis are given in Section 5.1.

4.1 Stakeholder analysis

In this section, all different groups and individuals who have an interest in or impact on the nitrate pollution problem in the research area are identified and their importance is assessed afterward. This information can then be used to understand the potential impact of the findings of the total report, and to ensure that the recommendations made in the report consider the interests and concerns of all different stakeholders. Additionally, this analysis can help identify any potential biases or conflicts of interest that may need to be considered when interpreting the results of the report. All the roles and interests of the stakeholders are stated below in Table 6. For an extensive explanation of each individual stakeholder, Appendix A.4 can be consulted.

Power interest grid

In a study where many different parties are involved, it is important to make a power interest grid to visualize where the power and interest of the different parties should lie. As a result, a good estimation can be made of the involvement and stakes of the different parties, see Figure 20. The following stakeholders are considered:

- The ministries and AyA are considered to be the most powerful stakeholders since politics make the policies and legislation by which the inhabitants and agriculture of the region are affected. Especially, the Ministry of Health has the most influence since they have the power to close down the springs and ASADAS in the region. Also, AyA is the party who is responsible for a clean water supply and is responsible for measuring pollution in their service areas and that of the ASADAS.
- SENARA and TEC are both lower in power and interest since it does not directly affect them negatively and both are large academic institutions with other priorities as well.
- The municipalities and ASADAS have slightly more power than the farmers and local inhabitants since the municipalities and ASADAS represent a community/village in the region which is in direct contact with AyA and the government.
- The local farmers and inhabitants have a clear stake in this case, however, their power is usually low in these situations.

Table 6: Stakeholder roles and interests

Stakeholder	Role	Interests, Values & Expectations
Ministries of Agriculture, Health and Environment & Energy	1. Final responsibility for water supply and sanitation 2. Make guidelines for pollution thresholds 3. Communication between all different parties involved	1. Clean drinking water for inhabitants of Costa Rica 2. Keeping the citizens content with their policies by being transparent and involved in local projects 3. Providing farmers with agricultural courses 4. Expect governmental institutions to perform their duties concerning water management appropriately
AyA	1. Enforce the regulations that are made by the ministries 2. Ensure all inhabitants in their service area have access to clean, potable drinking water, also for the ASADAS outside their service area 3. Responsible for measurements being done in their own service area and in that of the ASADAS	1. Clean drinking water for inhabitants of Costa Rica 2. Regain trust and participation with all stakeholders involved 3. Farmers doing an agriculture course provided by the Ministry of Agriculture (MAG) 4. Aiding in setting up an online database with valuable measurements 5. Generate awareness about spring contamination and stimulate ASADAS to perform and share nitrate measurements.
SENARA	1. Responsibility for the development of irrigation, drainage, and flood prevention 2. Conduct research on the preservation and development of aquifers & agricultural areas 3. Maintaining and improving the agro-productive capacity	1. Receive valuable data from AyA and ASADAS for their models and studies 2. Development of agricultural projects that are based on a fair distribution of land 3. Maintain optimal and efficient water resource management practices 4. Performing and distributing hydrological studies
Municipalities	1. Clean potable water, sanitary sewerage and treatment services 2. Repairing larger issues in sewage, septic tanks and other water-related problems	1. Clean drinking water for inhabitants of Costa Rica 2. Regain trust and participation with all stakeholders involved
ASADAS	1. Safeguard water supply 2. Execute measurements of springs and water tanks in their own ASADAS region 3. Ensure all inhabitants have access to clean, potable drinking water	1. Provide clean, affordable drinking water with a 24/7 service $\rightarrow$ no water trucks necessary anymore 2. Aiding in setting up an online database with valuable measurements 3. Regain trust and participation with all stakeholders/parties involved
TEC	1.Provide Costa Rican society with knowledge and education 2.Supervising students during their studies and research	1. Receive enough funding from government and partners to continue research and innovate in the long term 2. Solving acute problems and research questions, both in the region as internationally
Local Farmers	Provide food security and receive a liveable income	1. Food security, an equal chance on commercial markets 2. Continuation of their agricultural activities
Local Inhabitants	Keep water sources clean of pollutants	Receive clean and affordable drinking water

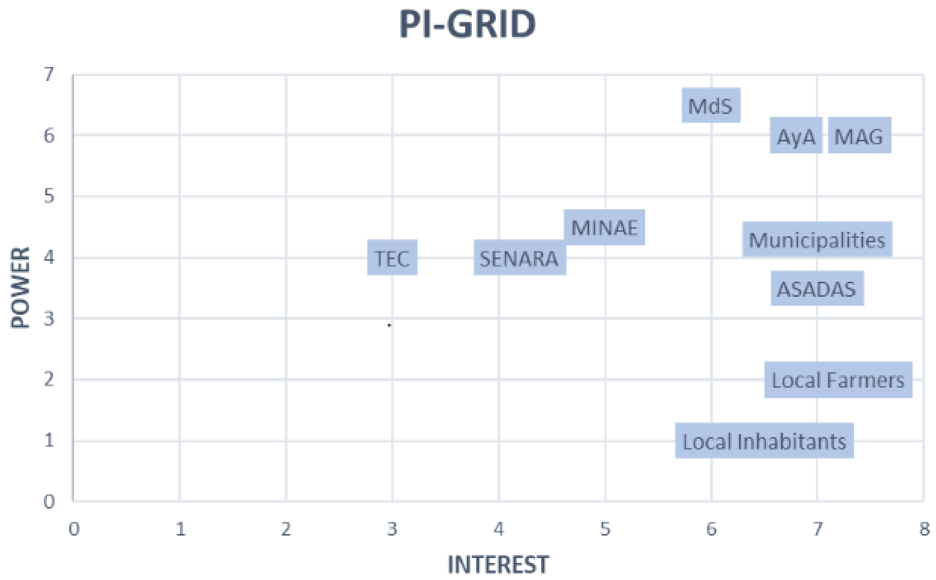

Figure 20: Power Interest Grid

Besides the PI-grid of how the stakeholder landscape is supposed to look, another PI-grid has been made with our own perception at the end of the project. Several stakeholders have different positions in the grid than they should have. These are presented in orange in Figure 21 and in the following list:

- It was noticed that the Ministries of Agriculture and Health and AyA have a smaller interest in the project than originally thought. Due to slow or non-existing communication, little resources spent, and the tough bureaucratic wall we faced over the last months, their interest score in the 'perception PI-grid' has dropped, however, their power still remains.
- The municipalities have both a lower power and interest in the region since most work and responsibility lies in the hands of the AyA and ASADAS, which was not known beforehand.
- Both the SENARA and TEC have less power and interest in the project than originally thought. Because their influence is little in these large-scale projects, their interest simultaneously drops as well.

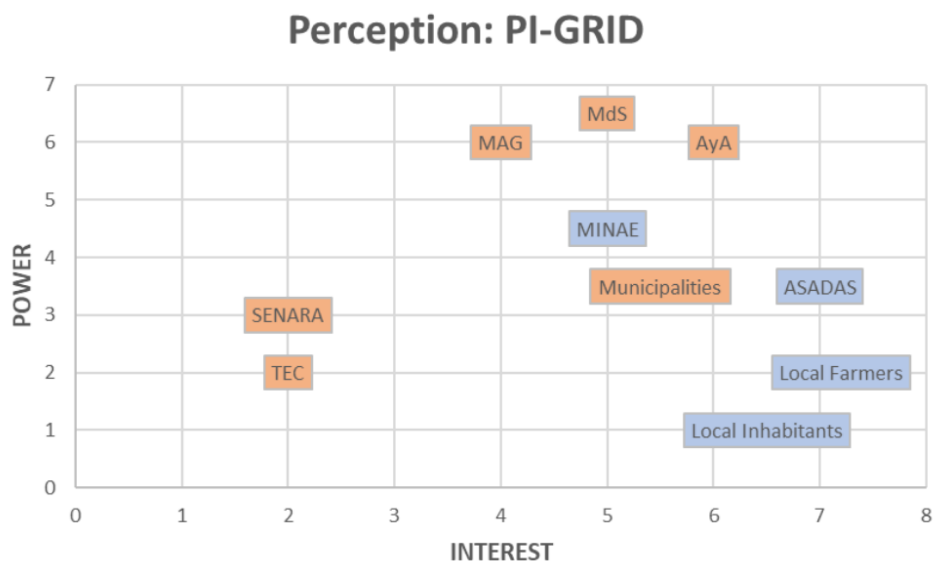

Figure 21: Perception Power Interest Grid

4.2 Nitrate pollution

The first step was relating the nitrate measurements with their spring location. These were displayed on maps for a visual representation to be able to identify areas of increased contamination.

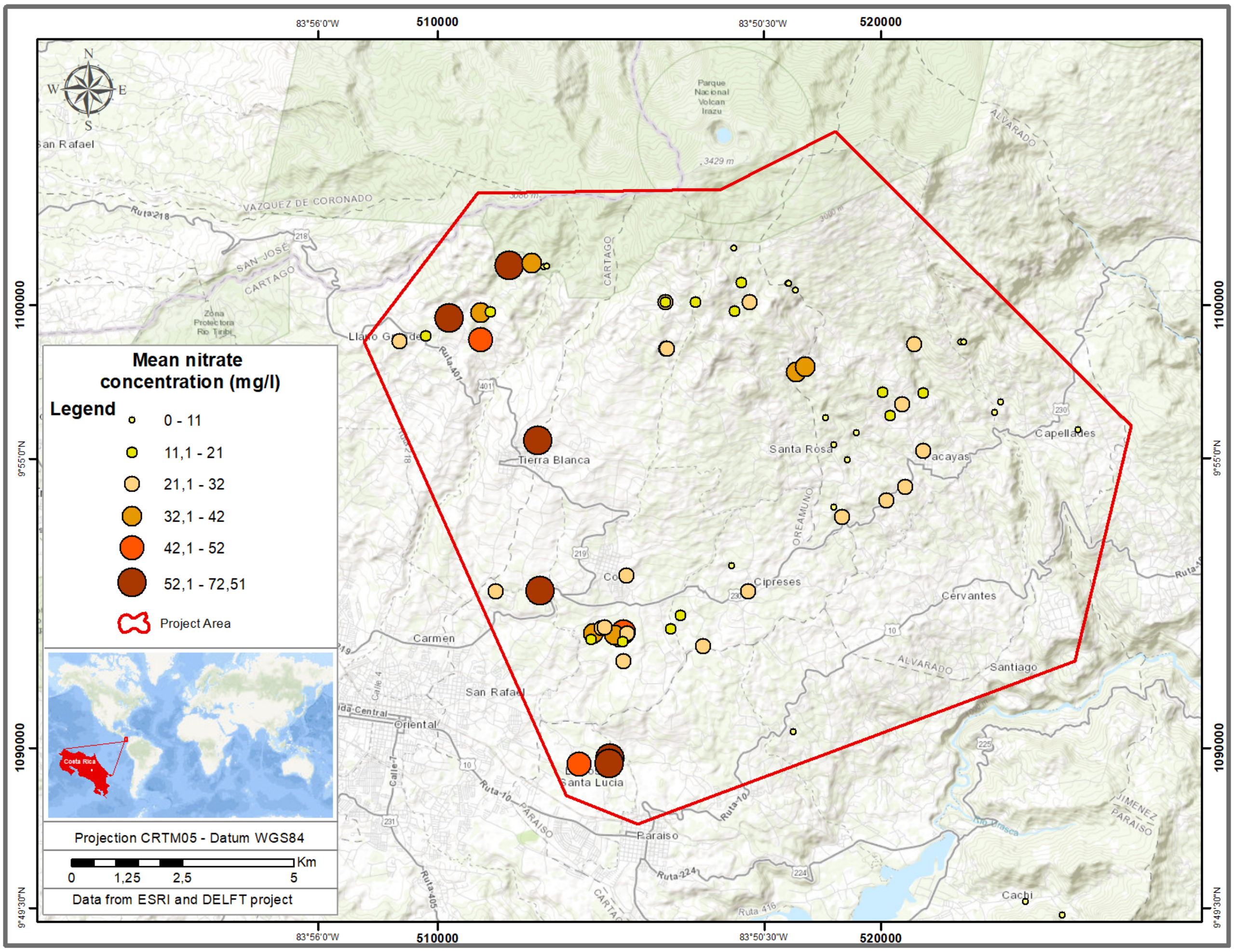

Figure 22: Mean nitrate pollution per spring

As can be observed in Figure 22, where the mean nitrate concentrations per spring over the past decade have been plotted, the highest nitrate concentrations were measured in the western half of the project area. These springs fall under the legislation of the Municipalities of Paraíso, Oreamuno and Cartago together with the ASADAS of Cot, Tierra Blanca and Llano Grande.

The nitrate concentration in these springs varies between 20 mg/L and 60 mg/L with outliers of measurements above 70 mg/L. The springs with the highest contamination are Rodillal, Ariete, Mero and Guayabal with concentrations of 60 mg/L, 56 mg/L, 72 mg/L and 68 mg/L respectively. In the east of the project area, the concentrations are observed to be lower. Here most mean concentrations in the springs lie beneath the 30 mg/L threshold with the exception of the Agua Fria and Manuel Granados springs of Santa Rosa where the measurements show 34 mg/L and 36 mg/L respectively.

4.3 Recharge/infiltrating areas

Secondly, the recharge areas of the 24 selected springs were calculated and displayed in QGIS. The map of these recharge areas is presented in Figure 23.

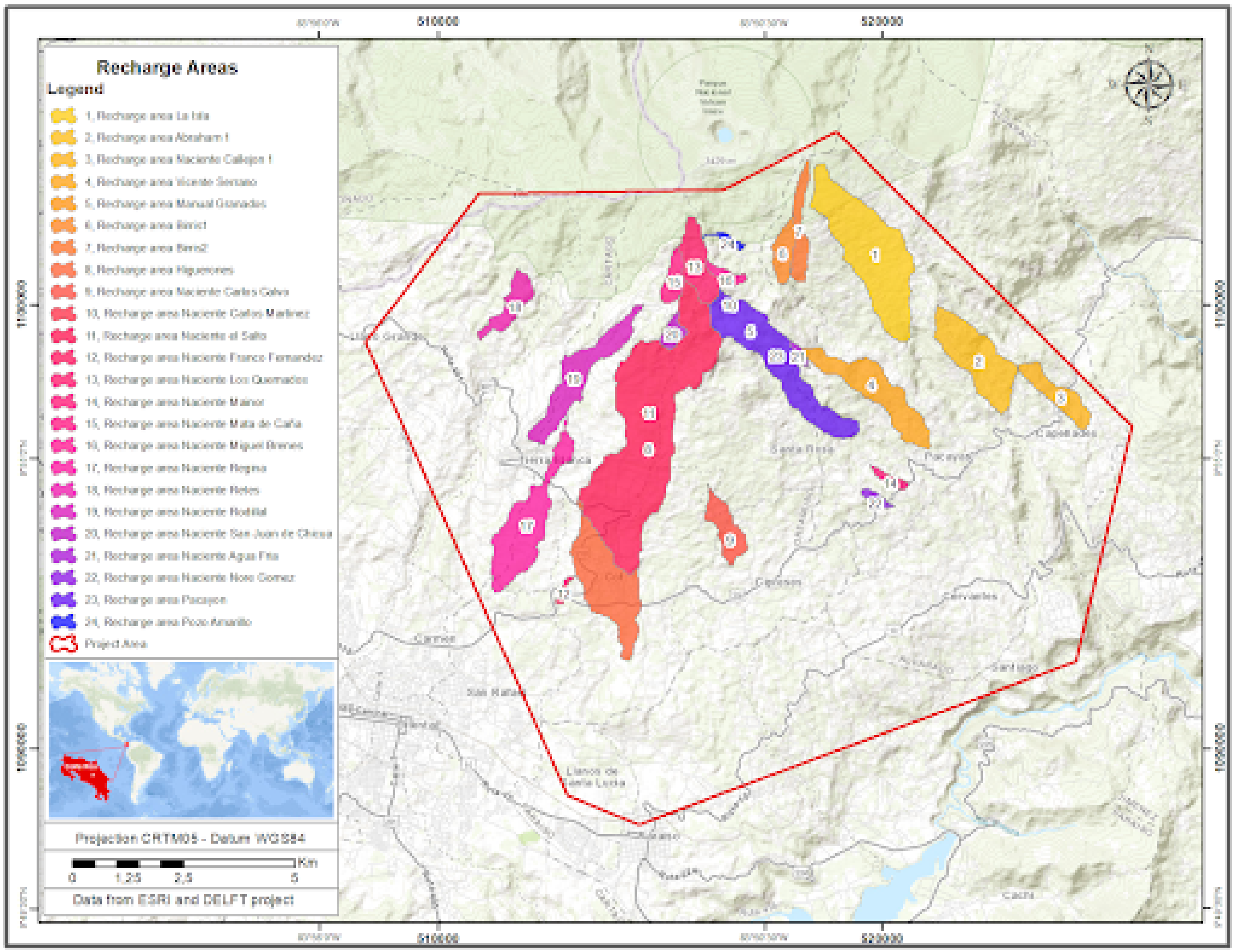

Figure 23: Recharge/infiltrating areas of the considered springs

As can be observed, these recharge areas can reach lengths of over 5 kilometers and share an infiltrating area with other springs. The surface areas vary between roughly 12 km^2 for the Higuerones spring to 0,1 km^2 for springs such as Franco Fernandez and Carlos Martinez.

4.4 Spatial analysis of recharge areas

In order to be able to correlate the exact spatial parameters of each recharge area to the contamination in the corresponding spring the zonal statistics within the separate recharge areas are analyzed.

Land use

The areas of each type of land use within individual recharge areas are calculated. These values are then converted to percentages of the total area and used as input for the nitrate concentration model.

Slope

The slope statistics of each capture zone are calculated and documented. The minimum, maximum, mean and standard deviation of the slope per recharge area is used as input for the nitrate concentration model.

Breaching of 200-meter protection zone

By analysing satellite data, the integrity of the by-law determined 200-meter radius protection zone was inspected. It became apparent that in many instances this area is breached. In Figure 24, three examples of breaching can be observed; agricultural and urban land use are in most cases present within the 200-meter boundary. The breaching status as defined in the methodology is documented and used as input in the nitrate concentration model. The proximity of contamination sources to the water source is a critical factor in nitrate pollution, as breaches in these areas will have the most immediate impact.

Figure 24: Springs Rodillal, Edwin Coto and Oscar Are. The orange circle represents the by-law-determined protection zone with a 200-m radius. Urban and agricultural activity are clearly located within the protection zone.

A complete list of springs with their spatial analysis is found in Appendix A.5.

4.5 Interviews

During the research period, some interviews with local farmers were conducted to get a better understanding of practices and sentiments in the area. The findings of the interviews will be mentioned below. However, it is important to note that the representativeness of these practices to the wider area is difficult to ascertain as only three farmers were interviewed. While the insights gathered from these interviews will provide valuable insights, the responses cannot be considered as universally applicable to the entire area.

Lettuce and spinach farmer

Figure 25: Snapshots of interviews farmer

The first farmer that was visited, specialized in lettuce and spinach. Images are presented in Figure 25 An interesting aspect that we observed and that was confirmed through the interview was that many farmers specialize in 1 or 2 crops. The effects of these monocultures have been discussed in a previous section 2.4. The harvest cycle occurs 6-7 times a year. Since there is little seasonal difference, farming is possible the whole year round without any breaks.

The farmer that we spoke to had more focus on sustainable farming practices. All his fertilizers and pesticides were organic and he made sure to use them consciously. After heavy rain events, he would add new noble pesticides, called Bellis. He made his serum, against worms. He would only inject baby crops with the serum so that they got some defence against a specific worm. Moreover, he was already using drip irrigation. In dry seasons, he would water the crops for 15 minutes per group every other day. When it was asked how he had learned that, he told that he did the research and investment himself. On the borders of his land, he had trees that block pesticides that travel the air to reach his field. Some of the weeds in his field would signal when there was a surplus of phosphor in the soil.

All in all, this farmer showed that like him, many farmers are very interested in having sustainable farming practices. When we asked his opinion on MAG (ministry of agriculture), he said that they only offer very basic courses. Mostly they just gave a few tips, some of which did not even work. They check the farmers sometimes, but after awarding the sustainable certification they don't follow up anymore.

Another interesting finding was the presence of his own water well. He had dug a 7-meter-deep hole and installed his pump, as presented in Figure 26. When we asked about it, he told us that probably many farmers have such wells. Since those wells are all informal they are not included in geological maps. These wells can affect the soil properties drastically and runoff flows can just flow in these wells rather than infiltrate through the soil.

Figure 26: Informal well with a depth of around 7 meters used only by the lettuce farmer. Notice the abundance of algae, a sign of eutrophication

Livestock

Figure 27: Snapshots of the interview with a livestock farmer

The livestock farmer that was interviewed had many cows and his colleagues on the same plot had horses and pigs (Figure 27). They were making their own fertilizer from the animals' manure. The manure of the cows would be removed from the barns once every three months. The cows were kept inside constantly, just like the pigs. Rain is not able to flush away a significant amount of the manure, since it was all covered.

The foundation was made from concrete to minimize the leaching. The farmer would mix chicken manure with several other ingredients, to produce nourishment for the cows (Figure 28). He explained that the fertilizer he made was from dried manure with added calcium. It was mentioned that in most other livestock farms, it is common to also add chemicals. Surrounding the cowsheds were fields of onions, which were nourished with their own fertilizer. The cows produced 2 tonnes of manure per week, from which the surplus would be sold. Similar to the lettuce farmer, he also made a private well to extract water. The well was located upstream of the barns and reportedly very deep, around 150 meters.

Figure 28: Manure handling

4.6 Modeling of nitrate concentration

In this sub-chapter, the results of the modelling of the nitrate levels are presented. The sub-chapter is divided into two parts: the results of the Pearson analysis and the results of the nitrate concentration model.

Pearson analysis

The results of the Pearson analysis of all parameters can be found in Table 7. A positive outcome of the Pearson analysis (>0) indicates that an increase of the variable results in an increase in the nitrate concentration in the spring. A negative outcome of the Pearson analysis indicates that an increase of the variable results in a decrease in the nitrate concentration in the spring.

The following criteria apply for the Pearson analysis (Schober et al., n.d.):

- 0.00 - 0.10: neglectable correlation
- 0.10 - 0.40: weak correlation
- 0.40 - 0.70: moderate correlation
- 0.70 - 0.90: strong correlation
- 0.90 - 1.00: very strong correlation

Only the variables associated with the buffer zone show a moderate (>0,4) correlation according to this Pearson analysis. The rest of the values only show weak correlations (values associated with land use and the minimal slope).
The correlation matrix of all parameters, the nitrate concentration and the outcome of the nitrate concentration model are given in Appendix A.5.

Table 7: Pearson results

Variable	Pearson outcome	Variable	Pearson outcome	Variable	Pearson outcome
Precipitation	-0.12	**Pastures x^2**	-0.07	**Max slope x^2**	0.02
Precipitation sqrt	-0.12	**Pastures sqrt**	-0.08	**Min slope**	0.24
Precipitation x^2	-0.11	**Buildings**	0.15	**Min slope sqrt**	0.22
Crops	0.18	**Buildings sqrt**	0.18	**Min slope x^2**	0.25
Crops sqrt	0.18	**Buildings x^2**	0.1	**STD slope**	0
Crops x^2	0.18	**Mean slope**	-0.07	**STD slope sqrt**	-0.02
Woods	-0.17	**Mean slope sqrt**	-0.07	**STD slope x^2**	0.02
Woods sqrt	-0.1	**Mean slope x^2**	-0.08	**Bufferzone respected**	0.51
Woods x^2	-0.22	**Max slope**	-0.01	**Bufferzone respected sqrt**	0.45

Nitrate concentration model
The regression model that is made has an R2 of 0,689, which indicates that 68,9% of the correlation, in reality, can be explained by the regression model. The outcomes of the parameters of the variables and the corresponding P-values are given in Table 8.

Table 8: Results nitrate concentration model

k	Parameter	Coefficient (b value)	P-value	k	Parameter	Coefficient (b value)	P-value
0	**Intersection**	**2788,414**	1,56E-05	**9**	**Max slope sqrt**	-292,606	0,263356
1	**Precipitation**	**-0,01223**	0,051892	**10**	**(Max slope)2**	-0,04013	0,75125
2	**Woods**	**-64,2316**	5,91E-08	**11**	**(Min slope)2**	3,453298	0,333451
3	**Pastures**	**-23,2761**	1,02E-05	**12**	**Min slope**	2,344369	0,772858
4	**Buildings**	**-345,388**	0,000201	**13**	**STD slope**	-622,91	0,014948
5	***Mean slope***	**591,6844**	8,69E-08	**14**	**STD slope sqrt**	2351,406	0,007526
6	***Mean slope sqrt***	**-3035,53**	1,59E-07	**15**	**(STD slope)2**	12,8586	0,044247
7	**(Mean slope)2**	**-6,54715**	2,27E-08	**16**	**Bufferzone respected**	13,87911	0,007936
8	**Max slope**	**25,86359**	0,402639				

Where:

- Parameter: the parameter which is considered
- Coefficient: the b value in the regression formula
- k: the number corresponding to the parameter
- P-value: the importance of the parameter to the model

The equation that describes the model can be found in Section 3.4.1.
Using this model, modeled predictions can be made on the nitrate concentrations of the springs using the different parameters as input. The results of these modeled nitrate concentrations and the measured nitrate concentrations levels are given in Appendix A.5. The results are then sorted from low to high based on the modeled nitrate concentration and plotted. Results are given in Figures 29 and 30.

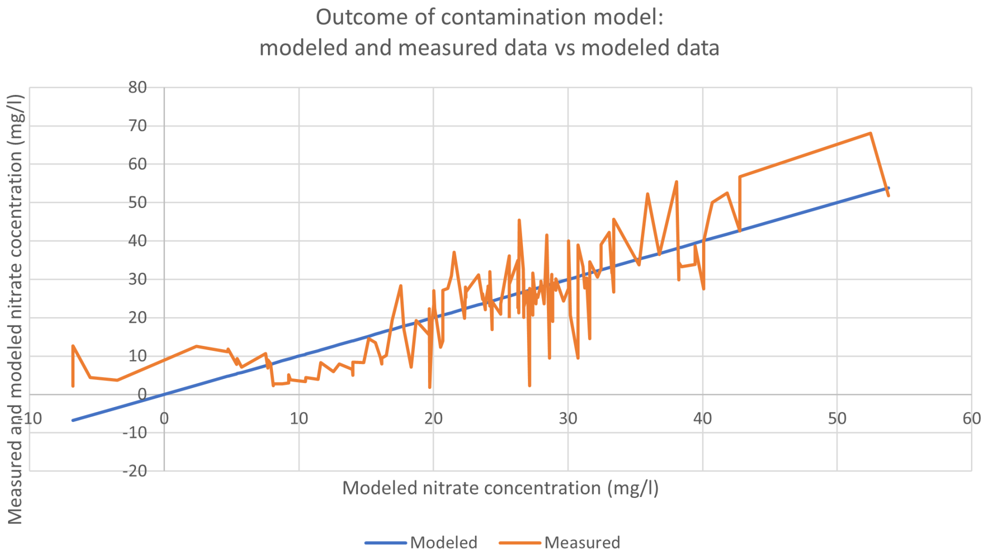

Figure 29: Result of contamination model: Modeled and measured data vs modeled data

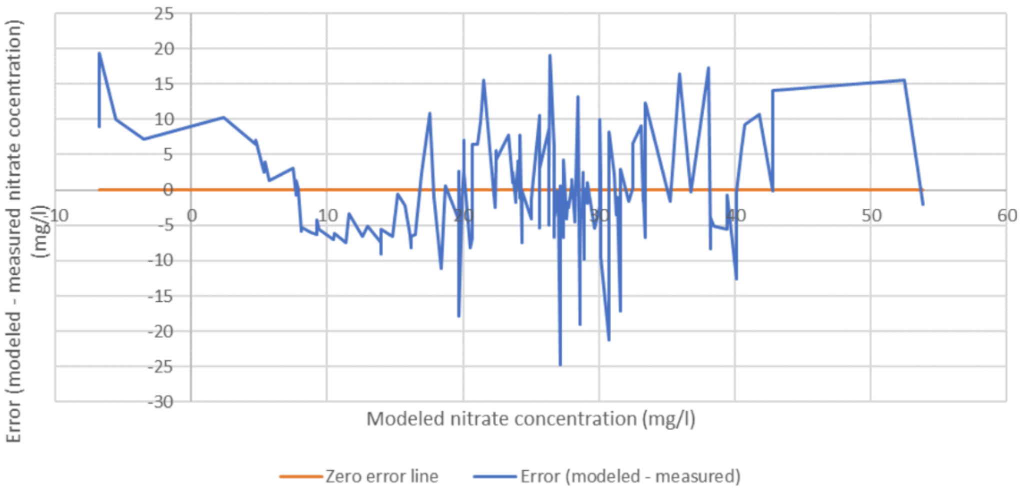

Figure 30: Result of contamination model: Errors in model (modeled - measured vs modeled

4.6.1 Spatial patterns in the precipitation

The results of the interpolation of the average precipitation measurements can be found in Figure 31. The results of the interpolations per month can be found in Appendix A.3.3. The goal is to indicate the spatial patterns in the precipitation data and to see whether they are sufficiently small that they can be neglected in the final model or not. If not so, this could be a major limitation of the nitrate concentration model.

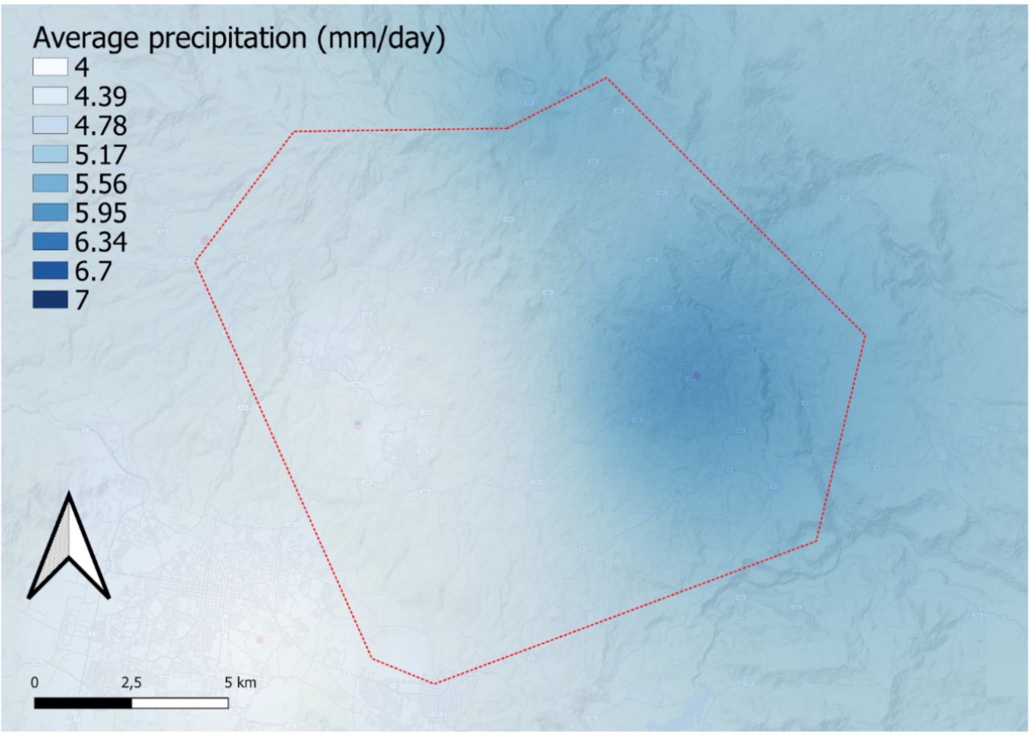

Figure 31: Average yearly precipitation in the research area

As can be seen, the spatial differences are relatively large; the lowest average precipitation value is 3.94 mm/day and the highest average precipitation value is 6.11 mm/day. Higher values are generally found in the eastern part of the research area and lower values in the western part of the research area. The variations in the spatial patterns of the precipitation are more than 1.5 within the research area. It is therefore difficult to neglect them. The issue is however that resources lacked to include this in the current model; this is, therefore, a major limitation in the model. A further explanation is given in the Section 6.

5 Financial Assessment

5.1 Financial assessment

The goal of this chapter is to process the knowledge gained from the previous chapters and add new findings on costs to develop an integrated framework which assesses the feasibility of multiple alternatives from a financial perspective. The assessment should act as a tool to support the government, AyA, and the ASADAS with the development of future water-related projects or innovations and to see which criteria are essential and what their potentials and limits are. The content and assessment method of the framework will be presented in detail below. In the following paragraphs, four alternatives will be discussed:

1. Water Trucks from Guarco to Cipreses & Santa Rosa de Oreamuno
2. Usage of PVC pipes and pumps from unused, potable springs to contaminated locations
3. Activated Carbon (AC) removal filters
4. Pressure vessel & filter system

Lastly, a more long-term sustainable, but more costly alternative for the urban nitrate pollution sources would be a wastewater treatment plant with sewage in the region. However, since the nitrate pollution in the region would require an advanced treatment plant, which will result in a multi-million dollar project which is very time-consuming (Marshall, 2022), and therefore this alternative will (for now) not be considered in the assessment.

5.1.1 Alternative 1: AyA Water Trucks from Guarco to Cipreses

For the last 4 months, AyA has been sending trucks to the Cartago region daily, specifically to districts Cipreses and Santa Rosa de Oreamuno, with potable water (only for drinking and cooking purposes) for the inhabitants. From the AyA Excel invoices are derived that per inhabitant approximately 2.44 litres of water (AyA, 2023) are necessary to sustain life in both villages. Respectively, the districts have 4,234 and 3,021 inhabitants, thus Cipreses needs 10,331 litres a day and Santa Rosa 7,317 litres a day. In total, this concludes to 17,702 litres (17.7 m^3) a day, which is approximately 4,671 gallons of water (1 gallon $\approx$ 3.79 litres). AyA's water truck size is either 15 or 7 cubic meters each, this would require approximately one 15 m^3 or two 7 m^3 water trucks in total to both villages every day.

Since this is an undesirable, costly, and time-consuming alternative for the polluted water springs, AyA would like to search for another alternative to solve this issue. However, the truck service has been utilized for the past few months and it indeed does work as a short-term solution. Therefore, the truck service is being considered as the first alternative to forming a baseline compared to the alternatives below. In that way, all alternatives can be assessed fairly and conclusions can be drawn from there. According to the invoice from AyA, the costs for this alternative consist of (AyA, 2023):

1. Investment costs water truck
2. Depreciation of the equipment
3. Fuel efficiency
4. Tires
5. Batteries
6. Preventive Maintenance
7. Repairs
8. Salaries and social charges

9. Insurance payment

10. Rights of movement and mandatory insurance

11. Administrative expenses

12. Cubic meter of drinking water costs

For an extensive overview of the total costs of the water trucks, Appendices A.6.1 and A.6.2 can be consulted. Here, a thorough explanation of the individual costs for the month of November and a summary of the total costs is given. In brief, a total of 82 water truck trips have transported 846 m^3 of potable water to only Cipreses for a total of ₡15,736,995.61 or **$26,329.08**, using an average value of ₡597.70 per US$ over the entire period from October till January. Overall, a cubic meter of water transported by AyA trucks costs $\$26,329.08/846 =$ **$31.12** per cubic meter of water. The costs for the water trucks to Santa Rosa de Oreamuno have not been shared and therefore these costs are not known and taken into account in this assessment.

5.1.2 Alternative 2: Usage of PVC pipes and pumps from unused, potable springs to contaminated locations

Furthermore, the clean, unused springs in the Cartago region can be utilized to replace or dilute the polluted springs to form a second alternative; PVC pipes and pumps from clean to polluted springs. Note that this is a viable solution in the case of nitrate pollution but not realistic in cases of micro-pollutant contamination. The costs for this alternative will consist of (with the pump costs in *italics*, since the pump will not be necessary for every situation):

1. PVC pipes + couplings for the entire length of the traject (from clean source to contaminated source)

2. Depreciation of the pipe system

3. *Pumping system to pump water from A to B*

4. *Fuel costs of pumping system*

5. Construction costs including staff and insurance cost

6. Maintenance costs of pipes and *pumping system*

To make a proper estimation of the costs involved in this alternative, several measured considerations have to be made. First of all, as a baseline, a constant flow of 10 Liters per second has been assumed, since the water pipe required to replace the polluted Edwin Coto spring needs to deliver 8,28 L/s or $8{,}28 \times 10^{-3}$ m^3/s. When a water velocity in the pipes of 1 m/s is assumed, the required surface area of the water pipes should be $8{,}28 \times 10^{-3}$ m^2; this corresponds to a pipe diameter of approximately 0,103 meters or 10 cm or 4 inches. With this flow, only certain PVC pipes are suitable for usage. This is because the 10L/s will flow with a velocity of 1m/s and thus the PVC pipe will be completely full all the time. Therefore, the PVC pipe needs to resist pressure and have a diameter of 100mm. Considering both the pressurized pipe and the 100mm diameter, the pipe of Figure 32 has been chosen as the most suitable and cost-effective. This pipe costs ₡ 66,100.00 / unit and consists of 6 meters in length (Construplaza, 2023). Since the exact route of the pipeline is not known, an additional 10% cost for coupling parts has been taken into account.

Figure 32: PVC pipes and Pump (Construplaza, 2023; Mercado Libre, 2023)

On top of that, due to a lack of data, it is not exactly known which springs in the Cartago region are currently not in use and are potable. Therefore, it has been assumed the maximum distance of the pipeline would be 7,000 meters, which covers the entire research area from the towns of Cipreses and Santa Rosa de Oreamuno. If a suitable source would be discovered nearby or if an unused source of another ASADAS can be utilized, the distance and thus the costs may be lower.

Moreover, for the PVC pipes depreciation, it is assumed that due to sunlight exposure and pressure in the pipes, the life span is 50 years and not 100 years as stated in the literature (PIPA, 2022). Also, just like the AyA trucks it is assumed the remaining value after the life span will be 20% of the original price (AyA, 2023).

Next, an estimation has to be made on the design, salary, and insurance costs. Together with the salaries given in the AyA budget and literature found, an additional 30% on top of the total pipe cost to cover the design, salaries, and insurance (AyA, 2023; A4architect, 2013).

If a potable source is downstream of Cipreses or Santa Rosa de Oreamuno, a pump is necessary to transport the water to a higher altitude. Two pumps were considered, one 320 US$ pump which could reach 40 meters in altitude and one 199 US$ pump which has a maximum of 23 meters in upward water transfer, see Figure 32 (Mercado Libre, 2023). The latter pump is chosen for its fuel efficiency and the small altitude differences between the villages in the Cartago region. The life span of these pumps is usually 15 years (Systems, 2016), therefore it is assumed that rounded up 4 pumps are necessary over a span of 50 years.

Lastly, the fuel usage and prices for the pump needed to be estimated for a period of 50 years. For the fuel pricing, it is assumed that the price per liter of diesel will be approximately 1.30 US$ (GlobalPetrolPrices, 2023). Since this is the current price and it will probably rise in the future, a relatively high annual inflation of 5% is assumed to compensate for this.

For a brief overview of the total costs of the pipe and pump system, Appendix A.6.3 can be consulted. Here, an explanation of the individual and total costs is given and for simplicity ₡597.70 per US$ is used to calculate the costs, similar to the previous alternative. In short, over 50 years a total of 5,256,000 m^3 of water could be extracted from another source in the region with an average flow of 10L/s and an operation time of 8 hours a day. For the PVC pipe system, a total investment of **$170,308.38** is needed, which results in a cost of $\$170,308.38/5,256,000 =$ **$0.032** per cubic meter of water, assuming a steady and clean water flow from the unused spring for the long-term. When a downstream source is used and a pump will become necessary, the costs will rise to $590.212,00 because of the pump and fuel costs. A combination of PVC pipes and a pump results in **$0.112** per cubic meter of water.

5.1.3 Alternative 3: Activated Carbon removal filters

As stated in table 5 in the theoretical framework, activated carbon (AC) can be a viable solution for the polluted springs in the Cartago region for micro-pollutant removal such as fungicides and pesticides. The majority of AC filters are not successful in the removal of nitrates. Therefore, the third alternative presented will be activated carbon in filters which can remove nitrates, a dangerous pollutant in the region. The costs for this alternative will consist of:

1. Composite vessel, piping and valve costs
2. Depreciation of the entire system
3. Construction/installation costs including staff and insurance costs
4. Activated carbon (replacement) costs over 50 years
5. Maintenance and administration costs

Firstly, to let the activated carbon work as a filter for the polluted water, a structure composite vessel is required (Lenntech, 2022). The polluted water will enter from the top part of the vessel and then under 150 psi (pound-per-square inch) pressure, the water will be pushed through the activated carbon filter at the bottom of the vessel, where the filtered water will come through another valve, see figure 33. Since the AC will be constantly under pressure, it is necessary to use Granular Activated Carbon (GAC) (Guillermo Romero Esquivel, 2023).

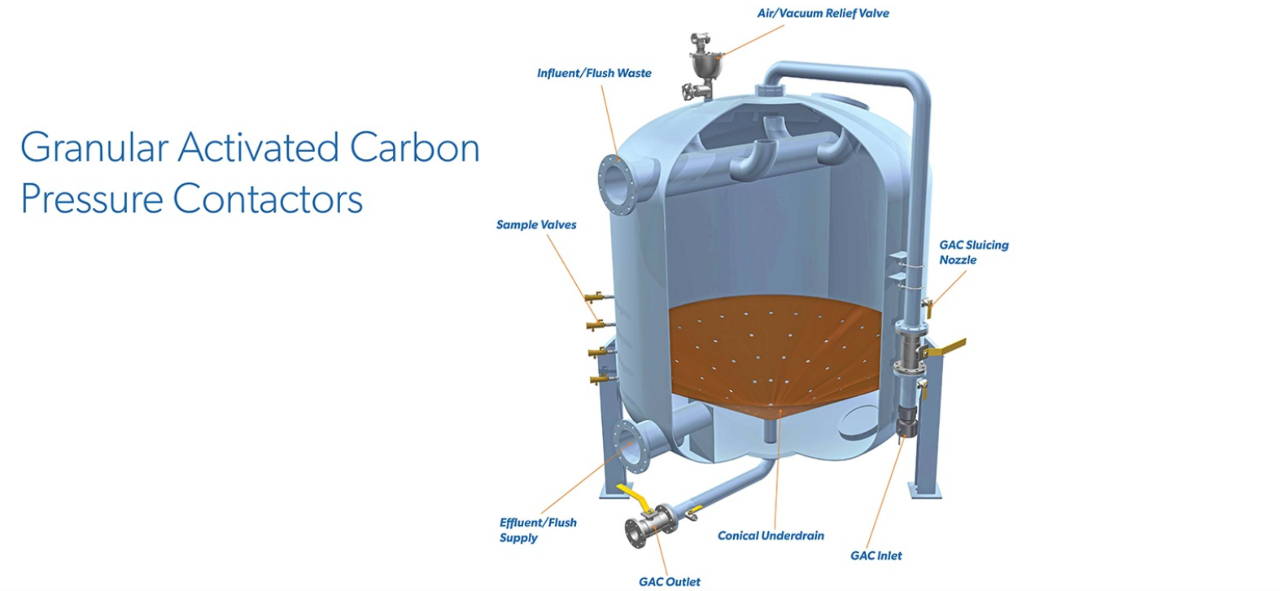

Figure 33: Granulated Activated Carbon (GAC) pressure vessel
(Lenntech, 2022)

For commercial and industrial water treatment and storage, the vessel,valves and GAC have the following characteristics:

- Cannot rust, therefore requires little to no maintenance
- Vessel type is 'TANQUE FIBRA DE VIDRIO 36X72,6 TOP 20FT' (Guillermo Romero Esquivel, 2023), dimensions are 36 inches in diameter and 72 inches in height with a price of $2,893.08/unit
- Cycle capacity of 1,024 litres of water and 566 litres of AC (Hidrogreen, 2023)
- Minimum of 250,000 cycles over entire life span (Lenntech, 2022)

- Valve type is 'VÁLVULA CLACK WS2H' with a price of \$4,669.73/unit (Guillermo Romero Esquivel, 2023)

Moreover, several assumptions have been made to calculate a total cost overview:

- Just like the AyA trucks and PVC/Pump alternatives, it is assumed the remaining value after the lifespan of the vessels will be 20% of the original price (AyA, 2023)
- An additional cost of 10% for piping in and around the system is assumed
- An additional cost of 10% for designing the system, salaries and insurance is assumed
- An additional cost of 5% for maintenance and administration of the system is assumed
- Over a period of 50 years, 4 pressure vessels will be required (rounded up), since the lifespan of a vessel is approximately 14.27 years, this is obtained through the following assumptions:
  - 2 cycles per hour including back-washing (Lenntech, 2022)
  - 24/7 service
  - 1,024.44 liters/cycle and 250,000 cycles $\rightarrow 250,000/2/24/365 = 14.27$ years and app. 2 m^3/hour production
- 4 piping systems and 8 valves are required over the span of 50 years
- The price per ton (1000kg) of GAC is \$2,712.00, according to a reliable price trend over the last 50 years (IndexBox Inc., 2022)
- The density of activated carbon is 1480 kg/m^3 (Aqua-Calc, 2023) and thus one AC filling of the vessel requires approximately 0,84 tons of AC (Hidrogreen, 2023)
- It is assumed that the AC needs to be replaced after three months, or app. 4,000 cycles (Hidrogreen, 2023), since there are $4 * 250,000 = 1,000,000$ cycles, 209,54 tons of AC are required over 50 years, which results in $\$2,712.00 * 209,54 = \$568,285.13$ for all AC

For a brief overview of the total costs of the AC removal filters, Appendix A.6.4 can be consulted. Here, an explanation of the individual and total costs is given and for simplicity ₡597.70 per US\$ is used to calculate the costs, similar to the previous alternatives. In short, over 50 years a total of 1,024,437 m^3 of water could be extracted from the AC filters with an average flow of 2 m^3/hour and a 24/7 operation time. For the composite vessel, piping and valve system, a total initial investment of \$53,823.18 is needed, together with the depreciation, construction/installation, salaries, AC replacement and maintenance cost a total cost of **\$619,417.15** is obtained. This results in a cost of $\$619,417.15/1,024,437m^3 = \mathbf{\$0.605}$ per cubic meter of water.

5.1.4 Alternative 4: Pressure vessel & filter system

Lastly, this alternative has been used for finalizing several water purifying projects in South America. One project in Guanacaste, North West Costa Rica, has achieved incredible results by filtering the groundwater and surface water of a region of pineapple farmers in one year's time, see 34 for an example (Sky Water Solutions, 2022).
The costs for this alternative will solely consist of:

1. Pressure vessel costs
2. Filters + replacement costs
3. Extra piping costs

The system consists of two or more filters which can purify the contaminated water. The available filters for the system are: iron, manganese, arsenic, bromacil, nitrate, chlorothalonil, silica etc. There is no maintenance required and the system ($3,985.00) will have a lifespan of 25 years, whereas the filters ($295.00/unit) last 12 months and need to be replaced every year. An additional 10% of costs is assumed for extra piping around the system.

Figure 34: Example pressure vessel & filter system (Sky Water Solutions, 2022)

For a summary of the total costs of the pressure vessel & filter system, Appendix A.6.5 can be consulted. Here, an explanation of the individual and total costs is given and for simplicity ₡597.70 per US$ is used to calculate the costs, similar to the previous alternatives. In short, over 50 years a total of 143,425.73 m^3 of water could be extracted from the system with an average flow of 12 gallons/minute (16.37 m^3/hour) and a 24/7 operation time. For the entire system plus filters, piping and installation, a total initial investment of **$247,302.00** is obtained. This results in a cost of $\$247,302.00/143,425.73m^3 =$ **$1.724** per cubic meter of water.

In conclusion, combining all costs will give Table 9. This financial assessment has been done over a time period of 50 years to obtain a first idea of all the costs involved and to create awareness of other alternatives. It has to be noted that all costs are rough estimations and thus the estimated costs per m^3 of water have been given in a range cheaper than the AyA water trucks.

Table 9: Costs of all alternatives in US Dollars over 50 years

Alternative	**Estimated Costs**	**Estimated Costs per m3 water**
1: Water Trucks from Guarco to Cipreses (over three months)	$26,329.08	$31.12
2: Usage of PVC pipes and pumps	a. Only PVC pipes: $170,308.38 b. PVC + pump: $590,212.00	∼250 to 750 times cheaper
3: Activated Carbon removal filters	$619,417.15	∼30 to 50 times cheaper
4: Pressure vessel & filter system	$247,302.00	∼15 to 30 times cheaper

6 Discussion

In this section, the results obtained during the research will be discussed in the following paragraphs.

6.1 Results

Farmer interviews
Altogether three farmers were interviewed. While some interesting insights were obtained from these conversations, it must be noted that these farms were located in close proximity. Therefore it is hard to conclude that farmer practices in the whole area are similar. Both agriculture farmers were also, coincidentally or not, all into sustainable and organic farming practices. It is suspected, based on observing the area, that these farmers are not a good representation of the general farming practices, especially fertilizer and pest/fungicide, in the research area. A lot of spraying on the fields has been observed, although no opportunity was present to interview these farmers.

Modelling
General
It is difficult to draw firm conclusions on the relationship between land use and the nitrate concentrations in the springs. The correlation between the nitrate concentration and the breaching of the 200-meter radius is the only correlation with a moderate correlation; the rest of the correlations are weak.

Precipitation
The data used to find correlations between the precipitation and the nitrate concentration is an average of the six precipitation measurement stations available in the region. It is expected that an improved spatial differentiation in the precipitation amount could lead to an improved model. Currently, the Pearson correlation value between the rainfall and the measurements is -0.12. It is likely that this value would be improved if the spatial difference would be included. Moreover, the current P-value of 0.052 indicates that there is little statistical value of the precipitation and this could also be improved by including the spatial differences.

Climate change has not been taken into account in the precipitation data as the effects were not found in a time frame between 2009 and 2022. On a longer time frame, the model currently used could not be sufficient as precipitation could become more intense and in a shorter time frame.
Currently, the average data of the whole month is used as the precipitation on a measurement time. This means that a measurement done on the 30th of November is linked to a different precipitation amount than a measurement on the 1st of December, while the differences between the amount of infiltrated water are not likely to be large. Additionally, measurements of the 1st and 31st of December are linked to the same precipitation amount while the infiltrated water amount could be different.

Land use

- The land use data is from 2020. Nitrate concentration measurements have been done between 2009 and 2021 and the land use in this period could have changed. It is not expected that the differences would be large as there are no new large cities in the research area, the woods are generally protected and there is no known expansion or decrease of the agricultural area. It is therefore not expected that this limitation has a large effect on the outcome of the model.

- In reality, there are large differences between the four different land use types. As shown in Section 3.3.2, the agricultural land is highly heterogeneous in crop type and used practices. From conversations with farmers, it was found that some farmers apply a more biological agricultural practice with little added nitrate whilst others apply more nitrate on their land. The same accounts for houses; some inhabitants could have a leaking septic tank or other point sources of nitrate affecting the spring.

Bufferzone protected

- Protection of the buffer zone is a major impact factor for the nitrate concentration as the highest Pearson correlation values are also found for the protection of the buffer zone. The buffer zone breaching has only been done for three scales (0, 0,5 and 1). It is likely that this low amount of scales is a big simplification which has effects on the outcome of the model, especially regarding the high Pearson correlation values.
- Even within two scales of breaching which are the same (e.g. two regions with a breaching factor of 0.5), large differences are possible. A small house with a leaking septic tank in a protection zone of a source could have an effect which is way larger than a large number of houses with appropriate septic tanks.

6.2 Limitations

Geo-hydrological perspective
Arguably the largest limitation was the lack of data and understanding of the geo-hydrological situation. Studies were sparse and difficult to acquire. Finally, a total of 4 studies were available that revealed anything about the geological and aquifer situation in the area. It was not possible to quantify the relative importance of nitrate infiltration and overland flow pathways. Some sources suggest that the area's soil order, Andisol, retards nitrate leaching through infiltration and therefore overland flows might play a larger role in contamination. Therefore, it is suggested that future studies are performed to assess and quantify the spring contamination pathways.

Lack of transparency was found in the studies in the delineation method of the infiltration area of springs. During the study, it was decided to use the upslope contributing area method to determine the areas for spatial analysis, however, this is valid only under the assumption that the groundwater flows follow the topographic gradient. Because of the steep slopes in the area, this is very probable but during the study, it was not feasible to verify the groundwater flows with measurements. The D8 upslope area method is beneficial considering the previously mentioned fact that overland and interflow may be of large importance since the topography is the sole determinant of the overland flow directions.

Furthermore, infiltration data was available through a SENARA study around 9 springs in the north of our area. How representative this data is for the rest of the area remains unknown.

Additionally, we discovered that there was a significant amount of private informal open wells built by farmers. Because of the informal nature of the wells, there is no information on them in the databases. These open wells notably change the geo-hydrology of an area, since for example overland water flow can freely enter here and groundwater can well up here. The effect of these informal wells on the geo-hydrology is not quantified.

Mitigation strategies
When suggesting mitigation strategies, it is important to have comparisons with similar climates and cultures. It was hard to find countries that are very similar where mitigation strategies have been implemented. Therefore, it arguably could still be risky to implement these mitigation strategies. Even though success has been accomplished in other areas, repetition does not necessarily have to follow in our own researched area. Implementation of certain strategies can prove to be more difficult in practice.

Data scarcity
It is important to mention that requiring the necessary data in order to execute the analyses was a long and time-consuming process. Often data was not available or only in scarce quantities. The used data for water quality parameters are measured between 2009-2021 and are often limited to 3-12 data points for each spring, where often there was no equal distribution over the years. Therefore the conclusion drawn on the basis of this data needs to be handled with caution. Due to high uncertain margins of the conclusions. The conclusion drawn on the basis of this data-set can only be used as an

indication for future research. In order to draw profound conclusions more data needs to be gathered on a periodic basis to confirm the indicated trends in this research.

Data measurements

The data sets obtained from AyA and the ASADAS are subjected to unknown uncertainty margins. Due to the unmonitored way of measuring uncertainty margins need to be accounted for when interpreting the results. The measurement of nitrate is sometimes done in remote locations where samples are transported in a way which increases the margins of error. Additionally, the samples are taken with different measurement devices, each with their individual unknown margin of error.

Nitrate concentration model

Precipitation data

- The precipitation data is assumed to only have monthly temporal differences and no spatial differences. In reality, there is a large difference between precipitation in the region; the station with the lowest average monthly precipitation found an average precipitation of 125.3 mm/month and the highest average monthly precipitation was 218.8 mm/month. It was however too difficult to define which recharge area had which precipitation amount, as some recharge areas spread out over multiple measurement stations.

Bufferzone protected

- The 200-meter radius that is stated in the law and used in this model does not take the actual geo-hydrological situation into account but is a simplification of reality. Downstream nitrate point sources are likely to have a smaller effect on the nitrate concentration in the springs than upstream point sources.

Financial assessment

First of all, in the financial assessment multiple assumptions had to be made to create a fair comparison between all four alternatives. However, the finances can be investigated more quantitatively. For example, for the PVC and pump alternative, it is not known where a suitable, unused spring is available for this project. As a result, an assumption of 7,000 meters in distance had to be made for the piping system, which is probably an over-assumption, since there are multiple suitable springs available in the region. Moreover, the PVC tubes most probably have to cross multiple roads, buildings or other obstacles, which would require the piping to be dug underground. These extra costs have not been taken into account and should be considered when a suitable spring has been found.

Also, due to a lack of data on the Activated Carbon alternative, a very rough estimate had to be made on several aspects. The total number of cycles, the amount of AC per cycle, flow rates and the exact dimensions of the system are not known beforehand. Therefore, it will be crucial to obtain all this data specifically for this project case, so a more precise cost calculation can be executed

Moreover, only several alternative options for products or services have been explored. This results in a narrow view of both the measures and the costs involved. Furthermore, the inflation rate, fuel prices, salary rates and depreciation for the upcoming 50 years are not known, which gives a large uncertainty in the values obtained.

Lastly, the Cartago region is highly susceptible to natural disasters like earthquakes, floodings, landslides and so forth. This damage risk has not been taken into account when calculating the costs. A contingency fund in case of any sudden damage may need to be considered.

6.3 Future Research

General updating of the database

A fair amount of time during the project was invested in gathering data and cataloguing that data in the right places to make it usable for the research. It is important for future research to have this data accessible and free to use so that more time can be invested in the analyzing part. Furthermore, increasing the amount of data points can be very valuable to minimize uncertainties and more accurately find correlations.

Geo-hydrology studies

- Tracer studies for identifying water and contamination pathways

  In order to understand which pathways the nitrate takes to reach the aquifer springs, by infiltrating or overland flows, it is advised to develop a future isotope tracer study. Based on the isotope composition of the spring water, better conclusions about the contaminant pathways can be drawn. It is advised to start research at the TEC in combination with experts on geo-hydrology.

- More extensive capture zone delineation studies

  Further contact with SENARA should be done to find out and check their capture zone delineation methods. It is often an extensive and complex process incorporating factors such as hydraulic conductivity, aquifer compositing and transitivity. Capture zones can be delineated using the time solutes take to travel from an origin to the spring.

- Quantify the impact of informal open wells constructed and used by farmers

  Since open wells are often dug by farmers for their own needs, these open pits likely facilitate the exchange between groundwater and potentially polluted overland flows. Contamination can in this case take a shortcut since it does not have to slowly infiltrate through the soil. During farm visits these open pits were found with abundant algae growth, indicating a high concentration of nutrients. Unfortunately, during the time period of this project, it was not possible to investigate these wells.

Alternative water supply (springs)
As the second alternative in the financial assessment in section 5.1.2, it has been proposed to construct a secondary PVC + pump system from an unused, clean spring to the contaminated villages of Cipreses and Santa Rosa de Oreamuno. For future research, it would be helpful to find out which unused springs in the region can be utilised for this purpose and/or which clean springs have excess discharge that can be shared. When a start has been made, a more precise cost analysis can be made, since exact distances and discharges are now known.

Other contaminants
The research of this project was focused on nitrate pollution. However, during the project time, we found that there were problems with other contaminants. These other contaminants have to be researched thoroughly. The framework of this report can be used for these other pollutants, like phosphorus and potassium.

In particular, pesticides should be researched better. Chlorothalonil appeared in our studies often, so extra care should go to this pesticide.

Further (financial) exploration of mitigation measures
The financial aspect of all mitigation measures can be investigated more quantitatively. This can be done by researching all alternatives more thoroughly. For example, by making a design for the PVC or AC alternatives, contacting companies for the actual pricing of certain products or services and obtaining reliable data on the inflation rate, fuel prices, salary rates and depreciation. These quantitative results could help in removing uncertainty and assumptions from the financial assessment. On top of that, a cost-benefit analysis of all possible solutions and products available on the market and within the government, AyA and ASADAS could lead to a better understanding of the costs involved. Lastly, more categories and corresponding criteria could be added to the assessment framework to obtain a more complete end product, think of a Multi-Criteria Analysis (MCA) for example, which assesses multiple categories with rankings and well-considered weights. Although the financial aspect

already covers the most crucial part of the decision-making, the structure can be improved by including categories such as sustainability, stakeholder preferences, legality, safety, risk and time management. These six additions would already make the framework much more valuable since they examine other important project aspects as well.

Difficulties to implement the strategies Many of our recommendations require a decent amount of change. Implementing these changes has to be done carefully and considering all the risks of different parties. It is important to note that all concerned parties should be involved in the decision-making process to stimulate cooperation and a support base.

Decision support tool
A tool can be developed to more specifically cater towards certain issues. For example, if a farmer wants to have more sustainable practices, a decision tree on what different measures can be taken or which measures can be improved can be very helpful. A better education system can also prove to be very valuable in order to expand sustainable practices.

Nitrate concentration model
Precipitation

- Taking spatial differences into account is possible in a number of ways; the most straightforward way to do this is to make an interpolation of the different precipitation measurement stations and run an analysis on the recharge areas. The sum of the precipitation in the recharge area could then be calculated. A large constraint is that the interpolation is likely to have a lot of lacks like not taking into account geography and the many micro-climates in the region.

  A possible improvement of this method is to use microwave links from cellular communication networks to make a better estimation of the precipitation in the region (Uijlenhoet et al., 2018). This method is more accurate than interpolation. During the timeframe of this research, this information was not available.

- Climatic effects could be included by researching the climatology of the region and the effects caused by global warming. Furthermore, increased effects of La Niña or El Niño could be included.

- To make a better estimate instead of the average monthly precipitation, the precipitation in a time period before the measurement could be used. Research should then be done on how long it takes before precipitation reaches the spring.

Land use

- A more elaborate and temporal research could be done on land use in the region. Analysis of the current and historical crop types in the region and the practices of farmers could be analyzed and included in the research. This could also be done for the practices of cattle farmers.

- More elaborate research on the state of the septic tanks in the region can be done to increase the model value. Possible parameters are the leaking of the septic tanks and the total amount and volume of the septic tanks.

Bufferzone protected

- More detailed research on the state of the buffer zone could be done by visiting all spring buffer zones and analyzing the buildings in this buffer zone. The state and location of the septic tanks in the buffer zone should be analyzed and considered. Weighing the contaminative potential of the buildings should be done in order to improve the buffer zone protection parameter in the model.

- To make a better estimation of the impact of each nitrate point source on the nitrate concentration in the spring, taking groundwater flow into account in order to make improved buffer zones is advised. As groundwater flow is generally downhill, this would likely result in buffer zones which are more oriented to the uphill part of the slope and less to the downhill side of the slope as regions upstream have a bigger effect on the spring water quality than downstream areas.

Other parameters

Soil moisture content

The soil moisture content is an interesting geo-hydraulic parameter in order to assess the possible saturation of the soil in the recharge area of a spring. The soil moisture content is assessed by a number of satellite missions, as ESA (2022).

Large point source contaminators

In the current model, large point source contaminators outside of the buffer zone are not considered. Large cattle farms could be a major source of contamination, like in the Netherlands, where reducing the nitrate emissions of the 1 % of most critical nitrate emitters seemed to be able to solve the nitrate crisis in a short time frame (Remkes, 2022).

A risk analysis should be done on the recharge areas of the springs to assess these large point source contaminators by monitoring their nitrate emissions and the effect on the water quality of the spring.

Nitrate source tracing

One of the findings in this project was the fact that urban areas in recharge areas contribute to an elevated nitrate concentration in the spring, especially when buildings are located within the protection areas. In further research, it could be interesting to monitor the springs on E.coli bacteria. In some reports on water quality in the springs there were already recordings of E.coli measurements but for the purpose of this project and due to time constraints they were not used. It could be interesting to take E.coli into account in order to be able to differentiate the nitrate originating from anthropogenic waste and agricultural practices.

7 Conclusions

7.1 Research sub-question 1: What are the main factors in the region contributing to the input of nitrate in the hydrological system?

The research area is characterized by the pronounced topography and intensive agricultural practice as well as some scattered urban areas without an integral sewage system. For this project, these factors have been thoroughly mapped out and analyzed.

The hilly environment makes for an increase in surface runoff during precipitation events which subsequently can result in a superficial wash of crop fields and pastures. The presence of fertilizers or livestock manure respectively this leads to an increased nitrate uptake by the system. Agricultural practices inside recharge areas pose a logical risk to the contamination in the resulting springs due to the usage of nitrogen-rich fertilizers, as well as livestock waste. Finally, urban areas can act as a nitrate source for the hydrological system if waste is not correctly disposed of. The sanitary culture in the research area is dominated by the usage of septic tanks. This practice inside of a recharge area poses a significant threat to the state of springs when not managed properly.

7.2 Research sub-question 2: How can the parameters be related to nitrate pollution?

Breaching of the 200-meter protection zone around a spring was found to have a moderate positive correlation with the nitrate concentration of the spring because of the close proximity to the spring and the lack of dilution. This is also the strongest correlation factor found affecting nitrate concentrations in springs.

In general, weak correlations were found between land use and nitrate concentrations in springs. For a linear correlation, the most important positive land use parameter determining the nitrate concentration is the portion of cropland, closely followed by the portion of buildings. A weak negative correlation, indicating a decrease in nitrate concentrations with an increase in the portion of a land use type, can be found for woods. No significant correlation could be found between the portion of pastures and the nitrate concentration.

In terms of topography, the minimum slope shows a weak positive correlation with the nitrate concentration; other parameters like the standard deviations of the slope, the maximum slope, and the minimum slope do not show a correlation with the nitrate concentration of the spring.

Correlation between the precipitation and the nitrate concentrations is more difficult. Whilst the total dataset does not show a significant correlation, the monthly averages of the nitrate concentration and the average monthly precipitation do. It is therefore likely that spatial patterns of the precipitation should be taken into account to make sufficient conclusions. Using 16 parameters, a polynomial multivariate regression analysis was made. An R^2 of 0.689 was found. The model confirms that there is a strong correlation between the parameters that were assessed.

7.3 Research sub-question 3: What mitigation strategies could be implemented to reduce nitrate contamination in water bodies identified as critical?

A large number of methods to mitigate pollution and reduce current nitrate concentration in water bodies have been researched and analyzed. From an agricultural viewpoint, adjusting nitrogen application rates and timing could be a non-immersive solution. The Ministry of Agriculture should take a proactive role in enhancing this environmental-friendly behavior. Furthermore, periodical changing of crop type can help to optimize the use of residual nitrogen. Moreover, proper manure management and the implementation of precision equipment such as drip irrigation and side dressers could help farmers in the region decrease their nitrate footprint tremendously.

For domestic measures, one could introduce more regular checks on septic tanks and leaking sewers in the soil. The unseen leakage can add up to a large nitrate inflow in the groundwater. Especially in the buffer zones around springs, this could be a key method to decrease nitrate concentrations.

Furthermore, as can be seen in Table 9 in Section 5.1, four technical water-filtering alternatives with their respective costs and costs per m^3 of water have been displayed. The most cost-efficient strategies are alternatives 2 and 3, which are the usage of PVC pipes and pumps from unused, potable springs to contaminated locations and Activated Carbon removal filters, with \$0.032 (PVC only) or \$0.112 (PVC + pump) and \$0.605 per m^3 of water respectively. It is worth noticing that using a piping + pump system will be approximately either 20 or 6 times cheaper than the Activated Carbon alternative. However, the remarkable difference between both alternatives is that the water from another spring will not be treated, whereas the water in the AC alternative will be purified from contaminants like nitrates and pesticides.

Lastly, the latter alternative of the pressure vessel & filter system is roughly 3 times as expensive (\$1.724) as the AC (\$0.605) per m3 of water. Similarly, both alternatives are actually able to filter out different sorts of nitrates, pesticides, and other contaminants. In comparison, the Ecoflow system provides all six polluted springs in Cipreses and Santa Rosa de Oreamuno with a filtering system and the AC only provides one central filtering location from where distribution will occur.

7.4 Research sub-question 4: What are the difficulties/obstacles to implementing these mitigation strategies?

<u>Difficulties/obstacles obtaining the necessary resources</u>

Some of the conclusions found in this paragraph were attained through talks with local inhabitants and farmers and meetings with official politicians and/or governmental bodies. It should be noted that even though we researched this topic, conclusions made underneath might not be as academically substantiated as the others. In order to fulfil profound and inclusive research, sufficient data should be centrally available. The current structure of information is largely scattered around a large number of different institutions (AyA, ASADAS, municipalities, and universities) without an overseeing ecosystem of relevant data on precipitation, measurements of pollution, current and historical land use maps, well locations, and recharge areas. This reduces transparency, enhancing the risk of data loss. Furthermore, it causes unnecessary delays in the information-gathering phase of current and new research projects.

For example, due to the high amount of responsibilities in combination with under-staffing, the complaints about AyA are growing. The following critics are frequently being addressed by multiple ASADAS; low data transparency, long waiting queues, poor communication, and limited support for sometimes pressing issues. This automatically enhanced the difficulties to gather the necessary data to execute proper research. Because AyA is one of the main sources of information when it comes to water-related quality parameters.

Difficulties/obstacles implementing long-term mitigation strategies

The following difficulties/obstacles are predicted while implementing long-term mitigation strategies. Due to the dense bureaucratic nature of AyA (legislative, executive, and controlling) in combination with under-staffing, this can possibly lead to an increase in waiting queues and inaccurate/delayed responses to pressing issues. This will also affect the effectiveness of the proposed mitigation strategies. Because implementation times will be prolonged by these issues. Another issue can be found in the conservative mindset of governmental bodies. Due to the innovative nature of the mitigation strategies, which are recommending fundamental system changes, this can lead to high resistance. It will take time to overcome these currently prevailing ideas. Future research groups need to continue this line of work and build a trusting relationship with AyA in order to let them accept and implement new ideas. Another predicted issue is in regard to the monetary units needed to implement the long-term mitigation strategies. Where the willingness of agricultural/livestock farmers to innovate is often high, the means to implement are often lacking. On top of this, essential knowledge to innovate and reduce fertilizer contamination is frequently unavailable. The necessary studies in order to innovate are often not provided by AyA.

8 Recommendations

In the following chapter, recommendations will be given based on the discussion and conclusions. Also, suggestions for future research are proposed.

Due to the multidisciplinary nature of the project team, the recommendations will be given from different angles, in order to create the most profound set of solutions. After thorough analysis in both a quantitative and qualitative way, the recommendations are given in a long- and short-term time span. In such a manner, the distinction is made between preventive and mitigation measures. Furthermore, the recommendations are given on the following themes; technical, societal and policy. The technical section presents recommendations that can be implemented with techniques and materials. Societal recommendations will be catered towards communities and municipalities to collectively find solutions. In the policy section, concrete steps for policymakers are presented. The substantiation of the recommendations from the literature can be found in the section on the literature framework.

The following four recommendations are prioritized above the others, this is done on basis of implementability and feasibility.

1. Adjust nitrogen application rates/timing
   It is advised that farmers should investigate the required fertilizer amount needed for the products that grow on their farmlands. It is recommended that the MAG micromanages the required steps that need to be executed in order to fulfil the crop research. In order to better understand the necessary amount of fertilizers. It should be emphasized that most crops in an early stage are virtually not open for fertilizer intake. High use of fertilizer in this stage is from an economical and contamination point of view an inefficient way of using fertilizer. It is recommended that MAG organizes practical information sessions on a frequent basis and provides information about the applicable nitrate rates.

2. Septic tank maintenance
   In order to maintain the most optimal operational purification rate the septic tanks should be subjected to regular maintenance. Since leakage of poorly maintained septic tanks is a common problem in the country, It is advised that the owners of the septic tank execute visual inspection on a monthly basis and report this to the AyA. When poor septic tank conditions are reported AyA should act accordingly and execute the proper maintenance or replace the septic tank when the conditions are beyond maintenance.

3. Implement the use of precision equipment such as drip irrigation and side dressers
   The use of drip irrigation with added fertilizer, fertigation, will increase the absorbability of nitrogen for crops due to the precise injection of fertilizers. It is advised to implement drip irrigation systems to increase the efficient use of fertilizers and to decrease the outflow of fertilizers due to overland flow. Additionally, while not as critical in Costa Rica, it can decrease wasted water. Apart from drip irrigation, the use of side dressers can also increase the efficiency of nitration use. A surplus of fertilizers will increase the probability of fertilizer outflow in local channels in times of high rainfall events. Due to the high employ-ability of a drip irrigation system, it is suitable for every soil type.

8.1 Short-term

Defined as recommendations that can be applied within one year with a small financial injection.

8.1.1 Technical

The following three recommendations are prioritized above the others, this is done on basis of implementability and feasibility. The additional recommendations are displayed afterwards.

1. Adjust nitrogen application rates/timing
   It is advised that farmers should investigate the required fertilizer amount needed for the products that grow on their farmlands. It is recommended that the MAG micromanages the required steps that need to be executed in order to fulfil the crop research. In order to better understand the necessary amount of fertilizers. It should be emphasized that most crops in an early stage are virtually not open for fertilizer intake. High use of fertilizer in this stage is from an economical and contamination point of view an inefficient way of using fertilizer. It is recommended that MAG organizes practical information sessions on a frequent basis and provides information about the applicable nitrate rates.

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- Supply Cipreses region with good quality water from neighbouring springs
  The exceeding fungicide levels in the springs of the Cipreses ASADAS is not suitable for human consumption as high levels of chlorothalonil may cause cancer. Therefore it is suggested to use excess water and/or unused springs from neighbouring ASADAS with safe levels of contaminants. Distribution pipes can be laid for a certain price explained in Section 5.1.

- Use tissue sampling and soil sampling
  Tissue sampling can increase the physiological understanding of the cultivated crops. Different tests can be done on the leaves from the crops. This will give accurate and real-time nitrate rates. This can then be used to assess if crops need more fertilizers or if the crop is already satisfied. Tissue sampling can be done on a regularly basis in order to increase physiological understanding. It is advised that testing units are made free of charge to make tissue and soil sampling available for the local public. The necessary equipment should be freely available in order to stimulate its use.

- Utilize residual nitrogen in soil by interchanging crops
  In order to optimize the use of residual nitrogen in the soil it is advised to change crop type periodically. It is important to make use of both deep/shallow-rooted crops. Deep-rooted crops can use the residual nitrogen that is left behind in the soil due to the inability of shallow-rooted crops to capture full capacity from the used fertilizers. It is advised to further research the specific crop use in order to optimize the captured fertilizers in the ground.

- Apply biological filter beds at the borders of agricultural land
  It is advised to implement biological filter beds at the border of the agricultural farmlands. These bio-purification systems or buffer zones can figure as ex-situ bioremediation treatment. This solution has a bilateral beneficial effect, reducing nitrate leaching and increasing fertilizer absorption in order to reduce the amount of stored nitrate in the soil. It is advised to further

increase the implementation of the mustard plants due to their effective behaviour in nitrate lifting.

- Mechanical filters and zero-valent iron filter
  Treat high concentrations nitrate water before discharging it into the recharge area. By reducing nitrate and capturing ammonium and phosphorus, economically it can be very beneficial.

- Proper manure management
  Since nitrate leaching from livestock farms originates from manure, its management can influence environmental contamination greatly. First of all, it is highly recommended to not have manure storage facilities within a recharge area of a spring. The storage should be placed outside or downslope of the capture zone. Regular cleaning of the livestock yard lowers nitrate leaching as well.

- Location choice
  It is recommended to place livestock farms downslope from the specifically identified wells. In order to reduce the amount of fertilizer present in the manure that flows towards the well due to overland flow in times of high precipitation events.

- Leakage sewage system
  In order to obtain a quantification of the leakage within the sewage system further research from the responsible authorities needs to be executed. This is important in order to obtain a complete picture of the sewage water that is being discharged into the environment without the proper treatment. It is advised for further research teams to investigate this matter and quantify the leakage within the sewage system. To detect leakage research can be done in techniques such as pipe endoscopy and thermography. Thermography makes use of differences in temperature on the surface of different materials. Where pipe endoscopy is able to monitor the inside of the pipe by making visual content. In order to monitor and photograph the pipe damage, foreign body penetration, leakage and hidden connection of branch pipes.

8.1.2 Societal

The recommendations in this section are made on assumptions that came out of the research. By talking to many local citizens, we accumulated a decent understanding of problems and suitable recommendations. Even though the effects of such recommendations were not studied in this research area, it should be noted that positive effects have been shown in other comparable projects across the globe.

- Implementation of citizens science
  In order to increase the amount of data available for research it is advised to make use of citizen science. Where citizen science is defined as: "Scientific work is undertaken by members of the general public often in collaboration with or under the direction of professional scientists and scientific institutions" (Vohland, 2021). It is advised to distribute nitrate strips in relevant locations in order to obtain a first indication of the level of contamination. Further research can then be executed on local hotspots identified by the local community. An easy-to-use digital entry system is a necessary component of the citizen science project. The procedure is further explained in the following chapter: 'Quick and dirty measurements for nitrate concentration in water.

- Education farmers about long-term negative impact
  From interviews, high willingness is observed among farmers to implement the correct methods of fertilizer/pesticide use. However, the correct knowledge is missing to properly implement these procedures. It is advised to organize information sessions to enlarge the awareness of farmers about the long-term effects of improper fertilizer/pesticides use and hand them the proper knowledge/tools to make sure they are able to farm their lands in a sustainable way.

- Creating awareness
  It is advised to keep the key stakeholders inside the information loop regarding the progress made in solving the contamination problem. Keep them up to date in order to create a common sense of responsibility. By updating the key stakeholders the feedback loop is closed and the efforts made in order to reduce the contamination are known to the general public. The local communities are concerned and want to know the implementation strategies from the governmental bodies. It is advised to organize periodic information meetings where key stakeholders can update the AyA about their efforts and express any future concerns.

8.1.3 Policy

The recommendations in this section are outside the scope of our research. Therefore, these recommendations are not intensively studied. They are still worth mentioning, because some problems that came up during this research could be solved by making these policy changes. It should be repeated that the effects of these policy recommendations could be very much different than policy changes in other countries.

- Positive stimulants and enlarging public understanding
  In order to enlarge the public understanding of the contamination of the wells, it is advised to organize information meetings on a periodic basis. It is advised to inform the farmers about application rates, placement of precision units, physiological crop behaviour and the importance of interchanging crops over the years. It is advised to create a policy that gives positive stimulants for those attending the meetings. For example; to give discounts when purchasing precision equipment such as side dressers and drip irrigation with subsidy money. It is advised to apply for a fund at the ministry of agriculture to obtain the monetary units needed for this policy. It is advised that an independent third party keeps supervision over this fund.

- Intended crop plan
  It is advised to create a regional policy that obligates by law to pre-investigate the number of necessary fertilizers that are intended to be used this year. This needs to be approved by an independent third party. In order to monitor the total amount of pesticides that are being used in the region.

- Free distribution of tissue and soil sampling
  It advised making tissue and soil sampling freely available to the general public. In order to stimulate the adjustment of fertilizers amount on in-situ measurements done into the fertilizer saturation index inside plants/soil. It is advised to create a policy that rewards farmers financially for those who are implementing in-site fertilizer adjustments.

- Financial stimulant filter beds/bio purification system
  It is advised to create a policy that financially stimulates agricultural/livestock farmers to implement filter beds/bio-purification systems on the sloping end of their property. In order to reduce fertilizer leasing and increase fertilizer absorbability. An independent third party should control the monetary units that are needed for this financial stimulation. It is advised to review the total amount of filter beds/bio purification systems on a yearly basis.

- Prohibiting manure storage in well recharge areas
  It is advised to create a policy that makes it illegal to have manure storage within the borders of the recharge areas. In order to reduce the number of fertilizers leaching directly from the manure storage.

- Create a policy to discourage cattle within the recharge areas
  It is advised to create a policy that discourages livestock farmers to keep cattle within the borders of the recharge area. Where information provision about the possible beneficial effects on well contamination can already encourage a positive feedback loop. The policy should obligate the livestock farms to deliver a plan where the exact grazing locations are indicated. The AyA

should compare these locations with the known breaching zones (the area around the wells) and accordingly give an approval/rejection. It is advised to create a policy that enables the AyA to litigate farmers that are unwilling to cooperate.

- Policy on maintenance septic tank
  In order to create a clear overview of the maintenance status of the septic tanks in the area, it is advised to create a policy that obligates owners to deliver a periodic report on the basis of visual inspection. The AyA should act accordingly and execute the proper maintenance in order to maintain the intended storage function of the septic tanks. The AyA should collect the captured contamination inside the septic tank on a regular basis.

- Policy on citizen science
  It is advised to apply for monetary units at the Ministry of Agriculture that enables AyA to distribute nitrate strips at the indicated fertilizer hot spots. To enlarge the amount of available data and make use of citizen science. In this way, the local farmers are more involved in the process which could enlarge their willingness to cooperate on sustainable measures to decrease local fertilizer pollution. The data acquired with these measurements should be collected by the AyA to enlarge the available data set. After extended citizen science further research groups can acquire a comprehensive grasp of the current situation. It is also advised to create an interactive online web page where the fertilizer values are updated on a periodic basis. Where farmers can see what the current status is from the soil. On the basis of this information fertilizer amounts can be tailor-made in specific areas.

8.2 Long-term

In this section recommendations that have an implementation period that exceeds a one-year time span will be given. Similar to the short-term recommendations, the effects of some of the recommendations made in this section are not extensively studied.

8.2.1 Technical

Building of Wetlands/ terracing
It is advised to create SFWs (surface flow constructed wetlands) on the downstream side of every recharge area. Upstream from the interlinked well. Literature suggests: “SFWs, if installed area-wide, can help to significantly reduce NO3- loads in a river basis and can be an important component of a comprehensive management strategy to reduce N loads in surface waters to acceptable levels’ (Bauwe et al., 2022b). It is advised to use plants that have a high ability to absorb nitrogen from the water. When strategically chosen, the plants can afterwards be sold in order to increase funding to further extend the SFWs.

8.2.2 Societal

Improve the Ministry of Agriculture (MAG) role in agriculture education and advice
While MAG is present in the region with a multitude of office buildings, their attitude is very passive, based on conversations with farmers and ASADAS. While farmers can appeal to the MAG for tips on farming practices, MAG does not actively reach out to farmers. When farmers were asked if they ever had conversations or checkups by the MAG, they answered that they never have been checked. Once gotten a certificate for their farms more than a decade ago, they had not shown up once.
We strongly recommend the ministry use the existing MAG network in the region and acquire a more outreaching attitude. A general sense of willingness is present when talking to farmers of the region but often enough they do not know the possibilities of the MAG or other institutions.

8.2.3 Policy

- Establish a different system for the protection zones around springs based on actual recharge areas
  It is advised to revise the protection zone calculations which dictate the well-breaching areas in

the law. At this point, it is done by a fixed radius around the well. However, results during the research have shown that upstream breaches are more prone to be strongly correlated to high nitrate values at the respective wells. Therefore, it is advised to adjust this fixed radius into more tailor-made breaching areas. More research is advised to adjust the breaching zones.

- Set up of systematic measurement system of water quality parameters in springs
  A consistent and timely monitoring and reporting system of nitrate concentrations should be implemented to improve future research.

- Set up an action plan (decision tree) when nitrate values exceed permissible limits
  A rigid action plan should be established when the monitoring system detects values above certain limits. The various limits should have different consequences. For example, when the legal limit is exceeded the spring should be closed and water should be brought in from neighbouring, uncontaminated springs. Before the legal limit is exceeded, some actions should already be undertaken, like the activities in the direct surrounding (upslope) of the springs should be carefully monitored and limited in using certain products.

- Creation of a large scale sewer system
  Due to the absence of a sewer system, septic tanks are being implemented as a substitute measure. However, septic tanks are appropriate for small-scale settlements. For large-scale settlements, it is recommended to implement a sewer system in order to reduce the leaking from septic tanks into the environment and cause possible well contamination. The economic feasibility of this measure is explained in section 5.

- Setup regional water authorities
  After obtaining information from different key stakeholders within the project area the following observation can be made. Due to the bilateral administrative nature (controlling and executive) of the AyA certain complications can be observed. The large administrative responsibilities in combination with under-staffing create long waiting queues and time-intensive maintenance is by default being postponed indefinitely. Next to high workloads and poor maintenance, it was observed that due to the bilateral administrative nature of AyA conflict of interest can occur.

  This phenomenon will be illustrated by the situation. Where AyA figures as a controlling governmental body, due to the high contamination regarding chlorothalonil multiple wells are being closed for drinking water consumption. However, the same governmental body (AyA) imposes legislation that rules that the alternative is coming from wells located in Guarco under the supervision of AyA. On their behalf, the AyA is organizing trucks that are distributing the water in areas with contaminated wells. This is contrary to the accepted principle of trias politica that figures as a baseline of legislation in a modern democracy. Crossing this principle can lower the legitimacy and general acceptance of the public.

Alternative system (implemented in Western Europe):
Separated legislative, executive and judicial power. In practice, this would result in separating:

- The right to create the necessary legislation regarding the improvement and maintenance of water quality. This should be a democratically chosen administrative governmental body. (legislative power)
- The right to control the recorded legislation and create allegations against the offenders of the law. (executive power)
- Check if the allegations have legal grounds and give penalties accordingly. (judicial power)
- A different body than the water authority should have the right to distribute water and the obligation to maintain the necessary infrastructure.

At this point, AyA is fulfilling multiple roles which can enhance bureaucratic clutter and create situations where conflict of interest can occur.

9 Addendum - Chlorothalonil

Chlorothalonil contamination carcinogenicity category 1B

While pesticides and fungicides are outside the scope of this nitrate-contamination-focused study, it is essential to mention the recently elevated concentration of chlorothalonil in two springs in the research area. At the end of October 2022, extreme concentrations of the fungicide Chlorothalonil were confirmed by AyA in the Carlos Calvo and Plantón springs that supply the village of Cipreses in the Oreamuno administrative region. The springs, which provide water to a mostly agricultural community of 2500 people, were ordered to be closed as of 20 October 2022 due to the unknown human health effects of the high concentrations. While the elevated concentrations were already reported in march 2022 by the Instituto Regional de Estudios en Sustancias Tóxicas de la Universidad Nacional (IRET-UNA), the confirmation of these concentrations by AyA and the subsequent decision to ban the use of the springs was only in October 2022. Conversations with the ASADAS of Cipreses however mentioned at the time of writing (February 2023) all wells are up and running. Citizens are advised to not drink the water and use it only for other domestic and agricultural uses, citizens are encouraged to get drinking water from the trucks.

The drinking water limit for Chlorothalonil concentration in the European Union and Switzerland is 0.1 µg/L ((EFSA) et al., 2018). The use of the general fungicide has been completely banned in the European Union and Switzerland in 2020 Kiefer et al. (2020). The Carlos Calvo source was found to have a Chlorothalonil concentration of 1.73 µg/L while the Planton source had a concentration of 19.36 µg/L. From this day on, the Ministry of Health ordered AyA to provide potable water with trucks, which is still the case at the time of writing in January of 2023. The European Chemistry Bureau has classified the substance in carcinogenicity category 1B, which signifies 'may cause cancer' ((EFSA) et al., 2018).

Chlorothalonil is the second most used fungicide in Costa Rica, while it is been banned in 32 countries around the world (García, 2022b). In addition, agricultural lands are found within 15 meters of the springs, where pesticides are widely applied. The time decontamination takes is at the moment not known by the responsible ASADA (García, 2022a). Links are suggested by environmental groups between the high usage of Chlorothalonil and the high rate of gastric cancer in the wider Cartago region. A study performed by (Sierra et al., 2016) showed that among countries in Latin- and Central America, Costa Rica has both the second highest incidence and mortality rate of stomach cancer only behind Chile. The WHO's mortality database confirms that stomach cancer is the number 1 cancer-related mortality cause in Costa Rica (World Health Organization, 2011). Worldwide, stomach cancer is the fourth leading cause of cancer death (Sierra et al., 2016).

Possible treatment - Biopurification Systems: Current Advances and Future Prospects of On-Farm Biodegradation of Fungicides and Pesticides

The improper handling of agro-chemical residues in agriculture poses a serious risk to the environment because of point source contamination. As a biotechnological tool for the on-farm treatment of pesticide-containing wastewater of agricultural origin, bio purification systems (BPS) have been developed to reduce environmental exposure to fungicides and pesticides. Highly recalcitrant compounds have shown poor elimination in BPS, despite being effective in the removal of a variety of fungi- and pesticides; in addition, the performance of BPS still needs to be evaluated by many. Real pesticide application cycles for particular crops should be used to evaluate the sustainability of agrochemicals (Rodríguez-Rodríguez et al., 2021).

The detoxification of point sources of pesticide residues, which pose risks as agents of water pollution, and the removal of wastewater contaminated with pesticides are both important tasks performed by biopurification systems (BPS), which are inexpensive, straightforward, and effective tools. Generally speaking, a BPS is an ex situ bioremediation treatment technology that consists of a solid-phase bioreactor or a composting facility. Its prophylactic purpose is to treat water that has been contaminated by agricultural chemicals to hasten their removal.

BPS configurations are easy to emulate in developing Latin American nations like Guatemala, Costa Rica, Chile, Peru, Ecuador, Brazil, and Argentina due to their simplicity. These BPS, also referred to as "biobeds," are composed of a highly active biological biomixture that is enclosed in a container or excavation. The original European "biobed" had three layers: a clay layer at the bottom (to prevent contamination breakthrough), a layer of peat, straw, and soil (1:2:1) on top, known as biomixture, and a layer of grass on top, which helps to maintain the proper humidity and serves as a helpful indicator of pesticide spills. Examples of Costa Rican adaptations of BPS are limited to a plastic container (without the clay layer) that serves as an impermeable material and typically does not include the grass surface layer. These systems have also been observed during visits on farms in the research area, they are thus already being implemented.

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A Appendices

A.1 Excel measurement data

More Excel files that are used can be found under this repository link: https://github.com/maxhelmich/Python-MDP-Costa-Rica.

A.2 Python code

The GitHub repository can be found under this link. https://github.com/maxhelmich/Python-MDP-Costa-Rica

A.3 Specific analyses precipitation

A.3.1 Qualitative analysis on the relation between precipitation and contamination levels

To make an appropriate estimation of the influence of precipitation and to assess whether the temporal patterns in the precipitation should be a factor to take into account in the nitrate concentration model, the correlation between the precipitation and nitrate concentration is assessed in this chapter.

For 2 regions, Cartago and Oreamuno, graphs are displayed that show the historical precipitation and nitrate concentration in the area in Figure 35 and Figure 36. In both cases, it can be observed that higher concentrations of nitrate were measured after a high rainfall event. Reasons for this can be explained, however, one must be careful to draw conclusions from it because the data can be skewed.

One reason could be that with high rainfall events, the topsoil gets saturated quickly. This can cause the rest of the precipitation to cause major runoff. This runoff might wash away a lot of fertilizer and pesticides, causing the nitrate in the water to increase in the short term Kelling & Peterson (1975). Another reason could be that farmers tend to fertilize and spray pesticides more after a rainfall event, again causing the nitrate to increase.

What is hard to judge, is whether the measured concentration is caused by the previous rainfall event. It could be very plausible that the nitrate that is washed off will be measured in the water at a much later point. On top of that, the locations where the nitrate is measured might differ a lot, meaning that high concentrations might be measured because of other causes than the rainfall event. Furthermore, there could just be a coincidence in the number of measurements taken after a rainfall event. If that frequency is higher than in dry periods, the data can be skewed as well.

So to draw a solid conclusion on the correlation between precipitation and nitrate concentration, more research should be done on the flow of water in specific areas. And data should be cataloged more precisely. The role of for example informally built open wells by farmers and its influence in nitrate rich overland flow groundwater infiltration is not quantified but could play a role during high intensity rain events.

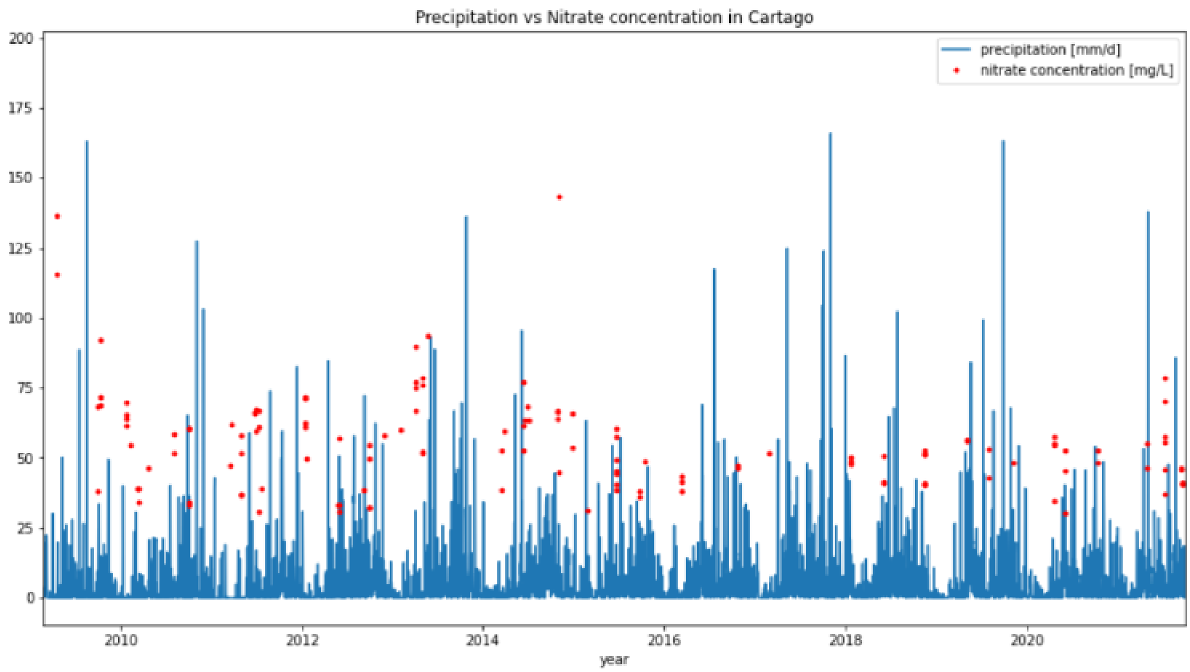


Figure 35: Precipitation versus nitrate concentration in Cartago

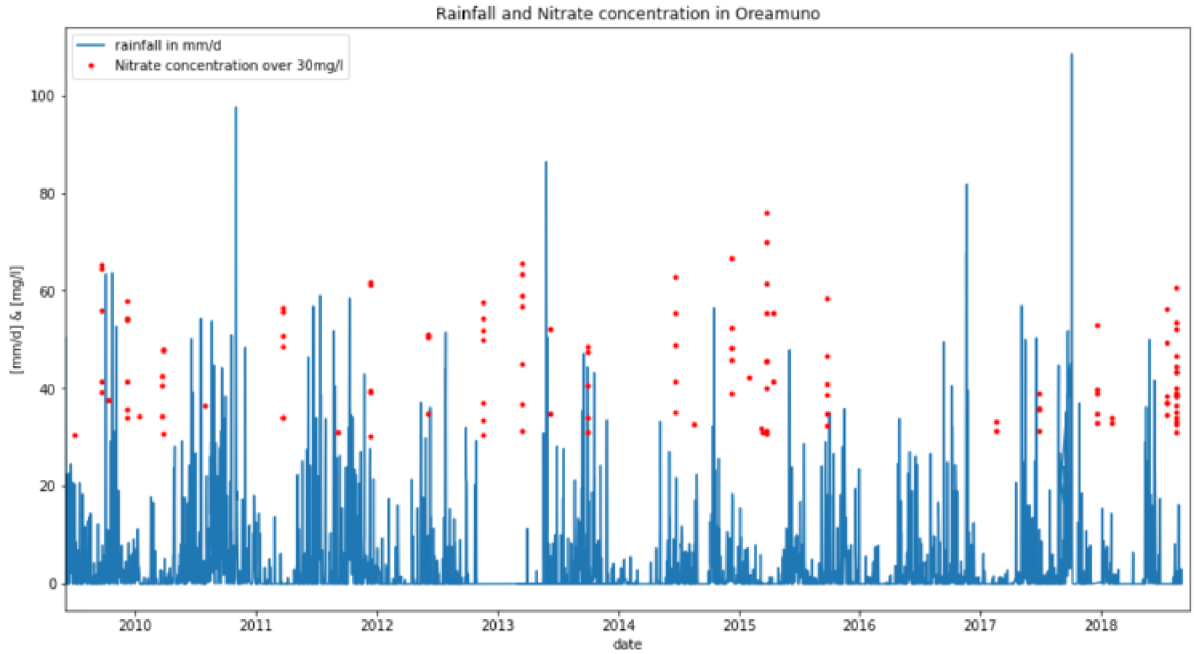


Figure 36: Precipitation versus nitrate concentration in Oreamuno

A.3.2 Analysis of the whole AyA data-set

On a more general scale of the whole AyA data-set AyA (2021), the monthly averages of the precipitation and the nitrate concentration are taken.

Firstly, it is assumed that there are no spatial differences in the temporal pattern of the correlation between the precipitation and nitrate concentration; i.e. it is assumed that the same correlation between precipitation and nitrate concentration exists in the whole study area. Therefore, the whole nitrate concentration data-set that is provided by AyA is used. Firstly, The 1,812 data points were sorted by month and the averages per month are taken.

Results are given in Figure XX. It was found that there is a Pearson correlation of 0.48 between the nitrate concentration and precipitation, which indicates a moderate correlation.

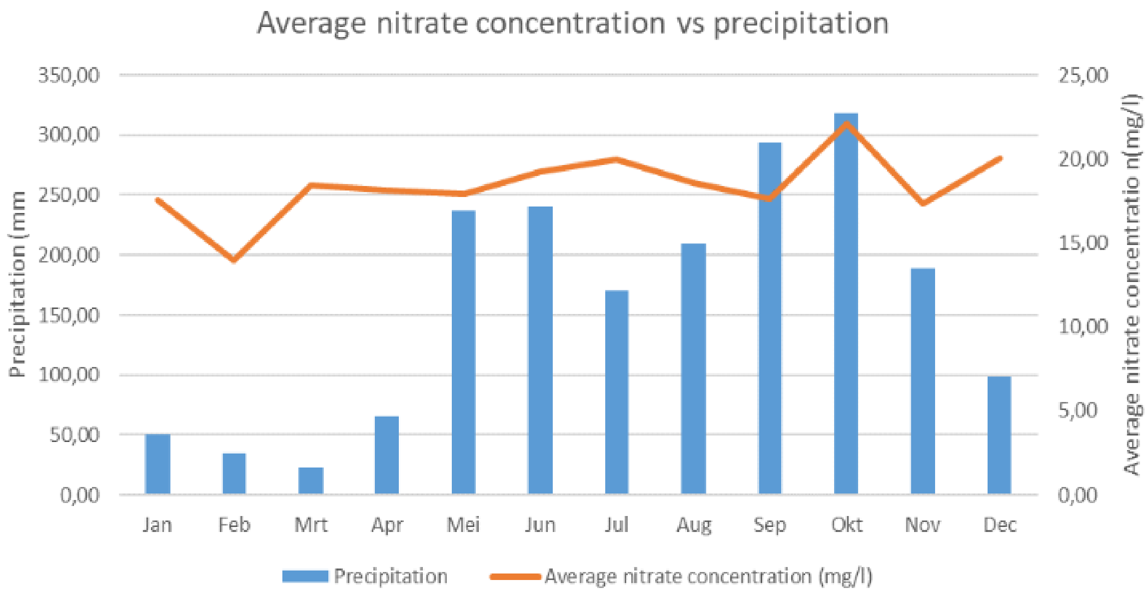


Figure 37: Nitrate concentration versus precipitation

All data points were categorized into three classes: lower than 30 mg/l (green), between 30 and 50 mg/l (yellow) and more than 50 mg/l (red). The percentages of these categories per month are taken and mapped in a bar plot. Results are given in Figure XX.

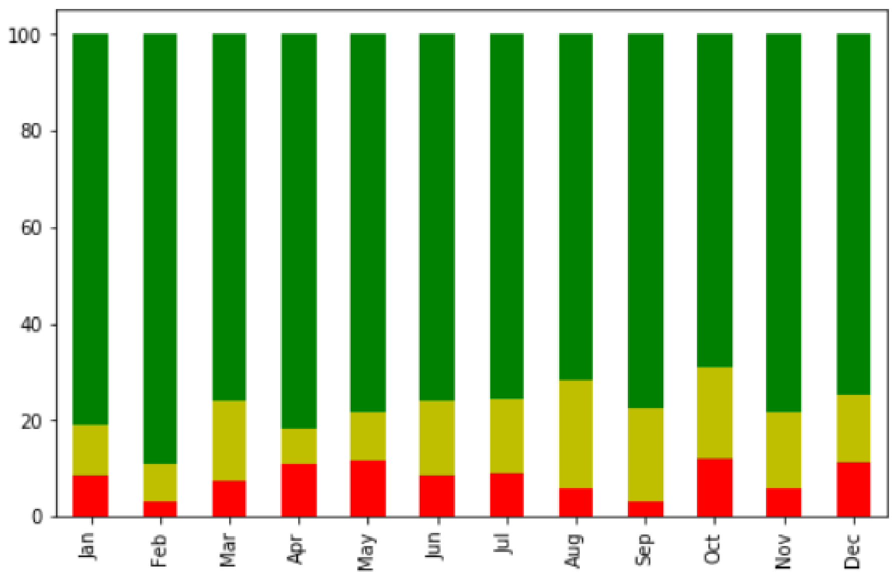
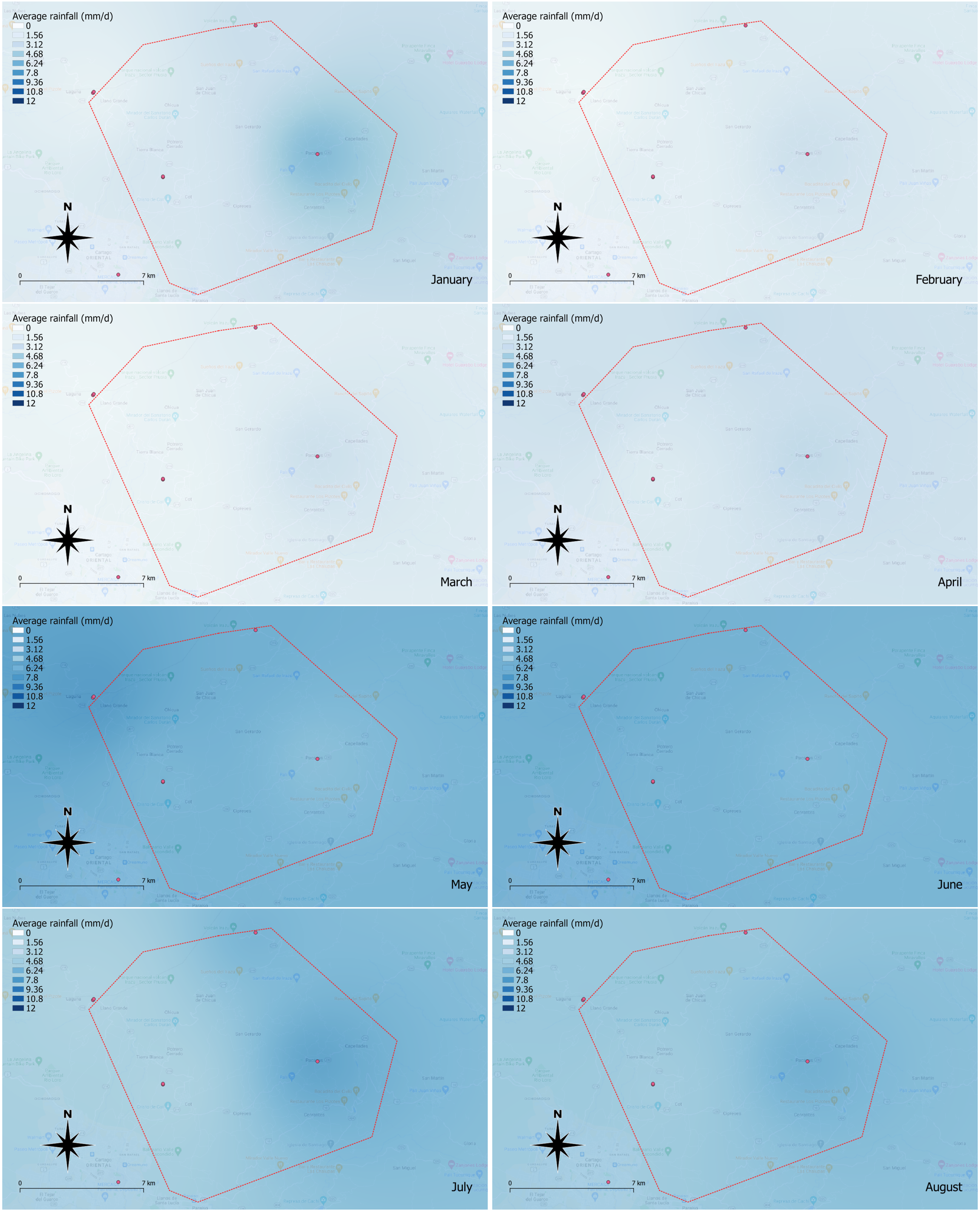
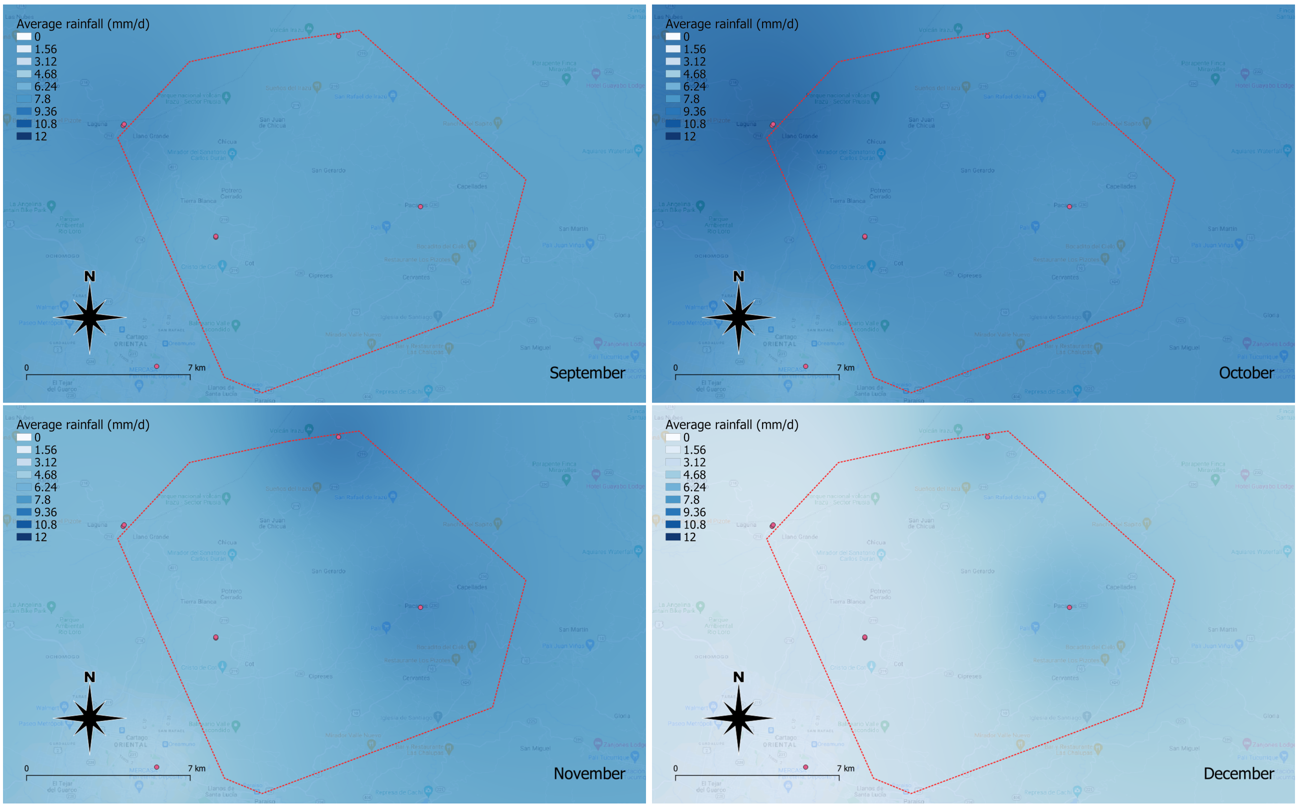


Figure 38: Bar plot of the nitrate concentrations

A.3.3 Results of the monthly interpolations of precipitation measurements




Average rainfall (mm/d)
0
1.56
3.12
4.68
6.24
7.8
9.36
10.8
12
N
0
7 km
September
October
November
December

A.4 Stakeholders

A.4.1 Report of the meetings and visits to different stakeholders

AyA (Carlos) - 25/11

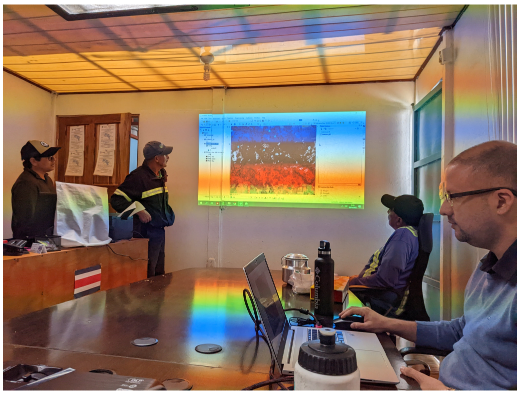
The main findings of the meeting with AyA were:

- There is a large data-set with all springs and wells in the country. This data-set also includes contact information to the owners of the springs/wells.
- The AyA does not do all of the measurements. Some are done by ASETEC (the lab of the TEC) and other labs.

ASADAS San Pablo - 30/11

In cooperation with two local plumbers Oscar and Juan, the ASADAS of San Pablo was able to give us the following information:

- All measurements of the past years for their wells and springs
- The locations of all wells and springs
- The locations of tanks in the municipalities with the complete 3 systems network



ASADAS Santa Rosa - 2/12

The ASADAS of Santa Rosa was able to give us the following data sets via their hard drive:

- All measurements of the past years for their wells and springs
- The locations of all wells and springs
- The locations of pipes and tanks in the municipalities
- Additional information on systems and measurements

Pacayas Municipality - 09/12

The Pacayas Municipality was able to give us the following data-sets:

- All measurements of the past years for their wells and springs
- The locations of all wells and springs
- The locations of pipes and tanks in the municipalities

Oreamuno Municipality - 22/11
The Oreamuno Municipality was extremely helpful. Daniel Coto and Andres sat down with us and promised to provide us with any data necessary. From this we received:

- All spring and well locations of the Municipality
- The extent of their legislative area
- Tanks and disinfection locations

San Juan de Chicua - 29/11
The San Juan de Chicua ASADAS had most of their data in digital maps which were produced by the TEC. The geographer of the Municipality of Paraíso received these and cleaned them up before providing them to us.

Visit Congress with Johana Obando Bonilla - 8/12
Group was invited to a panel concerning STEM education. After which we got a tour through the congress.



Paso Ancho - 14/12
A meeting with the ASADAS of Paso Ancho. Here we got information to complete the database with the last springs. There is only the critical ASADAS Cipreses left, but they are too busy at this moment to provide us with information and a meeting.

Field work day at AyA (Santa Rosa) - 1/12
In the morning, we arrived at the headquarters of AyA in Santa Rosa. Here we got some information on the springs that we were visiting. Normally, they perform the measurements with 2 or 3 people on quads, but this time we went with 4x4 trucks. We passed through dense jungles to arrive at three different springs. The difficulty to reach these springs made it understandable why so few measurements are carried out. AyA took samples to analyze at the lab and we carried out quick (in-situ) measurements with nitrate strips and droplets.

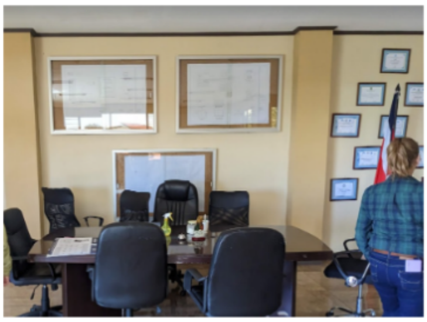


Visit Congress with Cipreses - 17/1
On this day Job and Sergio joined the ASADAS of Cipreses on a trip to the congress. Here there was a meeting with politician Oscar Izquierdo to talk about development investments in the Northern Cartago region.

Visit AyA headquarters - 17/1
After the congress meeting a meeting was called at the AyA headquarters in San Jose. For some weeks mails from the research group were dodged so we decided to just stop by. The meeting was about the financial costs of solving the contamination issue in some springs. After this meeting a lot of financial data was received which helped shape our financial analysis.

Meeting community leader and senior influential farmer Cipreses 12/1
Conversation with a senior farmer about possible meetings for interviews with other farmers. Hesitant at first, because farmers are shy about this problem, at the end we agreed to call the next morning when they will provide a list of available farmers. The next day we could pick up a client list from an agricultural shop with phone numbers from the farmers. The following day we visited two farmers.

Visit Tierra Blanca ASADAS - 19/1
First meeting with ASADAS Tierra Blanca. They were very interested in the project and wanted to cooperate. They emailed data from the quality test, although we already had this information. We were invited to visit some of their springs the following day.




Visit Llano Grande ASADAS - 19/1
Visit with Llano Grande ASADAS. The employees were also very interested and have sent data, but they did not have any technical studies from their springs. They were surprised by the infiltration areas because they have never seen them.

Visit of four springs of ASADAS Tierra Blanca - 20/1
Together with a team from the ASADAS and engineers from AyA, we visited the construction of a new water tank for Tierra Blanca. After which we drove up to the Prussia national park, below the top of the Irazú volcano. There a hike was started were we could visit four separate springs. All springs were tested by us with the nitrate strips and showed excellent results, all below 3 mg/l.



Interviews farmers in Cipreses area - 20/1
As mentioned in the report we interviewed two lettuce and spinach farmers and one mixed livestock farmer. Contact went very well, and everything was shown to us. The interview questions are found below.


Interview questions

- What crops are grown here now and in the previous years?
- Are there specific harvest seasons?
- Which type and quantity of fertilizers are applied to the field?
- During which periods are fertilizers applied?(, during early growing stages?, during later growing stages?)
- How do you determine the amount of fertilization?

- Are crops varied over seasons, for example using deep-rooted crops after shallow-rooted crops to use existing N?
- How is fertilizer applied to the field/crops? Familiar with precision placement equipment, such as side dressers? Or is fertigation used (dissolved N in irrigation)?
- Are the crops purely rainfed or what type of irrigation is used?
- Sandy or clay soil type? Do you know anything about infiltration and or overland flow?
- How much livestock practices? Manure management etc (rain protection?)
- Are nitrate lifting plants used?

A.4.2 Stakeholders background

In the list below, the most essential stakeholders within this project are mentioned and will be elaborated on in the following paragraphs:

- The Ministries of Agriculture, Health and Environment & Energy
- AyA
- SENARA
- Municipalities
- TEC
- Local Farmers
- Local Inhabitants

Ministries of Agriculture, Health and Environment & Energy
The ministries of Agriculture, Health and Environment Energy form legislative agreements and policies in Congress. The final responsibility for water supply and sanitation lies within the ministries as well. Foremost, the Ministry of Agriculture (MAG) is responsible for developing and implementing policies related to agriculture, farming, and food production. Generally, the goal of the ministry is to support and promote the agricultural industry to ensure a stable and secure food supply for the population. Therefore, the ministry of agriculture will be greatly supportive in keeping the agricultural area and their farmers in Northern Cartago operational (Ministerio de Agricultura y Ganadería, 2022).

Moreover, the Ministry of Health (MdS) is a government agency responsible for developing and implementing policies related to health care, public health, and medical research. In general, the goal of a ministry of health is to ensure that all members of the population have access to high-quality health care and to promote public health through education and other initiatives. The last factor has a large influence on water sanitation since clean and potable drinking water will result in healthier inhabitants. As a result, the ministry has a lot of power, since all restrictions and closings of springs in the region have been administered by the ministry (Ministerio de Salud Costa Rica, 2022).

Lastly, the Ministry of Environment & Energy (MINAE) is a government agency responsible for protecting and conserving the natural environment. This typically includes responsibilities such as managing natural resources, protecting wildlife and habitats, regulating the emission of pollutants, and promoting sustainability. The overall goal of the ministry is to ensure that the natural environment is protected for future generations(Ministerio de Ambiente y Energía, 2022).

AyA
AyA is the Costa Rican institution for aqueducts and sewers. They are responsible for regulating and guaranteeing clean potable water, sanitary sewerage and treatment services, according to the requirements of society. They carry out measurements and provide ASADAS with help and educational support to ensure clean drinking water. AyA will request measurements of ASADAS regularly. The ASADAS are situated outside of the service area of AyA, however they are still required to support them in ensuring the above-mentioned aspects.

SENARA
The National Groundwater, Irrigation and Drainage Service (SENARA) was established as a management organization for water resources and as a strategic partner with other organizations in the environmental and agricultural sectors (SENARA, 2022). On July 18, 1983, Law 6877 established SENARA and gave it the power and specific accountability for creating infrastructure, managing, and operating irrigation, drainage, and stormwater systems. In order to maintain the most effective and efficient practices for managing water resources, SENARA also carries out research on the preservation and utilization of aquifers. They concentrate on territorial expansion, climate change adaptation, water security, and food security (SENARA, 2022).

Municipalities
The Costa Rican municipalities have countless responsibilities, including the regulation and guarantee of clean potable water, sanitary sewerage and treatment services, according to the requirements of society. The sewage and its functionality is usually outsourced by AyA to the municipalities (AyA, 2023), so ensuring a functional water distribution and infrastructure will be executed by the municipalities. On top of that, municipalities are responsible for repairing larger issues in sewage, septic tanks and other water-related problems.

ASADAS
Asociaciones Operadoras de Sistemas de Acueductos y Alcantarillado Sanitario (ASADAS) are small-scale community organizations run by volunteers, which function as non-profit organizations that administer communal aqueduct and sewerage systems. In some smaller ASADAS, the plumbers are also volunteering. Local inhabitants can establish an ASADAS in their community if they don't have one. They will have to formally request AyA to create a well or use a spring and comply with their regulations as well (AyA, 2023).

TEC
As the local academic institution and only technical university in Costa Rica the Tecnológico de Costa Rica (TEC) plays an important role in the academic foundation of the project. With the aid of supervisors, students, laboratories and recent studies the project is being fulfilled and in the future will continue to do so. Besides these resources, TEC also supports the project financially indirectly by offering students a position in studying nitrate pollution in the region and supervising them along the way.

Local Farmers
Local farmers play a large role concerning the land-use and water quality in Costa Rica, especially in the Northern Cartago region. They provide the inhabitants of Costa Rica with food, so are essential for society. They use a great deal of water for irrigation and discharge a lot of water as well. Therefore, it is crucial to understand and visualize the water footprint of these stakeholders.

Local Inhabitants
Local inhabitants are the people that need (and have the right to) potable drinking water. If the water supply is polluted, they are affected directly and will get health problems. They are the group that benefits the most from clean drinking water. They have little impact on it, but should still be

considerate in not polluting their water discharge and direct environment (e.g. gardens, infrastructure etc).

A.5 Models

A.5.1 Properties of springs

No	Spring name	Measurement date	Precipitation	Cultivos	Arboles	Pastos	Edificiones	Mean slope
1	Pozo Amarillo	17-12-2014	98.971	0.496	0.368	0.132	0.004	14.403
2	Pozo Amarillo	7-5-2016	237.157	0.496	0.368	0.132	0.004	14.403
3	Pozo Amarillo	24-7-2010	170.143	0.496	0.368	0.132	0.004	14.403
4	Pozo Amarillo	10-10-2009	318.343	0.496	0.368	0.132	0.004	14.403
5	Pozo Amarillo	22-6-2017	240.329	0.496	0.368	0.132	0.004	14.403
6	Pozo Amarillo	27-5-2011	237.157	0.496	0.368	0.132	0.004	14.403
7	San Juan de Chica	7-3-2015	22.386	0.465	0.170	0.360	0.004	13.126
8	San Juan de Chica	26-2-2011	35.143	0.465	0.170	0.360	0.004	13.126
9	San Juan de Chica	4-7-2009	170.143	0.465	0.170	0.360	0.004	13.126
10	San Juan de Chica	9-3-2013	22.386	0.465	0.170	0.360	0.004	13.126
11	San Juan de Chica	19-4-2016	65.643	0.465	0.170	0.360	0.004	13.126
12	San Juan de Chica	19-1-2010	50.129	0.465	0.170	0.360	0.004	13.126
13	San Juan de Chica	23-3-2017	22.386	0.465	0.170	0.360	0.004	13.126
14	San Juan de Chica	7-3-2015	22.386	0.465	0.170	0.360	0.004	13.126
15	San Juan de Chica	26-2-2011	35.143	0.465	0.170	0.360	0.004	13.126
16	San Juan de Chica	4-7-2009	170.143	0.465	0.170	0.360	0.004	13.126
17	San Juan de Chica	9-3-2013	22.386	0.465	0.170	0.360	0.004	13.126
18	San Juan de Chica	19-4-2016	65.643	0.465	0.170	0.360	0.004	13.126
19	San Juan de Chica	23-3-2017	22.386	0.465	0.170	0.360	0.004	13.126
20	San Juan de Chica	29-3-2014	22.386	0.465	0.170	0.360	0.004	13.126
21	San Juan de Chica	19-1-2010	50.129	0.465	0.170	0.360	0.004	13.126
22	Birris 1	25-9-2021	293.529	0.311	0.009	0.674	0.006	13.740
23	Birris 1	14-4-2015	65.643	0.311	0.009	0.674	0.006	13.740
24	Birris 1	29-5-2020	237.157	0.311	0.009	0.674	0.006	13.740
25	Birris 1	20-1-2018	50.129	0.311	0.009	0.674	0.006	13.740
26	Birris 1	15-6-2013	240.329	0.311	0.009	0.674	0.006	13.740
27	Birris 1	15-2-2017	35.143	0.311	0.009	0.674	0.006	13.740
28	Birris 1	8-6-2013	240.329	0.311	0.009	0.674	0.006	13.740
29	Birris 1	10-8-2013	209.086	0.311	0.009	0.674	0.006	13.740
30	Birris 1	12-1-2010	50.129	0.311	0.009	0.674	0.006	13.740
31	Birris 2	28-5-2020	237.157	0.334	0.176	0.485	0.004	13.523
32	Birris 2	12-1-2010	50.129	0.334	0.176	0.485	0.004	13.523
33	Los Quemados	9-5-2016	237.157	0.154	0.429	0.414	0.003	11.404
34	Los Quemados	8-5-2021	237.157	0.154	0.429	0.414	0.003	11.404
35	Los Quemados	7-5-2016	237.157	0.154	0.429	0.414	0.003	11.404
36	Los Quemados	14-3-2020	22.386	0.154	0.429	0.414	0.003	11.404
37	Los Quemados	10-10-2009	318.343	0.154	0.429	0.414	0.003	11.404
38	Los Quemados	27-5-2011	237.157	0.154	0.429	0.414	0.003	11.404
39	Los Quemados	26-7-2010	170.143	0.154	0.429	0.414	0.003	11.404
40	Mata de Cana 2	14-3-2020	22.386	0.090	0.296	0.611	0.002	12.016
41	Mata de Cana 2	8-5-2021	237.157	0.090	0.296	0.611	0.002	12.016
42	Abraham 1	10-9-2013	293.529	0.150	0.197	0.650	0.004	21.628
43	Abraham 1	10-9-2014	293.529	0.150	0.197	0.650	0.004	21.628
44	Abraham 1	17-3-2015	22.386	0.150	0.197	0.650	0.004	21.628
45	Abraham 1	3-9-2015	293.529	0.150	0.197	0.650	0.004	21.628
46	Abraham 1	7-11-2017	188.900	0.150	0.197	0.650	0.004	21.628
47	Higuerones	19-7-2018	170.143	0.446	0.147	0.381	0.026	12.739
48	Higuerones	26-3-2015	22.386	0.446	0.147	0.381	0.026	12.739
49	Higuerones	22-11-2019	188.900	0.446	0.147	0.381	0.026	12.739
50	Higuerones	17-8-2018	209.086	0.446	0.147	0.381	0.026	12.739
51	Higuerones	21-6-2019	240.329	0.446	0.147	0.381	0.026	12.739
52	Higuerones	15-9-2020	293.529	0.446	0.147	0.381	0.026	12.739
53	Higuerones	8-12-2014	98.971	0.446	0.147	0.381	0.026	12.739
54	Higuerones	20-12-2017	98.971	0.446	0.147	0.381	0.026	12.739
55	Higuerones	23-6-2014	240.329	0.446	0.147	0.381	0.026	12.739
56	Higuerones	25-9-2015	293.529	0.446	0.147	0.381	0.026	12.739
57	Higuerones	28-6-2017	240.329	0.446	0.147	0.381	0.026	12.739
58	Higuerones	30-6-2016	240.329	0.446	0.147	0.381	0.026	12.739
59	Manual Granados	14-4-2015	65.643	0.084	0.201	0.712	0.004	19.723
60	Manual Granados	8-6-2013	240.329	0.084	0.201	0.712	0.004	19.723

61	Manual Granados	31-7-2010	170.143	0.084	0.201	0.712	0.004	19.723
62	Manual Granados	12-1-2010	50.129	0.084	0.201	0.712	0.004	19.723
63	Manual Granados	23-9-2021	293.529	0.084	0.201	0.712	0.004	19.723
64	Manual Granados	17-2-2017	35.143	0.084	0.201	0.712	0.004	19.723
65	Manual Granados	6-1-2017	50.129	0.084	0.201	0.712	0.004	19.723
66	Manual Granados	19-1-2018	50.129	0.084	0.201	0.712	0.004	19.723
67	Agua Fria	19-8-2014	209.086	0.422	0.040	0.490	0.047	15.643
68	Agua Fria	23-9-2021	293.529	0.422	0.040	0.490	0.047	15.643
69	Agua Fria	8-6-2013	240.329	0.422	0.040	0.490	0.047	15.643
70	Agua Fria	17-2-2017	35.143	0.422	0.040	0.490	0.047	15.643
71	Agua Fria	19-1-2018	50.129	0.422	0.040	0.490	0.047	15.643
72	Agua Fria	14-4-2015	65.643	0.422	0.040	0.490	0.047	15.643
73	Agua Fria	31-7-2010	170.143	0.422	0.040	0.490	0.047	15.643
74	Agua Fria	12-1-2010	50.129	0.422	0.040	0.490	0.047	15.643
75	Agua Fria	4-7-2019	170.143	0.422	0.040	0.490	0.047	15.643
76	Callejon 1	10-9-2013	293.529	0.433	0.061	0.497	0.010	11.839
77	Callejon 1	10-9-2014	293.529	0.433	0.061	0.497	0.010	11.839
78	Callejon 1	18-12-2014	98.971	0.433	0.061	0.497	0.010	11.839
79	Callejon 1	17-3-2015	22.386	0.433	0.061	0.497	0.010	11.839
80	Callejon 1	3-9-2015	293.529	0.433	0.061	0.497	0.010	11.839
81	Callejon 1	21-6-2017	240.329	0.433	0.061	0.497	0.010	11.839
82	Callejon 1	7-11-2017	188.900	0.433	0.061	0.497	0.010	11.839
83	Carlos Calvo	11-3-2011	22.386	0.049	0.025	0.923	0.003	21.649
84	Carlos Calvo	29-1-2020	50.129	0.049	0.025	0.923	0.003	21.649
85	Carlos Calvo	25-1-2012	50.129	0.049	0.025	0.923	0.003	21.649
86	Carlos Calvo	14-1-2010	50.129	0.049	0.025	0.923	0.003	21.649
87	Carlos Martines	12-1-2010	50.129	0.040	0.223	0.738	0.000	13.757
88	Carlos Martines	15-2-2017	35.143	0.040	0.223	0.738	0.000	13.757
89	Carlos Martines	25-9-2021	293.529	0.040	0.223	0.738	0.000	13.757
90	Carlos Martines	20-1-2018	50.129	0.040	0.223	0.738	0.000	13.757
91	Carlos Martines	14-4-2015	65.643	0.040	0.223	0.738	0.000	13.757
92	Carlos Martines	8-6-2013	240.329	0.040	0.223	0.738	0.000	13.757
93	El Salto	26-3-2015	22.386	0.460	0.173	0.360	0.007	8.205
94	El Salto	31-1-2015	50.129	0.460	0.173	0.360	0.007	8.205
95	El Salto	8-12-2014	98.971	0.460	0.173	0.360	0.007	8.205
96	El Salto	21-6-2019	240.329	0.460	0.173	0.360	0.007	8.205
97	El Salto	23-6-2014	240.329	0.460	0.173	0.360	0.007	8.205
98	El Salto	19-7-2018	170.143	0.460	0.173	0.360	0.007	8.205
99	El Salto	17-8-2018	209.086	0.460	0.173	0.360	0.007	8.205
100	El Salto	2-2-2018	35.143	0.460	0.173	0.360	0.007	8.205
101	El Salto	20-12-2017	98.971	0.460	0.173	0.360	0.007	8.205
102	El Salto	25-9-2015	293.529	0.460	0.173	0.360	0.007	8.205
103	El Salto	18-9-2020	293.529	0.460	0.173	0.360	0.007	8.205
104	El Salto	4-2-2021	35.143	0.460	0.173	0.360	0.007	8.205
105	El Salto	28-6-2017	240.329	0.460	0.173	0.360	0.007	8.205
106	El Salto	16-11-2012	188.900	0.460	0.173	0.360	0.007	8.205
107	El Salto	24-3-2010	22.386	0.460	0.173	0.360	0.007	8.205
108	El Salto	30-6-2016	240.329	0.460	0.173	0.360	0.007	8.205
109	El Salto	5-7-2016	170.143	0.460	0.173	0.360	0.007	8.205
110	El Salto	4-6-2012	240.329	0.460	0.173	0.360	0.007	8.205
111	Franco Fernández	15-3-2013	22.386	0.163	0.037	0.793	0.007	17.238
112	Franco Fernández	26-3-2015	22.386	0.163	0.037	0.793	0.007	17.238
113	Franco Fernández	8-12-2014	98.971	0.163	0.037	0.793	0.007	17.238
114	Franco Fernández	16-11-2012	188.900	0.163	0.037	0.793	0.007	17.238
115	Franco Fernández	17-8-2018	209.086	0.163	0.037	0.793	0.007	17.238
116	Franco Fernández	25-3-2010	22.386	0.163	0.037	0.793	0.007	17.238
117	Franco Fernández	21-6-2019	240.329	0.163	0.037	0.793	0.007	17.238
118	Franco Fernández	25-9-2015	293.529	0.163	0.037	0.793	0.007	17.238
119	Franco Fernández	30-9-2013	293.529	0.163	0.037	0.793	0.007	17.238
120	Franco Fernández	4-6-2012	240.329	0.163	0.037	0.793	0.007	17.238
121	Mainor	10-9-2013	293.529	0.414	0.147	0.422	0.017	19.702
122	Mainor	10-9-2014	293.529	0.414	0.147	0.422	0.017	19.702
123	Mainor	18-12-2014	98.971	0.414	0.147	0.422	0.017	19.702
124	Mainor	17-3-2015	22.386	0.414	0.147	0.422	0.017	19.702
125	Mainor	3-9-2015	293.529	0.414	0.147	0.422	0.017	19.702

126	Mainor	21-6-2017	240.329	0.414	0.147	0.422	0.017	19.702
127	Mainor	7-11-2017	188.900	0.414	0.147	0.422	0.017	19.702
128	Miguel Brenes	15-6-2013	240.329	0.154	0.355	0.490	0.001	9.390
129	Miguel Brenes	12-1-2010	50.129	0.154	0.355	0.490	0.001	9.390
130	Nore Gómez	21-6-2017	240.329	0.276	0.058	0.649	0.017	15.352
131	Nore Gómez	20-6-2018	240.329	0.276	0.058	0.649	0.017	15.352
132	Nore Gómez	10-9-2013	293.529	0.276	0.058	0.649	0.017	15.352
133	Nore Gómez	10-9-2014	293.529	0.276	0.058	0.649	0.017	15.352
134	Nore Gómez	18-12-2014	98.971	0.276	0.058	0.649	0.017	15.352
135	Nore Gómez	17-3-2015	22.386	0.276	0.058	0.649	0.017	15.352
136	Nore Gómez	3-9-2015	293.529	0.276	0.058	0.649	0.017	15.352
137	Regina	26-3-2015	22.386	0.616	0.059	0.311	0.014	12.705
138	Regina	15-3-2013	22.386	0.616	0.059	0.311	0.014	12.705
139	Regina	25-3-2011	22.386	0.616	0.059	0.311	0.014	12.705
140	Regina	21-6-2019	240.329	0.616	0.059	0.311	0.014	12.705
141	Regina	13-12-2011	98.971	0.616	0.059	0.311	0.014	12.705
142	Regina	11-9-2020	293.529	0.616	0.059	0.311	0.014	12.705
143	Regina	22-11-2019	188.900	0.616	0.059	0.311	0.014	12.705
144	Regina	16-11-2012	188.900	0.616	0.059	0.311	0.014	12.705
145	Regina	25-3-2010	22.386	0.616	0.059	0.311	0.014	12.705
146	Regina	20-12-2017	98.971	0.616	0.059	0.311	0.014	12.705
147	Regina	28-6-2017	240.329	0.616	0.059	0.311	0.014	12.705
148	Regina	17-8-2018	209.086	0.616	0.059	0.311	0.014	12.705
149	Regina	18-7-2018	170.143	0.616	0.059	0.311	0.014	12.705
150	Regina	30-6-2016	240.329	0.616	0.059	0.311	0.014	12.705
151	Regina	25-9-2015	293.529	0.616	0.059	0.311	0.014	12.705
152	Retes	5-6-2020	240.329	0.280	0.312	0.407	0.001	16.679
153	Rodillal	5-8-2010	209.086	0.522	0.157	0.311	0.011	18.890
154	Rodillal	3-10-2009	318.343	0.522	0.157	0.311	0.011	18.890
155	Pacayon	8-11-2017	188.900	0.058	0.248	0.689	0.005	21.205
156	Pacayon	22-6-2017	240.329	0.058	0.248	0.689	0.005	21.205
157	Pacayon	7-9-2015	293.529	0.058	0.248	0.689	0.005	21.205
158	Pacayon	19-12-2014	98.971	0.058	0.248	0.689	0.005	21.205
159	Pacayon	17-3-2015	22.386	0.058	0.248	0.689	0.005	21.205
160	Pacayon	11-9-2013	293.529	0.058	0.248	0.689	0.005	21.205
161	Vicente Serrano	11-9-2013	293.529	0.423	0.068	0.488	0.021	14.122
162	Vicente Serrano	10-9-2014	293.529	0.423	0.068	0.488	0.021	14.122
163	Vicente Serrano	18-12-2014	98.971	0.423	0.068	0.488	0.021	14.122
164	Vicente Serrano	17-3-2015	22.386	0.423	0.068	0.488	0.021	14.122
165	Vicente Serrano	3-9-2015	293.529	0.423	0.068	0.488	0.021	14.122
166	Vicente Serrano	8-11-2017	188.900	0.423	0.068	0.488	0.021	14.122
167	La Isla	10-9-2014	293.529	0.478	0.106	0.410	0.006	15.467
168	La Isla	11-6-2019	240.329	0.478	0.106	0.410	0.006	15.467
169	La Isla	5-11-2019	188.900	0.478	0.106	0.410	0.006	15.467
170	La Isla	16-2-2011	35.143	0.478	0.106	0.410	0.006	15.467
171	La Isla	21-11-2018	188.900	0.478	0.106	0.410	0.006	15.467
172	La Isla	21-6-2017	240.329	0.478	0.106	0.410	0.006	15.467
173	La Isla	10-9-2013	293.529	0.478	0.106	0.410	0.006	15.467
174	La Isla	17-3-2015	22.386	0.478	0.106	0.410	0.006	15.467

No	Spring name	Measurement date	Max slope	Min slope	STD slope	Bufferzone respected	Nitrate (mg/l)	Modeled
1	Pozo Amarillo	17-12-2014	48.363	0.007	6.815	0	13.470	-6.796
2	Pozo Amarillo	7-5-2016	48.363	0.007	6.815	0	8.470	-6.796
3	Pozo Amarillo	24-7-2010	48.363	0.007	6.815	0	8.260	-6.796
4	Pozo Amarillo	10-10-2009	48.363	0.007	6.815	0	7.910	-5.517
5	Pozo Amarillo	22-6-2017	48.363	0.007	6.815	0	6.490	-3.481
6	Pozo Amarillo	27-5-2011	48.363	0.007	6.815	0	5.000	2.384
7	San Juan de Chica	7-3-2015	26.218	1.011	4.801	0	29.690	4.709
8	San Juan de Chica	26-2-2011	26.218	1.011	4.801	0	28.210	4.732
9	San Juan de Chica	4-7-2009	26.218	1.011	4.801	0	28.000	5.382
10	San Juan de Chica	9-3-2013	26.218	1.011	4.801	0	26.970	5.382
11	San Juan de Chica	19-4-2016	26.218	1.011	4.801	0	26.200	5.421
12	San Juan de Chica	19-1-2010	26.218	1.011	4.801	0	23.490	5.764

13	San Juan de Chica	23-3-2017	26.218	1.011	4.801	0	23.140	7.518
14	San Juan de Chica	7-3-2015	26.218	1.011	4.801	0	31.950	7.707
15	San Juan de Chica	26-2-2011	26.218	1.011	4.801	0	27.730	7.707
16	San Juan de Chica	4-7-2009	26.218	1.011	4.801	0	26.460	7.891
17	San Juan de Chica	9-3-2013	26.218	1.011	4.801	0	24.800	8.094
18	San Juan de Chica	19-4-2016	26.218	1.011	4.801	0	24.750	8.094
19	San Juan de Chica	23-3-2017	26.218	1.011	4.801	0	24.550	8.745
20	San Juan de Chica	29-3-2014	26.218	1.011	4.801	0	23.040	9.254
21	San Juan de Chica	19-1-2010	26.218	1.011	4.801	0	22.110	9.254
22	Birris 1	25-9-2021	31.365	0.009	4.954	0	11.810	9.254
23	Birris 1	14-4-2015	31.365	0.009	4.954	0	10.650	9.373
24	Birris 1	29-5-2020	31.365	0.009	4.954	0	9.360	9.904
25	Birris 1	20-1-2018	31.365	0.009	4.954	0	9.050	10.473
26	Birris 1	15-6-2013	31.365	0.009	4.954	0	8.640	10.533
27	Birris 1	15-2-2017	31.365	0.009	4.954	0	8.030	11.409
28	Birris 1	8-6-2013	31.365	0.009	4.954	0	7.890	11.633
29	Birris 1	10-8-2013	31.365	0.009	4.954	0	7.110	12.569
30	Birris 1	12-1-2010	31.365	0.009	4.954	0	6.920	13.007
31	Birris 2	28-5-2020	35.966	0.000	5.809	0.5	9.560	13.961
32	Birris 2	12-1-2010	35.966	0.000	5.809	0.5	7.170	14.000
33	Los Quemados	9-5-2016	28.406	0.000	5.502	0.5	22.290	14.000
34	Los Quemados	8-5-2021	28.406	0.000	5.502	0.5	20.870	14.819
35	Los Quemados	7-5-2016	28.406	0.000	5.502	0.5	20.450	15.189
36	Los Quemados	14-3-2020	28.406	0.000	5.502	0.5	19.800	15.689
37	Los Quemados	10-10-2009	28.406	0.000	5.502	0.5	19.270	16.065
38	Los Quemados	27-5-2011	28.406	0.000	5.502	0.5	15.450	16.160
39	Los Quemados	26-7-2010	28.406	0.000	5.502	0.5	12.290	16.160
40	Mata de Cana 2	14-3-2020	49.876	0.000	7.099	0.5	16.860	16.160
41	Mata de Cana 2	8-5-2021	49.876	0.000	7.099	0.5	14.590	16.499
42	Abraham 1	10-9-2013	49.387	0.000	8.315	0.5	3.420	16.923
43	Abraham 1	10-9-2014	49.387	0.000	8.315	0.5	12.620	17.574
44	Abraham 1	17-3-2015	49.387	0.000	8.315	0.5	3.690	17.814
45	Abraham 1	3-9-2015	49.387	0.000	8.315	0.5	2.180	18.351
46	Abraham 1	7-11-2017	49.387	0.000	8.315	0.5	4.430	18.704
47	Higuerones	19-7-2018	49.876	0.000	7.205	0.5	37.060	19.697
48	Higuerones	26-3-2015	49.876	0.000	7.205	0.5	31.180	19.697
49	Higuerones	22-11-2019	49.876	0.000	7.205	0.5	30.990	19.697
50	Higuerones	17-8-2018	49.876	0.000	7.205	0.5	27.580	19.697
51	Higuerones	21-6-2019	49.876	0.000	7.205	0.5	27.190	19.709
52	Higuerones	15-9-2020	49.876	0.000	7.205	0.5	27.030	19.899
53	Higuerones	8-12-2014	49.876	0.000	7.205	0.5	26.680	19.899
54	Higuerones	20-12-2017	49.876	0.000	7.205	0.5	25.280	20.038
55	Higuerones	23-6-2014	49.876	0.000	7.205	0.5	25.260	20.038
56	Higuerones	25-9-2015	49.876	0.000	7.205	0.5	23.440	20.082
57	Higuerones	28-6-2017	49.876	0.000	7.205	0.5	23.140	20.516
58	Higuerones	30-6-2016	49.876	0.000	7.205	0.5	13.980	20.689
59	Manual Granados	14-4-2015	57.428	0.000	8.600	1	55.400	20.689
60	Manual Granados	8-6-2013	57.428	0.000	8.600	1	52.270	20.689
61	Manual Granados	31-7-2010	57.428	0.000	8.600	1	36.490	20.689
62	Manual Granados	12-1-2010	57.428	0.000	8.600	1	34.310	21.070
63	Manual Granados	23-9-2021	57.428	0.000	8.600	1	33.710	21.317
64	Manual Granados	17-2-2017	57.428	0.000	8.600	1	33.300	21.547
65	Manual Granados	6-1-2017	57.428	0.000	8.600	1	29.920	22.322
66	Manual Granados	19-1-2018	57.428	0.000	8.600	1	31.760	22.390
67	Agua Fria	19-8-2014	42.701	0.006	8.189	1	32.620	22.390
68	Agua Fria	23-9-2021	42.701	0.006	8.189	1	36.130	22.417
69	Agua Fria	8-6-2013	42.701	0.006	8.189	1	35.000	22.417
70	Agua Fria	17-2-2017	42.701	0.006	8.189	1	31.310	23.353
71	Agua Fria	19-1-2018	42.701	0.006	8.189	1	9.540	23.667
72	Agua Fria	14-4-2015	42.701	0.006	8.189	1	41.570	23.667
73	Agua Fria	31-7-2010	42.701	0.006	8.189	1	27.680	23.857
74	Agua Fria	12-1-2010	42.701	0.006	8.189	1	24.580	23.857
75	Agua Fria	4-7-2019	42.701	0.006	8.189	1	2.340	24.040
76	Callejon 1	10-9-2013	31.365	0.008	5.080	0	2.970	24.040
77	Callejon 1	10-9-2014	31.365	0.008	5.080	0	5.090	24.196

78	Callejon 1	18-12-2014	31.365	0.008	5.080	0	8.290	24.196
79	Callejon 1	17-3-2015	31.365	0.008	5.080	0	5.960	24.196
80	Callejon 1	3-9-2015	31.365	0.008	5.080	0	3.780	24.196
81	Callejon 1	21-6-2017	31.365	0.008	5.080	0	3.620	24.196
82	Callejon 1	7-11-2017	31.365	0.008	5.080	0	4.440	24.196
83	Carlos Calvo	11-3-2011	40.377	4.045	6.745	0.5	10.210	24.196
84	Carlos Calvo	29-1-2020	40.377	4.045	6.745	0.5	9.530	24.342
85	Carlos Calvo	25-1-2012	40.377	4.045	6.745	0.5	9.100	24.342
86	Carlos Calvo	14-1-2010	40.377	4.045	6.745	0.5	8.000	24.342
87	Carlos Martines	12-1-2010	49.876	0.000	7.305	0.5	17.390	24.992
88	Carlos Martines	15-2-2017	49.876	0.000	7.305	0.5	22.410	24.992
89	Carlos Martines	25-9-2021	49.876	0.000	7.305	0.5	19.350	25.634
90	Carlos Martines	20-1-2018	49.876	0.000	7.305	0.5	18.790	25.637
91	Carlos Martines	14-4-2015	49.876	0.000	7.305	0.5	1.900	25.637
92	Carlos Martines	8-6-2013	49.876	0.000	7.305	0.5	28.400	26.284
93	El Salto	26-3-2015	16.835	2.022	2.861	1	45.670	26.288
94	El Salto	31-1-2015	16.835	2.022	2.861	1	42.230	26.288
95	El Salto	8-12-2014	16.835	2.022	2.861	1	39.030	26.346
96	El Salto	21-6-2019	16.835	2.022	2.861	1	38.960	26.346
97	El Salto	23-6-2014	16.835	2.022	2.861	1	35.250	26.346
98	El Salto	19-7-2018	16.835	2.022	2.861	1	34.580	26.375
99	El Salto	17-8-2018	16.835	2.022	2.861	1	33.330	26.666
100	El Salto	2-2-2018	16.835	2.022	2.861	1	33.010	26.719
101	El Salto	20-12-2017	16.835	2.022	2.861	1	32.830	26.719
102	El Salto	25-9-2015	16.835	2.022	2.861	1	32.390	26.720
103	El Salto	18-9-2020	16.835	2.022	2.861	1	31.720	26.916
104	El Salto	4-2-2021	16.835	2.022	2.861	1	31.600	26.916
105	El Salto	28-6-2017	16.835	2.022	2.861	1	31.410	26.996
106	El Salto	16-11-2012	16.835	2.022	2.861	1	30.370	27.143
107	El Salto	24-3-2010	16.835	2.022	2.861	1	26.700	27.143
108	El Salto	30-6-2016	16.835	2.022	2.861	1	19.620	27.369
109	El Salto	5-7-2016	16.835	2.022	2.861	1	14.520	27.369
110	El Salto	4-6-2012	16.835	2.022	2.861	1	9.480	27.369
111	Franco Fernández	15-3-2013	48.805	0.004	8.014	1	56.800	27.625
112	Franco Fernández	26-3-2015	48.805	0.004	8.014	1	55.580	27.656
113	Franco Fernández	8-12-2014	48.805	0.004	8.014	1	52.480	27.751
114	Franco Fernández	16-11-2012	48.805	0.004	8.014	1	50.020	27.998
115	Franco Fernández	17-8-2018	48.805	0.004	8.014	1	46.550	27.998
116	Franco Fernández	25-3-2010	48.805	0.004	8.014	1	42.600	28.227
117	Franco Fernández	21-6-2019	48.805	0.004	8.014	1	39.840	28.420
118	Franco Fernández	25-9-2015	48.805	0.004	8.014	1	38.720	28.610
119	Franco Fernández	30-9-2013	48.805	0.004	8.014	1	33.940	28.610
120	Franco Fernández	4-6-2012	48.805	0.004	8.014	1	27.500	28.725
121	Mainor	10-9-2013	43.332	0.002	7.237	1	22.310	28.793
122	Mainor	10-9-2014	43.332	0.002	7.237	1	29.710	28.796
123	Mainor	18-12-2014	43.332	0.002	7.237	1	26.230	28.874
124	Mainor	17-3-2015	43.332	0.002	7.237	1	24.300	28.874
125	Mainor	3-9-2015	43.332	0.002	7.237	1	21.320	28.874
126	Mainor	21-6-2017	43.332	0.002	7.237	1	25.530	28.952
127	Mainor	7-11-2017	43.332	0.002	7.237	1	23.580	29.097
128	Miguel Brenes	15-6-2013	29.687	0.003	4.319	0	12.600	29.097
129	Miguel Brenes	12-1-2010	29.687	0.003	4.319	0	11.140	29.661
130	Nore Gómez	21-6-2017	44.312	0.000	7.576	0.5	20.940	30.033
131	Nore Gómez	20-6-2018	44.312	0.000	7.576	0.5	23.670	30.033
132	Nore Gómez	10-9-2013	44.312	0.000	7.576	0.5	16.900	30.033
133	Nore Gómez	10-9-2014	44.312	0.000	7.576	0.5	24.260	30.033
134	Nore Gómez	18-12-2014	44.312	0.000	7.576	0.5	22.830	30.088
135	Nore Gómez	17-3-2015	44.312	0.000	7.576	0.5	25.960	30.088
136	Nore Gómez	3-9-2015	44.312	0.000	7.576	0.5	19.000	30.153
137	Regina	26-3-2015	41.987	0.000	7.551	0.5	40.030	30.739
138	Regina	15-3-2013	41.987	0.000	7.551	0.5	36.720	30.739
139	Regina	25-3-2011	41.987	0.000	7.551	0.5	34.040	30.739
140	Regina	21-6-2019	41.987	0.000	7.551	0.5	31.590	30.739
141	Regina	13-12-2011	41.987	0.000	7.551	0.5	30.100	30.739
142	Regina	11-9-2020	41.987	0.000	7.551	0.5	29.940	31.121

143	Regina	22-11-2019	41.987	0.000	7.551	0.5	29.540	31.252
144	Regina	16-11-2012	41.987	0.000	7.551	0.5	28.730	31.367
145	Regina	25-3-2010	41.987	0.000	7.551	0.5	27.670	31.597
146	Regina	20-12-2017	41.987	0.000	7.551	0.5	27.210	31.597
147	Regina	28-6-2017	41.987	0.000	7.551	0.5	26.510	32.189
148	Regina	17-8-2018	41.987	0.000	7.551	0.5	25.290	32.467
149	Regina	18-7-2018	41.987	0.000	7.551	0.5	23.630	32.467
150	Regina	30-6-2016	41.987	0.000	7.551	0.5	20.690	33.064
151	Regina	25-9-2015	41.987	0.000	7.551	0.5	20.130	33.247
152	Retes	5-6-2020	36.931	0.003	7.158	0.5	45.410	33.247
153	Rodillal	5-8-2010	39.144	7.125	5.453	1	51.750	33.403
154	Rodillal	3-10-2009	39.144	7.125	5.453	1	68.060	33.403
155	Pacayon	8-11-2017	57.428	0.000	9.293	0.5	3.790	35.261
156	Pacayon	22-6-2017	57.428	0.000	9.293	0.5	2.800	35.911
157	Pacayon	7-9-2015	57.428	0.000	9.293	0.5	2.810	36.769
158	Pacayon	19-12-2014	57.428	0.000	9.293	0.5	3.400	38.047
159	Pacayon	17-3-2015	57.428	0.000	9.293	0.5	3.900	38.236
160	Pacayon	11-9-2013	57.428	0.000	9.293	0.5	2.320	38.236
161	Vicente Serrano	11-9-2013	41.993	0.000	7.321	1	19.000	38.236
162	Vicente Serrano	10-9-2014	41.993	0.000	7.321	1	28.760	38.420
163	Vicente Serrano	18-12-2014	41.993	0.000	7.321	1	27.760	39.441
164	Vicente Serrano	17-3-2015	41.993	0.000	7.321	1	30.560	39.441
165	Vicente Serrano	3-9-2015	41.993	0.000	7.321	1	21.770	40.091
166	Vicente Serrano	8-11-2017	41.993	0.000	7.321	1	20.630	40.091
167	La Isla	10-9-2014	55.471	0.002	5.642	0	28.660	40.473
168	La Isla	11-6-2019	55.471	0.002	5.642	0	28.010	40.720
169	La Isla	5-11-2019	55.471	0.002	5.642	0	26.830	41.819
170	La Isla	16-2-2011	55.471	0.002	5.642	0	25.750	42.755
171	La Isla	21-11-2018	55.471	0.002	5.642	0	25.280	42.755
172	La Isla	21-6-2017	55.471	0.002	5.642	0	22.890	42.755
173	La Isla	10-9-2013	55.471	0.002	5.642	0	20.420	52.478
174	La Isla	17-3-2015	55.471	0.002	5.642	0	29.070	53.814

A.5.2 Correlation Matrix

The correlation matrix is given in 39. The labels on the x- and y-axis are the following:

1. Precipitation (mm)
2. Square root of the precipitation (mm)
3. Square of the precipitation (mm)
4. Portion of crops (-)
5. Square root of the portion of crops (-)
6. Square of the portion of crops (-)
7. Portion of woods (-)
8. Square root of the portion of woods (-)
9. Square of the portion of woods (-)
10. Portion of pastures (-)
11. Square root of the portion of pastures (-)
12. Square of the portion of pastures (-)
13. Portion of buildings (-)
14. Square root of the portion of buildings (-)
15. Square of the portion of buildings (-)
16. Mean slope (-)
17. Square root of the mean slope (-)
18. Square of the mean slope (-)
19. Maximum slope (-)
20. Square root of the maximum slope (-)
21. Square of the maximum slope (-)
22. Minimum slope (-)

23. Square root of the minimum slope (-)
24. Square of the minimum slope (-)
25. STD slope (-)
26. Square root of the STD slope (-)
27. Square of the STD slope (-)
28. Bufferzone respected (-)
29. Square root of the bufferzone respected (-)
30. Square of the bufferzone respected (-)
31. Measured nitrate concentration (mg/l)
32. Modeled nitrate concentration (mg/l)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1,00															
2	0,99	1,00														
3	0,98	0,94	1,00													
4	0,04	0,04	0,02	1,00												
5	0,06	0,06	0,04	0,99	1,00											
6	0,01	0,02	-0,01	0,97	0,93	1,00										
7	0,07	0,07	0,06	-0,27	-0,28	-0,25	1,00									
8	0,05	0,05	0,05	-0,21	-0,22	-0,18	0,97	1,00								
9	0,09	0,10	0,08	-0,30	-0,29	-0,28	0,95	0,85	1,00							
10	-0,08	-0,09	-0,06	-0,84	-0,82	-0,82	-0,30	-0,35	-0,24	1,00						
11	-0,08	-0,08	-0,05	-0,82	-0,80	-0,81	-0,32	-0,36	-0,27	0,99	1,00					
12	-0,09	-0,10	-0,07	-0,83	-0,83	-0,80	-0,27	-0,33	-0,21	0,98	0,95	1,00				
13	0,08	0,09	0,06	0,36	0,39	0,30	-0,42	-0,40	-0,38	-0,17	-0,13	-0,22	1,00			
14	0,12	0,13	0,10	0,48	0,51	0,41	-0,50	-0,47	-0,45	-0,23	-0,19	-0,28	0,96	1,00		
15	0,02	0,03	0,00	0,21	0,23	0,16	-0,31	-0,31	-0,25	-0,08	-0,05	-0,13	0,95	0,83	1,00	
16	0,02	0,01	0,05	-0,51	-0,52	-0,47	-0,12	-0,12	-0,13	0,56	0,53	0,59	0,01	-0,01	0,04	1,00
17	0,02	0,01	0,05	-0,49	-0,50	-0,45	-0,13	-0,14	-0,13	0,55	0,52	0,58	0,03	0,01	0,06	1,00
18	0,02	0,01	0,05	-0,54	-0,55	-0,49	-0,08	-0,07	-0,11	0,57	0,54	0,60	-0,04	-0,05	0,00	0,99
19	0,12	0,12	0,12	-0,35	-0,38	-0,27	-0,06	-0,04	-0,07	0,36	0,33	0,38	0,16	0,12	0,14	0,72
20	0,12	0,12	0,12	-0,33	-0,37	-0,26	-0,08	-0,07	-0,08	0,36	0,33	0,38	0,18	0,14	0,16	0,72
21	0,12	0,11	0,12	-0,37	-0,41	-0,29	-0,01	0,02	-0,05	0,36	0,33	0,38	0,10	0,07	0,09	0,69
22	-0,11	-0,11	-0,10	0,10	0,07	0,11	-0,02	0,02	-0,09	-0,07	-0,09	-0,02	-0,18	-0,16	-0,16	-0,10
23	-0,19	-0,19	-0,18	0,17	0,15	0,16	0,00	0,05	-0,09	-0,15	-0,16	-0,10	-0,23	-0,20	-0,19	-0,25
24	0,01	0,00	0,02	0,04	0,02	0,07	-0,04	-0,02	-0,07	-0,01	-0,03	0,03	-0,08	-0,06	-0,09	0,12
25	0,08	0,08	0,09	-0,36	-0,39	-0,28	-0,12	-0,13	-0,09	0,41	0,38	0,42	0,33	0,28	0,31	0,75
26	0,08	0,08	0,09	-0,35	-0,38	-0,27	-0,13	-0,14	-0,08	0,39	0,37	0,41	0,32	0,27	0,30	0,75
27	0,08	0,08	0,09	-0,39	-0,42	-0,30	-0,11	-0,11	-0,10	0,43	0,40	0,44	0,32	0,27	0,32	0,74
28	0,08	0,08	0,07	-0,15	-0,15	-0,15	-0,11	-0,05	-0,16	0,19	0,21	0,17	0,34	0,33	0,32	0,12
29	0,09	0,10	0,08	-0,21	-0,22	-0,17	-0,06	-0,01	-0,11	0,22	0,24	0,20	0,33	0,32	0,30	0,15
30	0,05	0,05	0,04	-0,08	-0,06	-0,11	-0,15	-0,09	-0,20	0,15	0,16	0,12	0,32	0,31	0,31	0,08
31	-0,12	-0,12	-0,11	0,18	0,18	0,18	-0,17	-0,10	-0,22	-0,08	-0,07	-0,08	0,15	0,18	0,10	-0,07
32	0,15	0,14	0,15	0,01	-0,02	0,06	-0,35	-0,27	-0,38	0,19	0,23	0,13	0,17	0,22	0,06	0,14

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
17	1,00															
18	0,97	1,00														
19	0,74	0,66	1,00													
20	0,75	0,66	1,00	1,00												
21	0,71	0,65	0,99	0,97	1,00											
22	-0,14	-0,02	-0,45	-0,47	-0,42	1,00										
23	-0,30	-0,17	-0,64	-0,66	-0,59	0,94	1,00									
24	0,09	0,15	-0,16	-0,16	-0,16	0,89	0,70	1,00								
25	0,77	0,69	0,87	0,89	0,83	-0,48	-0,65	-0,20	1,00							
26	0,77	0,68	0,88	0,90	0,82	-0,49	-0,67	-0,20	1,00	1,00						
27	0,76	0,70	0,85	0,86	0,82	-0,45	-0,61	-0,20	0,99	0,97	1,00					
28	0,08	0,18	0,04	0,01	0,08	0,19	0,13	0,17	0,21	0,15	0,29	1,00				
29	0,11	0,20	0,12	0,09	0,15	0,15	0,06	0,15	0,31	0,26	0,39	0,97	1,00			
30	0,04	0,13	-0,06	-0,09	-0,01	0,23	0,20	0,18	0,07	0,02	0,16	0,96	0,85	1,00		
31	-0,07	-0,08	-0,01	-0,03	0,02	0,24	0,22	0,25	0,00	-0,02	0,02	0,51	0,45	0,55	1,00	
32	0,12	0,16	0,28	0,26	0,31	0,01	-0,11	0,09	0,20	0,18	0,24	0,40	0,42	0,34	0,23	1,00

Figure 39: Correlation matrix for all parameters

A.5.3 Model vs Measurements

The results of the modeled nitrate concentrations versus the measured nitrate concentrations in the springs are the following:

No	Spring name	Measurement date	Modeled nitrate concentration (mg/l)	Measured nitrate concentration (mg/l)	Error (mg/l)
1	Pozo Amarillo	17-12-2014	-6,80	13,47	-20,27
2	Pozo Amarillo	7-5-2016	-6,80	8,47	-15,27
3	Pozo Amarillo	24-7-2010	-6,80	8,26	-15,06
4	Pozo Amarillo	10-10-2009	-5,52	7,91	-13,43
5	Pozo Amarillo	22-6-2017	-3,48	6,49	-9,97
6	Pozo Amarillo	27-5-2011	2,38	5,00	-2,62
7	San Juan de Chica	7-3-2015	4,71	29,69	-24,98
8	San Juan de Chica	26-2-2011	4,73	28,21	-23,48
9	San Juan de Chica	4-7-2009	5,38	28,00	-22,62
10	San Juan de Chica	9-3-2013	5,38	26,97	-21,59
11	San Juan de Chica	19-4-2016	5,42	26,20	-20,78
12	San Juan de Chica	19-1-2010	5,76	23,49	-17,73
13	San Juan de Chica	23-3-2017	7,52	23,14	-15,62
14	San Juan de Chica	7-3-2015	7,71	31,95	-24,24
15	San Juan de Chica	26-2-2011	7,71	27,73	-20,02
16	San Juan de Chica	4-7-2009	7,89	26,46	-18,57
17	San Juan de Chica	9-3-2013	8,09	24,80	-16,71
18	San Juan de Chica	19-4-2016	8,09	24,75	-16,66
19	San Juan de Chica	23-3-2017	8,74	24,55	-15,81
20	San Juan de Chica	29-3-2014	9,25	23,04	-13,79
21	San Juan de Chica	19-1-2010	9,25	22,11	-12,86
22	Birris 1	25-9-2021	9,25	11,81	-2,56
23	Birris 1	14-4-2015	9,37	10,65	-1,28
24	Birris 1	29-5-2020	9,90	9,36	0,54
25	Birris 1	20-1-2018	10,47	9,05	1,42
26	Birris 1	15-6-2013	10,53	8,64	1,89
27	Birris 1	15-2-2017	11,41	8,03	3,38
28	Birris 1	8-6-2013	11,63	7,89	3,74
29	Birris 1	10-8-2013	12,57	7,11	5,46
30	Birris 1	12-1-2010	13,01	6,92	6,09
31	Birris 2	28-5-2020	13,96	9,56	4,40
32	Birris 2	12-1-2010	14,00	7,17	6,83
33	Los Quemados	9-5-2016	14,00	22,29	-8,29
34	Los Quemados	8-5-2021	14,82	20,87	-6,05
35	Los Quemados	7-5-2016	15,19	20,45	-5,26
36	Los Quemados	14-3-2020	15,69	19,80	-4,11
37	Los Quemados	10-10-2009	16,06	19,27	-3,21
38	Los Quemados	27-5-2011	16,16	15,45	0,71
39	Los Quemados	26-7-2010	16,16	12,29	3,87
40	Mata de Cana 2	14-3-2020	16,16	16,86	-0,70
41	Mata de Cana 2	8-5-2021	16,50	14,59	1,91
42	Abraham 1	10-9-2013	16,92	3,42	13,50
43	Abraham 1	10-9-2014	17,57	12,62	4,95
44	Abraham 1	17-3-2015	17,81	3,69	14,12
45	Abraham 1	3-9-2015	18,35	2,18	16,17
46	Abraham 1	7-11-2017	18,70	4,43	14,27
47	Higuerones	19-7-2018	19,70	37,06	-17,36
48	Higuerones	26-3-2015	19,70	31,18	-11,48
49	Higuerones	22-11-2019	19,70	30,99	-11,29
50	Higuerones	17-8-2018	19,70	27,58	-7,88
51	Higuerones	21-6-2019	19,71	27,19	-7,48
52	Higuerones	15-9-2020	19,90	27,03	-7,13
53	Higuerones	8-12-2014	19,90	26,68	-6,78
54	Higuerones	20-12-2017	20,04	25,28	-5,24
55	Higuerones	23-6-2014	20,04	25,26	-5,22
56	Higuerones	25-9-2015	20,08	23,44	-3,36
57	Higuerones	28-6-2017	20,52	23,14	-2,62
58	Higuerones	30-6-2016	20,69	13,98	6,71
59	Manual Granados	14-4-2015	20,69	55,40	-34,71

60	Manual Granados	8-6-2013	20,69	52,27	-31,58
61	Manual Granados	31-7-2010	20,69	36,49	-15,80
62	Manual Granados	12-1-2010	21,07	34,31	-13,24
63	Manual Granados	23-9-2021	21,32	33,71	-12,39
64	Manual Granados	17-2-2017	21,55	33,30	-11,75
65	Manual Granados	6-1-2017	22,32	29,92	-7,60
66	Manual Granados	19-1-2018	22,39	31,76	-9,37
67	Agua Fria	19-8-2014	22,39	32,62	-10,23
68	Agua Fria	23-9-2021	22,42	36,13	-13,71
69	Agua Fria	8-6-2013	22,42	35,00	-12,58
70	Agua Fria	17-2-2017	23,35	31,31	-7,96
71	Agua Fria	19-1-2018	23,67	9,54	14,13
72	Agua Fria	14-4-2015	23,67	41,57	-17,90
73	Agua Fria	31-7-2010	23,86	27,68	-3,82
74	Agua Fria	12-1-2010	23,86	24,58	-0,72
75	Agua Fria	4-7-2019	24,04	2,34	21,70
76	Callejon 1	10-9-2013	24,04	2,97	21,07
77	Callejon 1	10-9-2014	24,20	5,09	19,11
78	Callejon 1	18-12-2014	24,20	8,29	15,91
79	Callejon 1	17-3-2015	24,20	5,96	18,24
80	Callejon 1	3-9-2015	24,20	3,78	20,42
81	Callejon 1	21-6-2017	24,20	3,62	20,58
82	Callejon 1	7-11-2017	24,20	4,44	19,76
83	Carlos Calvo	11-3-2011	24,20	10,21	13,99
84	Carlos Calvo	29-1-2020	24,34	9,53	14,81
85	Carlos Calvo	25-1-2012	24,34	9,10	15,24
86	Carlos Calvo	14-1-2010	24,34	8,00	16,34
87	Carlos Martines	12-1-2010	24,99	17,39	7,60
88	Carlos Martines	15-2-2017	24,99	22,41	2,58
89	Carlos Martines	25-9-2021	25,63	19,35	6,28
90	Carlos Martines	20-1-2018	25,64	18,79	6,85
91	Carlos Martines	14-4-2015	25,64	1,90	23,74
92	Carlos Martines	8-6-2013	26,28	28,40	-2,12
93	El Salto	26-3-2015	26,29	45,67	-19,38
94	El Salto	31-1-2015	26,29	42,23	-15,94
95	El Salto	8-12-2014	26,35	39,03	-12,68
96	El Salto	21-6-2019	26,35	38,96	-12,61
97	El Salto	23-6-2014	26,35	35,25	-8,90
98	El Salto	19-7-2018	26,38	34,58	-8,20
99	El Salto	17-8-2018	26,67	33,33	-6,66
100	El Salto	2-2-2018	26,72	33,01	-6,29
101	El Salto	20-12-2017	26,72	32,83	-6,11
102	El Salto	25-9-2015	26,72	32,39	-5,67
103	El Salto	18-9-2020	26,92	31,72	-4,80
104	El Salto	4-2-2021	26,92	31,60	-4,68
105	El Salto	28-6-2017	27,00	31,41	-4,41
106	El Salto	16-11-2012	27,14	30,37	-3,23
107	El Salto	24-3-2010	27,14	26,70	0,44
108	El Salto	30-6-2016	27,37	19,62	7,75
109	El Salto	5-7-2016	27,37	14,52	12,85
110	El Salto	4-6-2012	27,37	9,48	17,89
111	Franco Fernández	15-3-2013	27,63	56,80	-29,17
112	Franco Fernández	26-3-2015	27,66	55,58	-27,92
113	Franco Fernández	8-12-2014	27,75	52,48	-24,73
114	Franco Fernández	16-11-2012	28,00	50,02	-22,02
115	Franco Fernández	17-8-2018	28,00	46,55	-18,55
116	Franco Fernández	25-3-2010	28,23	42,60	-14,37
117	Franco Fernández	21-6-2019	28,42	39,84	-11,42
118	Franco Fernández	25-9-2015	28,61	38,72	-10,11
119	Franco Fernández	30-9-2013	28,61	33,94	-5,33
120	Franco Fernández	4-6-2012	28,72	27,50	1,22
121	Mainor	10-9-2013	28,79	22,31	6,48
122	Mainor	10-9-2014	28,80	29,71	-0,91
123	Mainor	18-12-2014	28,87	26,23	2,64
124	Mainor	17-3-2015	28,87	24,30	4,57

125	Mainor	3-9-2015	28,87	21,32	7,55
126	Mainor	21-6-2017	28,95	25,53	3,42
127	Mainor	7-11-2017	29,10	23,58	5,52
128	Miguel Brenes	15-6-2013	29,10	12,60	16,50
129	Miguel Brenes	12-1-2010	29,66	11,14	18,52
130	Nore Gómez	21-6-2017	30,03	20,94	9,09
131	Nore Gómez	20-6-2018	30,03	23,67	6,36
132	Nore Gómez	10-9-2013	30,03	16,90	13,13
133	Nore Gómez	10-9-2014	30,03	24,26	5,77
134	Nore Gómez	18-12-2014	30,09	22,83	7,26
135	Nore Gómez	17-3-2015	30,09	25,96	4,13
136	Nore Gómez	3-9-2015	30,15	19,00	11,15
137	Regina	26-3-2015	30,74	40,03	-9,29
138	Regina	15-3-2013	30,74	36,72	-5,98
139	Regina	25-3-2011	30,74	34,04	-3,30
140	Regina	21-6-2019	30,74	31,59	-0,85
141	Regina	13-12-2011	30,74	30,10	0,64
142	Regina	11-9-2020	31,12	29,94	1,18
143	Regina	22-11-2019	31,25	29,54	1,71
144	Regina	16-11-2012	31,37	28,73	2,64
145	Regina	25-3-2010	31,60	27,67	3,93
146	Regina	20-12-2017	31,60	27,21	4,39
147	Regina	28-6-2017	32,19	26,51	5,68
148	Regina	17-8-2018	32,47	25,29	7,18
149	Regina	18-7-2018	32,47	23,63	8,84
150	Regina	30-6-2016	33,06	20,69	12,37
151	Regina	25-9-2015	33,25	20,13	13,12
152	Retes	5-6-2020	33,25	45,41	-12,16
153	Rodillal	5-8-2010	33,40	51,75	-18,35
154	Rodillal	3-10-2009	33,40	68,06	-34,66
155	Pacayon	8-11-2017	35,26	3,79	31,47
156	Pacayon	22-6-2017	35,91	2,80	33,11
157	Pacayon	7-9-2015	36,77	2,81	33,96
158	Pacayon	19-12-2014	38,05	3,40	34,65
159	Pacayon	17-3-2015	38,24	3,90	34,34
160	Pacayon	11-9-2013	38,24	2,32	35,92
161	Vicente Serrano	11-9-2013	38,24	19,00	19,24
162	Vicente Serrano	10-9-2014	38,42	28,76	9,66
163	Vicente Serrano	18-12-2014	39,44	27,76	11,68
164	Vicente Serrano	17-3-2015	39,44	30,56	8,88
165	Vicente Serrano	3-9-2015	40,09	21,77	18,32
166	Vicente Serrano	8-11-2017	40,09	20,63	19,46
167	La Isla	10-9-2014	40,47	28,66	11,81
168	La Isla	11-6-2019	40,72	28,01	12,71
169	La Isla	5-11-2019	41,82	26,83	14,99
170	La Isla	16-2-2011	42,76	25,75	17,01
171	La Isla	21-11-2018	42,76	25,28	17,48
172	La Isla	21-6-2017	42,76	22,89	19,87
173	La Isla	10-9-2013	52,48	20,42	32,06
174	La Isla	17-3-2015	53,81	29,07	24,74

A.6 Financial assessment

A.6.1 Example AyA water truck costs for november

1. Investment water truck

Brand: Freightliner Average dollar cost: **₡602.88/USD**
Costs: **₡120,485,568.00 → $199,850**

2. Depreciation of the equipment

Useful Life: 10 years
Salvage Value: 20% of initial value
Depreciation per year = [₡120,485,568.00 – 20% = ₡96,388,454.40] / 10 years = ₡9,638,845.44 / 12 months = ₡803,237.12 / 30 days = ₡26,774.57 / 60 minutes = ₡446.24 per minute
Costs per day: **₡26,774.57**

3. Fuel efficiency

Average price per liter of diesel: ₡824.00
Efficiency: 7.04 kilometers per liter of diesel
Cost per kilometer = ₡824.00 / 7.04 = **₡117.05**

4. Tires

Tire Type and Brand: 425/65 R22.5 & 11 R22.5 Bridgestone
Average Duration: 100,000 kilometers
Front: ₡451,353.84 (2 tires)
Rear: ₡155,976.38 (12 tires)
Cost per Kilometer = 2 × ₡451,353.84 = *₡902,707.68* + 12 x ₡155,976.38 = *₡1,871,716.56* Total = *₡2,774,424.24* / 100,000 Kms = **₡27.74**

5. Batteries

Number of Batteries: 2
Average Duration: 100,000 kilometers
Brand: Auto craft
Model: 4DLT
Cost: ₡131,645.00 x 2 =₡263,290.00
Cost per kilometer = ¢124,300 /100,000= ₡263,290.00 / 100,000 = **₡2.63**

6. Preventive Maintenance

Service	Effective kilometers	Utilised quantity	Cost ¢	Cost per kilometer
Grease	5,000	2	₡5,164.60	₡1.03
Motor Oil	5,000	19.5	₡184,000.00	₡36.80
Filter Motor Oil	5,000	1	₡24,601.50	₡4.92
Filter secundary combustion	5,000	1	₡23,408.00	₡4.68
Filter primary combustion	5,000	1	₡112,282.65	₡22.46
Total investments			**₡349,456.75**	
Total daily costs of preventive maintenance:				**₡69.89**

7. Repairs

Maintenance frequency: every 50,000.00 kilometers
2% of the original value of the vehicle per year

- Cost per kilometer = ₡120,485,568.00 * 2% = ₡2,409,711.36 / 50,000 Kms = **₡48.19**

8. Salaries and social charges

Daily cost (total divided by days in the month): **₡71,772.12**

- Supervisors (1): ₡343,950.00 monthly salary
- Helpers (1): ₡304,750.00 monthly salary
- Extras for both: ₡810,874.00

Subtotal: ₡1,459,574.00

- Social Charges (=47.52% of subtotal): ₡693,589.56

Total: ₡2,153,163.56

9. Insurance payment

- Injury or death of people: **₡8,741.00 every half year**
- Damage to property of third parties: **₡22,153.00 every half year**

10. Rights of movement and mandatory insurance: **₡65,094.00 annually**
11. Administrative expenses

It is estimated to be 10% of the fixed costs: **₡17,389.67 daily**

12. Cubic meter of drinking water costs: **₡1,620.00 per m3**

DISTRIBUTION OF COSTS
DAILY FIXED COSTS: ₡173,896.66

- Depreciation: ₡26,774.57
- Salaries and social charges on AyA location: ₡71,772.12
- Daily salaries of driver and assistant: ₡12,500.00 (6 Officials)
- Insurance payment coverage: ₡171.63
- Circulation rights and obligatory insurance.: ₡178.34

DAILY VARIABLE COSTS PER KILOMETER TRAVELED: ₡5,310.16

- Fuels: ₡2,340.91
- Tires: ₡554.88
- Batteries: ₡52.66
- Preventive Maintenance: ₡1,397.83
- Repairs: ₡963.88
- 1 Trip = 20 kilometers

Total daily fixed costs (daily fixed costs + administrative costs): **₡191,286.33**
Total daily variable costs: **₡5,310.16**
Distribution of water: **15 m3 per trip**
Amount of cubic meters of water distributed: **450 m3**
Number of trucks: **1**
Time span November: **30 days**

TOTAL COST OF THE TRUCK (FIXED + VARIABLE): ₡5,897,894.77
TOTAL COST OF DRINKING WATER: ₡729,000.00

TOTAL COMBINED COSTS: ₡6,626,894.77 = $10,992.06

A.6.2 Costs AyA water trucks October to January

Table 14: Total AyA water truck costs October to January

Costos	Cantidad de metros cúbicos de agua transportados	Costos por transporte del agua	Costo del metro cúbico de agua repartido	Monto por c oncepto de agua repartida
Costo del 28 de Octubre al 31 de Octubre del 2022 con 1 camiones de 15000 litros Cipreses	60 M3	₡789,884.99	₡1,620.00	₡97,200.00
Costo del 1 de Noviembre al 30 de Noviembre del 2022 con 1 camiones de 15000 litros Cipreses	450 M3	₡5,897,894.77	₡1,620.00	₡729,000.00
Costo del 1 de Diciembre al 31 de Diciembre del 2022 con 1 camiones de 7000 litros Cipreses	217 M3	₡4,971,166.22	₡1,620.00	₡351,540.00
Costo del 1 de Enero al 17 de Enero del 2023 con 1 camiones de 7000 litros Cipreses	119 M3	₡2,707,529.63	₡1,620.00	₡192,780.00
TOTAL METROS CÚBICOS TRANSPORTADOS (M3)	**846 M3**			
SUBTOTAL DE GASTOS POR COSTOS FIJOS Y VARIABLES	**₡14,366,475.61**			
SUBTOTAL DE MONTO POR AGUA ENTREGADA	**₡1,370,520.00**			
TOTAL DE GASTOS POR COSTOS FIJOS Y VARIABLES + MONTO DE AGUA	**₡15,736,995.61**			
TOTAL DE GASTOS POR COSTOS FIJOS Y VARIABLES + MONTO DE AGUA EN DÓLARES	**$26,329.08**			
CANTIDAD APROXIMADA DE VIAJES REALIZADOS	**82**			
WATER CAPITA PER DAY IN CIPRESES (L/person/day)	**2.44**			
COSTO PROMEDIO POR VIAJE (INCLUYE MONTO DE AGUA)	**₡191,914.58**			
COSTO PROMEDIO POR VIAJE EN DÓLARES (INCLUYE MONTO DE AGUA)	**$321.09**			
Average dollar to colones conversion over entire period	₡597.704			

A.6.3 Costs of PVC pipes and pumps

Table 15: Costs of AC removal filters

COST CALCULATION SHEET FOR PVC PIPE & PUMP 10 L/s		
	597,704	
Cost piping		
Pipe 6m	66100	Colones
Per m	11017	Colones
Coupling part	**12118,33**	**Colones**
TC/mtr	**$20,27**	**US$**
Max distance	**7000**	**meters**
Costs pipe system	**$141.923,65**	**US$**
Maintenance + administration	**$14.192,37**	**US$**
Cost depreciation		
Life span	**50**	**years**
Value after life span	**20,00%**	**percent**
Depreciation/day	**$6,22**	**US$**
Design, salaries and insurances		
Costs	**$42.577,10**	**US$**
Cost pumping		
TC pump 1	320	USD
Max pumping height P1	40	mtr
TC pump 2	199	USD
Max pumping height P2	23	
Quantity needed	4	units
Sum pump costs over 50 yrs	**$796,00**	**USD**

Fuel price/liter	**1,3**	**USD/liter**
Fuel use P1	1,4	liter/hr
Costs P1	1,82	USD/hr
Costs P1	15943	USD/yr
Fuel use P1	0,5	liter/hr
Costs P2	0,65	USD/hr
	$1.898,00	**USD/yr**
	105,00%	
Sum fuel costs over 50 years	**$419.107,62**	**USD/50 years**
Cost type	Cost per	unit
Cpi	20,27	USD/m
Cpu	320	USD/40 mtr

A.6.4 Costs of AC removal filters

Table 16: Costs of AC removal filters

COST CALCULATION SHEET FOR AC FILTERS 50 YEARS		
	597,70	
Cost pressure vessel, piping and valves		
Pressure vessel (4)	$11.572,32	US$
Piping (4)	$4.893,02	US$
Valves (8)	***$37.357,84***	**US$**
Costs mechanical system	***$53.823,18***	**US$**
Maintenance + administration	**$2.691,16**	**US$**
Cost depreciation		
Life span	**14,27**	**years**
Total vessels over 50 years round up	**4,00**	
Value after life span	**20,00%**	**percent**
Depreciation/day	**$8,27**	**US$**
Depreciation over life span	**$43.058,54**	**US$**
Design, salaries and insurances		
Costs	**$5.382,32**	**US$**
Cost activated carbon		
Price per ton	$2.712,00	USD
Density of activated carbon	1480	kg/m^3
AC filling of the vessel	0,84	tons
Total fillings necessary for 4 vessels	209,54	tons
Sum AC costs over 50 yrs	**$568.285,13**	**USD**
TOTAL COSTS	**$619.417,15**	**USD**
Total volume in 50 years	**1.024.437,00**	**m3**
Average volume out of one vessel	**2**	**m3/hour**
Costs per m3	**0,605**	**USD/m3**

A.6.5 Costs of pressure vessel & filter system

Table 17: Costs of pressure vessel & filter system

Ecoflow (no maintenance)	12	GPM (flow rate)
	23.904,29	m3
System costs		
System	$3.985,00	including installation costs
Lifespan	25	years
Cipreses	*4*	**contaminated sources**
Santa Rosa	*2*	**contaminated sources**
Filter + piping costs		
Filters (2)	**$295,00**	**replace both after 12 months**
Lifespan	**1**	**year**
Piping	**$3.747,00**	
Subtotal	**$37.470,00**	
Total costs	**$41.217,00**	**for 50 years**
Total	**$247.302,00**	**for all polluted springs**
Hourly flow	**16,37**	**m3**
Total flow	**143.425,73**	**m3**
Costs/m3	**$1,724**	**USD/m3**
Max pumping height P1	40	mtr
TC pump 2	199	USD
Max pumping height P2	23	
Quantity needed	4	units
Sum pump costs over 50 yrs	**$796,00**	**USD**
Fuel price/liter	**1,3**	**USD/liter**
Fuel use P1	1,4	liter/hr
Costs P1	1,82	USD/hr
Costs P1	15943	USD/yr
Fuel use P1	0,5	liter/hr
Costs P2	0,65	USD/hr
	$1.898,00	**USD/yr**
	105,00%	
Sum fuel costs over 50 years	**$419.107,62**	**USD/50 years**
Cost type	Cost per	unit
Cpi	20,27	USD/m
Cpu	320	USD/40 mtr