



Hydrogeological and Morphological Characterization of Río Cuarto Maar Lake in Costa Rica

An analysis of lake geometry, water balance and groundwater interaction

Filip Bergkvist

Maja Starck

Master of Science Thesis 30HP
ISRN LUTVDG(TVTG-5198)/1-84/(2026)

Engineering geology
Faculty of Engineering
Lund university



Hydrogeological and Morphological Characterization of Río Cuarto Maar Lake in Costa Rica

An analysis of lake geometry, water balance and groundwater
interaction

Filip Bergkvist and Maja Starck



LUND
UNIVERSITY

MASTER THESIS

Submitted to the Division of Engineering Geology, Faculty of Engineering, Lund University in
Partial Fulfilment of the Requirements for the Degree of Master of Science in Lund 2026

Cover photo by authors

Lund University, Faculty of Engineering

Division of Engineering Geology

Hydrogeological and Morphological Characterization of Río Cuarto Maar Lake in Costa Rica:
An analysis of lake geometry, water balance and groundwater interaction

Hydrogeologisk och morfologisk karakterisering av maarsjön Río Cuarto i Costa Rica:

En analys av sjöns geometri, vattenbalans och grundvatteninteraktion

Author(s): Bergkvist, Filip; Starck, Maja

Supervisor(s): Mendoza, Alfredo (Engineering Geology, LTH); Alpízar Segura, Yemerith
(UTN)

Examiner: Johansson, Sara (Engineering Geology, LTH)

ISRN LUTVDG/(TVTG—5198) /1-84/(2026)

Keywords: bathymetry, water balance, groundwater–lake interaction, volcanic crater lake, water
quality, hydrogeology, GIS, Río Cuarto Lake, Costa Rica

Language: English

The work is performed in collaboration with Universidad Técnica Nacional (UTN) de Alajuela.

Digital edition Lund 2026

Abstract

Volcanic crater lakes are important freshwater systems, but their hydrological functioning is often difficult to understand due to limited monitoring data and uncertainty in groundwater contribution. Río Cuarto Lake, located in the north part of Costa Rica, is a volcanic crater lake where the sources and movement of water are not fully known. This master's thesis aimed to describe the lake's morphology, water balance and water quality conditions and investigate if available hydrological and chemical observations could indicate interaction between groundwater and the lake.

The study methodology combined field measurements and spatial analysis to develop an overall understanding of the lake system. Bathymetric data was collected using sonar and GPS and used in GIS analysis to estimate depth, area and volume of the lake. A conceptual water balance was developed by using precipitation, evaporation, inflow and recharge estimates based on meteorological data and the Schosinsky soil water balance method. Water samples were collected from different depths and analysed in both field and laboratory to examine differences in water quality in the water column and to identify potential indicators of groundwater influence.

The results showed that Río Cuarto Lake has a steep-sided basin with a deep central area and stable stratification in the water column. Differences in water chemistry between surface and deeper water layers, together with the imbalance observed in the water balance calculations suggest that additional water sources besides direct rainfall and surface inflow could contribute to the lake system. However, uncertainties related to catchment area, simplified modelling assumptions and limited monitoring data limit the ability to prove groundwater interaction in the lake.

Overall, the study provides new baseline information on the hydrology and water quality of Río Cuarto Lake and highlights the importance of continued monitoring and improved hydrological measurements for understanding lake behaviour in volcanic environments over the long haul.

Sammanfattning

Vulkaniska kratersjöar är viktiga sötvattenssystem, men deras hydrologiska funktion kan vara svår att förstå på grund av begränsning i data och osäkerheter kring grundvattnets bidrag till dem. Sjön Río Cuarto, som ligger i norra Costa Rica, är en sådan vulkanisk kratersjö där vattenkällor och vattenrörelser i sjön inte är helt kända. Syftet med detta examensarbete var att beskriva sjöns morfologi, vattenbalans och vattenkvalitet samt att undersöka om tillgängliga hydrologiska och kemiska observationer kan indikera interaktion mellan grundvatten och sjön.

Metoderna i studien kombinerade fältmätningar och geografisk analys för att skapa en övergripande förståelse av sjösystemet. Batymetriska data samlades in med hjälp av ekolod och GPS och användes sedan i GIS analys för att beräkna sjöns djup, area och volym. En konceptuell vattenbalans togs fram baserat på nederbörd, avdunstning, tillflöde och infiltration med hjälp av meteorologiska data och Schosinskys jordvattenbalansmetod. Vattenprover samlades in från olika djup och analyserades både i fält och i laboratorium för att undersöka skillnader i vattenkvalitet genom vattenkolumnen och identifiera möjliga indikatorer på grundvattenpåverkan.

Resultaten visade att Río Cuarto-sjön har ett brant sluttande bassängområde med en djup central del och en stabil skiktning i vattenkolumnen. Skillnader i vattenkemi mellan ytvatten och djupare vattenlager, tillsammans med obalansen som observerades i vattenbalansberäkningarna, tyder på att ytterligare vattenkällor utöver direkt nederbörd och ytligt tillflöde kan bidra till sjösystemet. Samtidigt begränsar osäkerheter kopplade till avrinningsområdets avgränsning, förenklade modellantaganden och begränsade mätdata möjligheten att fastställa grundvatteninteraktion.

Studien bidrar med ny basinformation om hydrologi och vattenkvalitet i Río Cuarto-sjön och visar på behovet av fortsatta undersökningar och förbättrade hydrologiska mätningar för att bättre förstå sjöns funktion i vulkaniska miljöer över tid.

Resumen

Los lagos volcánicos de cráter son sistemas importantes de agua dulce, pero su funcionamiento hidrológico puede ser difícil de comprender debido a la limitada disponibilidad de datos de monitoreo y a la incertidumbre sobre la contribución de las aguas subterráneas. El lago Río Cuarto, ubicado en la parte norte de Costa Rica, es un lago volcánico de cráter donde las fuentes y el movimiento del agua no se conocen completamente. El objetivo de esta tesis fue describir la morfología del lago, su balance hídrico y las condiciones de calidad del agua, así como investigar si las observaciones hidrológicas y químicas disponibles pueden indicar interacción entre el agua subterránea y el lago.

La metodología del estudio combinó mediciones de campo y análisis espacial para desarrollar una comprensión general del sistema lacustre. Los datos batimétricos se recolectaron utilizando un sonar y sistemas GPS, y se analizaron mediante herramientas SIG para estimar la profundidad, el área y el volumen del lago. Se desarrolló un balance hídrico conceptual utilizando estimaciones de precipitación, evaporación, entradas de agua y recarga basadas en datos meteorológicos y en el método de balance hídrico de suelos de Schosinsky. Se recolectaron muestras de agua a diferentes profundidades y se analizaron tanto en campo como en laboratorio para examinar las diferencias en la calidad del agua dentro de la columna de agua e identificar posibles indicadores de influencia de aguas subterráneas.

Los resultados mostraron que el lago Río Cuarto presenta una cuenca con pendientes pronunciadas, una zona central profunda y una estratificación estable en la columna de agua. Las diferencias en la química del agua entre la superficie y las capas más profundas, junto con el desequilibrio observado en los cálculos del balance hídrico, sugieren que fuentes adicionales de agua, además de la precipitación directa y los aportes superficiales, podrían contribuir al sistema lacustre. Sin embargo, las incertidumbres relacionadas con la delimitación de la cuenca, las suposiciones simplificadas del modelo y la limitada disponibilidad de datos de monitoreo limitan la posibilidad de confirmar la interacción entre el agua subterránea y el lago.

En general, este estudio proporciona información base sobre la hidrología y la calidad del agua del lago Río Cuarto y destaca la importancia de continuar con el monitoreo y mejorar las mediciones hidrológicas para comprender mejor el comportamiento del lago en ambientes volcánicos a largo plazo.

Preface

This master's thesis was carried out as a collaborative field study focusing on the hydrological and environmental conditions of Río Cuarto Lake, located in northern Costa Rica. The project was conducted as part of the authors' degree programme and aimed to improve the understanding of hydrological processes in a volcanic lake environment.

The study was conducted in cooperation between Lunds tekniska högskola in Sweden and Universidad Técnica Nacional in Costa Rica, where valuable supervision and practical support were provided during the fieldwork period. The collaboration enabled access to local knowledge, data and logistical assistance that were essential for completing the study.

Fieldwork included bathymetric mapping, water quality sampling and hydrological observations within the lake and its surrounding catchment area. The collected data were later analysed using geographic information systems (GIS) and hydrological calculations to develop a general overview of the lake system.

The study was financially supported by Swedish International Development Cooperation Agency through the Minor Field Studies programme, as well as by a scholarship from Sveriges Ingenjörer. These contributions made it possible to carry out the fieldwork in Costa Rica.

Acknowledgements

This master's thesis was made possible through a collaboration between Lunds Tekniska Högskola in Sweden and Universidad Técnica Nacional in Costa Rica. The collaboration provided valuable academic support, local knowledge and logistical assistance throughout the fieldwork period.

We would like to express our sincere gratitude to our local supervisor, Yemerith Alpízar Segura, for her continuous guidance, support and active participation during some of the fieldwork sessions. Her knowledge of the study area and assistance with practical arrangements were essential for the completion of this study.

We are also very thankful to Sylvia Jiménez Cavallini, Felipe Sánchez and Karina Picado for their valuable help during the fieldwork. Sylvia provided valuable support during some fieldwork activities, Felipe contributed by capturing aerial photographs using a drone, and Karina assisted with laboratory analyses at the facilities of Universidad Técnica Nacional and multimeter testing in Río Cuarto.

A special thanks also goes to Elemer Briceño Elizondo for warmly welcoming us to Universidad Técnica Nacional and for providing transportation to and from the field site in Río Cuarto. His support made the fieldwork period both possible and enjoyable.

During our study, we also met María Martínez Cruz from the Universidad Nacional in Costa Rica, who shared reports and information from previous studies of Río Cuarto Lake that were not publicly available. We also received local reports from Universidad Técnica Nacional, which provided valuable background information. These experiences highlighted the importance of collaboration and knowledge sharing between organisations working in the area.

We also thank Alfredo Mendoza, our supervisor at Lund University, whose encouragement and guidance made this project and the opportunity to conduct fieldwork in Costa Rica possible.

Finally, we gratefully acknowledge the financial support provided by the Swedish International Development Cooperation Agency through the Minor Field Studies programme, as well as funding from Sveriges Ingenjörer. This support was essential for enabling the fieldwork and completion of this thesis.

Abbreviations and explanations

General abbreviations

CC	Field Capacity
CSV	Comma-separated values
DO	Dissolved Oxygen
EC	Electrical Conductivity
GIS	Geographic Information System
GPS	Global Positioning System
GPX	GPS Exchange Format
IDW	Inverse Distance Weighting
IMN	Instituto Meteorológico Nacional
ORP	Oxidation Reduction Potential
PM	Permanent wilting point
USGS	US Geological Survey

Coordinate systems and spatial reference terms

CRTM05	Costa Rica Transverse Mercator 2005
EPSG	European Petroleum Survey Group code
WGS 84	World Geodetic System 1964
LCRN	Costa Rican National Geodetic Reference Network (Lambert Costa Rica Norte)

Content

1	Introduction.....	11
1.1	<i>Background.....</i>	11
1.2	<i>Aim and Objectives</i>	11
1.3	<i>Thesis Outline</i>	12
2	Description of the Río Cuarto Lake Area.....	13
2.1	<i>Geology, Hydrology and Climate</i>	13
2.2	<i>The Río Cuarto Maar Lake</i>	15
2.3	<i>Observed features at the lake site</i>	18
3	Theory	20
3.1	<i>Formation and Characteristics of volcanic maar lakes</i>	20
3.2	<i>Previous studies of the Río Cuarto Lake.....</i>	21
3.3	<i>Hydrological Processes in Lake Systems.....</i>	22
3.4	<i>Groundwater Flow Systems</i>	22
3.5	<i>Soil Water Balance and Groundwater Recharge.....</i>	23
3.5.1	<i>Main components of the soil water balance</i>	23
3.6	<i>Water Quality and Lake Stratification</i>	25
3.6.1	<i>Water Quality Indicators</i>	26
3.7	<i>Groundwater and Lake interactions</i>	28
4	Methods and Field Work	29
4.1	<i>Bathymetric Survey</i>	29
4.1.1	<i>Field Data Collection</i>	29
4.1.2	<i>Data Processing and GIS Integration</i>	30
4.2	<i>Hydrological Balance</i>	32
4.2.1	<i>Field investigations and measurements.....</i>	32
4.2.2	<i>Meteorological data.....</i>	37
4.2.3	<i>The Schosinsky Soil Water Balance Model.....</i>	38
4.2.4	<i>Río Cuarto Lake Water Balance</i>	44
4.3	<i>Water Sampling and Analysis</i>	45
4.3.1	<i>Sampling Strategy</i>	46
4.3.2	<i>Multimeter Probe Measurement.....</i>	47
4.3.3	<i>Water Quality Parameters Standards</i>	48
4.3.4	<i>Water Transparency</i>	48
4.4	<i>Groundwater Assessment.....</i>	49
4.4.1	<i>Groundwater indicators.....</i>	49
4.4.2	<i>Water Balance Approach</i>	49
5	Results.....	50
5.1	<i>Bathymetric Survey</i>	50

5.2	<i>Hydrological Balance</i>	53
5.2.1	Field investigations and measured catchment properties.....	53
5.2.2	Meteorological Conditions.....	58
5.2.3	Schosinsky Soil Water Balance and Recharge.....	59
5.2.4	Lake water balance.....	60
5.3	<i>Water Sampling and Analysis</i>	61
5.3.1	Water column multimeter probe	61
5.3.2	Water column lab analysis	62
5.3.3	Spring sample lab analysis results.....	67
5.3.4	Water Transparency	67
6	Discussion	68
6.1	<i>GIS and bathymetric analysis</i>	68
6.2	<i>Water balance and hydrological interpretation</i>	69
6.3	<i>Water quality and vertical stratification</i>	69
6.4	<i>Indications of groundwater–lake interactions</i>	70
6.5	<i>Methodology evaluation and sources of uncertainty</i>	71
6.6	<i>Improvements in future studies</i>	72
6.7	<i>Possible implications for studies in Sweden</i>	72
7	Conclusion	73
8	References	74
9	Appendix	78
9.1	<i>Monthly Soil Water Balance Calculations</i>	78
9.2	<i>Water Quality Results</i>	83

1 Introduction

1.1 Background

Costa Rica is a country in Central America with a geographic area of approximately 51100 km². The country is characterized by high environmental diversity, with significant variations in elevation, climate, and land use. These factors have created a wide range of ecosystems and hydrological environments that can change significantly over short distances (Beita et al., 2021). Costa Rica has a complex climate due to its varied topography and its location between the Caribbean Sea and the Pacific Ocean. Rainfall patterns differ between regions, and the North and Caribbean regions generally have more persistent precipitation throughout the year than the Pacific side of the country. These regional differences influence hydrological conditions and are therefore relevant for understanding lake systems such as Río Cuarto Lake (Mendez et al., 2020).

The distribution of rainfall in Costa Rica is primarily controlled by atmospheric circulation systems rather than temperature variations, making precipitation the main climatic factor influencing environmental and hydrological processes. The country also shows large variations in elevation, where mountain ranges and volcanic highlands form part of the complex landscape. As a result, the influence of atmospheric systems differs between regions across the country (Alfaro & Pérez-Briceño, 2014).

The large variations in climate, topography, and rainfall make Costa Rica an interesting region for hydrological studies. Understanding these processes is important for effective water resource management and sustainable use of water resources. The country's volcanic terrain has also resulted in several crater lakes, which represent unique hydrological systems and potential freshwater resources. Understanding how these lakes function can support their sustainable management and use.

1.2 Aim and Objectives

The aim of this study is to conduct a hydrological and morphological characterization of the volcanic crater lake Río Cuarto Lake in Costa Rica and to improve understanding of the processes controlling its water balance and overall hydrological functioning. The aim is also to evaluate whether available hydrological and water quality observations can provide indications of interaction between groundwater and the lake.

Río Cuarto Lake is a deep volcanic maar lake with limited permanent surface inflows and a relatively small outflow, which raises questions about how the lake maintains its water level and how subsurface processes may influence the system. Understanding these processes is important for interpreting lake behaviour in volcanic environments, for assessing potential future changes related to climate variability, and for informing water resource planning and management strategies in similar volcanic lake systems.

Due to the limited availability of direct groundwater measurements in the catchment, the study is designed as an initial hydrological assessment rather than a fully constrained hydrological model. The results should therefore be interpreted as first-order indications of lake behaviour and potential groundwater influence rather than definitive predictions.

The objectives of this study are the following:

- Describe the geometric and morphological characteristics of Río Cuarto Lake, including depth distribution, basin shape and total water volume, based on field-based bathymetric mapping.
- Estimate the hydrological water balance of the lake using precipitation, evaporation, inflow and recharge calculations derived from meteorological data and the Schosinsky soil water balance approach.
- Analyse vertical variations in selected water quality parameters to evaluate lake stratification and chemical conditions within the water column.
- Identify hydrogeological and water quality indicators that could indicate interaction between groundwater and the lake system.
- Evaluate the applicability of the study methods for understanding lake systems in data-limited environments and their potential relevance for lakes experiencing climate-related hydrological changes.

1.3 Thesis Outline

This thesis begins with a background describing the geographical, geological and hydrological setting of Río Cuarto Lake and its surrounding catchment. The background also explains important concepts related to lake hydrology, groundwater recharge and water quality processes relevant to volcanic lake systems.

The methodology section then presents the field measurements and analytical approaches used in the study. These include bathymetric mapping using sonar and GPS, hydrological balance estimation using meteorological data and the Schosinsky soil water balance method, and water quality sampling conducted at different depths within the lake. Data processing and spatial analysis performed in GIS are also described.

The results section presents the findings from the bathymetric survey, including lake depth distribution, basin geometry and estimated lake volume. Results from the hydrological water balance calculations and water quality measurements are also presented, focusing on stratification patterns and potential indicators of groundwater influence.

The discussion section interprets the results in relation to lake morphology, hydrological processes and possible groundwater–lake interactions. Methodological limitations and sources of uncertainty are evaluated, and the potential application of the study methods to other lake systems, including Swedish lakes, is discussed.

The thesis concludes with a summary of the main findings and highlights key implications for understanding hydrological processes in volcanic lakes. Recommendations for future monitoring and research are also provided.

2 Description of the Río Cuarto Lake Area

2.1 Geology, Hydrology and Climate

Río Cuarto Lake is a volcanic maar lake located in Alajuela Province in northern Costa Rica. The northern part of Costa Rica is located on the northeastern side of the country, where precipitation is more persistent throughout the year than in many Pacific regions. This humid climate is important for understanding the hydrological conditions of Río Cuarto Lake (Mendez et al., 2020).

Río Cuarto lake is a volcanic maar lake located on the Caribbean slope of the Cordillera Volcánica Central in Costa Rica. The lake is located at approximately 360 m a.s.l, and it is surrounded by steep crater walls covered by tropical forest vegetation. The watershed area is relatively small, and small streams originate from the crater rim, while a small river flows from the lake into Río Cuarto River (Gocke et al., 1990). The location of Río Cuarto Lake is shown in Figure 2.1 and Figure 2.2.

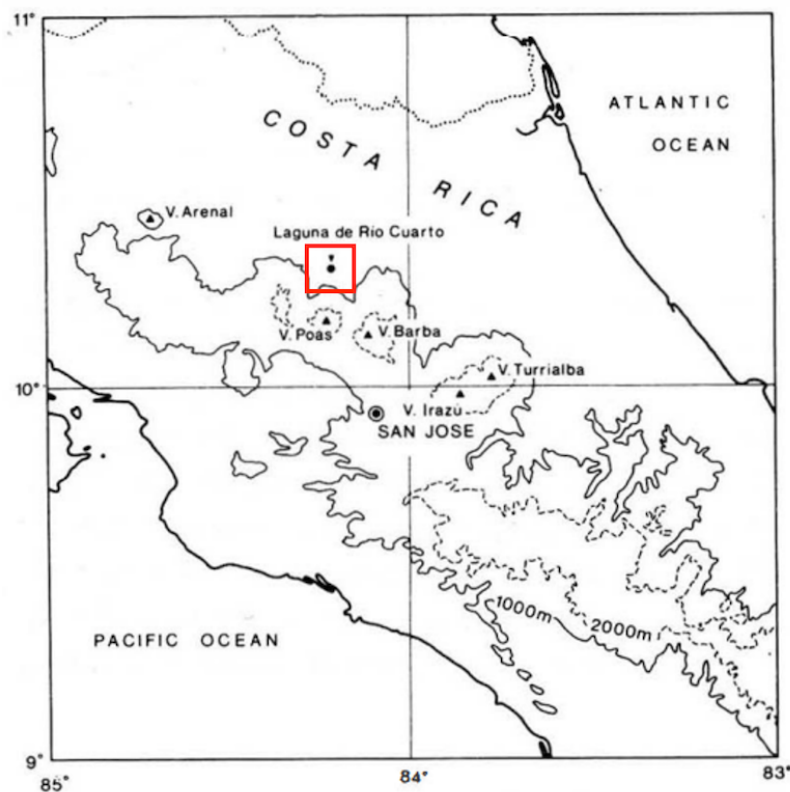


Figure 2.1: Location of Río Cuarto Lake within the Central Volcanic Range of Costa Rica. The red box highlights the Río Cuarto study area, while Río Cuarto Lake is labelled separately as Laguna de Río Cuarto. The triangles indicate main volcanoes in central Costa Rica, including Arenal, Poás, Barba, Irazú and Turrialba. The solid irregular lines represent the coastline and national boundaries, the straight lines show latitude and longitude, and the dashed lines show elevation contours. Modified from Gocke et al. (1990).

The rainfall in the northern part of Costa Rica is strongly influenced by cold fronts, low pressure systems and by the indirect effects of tropical cyclones coming from the Caribbean Sea. These meteorological systems contribute to frequent and sometimes intense rainfall events, especially in the northern and Caribbean-influenced regions of the country. Also, these climatic conditions influence the general water balance of the lake system (Retana, 2012).

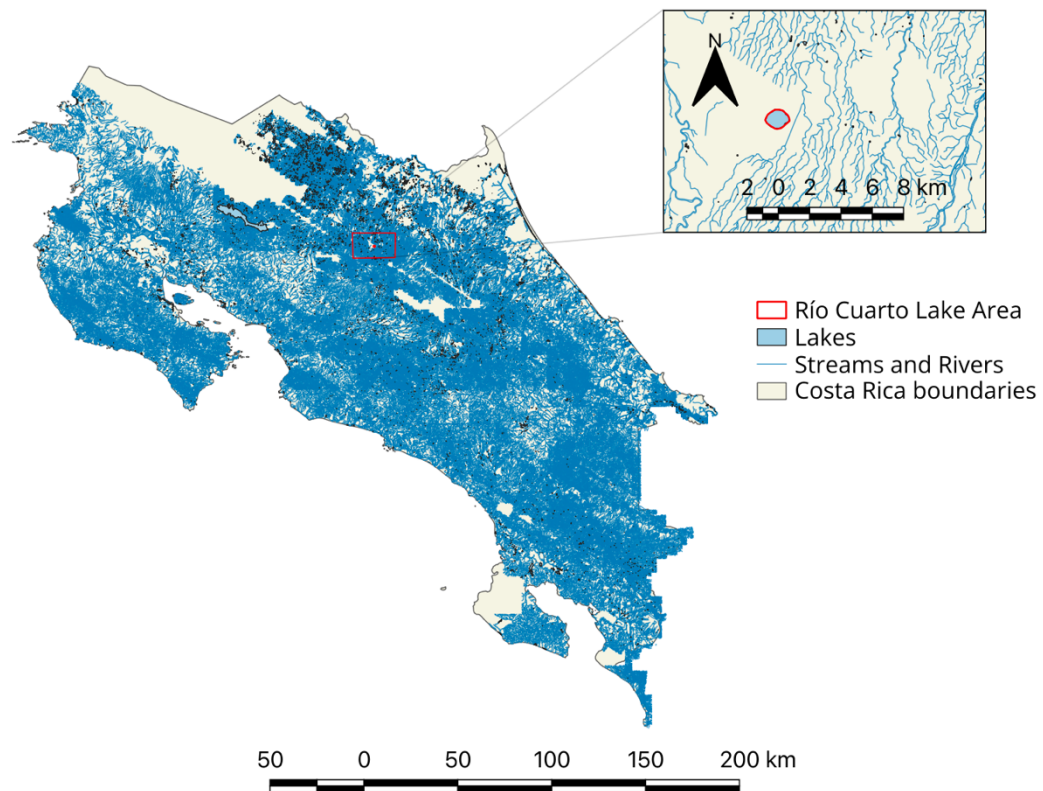


Figure 2.2: Regional surface water network around the Río Cuarto Lake study area, showing the high density of mapped rivers, streams and water bodies in the surrounding landscape. Spatial data layers were obtained from the Costa Rican National Geographic Institute (IGN) through the National Spatial Data Infrastructure (SNIT) at a cartographic scale of 1:25,000. Data gaps around Río Cuarto Lake reflect missing information in the available public spatial layers.

2.2 The Río Cuarto Maar Lake

The Río Cuarto Maar, shown in Figure 2.3, is a volcanic crater lake located in the Alajuela Province of Costa Rica. The lake is situated on the eastern side of the Central Volcanic Range, a volcanic mountain chain in central Costa Rica that includes several major volcanoes, such as Poás, Barva, Irazú and Turrialba (Gocke et al., 1990). Poás volcano is located approximately 18 km south of Río Cuarto Lake, as shown in Figure 2.1. The maar lake is situated along a 27 km north-south fracture system connected to the Poás volcano. The maar formed through explosive volcanic activity from this fracture system. Volcanic deposits related to the formation of Río Cuarto include pyroclastic surges, ballistic materials and airfall tephra, which were produced during three main explosive periods. The distribution suggests that volcanic material was transported westward due to the wind direction at the time. No radiocarbon ages are currently available for the formation time of Río Cuarto Maar. However, based on archaeological data, it is suggested that the volcano erupted between 3000 and 4000 years ago (Alvarado et al., 2011).



Figure 2.3: Río Cuarto Maar Lake.

The Río Cuarto Maar lake's outermost edge has a maximum elevation of 52 m above lake level (412 m.a.s.l.). The Maar is nearly circular in shape, with a maximum diameter from east to west of 758 m and a surface area of 0.33 km^2 (Cabassi et al., 2014). The Maar Lake is the deepest natural lake in Costa Rica with a maximum depth of 67 m, an average depth of 45.5 m and a water volume of $15 \times 10^6 \text{ m}^3$ according to Gocke et al. (1987). Lake morphometry can be described by a steep-sided frustum model, meaning steep sides but flat bottom. Topographic features and location of Río Cuarto Lake is shown in Figure 2.4.

Documentation of surface water connections is limited since the crater morphology is closed and no permanent surface inflows or outflows were described in previous geological studies of the area (Alvarado et al., 2011). The absence of major surface inflows and outflows does, however, not mean that the lake is hydrologically isolated. In Lake Hule, another volcanic maar lake in northern Costa Rica located close to Río Cuarto Lake and shown in Figure 2.1, groundwater was estimated to contribute $61.3 \pm 8.1\%$ of the annual inflow. This shows that groundwater can be an important part of the water balance in similar volcanic lake systems (Esquivel-Hernández et al., 2024).

The lake's physical and chemical structure shows stable stratification and restricted water mixing, which is typical for hydrological systems not dominated by major surface inflows or outflows (Cabassi et al., 2014). Lake temperatures vary with the stratification layers; for the top layer (epilimnion), the temperature fluctuates between 24.6 and 29.9 °C, while the bottom layer (hypolimnion) remain stable at 24.2-24.4 °C (Gocke et al., 1987). The absence of major surface inflows and outflows does not imply hydrological isolation, previous studies of other volcanic maar lakes in northern Costa Rica have shown that groundwater exchange can play a key role in regulating lake water levels through subsurface flow paths (Esquivel-Hernández et al., 2024).

In Río Cuarto Lake, so-called rollover events have been observed, where bottom layers of water (hypolimnion) mix with top layers (epilimnion). During these events, the water colour goes from blue green to a more yellow-red tone, and fish along with other fauna end up dead. The theory is that these rollover events occur when the shallow water cools down and sinks due to low air temperatures and strong winds, resulting in warmer anoxic water from below rising to the surface (Cabassi et al., 2014). The lake is also influenced by hypothermal CO_2 entering from the bottom, which maintains stable stratification levels and anoxic conditions in the hypolimnion. The accumulation of gases in the lake is therefore controlled by both geological input and biological activity (Cabassi et al., 2014).

The geological, hydrological and geochemical characteristics of Río Cuarto maar lake make it an important site for studying the dynamics of tropical volcanic lake systems.

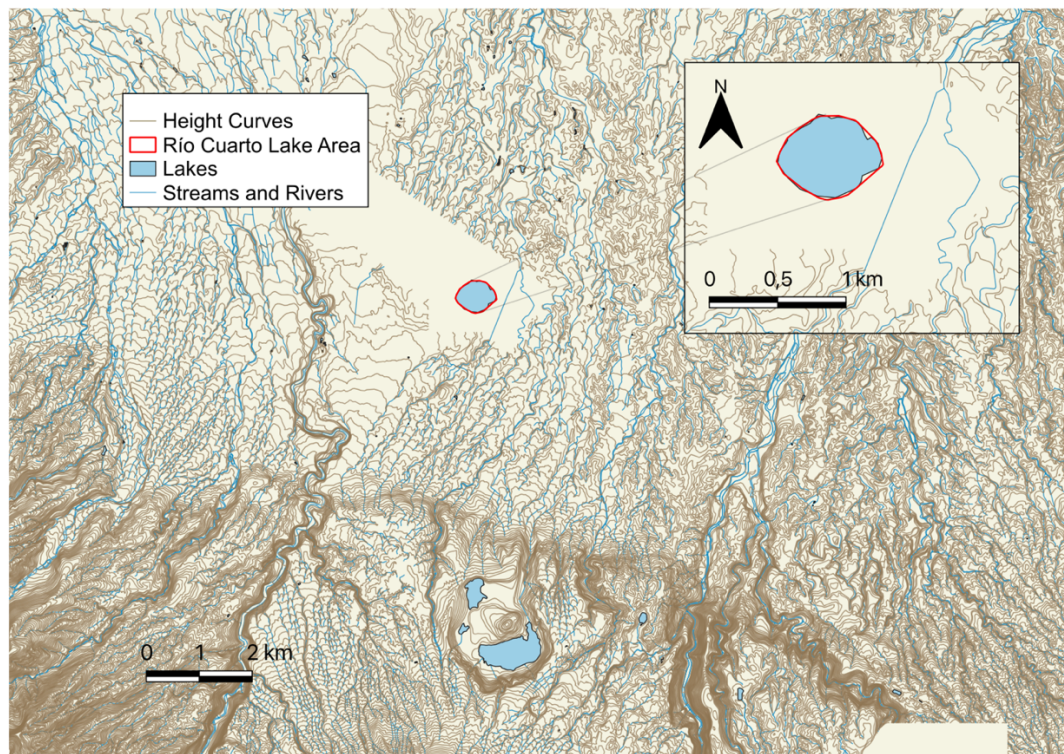


Figure 2.4: Topographic map of the Río Cuarto Lake area showing elevation contours and surface water features. The inset map indicates the location of the study area. Data gaps around the lake are due to missing information in the available public spatial layers.

2.3 Observed features at the lake site

At the site, a few constructed inflows were observed, leading rainwater and runoff from nearby residential areas toward the lake. Drainage channel observed at the western slope at the site is shown in Figure 2.5 and 2.6. At the location, a small, constructed tunnel structure was observed at the base of the channel, allowing water to pass beneath the ground surface or pathway before continuing in a slope towards the lake. The constructed inflows consisted of manually dug drainage channels located on the western side of the lake site, along the small road leading to the lake. These channels were relatively small and not very deep with exposed soil walls and coarse sediments at the bottom, allowing for surface flow during rainfall events.

These drainage structures might locally support surface water transport to the lake during periods of heavy precipitation. However, based on field observations, these inflows are small and not permanent streams. Their presence in the area indicates some degree of human influence on natural runoff pathways at the catchment area.



Figure 2.5 and 2.6: Observed drainage channels located on the western slope of Río Cuarto Lake, directing surface runoff toward the shoreline of the lake. A small, constructed tunnel structure can be seen on the left picture at the bottom.

No previous studies mention permanent outflows and inflows to the lake. However, in addition to the constructed drainage features near the lake, a small surface water outflow was observed downstream from the lake area shown in Figure 2.7. Based on field observation and map analysis, the stream appears to be connected to the Río Cuarto stream, which flows away from the lake catchment and later connects to a downstream network of streams. Downstream section of the stream can be seen in Figure 2.8. Nine small inflows were also observed at the site, connecting to the Río Cuarto Lake.



Figure 2.7: Stream channel located at the Río Cuarto Lake site, here discharge measurements were conducted. The channel represents a surface water outflow pathway from the lake catchment. The image shows shallow flow conditions.

Flow measurements were done at the location of the outflow stream to estimate discharge conditions. The stream channel was characterized by shallow flow depth and visible current movements indicating relatively low discharge conditions during the measurement periods.

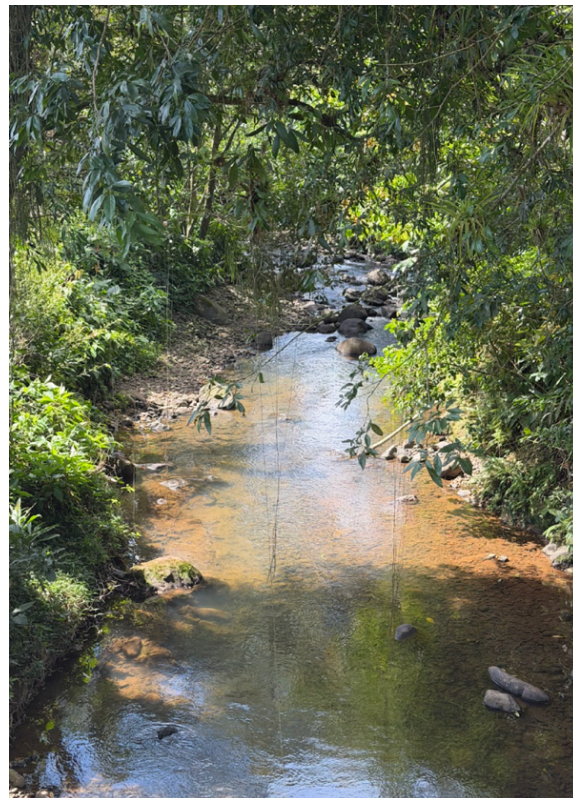


Figure 2.8: Downstream section of Quebrada, a stream located farther from Río Cuarto Lake and closer to the urban area. It forms part of the drainage network that transports runoff away from the lake catchment.

3 Theory

3.1 Formation and Characteristics of volcanic maar lakes

Maar lakes are lakes formed by phreatomagmatic eruptions, explosive volcanic events where rising magma interacts with groundwater or other forms of water such as surface water or ice. These kinds of eruptions construct a characteristic maar structure that includes a deep funnel shaped volcanic vent filled with pyroclastic material as well as a crater at surface levels which could later be filled with water (Uhl et al., 2024). Because of the complexity of the influencing geological factors on the eruptions, maar craters usually have complicated internal structures and asymmetrical morphologies. The geological factors affecting the eruptions are magma supply, water availability, depth of the explosion and wall rock properties (Cavazos-Alvarez et al., 2025).

Morphological analysis of maar craters is the main approach for determining the history of eruptions forming them. Many maars are not formed by a single explosion but rather by a sequence of eruptions along the path of subsurface magma flow over time. These events create combined craters where spatial relationships between overlying circular explosion tracks can be analysed to understand relative timing and resettling of eruptive centres. After the eruptions cease, the craters may develop into closed basins with water storage capacity, resulting in the formation of volcanic lakes. Geomorphological processes after the eruption phase can further alter the structure of the crater, such as sedimentation, the collapse of unstable crater walls and erosion. Because of this, the morphology of maars today reflects both the effects of eruptive processes as well as subsequent geomorphological evolution (Cavazos-Alvarez et al., 2025).

Maars can be compared with inverted cones below the pre-eruption ground surface and often develop into lakes (Alvarado et al., 2011). Maar lakes and other deep volcanic lakes often have small surface areas compared to their depth and are surrounded by steep crater walls. These crater walls reduce water mixing caused by wind at the lake's surface, which maintains water layering. This stable lake structure promotes thermal and chemical stratification and limits vertical mixing within the lake, leading to oxygen deficiency in the deeper parts (Uhl et al., 2024). The water column existing in deep lakes such as maar lakes is often divided into three layers: a mixed surface layer called the epilimnion, a colder and denser bottom layer called the hypolimnion and a middle layer with the strongest temperature change known as the thermocline. The water temperature in the hypolimnion can be up to 10 °C lower than in the epilimnion (Horlacher et al., 2012). When vertical mixing is limited, which is typical for maar lakes, oxygen in the deep-water layers is slowly used up while new oxygen from the surface cannot reach the bottom easily. As a result, the hypolimnion may develop extremely low oxygen levels or become completely free of oxygen and remain permanently anaerobic (Horlacher et al., 2012).

The formation of maars suggests a strong connection between magma and groundwater at depths of about 200-300m. This can suggest the presence of groundwater systems in maar lakes as well as subsurface flow along fracture zones and sustained connection between crater basin and surrounding aquifers (Alvarado et al., 2011). The extensive displacement and fracturing of country rock during phreatomagmatic crater formation would have significantly modified subsurface permeability structures and thereby changed groundwater flow patterns.

Maar lakes are also important sedimentary systems since the steep-side crater morphology and limited external inflow develop calm bottom water conditions that support fine sediment accumulation. Also, the restricted circulation allows undisturbed sedimentation resulting in deposits that can give environmental and climatic information for long time periods (Uhl et al., 2024).

A lot of maar lakes show a likelihood to support lasting stratification, and some can develop meromictic conditions, where deep water and surface water do not mix at all. In those systems, the hypolimnion can remain isolated constantly from atmospheric influence, increasing chemical gradients within the water column and contributing to stable redox conditions (Uhl et al., 2024). Due to the shape of maar lakes and that they usually have closed basins, their hydrological behaviours are strongly related with basin geometry and subsurface processes rather than large surface inflows, making them sensitive to internal processes and groundwater interactions (Uhl et al., 2024).

3.2 Previous studies of the Río Cuarto Lake

Previous studies and investigations of Río Cuarto Lake in northern Costa Rica provide important background information for understanding the behaviour of the Río Cuarto Maar Lake.

A detailed vertical profile of temperature, pH, redox potential, dissolved gases and isotopic compositions along the water column was carried out by Cabassi et al. (2014). The results showed that Río Cuarto Lake is characterized by stable thermal and chemical stratification, as well as vertical separation of the water column into layers with limited mixing. In Río Cuarto Lake, the hypolimnion was characterized by elevated concentrations of dissolved gases. The study also showed that the lake contains significant amounts of dissolved CO_2 , CH_4 , and N_2 in the deeper layers of the lake, partly influenced by hydrothermal CO_2 input. Cabassi et al. (2014) explained that the addition of CO_2 contributes to stable density stratification in the water column and supports anoxic conditions in the hypolimnion.

In a study of Río Cuarto Lake, Jiménez Rivera (2022) reported that the lake is stratified into an upper epilimnion and a deeper hypolimnion. Approximately 55% of the lake volume was described as anoxic, while around 45% was aerobic. These conditions allow gases such as CO_2 and CH_4 to accumulate in deeper water layers and contribute to distinct chemical conditions within the lake system (Jiménez Rivera, 2022).

Previous events in Río Cuarto Lake have been associated with changes in water colour and temperature, unpleasant odours and fish mortality. These changes may be linked to disturbances in lake stratification, where gas-rich deep water can move upward and affect oxygen conditions and water chemistry. Jiménez Rivera (2022) also suggested that fish mortality may be related to the upward movement of deep-water.

Overall, the previous studies show that Río Cuarto Lake is a stratified volcanic maar lake system characterized by gas accumulation, hydrothermal influence and active biochemical processes. These findings provide important baseline information for understanding the hydrological and geochemical behaviour of Río Cuarto Lake in the present study.

3.3 Hydrological Processes in Lake Systems

The hydrological cycle describes the movement of water between the atmosphere, land surface and subsurface. Solar radiation and gravity drive the cycle, and it includes processes such as precipitation, evaporation, infiltration, surface runoff and groundwater flow. When observing a lake at basin scale, the water balance can be understood as the outcome of inputs and outputs within the larger hydrological system. The main atmospheric input is the precipitation falling directly on the lake surface and surrounding catchment. A part of this water returns to the atmosphere through evaporation while another part infiltrates into the soil contributing to groundwater recharge (Yang et al., 2021).

Hydrological processes are not occurring without the effects of changes in land use, vegetation cover and climate conditions. These modify runoff patterns, evapotranspiration rates and groundwater recharge which in turn influence lake water levels and water balance (Yang et al., 2021). In lakes where surface inflow and outflow are limited, groundwater interactions play a crucial role in understanding the total water balance.

Climate change affects the hydrological cycle by interfering with precipitation patterns, rates of evaporation and the frequency of extreme meteorological events. Climate changes can in turn alter water availability and lake levels over time, making it important to analyse hydrological processes with a wider climatic context (Yang et al., 2021).

3.4 Groundwater Flow Systems

Groundwater flow within a basin can be organized into three different system types depending on topography and overall basin geometry. Local systems originate at a topographic high while discharge occurs at an adjacent topographic low, forming shallow flow paths beneath individual hills and valleys. Intermediate systems have discharge and recharge areas separated by one or more topographic features, with groundwater flow spanning beneath several hills and valleys. Regional systems extend from the main groundwater divide down to the lowest point in the basin (Tóth, 1963).

The three system types can coexist where local and possibly intermediate systems dominate shallow zones while regional systems control deeper flow. Although the systems are conceptually separate, they typically transition gradually, as do their flow characteristics. The highest flow velocities and densities occur in the shallow local systems, which decreases with depth toward the intermediate and the slower regional system. This combined structure means that the intermediate and regional systems may contribute groundwater from areas beyond the topographically defined surface catchment. In addition, the groundwater transported from these slower and further reaching systems can have different chemical properties in comparison to groundwater from local systems (Tóth, 1963).

3.5 Soil Water Balance and Groundwater Recharge

Potential aquifer recharge in the terrestrial portion of the Río Cuarto lake catchment was estimated using the soil water balance model developed by Schosinsky (2006). The approach is common for groundwater studies in Central America since it is developed for regional climatic and geological conditions, while not requiring extensive data. This made it suitable for the Río Cuarto lake catchment and this study.

The model operates on a monthly time step and is based on soil characteristics as well as monthly values for precipitation and temperature. Input data included site-specific parameters and coefficients, including vegetation interception, terrain slope, and soil hydraulic properties. These factors determine the volume of water that percolates below the root zone and contributes to the underlying aquifer (Schosinsky, 2006).

3.5.1 Main components of the soil water balance

The main components of the model are described in the following sections: interception, infiltration and surface runoff, soil moisture balance, evapotranspiration, and aquifer recharge.

3.5.1.1 *Interception*

The first component of the model accounts for the portion of precipitation intercepted by vegetation before reaching the soil surface, which varies with vegetation type and density.

3.5.1.2 *Infiltration and surface runoff*

After accounting for foliage retention, the remaining rainwater reaching the soil surface is partitioned into either infiltration or surface runoff. The volume of water that infiltrates is determined by monthly precipitation and the soil infiltration coefficient (C_i). This coefficient integrates several site-specific characteristics, including soil texture, terrain slope, and surface vegetation cover (Schosinsky, 2006). Higher slopes and less permeable soils reduce infiltration capacity while increasing surface runoff.

3.5.1.3 *Soil moisture storage*

The soil moisture balance within the root zone serves as the storage component of the recharge calculation (Schosinsky, 2006). The model conceptualizes the soil as a control volume with a surface area of 1 m^2 and a depth corresponding to the effective root depth. Within this control volume, soil moisture varies between the field capacity (CC) - the maximum amount of water the soil can retain against gravity, and the permanent wilting point (PM) - the moisture level below which plants cannot extract water. These variations occur due to infiltration as well as water losses through evapotranspiration. The difference between CC and PM represents the available water capacity, which determines both plant water availability and the soil's buffering capacity between precipitation events.

3.5.1.4 Evapotranspiration

Evapotranspiration in the Schosinsky (2006) model is defined as the sum of plant transpiration and soil evaporation within the root zone. Maximum evapotranspiration occurs when soil moisture (HS) is at field capacity (CC). As soil moisture decreases below this level, plant transpiration is progressively reduced because plants partially close stomata to limit water loss. When soil moisture reaches the permanent wilting point (PM), plants can no longer extract water, and both transpiration and root water uptake cease entirely.

The model distinguishes between potential evapotranspiration (ETP) - the maximum evapotranspiration that would occur under unlimited water availability, and actual evapotranspiration (ETR) - the evapotranspiration that occurs given the available soil moisture.

3.5.1.5 Groundwater recharge

In the model, recharge occurs when infiltration exceeds both the evapotranspiration demand and the storage capacity of the soil within the root-zone, allowing excess water to percolate downwards into the aquifer and groundwater system. It should be noted that this approach estimates diffuse recharge through the soil profile and does not account for flow through fractures or macropores, which may be locally significant in the volcanic terrain.

3.6 Water Quality and Lake Stratification

Water chemistry describes the chemical structure of lake water, while geochemical analysis uses this information to understand processes that affect this structure. In volcanic lake systems, geochemical parameters can be used to get an understanding of processes occurring beneath the crater lake, including volcanic and hydrothermal activity. The chemical structure of lake water can demonstrate influence from precipitation, surface runoff, groundwater inflow as well as fluids or gases originating from volcanic or hydrothermal systems below the lake. Since volcanic lakes often have an absence of visible surface inflows or outflows, water chemistry becomes important for understanding how the lake system functions (Rouwet & Tassi, 2011).

Dissolved gases entering a volcanic lake with volcanic fluids can significantly affect water chemistry. These gases and dissolved substances can change parameters such as pH, ionic composition and total dissolved solids. pH is a particularly informative parameter in volcanic lakes since it can indicate acidic or basic inputs from deeper parts of the lake. Acidic conditions may occur when volcanic gases dissolve in the water. In contrast, more neutral or alkaline conditions might suggest stronger influence from precipitation or groundwater. However, pH alone is not sufficient to describe the geochemical behaviours of a lake and should therefore be interpreted together with other chemical parameters (Rouwet & Tassi, 2011).

Measurements of water variables can provide information about water sources, conditions for mixing and possible interactions between groundwater and lake water. In lakes with none or very small surface inflows and outflows chemical data can be especially useful since it can circumstantially evidence of subsurface water exchange (Shaw et al., 2013; Herrera & Custodio, 2016). Parameters such as pH, dissolved oxygen, nutrients and major ions are typically measured to get more information about the lake since they can be connected to biological activity, oxygen conditions and interactions between water and surrounding soils. Because of this it is useful to analyse water quality variables when studying lake hydrology and stratification (Shaw et al., 2013).

Oxygen depletion in lakes is a significant environmental challenge driven by factors such as eutrophication, thermal stratification, and organic matter decomposition. When hypolimnion water becomes isolated from atmospheric oxygen exchange, microbial decomposition and the breakdown of organic substances consume dissolved oxygen faster than it can be replenished. This results in anoxic conditions that trigger phosphorus and iron release from sediments, altering redox conditions (Nürnberg, 1995). A recent study by Jiménez (2022) suggests that stratification occurs at depths of around 40 meters down, instead of 22 to 25 meters deep suggested by previous sources.

In stratified lakes with anoxic conditions, the sudden change in stratification can cause severe ecological damage. This is mentioned shortly in section 3.2 for the Río Cuarto lake, where Alvarado et al. (2011) document that cold conditions and strong winds increase surface-water density, leading to a destabilization which allow ferrous iron (Fe^{2+})-rich bottom water to mix upward. This results in rapid oxidization of the ferrous iron into iron hydroxide ($\text{Fe}(\text{OH})_3$), causing yellow-reddish water discoloration, oxygen depletion, and fish mortality.

Below are descriptions of the water quality parameters analysed in this thesis. The selected water quality parameters were used to describe the chemical and physical conditions in Río Cuarto Lake and to support the interpretation of vertical changes in the water column. The parameters included pH, dissolved oxygen, phosphate, nitrate, coliform bacteria, electrical conductivity and oxidation-reduction potential.

3.6.1 Water Quality Indicators

3.6.1.1 pH

pH measurements are done to evaluate the acidity or alkalinity conditions in the lake. Higher pH values in lakes can occur during enhanced photosynthetic activity, since CO₂ is removed from the water and the carbonate balance changes (Boers, 1991). pH is also relevant because it can influence chemical processes in the water column and sediments.

3.6.1.2 Dissolved oxygen

Dissolved oxygen (DO) can give information about oxygen availability and redox conditions in lake systems. In stratified lakes, oxygen concentrations can vary with depth due to limited mixing between surface water and deeper water. Low oxygen levels or anoxic conditions can influence chemical reactions in sediments and contribute to phosphorus release into the water column (Wu et al., 2014).

3.6.1.3 Phosphate

An important nutrient in lake systems is phosphate since it has an important role in eutrophication processes, including algal blooms and oxygen depletion. Phosphorus release from sediments in the lake is affected by dissolved oxygen conditions, temperature and pH (Wu et al., 2014). Higher pH can promote phosphate release from sediments, but Boers (1991) showed that the magnitude of this effect depends on how the pH increase occurs. Therefore, phosphate was included to evaluate nutrient conditions and possible sediment-water interactions in the lake.

3.6.1.4 Nitrate

Nitrate (NO₃⁻) is a key chemical parameter in lake systems. It works as a nutrient for biological production but can also influence redox-related processes in the water and surface sediment. In lakes, nitrate can affect the behaviour of phosphorus in the sediment. Previous studies have shown that when nitrate concentrations are high, phosphate is less likely to be released from sediment into the water column. When nitrate concentrations are low, phosphate release from sediment can become more likely, especially under poor oxygen conditions (Andersen, 1982). By measuring nitrate, information can be given about nutrient dynamics and conditions that may affect phosphorus release in the lake system.

3.6.1.5 Coliform bacteria

Coliform bacteria are used as indicators of microbial contamination in water. The presence of coliform bacteria can indicate influence from polluted sources such as sewage, agricultural runoff or human and animal waste (Shafi et al., 2013). Monitoring coliform bacteria can therefore help evaluate whether the water may be affected by contamination.

3.6.1.6 Electrical conductivity

Electrical conductivity is a parameter often used in water quality assessment, and it measures the ability of water to conduct an electrical current. The concentration of dissolved ions in lake water is directly connected to electrical conductivity, and higher concentrations of dissolved salts generally lead to higher electrical conductivity. Therefore, electrical conductivity can be used to provide information about total dissolved solids and chemical differences in the lake system (Pal et al., 2015).

3.6.1.7 Oxidation-Reduction Potential

Oxidation-reduction potential (ORP) is used to describe redox conditions in the lake system and can give information about oxidizing and reducing processes in the water column. In stratified lakes, redox conditions often change with depth, especially in the hypolimnion when oxygen decreases (Sigg et al., 1991). Since different redox reactions can occur at the same time, oxidation-reduction potential should be interpreted as an indicative parameter rather than as a direct measure of one specific chemical process.

3.7 Groundwater and Lake interactions

To understand the hydrology of volcanic maar lakes in tropical regions it is important to consider interaction between groundwater and surface water. Groundwater–lake interactions represent an important part of lake hydrology but are usually difficult to demonstrate, as groundwater exchange often occurs without visible surface inflows or outflows (Xu et al., 2021).

Studies of closed volcanic lake systems have shown that an absence of surface inflows or outflows does not automatically mean hydrological isolation. It is possible that groundwater inflow and outflow occur through subsurface pathways that are controlled by geological structures. These pathways can maintain quite stable lake levels even with constant water exchange. Conceptual hydrogeological models are for that reason useful for understanding the interactions between lake and groundwater in volcanic basins (Herrera & Custodio, 2016).

One way to indicate the influence of groundwater is by analysing water chemistry. As groundwater moves from recharge to discharge areas it interacts with geological materials which allows hydrogeochemical processes such as dissolution, precipitation and ion exchange to occur. These processes control the concentration of major ions in groundwater, which in turn reflect both the lithology and history of aquifer flow. Because of this, the composition of dissolved major ions can be used as a tool to evaluate groundwater contribution to lake systems (Okiongbo & Akpofure, 2014).

Groundwater and surface water inflow play a critical part in lake water chemistry and water quality. While it is somewhat simple to characterize surface inflows to lakes, the groundwater and lake interactions and the influence it has on water quality is on the other hand less apparent. However, in a study on groundwater and lake interactions it was shown that groundwater inflows may improve water quality locally by containing more oxygen and reducing substances such as ammonium and hydrogen sulphide that typically form in low oxygen conditions (Shaw et al., 2013).

4 Methods and Field Work

This section describes the methodological framework and field procedures used to characterize the hydrology, morphology and water quality of Río Cuarto Lake. Together these methods were used to collect and process field and spatial data to gain more information about the lake system and its connection with the surrounding environment.

4.1 Bathymetric Survey

Bathymetric data were collected to describe the morphology of Río Cuarto Lake and to support hydrological and volumetric calculations. Data collection was carried out using a portable depth sonar device and handheld GPS units for spatial positioning. The collected data was then used for spatial analysis in QGIS, including depth maps, calculation of lake area and volume as well as a three-dimensional visualization of the lake basin structure.

4.1.1 Field Data Collection

Bathymetric data for Río Cuarto Lake were collected by using a portable echo sonar (Deeper Pro) and two GPS units (Garmin Montana Series) and an inflatable paddleboard. The sonar device was attached to a line approximately 1.5 m behind the paddleboard to reduce paddling movement disturbance and improve measurement stability, field work is shown in Figure 4.1.

Depth measurements and location data from the GPS units were collected by paddling in parallel transects across the lake. The Deeper Pro sonar was connected to a mobile device with the application Fish Deeper, which showed depth and map lines while in the field, assisting with spacing and accuracy. The transects were done in parallel lines to provide an even spatial distribution as well as coverage of both the central and nearshore areas of the lake. Bathymetric data collection was done during a total of seven field days from 28th January until 18th February 2026. During each field day, between two and eight transects were completed depending on the battery on devices, weather and other logistical interference. The sonar collected depth values were exported as CSV files from the Fish Deeper site after each field session.



Figure 4.1: Bathymetric mapping field work conducted on Río Cuarto Lake pictured with a Drone.

Depth measurements were georeferenced by using two independent GPS units during fieldwork. One unit recorded positions directly in the official Costa Rican projected coordinate system CRTM05, while the second unit recorded positions referenced to the Costa Rican national geodetic reference network LCRN. The use of two GPS systems allowed cross-verification of positional accuracy. The GPS coordinates with the system CRTM05 was the ones used for the bathymetric survey and data processing.

4.1.2 Data Processing and GIS Integration

The exported sonar files in CSV format contained water depth, surface temperature and timestamp information while the GPS files in GPX format contained geographic coordinates and corresponding timestamps. The sonar recorded at a higher temporal frequency than the GPS units, meaning that a lot of depth measurements often corresponded to the same GPS position between GPS logging intervals.

To assign geographic coordinates to the sonar depth measurements, the sonar and GPS datasets were connected and synchronized using timestamps. This was done with a Python-based workflow that was developed to create connected files for each field day data. For each field session the GPX file was read to extract timestamped latitude and longitude coordinates while the sonar CSV file gave timestamped and depth measurements. Since the timestamps for the sonar were originally stored in Unix time format, they were first converted to standard datetime values. Each sonar observation was then matched to the nearest available GPS timestamp within the corresponding field period. This produced a georeferenced table in which each depth measurement was connected to a spatial position.

The combined and synchronized daily datasets were changed from geographic coordinates (WGS 84) to the projected coordinate system CRTM05 (EPSG:5367), which was used throughout the analysis in QGIS.

In QGIS, the bathymetric depth measurement points were first imported as a point layer and visually checked against a satellite basemap to evaluate positional accuracy over the lake. A polygon representing the lake boundary was then created to constrain interpolation to the correct area. The point depth data were interpolated using the Inverse Distance Weighting (IDW) method in QGIS to generate a bathymetric raster surface representing the underwater morphology of the lake. The interpolated raster was generated with a spatial resolution of 5m x 5m in the projected coordinate system CRTM05 (EPSG:5367). From this raster, depth contours were created and used to visualize the spatial distribution of lake depth.

In addition to this, a three-dimensional visualization of the bathymetric surface was created in QGIS using the 3D map view. This model was used to illustrate the morphology of the lake basin, to visualize the steep crater walls and spatial distribution of the deepest zones.

The lake surface area was calculated from the lake polygon in QGIS. Lake volume was estimated from the interpolated bathymetric raster using the Raster Surface Volume tool in QGIS, where the water surface was used as the reference level. The volume calculation is done by summing the product of the water depth in each cell and the corresponding cell area, expressed as:

$$V = \sum_{i=1}^n d_i \cdot A_{cell} \quad (4.1)$$

d_i = depth in each raster cell

V = lake volume (m^3)

A =lake area (m^2)

n = total number of raster cells within the lake boundary

The mean lake depth was then calculated as:

$$D_{mean} = \frac{V}{A} \quad (4.2)$$

D_{mean} = mean depth (m)

4.2 Hydrological Balance

The hydrological balance of the Río Cuarto lake catchment was assessed to identify and quantify the main water flows within the lake system. To achieve this, a multi-step approach was applied.

First, field investigations were conducted within the catchment, including soil sampling and analysis to determine soil and infiltration properties. Where possible, observations of surface water movement were documented and any identifiable surface inflows or outflows were examined.

Second, field investigations were accompanied by secondary data collection of meteorological records and geospatial data from institutional sources. This was done to characterize climatic conditions and catchment features.

Third, the Schosinsky (2006) soil water balance model was applied to the terrestrial part of the catchment to integrate these datasets and estimate the potential aquifer recharge. Finally, a standard lake water balance was applied to the lake, allowing comparison between terrestrial recharge and lake water fluxes to determine the potential contribution of groundwater to the lake system.

4.2.1 Field investigations and measurements

4.2.1.1 *Soil sampling*

Soil sampling was done at six different locations around the Río Cuarto catchment to analyse soil water retention properties relevant for hydrological and recharge calculations. To simplify the laboratory analysis, the samples were grouped into three soil classes, RC1, RC2 and RC3, based on their geographic location within the area, see figure 4.2. RC1 represents the south-central and south-eastern parts of the catchment near lake level, RC2 consist of one sample near lake level on the northern side and one on the crater wall in west, while RC3 correspond to the visitor centre area and a second nearby location at the top of the crater wall.

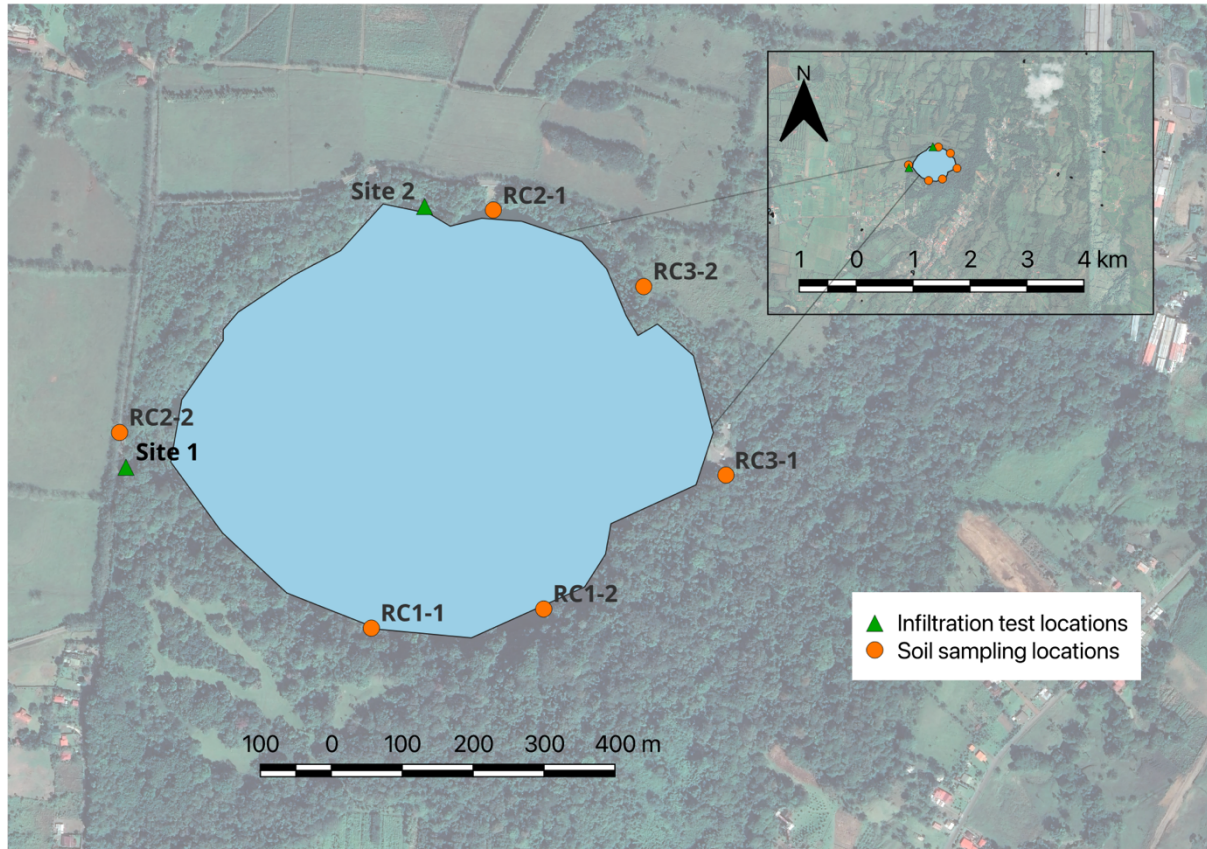


Figure 4.2: Soil sampling locations (RC1, RC2 and RC3) and infiltration test locations (Site 1 and Site 2) around Río Cuarto Lake. Basemap source: Google Satellite imagery.

Soil samples were collected by using a PVC ring inserted into the upper soil layer following the ring test procedure mentioned by Schosinsky (2006). The ring was inserted into the soil by using a hammer to isolate a representative surface layer sample, seen in Figure 4.3 and 4.4. This method allows the estimation of soil hydraulic properties related to water retention, which are relevant for groundwater recharge and water balance calculations.



Figure 4.3 and Figure 4.4: Soil sampling by gently hammering down a PVC ring into the top layer of the soil. The right picture shows the ring when it has been hammered down into the soil.

The soil samples were sent to a specialized laboratory for analysis of soil water retention properties, where laboratory personnel conducted the analyses to determine field capacity (CC) and permanent wilting point (PM) for each representative soil class. Field capacity (CC) was defined as the water content at a metric potential of 0.33 bar while the permanent wilting point (PM) corresponds to a metric potential of 15 bar. These parameters were used to evaluate the soil water storage in different parts of the study area.

4.2.1.2 Infiltration Tests

A double ring infiltrometer was used at two locations above the crater walls to estimate the hydraulic conductivity of the soil, see site 1 and site 2 in Figure 4.2. The two rings were inserted 5-10 cm into the upper soil layer, seen in Figure 4.5. Then water was poured into both rings to the same level above the ground, and the water level in the inner ring was measured at selected times, more often in the beginning, up until one hour (Ibañez et al., n.d.). As the test progressed, the infiltration rate gradually stabilized. The selected hydraulic conductivity was the value at the end of the test where the infiltration rate approached steady state flow.

The double-ring method minimizes lateral flow and provides a more reliable estimate of vertical infiltration compared to single-ring methods (Ibañez et al., n.d.). The hydraulic conductivity (f_c) that were acquired from these tests were used to support parametrization of the soil infiltration coefficient (Kf_c) in the Schosinsky model.



Figure 4.5: Double ring infiltrometer in field.

4.2.1.3 Lake Inflow Measurements

A volumetric analysis was used to estimate visible water seepage into the lake. According to Gore and Banning (2017), the volumetric approach provides reliable results when flow is concentrated and measurable.

Nine seepage paths were found leading into the lake, all of which were located on the southwest and south side of the lake. In Figure 4.2, they would all be located roughly in between RC2-1 and RC2-2. The inflows were uneven and not concentrated by default. A bucket with geometry suited for the specific site conditions was used at two locations where the inflow could be channelled and collected. The bucket volume was divided by the time required to fill it, to calculate the respective flowrates (Gore, JA & Banning, J, 2017).

Because of access difficulty to reach and measure all the observed seepage points, the remaining inflows were estimated visually. The two measured sites were used as references and compared with video recordings of the other inflows taken on the same days. By comparing the speed and size of the water streams in the videos with the known flow from the measured sites, a total estimated inflow for the entire lake was calculated.

4.2.1.4 Lake Outflow Measurements

The only surface outflow from the lake was located close to RC3-1 in Figure 4.2. Discharge from the outflow at the eastern side of the lake, to a stream later connecting with Río Cuarto River, was estimated with an application of the area-velocity method according to Gore and Banning (2017). The technique is called the midsection method, which is recommended by the USGS (US Geological Survey).

A cross-section of the outlet stream was selected and measured as 4.5 meters downstream from the outlet point. This was done to ensure stable flow conditions, see Figure 4.6. This location was chosen to ensure relatively uniform and stable flow conditions, since the flow at the outlet point was disrupted by protruding objects. The cross-section width was then measured with measuring tape and divided into multiple segments. The width of each segment was measured to analyse the respective velocities along the transect.



Figure 4.6: The only visible outflow from the lake. The figure shows water flowing east, left in the image. The orange line represents the 4.8 m wide cross-section used for flow measurements.

Velocity and depth were measured using a portable flow probe. The used probe measured velocities down to 0.1 m/s (Xylem, 2026). Water depth was measured at the centre of each subsection using the graduated scale integrated on the probe. For all velocity measurements, the probe was positioned at approximately 0.4 times the total water depth above the streambed within each subsection, following standard practice for shallow stream measurements (Gore, JA & Banning, J, 2017). To minimize flow disturbance, the operator stood downstream of the probe during measurements.

The discharge measurements were repeated twice to assess short-term variability and account for possible outlier results. In addition, the outflow was observed regularly during the study. Since the flow and water level remained stable, the two conducted tests were deemed sufficient to capture the outflow for the studied period. The values from both tests were averaged, and the mean representative discharge was calculated using Equation 4.4.

Discharge was calculated using the following formula, in accordance with Gore and Banning (2017):

$$Q = A \cdot v = \sum(b_x \cdot d_x \cdot v_x) \quad (4.3)$$

A = Cross-sectional area of the channel

v = Mean water-column velocity for the transect

b_x = Width of the given cell

d_x = Depth of the given cell

v_x = Velocity through the cell

4.2.2 Meteorological data

Meteorological data were collected from the Costa Rican National Meteorological Institute (IMN). The dataset was measured from station 69717, Hotel Pozo Azul (Río Tirimbina), located at 215 m a.s.l., approximately 30 km northeast from Laguna de Río Cuarto. This was the closest available station. The data cover the period 18 September 2013 to 10 January 2026 and include hourly precipitation (mm) and mean hourly air temperature (°C).

Several data gaps were identified for all the stated parameters, with precipitation showing the highest frequency of missing values. To remove these data gaps, two approaches were implemented for precipitation. For the years 2013, 2014, 2016, 2021, 2022, and 2026, where more than a month of precipitation data were missing or the year was incomplete, the entire years were discarded. This approach maintained complete annual cycles (2015, 2017-2020, 2023-2025) which allowed for continuous soil moisture estimations in the Schosinsky soil moisture balance model. Minor precipitation gaps of only a few hours within the selected years were addressed by assigning zero values, as the surrounding values were zero in nearly all cases. For mean hourly temperature, missing data points (approximately 70 out of 70 000 data points) were excluded from the calculations to use only measured values.

4.2.3 The Schosinsky Soil Water Balance Model

The Schosinsky (2006) soil water balance model was applied to estimate potential aquifer recharge in the terrestrial portion of the Río Cuarto lake catchment. The approach is commonly used for groundwater studies in Central America since it is developed for regional climatic and geological conditions, while not requiring extensive data. This made it suitable for the Río Cuarto lake catchment and this study. The lake itself was excluded from this analysis and required a separate hydrological approach, described in 4.2.4.

The model operates on a monthly time step and uses monthly precipitation and temperature data, combined with site-specific parameters such as vegetation interception, terrain slope, and soil hydraulic properties. These factors determine the volume of water that percolates below the root zone and contributes to the underlying aquifer (Schosinsky, 2006). The following sections describe the main model components and calculations: interception, infiltration, soil moisture balance, evapotranspiration, and aquifer recharge.

4.2.3.1 Interception

The first component of the model accounts for the portion of precipitation intercepted by vegetation before reaching the soil surface, which varies with vegetation type and density. According to Schosinsky & Losilla (2000), monthly precipitation under 5 mm was assumed to be fully intercepted by vegetation. To determine the interception for rainfall higher than 5 mm a month, a foliage coefficient based on land cover (C_{fo}) was applied. For normal foliage, which is the value applied in this study, $C_{fo} = 0.12$. The other option is for dense foliage, $C_{fo} = 0.20$ (Schosinsky, 2006).

Monthly interception (Ret) was calculated using the following conditions depending on monthly precipitation (P) and the foliage coefficient (C_{fo}) (Schosinsky, 2006):

$$Ret = \begin{cases} P, & \text{if: } P \leq 5\text{mm/month} \\ P \cdot C_{fo}, & \text{if: } P > 5\text{mm / month and } (P \cdot C_{fo}) \geq 5\text{mm/month} \\ 5\text{mm/month}, & \text{if: } P > 5\text{mm / month and } (P \cdot C_{fo}) \leq 5\text{mm/month} \end{cases}$$

4.2.3.2 Infiltration

After accounting for foliage retention, the remaining rainwater reaching the soil surface was partitioned into either infiltration or surface runoff based on soil and terrain characteristics. The volume of water that infiltrates is determined by monthly precipitation and the soil infiltration coefficient (C_i). This coefficient integrates several site-specific characteristics, including soil texture, terrain slope, and surface vegetation cover (Schosinsky, 2006). Higher slopes and less permeable soils reduce infiltration capacity while increasing surface runoff.

The soil texture infiltration coefficient (Kf_c) was derived from the basic soil infiltration parameter (f_c), a parameter distinct from field capacity (CC). The value f_c corresponds to the hydraulic conductivity of the upper 30 cm of soil, once saturated from rain, and was estimated with the double ring infiltrometer test described in 4.2.1.2. The relationship between these two variables were defined by the following conditions (Schosinsky, 2006):

$$Kf_c = \begin{cases} 0.267 \cdot \ln(f_c) - 0.000154f_c - 0.723, & \text{if: } 16 \leq f_c \leq 1568 \text{ mm/day} \\ 0.0148 \cdot \frac{f_c}{16}, & \text{if: } f_c < 16 \text{ mm/day} \\ 1, & \text{if: } f_c > 1568 \text{ mm/day} \end{cases}$$

The coefficients for terrain slope (K_p) and surface vegetation cover (K_v) were derived from standardized table values for different conditions provided by Schosinsky (2006). The slope coefficient (K_p) ranges from values between 0.30 for very flat terrain to 0.06 for steep slopes exceeding 7%. Conversely, the vegetation cover coefficient (K_v) ranges from 0.09 for sparse grass to 0.21 for dense cover exceeding 75%. This is because dense vegetation cover attenuates surface runoff, which enables a longer duration for infiltration to occur. K_p was set to 0.06, representing the steep conditions surrounding the lake, while K_v was set to 0.2, which is the predetermined value for forests according to Schosinsky 2006.

Once the components for soil texture (Kf_c), terrain slope (K_p), and vegetation cover (K_v) were determined for the Río Cuarto catchment, the soil infiltration coefficient (C_i) was calculated. This coefficient represents the fraction of rainfall reaching the ground available for soil infiltration. According to Schosinsky (2006), C_i was determined based on the following conditions:

$$C_i = \begin{cases} 1, & \text{if: } Kf_c + K_p + K_v > 1 \\ Kf_c + K_p + K_v, & \text{if: } Kf_c + K_p + K_v \leq 1 \end{cases}$$

With the foliage retention (Ret), infiltration coefficient (C_i), and monthly precipitation (P) established, the soil infiltration (P_i) and surface runoff (ESC) were calculated monthly with the following two equations according to Schosinsky (2006):

$$P_i = (C_i)(P - Ret) \quad (4.4)$$

$$ESC = P - Ret - P_i \quad (4.5)$$

The coefficients used in the calculations regarding interception and infiltration are presented in Table 4.1.

Table 4.1: Dimensionless coefficients from Schosinsky (2006) used to adjust monthly interception (Ret), soil infiltration (Pi) and surface runoff (ESC).

Dimensionless Coefficients	Value	Unit	Source
C_{fo}	0.12	-	Schosinsky (2006)
K_{fc}	0.985	-	Infiltration test
K_v	0.2	-	Field observations
K_p	0.06	-	Topographic analysis
C_i	1	-	Calculated in this study

The foliage coefficient for land cover (C_{fo}) was set to 0.12, representing normal vegetation cover conditions in a mixed land cover catchment. The soil texture infiltration coefficient (K_{fc}) was calculated based on the measured hydraulic conductivity ($f_c = 1200$ mm/day). The vegetation cover coefficient (K_v) was set to 0.2, corresponding to forested areas. The terrain slope coefficient (K_p) was set to 0.06 for slopes exceeding 7%, which is representative of the steep crater walls surrounding Río Cuarto Lake. The soil infiltration coefficient (C_i) was set to 1 since the sum of K_{fc} , K_v and K_p exceeded 1.

4.2.3.3 Soil Moisture Balance

The soil moisture balance within the root zone serves as the storage component of the recharge calculation (Schosinsky, 2006). The model conceptualizes the soil as a control volume with a surface area of 1 m² and a depth corresponding to the effective root depth. Soil moisture within this control volume was evaluated monthly to track storage changes for recharge calculations.

Effective root depth was assigned to 2500 mm based on the predetermined values for the forest vegetation type (Schosinsky, 2006, table 3). Within this control volume, soil moisture varies between the field capacity (CC) - the maximum amount of water the soil can retain against gravity, and the permanent wilting point (PM) - the moisture level below which plants cannot extract water. The difference between CC and PM represents the available water capacity, which determines both plant water availability and the soil's buffering capacity between precipitation events. These variations occur due to infiltration as well as water losses through evapotranspiration. CC and PM were calculated as average values between the three soil classes described in section 4.2.1.

The average gravimetric percentages for field capacity and permanent wilting point were converted to volumetric percentages by multiplication with estimated soil density (1.35 g/cm³), then multiplied by the root zone depth to determine the storage capacity range in millimeters. All subsequent soil moisture parameters were expressed in millimeters.

At the beginning of each month, the soil contains an initial soil moisture (HS_i), which was assumed equal to the final soil moisture (HS_f) of the previous month:

$$HS_i = HS_f \text{ (previous month)} \quad (4.6)$$

For the first month in each new yearly data set, 2015, 2017 and 2023, the initial soil moisture (HS_i) was assumed to be equal to the field capacity (CC), representing fully replenished soil conditions. Because the model was applied using several years of monthly data, the influence of this initial assumption diminished as soil moisture conditions adjusted to the prevailing precipitation and evapotranspiration conditions. The monthly soil moisture values were later utilized for the evapotranspiration and recharge calculations. The calculation of the final soil moisture (HS_f) is detailed in section 4.2.3.5, Aquifer recharge.

Next, the initial soil moisture HS_i together with the rainfall infiltration (P_i), was used to determine available soil moisture (HD) for evapotranspiration within the soil layer above the permanent wilting point (PM). This was calculated according to Schosinsky (2006) as:

$$HD = HS_i + P_i - PM \quad (4.7)$$

4.2.3.4 Evapotranspiration

Evapotranspiration in the Schosinsky (2006) model is defined as the sum of plant transpiration and soil evaporation within the root zone. The model distinguishes between potential evapotranspiration (ETP) - the maximum evapotranspiration that would occur under unlimited water availability, and actual evapotranspiration (ETR) - the evapotranspiration that occurs given the available soil moisture. Maximum evapotranspiration occurs when soil moisture (HS) is at field capacity (CC). As soil moisture decreases below this level, plant transpiration is progressively reduced because plants partially close stomata to limit water loss. When soil moisture reaches the permanent wilting point (PM), plants can no longer extract water, and both transpiration and root water uptake cease entirely.

Potential evapotranspiration (ETP) was first estimated as the initial step in the evapotranspiration calculation for the Río Cuarto lake catchment. Due to the high variability in plant species and vegetation development stages, estimating evapotranspiration rates for individual plants or sections was unfeasible. Instead, a catchment-wide value of potential evapotranspiration (ETP) was used to represent average evapotranspiration conditions across the catchment. Meteorological data obtained from the nearest IMN weather station did not include all variables required for more complex evapotranspiration models, such as the Penman-Monteith equation. Consequently, the following empirical model developed by Blaney and Criddle (Blaney & Criddle, 1950; Schosinsky 2006) was utilized to estimate the monthly catchment-wide potential evapotranspiration (ETP):

$$ETP = (8.10 + 0.46T) \cdot Ps \quad (4.8)$$

In Equation 4.8, T represents to the monthly mean temperature in degrees Celsius, while Ps is the percentage of annual daylight hours occurring during the given month. Values for Ps were obtained from the monthly daylight hour average distribution table provided by Schosinsky (2006).

The values acquired by soil analyses for field capacity (CC) and permanent wilting point (PM) were given in percentage of dry soil weight. To stay consistent with units, these two parameters were converted to millimeters, using the bulk density. The results for CC and PM can be seen in section 5.2.1.1.

The bulk density was estimated to $1,35 \text{ g/cm}^3$, which is the average value for clay loam according Schosinsky (2006). Percentage moisture by volume was estimated by multiplying percentage dry soil weight with bulk density in g/cm^3 . Millimeters of water was estimated by dividing percentage moisture by volume with 100 and multiplying this with the root depth in mm. The root depth was estimated to be 2500 mm, as stated in 4.2.3.3.

To account for the influence of soil moisture on evapotranspiration between the limits of field capacity (CC) and the permanent wilting point (PM), potential evapotranspiration (ETP) was adjusted using two soil moisture coefficients following the Schosinsky (2006) method. Both coefficients were constrained between 0 and 1 to ensure physically realistic values. The first coefficient (C1) represents the maximum soil moisture condition, which is after infiltration but before evapotranspiration:

$$C1 = \frac{(HSi - PM + Pi)}{(CC - PM)} \quad (4.9)$$

In Equation 4.9, HSi represent the monthly initial soil moisture, Pi the soil infiltration, CC the field capacity and PM the permanent wilting point. Based on the soil moisture coefficient C1, an estimate of the real potential evapotranspiration (ETR1) was calculated as a fraction of the potential evapotranspiration (ETP):

$$ETR1 = C1 \cdot ETP \quad (4.10)$$

The second moisture coefficient (C2) represents the soil moisture condition after evapotranspiration, accounting for both rainfall infiltration and evapotranspiration losses:

$$C2 = \frac{(((HSi + Pi) - PM) - ETR1)}{(CC - PM)} \quad (4.11)$$

Because infiltration and evapotranspiration occur continuously throughout the month, the effective moisture coefficient was assumed to correspond to the average of C1 and C2. The real potential evapotranspiration (ETPR) was therefore estimated as:

$$ETPR = \left(\frac{C1 + C2}{2} \right) \cdot ETP \quad (4.12)$$

Actual evapotranspiration (ETR) was limited by the amount of soil moisture available above the permanent wilting point. When the real potential evapotranspiration (ETPR) exceeded the available soil moisture (HD), actual evapotranspiration (ETR) was limited to HD. Otherwise, ETR was assumed equal to ETPR, see conditions below:

$$ETR = \begin{cases} ETPR, & \text{if: } ETPR \leq HD \\ HD, & \text{if: } ETPR > HD \end{cases}$$

Where ETPR represents potential evapotranspiration adjusted by soil moisture availability.

4.2.3.5 Aquifer Recharge

In the model, recharge occurs when infiltration exceeds both the evapotranspiration demand and the storage capacity of the soil within the root zone, allowing excess water to percolate downwards into the aquifer and groundwater system. Groundwater recharge was estimated using the soil water balance approach proposed by Schosinsky (2006), using values of the previously determined parameters. The method evaluates monthly variations of soil moisture within the control volume.

First, the soil moisture at the end of the month (HS_f) was calculated based on the available soil moisture (HD), the permanent wilting point (PM), actual evapotranspiration (ETR) and field capacity (CC), using the following conditional rules:

$$HS_f = \begin{cases} HD + PM - ETR, & \text{if } (HD + PM - ETR) < CC \\ CC, & \text{if } (HD + PM - ETR) \geq CC \end{cases}$$

Recharge represents water percolating below the root zone after satisfying evapotranspiration and soil storage. Following the parameters and conditions established in the previous sections, the potential monthly recharge (R_p) was calculated with Equation 4.13.

$$R_p = P_i + HS_i - HS_f - ETR, \quad \text{for } R_p \geq 0 \quad (4.13)$$

To convert the recharge estimates from depth (mm) to volume, the terrestrial drainage area of 17.40 ha, corresponding to $174 \cdot 10^3 \text{ m}^2$ reported by Gocke et al. (1987), was applied.

It should be noted that this approach estimates diffuse recharge through the soil profile and does not account for flow through fractures or macropores, which may be locally significant in the volcanic terrain.

4.2.4 Río Cuarto Lake Water Balance

Previously the Schosinsky approach was utilized to account for groundwater recharge in the terrestrial part of the Río Cuarto Lake catchment. A larger portion of the catchment surface area consists of the lake itself, which requires a different hydrological approach. The water balance of the lake involves direct exchange processes with the atmosphere and the surrounding aquifer. These processes were calculated with equations 4.14 and 4.15, adapted from Fetter and Kreamer (2022).

$$GW_{net} = GW_{in} - GW_{out} \quad (4.14)$$

$$\Delta S = P - E + Q_{in} - Q_{out} + GW_{net} \quad (4.15)$$

Where ΔS represents changes in lake water storage, P is precipitation, E is evaporation, Q_{in} and Q_{out} are surface water inflows and outflows, and GW_{in} and GW_{out} are groundwater inflow to and outflow from the lake.

4.3 Water Sampling and Analysis

Water sampling and analysis were conducted to characterize the vertical variability of chemical conditions in Río Cuarto Lake. One sampling location was selected in the centre of the lake, where samples were collected at surface level (0–1 m depth) and at selected depths in the water column: 10 m, 18 m, 23 m, 30 m, 45 m and 60 m. One water sample was collected at each selected depth.

The selected depths were chosen based on Cabassi et al. (2014), who concluded that the transition between the epilimnion and hypolimnion in the lake usually occurs between 20 and 25 m depth, depending on the time of year (May–June and January–February). The selected depths therefore represent different parts of the lake water column, including the surface layer, the thermocline region and deeper anoxic waters.

Measurements with the portable multimeter probe were performed on the collected depth samples, while the collected water samples were also analysed in the laboratory for additional water quality parameters. In addition to the lake samples, a single water sample was collected from spring inflow IF2 on the western side of Río Cuarto Lake. This spring is the same as inflow 2 (IF2) from the inflow calculations in Section 5.2.1.3. The spring sample was analysed in the laboratory using the same method as the lake water column samples.

The spring was selected because it represents water entering the lake directly from the surrounding catchment and was therefore considered a suitable groundwater-influenced reference sample. Although one sample cannot fully represent temporal variability, it provides an initial indication of the chemical characteristics of water entering the lake from the shoreline and can be compared with the lake water column samples. The spring can be seen in Figure 4.7.



Figure 4.7: Spring inflow IF2 located on the western side of Río Cuarto Lake, where a single water sample was collected

4.3.1 Sampling Strategy

Deeper water samples were collected using a Kemmerer water sampler, shown in Figure 4.8. The sampler was lowered to the desired depth using a rope with depth markings. Once the sampler reached the planned depth, the device was triggered by releasing a weight along the line, which caused the sampler to close and capture water from that depth. After retrieval, the water was transferred into pre-labelled sample containers. All containers were rinsed with lake water prior to filling to minimize contamination.

The surface sample (0–1 m) was collected manually using a clean sample container rinsed with lake water. One water sample was collected from each selected depth in the central basin. The sample collected at 10 m depth was measured directly after collection using the portable multiparameter probe. Water samples collected from the other depths (18 m, 23 m, 30 m, 45 m and 60 m) were stored in sealed containers and measured with the probe four days after collection, because the probe was not available during the full sampling campaign. This time delay may have influenced parameters sensitive to oxidation, degassing and biological activity, particularly dissolved oxygen and redox potential. The collected water column samples were also used for laboratory analysis.



Figure 4.8: Kemmerer water sampler used for collecting water samples at selected depths in the water column.

4.3.2 Multimeter Probe Measurement

Measurements with the portable multiparameter probe were performed on the collected water samples. The sample from 10 m depth was measured directly after collection during the sampling campaign, while the samples from 18 m, 23 m, 30 m, 45 m and 60 m were measured four days after collection. The measurements were conducted using a portable multiparameter probe (APERA SC751), shown in Figure 4.9.

The following parameters were recorded:

- pH
- electrical conductivity (S cm⁻¹)
- dissolved oxygen (mg L⁻¹)
- oxidation reduction potential (mV)

The probe was calibrated according to the manufacturer's instructions.



Figure 4.9: Portable multimeter probe (APERA SC751) used when measuring water quality.

4.3.3 Water Quality Parameters Standards

To evaluate the measured water quality results in this study, reference values from established water quality standards were used, shown in Table 4.2. The reference values applied in this study was based on the Costa Rican regulation for the evaluation and classification of surface water bodies (MINAE, 2007). These standards define recommended threshold values for physical and chemical parameters commonly used to assess the condition of freshwater ecosystems.

Table 4.2: Reference values for selected water quality parameters based on the Costa Rican water quality regulation (MINAE, 2007).

Parameters	Unit	Reference Value	Type
pH	-	6.5-8.5	Range
Temperature	[°C]	<30	Maximum
Dissolved Oxygen (DO)	[mg/L]	>5	Minimum
Conductivity	[μS/cm]	<500	Maximum
BOD ₅	[mg/L]	<3	Maximum
NH ₄ ⁺	[mg/L]	<0.5	Maximum
NO ₃ ⁻	[mg/L]	<10	Maximum
PO ₄ ³⁻	[mg/L]	<0.05	Maximum
Coliform Bacteria	[Pres/Abs]	Absent	Requirement
Redox Potential	[mV]	>100	Minimum

4.3.4 Water Transparency

Water transparency was assessed by using a Secchi disc with alternating black and white quadrants. The Secchi depth is used as an indicator of water clarity in lakes and is considered a reliable water quality parameter when transparency exceeds approximately 1.5 m (Lee et al., 1995). The disc was slowly lowered into the water and until it reached a depth where it was no longer visible from the surface. This disappearance depth was recorded as the Secchi depth.

The measurement was done during stable weather conditions without rain, strong wind or intense sunlight, to reduce disturbances to the water surface and improve reliability of the observation. The Secchi depth was used as a simple indicator of water clarity and the depth to which light can reach into the lake.

4.4 Groundwater Assessment

Since no monitoring wells or groundwater level loggers were available at the site, direct measurements of groundwater levels could not be conducted during the fieldwork. Therefore, groundwater–lake interactions were assessed using hydro-chemical indicators and conceptual water balance calculations.

4.4.1 Groundwater indicators

The potential influence of groundwater on the lake was evaluated using indicators from field measurements and laboratory analyses. These indicators included:

- vertical variations in electrical conductivity (EC), pH, dissolved oxygen (DO), and redox potential
- concentrations of nutrients and hardness-related parameters
- comparisons between surface water and deeper water chemistry
- evaluation of conceptual lake water balance calculations

If groundwater inflow occurs into the lake, it may affect the chemical composition of the water. In this study, potential groundwater influence was evaluated using the measured physicochemical parameters, including pH, electrical conductivity, redox potential, dissolved oxygen, ammonium, nitrate, phosphate, calcium hardness, and magnesium hardness.

Higher electrical conductivity (EC) values in deeper water compared to surface water could be an indication of subsurface inflow of mineral-rich groundwater or the accumulation of dissolved substances under low-oxygen conditions in deeper parts of the lake. However, such differences may also reflect internal lake processes, including thermal stratification and reduced vertical mixing.

4.4.2 Water Balance Approach

Groundwater contribution to the lake system was further evaluated using a conceptual water balance approach based on the Schosinsky (2006) soil and water balance model applied to the lake catchment. The model uses climatic inputs, such as precipitation and evaporation, together with soil and land cover characteristics to estimate potential groundwater recharge.

If the estimated recharge is significant compared to evaporation losses and lake volume changes, groundwater is likely to represent an important component of the lake water balance. On the other hand, if recharge is small relative to evaporation, the lake system is likely to be dominated by direct precipitation and evaporation with a limited groundwater connection.

However, due to the absence of direct groundwater level monitoring, groundwater–lake interactions in this study can only be evaluated conceptually.

5 Results

5.1 Bathymetric Survey

The distribution of bathymetric survey points, measured from transects over the lake, shows that measurements were collected across the entire lake basin, with slightly higher point density along the main transects (Figure 5.1).

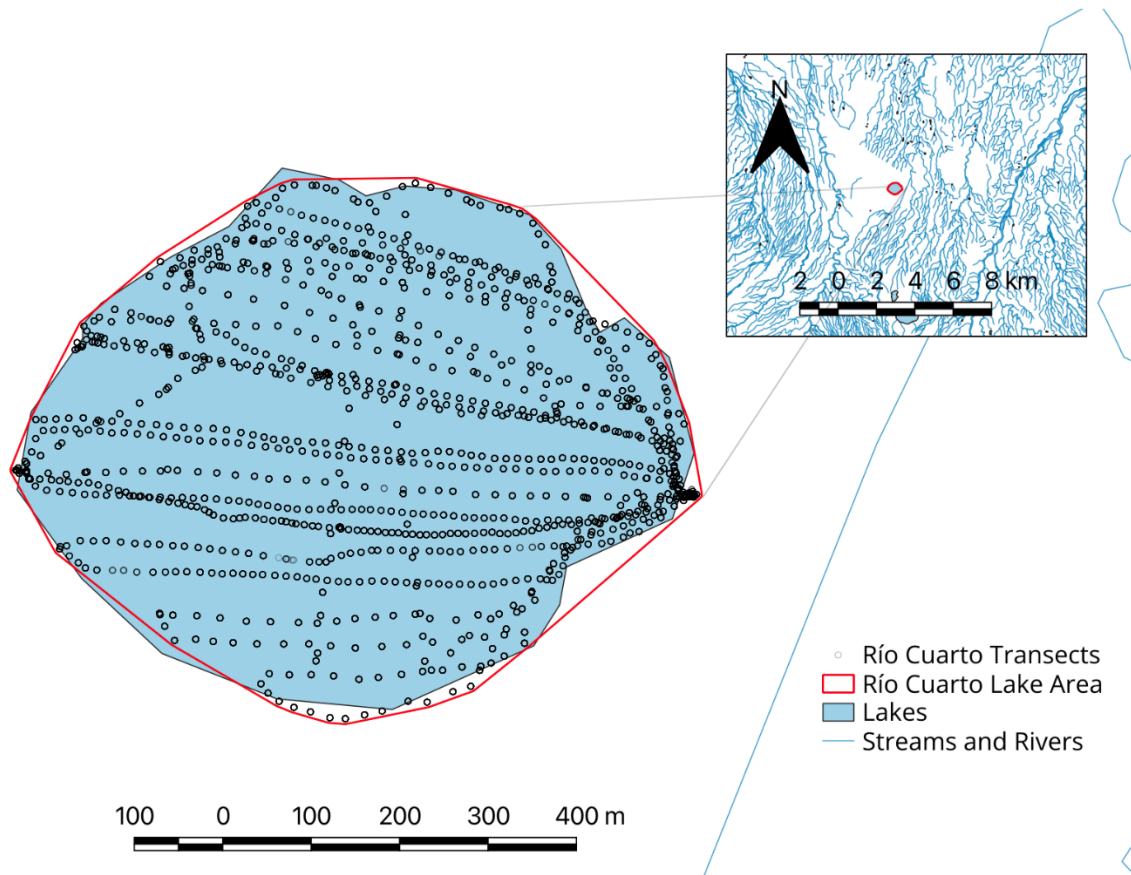


Figure 5.1: Distribution of bathymetric survey points across Río Cuarto Lake. The inset map shows the location of the study area within the surrounding region. The red lake area polygon was created to include all measurement points collected on Río Cuarto Lake during the bathymetric survey.

The bathymetric interpolation shows that Río Cuarto Lake has a steep-sided basin morphology, where depth increases from the shoreline towards the central part of the lake. The maximum measured depth during the survey was 73.6 m, indicating that the lake is deeper than previously reported values in earlier studies.

The depth contour map shows that the deepest zones are concentrated in the central basin, while shallower areas are mainly located along the lake margins (Figure 5.2).

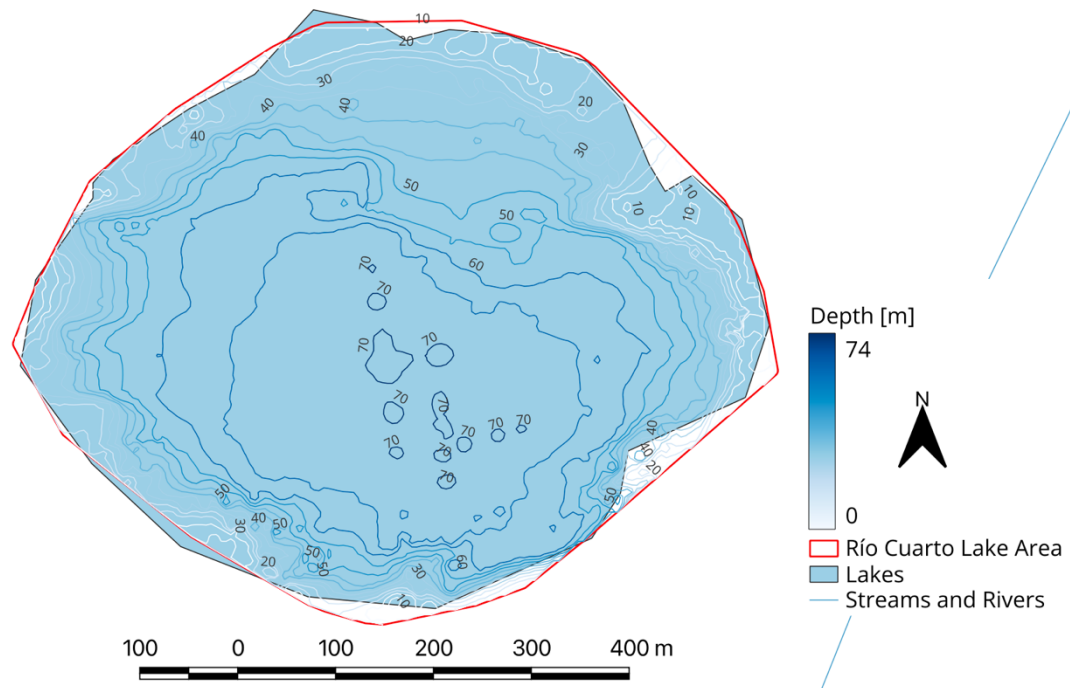


Figure 5.2: Bathymetric depth contour map of Río Cuarto Lake. The map illustrates the spatial distribution of lake depth, showing the deepest zones concentrated in the central basin and shallower areas along the lake borders. The red lake area polygon was created to include all measurement points collected on Río Cuarto Lake during the bathymetric survey.

The three-dimensional model of the interpolated bathymetric surface illustrates the crater-shaped morphology of the lake basin. The model shows steep slopes from the shoreline towards the deepest central parts of the lake (Figure 5.3). Shallow areas are mainly found near the lake edges, while the central basin contains the greatest depths.

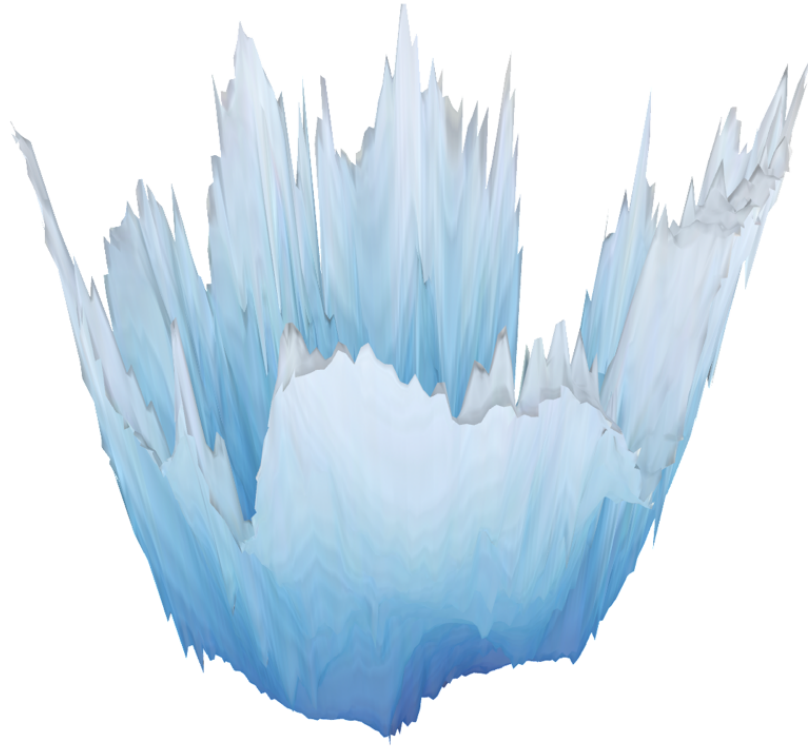


Figure 5.3: Three-dimensional bathymetric model of Río Cuarto Lake. The model is shown with vertical exaggeration to improve visualization of the lake basin morphology; therefore, the vertical scale is not directly comparable to the horizontal scale.

The bathymetric analysis of Río Cuarto Lake resulted in a lake surface area of $336 \cdot 10^3 \text{ m}^2$ and a total lake volume of $16.25 \cdot 10^6 \text{ m}^3$. Based on these values the average lake depth was calculated to 48.3 m. These values are based on interpolated bathymetric data from field measurements collected during the study period.

Table 5.1: Bathymetric analysis results of Río Cuarto Lake.

Parameter	Value
Maximum depth	73.6 m
Mean depth	48.3 m
Lake area	$336 \cdot 10^3 \text{ [m}^2\text{]}$
Lake volume	$16.25 \cdot 10^6 \text{ [m}^3\text{]}$

5.2 Hydrological Balance

The hydrological balance of Río Cuarto Lake catchment was estimated based on field measurements, meteorological data, the Schosinsky soil water balance model, and a standard lake water balance model. Detailed monthly calculations are included in the Appendix.

5.2.1 Field investigations and measured catchment properties

5.2.1.1 Soil Properties

The soil water retention analysis showed clear differences between the three representative soil classes in the Río Cuarto catchment. These differences reflect spatial variations in soil hydraulic properties that influence groundwater recharge and water availability in the study area. Field capacity (FC) and permanent wilting point (PWP) are presented as gravimetric water content (% of dry soil weight).

Sample RC1, representing the south-central and south-eastern parts of the catchment, showed the highest water retention capacity. FC for RC1 was 89.30%, while PWP was 31.51%. These values indicate high available water content and suggest that soils in this area can retain large amounts of water following rainfall events.

Sample RC2, representing the northern and western parts of the catchment, showed lower water retention capacity. FC for RC2 was 40.25%, while PWP was 26.74%. These lower values suggest faster infiltration and reduced water storage within the root zone compared to RC1.

Sample RC3, representing the visitor centre area and the sampling location at the top of the crater wall, showed intermediate to high water retention values. FC for RC3 was 75.97%, while PWP was 33.71%. These results indicate moderate water storage capacity in this part of the catchment.

Table 5.2: Laboratory results of soil sampling analyse.

Sample	Coordinates	Location/Area	Field Capacity (FC) %	Permanent Wilting Point (PWP) %	Available Water Content (%)
RC1	1: 476163E, 1144855N. 2: 476406E, 1144882N	South Side (central/eastern)	89.30	31.51	57.79
RC2	1: 476335E, 1145445N 2: 475808E, 1145131N	North Side	40.25	26.74	13.51
RC3	1: 476663E, 1145071N 2: 476547E, 1145337N	Visitor centre and sample 2	75.97	33.71	42.26
Average	-	Study Area	68.51	30.65	37.85

The results show spatial variability in soil water retention properties across the Río Cuarto catchment. The differences between soil classes could influence infiltration, groundwater recharge and the overall hydrological response of the catchment system. The average gravimetric percentages for field capacity and permanent wilting point were converted to volumetric percentages by multiplication of estimated soil density (1.35 g/cm^3) and then converted to millimetres for the 2.5 m root zone, see table 5.3.

Table 5.3: Conversion of average Field capacity (FC) and Permanent wilting point (PM) into mm

Parameter	% Dry soil weight	% Volume	mm
FC	68.51	92.48	2312.10
PM	30.65	41.38	1034.55

5.2.1.2 Infiltration Capacity

Infiltration tests were done at two locations within the Río Cuarto catchment to evaluate soil permeability and recharge potential. Figure 5.4 show the results from the infiltration capacity.

At Site 1, the water level in the inner ring decreased from 16.8 cm at the start of the test to 8.7 cm after 30 minutes. After these 30 minutes the water in the inner ring was refilled from 8.7 cm to 15.5 cm to maintain sufficient water depth in the ring and allow continued measurement of infiltration (see Figure 5.5). During the following 30 minutes, the water level decreased further to 9.5 cm. The result indicates a quite high infiltration capacity and suggests that the soil at this location allows fast vertical water movement.

At site 2, the water level decreased from 19.0 cm to 15.9 cm during the same period. The smaller difference in water level indicates lower infiltration capacity compared to Site 1, suggesting slower water movement through the soil. Results are summarized in Table 5.4.

Table 5.4: Results from infiltration tests using double-ring infiltration method.

Test Site	Coordinates	Initial water level [cm]	Final water level [cm]	Test duration [min]	Water level decrease [cm]
1	475817E, 1145082N	16.8	8.7	30	8.1
1 (refilled)	475817E, 1145082N	15.5	9.5	30	6.0
2	476238E, 1145450N	19.0	15.9	60	3.1

The infiltration rate at Site 1 had an average of 0.27 cm/min during the first 30 minutes and 0.20 cm/min after water refilling giving a mean value of 0.24 cm/min. The average infiltration rate at Site 2 was approximately 0.05 cm/min during the 60-minute test period. An average hydraulic conductivity was chosen for the catchment representing the infiltration rate at the end of the 60 minutes for both sites, since the rate approached steady conditions at the end. For test site 1 this was 1.4 mm/min and for test site 2 this was 0.3 mm/min, resulting in an average hydraulic conductivity of 0.85 mm/min or roughly 1200 mm/day.

These results show a spatial variability in infiltration capacity within the catchment and were used to support estimation of recharge parameters in the Schosinsky water balance model.

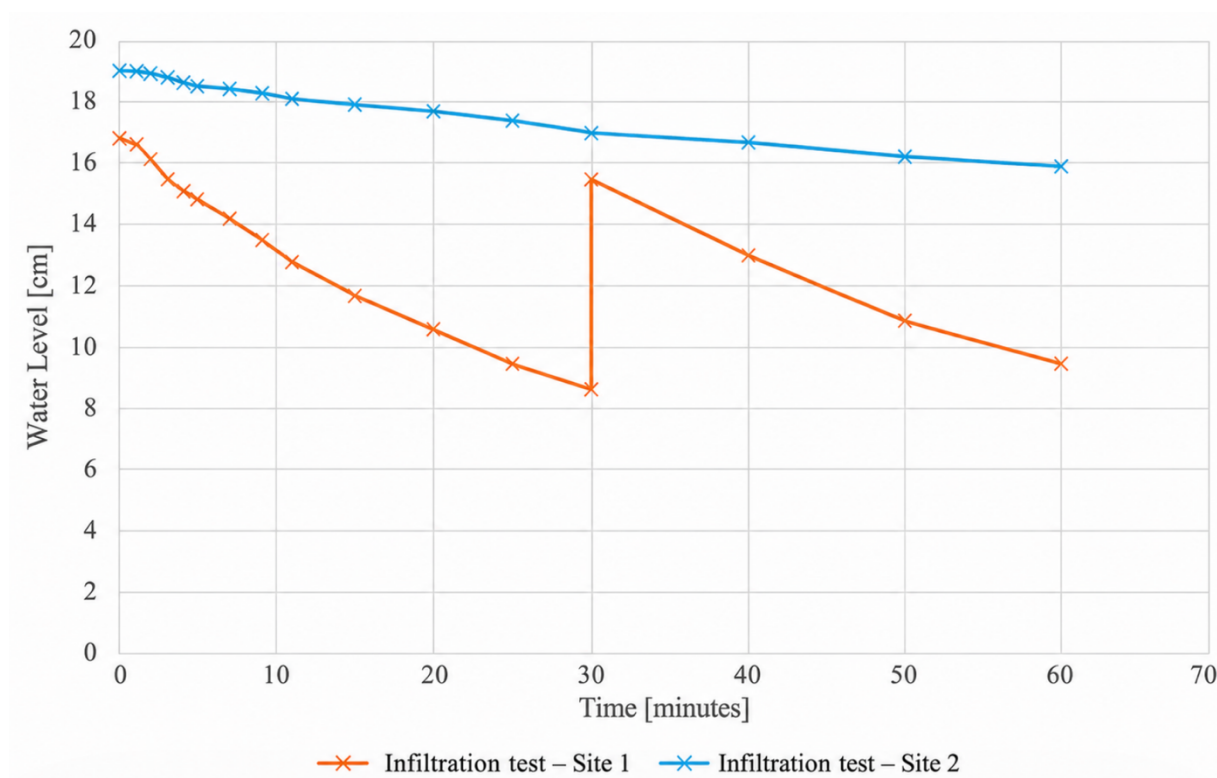


Figure 5.4: Change in water level over time during double-ring infiltration tests at two sites in the Río Cuarto catchment. Site 1 and Site 2 represent separate infiltration test locations. The increase in water level at Site 1 after 30 minutes is due to additional water being added to the double-ring infiltrometer.

The measured infiltration rates demonstrate moderate to high permeability in the catchment soils, supporting the potential for groundwater recharge.

5.2.1.3 Observed Lake Inflow

The observed inflows provide an estimate of the visible surface water contribution to Río Cuarto Lake during the field period. The results from the inflow observations and calculations are summarized in Table 5.5.

Table 5.5: Measured and estimated inflows around Río Cuarto Lake. Inflows were numbered anticlockwise from IF1 (west) to IF9 (southeast). IF2 and IF4 were measured using the volumetric bucket method, while the remaining inflows were visually estimated using video comparison.

Inflow	$Q_{in,min}$ [l/s]	$Q_{in,min}$ [10^3 m³/year]	$Q_{in,max}$ [l/s]	$Q_{in,max}$ [10^3 m³/year]
IF 1	0.5	15.8	1.5	47.3
IF 2	12	378	18	568
IF 3	2	63.1	3	94.6
IF 4	6	189	8	252
IF 5	1	31.5	2	63.1
IF 6	1	31.5	2	63.1
IF 7	1	31.5	2	63.1
IF 8	8	252	12	378
IF 9	4	126	7	221
Total	35.5	1119	55.5	1750

The mean observed inflow, calculated from the values presented in Table 5.5, was estimated as $1430 \cdot 10^3$ m³/year.

5.2.1.4 Measured Lake Outflow

The lake outflow was measured to quantify the amount of water leaving the lake through the identified outlet. The results of the measured lake outflow are presented in Table 5.6.

Table 5.6: Measurements and results for the lake discharge along the 4.8 m wide cross-section using the area-velocity approach. Width is measured from the north bank as reference.

Width (b)[m]	Depth (d)[m]	Velocity (v)[m/s]	Discharge (q) $q_x = b_x \cdot d_x \cdot v_x$ [m ³ /s]
0.3	0.20	0.0	0
0.2	0.27	0.1	0.0054
0.5	0.36	0.2	0.036
0.5	0.38	0.1	0.019
0.5	0.40	0.05	0.01
1	0.44	0.1	0.044
0.5	0.42	0.1	0.021
1.3	0.28	0.0	0
			$\sum 0.135$

The total discharge was calculated to $0.135 \text{ m}^3/\text{s} = 135 \text{ l/s}$, corresponding to $4260 \cdot 10^3 \text{ m}^3/\text{year}$.

5.2.2 Meteorological Conditions

Meteorological conditions were analysed using historical monthly precipitation and temperature data to provide input for the hydrological balance calculations. Precipitation and temperature results are presented in Figure 5.5 and Figure 5.6.

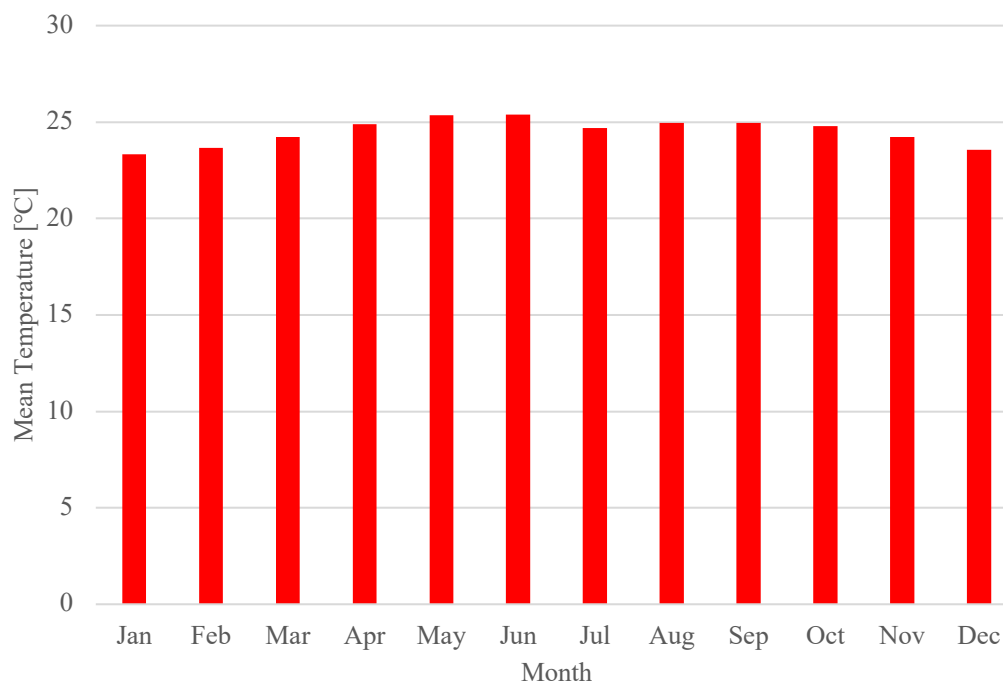


Figure 5.5: Mean monthly temperature data based on data from the years 2015, 2017, 2018, 2019, 2020, 2023, 2024 and 2025. Source: IMN weather station 69717.

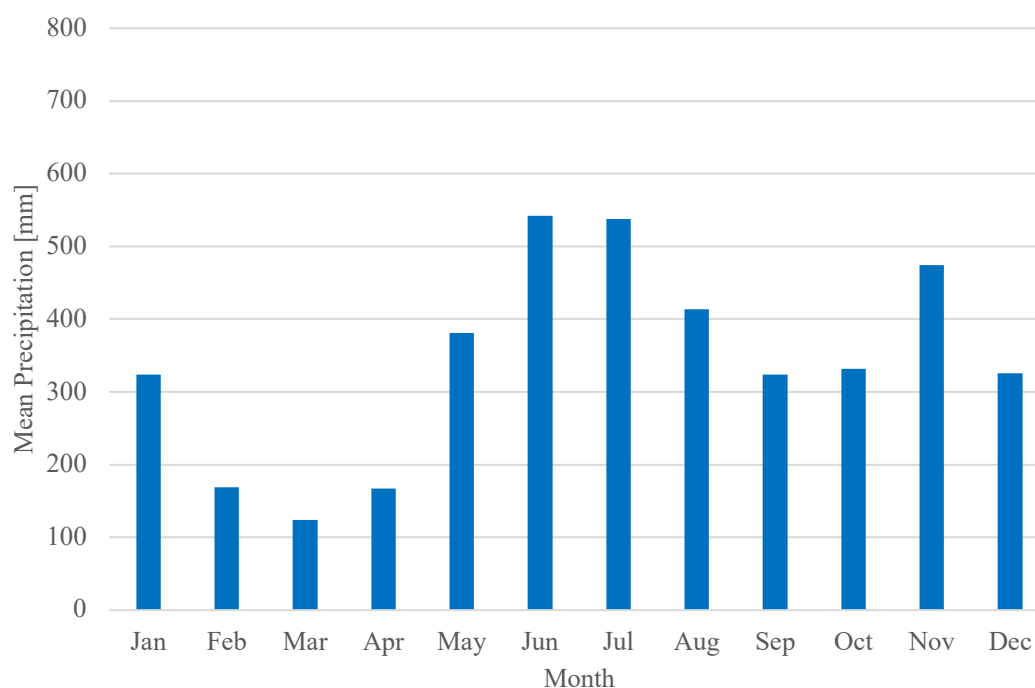


Figure 5.6: Mean monthly precipitation based on precipitation data from 2015, 2017, 2018, 2019, 2020, 2023, 2024 and 2025. Source: IMN weather station 69717.

5.2.3 Schosinsky Soil Water Balance and Recharge

This section presents the resulting recharge estimates from the Schosinsky soil water balance model, which were used in the overall hydrological balance assessment.

5.2.3.1 Annual Recharge

Annual recharge results provide an indication of how much precipitation may contribute to subsurface flow and possible groundwater interaction with the lake. The annual recharge results are presented in Tables 5.7 and 5.8. More comprehensive data and parameters involved in the recharge estimates can be found in the appendix under section 9.2.

Table 5.7: Total precipitation, actual evapotranspiration (ETR), recharge potential and equivalent recharge volume for the years 2015, 2017, 2018, 2019, 2020, 2023, 2024, 2025.

Year	Total Precipitation [mm]	Total ETR [mm]	Total Recharge Potential [mm]	Recharge volume [$10^3 m^3$]
2015	4713	1964	2183	379
2017	3375	1977	993	173
2018	4225	1933	1798	313
2019	3468	1935	1163	194
2020	3361	1956	1001	174
2023	3420	1962	1047	182
2024	5292	1979	2677	466
2025	5054	1951	2496	434

Table 5.8: Recharge Statistics for the years 2015, 2017, 2018, 2019, 2020, 2023, 2024, 2025.

Parameter	Value [mm]
Mean annual recharge	1670
Minimum recharge	993
Maximum recharge	2677
Standard deviation	710

5.2.4 Lake water balance

Lake water balance results are presented in Table 5.9. The lake water balance was evaluated by comparing the calculated atmospheric and surface-water components of Río Cuarto Lake. Precipitation on the lake surface, lake evaporation, observed surface inflow and measured surface outflow were evaluated to assess whether the measured lake discharge could be explained without an additional groundwater contribution.

$$\Delta S = P - E + Q_{in} - Q_{out} + GW_{net}$$

Where GW_{net} represents the net groundwater exchange term ($GW_{in} - GW_{out}$). The lake surface area was determined from GIS analysis and estimated at $336 \cdot 10^3 \text{ m}^2$.

Table 5.9: Mean annual water balance for Río Cuarto Lake

Component	Symbol	Value [$\cdot 10^3$]	Unit
Lake surface area	A_{Lake}	336	m^2
Precipitation over lake	P	1380	m^3/year
Evaporation over lake	E	710	m^3/year
Net atmospheric contribution	P - E	670	m^3/year
Recharge volume	V	290	m^3/year
Surface inflow	Q_{in}	1430	m^3/year
Total water inputs	$(P - E) + Q_{in}$	2100	m^3/year
Surface outflow	Q_{out}	4260	m^3/year
Residual imbalance	$Q_{out} - ((P - E) + Q_{in})$	2160	m^3/year
Net groundwater exchange	GW_{net}	Not directly known	m^3/year
Change in storage	ΔS	Not directly known	m^3/year

Mean annual precipitation directly over the lake surface was calculated to $1380 \cdot 10^3 \text{ m}^3/\text{year}$ based on meteorological data and lake area. Mean annual lake evaporation was estimated using the regional daily evaporation value of 5.8 mm/day reported for the Northern climatic region of Costa Rica by Hernández Espinoza (2014). Based on the Río Cuarto lake area of $336 \cdot 10^3 \text{ m}^2$, this results in an estimated annual evaporation volume of $710 \cdot 10^3 \text{ m}^3/\text{year}$. The resulting net atmospheric contribution (P-E) was therefore $670 \cdot 10^3 \text{ m}^3/\text{year}$.

Observed surface inflow around the lake was approximated to be $1430 \cdot 10^3 \text{ m}^3/\text{year}$ as a mean value based on minimum and maximum inflow estimations. The total water input to the lake was $2100 \cdot 10^3 \text{ m}^3/\text{year}$.

In comparison, the measured lake outflow corresponded to $4260 \cdot 10^3 \text{ m}^3/\text{year}$. However, the known atmospheric and observed surface inflow components were not enough to explain the measured outflow. The remaining imbalance of $2160 \cdot 10^3 \text{ m}^3/\text{year}$ indicates that additional water sources or unknown balance terms are required.

5.3 Water Sampling and Analysis

Water sampling and field measurements were conducted to evaluate spatial and vertical variations in lake water quality. The analysis focused on parameters that can indicate stratification, groundwater influence and changes in chemical conditions within the lake.

5.3.1 Water column multimeter probe

The multimeter probe measurements were used to assess vertical changes in basic water quality parameters within the lake water column. The results from the multimeter probe are presented in Table 5.10.

Table 5.10: Results from measurements performed with the APERA SX751 portable multimeter probe on water samples collected from selected depths in the central basin. No measurement was performed on the surface water.

Depth [m]	pH	DO [mg/L]	Electrical Conductivity [$\mu\text{S}/\text{cm}$]	Redox potential [mV]
10	7.98	6.8	135.8	+158
18	7.74	6.4	134.3	+156
23	7.85	7.3	135.8	+158
30	7.75	5.3	134.8	+156
45	7.23	4.3	135.9	+162
60	7.18	6.5	235	+173
Spring	7.62	7.0	178.9	+162

5.3.2 Water column lab analysis

Figure 5.7 demonstrates the pH values measured in the water column. Figures 5.8, 5.9 and 5.10 summarize the laboratory results from the measured water-quality parameters from surface and depth specific samples collected in Río Cuarto Lake. Figure 5.11 presents the main physicochemical parameters, while Table 5.11 presents nutrient, microbiological, and supplementary chemical parameters in the water column.

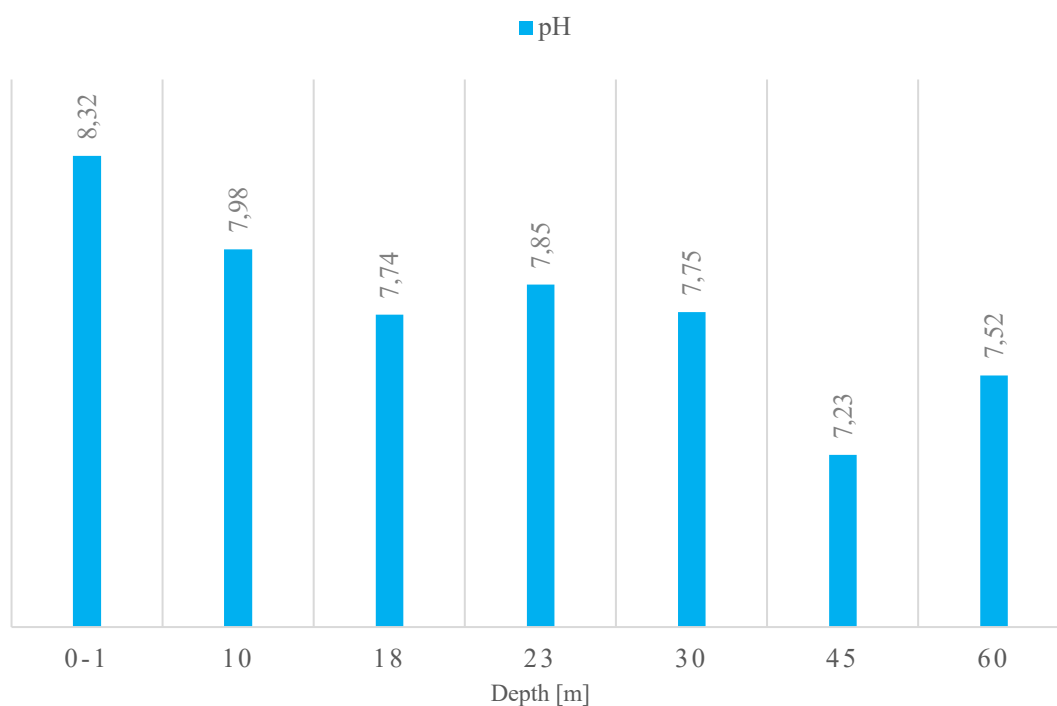


Figure 5.7: pH values measured at the depths 10 m, 18 m, 23 m, 30 m, 45 m and 60 m in Río Cuarto Lake.

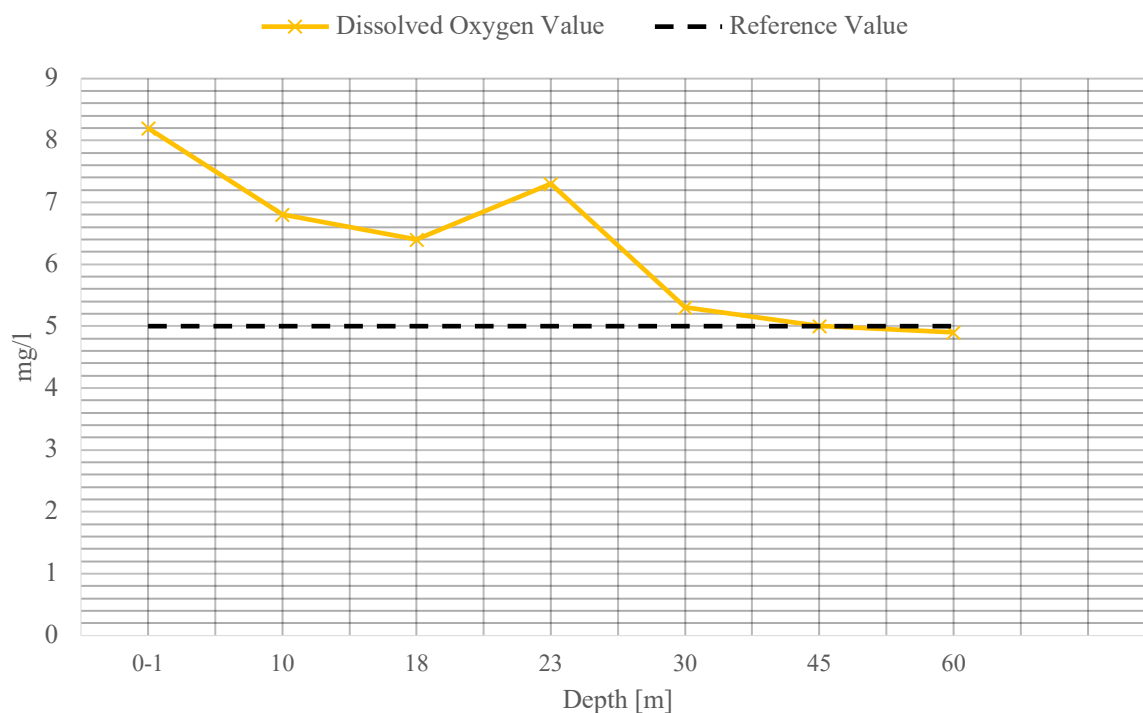


Figure 5.8: Vertical profile of dissolved oxygen concentration at the depths 10 m, 18 m, 23 m, 30 m, 45 m and 60 m in Río Cuarto Lake. The dashed line indicates the reference value of 5 mg/l.

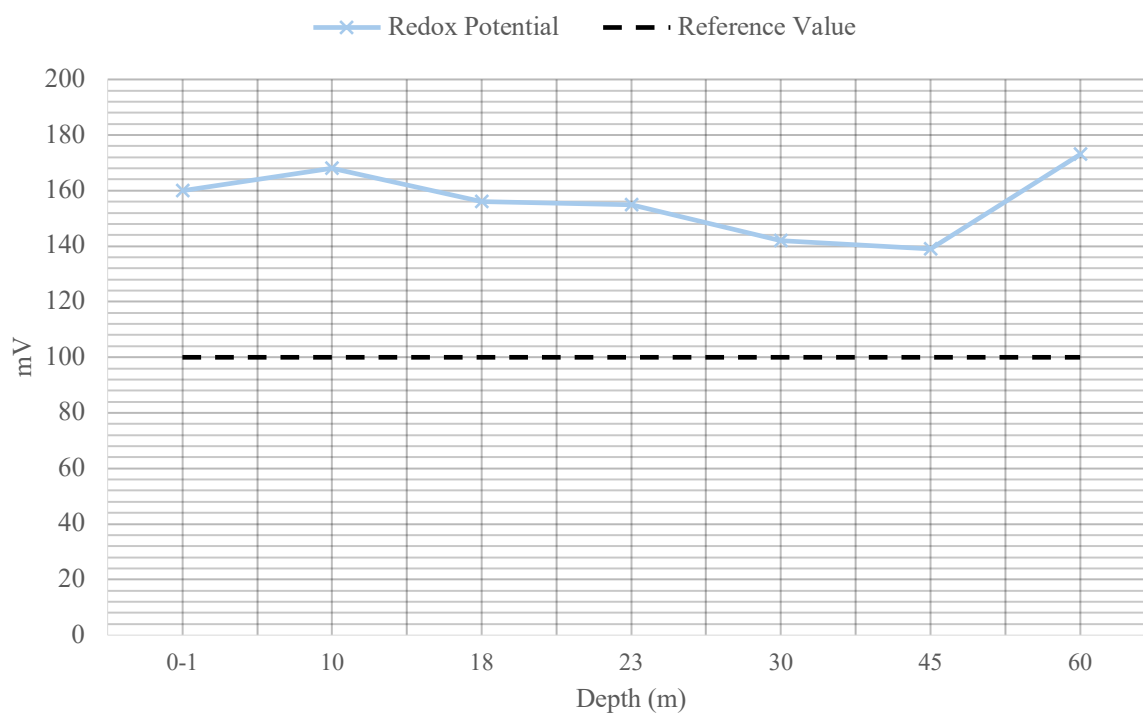


Figure 5.9: Vertical profile of redox potential (ORP) at the depths 10 m, 18 m, 23 m, 30 m, 45 m and 60 m in Río Cuarto Lake. The dashed line indicates the minimum reference value of 100 mV.

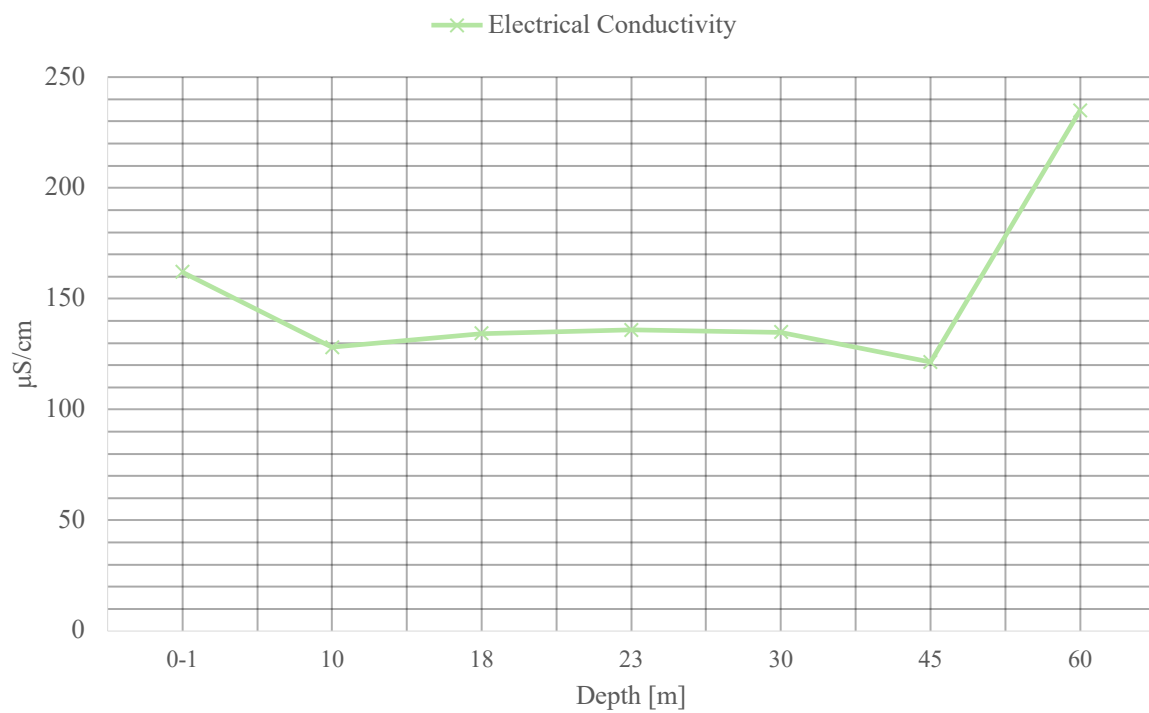


Figure 5.10. Vertical profile of electrical conductivity measured at the depths 10 m, 18 m, 23 m, 30 m, 45 m and 60 m in Río Cuarto Lake. No reference value.

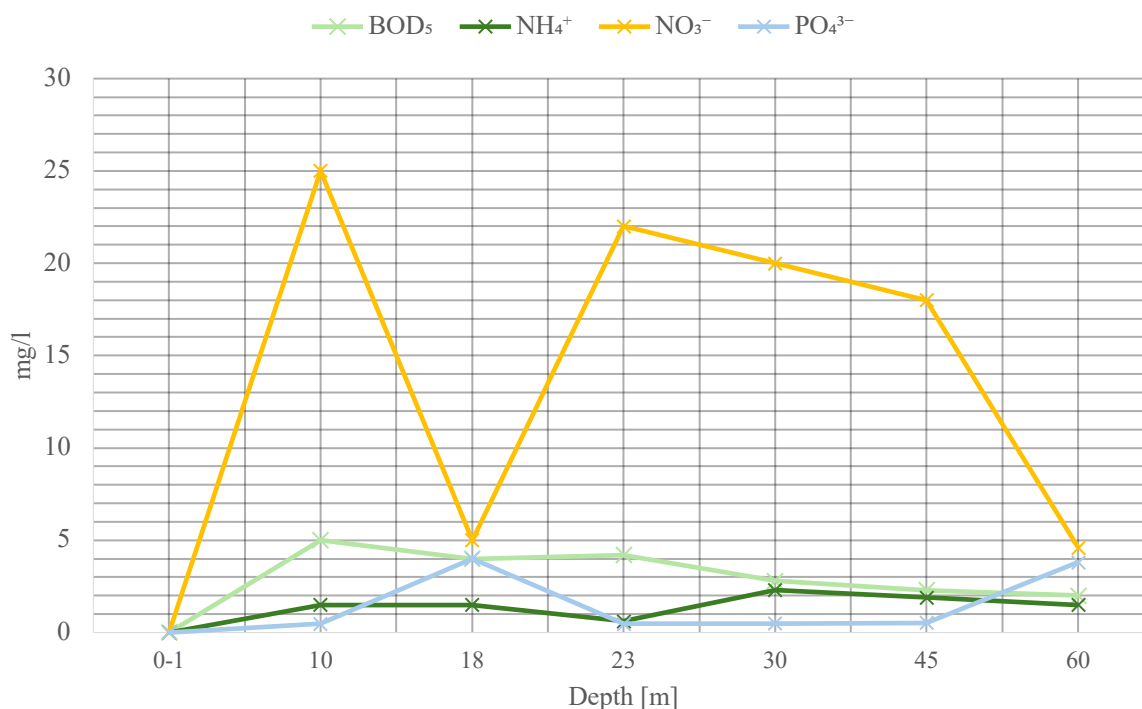


Figure 5.11. Vertical distribution of selected nutrient concentrations (biochemical oxygen demand, ammonium, nitrate and phosphate) measured at different depths in Río Cuarto Lake.

Table 5.11: Lab results of nutrient, microbiological, and supplementary chemical characteristics of surface and depth specific samples from Río Cuarto Lake. No analysis was performed on the surface sample (0-1m)

Depth	Coliforms	Magnesium Hardness [mg/L]	Calcium Hardness [mg/L]	Residual chlorine [mg/L]
10 m	Present	2.0	0.89	0.19
18 m	Present	2.1	0.83	0
23 m	Present	3.3	0.92	0
30 m	Present	3.2	0.9	0
45 m	Present	3.2	0.9	0
60 m	Present	1.9	0.79	0

The results from the lab analysis indicates generally stable results of the physicochemical conditions in the water column. The pH values are close to neutral with some of them having some alkaline results. The conductivity is relatively low and dissolved oxygen concentrations are above 5 mg/L on all the sampled depths besides the one on 60 m depth. In the lake samples, redox potential is positive which indicates oxidizing conditions.

Conductivity was similar between the 10 and 45 m sample. However, the 60 m sample showed an increase that suggests a different chemical environment in the deeper water.

The nutrient and microbiological results indicate signs of weaker water quality at several depths. Ammonium, nitrate and phosphate concentrations were elevated in multiple samples and coliform bacteria was present in all the analysed samples. Phosphate concentrations were especially high at 18 m and 60 m and nitrate highest at 10, 23, 30 and 45m. Residual chlorine was only detected in the 10 m sample. These results suggest a nutrient rich water with microbiological contamination even if the physiochemical conditions are relatively stable.

5.3.3 Spring sample lab analysis results

The water quality lab analysis results of the spring water are summarized in Table 5.12. These values are used as a groundwater-influenced reference for comparison with the lake water column samples.

Table 5.12. Water quality results of the spring water sample collected in the Río Cuarto study area. Values not presented was not tested.

Parameter	Unit	Value
pH	[-]	7.76
Temperature	[°C]	14
BOD_5	[mg/L]	-
NH_4^+	[mg/L]	0
NO_3^-	[mg/L]	4
PO_4^{3-}	[mg/L]	0.46
Coliforms	[-]	Fecal Coliforms detected
Magnesium Hardness	[mg/L]	1.61
Calcium Hardness	[mg/L]	2
Residual chlorine	[mg/L]	0.03

5.3.4 Water Transparency

Water transparency was measured using a Secchi disc which reached approximately 7 m down before visually disappearing. The water was clear with low turbidity at the time of assessment.

6 Discussion

6.1 GIS and bathymetric analysis

The bathymetric model used in this study was based on depth measurements collected with a sonar device together with coordinates from GPS units. The combined data resulted in datasets that were synchronized using timestamps to create a georeferenced point dataset, which was then used for interpolation and contour generation in QGIS. The spatial distribution measurements and overall coverage of the lake provide certainty that the general basin morphology is represented accurately.

The bathymetric analysis confirmed that Río Cuarto Lake has a steep-sided basin morphology with the deepest areas located in the central part of the lake. The measured maximum depth, roughly 73 meters down, was deeper than previously reported values of 67 meters. This suggests that earlier studies may have underestimated the true depth of the basin, or that the sonar in this study could have had a small error. This difference could be related to improved coverage during the present survey or to limitations in earlier measurement techniques. The steep slopes observed along the crater walls are consistent with the morphology of volcanic maar lakes and the lake also has limited shallow areas close to the shoreline. Such basin geometry is typical for crater lakes that are formed by explosive volcanic processes and could also influence water circulation patterns in the lake. Specifically, steep basin sides and a deep central basin can contribute to stable water layers and reduced vertical mixing in deeper parts of the lake. These physical characteristics are important for understanding both hydrological processes and water quality conditions in the system.

6.2 Water balance and hydrological interpretation

A big uncertainty in the water balance model is the lake outflow, as it was nearly double the total inputs. Monthly precipitation data shows higher numbers between May and January suggesting a higher lake level than normal in January and February. Since the sampling was conducted these months, the measured outflow could be a result of a higher lake level. Another possible reason for the high lake outflow in relation to water inputs is that the inflows could have been underestimated. A final potential reason could be an overestimation of the flow values generated by the flowmeter, due to rounding of the few decimals shown on the display.

The water balance results indicate that the estimated surface inflow is greater than the calculated recharge within the terrestrial part of the catchment. It is likely that a substantial part of the recharge contributes to the surface inflow, but this leaves a significant portion of inflow unexplained. One possible reason for the imbalance is the addition of water not generated within the catchment. This could be intermediate groundwater flow, groundwater inflow from fractures in the surrounding rock formations or inflow from the constructed ditches shown in Section 2.3. However, uncertainty in the defined catchment area could also influence these results since the catchment boundary was based on existing data that might be outdated. If the catchment area is larger than assumed, the calculated recharge values would be underestimated, resulting in smaller difference between inflow and recharge.

Another important factor is the use of monthly rainfall data in the Schosinsky method. In the Río Cuarto region, rainfall is influenced by tropical weather that can create frequent and sometimes intense rainfall events. These events could generate temporary surface runoff that is not captured by the monthly runoff calculations. As a result, the model heavily underestimates the contribution of immediate surface runoff into the lake.

The stated points and reasons are why the water balance results should be interpreted as an initial estimate, rather than a complete description of the hydrological processes in the catchment.

6.3 Water quality and vertical stratification

The water quality measurements showed clear vertical differences in the water column, particularly in electrical conductivity, dissolved oxygen and redox potential. These variations show that the lake is stratified and that deeper water layers are chemically different from surface water, which aligns with the stated previous research. Lower oxygen concentrations and higher conductivity values at deeper layers of the water column suggest limited vertical mixing and stable conditions there. Such conditions are typical for deep volcanic lakes and could influence nutrient cycling, biological activity and the overall ecological functioning of the lake. Phosphorus release from sediments can be affected by dissolved oxygen, temperature and pH (Wu et al., 2014), and the effect of higher pH on phosphate release can depend on how the pH increase occurs (Boers, 1991).

The observed chemical differences in deeper water layers reflect a combination of physical stratification and chemical processes occurring near the lake bottom. The deeper hypolimnion layer could reduce the risk of overturning events in the lake, as it makes it more difficult for deeper water to rise to the surface. However, additional measurements over a longer period would be required to determine whether these patterns are stable throughout the year or vary seasonally, as well as additional studies of the turnover events.

6.4 Indications of groundwater–lake interactions

Several observations from the study suggest that groundwater could have a role in the hydrological functioning of Río Cuarto Lake. The most important indication is the imbalance observed in the water balance calculations, where an absence of $2150 \cdot 10^3 \text{ m}^3/\text{year}$ was identified. The estimated water inputs do not fully explain the measured outflow and observed water storage in the lake, suggesting that additional water sources such as groundwater or unmeasured seepage could contribute to the lake system.

Another indication for possible groundwater interaction comes from the chemical differences observed in deeper parts of the water column. Electrical conductivity values were relatively stable between 10 m and 45 m depth (approximately 128 to 136 $\mu\text{S}/\text{cm}$) but increased to 235 $\mu\text{S}/\text{cm}$ at 60 m depth, suggesting different chemical conditions in the deepest part of the lake. Dissolved oxygen concentrations decreased with depth, from about 8.2 mg/L near the surface to approximately 4.9 mg/L at 60 m depth, indicating reduced mixing and more stable conditions characteristic of stratified lakes. Changes in redox potential and variations in ammonium concentrations were also observed at 60 m depth. Since ammonium typically forms under low-oxygen conditions, the observed patterns could indicate the presence of additional oxygen sources or mixing processes. One possible explanation is the inflow of groundwater with different chemical properties (Shaw et al. 2013), although other processes such as sediment interactions or internal lake dynamics could also contribute to these patterns.

The spring inflow sample showed a lower temperature than the lake surface water and contained measurable concentrations of ammonium, nitrate and phosphate, as well as detectable fecal coliforms. This distinct chemical composition could provide supporting information when evaluating possible groundwater influence in the system, although further studies would be needed to better understand the source and significance of these observations.

The combined hydrological and water quality indicators suggest that groundwater could interact with the lake system. Groundwater from intermediate flow systems or subsurface pathways could contribute to the lake from outside the surface catchment boundaries. Geological features such as fractures, faults and volcanic structures could allow groundwater to move through the subsurface and enter the lake without being captured by the data collected in the field investigations.

However, these findings should be interpreted as indications rather than direct evidence of groundwater inflow. The chemical differences between depths could also be caused by internal lake processes such as stratification and sediment interactions rather than groundwater inflow. Further investigations, including groundwater monitoring, would be needed to confirm the presence and magnitude of groundwater interaction in Río Cuarto Lake.

6.5 Methodology evaluation and sources of uncertainty

The methods applied in this study were important for developing an understanding of the hydrological processes and water quality conditions of Río Cuarto Lake. The combination of bathymetric mapping, water balance calculations and field-based water quality measurements provided important understanding for the lake system. However, certain methodology challenges and data related limitations were identified that could be addressed to strengthen future investigations and analysis.

Measurements were done over a relatively short time, which means that the results might not fully represent seasonal changes in hydrological conditions. Rainfall patterns and water levels can vary throughout the year, and measurements conducted over a short time could therefore reflect more temporary conditions rather than trends over a longer time. By having a longer field time, a more representative understanding of the hydrological behaviour of the lake could be provided.

Another methodological challenge was the estimation of inflow and outflow conditions. Several small inflows were identified during field observations but instead of continuous flow measurements, most values were estimated visually in the field together with video analysis. This approach allowed the study to progress under practical constraints in the field, but it led to uncertainty in the water balance calculations. Even small errors in flow estimates can influence the overall lake balance calculation. This is particularly the case in a system where multiple small inflows contribute to the total water input, as well as one outflow dependant on lake water level.

The definition of the catchment area also represents a source of uncertainty in the analysis. The catchment boundary used in this study was based on potentially outdated data from Gocke et al. (1987) together with GIS data from this study. Since recharge and runoff calculations are directly dependent on catchment size, the uncertain catchment area has potentially resulted in a deviation from more correct values. A catchment analysis using updated elevation data and hydrological modelling would improve the accuracy of future assessments.

Water quality analysis provided useful information on vertical variations within the water column, but some practical limitations influenced the sampling process. Samples collected from the water column were analysed some days after collection due to logistical limits. This delay could have affected parameters sensitive to storage conditions, especially dissolved oxygen and redox potential. The measurements still indicate general trends in water quality, but future studies could benefit from faster sample analysis or the use of in situ sensors.

The hydrological modelling method used in this study also included some simplifications. The Schosinsky method relies on generalized soil parameters and assumes relatively uniform conditions across the catchment area. Since soil characteristics, vegetation cover and terrain conditions vary in the catchment, this can influence infiltration, runoff and recharge processes. Using a single set of parameter values for the entire catchment could therefore not represent the correct hydrological conditions.

Despite these simplifications, the modelling approach provided a practical methodology for estimating recharge and water balance components in a system where detailed hydrological data are limited. The results should therefore be interpreted as estimated and not exact values. However, the results do still provide useful insight into the hydrological functioning of the lake and its catchment.

6.6 Improvements in future studies

Future studies should have longer monitoring periods and continuous measurement of the lake water level in the catchment area to gain better results. Soil samples should be collected at more locations around the catchment area to better depict differences in soil characteristics. In addition to this, dividing the catchment area into several parts could improve the calculations to account for these differences in soil characteristics, together with other terrain attributes, topographic features and vegetation cover.

Another improvement would be to install several monitoring wells to enhance groundwater understanding, by enabling groundwater sampling, level measurements and tracking of seasonal variations.

Additional meteorological data required for more comprehensive evapotranspiration estimates such as the Penman Monteith equation, together with missing topographic maps over the region, would also strengthen future studies of Río Cuarto Lake and surrounding catchment.

Lastly, continued monitoring and repeated measurements over longer time periods would improve the reliability of hydrological assessments and support more understanding of the long-term behaviour of Río Cuarto Lake.

6.7 Possible implications for studies in Sweden

Some Swedish lakes, particularly in southern Sweden, continue to experience eutrophication despite reduced external nutrient inputs in recent decades. Internal nutrient release from lake sediments can maintain low oxygen conditions and negatively affect water quality and aquatic ecosystems (Havs- och Vattenmyndigheten, 2023). At the same time, climate change is influencing thermal stratification patterns in temperate lakes. A recent study of Lake Mälaren by Drakare et al. (2025) showed that rising surface water temperatures have extended seasonal stratification periods, resulting in longer periods of low oxygen concentrations in deeper water layers.

Similarly, Jane et al. (2022) analysed more than 400 lakes and found that many temperate lakes are experiencing longer stratification periods linked to climate change, which reduce vertical mixing and oxygen replenishment in deeper waters. Continued warming may therefore increase the risk of hypoxic conditions in some Swedish lakes and gradually alter lake dynamics over time.

Although Río Cuarto Lake differs significantly from Swedish lakes in terms of climate and hydrological setting, studies of strongly stratified systems may still provide valuable insights into potential future lake responses under changing climate conditions. In addition, the indirect approaches used in this study to assess groundwater–lake interactions could be useful in Swedish studies where groundwater monitoring is limited. Combining water balance calculations, water level monitoring and water chemistry analyses may provide an initial indication of groundwater influence in data-scarce lake systems.

The Schosinsky (2006) soil water balance model would likely require adaptation before being applied to Swedish conditions due to processes such as snow accumulation, snowmelt and frozen soils. However, the general conceptual approach of combining meteorological, hydrological and soil data to estimate recharge may still be useful in certain Swedish catchments.

7 Conclusion

This study investigated the morphology, hydrogeology and water quality conditions of Río Cuarto Lake to improve the understanding of the hydrological functioning of the lake and potential groundwater interactions. The results showed that the lake has a steep-sided basin with a deep central area, which is characteristic of volcanic maar lakes. The measured maximum depth was greater than previously reported values which could mean that earlier studies underestimated the true depth of the basin. The updated bathymetric data provide a new representation of the lake geometry and form an important basis for hydrological and environmental assessments of the system.

The water balance calculations showed a difference between estimated inflow and recharge, indicating that the known hydrological components do not fully explain the observed water storage, inflows and outflows from the lake. This imbalance suggests that additional water sources, such as groundwater inflow or unaccounted surface water contributions could influence the lake system. However, uncertainties related to catchment boundary, simplified modelling assumptions and limited temporal data signifies that the calculated values should be interpreted as approximations and not exact estimates.

Water quality measurements showed vertical differences within the water column, particularly in electrical conductivity, dissolved oxygen and redox potential. These patterns indicate that the lake stratification is deeper than previously thought. This highlights that deeper water layers are chemically different from shallow water and could influence the occurrence of turnover events. However, further studies are necessary to improve understanding of seasonal variations and the risk for such events.

Together, the results of this study suggest that groundwater could play a role in the hydrological functioning of Río Cuarto Lake. However, further investigations including the installation of groundwater monitoring wells, longer monitoring periods, more extensive soil analysis, improved hydrological measurements and updated catchment analysis are advised to better evaluate groundwater contributions and improve the understanding of the lake system.

Overall, this study provides updated baseline data on lake morphology, water balance and water quality conditions in Río Cuarto Lake. These results contribute to the understanding of hydrological processes in volcanic crater lakes and provide a basis for future monitoring, modelling and water resource management in the region.

8 References

- Alfaro, EJ & Pérez-Briceño, PM. 2014, “Análisis del impacto de fenómenos meteorológicos en Costa Rica, América Central, originados en los mares circundantes”, *Revista de Climatología*, vol. 14, pp. 1–11.
- Alvarado, GE, Soto, GJ, Salani, FM, Ruiz, P & Hurtado de Mendoza, L. 2011, “The formation and evolution of Hule and Río Cuarto maars, Costa Rica”, *Journal of Volcanology and Geothermal Research*, vol. 201, no. 1–4.
- Andersen, J.M. 1982, “Effect of nitrate concentration in lake water on phosphate release from the sediment”. *Water Research*, 16, pp. 1119–1126.
- Beita, CM, Fagan, ME, DeClerck, FAJ & Harvey, CA. 2021, “Ecological corridors in Costa Rica: An evaluation applying landscape structure metrics”, *Conservation Science and Practice*, vol. 3, no. 4.
- Blaney, H. F. & Criddle, W. D. 1950, “Determining water requirements in irrigated areas from climatological and irrigation data”. Washington, D.C.: USDA Soil Conservation Service (SCS-TP-96).
- Boers, P.C.M. 1991, “The influence of pH on phosphate release from lake sediments”, *Water Research*, vol. 25, no. 3, pp. 309–311.
- Cabassi, J et al. 2014, “Geosphere-biosphere interactions in bioactive volcanic lakes: Evidences from Hule and Río Cuarto (Costa Rica)”, *PLOS ONE*, vol. 9, no. 7.
- Cavazos-Alvarez, J.A., Carrasco-Núñez, G., Macías-Medrano, S.E., Mancera-Alejandre, J. & Valley, R.D. 2025, “Integrated sonar-drone geomorphological mapping of maar lakes: Insights into compound maar eruptive histories”, *Geomorphology*, vol. 489, pp. 1–15.
- Drakare, S., Wallman, K., Djodjic, F., & Segersten, J. (2025). “Fokus på Mälaren 2024: Sammanfattande resultat från miljöövervakning och forskningsprojekt knutna till samarbetet mellan SLU och Mälarens vattenvårdsförbund”. SLU, Vatten och miljö, Report 2025:05. Mälarens vattenvårdsförbund, Report 2025:02.
- Esquivel-Hernández, G., Montealegre-Viales, E., Sánchez-Gutiérrez, R., Villalobos, M., Pérez-Salazar, R., Sánchez-Murillo, R., Mena-Rivera, L. & Birkel, C., 2024. “Tracing groundwater–surface water interactions in a volcanic maar lake using stable isotopes and radon-222”, *Journal of Geophysical Research: Biogeosciences*, vol. 129, no. 2.
- Fetter, CW & Kreamer, D. 2022, *Applied hydrogeology*, 5th edn. Waveland Press, Long Grove, Illinois, pp. 10–12.
- Gore, JA & Banning, J. 2017, “Discharge measurements and streamflow analysis”, in *Methods in Stream Ecology*, vol. 1: Ecosystem Structure, 3rd edn, Academic Press, pp. 49–72.

- Gocke, K., Bussing, W. & Cortés, J. 1987, "Morphometric and basic limnological properties of the Laguna de Río Cuarto, Costa Rica". *Revista de Biología Tropical*, vol. 35, no. 2, pp. 277–285.
- Gocke, K., Bussing, W., & Cortés, J. 1990, "The annual cycle of primary productivity in Laguna de Río Cuarto, a volcanic lake (maar) in Costa Rica". *Revista de Biología Tropical*, vol. 38, no. 2B, pp. 387–394.
- Havs och Vattenmyndigheten. 2023, "Övergödning" (Eutrophication). Available at: <https://www.havochvatten.se/miljopaverkan-och-atgarder/miljopaverkan/overgodning-och-algblomning/overgodning.html> (Accessed: 22 April 2026).
- Hernández Espinoza, K. 2014, "Cálculo de la evaporación en Costa Rica mediante el método FAO-56". *Tópicos Meteorológicos y Oceanográficos*, pp. 43–49.
- Herrera, C & Custodio, E. 2016, "Groundwater flow in a closed basin with a saline shallow lake in a volcanic area", *Science of the Total Environment*, vol. 541, pp. 303–318.
- Horlacher, H., Heyer, T., Ramos, C.M. & da Silva, M.C. 2012, Management of hydropower impacts through construction and operation. In: A. Sayigh (ed.) *Comprehensive Renewable Energy*, vol. 6. Oxford: Elsevier, pp. 49–91.
- Ibañez Asensio, S., Moreno Ramón, H., & Gisbert Blanquer, J.M. (n.d.). "Características del Infiltrómetro de Doble Anillo (Anillos de Munz)". <https://riunet.upv.es/server/api/core/bitstreams/6e362130-6edf-4567-8daf-785fe5159e02/content> (Accessed: 12 May 2026).
- Jane, S.F., Mincer, J.L., Lau, M.P., Lewis, A.S.L., Stetler, J.T. & Rose, K.C. 2022, "Longer duration of seasonal stratification contributes to widespread increases in lake hypoxia and anoxia." *Global Change Biology*, 29(4), pp. 1009–1023.
- Jiménez Rivera, C. 2022, "Desgasificación asociada a el lago del volcán Río Cuarto y su potencial de peligro sobre la comunidad de Río Cuarto". Trabajo de graduación, Universidad Nacional, Facultad de Ciencias de la Tierra y el Mar, Escuela de Ciencias Geográficas. Heredia, Costa Rica.
- Lee, G.F., Jones-Lee, A. & Rast, W. 1995, "Secchi depth as a water quality parameter." Report of G. Fred Lee and Associates, El Macero, California.
- Mendez, M., Maathuis, B., Hein-Griggs, D. & Alvarado-Gamboa, L-F. 2020, "Performance evaluation of bias correction methods for climate change monthly precipitation projections over Costa Rica", *Water*, vol. 12, no. 2, article 482.
- Ministerio de Ambiente y Energía (MINAE). 2007, "Reglamento para la Evaluación y Clasificación de la Calidad de Cuerpos de Agua Superficiales", Decreto Ejecutivo No. 33903. San José, Costa Rica.
- Nürnberg, G.K. 1995, "Quantifying anoxia in lakes", *Limnology and Oceanography*, 40(6), pp. 1100–1111.

- Okiongbo, KS & Akpofure, E. 2014, "Identification of hydrogeochemical processes in groundwater using major ion chemistry", *Journal of Applied Sciences and Environmental Management*, vol. 18, no. 3.
- Pal, S., Bera, S., Chattopadhyay, S. & Saha, S. 2015, "Electrical conductivity of lake water as environmental monitoring – A case study", *International Journal of Advanced Research in Engineering and Applied Sciences*, vol. 4, no. 3, pp. 16–25.
- Retana, JA. 2012, "Eventos hidrometeorológicos extremos lluviosos en Costa Rica desde la perspectiva de la adaptación al cambio climático", *Revista de Ciencias Ambientales*, vol. 44, no. 2, pp. 5–16.
- Rouwet, D. & Tassi, F. 2011, "Geochemical monitoring of volcanic lakes: a general overview", *Journal of Volcanology and Geothermal Research*, vol. 178, no. 2, pp. 107–123.
- Schosinsky, G & Losilla, M. 2000, "Modelo analítico para determinar la infiltración con base en la lluvia mensual", *Revista Geológica de América Central*, vol. 23, pp. 43–55.
- Schosinsky, G. 2006, "Cálculo de la recarga potencial de acuíferos mediante un balance hídrico de suelos", *Revista Geológica de América Central*, vol. 34–35, pp. 13–30.
- Shafi, S., Kamili, A.N. & Shah, M.A. (2013) "Coliform bacterial estimation: A tool for assessing water quality of Manasbal Lake of Kashmir, Himalaya", *African Journal of Microbiology Research*, 7(31), pp. 3996-4000. doi: 10.5897/AJMR2013.5863.
- Shaw, GD, White, ES & Gammons, CH. 2013, "Characterizing groundwater–lake interactions and their impact on lake water quality", *Journal of Hydrology*, vol. 492, pp. 69–78.
- Sigg, L., Johnson, C.A. & Kuhn, A. 1991, "Redox conditions and alkalinity generation in a seasonally anoxic lake (Lake Greifen)", *Marine Chemistry*, vol. 36, pp. 9–26.
- Tóth, J. 1963, "A theoretical analysis of groundwater flow in small drainage basins", *Journal of Geophysical Research*, 68(16), pp. 4795–4812.
- Uhl, D et al. 2024, "Deep-time maar lakes and other volcanogenic lakes as Fossil-Lagerstätten – An overview", *Palaeobiodiversity and Palaeoenvironments*, vol. 104, no. 4.
- Wu, H., Chen, J., Xu, J., Zhan, H. & Li, W. 2014, "Effects of pH, temperature and dissolved oxygen on phosphorus release from sediments", *KSCE Journal of Civil Engineering*, vol. 18, no. 1, pp. 323–329.
- Xylem Inc. 2026, "YSI Flow Probe water quality and flow measurement specifications".
<https://www.ysi.com> (Assessed: 7 February 2026).
- Xu, S., Frey, S.K., Erler, A.R., Khader, O., Berg, S.J., Hwang, H.T., Callaghan, M.V. & Sudicky, E.A. 2021, "Investigating groundwater–lake interactions in the Laurentian Great Lakes with a fully-integrated surface water–groundwater model", *Journal of Hydrology*, vol. 594, article 125911.

Yang, D., Yang, Y. & Xia, J. 2021, “Hydrological cycle and water resources in a changing world: A review”, *Geography and Sustainability*, vol. 2, pp. 115–122.

9 Appendix

9.1 Monthly Soil Water Balance Calculations

Table 9.1: Calculation of recharge potential and equivalent water volume, year 2015

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	555	23	67	488	0	2312	1766	8	152	1	152	1	152	152	2312	336	58 549
Feb	347	23	42	305	0	2312	1583	7	140	1	140	1	140	140	2312	166	28 807
Mar	119	24	14	105	0	2312	1382	8	161	1	161	1	157	157	2259	0	0
Apr	185	25	22	162	0	2259	1387	8	163	1	163	1	160	160	2262	0	0
may	528	25	63	464	0	2262	1692	9	179	1	179	1	179	179	2312	236	41 006
Jun	574	25	69	505	0	2312	1782	9	176	1	176	1	176	176	2312	328	57 137
Jul	442	25	53	389	0	2312	1666	9	180	1	180	1	180	180	2312	209	36 309
Aug	591	25	71	520	0	2312	1797	9	178	1	178	1	178	178	2312	342	59 460
Sep	305	25	37	268	0	2312	1546	8	161	1	161	1	161	161	2312	108	18 713
Oct	280	25	34	247	0	2312	1524	8	164	1	164	1	164	164	2312	83	14 400
Nov	381	24	46	335	0	2312	1613	8	161	1	161	1	161	161	2312	175	30 389
Dec	408	25	49	359	0	2312	1636	8	157	1	157	1	157	157	2312	201	35 037

Table 9.2: Calculation of recharge potential and equivalent water volume, year 2017

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	348	24	42	307	0	2312	1584	8	155	1	155	1	155	155	2312	152	26 432
Feb	88	24	11	77	0	2312	1355	7	144	1	144	1	140	140	2249	0	0
Mar	171	24	20	150	0	2249	1365	8	163	1	163	1	158	158	2242	0	0
Apr	123	26	15	108	0	2242	1315	8	167	1	167	1	158	158	2192	0	0
may	491	26	59	432	0	2192	1589	9	184	1	184	1	184	184	2312	128	22 307
Jun	337	26	40	296	0	2312	1574	9	180	1	180	1	180	180	2312	116	20 239
Jul	438	25	53	386	0	2312	1663	9	182	1	182	1	182	182	2312	204	35 461
Aug	285	25	34	251	0	2312	1528	9	181	1	181	1	181	181	2312	70	12 201
Sep	288	25	35	253	0	2312	1531	8	163	1	163	1	163	163	2312	90	15 575
Oct	216	25	26	190	0	2312	1468	8	164	1	164	1	164	164	2312	26	4567
Nov	363	24	44	320	0	2312	1597	8	160	1	160	1	160	160	2312	160	27 840
Dec	227	23	27	200	0	2312	1477	8	153	1	153	1	153	153	2312	47	8183

Table 9.3: Calculation of recharge potential and equivalent water volume, year 2018

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	385	23	46	339	0	2312	1616	8	151	1	151	1	151	151	2312	188	32 642
Feb	96	23	12	84	0	2312	1362	7	141	1	141	1	138	138	2259	0	0
Mar	88	24	11	77	0	2259	1302	8	163	1	163	1	154	154	2182	0	0
Apr	105	25	13	93	0	2182	1240	8	162	1	158	1	148	148	2127	0	0
May	321	25	38	282	0	2127	1375	9	181	1	181	1	175	175	2234	0	0
Jun	649	25	78	571	0	2234	1771	9	175	1	175	1	175	175	2312	318	55 345
Jul	950	24	114	836	0	2312	2113	9	177	1	177	1	177	177	2312	658	114 539
Aug	563	25	68	495	0	2312	1773	9	177	1	177	1	177	177	2312	318	55 285
Sep	291	25	35	256	0	2312	1534	8	161	1	161	1	161	161	2312	95	16 554
Oct	195	25	23	172	0	2312	1449	8	163	1	163	1	163	163	2312	9	1558
Nov	424	24	51	373	0	2312	1650	8	160	1	160	1	160	160	2312	212	36 973
Dec	159	24	19	140	0	2312	1417	8	154	1	154	1	153	153	2299	0	0

Table 9.4: Calculation of recharge potential and equivalent water volume, year 2019

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	71	23	9	63	0	2299	1327	8	153	1	153	1	147	147	2214	0	0
Feb	105	24	13	92	0	2214	1272	7	144	1	143	1	135	135	2172	0	0
Mar	153	24	18	134	0	2172	1271	8	161	1	160	1	150	150	2156	0	0
Apr	121	25	15	107	0	2156	1228	8	164	1	158	1	148	148	2115	0	0
May	441	25	53	388	0	2115	1468	9	181	1	181	1	181	181	2312	10	1688
Jun	401	25	48	352	0	2312	1630	9	177	1	177	1	177	177	2312	175	30 466
Jul	532	25	64	468	0	2312	1746	9	180	1	180	1	180	180	2312	288	50 195
Aug	272	25	33	240	0	2312	1517	9	178	1	178	1	178	178	2312	62	10 824
Sep	179	25	21	157	0	2312	1435	8	161	1	161	1	161	161	2308	0	0
Oct	273	25	33	240	0	2308	1514	8	162	1	162	1	162	162	2312	74	12 929
Nov	474	24	57	417	0	2312	1695	8	159	1	159	1	159	159	2312	258	44 962
Dec	446	24	54	393	0	2312	1670	8	154	1	154	1	154	154	2312	239	41 590

Table 9.5: Calculation of recharge potential and equivalent water volume, year 2020

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	399	24	48	351	0	2312	1629	8	155	1	155	1	155	155	2312	197	34 254
Feb	145	24	17	127	0	2312	1405	7	143	1	143	1	142	142	2297	0	0
Mar	45	25	5	40	0	2297	1302	8	164	1	164	1	155	155	2182	0	0
Apr	209	25	25	184	0	2182	1331	8	165	1	165	1	158	158	2208	0	0
may	211	25	25	186	0	2208	1359	9	182	1	182	1	175	175	2218	0	0
Jun	583	25	70	513	0	2218	1697	9	177	1	177	1	177	177	2312	243	42 233
Jul	308	25	37	271	0	2312	1549	9	181	1	181	1	181	181	2312	91	15 813
Aug	419	25	50	369	0	2312	1646	9	178	1	178	1	178	178	2312	190	33 132
Sep	177	25	21	156	0	2312	1433	8	161	1	161	1	161	161	2307	0	0
Oct	302	25	36	265	0	2307	1537	8	162	1	162	1	162	162	2312	98	17 062
Nov	326	25	39	287	0	2312	1564	8	162	1	162	1	162	162	2312	125	21 779
Dec	236	23	28	208	0	2312	1486	8	151	1	151	1	151	151	2312	57	9980

Table 9.6: Calculation of recharge potential and equivalent water volume, year 2023

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	184	23	22	162	0	2312	1439	8	151	1	151	1	151	151	2312	10	1818
Feb	124	23	15	109	0	2312	1387	7	141	1	141	1	139	139	2283	0	0
Mar	163	24	20	143	0	2283	1392	8	160	1	160	1	157	157	2269	0	0
Apr	115	24	14	101	0	2269	1335	8	161	1	161	1	155	155	2215	0	0
may	181	26	22	159	0	2215	1340	9	184	1	184	1	175	175	2199	0	0
Jun	438	26	53	385	0	2199	1550	9	179	1	179	1	179	179	2312	94	16 336
Jul	459	25	55	404	0	2312	1681	9	183	1	183	1	183	183	2312	221	38 449
Aug	316	25	38	278	0	2312	1556	9	180	1	180	1	180	180	2312	98	17 059
Sep	441	25	53	388	0	2312	1665	8	162	1	162	1	162	162	2312	226	39 243
Oct	360	25	43	317	0	2312	1594	8	164	1	164	1	164	164	2312	152	26 470
Nov	433	25	52	381	0	2312	1659	8	162	1	162	1	162	162	2312	219	38 115
Dec	206	24	25	182	0	2312	1459	8	155	1	155	1	155	155	2312	27	4673

Table 9.7: Calculation of recharge potential and equivalent water volume, year 2024

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	126	24	15	111	0	2312	1389	8	156	1	156	1	153	153	2270	0	0
Feb	246	23	29	216	0	2270	1452	7	141	1	141	1	141	141	2312	33	5767
Mar	103	25	12	90	0	2312	1368	8	166	1	166	1	161	161	2241	0	0
Apr	270	25	32	237	0	2241	1444	8	165	1	165	1	165	165	2312	1	229
may	362	26	43	318	0	2312	1596	9	185	1	185	1	185	185	2312	134	23 256
Jun	558	26	67	491	0	2312	1769	9	179	1	179	1	179	179	2312	312	54 360
Jul	652	25	78	574	0	2312	1851	9	181	1	181	1	181	181	2312	393	68 318
Aug	250	25	30	220	0	2312	1498	9	179	1	179	1	179	179	2312	42	7230
Sep	589	25	71	518	0	2312	1796	8	162	1	162	1	162	162	2312	356	62 023
Oct	583	24	70	513	0	2312	1791	8	162	1	162	1	162	162	2312	352	61 166
Nov	809	24	97	712	0	2312	1989	8	159	1	159	1	159	159	2312	552	96 113
Dec	744	23	89	655	0	2312	1932	8	153	1	153	1	153	153	2312	502	87 361

Table 9.8: Calculation of recharge potential and equivalent water volume, year 2025

Month	P (mm)	T (°C)	Ret (mm)	Pi (mm)	ESC (mm)	HSi (mm)	HD (mm)	Ps (%)	ETP (mm)	C1	ETR1 (mm)	C2	ETPR (mm)	ETR (mm)	HSf (mm)	Rp (mm)	V (m ³)
Jan	525	23	63	462	0	2312	1740	8	152	1	152	1	152	152	2312	310	53 859
Feb	199	24	24	175	0	2312	1452	7	141	1	141	1	141	141	2312	33	5810
Mar	151	24	18	133	0	2312	1410	8	162	1	162	1	161	161	2284	0	0
Apr	207	24	25	182	0	2284	1432	8	160	1	160	1	160	160	2307	0	0
may	511	25	61	449	0	2307	1722	9	180	1	180	1	180	180	2312	264	45 906
Jun	796	24	96	701	0	2312	1978	9	174	1	174	1	174	174	2312	527	91 718
Jul	521	24	62	458	0	2312	1736	9	178	1	178	1	178	178	2312	280	48 689
Aug	611	25	73	538	0	2312	1815	9	177	1	177	1	177	177	2312	361	62 759
Sep	324	24	39	285	0	2312	1562	8	160	1	160	1	160	160	2312	125	21 817
Oct	446	24	53	392	0	2312	1670	8	161	1	161	1	161	161	2312	231	40 281
Nov	587	23	70	516	0	2312	1794	8	156	1	156	1	156	156	2312	360	62 654
Dec	178	23	21	156	0	2312	1434	8	152	1	152	1	152	152	2312	5	856

9.2 Water Quality Results

Table 9.9: Lab results of nutrient, microbiological, and supplementary chemical characteristics of surface and depth specific samples from Río Cuarto Lake

Depth	BOD ₅ [mg/L]	NH ₄ ⁺ [mg/L]	NO ₃ ⁻ [mg/L]	PO ₄ ³⁻ [mg/L]
Surface	-	-	-	-
10 m	5.0	1.5	25	0.48
18 m	4.0	1.5	5	4.0
23 m	4.2	0.62	22	0.48
30 m	2.8	2.3	20	0.49
45 m	2.3	1.9	18	0.53
60 m	2	1.5	4.6	3.8
Spring	-	0	4	0.46

Table 9.10: Lab results of physicochemical water-quality characteristics of surface and depth specific samples from Río Cuarto Lake

Depth	pH	Temperature [°C]	Dissolved oxygen [mg/L]	Electrical Conductivity [μS/cm]	Redox Potential (ORP) [mV]
Surface	8.32	23.5	8.2	162	160
10 m	7.98	28.3	6.8	128	168
18 m	7.74	25.9	6.4	134.3	156
23 m	7.85	22.4	7.3	135.9	155
30 m	7.75	23.5	5.3	134.8	142
45 m	7.23	23.2	5.0	121.4	139
60 m	7.52	26.2	4.9	235	173
Spring	7.76	14.0	-	-	-