Physico-chemical evaluation of the water quality in Rocha River

A qualitative and comparative analysis including aspects of social and environmental factors

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MSc Thesis, 30 ECTS
ISRN LUTVDG/(TVTG-5160)/1-65/(2019)

Thesis work for Masters in Science 30 ECTS
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This study was performed within the framework of The Minor Field Studies (MFS) Scholarship Programme, which is funded by the Swedish International Development Cooperation Agency, Sida. The responsibility for the accuracy of the information presented in this MSc thesis rests entirely with the authors.

Acknowledgment

We are grateful for the opportunity the MFS-scholarship has given us to perform our MSc thesis abroad. We gained great experience in Bolivia and the time spent in Cochabamba will forever be cherished. We would like to express sincere gratitude to our supervisors Gerhard Barmen and Andrés Gonzales, for supervising and encouraging us to pursue this journey.

We would further like to give a special thank you to Ana María Romero Jaldín, head of C.A.S.A, and Mauricio Villazón, head of Laboratório de Hidráulic, for all the help we have gained with everything from trying to solve our modelling problems and interpreting our results to finding available cars for our fieldwork. The collaboration between the two departments has eased our work and for that we thank all people involved. To all the students from UMSS that put aside their study to help us: we could not have done the field study without you and thank you for all the joyful moments.

Warm regards,
Stina Jacobson and Ida Sekizovic

Abstract

In this study, a physico-chemical analysis of the Rocha River was performed during the beginning of the rainy season 2018 in order to examine the current state of the water quality in the river at six different locations. The river, located in the Cochabamba department, Bolivia, was examined from upstream in Sacaba to downstream in Sipe Sipe. An additional aim was to determine social and environmental contributing factors for the water quality of the Rocha River.

The chemical analysis was based on the following parameters: electrical conductivity, dissolved oxygen, 5-day biochemical oxygen demand, chemical oxygen demand, nitrates and fecal coliforms. To examine the state and range of usage for the water in Rocha River the results of the water quality for each parameter was compared with the regulations for drinking water, agriculture water and environmental water from WHO, EPA and FAO as well as Bolivian regulations. The stage and water flow of the river at respetive locations were measured and modelled in Hec-RAS to draw conclusions on how the physical parameters might affect the distribution of the pollution in Rocha River.

The quality of the river water in this study was classified as “very”- and “highly polluted” water according to the performed organic pollution (ICO)-index. In line with previous studies, the deterioration has continued over the years since 1998 and has now reached even the outskirts of the valley from upstream in Sacaba to downstream in Sipe Sipe. From the results, the prominent parameters of the pollution were the low dissolved oxygen levels and high coliform concentrations at all locations downstream of Chiñata. The results of the high pollution is correlated with areas where the population is dense, the presence of industrial activity is high and the connection to sewage systems is poor or nonexistent. A main contributing factor of the pollution is that large volumes of untreated wastewater is directly discharged to the Rocha River along its course to the extent that it disturbs the possibilty of natural river restoration.

Based on the Bolivian Environmental Law No.1333 and the analysed parameters, the water was classified as “D” at five out of the six sampling locations. This highly constrains the usage of the river water regarding health and environmental aspects. However, the water scarcity in the area enforces the farmers to use water from the Rocha River as irrigation, which may contribute to degradation of soil, pollution of the groundwater and induce health risks.

Keywords: Cochabamba, Rocha River, water quality analysis, water pollution, wastewater, regulations, ICO-index, Hec-RAS, minor field study

Resumen

En el presente estudio, análisis físico-químico del Río Rocha, fue realizado durante el inicio de la estación lluviosa del 2018 con objeto de examinar el estado actual de la calidad de agua en seis diferentes lugares del Río Rocha. El río, localizado en el departamento de Cochabamba, Bolivia, fue analizado desde aguas arriba en Sacaba, hasta aguas abajo en Sipe Sipe. Un objetivo adicional de esta investigación fue la determinación de las contribuciones de los factores sociales y ambientales a la calidad de agua del Río Rocha.

El análisis químico fue basado en los siguientes parámetros: conductividad eléctrica, oxígeno disuelto, demanda bioquímica de oxigeno a 5 días, demanda química de oxigeno, nitratos, y coliformes fecales. Para la examinación del estado y alcance de uso de agua del Río Rocha, los resultados obtenidos fueron comparados con regulaciones medioambientales de agua para consumo humano, y agua para riego. Estas regulaciones son de la OMS, EPA, FAO y normas bolivianas. El caudal y altura del Río Rocha fue medido en las estaciones determinadas, y fueron modeladas en el programa Hec-RAS para bosquejar conclusiones acerca de cómo las variaciones físicas de algunos parámetros afectan la distribución de contaminación en el Río Rocha.

En este estudio la calidad de las aguas del Río Rocha fue clasificada como “Muy contaminado” y “Altamente contaminado”, según a los análisis realizados con el índice de contaminación ICO. Estos resultados están en línea con estudios previos, la deterioración de las aguas fue continua desde el año 1998, y actualmente abarca las afueras del valle central desde Sacaba hasta Sipe Sipe. De los resultados obtenidos, el parámetro de contaminación más crítico fueron los valores bajos de Oxígeno Disuelto y valores elevados de coliformes, los cuales ocurren a lo largo del río aguas debajo de Chiñata. Los resultados obtenidos de alta contaminación están directamente correlacionados con áreas donde la densidad poblacional es mayor. En estas áreas la actividad industrial es alta y las conexiones de alcantarillado son pobres o inexistentes. Un factor principal que contribuye a la contaminación del río son los grandes volúmenes de agua residual no tratada que son vertidos directamente al Río Rocha a lo lardo de todo su curso, y lo cual repercute en la posibilidad de restauración natural del río.

Basados en la Ley de Medioambiente de Bolivia No 1333, y en los análisis de los parámetros estudiados, el agua en el río fue clasificada como “D” en cinco de las seis estaciones estudiadas. Esta categorización restringe altamente el uso de las aguas para evitar daños a las salud y medioambiente. Sin embargo, la escasez de agua en el área de estudio obliga a agricultores a usar las aguas del Río Rocha, lo cual contribuye a la degradación de los suelos, a la contaminación de aguas subterráneas e induce grandes riesgos a la salud humana.

Palabras claves: Cochabamba, río Rocha, análisis de la calidad del agua, contaminación del agua, aguas residuales, regulaciones, índice de contaminación de orgánica, Hec-RAS

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1. Introduction

The rapid population growth, economic development and urbanization, mainly in low income developing countries are increasingly challenging the reach of UN Sustainable Development Goal number six (SDG 6); to ensure clean and accessible water and sanitation for all (UN-Water, n.d.). Due to the increased demand for water, the volume of generated wastewater increases globally, and so does the quantity of pollution contaminating available water resources. To prevent devastating effects on the environment as well as on health and well-being for large parts of the global population, new approaches to water and wastewater management must be applied where water is managed properly all the way through its cycle.

1.1 Bolivia

The Plurinational State of Bolivia is a highland country with major natural assets in the form of natural gas, oil and minerals (Arnade and McFarren, n.d). Due to several historical events, Bolivia suffers from uneven social and economic development within the country and is one of the poorest countries in South America (Utrikespolitiska institutet, 2018). During the last decades Bolivia has under the SDG 6 improved the access to drinking-water and ratified sanitation as a fundamental human right. According to a UN-water global analysis in 2013/14, one of the main obstacles to achieve this goal in Bolivia is related to the improvement and expansion of sewerage systems and treatment of wastewater, which today, is discharged into water bodies with little or no treatment. An additional issue is the lack of promotion of proper management of solid waste and wastewater in rural areas (WHO, 2015).

1.2 Cochabamba and the Rocha River

The field study was performed in the Central Valley of Cochabamba and by its main stream, Rocha River, that flows through the city and drains the water of the valley located in the Andes mountain range (figure 1.1). In the Department of Cochabamba the current population is approximately 1,900,000 inhabitants of which 69% lives in urban areas and 31% in rural areas (INE, 2016).

Due to its relatively mild and dry climate Cochabamba is called “the city of eternal spring” and because of its long history of agriculture and fertile soil it has also been named “the breadbasket of Bolivia”. However, due to a moderate precipitation and high evapotranspiration rates the area suffers from water shortage. Groundwater has since the colonial times been the most important water resource in the Cochabamba valley but it is becoming increasingly limited due to an unsustainable exploitation and can no longer satisfy the demand. During the dry season there is no natural flow in parts of the Rocha River, and the small amounts of existing standing water originates from the wastewater that is discharged into the river along its course (Renner & Velasco, 2000).

Figure 1.1 The valley of Cochabamba.

Similar to many cities in Bolivia, Cochabamba has many inhabitants coming from surrounding rural regions which settle in dense communities with little control over the housing developments. These settlements are seldom included in the water and wastewater pipe system of the city. An estimation given is that the population of Cochabamba will rapidly increase and reach approximately 2,200,000 inhabitants by the year of 2025 (ADA, 2017), leading to a further increased demand for water, mainly for domestic use and irrigation. In turn, this will also result in an added volume of discharged wastewater polluting the Rocha River.

Previous studies have shown that the river is highly polluted (Contraloría General del Estado, 2017), but there is also a high commitment and interest from people and organizations working for solutions to improve the situation.

1.3 Aim of the study

To mitigate and avert the pollution of the Rocha River more empirical data of actual condition is needed. Therefore, in order to facilitate decisions on future measures, the overall aim of the study is to examine the current state of the water quality in the Rocha River at different sections in the Cochabamba valley. An additional aim is to determine social and environmental contributing factors for the water quality of the Rocha River. An expectation is also that the study will improve the understanding of how, and to what extent, the quality of the water from the river is affecting the surrounding population and its environment.

1.3.1 Specific methods

The overall goal will be to target the aim with the following specific methods:

- *Determination of the physico-chemical characteristics of the Rocha River water*: Along the river, sampling locations will be determined where the physico-chemical water sampling will occur. The parameters that will be measured and analysed are pH, temperature (T), electrical conductivity (EC), dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), nitrates (NO_3^-) and fecal coliforms (CF). The collected water samples will be analysed in the laboratory *Centro de Aguas y Saneamiento Ambiental* (C.A.S.A.) at *Universidad Mayor de San Simón* (UMSS).
- *Evaluation and classification of the water quality:* The physico-chemical results from the sampling will be added into the flow analysis and water quality model Hec-RAS. The purpose of the model is to receive an overview of how the flow and water quality varies with time and distance. The chemical results will also be assessed according to various international and national water quality regulations.
- *Assessment on the aspects of social and environmental influences:* Research on how and to what extent, the quality of the water from the river is affecting the surrounding population and the environment. Maps, satellite images and published articles will be studied. On site, scrutinization of the natural and anthropogenic effects of the contamination will be documented continuously during the field work.

2. Description of the Rocha River area

2.1 Geology, hydrology and climate

The valley of Cochabamba is a tectonic depression in the eastern part of the Bolivian Andes (figure 2.1). The altitude is approximately 2500 m.a.s.l. and the valley is surrounded by mountains that in the northern part exceed elevations of 5000 m.a.s.l (Renner & Velasco, 2000).

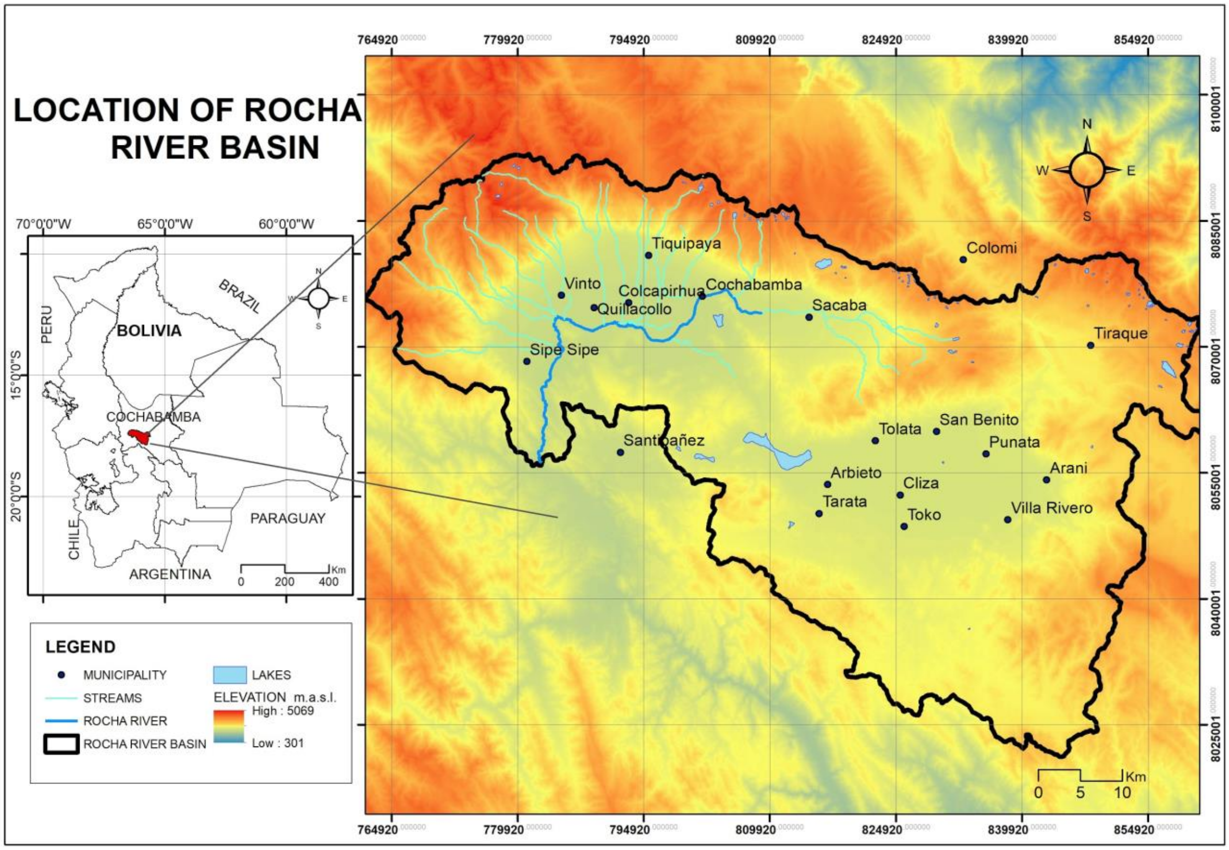

Figure 2.1 The location of Rocha River basin and the valley of Cochabamba.

The surrounding mountains have with time eroded and the rivers that flow towards the valley have transported and deposited the eroded material as sediments. In areas next to the slopes, mainly in the northern and western areas, fluvial fans are formed of coarse grained sediments and towards the center of the valley the sediment is of finer grains. The lower part of the valley is mainly composed of lake deposits, primarily clays and muds, as the valley for periods of time was occupied by a lake (Renner & Velasco, 2000).

The quality and constituents of the groundwater vary in the different parts of the valley and is correlated with the different types of sediments, this is shown in a project performed in 1993-1995 (Renner & Velasco, 2000). One example is that the electric conductivities and ionic loads were significantly higher in the south-west areas compared to the northern areas. This can be attributed to i) the sediments in the south-west areas being developed from carbonated rocks and dolomites, red clays and mudstone (which are more easily dissolvable compared to the more coarse grained sediments of the northern parts), ii) the flow velocity is higher and iii) the younger groundwater in the northern areas since it is a zone of recharge with high permeability (Renner & Velasco, 2000).

Natural recharge of the aquifers occurs mainly through rainwater in the mountain range that flows through rivers into the fluvial fans that act as recharge zones where the water infiltrates and then flows towards the low areas of the valley, where the Rocha River is situated. During the rainy season the Rocha River can recharge the aquifers whereas the river can gain water from the aquifer during the dry season (Renner & Velasco, 2000).

The climate in the Cochabamba valley is tropical and semi-arid with no drastic temperature changes during the year. The rainy season is mainly December to March and the driest months are May to July. The average annual precipitation in the valley is moderate, 400-500 mm and the average annual temperature is 17.5 °C, with a monthly average minimum of 5 °C and maximum of 22 °C (World Weather Online, 2019). This climate results in a relatively high evapotranspiration and water shortages in the area are common.

Regarding climate change and variability, a high inter-annual rainfall variability has been observed and the mean precipitation has decreased in this region of the Andes. The average temperature increase in South America from 1920 to 2006 is 0.7 °C which has led to concerns regarding melting glaciers and snow in the mountains which would further increase the reduction in water supplies. A future scenario of the changing climate is that the Andes will become warmer and drier where locations at higher altitude are more affected (Gonzales Amaya, et al., 2018).

2.2 Rocha River

The Rocha River Basin is located in the Department of Cochabamba and begins in the Tiraque mountain range where the Rocha River originates from the Maylanco River. The basin ends in the municipality of Capinota where Rocha River joins the Arque River forming the Caine River. Further downstream the Caine River turns into the Río Grande that eventually flows into the Amazon River (see figure 2.2) (Medrano & Derpic, 2006).

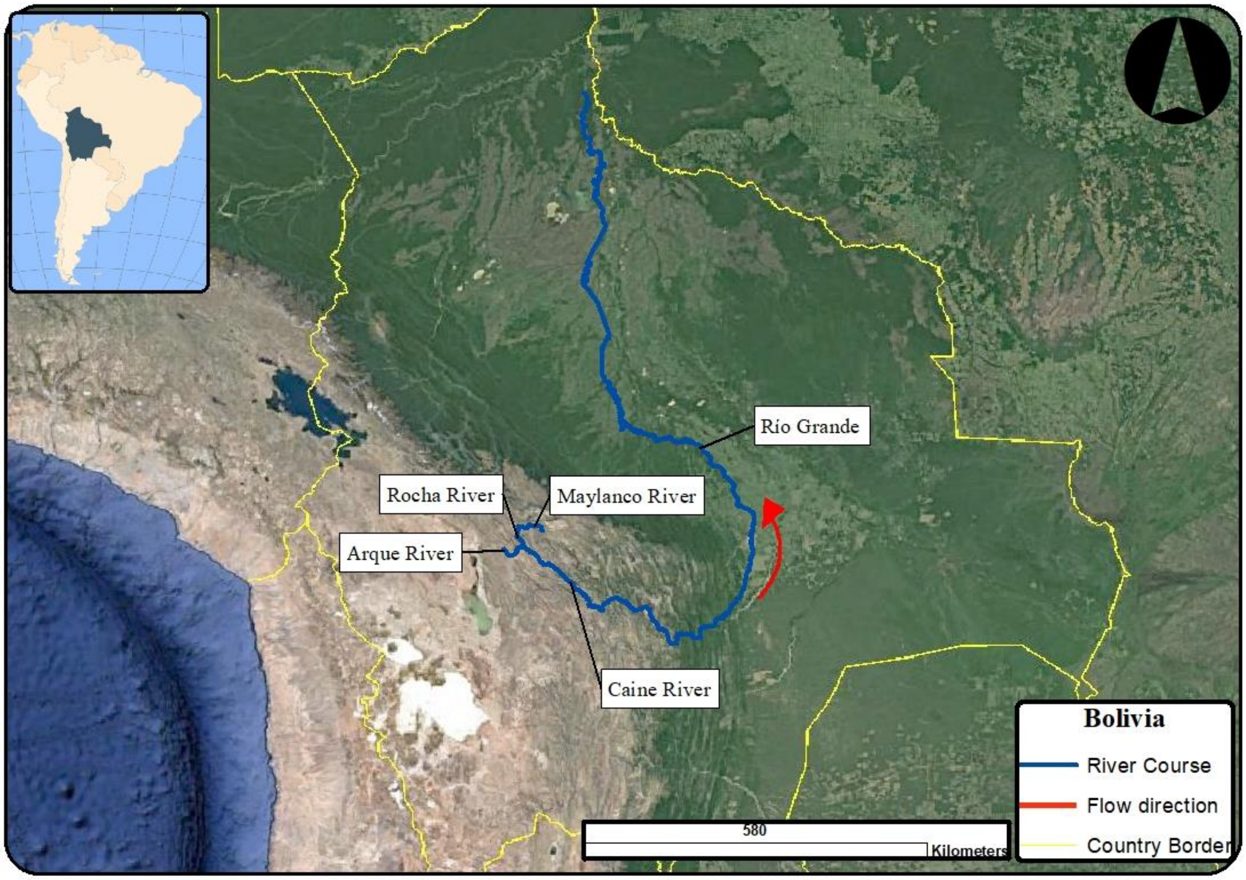

Figure 2.2 Satellite image of Bolivia and the course of Rocha River (Pictures from Google Earth Pro 2018 and Microsoft World Atlas 2018).

The main channel of the Rocha River has a total extension of 81.2 km and in 2012, approximately 1,320,000 people were living around the river (Gobierno Autónomo Departamental de Cochabamba et al., 2014). The river directly involves the municipalities of Sacaba, Cercado, Colcapirhua, Quillacollo, Vinto and Sipe Sipe (see figure 2.3). Sacaba is the municipality with the highest growth rate, although it still has large rural areas. The most densely populated urban areas are Cercado and Colcapirhua, whereas Quillacollo is more of a suburban area with many industries. Vinto and Sipe Sipe are predominantly rural areas with agricultural lands (MMAyA, 2014).

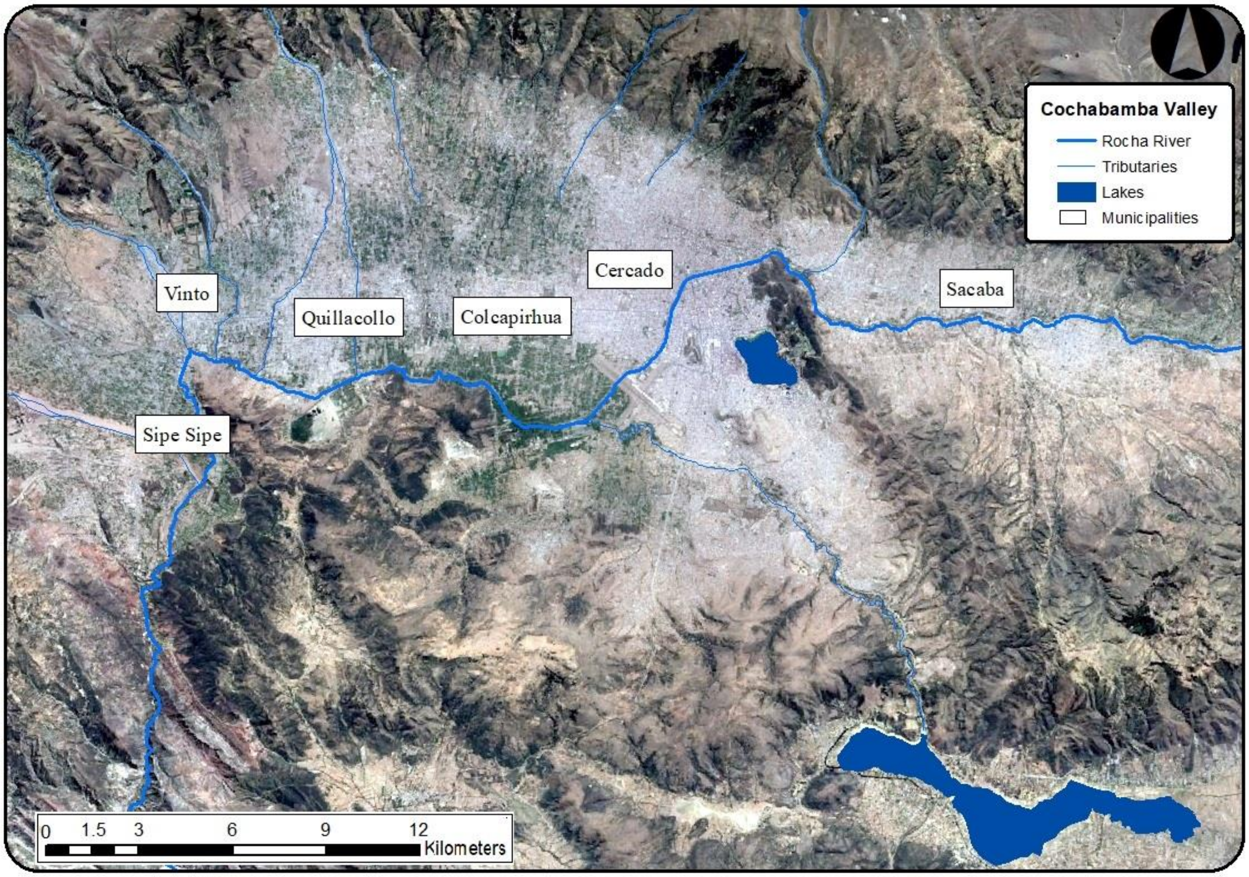

Figure 2.3 Satellite image of the Cochabamba valley, Rocha River and the involved municipalities (Picture from Google Earth Pro 2018).

The main utilization of the Rocha River is for agricultural purpose, both for its irrigation water as for the fertile sediments left by the periods of overflows (Gobierno Autónomo Departamental de Cochabamba, et al., 2014).

A change in the rainfall regime together with increased demand for water, due to the rapid population growth, has strongly influenced the state of the water in the basin. The amount of water stored in the subsoil has decreased and the underground runoff of the Rocha River basin has almost disappeared (Gobierno Autónomo Departamental de Cochabamba, et al., 2014). The deficiency of groundwater sources has increased the usage of the river water for agricultural purposes, especially during the dry months (Contraloría General del Estado, 2017). Furthermore, the increased demands for water to the population leads to an increased volume of wastewater, which reaches the Rocha River without treatment. A result of this is that during the dry months when the flow of the river is strongly reduced, the remaining flow is merely all wastewater. During the rainy period, the rainfalls and floods with their large amount of water and fast flows clean the accumulated pollution in the river bed as well as the waste and transport it to the lower areas of the basin where it is deposited. The Rocha River can then to some level regain its quality although it no longer manages to fully recover its characteristics (Contraloría General del Estado, 2017).

2.3 Cochabamba - water situation

2.3.1 History of the urban water and Rocha River

Cochabamba has a history of water struggles and the most substantial is the event known as the Water War. During the late 20th century there was an expanding division between the wealthier and modern northern areas and the poor southern areas with large demographic growth inhabited mostly by farmers and migrants from rural areas and highland mines (Bustamante & Médieu, 2012). In the year of 2000 the water supplies and sewage services became privatised, leading to increasingly expensive water tariffs. This resulted in the outbreak of severe social conflicts which eventually lead to the cancellation of the privatisation agreement (Global Water Partnership, 2017).

This event clearly illustrates the vital importance of social and community participation when it comes to development and policies related to water resources management. Today the water of Cochabamba is run and controlled by a cooperation between government representatives, social organisations, the private sector, academic institutions and the municipality (MMAyA, 2014). However, there still exists undeniable problems regarding the policy and management, and solutions for equal accessibility to clean water has not yet been found.

Previous studies on Rocha River

With the continuously increasing population in the Cochabamba valley the quality of the water in Rocha River has deteriorated. Since the late 20th century studies have been performed on the river to evaluate the extent of the contamination. In 2011 the report No. K2 / AP06 / M11 was issued which revealed that the quality of the water along the Rocha River channel goes from "polluted" to "very polluted" (see organic pollution index (ICO) in subchapter 3.5.1 and table 2.1) and that it is unsuitable for irrigation. The report provides 44 recommendations to the municipal and autonomous governments in the framework of the Bolivian Environmental Law No.1333 to work as a strategic guideline for the recovery and restoration of the river (Gobierno Autónomo Departamental de Cochabamba, et al., 2014). At the time the only existing wastewater treatment plant (WWTP) in the seven municipalities was the Alba Rancho WWTP in the municipality of Cercado operated by the public company SEMAPA. After the report No. K2 / AP06 / M11 plans were developed to implement 11 new WWTP´s around the seven municipalities. However, up to year 2014 only one additional treatment plant, El Abra in Sacaba, was in construction (Gobierno Autónomo Departamental de Cochabamba, et al., 2014).

A follow-up on the recommendations was presented in Contraloría General del Estado (2017), which also presents a summary of the variation of the contamination in Rocha River between the years 1998, 2011 and 2017, which for the organic pollution is illustrated in table 2.1.

Table 2.1. The organic pollution in Rocha River, classified according to ICO-index (subchapter 3.4.1), for different municipalities for the years 1998, 2011 and 2017 (Contraloría General del Estado, 2017).

Municipality	Year 1998		Year 2011		Year 2017
	Upstream	Downstream	Upstream	Downstream	
Sacaba	Weakly polluted	Moderately polluted	Not polluted	Highly polluted	Highly polluted
Cercado	Polluted - Very polluted	Highly polluted	Polluted - Very polluted	Polluted - Very polluted	Highly polluted
Colcapirhua	Highly polluted	Highly polluted	Very polluted	Highly polluted	Highly polluted
Quillacollo	Highly polluted	Highly polluted	Highly polluted	Highly polluted	Highly polluted
Vinto	Highly polluted	Very polluted	Highly polluted	Highly polluted	Highly polluted
Sipe Sipe	Very polluted - Polluted	Moderately polluted	Very polluted - Highly polluted	Polluted - Moderately polluted	Highly polluted

From measurements taken at 20 points along the course of the river, from Sacaba to Sipe Sipe, it could be concluded that the water quality has deteriorated in all parts of the river. In 2017 all sections of the river where classified as the highest level of organic pollution (see ICO-index in subchapter 3.4.1) whereas in 2011 and 1998 there were still some parts that could be classified as “not polluted” or “weakly polluted” in the outskirts of Sacaba and Sipe Sipe.

The organic load in 2017 was measured to approximately 4 tons/day as BOD_5 and more than 13 ton/day as COD. The amount of total dissolved solids (TDS) was estimated to between 1 and 7 tons/day and the total suspended solids (TSS) could fluctuate between 1 and 15 tons/day. The TDS and TSS are deposited in the clay of the riverbeds mostly in the lowlands (Contraloría General del Estado, 2017). The exact data from the measurements taken from the 20 points along the Rocha River in 2017 is presented in Appendix 4.1 and a map with the 20 points in figure 5.1.

The reason that the water quality has worsened, despite the efforts made according to the recommendations from 2011, is supposedly the increasing volumes of discharge as a result from the population increase and industrial development. The extent and synergetic effect of pollution that the river receives has cancelled the ability to naturally decompose the organic material along its course, and thus pollution is continuously kept at the critical level (Contraloría General del Estado, 2017).

2.3.2 Distribution of potable water

In the Department of Cochabamba only 54% of the households have access to tap water in their homes and only 27% have services with safe drinking water. This percentage corresponds mainly to the municipality of Cercado where the operator SEMAPA has surface water purification plants and chlorination for groundwater. This means that 73% of the population consumes water with an average or high health risk (MMAyA, 2014). Some parts of the population use private pumps for drinking water, where, the groundwater might be recharged with polluted river water. Values from 2012 (MMAyA, 2014) determines that there is a water deficit of 1361 L/s in the department and this together with the low coverage of the drinking water-network has led to an immense increase of inhabitants purchasing their potable water from water trucks providing untreated water and by providers of bottled water (ADA, 2017).

2.3.3 Wastewater in the Department of Cochabamba

Along the banks of the Rocha River, solid waste is visible throughout its course. The private activity, including large volumes of construction material being dumped into the river at near sight, counts as the solid waste that has the highest pollution contributing factor to Rocha River. This is a result from not having an official dumping site at the municipalities in the department of Cochabamba (Gobierno Autónomo Departamental de Cochabamba, et al., 2014).

The municipalities of the Cochabamba department (shown in figure 2.3) have different quality of wastewater that is directly discharged to the Rocha River and contributing to deterioration of the water quality. Most of the direct discharges into the Maylanco-Rocha River are domestic wastewater without any type of treatment (UMSS, 2018). The municipalities' direct impact is presented below, from upstream to downstream.

Chiñata

In the eastern outskirts of the Sacaba department is an area named Chiñata, where the population is low and no industries are located. Untreated wastewater discharge pipes to the Maylanco-Rocha River have been located in this area according to recent studies (UMSS, 2018).

Sacaba

Sacaba is the large industrial and slaughter area of Cochabamba with pulp industry, dairy industry, a Pepsi factory, among others (Contraloría General del Estado, 2017). From some slaughter areas wastewater channels have been located with untreated water and direct discharge to the Rocha River (UMSS, 2018). It is believed that some industries discharge wastewater at night to reduce the risk for fines due to heavily polluted wastewaters. An example of this is a pig-farm located in Sacaba (Appendix 1, ID 18) which had humid pipes with no discharge during the day, and the inspection from 2018 drew the conclusion that the discharge was performed during nighttime (UMSS, 2018).

According to the Contraloría General del Estado report (2017), El Abra WWTP in Sacaba does not work to its fullest capacity. A more recent study from 2018 indicated that the WWTP El Abra and WWTP San Pedro Magister have direct discharge to the Rocha River but does not mention to what capacity. The location of the wastewater discharge pipes can be found in Appendix 1 (UMSS, 2018).

Cercado

Cercado, the inner city of Cochabamba, is where the population is the highest and where direct discharges to the river are from activities such as car washes and dry laundry facilities as well as leather industries. Also, high concentration of solid waste is being thrown along the river. During recent years the number of large leather industries have decreased by moving to Santa Cruz, while artisanal leather industries with lacking local treatment are increasing (Contraloría General del Estado, 2017).

In the downtown area of Cercado, where the tributary Tamborada River flows, two industries are located; the local slaughterhouse and the Venezuela-tannery. As the sewer treatment system is poor in the south part of the city, the discharge from these industries is a source of direct pollution to the Tamborada River, which, joins the Rocha River just before the Alba Rancho WWTP. Also, domestic waste from households in this area is not connected to a sewage system, and may hence be, directly discharged to the Tamborada River (Contraloría General del Estado, 2017).

Colcapirhua

In this area the main direct discharge to the Rocha River is from the local textile industry, which has a local treatment system that does not work effectively (Contraloría General del Estado, 2017).

Quillacollo

Quillacollo is an area where several tributing rivers from the surrounding mountains connect with Rocha River. The water from the tributary rivers contain outflows from tanneries and domestic wastewater in the area. Furthermore, untreated wastewater from Cercado that is discharged to the Valverde channel is discharged to the Rocha River in this area (Contraloría General del Estado, 2017).

Vinto

Direct untreated wastewater discharge to Rocha River in this area come from pig farms that are located along the river. The untreated waste that is discharged contains solids as well as remains of animals and raw domestic waste (Contraloría General del Estado, 2017).

Sipe Sipe

Sipe Sipe is a slaughterhouse area. Several pig farms, as well as chicken farms, are located here and the wastewater from farms and domestic wastewater is discharged to Rocha River without treatment (Contraloría General del Estado, 2017).

2.3.4 Wastewater treatment

Regarding the sewage systems in the department, 70% of the homes have some form of disposal system, 86% in the urban areas and 41% in the rural areas. The existing sewerage system collects approximately 65 % of the wastewater generated by the population and some small industries in the urban areas. In rural areas the collection is virtually non-existent. The wastewater from Cochabamba city arrives at the Alba Rancho WWTP via two main sewers. Both sewers arrive at a pumping station called Valverde, from where some of the wastewater is pumped to Alba Rancho WWTP located in Cercado (Zabalaga et al., 2007). The rest of the wastewaters, waters coming from the north-west part of the city, is summoned to the Valverde pumping station that forwards it without treatment to the channel Valverde that is discharged into the Rocha River (Contraloría General del Estado, 2017).

Alba Rancho WWTP

The Alba Rancho plant has the capacity to treat only 50% of incoming water (Zabalaga et al., 2007). Overall, approximately 19% of the total wastewater in the department of Cochabamba is treated (MMAyA, 2014), whereas the remaining 81% is discharged directly without any treatment into the water courses of the region, Rocha River being the recipient to all of them (Contraloría General del Estado, 2017). The Alba Rancho uses primary and secondary facultative ponds operated by the water company SEMAPA. The effluent is of low quality and according to Zabalaga et al. (2007) the effluent does not meet the requirements of the Bolivian environmental law No.1333 regarding the BOD_5, COD, TDS and fecal coliforms.

Further improvement of the effluent quality from Alba Rancho has not been published, the effluent quality does not comply with standards proposed by world health organisation (WHO, 1989) for effluent reuse with regards to fecal coliform values (Zabalaga et al., 2007). Yet, the treated effluent of Alba Rancho WWTP is considered an important water resource for the agricultural irrigation of the La Mayca area (south western part of the municipality of Cercado and south of Colcapirhua, figure 2.3), that is surrounding the Alba Rancho WWTP (Zabalaga et al., 2007).

As mentioned, the city suffers from water shortages and consequently the population has to reduce water consumption, which in turn leads to more concentrated wastewater. Furthermore, the water operator SEMAPA regularly decreases the hours of water distribution during the summer when the reservoirs in the mountains are reaching a critically low level.

2.3.5 Agriculture

Currently, the department with the most developed irrigation system in Bolivia is Cochabamba, with a total irrigation area of 32% of the department (MMAyA, 2012). The low rainfall and low surface water flows along with industrial pollution and low wastewater treatment, the irrigation water available for the farmers is thus of low quality (Huibers et al., 2004). Most of the basins in the central valley region of Cochabamba presents soil erosion and occasionally, during periods of intense rainfall, short duration floods can occur in the rural areas (Reyna-Bowen et al., 2017).

In the Cochabamba valley soil degradation has forced farmers to replace vegetable crops with more salt-tolerant fodder crops, such as maize and alfalfa. Vegetables are also grown in the area but mostly used for private consumption (Huibers et. al, 2004). The electrical conductivity of the irrigation water for alfalfa is 1300 - 10 000 µS/cm. The maximum salt tolerance for a 100% yield potential is 1300 µS/cm and with higher electrical conductivity value the yield decreases. At 10 000 µS/cm the alfalfa ceases to growth. For maize the corresponding values are 1100 - 6700 µS/cm (Ayers & Wescot, 1994).

The farmers from the area, La Mayca, have made an agreement with SEMAPA about irrigation with effluent from the facultative stabilisation pond at the Alba Rancho. This agreement was made because the farmers from La Mayca were cut off from the supply source Angostura Dam and partly also from the Rocha River when the airport was built in the 1980s (Huibers et. al, 2004). This has resulted in that crops are irrigated with polluted waters, which is either diluted or partly treated at the Alba Rancho WWTP. The fodder crops are used for grazing of cows and eventually milk production. Thus, the farmers irrigate with waters containing high concentrations of pathogens, salts and heavy metals (Huibers et al., 2004).

In other areas of the Cochabamba department, cultivators deny using wastewater for irrigation claiming they use groundwater from the wells nearby as their water source. However, many wells are probably also polluted, especially the shallow ones, and do not yield enough water for the irrigated area (Huibers et al., 2004).

In areas such as Tiquipaya, which is located north of Quillacollo, more intensive agriculture production occurs involving dairy farming and vegetables. The crops are during dry season irrigated with water from a series of small reservoirs which collects runoff from the mountains in the catchment (Bustamante et al., 2004).

Very few studies show which irrigation technique farmers in Cochabamba use but one study states that farmers in this area introduced the use of chemical fertilizers and pesticides for potato cropping in the 1970s (Lagos, 1994).

3. Theory and literature studies

3.1 River characteristics and restoration techniques

The impact of the physical, chemical and biological processes in a river is affected by the whole stream corridor which includes the land, plants, animals and network of streams within. The corridor provides several functions in action such as stream flow, storing water, removing harmful materials from the water and provides habitats for aquatic and terrestrial plants and organisms. Changes within the surrounding ecosystem will impact the mentioned above. Stream system functions within natural ranges of flow, sediment movement, temperature, and other variables in the dynamic equilibrium. The dynamic equilibrium is lost when changes in the mentioned variables occur beyond the natural ranges. This results in adjustments in the ecosystem that might conflict with social needs. Increase in population and industrial activities place heavy demands on the streams which can cause degradation of water quality, decreased water storage, loss of habitat for fish and wildlife, and decreased recreational and aesthetic values. For restoration in a stream to occur the dynamic equilibrium must be recovered and function at a self-sustaining level (FISRWG, 1998). Parameters and river characteristics that enhance or disturb the dynamic equilibrium as well as some restoration techniques are described below.

The complete oxidized state of nitrogen is nitrate, NO_3^-, which is commonly found in natural ground and surface waters (Kellman & Hillaire-Marcel, 1998). Denitrification, stepwise reduction of nitrate, takes place in anaerobic conditions with high contents of soluble carbon and bacteria, resulting in gaseous N_2 (Martens, 2005). However, when relatively high O_2 levels are present in the water, denitrification tends to instead occur in stream sediments due to diffusion of NO_3^- into the sediments from the overlying water (Kellman & Hillaire-Marcel, 1998). Stream sediments is controlled by a complex set of exchanges and interactions between the overlying water and underlying sediments. The optimal sediment for denitrification includes pool and riffle sequences along the stream bottom (Kellman & Hillaire-Marcel, 1998).

In surface water, nitrate, NO_3^-, and other nutrients such as phosphorus and sulfur, stimulates plant growth, especially of algae, which may cause water quality problems associated with eutrophication. Most of the nitrate loss is due to plant uptake. The time of day measurements are performed can have an effect on the nitrate losses in the river as increased photosynthetic activity mid-day may increase biological nitrate uptake (Kellman & Hillaire-Marcel, 1998). Commercial fertilizers contain nitrogen in the form of nitrates. Thus, an estimation of the concentration of nitrates is an appropriate measure if the water body is located near agricultural land. High levels of nitrate in water may indicate biological wastes in the final stages of stabilization, and the sources may be domestic as well as industrial wastes (Edge analytical, n.d.).

Changes in pH do not only affect the organisms and habitats in water bodies but is also a good environmental indicator. Chemical reactions cause changes in pH, for example, when ammonia (NH_3) reacts with water and forms ammonium (NH_4^+) and hydroxyl ion (OH^-) which means that the pH of the water increases. An increase of hydroxyl ions in the water body, pushes the ammonia equilibrium to the left and more ammonia is formed, which is the toxic form (Oram, n.d). Thus, the pH of water determines the solubility and biological availability of chemical constituents such as nutrients; phosphorus, nitrogen and carbon, as well as heavy metals. For example, in addition to affecting how much and what form of phosphorus is most abundant in the water, pH also determines whether aquatic life can use it. In the case of heavy metals, the degree to which they are soluble determines their toxicity. Metals tend to be more toxic at lower pH because they are then more soluble (Perlman, 2018). In waters with high amount of aquatic vegetation, uptake of the carbon dioxide by plants during photosynthesis removes carbonic acid from the water, which can increase pH by several units. Restoration techniques that decrease plant growth in rivers and stabilize the variable pH due to photosynthesis is through increased shading or reduction of nutrient loads as well as increase in reaeration (FISRWG, 1998).

In general, oxygen transfer in natural waters depend on the following; i) internal mixing and turbulence due to velocity gradients and fluctuation, ii) temperature, iii) wind mixing, iv) waterfalls, dams, and rapids, v) surface films and vi) water column depth (FISRWG, 1998). However, external loads of oxygen demanding wastes or abundant plant growth caused by large nutrient load followed by decomposition of vegetative material can lower the oxygen concentration significantly. Dissolved oxygen measurements provides a good indication of water quality sincr changes in the oxygen concentrations can be an early indication of changing conditions in the water body (Bartram and Ballance, 1996). If the oxygen level drops too low, fish will suffocate and the aqueous environment will be quite favorable for harmful bacteria (Moretto and Kalcher, 2015). A low level of dissolved oxygen can also cause the formation of hydrogen sulfide (which gives off a bad smell) by reactions in anoxic state. This can change the types of aquatic organisms present in such conditions and can even cause the local extinction of species (UMSS, 2018). Aquatic organisms such as fish can recover from short periods of low dissolved oxygen concentration. However, if water has dissolved oxygen concentrations of 2 mg/L or less during a longer period of time it can result in “dead” water bodies. Example of stream restoration techniques regarding the dissolved oxygen concentration is by the installation of artificial level differences to increase reaeration as it is the primary way for introducing oxygen into most waters (FISRWG, 1998).

Organic load may arise from a variety of land use practices and natural events such as; storm events, erosion, and wash off. Large-scale animal operations and improper manure application, can result in significant BOD load to the near water bodies. As mentioned, urban runoff is often loaded with high concentrations of organic materials from variety of different anthropogenic sources (FISRWG, 1998). Severe organic pollution may lead to rapid de-oxygenation of river water, with the consequences mentioned above (EEA, 2018).

Straight rivers are a result of artificial construction for social needs. A meandering stream consists of a series of turns and has a relatively low gradient. The positive effect of meandering rivers is the reduced flow rate and the reduced flood risk due to the increased water storage. Thus, the meandering form has a positive impact on sedimentation of particles and nutrients as well as a positive effect on biodiversity (Naturvårdsverket, 2008).

The connection between groundwater and river channel are in general the strongest with gravel river beds in well-developed alluvial floodplains. Coarse sediment particles are found in riffle areas while small particles occur in pools (FISRWG, 1998).

3.2 Water quality

Irregular sources of pollution results in water quality variations and may be apparent over a matter of days or months (Bartram and Ballance, 1996). Variables that give the bare minimum of information on the water quality is a combination of temperature, electrical conductivity (EC), pH, dissolved oxygen (DO) and total suspended solids (TSS). In several monitoring programs a known, or suspected, water pollution condition is the reason for deciding to analyze for specific water quality variables (Hunt and Wilson, 1986).

If organic wastes are known to be discharged into the river from domestic sewage then the variables that should be measured are biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), dissolved organic nitrogen, total phosphorus and fecal coliforms (Hunt and Wilson, 1986).

The variables that should be measured if the water of interest is located in, or passing through, agricultural land are; nitrate, nitrite, ammonia, total phosphorus (filtered and unfiltered), reactive silica, transparency and chlorophyll a. These variables are mainly of interest after the usage of fertilizers as well as pesticides and herbicides (Hunt and Wilson, 1986).

Industrial effluents may contain toxic chemicals, organic or inorganic or both, depending on the industrial process. Some knowledge of industrial processes is, therefore, necessary before a rational decision can be made on the variables for which analyses should be made. Examples of the water quality variables that should be measured in industrial waters are total solids, BOD, COD, benzene, cyanide, arsenic and different metals.

3.2.1 Measurement of water quality variables

Below are the chosen water quality variables in polluted rivers defined and described. The presented measuring procedure is according to WHO (1989).

Temperature

Temperature is measured in situ because a water sample will gradually reach the same temperature as the surrounding air. The common technique to measure the temperature is with a glass thermometer (Bartram and Ballance, 1996). An increased freshwater temperature will affect the chemical reactions and kinetics, which leads to a deterioration of the water quality and ecological status (Whitehead et al., 2009).

pH

Determination of the pH of water should, if possible, be made in situ. If this is not possible, the measurement should be made immediately after the sample has been obtained with an electrochemical analysis (Bartram and Ballance, 1996). This is performed with an electrochemical cell for pH measurements consisting of an indicating electrode, whose potential is proportional to pH, and a reference electrode, whose potential is independent of pH. The potential can be measured between the indicating electrode and the reference electrode, which depends on the pH of the sample and the temperature of the sample, as pH is temperature dependent (Bier, 2018). When the temperature increases the autoprotolysis of water increases, which means that the pH decreases as there will be a higher concentration of hydrogen ions in the water body.

Electrical Conductivity, EC

The ability of water to conduct an electric current is known as conductivity and depends on the concentration of ions in a solution. The measurement should be made in situ with a measurement meter, or immediately after a water sample has been obtained, due to the possibility that conductivity may change with storage time. The electrical conductivity is measured with an electrochemical probe, where the cations in the sample migrate to the negative electrode, the anions to the positive electrode and the solution acts as an electrical conductor (Bier, 2018). Conductivity is also temperature-dependent; it increases with temperature. Measurements will therefore be the most accurate when made at the same temperature as that at which the cell constant is determined. (Hunt and Wilson, 1986).

5-day Biochemical Oxygen Demand, BOD_5

The biochemical oxygen demand (BOD_5) estimates the relative oxygen requirements of effluents and polluted waters with an empirical test, in which a standardised laboratory procedure is performed as soon as possible after the sample has been collected, in this case with a five-day incubation period. The results are used as an approximate measurement of the amount of biochemically degradable organic matter present in the water sample. The present microorganisms in the sample use the organic matter as a source of carbon (Hunt and Wilson, 1986).

BOD_5 is commonly determined by the standardised Winkler dilution method. The sample is diluted since the sample water, that is known to be polluted, will have a BOD_5-value higher than the amount of oxygen available in the bottle during the incubation period. Otherwise the biological activity will use up the dissolved oxygen in the bottle before the five days incubation period. Predicting the effect of pollution on a water body is straightforward with this method. However, there are also other, possibly influencing, factors excluded in the determination of BOD_5, such as the actual temperature of the water body, water movements, sunlight, oxygen concentrations, biological populations (including planktonic algae and rooted plants) and the effects of bottom deposits. Furthermore, the polluting effect of an effluent on a water body may be considerably altered by the photosynthetic action of plants and algae present, although, it is impossible to determine this effect quantitatively in 5-day BOD experiments. A further complication in the BOD_5 test is that much of the oxygen consuming capacity of samples may be due to ammonia and organically bound nitrogen, which will eventually be oxidized to nitrite and nitrate if nitrifying bacteria are present (Hunt and Wilson, 1986).

BOD is the most commonly used parameter to define the intensity of the wastewater by measuring waste loadings to treatment plants and evaluating the efficiency of the treatment system. However, it is of limited values in measuring the actual oxygen demand of surface waters. The tests are highly questionable for stream oxygen demands since the laboratory environment cannot reproduce the physical, chemical and biological stream conditions (Hammer & Hammer, 2014).

Chemical Oxygen Demand, COD

The chemical oxygen demand is commonly used to characterize the organic strength of wastewater and pollution of natural waters (Hammer & Hammer, 2014). The COD is determined by measuring the amount of oxygen consumed by organic matter from boiling acid potassium dichromate solution. This reference method is named the dichromate method. The test will indicate the amount of oxygen required for complete oxidation of the water sample (Bartram and Ballance, 1996).

Dissolved oxygen

With the standardised Winkler titration method for determining dissolved oxygen in a water body the water sample is collected in a glass bottle, preserving manganous sulfate is added to the sample as well as the strongly basic mixture of sodium azide and potassium iodide. The concentration is then determined the same day in the laboratory when a precipitate form is acidified with sulfuric acid. Iodine is then released and titrated with phenylarsine oxide using a starch indicator (NEMI, n.d.).

Nitrates

The determination of nitrate, NO_3^-, assesses the degree of oxidation. Nitrogen is limited in unpolluted natural waters and contain only minute amounts of nitrate (Hammer & Hammer, 2014). To determine the concentration of nitrate the Cadmium Reduction Method is commonly used, where nitrate is reduced to nitrite in a cadmium column and nitrite is then determined with absorbance of a dye that is added. The absorbance of the dye is proportional to the concentration of nitrite present. The amount of nitrite, that is reduced from nitrate, is then determined. The determination should be made on fresh samples to prevent bacterial conversion of the nitrite to nitrate or ammonia. The determination of nitrate in water is difficult due to interferences and the level of difficulty increases with polluted water such as wastewater (Edge analytical, n.d.).

Coliforms

The procedure used for determining the concentrations of thermotolerant (fecal) coliforms in the water samples is with the Membrane Filter Technique; Fecal Coliform Membrane Filter Procedure. In the laboratory thermotolerant coliforms are grown on media containing lactose, at a temperature of 44°C. The coliforms are then identified by the production of acid and gas from the fermentation of lactose.

As the thermotolerant coliforms present in natural water consists of more than 95% of the intestinal organism Escherichia coli (E.coli), a conclusion can be drawn that the water has fecal contamination. Thus, it is often unnecessary to perform further testing to confirm the specific presence of E. coli (Bartram and Ballance, 1996).

3.3 Health aspects of polluted surface water

Algal bloom can have health effects such as rashes, stomach or liver illness, problems with respiratory system and disorders of the nervous system on humans that drinks, accidentally swallows or swim in the water (EPA, 2018).

Nitrate is a nutrient that often reaches the surface water from wastewater or agricultural lands that, if highly concentrated, can cause blue baby syndrome if the water is drunken by infants (EPA, 2018). From the agriculture the surface water can also be contaminated by pesticides that can contain biologically active chemicals. These can severely harm humans by various effects including cancer, diabetes as well as disruption of the endocrine, reproductive and immune system (Schwarzenbach et al., 2010).

Wastewater containing human excreta with pathogens and intestinal worms poses risks like diarrhea, cholera, typhoid, hepatitis A and B and dysentery, both if water is drunken, accidentally ingested through skin contact or swimming. If the water is used untreated for irrigation, the farmers are in risk for eczema from handling the water and the plants can transmit the pathogens to the consumers (WHO, 2006). Plants can also accumulate heavy metals and are affected with inhibited growth when they are irrigated by water containing high salinity levels (WHO, 2006).

If wastewater is mixed with fresh water, it is also inevitably polluted by micro pollutants of large structural variety such as pharmaceuticals and hormones. The adverse effects of these are often subtle and not acute and therefore difficult to estimate, although they can be chronic (Schwarzenbach et al., 2010).

3.4 Legislation and guidelines

For drinking water and certain irrigation and freshwater purposes there are general international guidelines stated by intergovernmental and international organizations such as the World Health Organisation (WHO) and Food and Agriculture Organization of the United Nations (FAO). For the regulations of the water quality in freshwater and rivers there are Bolivian legal provisions that regulates the Law of the Environment No. 1333 with regards to the prevention and control of water pollution. The regulations and guidelines relevant for this project are seen in table 3.1, where environmental water represents the quality regulations for freshwater and rivers. Table 3.2 is an extract from the Environmental Law No.1333 representing the maximum values in receiving water bodies for the parameters; BOD_5, COD, DO, Nitrates (NO_3^-), pH, TDS and temperature.

Table 3.1. Water quality regulations for drinking water, water for agriculture and environmental water.

Parameter	Drinking water	Water for agriculture	Environmental water
pH	6.5-8.5 (WHO, 2018)	6.5-8.5 (FAO, 1996)	6.9-8.5 (MDSMA[1], 1996)
EC	2500 µS/cm (WHO, 2018)	3000 µS/cm (FAO, 1996)	~2300 µS/cm (MDSMA, 1996)
BOD_5	0 (WHO, 2018)	Crops for human consumption 30 mg/L O_2 (EPA, 2012)	80 mg/L O_2 (MDSMA, 1996)
COD	0 (WHO, 2018)	-	250 mg/L O_2 (MDSMA, 1996)
DO	4-8 mg/L (WHO, 2018)	>3 mg/L (WHO, u.d.)	Warm-water biota >5 mg/L (WHO, u.d.)
Nitrate NO_3^-	<45 mg/L (WHO, 2018)	22-133 mg/L (FAO, 1996)	49 mg/L (WHO, 2016) 88 mg/L (MDSMA, 1996)
Coliforms	0 cfu/100 mL (WHO, 2018)	Unrestricted*: 10^3-10^5 cfu/100mL (WHO, 2018) Restricted**: 10^4-10^6 cfu/100mL (WHO, 2018)	Fecal coliforms 1000 cfu/100mL (MDSMA, 1996)

**Use of treated wastewater to grow crops that are normally eaten raw. **Use of treated wastewater to grow crops that are not eaten raw by human.*

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[1] *Ministerio de Desarrollo Sostenible y Medio Ambiente* (Bolivian Ministry of Sustainable Development and Environment) (MDSMA)

Table 3.2 Maximum values for the parameters; BOD_5, COD, DO, Nitrates, pH, TDS and temperature in receiving bodies from Anno A-2, Bolivian Environmental Law No.1333. The different qualities of water classes "A"-"D" are presented in Appendix 2.

Parameter	**Unit**	**Class A**	**Class B**	**Class C**	**Class D**
BOD_5	mg/L	<2	<5	<20	<30
COD	mg/L	<5	<10	<40	<60
DO	%	>80 %	>70 %	>60 %	>50 %
NO_3^-	mg/L	20	50	50	50
pH	-	6.0-8.5	6.0-9.0	6.0-9.0	6.0-9.0
EC	µS/cm	1563	1563	2344	2344
Temperature*	C	+/-3	+/-3	+/-3	+/-3

**The allowed temperature difference from source and receiving water body.*

3.4.1 Organic pollution index ICO

The ICO index is based on the Prati-index which is widely used index to determine pollution in water bodies. Out of the 13 parameters used in the Prati-index the ICO-index prioritises indicator parameters for organic pollution only. The ICO-index has been used in previous studies on the Rocha River and is developed in the article Romero (1998). Table 3.3. and equation 3.1 explains the contexture of the index.

Table 3.3 ICO-index, where Y is the measured value for each parameter.

Parameter	**Ranges/Units**	**Equations**
DO	0-50%	$X = 4.2 - 0.437\left(\frac{100-Y}{5}\right) + 0.042\left(\frac{100-Y}{5}\right)^2$
	50-100%	$X = 0.08(100 - Y)$
	>100%	$X = 0.08(100 - Y)$
BOD_5	mg/L	$X = \frac{Y}{1.5}$
COD	mg/L	$X = 0.1Y$
NO_3^-	mg/L	$X = 2^{2.1\log\left(\frac{Y}{4}\right)}$

$$ICO = \frac{1}{m}\frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n} X_{ij} \tag{3.1}$$

Where:
ICO= The modified organic pollution index from Prati
m= Number of samples
n= Number of parameters
X_{ij}= Pollution unit

The organic pollution index can then be interpreted by a scale of classification seen in table 3.4.

Table 3.4 Classification of pollution according to the Prati based ICO-index

Level	ICO	Pollution of water	Colour of quality
1	0-1	Not polluted	BLUE
2	1-2	Weakly polluted	GREEN
3	2-4	Moderately polluted	YELLOW
4	4-8	Polluted	ORANGE
5	8-16	Very polluted	RED
6	>16	Highly polluted	BLACK

3.5 Preparatory work for sampling

There is a general need to attempt to define the minimal number of sampling positions and occasions that will provide the desired information. The basic aims of sampling may according to Hunt and Wilson (1989) be summarized as: i) To select the positions and times of sampling, such that the required information on quality can be executed with adequate accuracy at minimal cost, ii) To ensure that the concentrations of parameters in samples are identical to those in the water of interest at the positions and times of sampling and iii) To ensure that the concentrations of parameters in samples do not change in the period between sampling and analysis.

Before performing sampling of fresh water bodies one needs to formulate the following information as detailed as possible: i) what are the objectives with the measurements, ii) which parameters that are of interest, iii) where and when the samples are to be collected, iv) which analytic methods are to be used, as well as, v) how samples are going to be performed, handled, interpreted and reported (Hunt and Wilson, 1986).

To obtain the quality of a river that is of interest it is important to specify the following: i) the parameters of interest and the analyses that are required, ii) the particular rivers of interest and locations, iii) the required accuracy of results is stated and implied so that appropriate methods of sampling and analysis may be used (Hunt and Wilson, 1986). In the following subchapters the statements above will be further explained.

3.5.1 Sampling locations

Sample locations should be located at cross sections where lateral and vertical mixing of effluents are complete. To avoid non-representative samples caused by surface films and the bottom deposits, it is recommended that samples should not be collected closer than 30 cm to the surface or bottom. When the aim is to assess the quality of a river, the number of potentially relevant sampling locations is usually significantly large. It is therefore, necessary to assign different priorities to various locations in order to achieve a practicable sampling program. One way is to identify locations where quality problems may be most severe (Hunt and Wilson, 1986).

Various factors are involved in selecting the exact locations of sampling points. One example of exact location can be dependent on if the location is approachable. Also, selecting sampling positions are dependent on the variety of processes that can affect the spatial heterogeneity of the water bodies (Hunt and Wilson, 1986). For only a single sample to be required the water needs to be sufficiently well mixed at the sampling station. What may prevent this is for example: The mixing of tributary water with main river water if the flow in the river is laminar and the waters are at different temperatures. The complete mixing of tributary and main stream waters may not take place for a significant distance, sometimes many kilometers, downstream of the junction (Bartram and Ballance, 1996).

The most desirable sampling position is at a bridge, it is easily accessible and identifiable as well as a bridge is often a hydraulic gauging station. The gauging station allows one to collect the stream flow information at the time of sampling. (Bartram and Ballance, 1996).

To be sure that the sample collected is completely mixed it is necessary to take several samples at points across the width and depth of the river. If the results do not vary significantly from one another, a station may be established at mid-stream or at another convenient location of the river. (Bartram and Ballance, 1996).

3.5.2 Time and frequency of sampling

The time of sampling can be of particular concern when the quality of the water that is of interest shows more or less regular variations. Within any water body, the water quality can differ with time and place. Water quality differences may result from either internal or external processes, where external processes being addition of pollutants. Internal processes are usually cyclic, for example, the diurnal (24-hour) variations, which, can result from biological cycles and daylight/darkness cycles which usually cause changes in, e.g., dissolved oxygen and pH. Another example is the cyclic nature of waste discharges from domestic and industrial sources (Bartram and Ballance, 1996). Also, variations such as minute-to-minute and day-to-day differences resulting from water mixing and fluctuations in inputs, usually as a result of meteorological conditions (Hunt and Wilson, 1986).

In other situations, the frequency may be of interest; for example if the interest is a representation of the water quality during a defined period (Hunt and Wilson, 1986). The differences in water quality at different times of the year will be much greater for a stream than for a large river. This means that the sampling frequency necessary to allow average water quality to be described correctly is normally much greater for a stream than for a river (Bartram and Ballance, 1996). Hence, problems may arise of deciding the times at which to collect samples so that the samples represent the quality during the period of interest (Hunt and Wilson, 1986). In random sampling, the times of sampling are as stated, random. In systematic sampling, a particular pattern of sampling times is chosen and used for example; samples are collected daily or weekly with a constant interval between samples (Hunt and Wilson, 1986).

Natural waters such as rivers provide several examples of systematic variability. For example, an increased use of a chemical substance in a catchment area of a river may lead to an increasing trend in the concentration of that chemical in the river waters. Other examples are the cyclic variations such as the daily and annual cycles that several parameters show in surface waters as a result of daily and annual variations in temperature and sunlight, e.g., the diurnal variations of dissolved oxygen in rivers. And, not to forget, weekly or even daily cycles may arise through industrial activity (Hunt and Wilson, 1986).

Most water bodies are affected by events that cause significant deterioration of the water quality, e.g., flood conditions in rivers. The possibility of such periods should be considered when planning sampling and, even more importantly, when considering the information required on quality. It is generally necessary to decide if, and exactly what, information on the abnormal quality is required.

3.5.3 Quality-control programs

There are two common types of control program for water quality analysis: The threshold control and the process control (Hunt and Wilson, 1986). In threshold control, the primary aim is to ensure that the concentrations of one or several parameters do not exceed specified limits; provided that this aim is achieved, the parameter concentrations are unimportant. Thus, any water quality standard specifying that a parameter must not exceed a specified limit implies the need for threshold control. Situations do occur where a concentration of a parameter should not be less than a specified limit, its concentration above that limit being unimportant. An example of this is dissolved oxygen in river waters. In process control the specific concentration of one or more parameters is examined and controlled within narrow limits of specified values (Kateman & Pijpers, 1981)

3.5.4 Potential consequences with sample-collection devices

Examples of the potential consequences from physical, chemical and biological processes that may disturb the results of the samples when collected are described below.

Physical processes

A frequent example is the deposition of undissolved, solid materials onto the walls of a device. Another example is the loss of dissolved gases that may occur if the pressure decreases while samples are in the devices (Hunt and Wilson, 1986).

Chemical processes

Chemical processes may occur between different constituents of a sample e.g., the, reaction between chlorine and organic compounds, and may lead to increases or decreases of concentrations of the specified parameter. It seems that the more important processes are those involving reactions between sample and the sample-collection device itself. Such processes may lead to increased variable concentrations when the examined variables are leached from the device e.g., organic compound from plastic materials. Decreased concentrations may result from direct reaction of the parameters with materials of construction of the device, e.g., dissolved oxygen can react with steel or copper. Thus, for chemical processes not to occur after sampling it is important to use recommended collection devices (Hunt and Wilson, 1986).

Biological processes

When natural waters are sampled, various biological species may settle on the surfaces of the sample-collection device and react with the sample. For example, large proportions of the ammonia in a sample may be oxidised by bacterial films with simultaneous release of other nitrogen species into the sample. The general metabolism of biota may also release various substances into the sample, e.g., dissolved oxygen and organic substances (Hunt and Wilson, 1986).

3.5.5 The materials of the containers

Plastic materials are usually unsuitable when organic compounds are of interests in samples since it has been reported that leaching of various organic materials occur from a range of plastics when in contact with water. Under those circumstances, metal or glass devices seem preferable for organic variables. Each sampling situation should be considered individually since the choice of material for sample-collection devices is governed by the variable of interest. Another important factor is the cleanness of internal surfaces of the containers, especially with regards to undissolved solid materials and biological films on surfaces (Hunt and Wilson, 1986).

3.5.6 Sample stabilisation

Chemical, biological and physical processes may occur in samples between the time of sampling and analysis. Such processes are a common source of instability of many variables. The rates of the various reactions are sometimes sufficient to cause important changes in concentration within a few hours or within a day. Precipitation processes may also occur as well as oxidation and reduction processes during the time between collection and analysis. The most common analysing technique is to remove samples from the water-body and then analyze in a laboratory. Although, some of the problems can be eliminated by the use of in-situ measurement techniques in which the analytical sensor is merged in the water body at the desired position.

3.5.7 Hydraulic methods for measurements of a river

To interpret the water quality variables in a sample taken from a river, knowledge about the discharge of the river at the time and place of sampling is required. To be able to calculate the mass flux of chemicals in the water, a time series of discharge measurement is essential. The flow rate of a river is the volume of water flowing through a cross-section in a unit of time. It is calculated as the product of average velocity and cross-sectional area but is affected by water depth, alignment of the channel, gradient and roughness of the river bed (Bartram and Ballance, 1996).

3.5.8 Measuring stream flow

The most accurate method to measure stream flow is to measure the cross-sectional area of the stream and then, using a current meter, determine the average velocity in the cross-section (see figure 3.1). If a current meter is not available, a rough estimate of velocity can be made by measuring the time required for a weighted float to travel a fixed distance along the stream and this method is also used for shallow waters where the current meter cannot be used (Bartram and Ballance, 1996).

The velocity varies across a channel, and measurements must therefore be made at several points across the channel (see figure 3.1). The depth of the river varies across its width, so the usual practice is to divide the cross-section of the stream into a number of vertical sections and to measure velocity at each of these points. No section should include more than 10-20 % of the total discharge. Thus, between 5 and 10 vertical sections are measured, but of course the amount depends on the width of the stream (Bartram and Ballance, 1996).

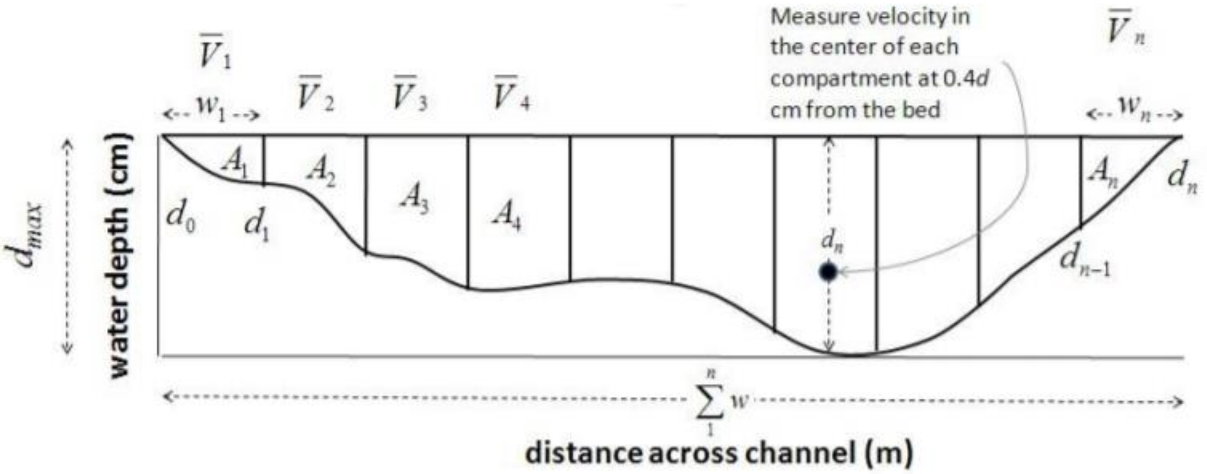

Figure 3.1 Cross-section of a river divided into vertical sections for flow measurement (Ethz.ch, nd).

The cross-section of a stream at the point of measurement, should fulfil some characteristics for the best flow measurement. For example, the velocities at all points should be parallel to one another and at right angles to the cross-section of the stream. Also, the cross-section should be located at a section where the stream is nominally straight for at least 50 meters upstream and downstream of the measuring point, as well as locating a bed of the channel that is fairly regular and stable. Other characteristics are; a depth greater than 30 cm and no overflow of the stream bank. There are even more characteristics to be fulfilled for an optimal measurement of flow but not all can always be fulfilled and estimations have to be made (Bartram and Ballance, 1996).

3.5.9 Estimation of river discharge

The discharge can be estimated with several methods and the most common one is the Manning equation, see equation 3.2, which, although developed for conditions of uniform flow in open channels, may give an adequate estimate of the non-uniform flow which is usual in natural channels.

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \tag{3.2}$$

Where;

Q = Discharge [m^3/s]
A= Cross-sectional area [m^2]
P= The wetted perimeter [m]
R= Hydraulic radius and equal to A/P [m]
S= The slope of the gradient of the stream bed [m/m]
n= The roughness coefficient

More accurate values for discharge can be obtained with a permanent gauging station that is established on a stretch of a river where there is a stable relationship between water level and discharge. In this case readings need only be taken of the recorded water level (stage) from the gauge, then the discharge may be read from a stage-discharge curve. The water quality samples do not have to be taken exactly at a gauging station. A short distance upstream or downstream is acceptable if no inflow or outflow occurs between the sampling and gauging stations (Bartram and Ballance, 1996).

Unstable flow can produce a loop in the stage-discharge plot for an individual storm event, and is not usually apparent in the annual rating curve that is commonly used in hydrological survey programs. Unstable cross-sections cause stage- discharge variability and can produce sudden and significant shifts in the rating curve as a result of erosion or deposition of material in the river bed (Bartram and Ballance, 1996).

3.6 Water quality modelling and flow analysis

The software used for flow analysis and water quality modelling in this project is Hec-RAS which is a river analysis system developed by the U.S. Army Corps of Engineers. With this software one can perform one- and two-dimensional analyses for both steady and unsteady flow hydraulics combined with general water quality modelling (U.S. Army Corps of Engineers, 2012).

The computations are based on the one-dimensional energy equation. Manning’s equation (eq. 3.2) is applied to evaluate the frictional energy losses, whereas a function of the change in velocity head calculates the energy losses from contraction and expansion. For calculations of flow regimes, such as hydraulic jumps where the water surface profile shows a large variation, the momentum equation is used (U.S. Army Corps of Engineers, 2012).

For the water quality analysis Hec-RAS solves the one-dimensional advection and dispersion equations by explicit numerical methods. To determine whether a specific part of the river, called a water cell, is a source or a sink pertaining to heat energy the model uses the equation for heat transport seen in equation 3.3

$$Heat_{source/sink} = \frac{Q_{net} \times A_s}{\rho_w \times C_{pw} \times V} \tag{3.3}$$

Where;

Q_{net}=net heat flux at the air-water interface [W/m^2]

ρ_w= density of water [kg/m^3]

C_{pw}= specific heat of water [J/kg/C]

A_s= surface area of the water cell [m^2]

V= volume of the water cell [m^3]

Further requirements to model the water temperature is a time series of complete meteorological data set of the study area for the simulated period. Hec-RAS simulates the river nutrients by including the rate constants of each parameter that control the rate of the source/sinks term (S) in the advection-dispersion equation for thermal energy (equation 3.4). The rate constants included represents the physical and chemical reactions between biochemical oxygen demand, dissolved oxygen, algae, nitrate, phosphorus and sediments.

$$\frac{\delta}{\delta t}(V\Phi) = -\frac{\delta}{\delta x}(Q\Phi)\Delta x + \frac{\delta}{\delta x}\left(\Gamma A \frac{\delta\Phi}{\delta x}\right)\Delta x \pm S \qquad (3.4)$$

Where;
Q= flow [m^3/s]
A= cross sectional area [m^2]
V= volume of the water cell [m^3]
Φ= water temperature (C) or concentration [kg/m^3]
Γ= user defined dispersion coefficient [m^2/s]
S= sources/sinks [$C°m^3/s$] or [kg/s]

4. Methods and field work

The parameters that were measured and analysed were pH, temperature, electrical conductivity (EC), dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrates (NO_3^-) and fecal coliforms (CF). The limited budget for the master thesis restricted; i) the number of parameters, ii) the quantity of water samples per parameter, iii) the frequency of sampling as well as iv) the number of sampling points.

4.1 Physico-chemical water sampling

4.1.1 Site specifics

The budget allowed for six sampling points along the Rocha River. The ID and name of these points are presented in table 4.1 and shown in figure 4.1, as well as presented with coordinates for each point in Appendix 1. The sampling points were chosen according to the theory presented in subchapter 3.5. Four of the water sample locations were performed under bridges where gauging stations are located according to theory from subchapter 3.5.9. One of the sampling points (ID 4) was located according to theory from subchapter 3.5.1, which states that water quality sampling is best performed after wastewater treatment plant discharge, in this case after the Alba Rancho WWTP. The last location (ID 6) was chosen because of its distance from the inner city, to determine if the quality of the river is still deteriorating or improving.

Table 4.1. The sampling points with respective names and type of surrounding area.

ID	Sample location	Municipality	Area
1.	Chiñata	Sacaba	Rural
2.	Quintanilla	Sacaba	Semi Urban
3.	Puente Cajón	Cercado	Urban
4.	Puente Zofráco	Colcapirhua	Urban
5.	Puente Pico de Loro	Vinto	Urban
6.	Entrada Malcorancho	Sipe Sipe	Rural

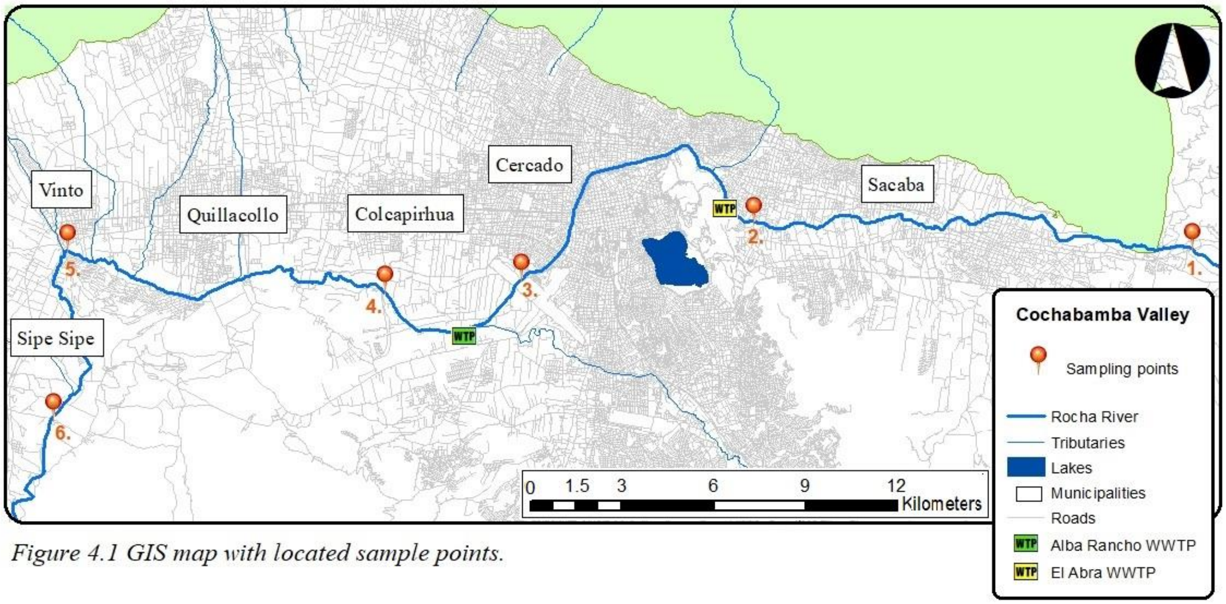

Figure 4.1 GIS map with located sample points.

4.1.2 Chemical parameters and methods

Systematic sampling was performed, described in subchapter 3.5.2, once every two weeks during the limited time in Cochabamba (22 October to 16 December), which resulted in three sampling weeks. The technique for the chosen frequency is described in subchapter 3.5.2. The time of day of the water sampling was during the hours between 08:00-17:00, approximately same time for each point during the three weeks. The water sample collection and physical measurement for the six points were divided into two days, three locations per day. The first sampling (occasion 1) was performed 30-31 October, the second sampling occasion was performed 13-14 November and the third sampling occasion was 27-28 November. Worth mentioning is that heavy rainfall occurred the nights before sampling for both days during sampling occasion 3. Regarding the first two sampling occasions there was no rainfall for several days before the sampling.

Apart from the limited economic budget, the rationale for the chosen parameters can be found in subchapter *3.2 Water Quality*. An assumption was made that the river was well mixed at mid-stream and thus no sample collections were made beforehand as suggested in subchapter 3.5.1.

In order to minimize the chemical, biological and physical processes that may occur in samples, different material for each container was used (table 4.2). The background for the chosen material of sample container can be found in subchapter 3.5.5. According to subchapter 3.5.6 the most common analyzing technique for water quality is to remove samples from the water-body and then analyze in a laboratory. As measurements taken in situ, which is preferable, was not an option in this study, the chosen parameters except for temperature were determined in the laboratory at C.A.S.A within UMSS. The technique used for determination of the parameters are presented in Appendix 3.1 and briefly described in subchapter 3.2.1.

To prevent high rate reactions preservatives were added for COD, nitrites and coliforms (table 4.2). The stabilisation processes for all the chosen parameters are also presented in table 4.2.

Table 4.2 A summary of which type of containers were used with the recommended stabilisation procedure for the specific variables (Hunt and Wilson, 1986).

Variable	Sample container	Stabilisation procedure
BOD_5	Glass	Glass-stoppered bottles of a nominal capacity of 750 mL was filled completely. If storage unavoidable, instant refrigeration and test the effect of the delay. Do not freeze.
COD	Glass	Preserved to $pH < 2$ by adding sulphuric acid, 2 mL H_2SO_4 to bottle containing 750 mL of water sample. Effective time of stabilisation may vary from few hours to several days, and must be tested.
Coliforms	Plastic	500 mL bottle sterilized and wrapped in paper.
DO	Glass	Filled 300 mL bottle completely. “Fixed” sample as Winkler method was used by adding 2 mL of Iodide azide and 2 mL of manganous sulfate.
EC	Glass	Filled 750 mL bottle completely and refrigerated.
Nitrates	Plastic	Filled 200 mL bottle completely. Added 2 mL of chloroform for short-term preservation and refrigerated at 4 °C. Analysed as soon as possible.
pH	Glass	Filled 750 mL bottle completely. If delays unavoidable need to refrigerate.

4.1.3 Physical parameters and methods

The physical measurements performed on the Rocha River were the water velocity and the water depth. These were performed at all six locations simultaneously with the water quality analysis. The velocity of the river was measured according to the method described in subchapter 3.5.8 and shown in figure 3.1. At the sampling location Chiñata (ID 1) the water velocity was measured with a weighted float due to the shallow water. At the remaining sampling locations, a current meter was used. On the first sampling occasion, no flow measurements were performed at Puente Zofráco (ID 4) due to time constraints.

Between the dates 15 December 2017 to 4 December 2018, stage data from gauging stations located on the bridges at the sampling points of Chiñata (ID 1), Quintanilla (ID 2), Puente Cajón (ID 3) and Pico de Loro (ID 5) was obtained for every 15 minute. The stage data together with the results of flow from the physical measurements was used to find a rating curve-equation relating the stage and flow values at that location. The flow values from the stage data of the gauging stations was then calculated for the whole period.

Hec-RAS

To be able to process geospatial data in Hec-RAS the extension software Hec-GeoRAS combined with ArcGIS was utilized. From a digital terrain model in ArcGIS the tools of Hec-GeoRAS created new layers and produced an import file to Hec-RAS containing necessary geometric data for the river (U.S. Army Corps of Engineers, 2012).

The calculated flow data from the gauging stations was used as input boundary conditions for the respective locations in the model for unsteady flow simulations. In Hec-RAS an unsteady flow and a 1-dimensional mixed flow regime was assumed. The variation of Manning's n-value (eq. 3.2) was estimated to 0.074 between ID 1-2, 0.087 between ID 2-4, 0.055 between ID 4-5 and 0.03 between ID 5-6.

The simulated flow was then used in the Hec-RAS water quality model, which was run for the period of sampling, 30 October 2018 to 29 November 2018. The results of the measured chemical parameters was used as input boundary conditions. Meteorological data sets for Cochabamba including short wave radiation, wind speed, atmospheric pressure, air temperature, relative humidity and cloudiness was found from (Nasa, 2019) and entered into the model. The water quality model computes the dispersion coefficient based on the hydraulic variables at each position. The lower and upper limits for the computed values was calibrated to receive the best output. and no consideration was taken to the influence and existence of algae, phosphorous, nitrogen in the form of nitrite, ammonium and organically bound nitrogen. Further, all nutrient modelling parameters was put as the default values of the Hec-RAS software (U.S. Army Corps of Engineers, 2012).

4.2 Evaluation and classification of water quality

The threshold control described in subchapter 3.5.3 is the method chosen for the control of the results from the water quality analysis. The results from the chemical water analysis was compared with the recommended values given in tables in subchapter 3.4. The chosen parameters for water quality regulations; drinking water, irrigation water and environmental waters are presented in table 3.1.The threshold values for the examined parameters from the Bolivian Environmental Law No. 1333 are presented in table 3.2.

The ICO-index was calculated according to equation 3.1 and table 3.3, where number of parameters n=4 and the number of samples are for the three occasions m=3.

The results from the chemical analysis and the ICO values was compared with the results from Contraloría General del Estado (2017). The values from the 2017-study are presented in Appendix 4.1 and 4.2.

4.3 Aspects of the social and environmental influence

The social and environmental influences are documented with; i) photographs from site during field work, ii) localisation of near industries and other pollution factors/contributors and iii) detection of direct pipe discharge to the Rocha River, registered during field work as well as from previous studies.

5. Results and Discussion

The results for all the parameters from the chemical analysis are presented in Appendix 3.2. In subchapter 5.1 the parameters are discussed separately for each location and compared to the regulation values given in subchapter 3.4 *Legislation and guidelines*. In subchapter 5.2 the water samples from each sampling point was classified according to the ICO-index and compared to the classification results from previous studies. The measured and modelled flow velocity of Rocha River is presented subchapter 5.3. In subchapter 5.4 the social and environmental influences are discussed. In the last subchapter (5.5) the variation of the water quality along Rocha River is presented.

5.1 Chemical parameters and water quality classification

The results of the chemical analysis are presented in separate tables for each parameter, table 5.1-5.7. The six sampling points presented in table 4.1 and figure 4.1 are in the following tables listed from upstream to downstream, ID 1-6.

As can be seen in table 5.1 two water samples from the quality water analysis resulted in pH above recommended values. The rest of the results for all three sampling occasions and six locations are in the quality regulation range for; drinking water, water for agriculture and environmental waters (table 3.1). However, according to UMSS (2018) the desired level of pH for irrigation waters in the region is between 5 and 7.5. As the pH exceeds the value of 8.5 during two occasions, the waters at those two points do not fulfill the requirements for classification “A” from the Bolivian Environmental law No.1333.

Table 5.1 pH results from the water quality analysis at the six sampling points. Values exceeding the regulations given in table 3.1 are presented as bold. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3	Water classification
1	8.18	**8.67**	8.27	A-D
2	7.49	8.24	6.72	A
3	7.68	8.32	7.58	A
4	8.08	8.22	7.51	A
5	7.56	7.71	7.29	A
6	**8.54**	7.29	6.98	A-D

The high pH may be the cause of several chemical reactions. For example the high nitrogen load in Rocha River can be the cause of high pH as mentioned in subchapter 3.2.1 or the reaction of photosynthesis mentioned in subchapter 3.1. However, no conclusions can be made as no tests were performed on the amount of ammonium in the water. But if so, the high pH and the high amount of hydroxyl ions could lead to the formation of ammonia which is the toxic form. Also worth mentioning is that the high pH shown in table 5.1 is favorable if heavy metals are present as they are less toxic at higher pH.

Although the pH-values were not below the lower threshold, the pH decreases were significant for ID 2 and ID 6 during sampling occasion 3, and showing values deviating from the other points. This could be an indication that the water at these locations was largely affected by the heavy rainfall.

The electrical conductivity values from table 5.2 are all below the regulation limits for; drinking water, water for irrigation and environmental waters (table 3.1) and according to table 3.2 the water could be classified as “A”-”B” for ID (1, 3, 5), while the values for ID (2, 4, 6) was classified as “C”-”D”.

The low amounts of salts facilitates the buffering of the pH in the water, which (according to table 5.1) tended to be alkaline.

Table 5.2 Electrical conductivity results given in µS/cm from the water quality analysis for the six points. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.

ID	Sample Occasion 1	Sample Occasion 2	Sample Occasion 3	Water classification
1	427	400.5	384	A-B
2	1452.5	1817	1497	C-D
3	1055	1151	790	A-B
4	624.5	1650	959	C-D
5	689	676	452.5	A-B
6	1636	463	437	C-D

The overall results for ID 2-6 of the BOD_5 concentrations (table 5.3), indicated that the water is not suitable for any of the regulations given in table 3.1. However, in Chiñata (ID 1), the Rocha River may be used for irrigation. Also, the results indicated that the concentration of BOD_5 for (ID 1) were satisfactory regarding environmental factors. The results of the water quality analysis from Puente Cajón (ID 3) were below the threshold for environmental waters according to the Bolivian Ministry of Sustainable Development and Environment (MDSMA, 1996).

The water in Chiñata may be classified as “A”-”B” according to the environmental law No.1333. The rest of the samples exceeded the threshold for classification “D”, except for ID 4 and 5 during occasion 3 where they can be classified as “C” and “D” respectively.

Table 5.3 BOD_5 results from the water quality analysis at the six sampling points given in mg O_2/L. Values exceeding the regulations given in table 3.1 are presented as bold. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.

ID	Sample Occasion 1	Sample Occasion 2	Sample Occasion 3	Water classification
1	2	<2	<2	A-B
2	**261**	**506**	**620**	–
3	**54**	**69**	**38**	–
4	**91**	**84**	17	C/ –
5	**74**	**108**	24	D/ –
6	**93**	**72**	**60**	–

Just as the values for BOD_5, none of the values for COD (table 5.4) were below the limit for drinking purposes. All the locations showed values that were below the limit for environmental waters, except for ID 2. The results exceeded the limitation for Bolivian environmental law No.1333 classification, except for the sample at Chiñata (ID 1) that could be classified as “C”-”D”.

Table 5.4 COD results given in mg O_2/L from the water quality analysis at the six sampling points. Values exceeding the regulations for environmental waters given in table 3.1 are presented as bold. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3	Water classification
1	21	45	18	C-D
2	**555**	**713**	**854**	–
3	111	219	85	–
4	156	**259**	123	–
5	117	171	103	–
6	237	190	167	–

According to the water sample analysis of the dissolved oxygen, the values were very low and below all threshold values (table 3.1) at all locations except at Chiñata (ID 1). The results (table

5.5) that do not have exact values is due to the concentration of the dissolved oxygen was below the detection limit. Noticeable from table 5.5 was that the oxygen levels were increased and detectable at (ID 3) and decreased again at (ID 4). The dissolved oxygen thresholds from the Bolivian environmental law are given in percent saturation (table 3.2). The results from the water analysis were converted from mg O_2/L to percent and presented in Appendix 3.3. The result indicates that the water located at Chiñata (ID 1) should be classified as "A". Remaining samples resulted in dissolved oxygen between 0.66 -34%, where values above 50% are classified as "D". These values were therefore too low to be classified according to table 3.2.

Table 5.5 Results of dissolved oxygen from the water quality analysis at the six sampling points given in mg O_2/L. Values in bold represent values that are below the regulation thresholds for environmental waters, drinking water and water for irrigation, from table 3.1. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3	Water classification
1	7.25	7.32	7.54	A
2	**<0.05**	**<0.05**	**<0.05**	–
3	**0.2**	**0.2**	**2.34**	–
4	**<0.05**	**<0.05**	**<0.05**	–
5	**<0.05**	**<0.05**	**2.04**	–
6	**<0.05**	**1.11**	**2.14**	–

The values of nitrates (table 5.6) were at all sampling points passing the regulation limits for drinking water, irrigation waters and environmental waters. Further, the water could at all locations be classified as “A” with the respect of nitrate. The low values can be explained by the denitrification process in the almost anoxic state of the river water as well as algal metabolism where nitrate is consumed.

Table 5.6 Results of nitrates mg NO_3^-*/L from the water quality analysis at the six sampling locations. The water classification according to the Bolivian Environmental law No. 1333 (table 3.2 and Appendix 2) are presented in the last column.*

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3	Water classification
1	0.13	0.27	0.13	A
2	<0.03	0.31	0.4	A
3	0.13	0.22	4.51	A
4	0.13	0.27	0.04	A
5	0.04	0.22	9.39	A
6	0.04	0.13	6.25	A

The water from Rocha River in Chiñata (ID 1) can with regards of coliforms be used for irrigation of crops according to unrestricted and restricted limits given in table 3.1. The rest of the analyses of coliforms showed values that exceeded all thresholds. The highest values were seen at Quintanilla (ID 2).

Table 5.7 Results of coliforms cfu/100 mL from the six sampling locations. The values in bold indicates that the concentration exceeds the regulation values for drinking water, irrigation and environmental water in table 3.1.

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3
1	655	694	580
2	**$7.5*10^{7}$**	**$5.3*10^{7}$**	**$1*10^{8}$**
3	**$6.4*10^{6}$**	**$1.2*10^{7}$**	**$1.2*10^{7}$**
4	**$1*10^{7}$**	**$1.7*10^{7}$**	**$6.5*10^{6}$**
5	**$8.9*10^{6}$**	**$7.7*10^{6}$**	**$3.3*10^{6}$**
6	**$1.2*10^{7}$**	**$2.9*10^{6}$**	**$9.5*10^{6}$**

A general observation from all the chemical parameters was that the results from sample occasion 3 was significantly affected by the rainfalls that occurred the days before sampling, most evidently shown for BOD_5, COD, DO and NO^-_3 (table 5.3-6). The increased volume of water (seen in figure 5.2) diluted the amount of organic matter in the river which led to increased oxygen values. The rainfall could also have led to an increased turbulence in the stream, transporting more oxygen to the waterbody. The somewhat increased concentrations of NO^-_3 at occasion 3 could further be explained by NO^-_3 leaching from soils to the river water during heavy rain, or, the higher levels of oxygen which inhibit the process of denitrification. The correlation of increased oxygen and NO^-_3 -values during sampling occasion 3 is seen for ID 3, 5, and 6 (table 5.6). Regarding ID 5 and 6, the NO^-_3 increase is likely mainly due to leaching from the soils of the agricultural lands in those areas. Another explanation note regarding the rainfall is the potential effect it had on the pH values (table 5.1). The rain, which was likely acid due to air pollution, could be the explanation to the lower pH values seen at ID 2 and 6.

An aspect worth mentioning concerning the method of the chemical analysis is that it entails a few uncertainties and estimations. In light of what is written in subchapter 3.2.1, regarding that realistic stream conditions are difficult to produce in a laboratory during the Winkler dilution method, it is implied that the BOD_5 results in table 5.3 should be interpreted more as an indication. One possibility is for example that the BOD_5 concentrations in reality could be higher than the results received, taking the risk that the oxygen in the bottle of incubation could be consumed within the five days into account.

Moreover, the reliability of the results could be improved by following the sampling method in subchapter 3.5.1, stressing the importance of taking replicate samples at each location. This would diminish the factor of uncertainty regarding the possibility that the water is not sufficiently mixed. A further factor of uncertainty regarding the chemical analysis method, mentioned in subchapter 3.2.1, is the amount of time between the sampling at the river and the analysis performed at the lab. As several parameters are temperature dependent and the sampling lasted during long days of sun and high temperatures, there is a possibility that the samples were not sufficiently incubated in the styrofoam transport box used (seen in Appendix 5, figure A), which could have affected the results.

5.2 ICO-index

The estimated organic pollution obtained in this study, was classified according to ICO-index described in subchapter 3.5.1 and presented in table 5.8 for the six sampling locations (ID 1-6). The ICO-index for Contraloría General del Estado (2017) was calculated with the values from Appendix 4.1 for the corresponding locations. No corresponding locations existed for ID 1 and 2. The calculations are presented in Appendix 3.3 and Appendix 4.2 and a map of the distribution of sampling points is seen in figure 5.1.

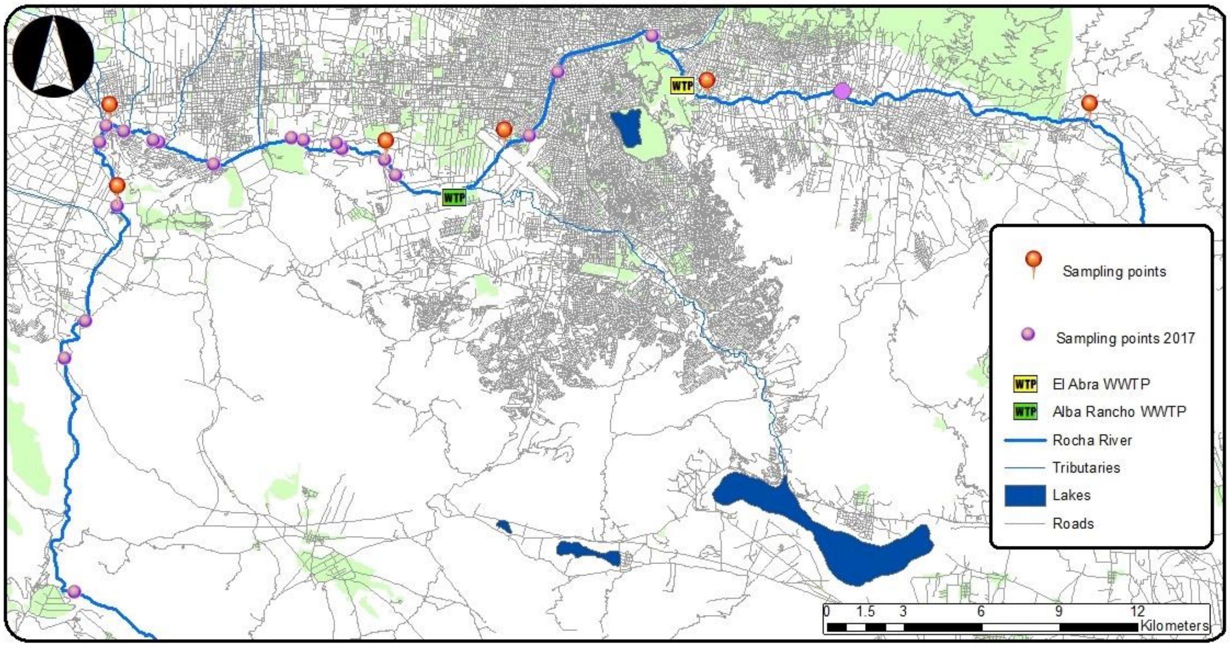

Figure 5.1 The sampling points of this project and Contraloría General del Estado (2017).

Table 5.8 The organic pollution, classified according to the ICO-index

Zone	**ID**	**ICO**	**Pollution of water**	**Colour of quality**	**ICO (2017)**	**Colour of quality (2017)**
Chiñata	1	1.38	Weakly polluted	GREEN	-	-
Quintanilla	2	97.79	Highly polluted	BLACK	-	-
Puente Cajón	3	14.90	Very polluted	RED	60.18	BLACK
Puente Zofráco	4	18.19	Highly polluted	BLACK	61.83	BLACK
Puente Pico de Loro	5	17.40	Highly polluted	BLACK	48.69	BLACK
Entrada Mallcorancho	6	19.85	Highly polluted	BLACK	105.27	BLACK

According to the ICO index, the water sample in Chiñata (ID 1) is classified as "weakly polluted", turning to "highly polluted" at the location of Quintanilla (ID 2). After passing through Cercado the water quality increases and improves the classification from black to red at Puente Cajón (ID 3). The organic pollution becomes "highly polluted" again at ID 4-6 after passing the Alba Rancho WWTP and the agricultural areas downstream.

The "highly polluted" waters are all waters with an ICO index above 16. The ICO-index values for the water samples from Contraloría General del Estado (2017) are considerably higher, much depending on that the nitrate results seen in Appendix 4.1 are very high compared to the results from table 5.6. However, the director of C.A.S.A stated that when taking photosynthesis and denitrification into perspective, the low ICO-results from this project (table 5.6) are to be considered as more reasonable (A.M Romero Jaldín 2019, personal communication, 31 January). The water sampling of the compared study was performed during the same season, October 2017 indicating that the values should not deviate as much as found in this comparison.

5.3 Hec-RAS

The results of the measured flow from the six sampling points is displayed in table 5.9 where one can see how the river flow is increasing downstream in the river course. On sample occasion 3 the flow increased distinctly at all downstream points which is due to the heavy rainfall that occurred the nights before sampling. As mentioned, no flow measurements was performed at ID 4 on the first sampling occasion.

Table 5.9 Measured river flow (m^3/s) from the three sample occasions at the six sampling points.

ID	Sample occasion 1	Sample occasion 2	Sample occasion 3
1	0.00062	0.000434	0.000611
2	0.09	0.058	0.068
3	0.19	0.177	0.406
4	–	0.439	1.163
5	4.01	1.953	7.333
6	4.57	2.353	9.681

5.3.1 Flow analysis

The flow results from the performed Hec-RAS modelling correlates well with the continuous measured flow at the gauging stations at Puente Cajón (ID 3) and Pico de Loro (ID 5) (figure 5.2). The modelled flow at Quintanilla has the same trend as the calculated flow values but the amount of flow deviates with an average of 0.28 m^3/s.

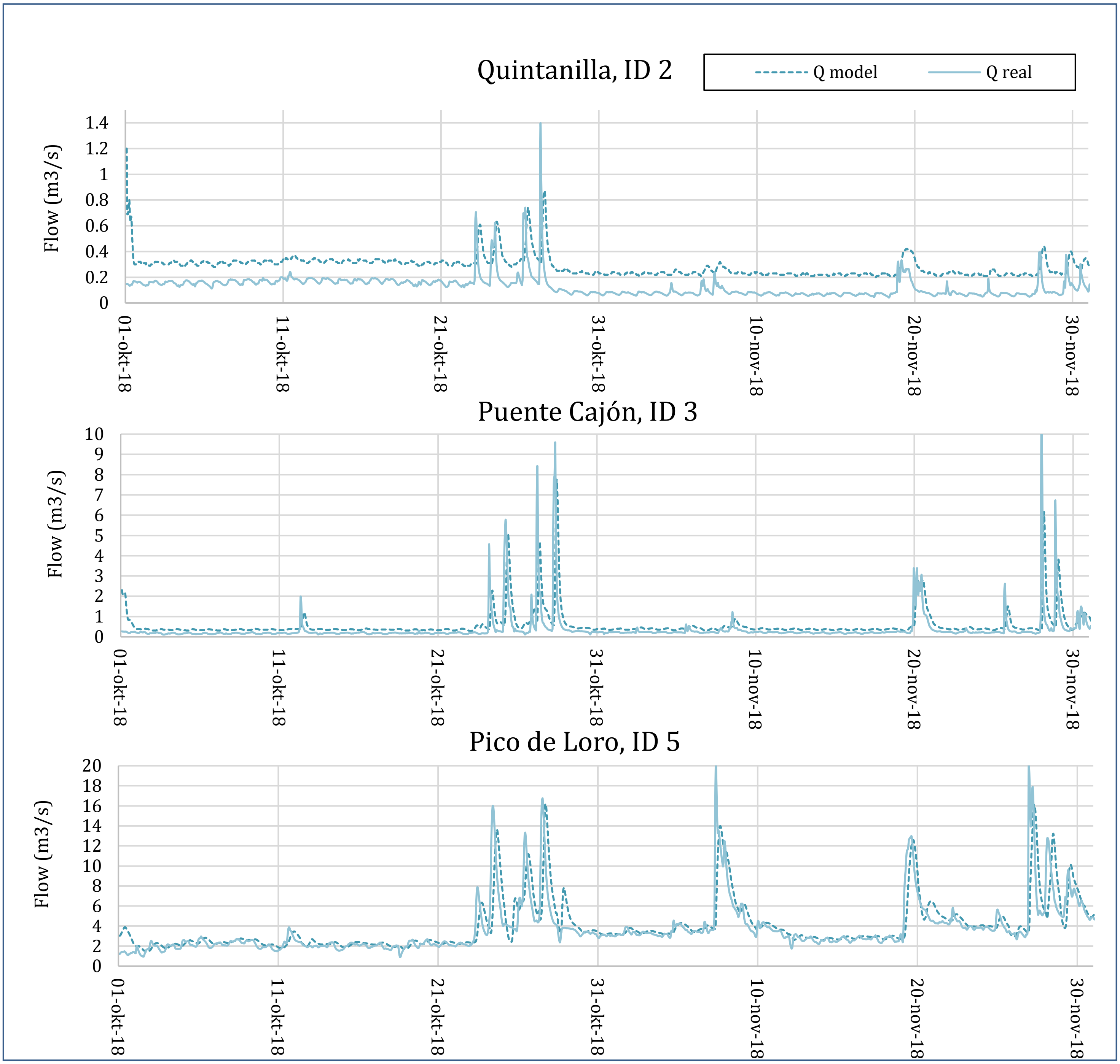

Figure 5.2. Shows the flow variations (m^3/s) in Rocha River at the locations (ID 2, 3 and 5) for October and November 2018. The dotted line represents the modelled flow in Hec-RAS (Q model) and the full line represents the calculated flow from the gauging stations and field measurements (Q real).

In figure 5.3 and 5.4 the seasonal variations can be seen and flow peaks are concentrated during the rainy season December –March. During April-October the river flows are relatively constant. The two figures illustrate how the flow increases downstream in the river. The flow characteristics in Chiñata (ID1) is more of a small stream, during the dry season the flow varies between 0.001-0.003 m^3/s and during rainy season the flow reached values up to 0.07 m^3 /s. The flow characteristics in Entrada Mallcorancho (ID 6) varies during the dry season around 1.0 m^3/s and during the rainy season it can reach values up to 80 m^3/s.

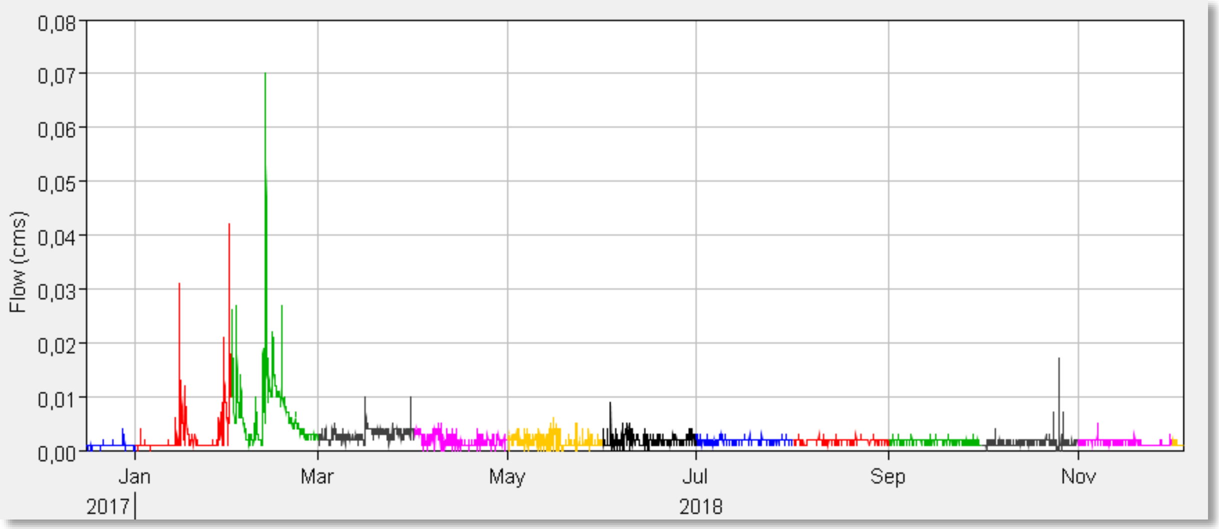

Figure 5.3 Seasonal flow variations (m^3/s) at location Chiñata (ID 1) from 15 Dec 2017 to 4 Dec 2018.

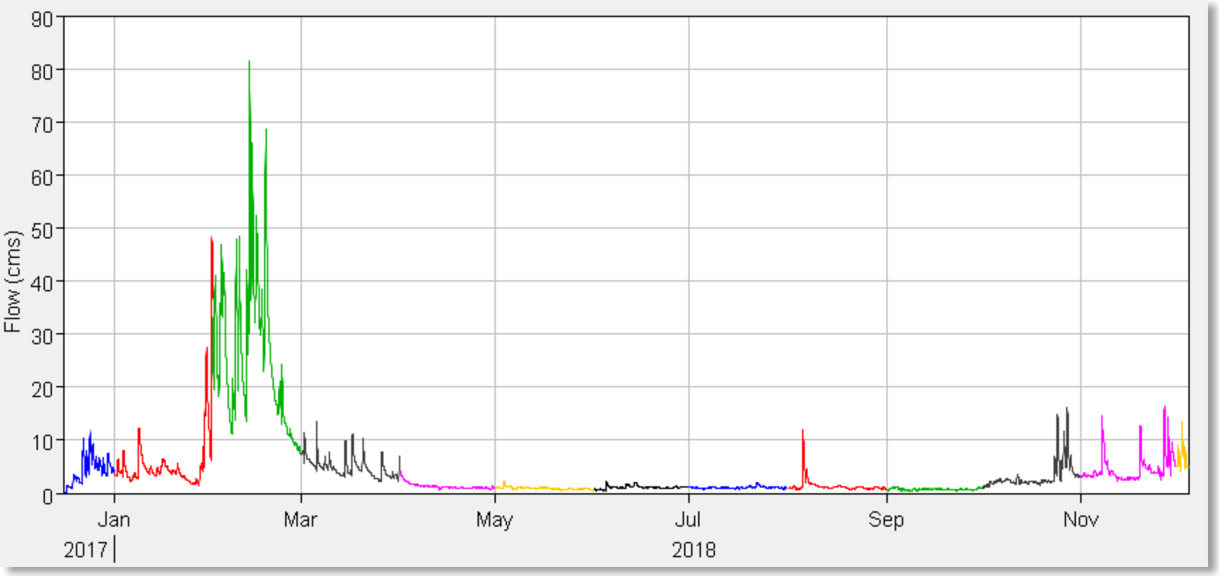

Figure 5.4 Seasonal flow variations (m^3/s) at Entrada Mallcorancho (ID 6) from 15 Dec 2017 to 4 Dec 2018.

The large flows and increased stage at Entrada Mallcorancho (figure 5.4) has required the building of levees to prevent flooding (seen in figure E, Appendix 5). The results from the Hec-Ras modell (figure 5.2) and measured river flows in table 5.9 indicates that the rainfall event before sampling occasion 3 (27-28 October) was more intense downstream which also can be seen in the increased dissolved oxygen values at location Puente Pico de Loro and Entrada Mallcorancho (ID 5 and 6). From figure 5.2 it can further be assumed that the Hec-RAS model is performing well. However, with more time, further calibration of the model could have been done to enhance the different trends by adjusting parameters such as boundary conditions, geometry of river cross-sections as well as the Manning´s coefficients.

5.3.2 Chemical analysis

Time for this part of the modelling was limited and the results were obtained on the very end of the project period. No conclusive results was accessed for dissolved oxygen, temperature and nitrate. Hence, more time for calibration of the water quality model was needed. In this report, only the results for BOD_5 is presented from the Hec-RAS water quality model, since the focus in this study was mainly on organic pollution.

The total mass of BOD_5 passing through Quintanilla (ID 2) during 30 October to 29 November could with the Hec-RAS water quality model be calculated to 104 tons.

Figure 5.5 illustrates the modelled result of the BOD_5 variations at Quintanilla (ID 2). In the graph it can be seen that there are relatively large deviations between the model and the observed values from the measured water quality sampling, although they follow the same increasing pattern. The results from the water quality model can therefore be questioned. However, as mentioned in subchapter 5.1, neither the BOD_5 results obtained from the Winkler dilution method can be seen as exact.

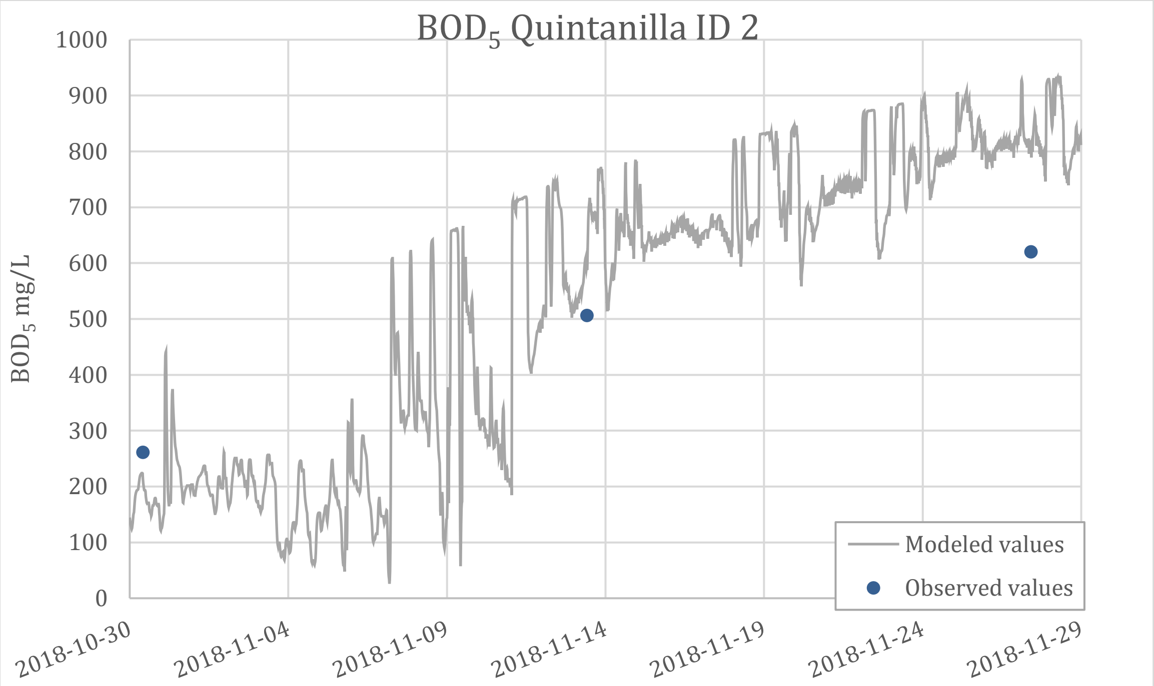

Figure 5.5 Changes in concentration of BOD_5 mg/L at Quintanilla ID 2 during the sample period. The line represents the modelled variation in BOD_5 concentration and the dots represents the measured values from the water quality sampling (table 5.3).

To improve the model output for all parameters at all points in the river, more calibration and time series data are needed. As seen in figure 5.3 and 5.4 the flow varies significantly during the year at the up- and downstream sections of the river and thus, the water quality at different times of the year will have a great variation along the river course. For further studies, it is therefore highly recommended to include water quality samples taken at more locations along the river and at more time points distributed over the whole year.

5.4 Social and environmental influences

5.4.1 Visible pollution

The amount of solid waste in Rocha River could not be ignored during the fieldwork (figure 5.6). Large amounts of solid waste thrown directly into the river by individuals passing the bridges were frequently observed (ID 1-6). The behavior can be explained by the few, or none, existing official dumping sites for waste, as well as a lack of public interest and awareness. Both investments, engagements and time is needed to improve the state of Rocha River. The beneficial factors for the local individual is the improved water supply, esthetic surrounding and healthy environment which on all levels increases the quality of life. However, for this to occur, the opportunity and public desire is required to change the customary habits into a more holistic approach.

Figure 5.6 Solid waste in Rocha River under Puente Cajón (ID 3).

Figure 5.7 Rocha River passing through Cercado, aeration occurring.

Visible urban water has many recreational benefits. However, the appearance of the river in the inner city (figure 5.7) leaves little room for these values as it has high turbidity (especially after heavy rainfall), litter content and an unpleasant scent. Good intentions for the river restoration can also be seen in this picture, as different elevation steps have been created for an increased aeration.

As mentioned in subchapter 2.3.4 there are several domestic and industrial untreated wastewater pipes directly discharging into the Rocha River. Denoted pipes with highly polluted discharge in Sacaba from the previous study UMSS (2018) is from a slaughterhouse (ID 18, Appendix 1) and from a WWTP (ID 14, 15, Appendix 1). With knowledge of the lacking sewer connections in Sacaba and the level of contamination, more pipes and channels of polluted wastewater are assumed to be existing in this area.

During the fieldwork a direct untreated wastewater channel was encountered at (ID 2) (figure 5.8). From the figure one might understand the difficulty in locating these types of discharges into the river as the amount of vegetation in the river bank is large and the discharge may be irregular.

Figure 5.8 Untreated wastewater discharge to Rocha River at ID 2.

Figure 5.9 Rocha River at Puente Zofráco (ID 4)

Anoxic environment was observed after the WWTP Alba Rancho (ID 4) as the water of the shallow Rocha River in this area had a distinct black colour (seen in figure 5.9) which is an indication of high levels of oxidized organic matter.

5.4.2 Agricultural aspects

Several farmers with agricultural land located next to the Rocha River have implemented direct irrigation pipes from the Rocha River to the fields, located and documented (figure 5.10) during fieldwork. Seen in figure 5.10 is diverted water from Rocha River and used for irrigation of maize without any treatment at location (ID 2).

Figure 5.10 Pipe with untreated Rocha River as irrigation water for maize at Quintanilla (ID 2)

All the electrical conductivity results from table 5.2 pass the recommended limits for irrigation water. However, as mentioned in subchapter 2.3.5, specific crops have different yield potential at different electrical conductivity values for irrigation water. As stated above, the irrigation water in figure 5.10 is diverted direct from the Rocha River and thus the electrical conductivity for the irrigation occurring are the values for (ID 2) in table 5.2. The fields at Quintanilla were irrigated with an electrical conductivity value of 1453-1817 µS/cm during the field work. A conclusion based solely on the electrical conductivity values of the irrigation water is that the high salt content in the water reduces the potential yield which means that the farmer could produce more maize (at electrical conductivity value of 1100 µS/cm or less) if the irrigation water was less polluted. Also, none of the water samples exceeded the maximum electrical conductivity values for alfalfa and maize which means that these two crops will grow if irrigated with water from the Rocha River, but the higher the electrical conductivity value the lower the yield potential. Worth mentioning is that farmers in the La Mayca area south of Alba Rancho WWTP irrigate with wastewater from the treatment plant, which means that the water from these ponds needs to be analysed before a conclusion could be made about the salt content of the irrigation water in that area. Known is however that the WWTP does not have a disinfection step in the treatment process.

According to Huibers et al. (2004) the agricultural soil in the valley of Cochabamba is deteriorating and farmers grow mostly crops that are more salt-tolerant. A physicochemical analysis of the soil would have been required in this study to be able to investigate how the polluted irrigation water is affecting the cultivation accumulation of pollution in the soil. To irrigate with wastewater or heavily polluted river water is often a prerequisite in water scarce areas. Nevertheless, when irrigating with heavily polluted water precaution measures must be considered as it may affect the human health and soil degradation in the long term as well as possible percolation contaminating groundwater. Thus, beneficial for irrigation and health in rural areas would be to increase the restriction of local industrial wastewater treatment, improve the sewer systems and expand the municipal WWTP. A suitable measure in the La Mayca area would for example be to implement improved simple low-cost treatment techniques in order to reduce coliform and electrical conductivity concentrations in the ponds at Alba Rancho, reducing the risks both in the actual area and downstream.

A common observation during fieldwork was that farmers also grow vegetables which are more sensitive to high electrical conductivity concentrations. No knowledge was gained during fieldwork of how the vegetables were irrigated. In this study the overall classification of the Rocha River water in the farmland area near the Alba Rancho WWTP and sample location Puente Zofráco (ID 4) is “D” according to Bolivian environmental law (disregarding pH and nitrate). As stated in this law (Appendix 2) vegetables cannot be eaten raw if irrigated with quality of water class “D”. If the Rocha River water in this area is used as irrigation of vegetables, the growth and safety of consumption would be improved for example by dilution as an improvement of the quality could be seen after the rainfall on sample occasion 3 (subchapter 5.1).

5.4.3 River characteristics

Regarding the river bed observations, coarse grained sediment was solely observed in Chiñata (ID 1, figure B, Appendix 5). The rest of the river sediment was similar to the sediment in figure C, Appendix 5, which might be described as consolidating alluvial deposits with a thick layer of organic matter that has sedimented in anoxic environment. According to Renner & Velasco (2000), coarse grained sediments are found in the northern parts of the valley which leads to higher permeability and higher recharge to groundwater. As the water quality in the northern parts at ID 1 is classified as “weakly polluted” according to ICO-index and passes all regulation limits for environmental waters, the risk of the river contaminating the groundwater is considered as low even though percolation may occur. At the remaining points ID 2-6 the consolidating sediment is of advantage as it prevents the groundwater in those areas to be affected. However, as the polluted water travels far downstream, where the type of sediments is not explored in this project, the risk of groundwater being contaminated by the water in the Rocha River stream cannot be excluded. In subchapter 5.1 no indications could be found regarding the impact of electrical conductivity from the groundwater into the river. The previous study (Renner & Velasco, 2000) indicated that the groundwater in the south-western part of the valley (involving ID 5 and 6) had a higher ionic concentration due to the sediments but this could not be seen in the data from our project (table 5.2).

A character of the river also indicated by the low oxygen levels (table 5.5), was that no aquatic life was encountered during the sampling. According to the Federal Interagency Stream Restoration Working Group (1998), mentioned in subchapter 3.1, oxygen concentration at 2 mg/L or lower during a longer period of time indicates that the water bodies are “dead” and that larger organisms cannot be present.

Taking the theory in subchapter 3.1 *River Restoration* into consideration, the river has optimal characteristics for sedimentation and self-recreation as it is well meandering and contains high amounts of vegetation, stones and cobbles (Appendix 5, figure D), elevation differences and a large variation in flow (subchapter 5.3). Unfortunately, the extent of the continuous pollution is preventing the recreation to occur.

5.4.4 Health aspect

As the river passes through a densely populated area and is surrounded by 1,323,000 inhabitants (subchapter 2.2) it is, as observed, inevitable that people are residing and working in very close vicinity to the river. Accidental ingestion through skin contact with the water is therefore the prominent possibility for getting deceased by the pollution. Many severe health risks can be excluded if it is assumed that the river water is not directly used as drinking resource. However, even though the water in the river channel is consolidated, the water used as irrigation may percolate down and contaminate the groundwater. This puts people using private pumps as drinking water source under high health risks as they indirectly can consume the pollutants including heavy metals from the industries.

From the results from the chemical parameters in subchapter 5.1 it can be concluded that the main health risks can be correlated with the high concentrations of thermotolerant coliforms (table 5.7) in the river water. Of the existing coliforms in freshwater 95% is estimated to be E.coli (Bartram and Ballance, 1996) which determines a fecal content in the water. According to subchapter 3.3 these pathogens therefore expose the population of a risk for diseases including diarrhea, cholera, typhoid, hepatitis A and B and dysentery. In addition to this, the farmers and other workers having direct contact with the river water are in risk for eczema. Depending on the crop irrigated with the polluted water, the plants can also transmit the pathogens to the consumers, which dramatically increases the zone where and amount of people that can possibly be affected. Furthermore, the inhabitants without connected sewer services using in situ sanitation systems such as septic tanks and latrines are in a situation of high risk of the same mentioned diseases.

More parameters including heavy metals, algae, helminth eggs and other pathogens need to be measured in the river to be able to perform a more thorough risk analysis. To reduce health risks related to the Rocha River along its course, large improvements needs to occur early on upstream in the Sacaba area. This proposal is based on the fact that the results of the water quality parameters related to health issues from this area and further on downstream was classified as "D" according to Bolivian Environmental law (Appendix 2), which states that the river is harmful to be in contact with. Further, the concentration of coliforms in the mentioned parts of the river distinctly exceed the national regulations (table 3.1) for healthy environmental waters.

5.5 The variation of water quality along Rocha River

According to the chemical analysis Chiñata (ID 1) had the best quality out of the six sampling points and was classified as "weakly polluted" according to the ICO-index. Even though there are direct discharge pipes located in Chiñata (e.g. ID 7, Appendix 1) according to UMSS (2018), this did not result in any tangible impact on the river quality. The combination of low population in this area and no industrial activities is probably the major explanation to the low organic pollution. As the river flow at this location is low (subchapter 5.3) it becomes more sensitive to variation and changes of the volume of wastewater that is discharged into the river. To preserve the water quality status in Chiñata it is therefore critical to implement a secure and complete connection of sewer systems presuming that the estimated population increase also develops in the Chiñata area.

The population becomes denser as the river flows through Sacaba where the sewer system connection is poor and several industries and slaughterhouses are located. Out of the six sampling points the results from this area (Quintanilla, ID 2) reached the highest organic pollution index (ICO index, table 5.8).

The results clearly indicated that untreated domestic and industrial wastewater in this area is directly discharged into the river as described in UMSS (2018) where several discharge pipes were located. An interesting supplement to this study would be to perform water sampling during the night, since previous study UMSS (2018) indicated that untreated wastewater from industries is most likely discharged during night hours.

Further downstream, at the inner city of Cercado, the public sewer network is more developed which can be seen in the slightly lower organic content and higher oxygen levels in the sample from Puente Cajón (ID 3). This is likely an effect of the avoided direct domestic discharge to the river. The slight water quality improvement is also seen in the calculated ICO-index as the pollution classification improved from “highly polluted” (*black classification*) to “very polluted” (*red classification*). Studying the results for BOD_5 at Puente Cajón (table 5.3) that passes the Bolivian regulation value of 80 mg/L for environmental waters. An interesting comparison between the regulation value for BOD_5 of 80 mg/L and 10 mg/L, which is the discharge regulation for environmental waters according to Swedish law, illustrating that state regulations for approved water quality can vary significantly between countries.

The improved water quality downstream of Cercado does not proceed which might be caused by insufficiently treated wastewater discharge from the Alba Rancho WWTP as well as the connection with the tributary Tamborada River. The contribution of polluted water to Rocha River from the Tamborada River is untreated domestic wastewater from the southern parts of the department that is not connected to the public sewer system, and with big fluctuation in volume between the seasons. In subchapter 2.3.4 it is mentioned that approximately 65% of the wastewater from the city is collected in sewers and only a small percentage is treated at the Alba Rancho WWTP. Hence, the majority of the wastewater is directly discharged untreated and eventually ending up in Rocha River. This information gave a presumption that the water quality at Puente Zofráco (ID 4) would result in the lowest water quality of the six points. This was visually confirmed at the site (figure 5.9), where the river seemed to have a high content of oxidized organic matter, revealed by the black colour of the water. However, the chemical analysis results of BOD_5 and coliforms (table 5.3 and 5.7) did not clearly show this. Instead, equally high values could be seen at all sampling points (disregarding ID 1). This could possibly be explained by the fact that the wastewater from a high percentage of the population is directly discharged into the river along its course.

In the urban areas of Sacaba, Cercado and Colcapirhua there are as described in subchapter 2.3.3 many different industries and facilities producing wastewater. As mentioned in UMSS (2018); to be able to differentiate between the different types of wastewaters from the different industries including leather industries, car washes and laundry facilities, common in these urban areas, samples need to be taken directly from the industry effluents. This, as well as knowledge of the industrial processes, is needed to be able to determine exactly what parameters that should be examined (subchapter 3.2).

Results from samples obtained at Puente Pico de Loro (ID 5) and Entrada Mallcorancho (ID 6) were from water passing lands of more rural and agricultural characteristics and low population near the river. The flow analysis showed large volumes of river water and high flow velocities (subchapter 5.3.1). All this combined with the observed potential for self-restoration, indicated that the river could have an improved water quality in the samples obtained from these areas. The results contradicted this theory as the ICO-index classified the water at point ID 5 and 6 as “Highly polluted”. The input discharges from slaughterhouses in these areas combined with the extent and synergetic effects of the pollution upstream is likely preventing the ability of restoration to occur.

6. Conclusions

The state of the water quality in the Rocha River is according to the ICO-index ranging from "very" to "highly polluted" water along the river from Sacaba to Sipe Sipe (ID 2-6). Only the results from rural Chiñata (ID 1) high upstream show a water quality passing WHO-, EPA- and FAO-regulations as well as Bolivian regulations and is classified as "weakly polluted". According to the Bolivian Environmental law No.1333, the water from Sacaba to Sipe Sipe (ID 2-6) can at best be classified as "D" with the parameters measured in this study. This restricts the recommended use of the river for drinking, agricultural and environmental purposes. The prominent parameter that restricts the water usage is however the content of coliforms at all locations below Chiñata. An overall conclusion of the organic pollution of Rocha River is that the deterioration has continued over the years since 1998 and has now reached even the outskirts of the valley upstream in Sacaba and downstream in Sipe Sipe. This conclusion is in accordance with previous studies on the river. Subchapter 5.3.1

Comparing the results of water quality in areas with sewer system connection (Cercado ID 3) and suburban areas without, proves that the domestic and industrial discharge with high organic content that is directly discharged in the suburban areas without public network connections is a factor of high consequence for the pollution and oxygen depletion of the river. Taking the estimated population growth in the department into account, the untreated wastewater discharge will likely increase and worsen the state of the river, assuming that the development and distribution of public sewer systems, as well as WWTP, is not increasing to the same extent. Furthermore, large amounts of solid waste in Rocha River contributes to the water pollution. A plausible reason for this practice might be the lack of official dumping sites for the inhabitants in the Cochabamba department.

Of the parameters measured, the high amount of coliforms along the river is the factor most critical to the health of the population, mainly for people residing in close contact with the water. A conclusion in this study, regarding the restricted use of untreated river water as irrigation in the agricultural areas is based on the coliform and electrical conductivity results from the water chemical analysis. The high amount of coliforms may spread to the consumers if crops and vegetables are irrigated with the river water. The high electrical conductivity values indicates that the crop selection is restricted to highly salt tolerant crops and thus preventing cultivation of a variety of crops and vegetables. It may also contribute to soil degradation leading to a possible prevention of future cultivation. Although a recirculation of nutrients and water is favourable, the polluted waters on the farmlands can potentially percolate and badly affect the groundwater. There is currently a water deficit in the department, and future scenarios predict a dryer and warmer climate. These conditions, together with the fact that the pollution in Rocha River prevents an available water source to be safely utilized, and with the potential of contaminating other existing sources puts the community of Cochabamba under an even harder water stress affecting the whole society.

7. Recommendations

In this study several contributing and resulting factors of the pollution in Rocha River is discussed. To receive more profound explanations to the problems stated in the aim of the study, more analyses are required on the river and its surroundings. Below are recommendations for further studies.

- The conclusions made in this study are solely based on the parameters measured. A wider range of parameters measured would result in a more complete overview of the pollution. Moreover, parameters such as heavy metals, algae, helminth eggs and other pathogens are required to perform a more thorough risk analysis on the effects of the pollution.

- The parameters investigated in this study give no information on the specific effects on the Rocha River from the industrial effluents. To be able to differentiate between the different types of wastewaters from the different industries; samples need to be taken directly from the industry effluents. Furthermore, to be able to determine exactly what parameters that are linked to the industrial discharges more information of the industrial processes is required.

- It is recommended to obtain water samples directly at the effluents of the Alba Rancho WWTP to be able to determine whether the increase in pollution seen after ID 4 is due to the connection with the Tamborada River or due to the WWTP discharge.

- To be able to see how the irrigation with the polluted water from Rocha River might affect the cultivation and accumulation of pollution in the soils of the agricultural lands, a physicochemical analysis of the soil is recommended.

- To support the conclusions drawn on the health risks and environmental impacts, it is recommended to perform a more thorough analysis on the possibility of the Rocha River contaminating the groundwater. Preferably, water quality sampling should be performed at wells in close vicinity to agricultural fields that are irrigated with the river water. It has been assumed that the river bed is preventing the water in the channel to percolate. However, more detailed studies on the sediments are required to conclude this.

- The Hec-RAS flow analysis, shows how the river flow varies between seasons. To get an overview of how the pollution in Rocha River is affected by this, quality samples are needed from more time points distributed over the whole year. Furthermore, as calibration of the water quality model is needed to validate the output, more measured data at each location is required. The data and the developed Hec-RAS model from this study can be used as an initiation for near future simulations.

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Appendix 1: Coordinates

Table A1. Coordinates for the sample locations (ID 1-6) and other significant locations are given in Universal Transverse Mercator coordinate system (UTM).

ID	Municipality	Sampling point	x (UTM)	y (UTM)	Zone
1	Sacaba	Chiñata	183414	8073210	20S
2	Sacaba	Quintanilla	806799	8074278	19S
3	Cercado	Puente Cajón	799287	8072403	19S
4	Colcapirhua	Puente Zofráco	794863	8072068	19S
5	Vinto	Puente Pico de Loro	784674	8073597	19S
6	Sipe Sipe	Entrada Mallcorancho	784935	8070502	19S
7	Chiñata	WW discharge pipe to the Mayalanco-Rocha River	183434	8073165	20S
8	Sacaba	Wastewater discharge channel to the Maylanco-Rocha river	813020	8073100	19S
9	Sacaba	Wastewater discharge pipe to the Maylanco-Rocha river	815002	8074387	19S
10	Sacaba	Wastewater discharge pipe to the Maylanco-Rocha River	812880	8073887	19S
11	South Quintanilla	Wastewater discharge channel to the Maylanco-Rocha river	807862	8074062	19S
12	South Quintanilla	Wastewater discharge pipe connected to sewer system	807861	8074055	19S
13	South Quintanilla	Wastewater discharge channel towards Maylanco/ Rocha	806363	8074449	19S
14	Sacaba	Wastewater Treatment Plant EL ABRA- EMAPAS	806244	8074495	19S
15	Sacaba	Wastewater Treatment Plant San Pedro Magisterio, Discharge Pipe	805933	8075307	19S
16	Sacaba	Slaughter Area	813020	8073100	19S
17	Sacaba	Slaughter Area :Wastewater discharge channel to the Maylanco-Rocha river without flow	813065	8073218	19S
18	Sacaba	Wastewater discharge channel to Maylanco-Rocha river: There is discharge, during the inspection it was humid, it is believed that the discharges are made at night (pig farm)	809846	8074417	19S

Appendix 2: Classification A-D

Table A2. Classification of water bodies (A-D) according to their suitability from Bolivian Environmental Law No.1333.

Order	Use/Application	Class A	Class B	Class C	Class D
1	For domestic drinking water supply after:				
	a) Only one disinfection and no treatment.	Yes	No	No	No
	b) Only physical treatment and disinfection	Not Necessary	Yes	No	No
	c) Physical - chemical treatment, complete coagulation flocculation, filtration and disinfection.	Not Necessary			
	d) Prolonged storage or presedimentation, followed by treatment, like in c).	Not Necessary	Not Necessary	Not Necessary	Yes
2	For primary contact recreation: swimming, diving.	Yes	Yes	Yes	No
3	For the protection of hydrobiological resources	Yes	Yes	No	No
4	For irrigation of raw consumed vegetables and fruits which are ingested raw without removal of peel.	Yes	Yes	No	No
5	For industrial purposes	Yes	Yes	Yes	Yes
6	For the natural and /or intensive breeding (aquaculture) of species intended for human consumption	Yes	Yes	Yes	No
7	Water adapted for animals	No	Yes	Yes	No
8	For navigation	No	Yes	Yes	Yes

Appendix 3: Methods and results

Water quality analysis methods and water quality results

A3.1 Water quality analysis method

Table A3.1. Techniques used at the C.A.S.A lab for determining the values of the parameters.

Parameter	Technique / method	Detection limit	units
pH	Electrochemical	0.10	-
EC	Electrochemical	0.10	µ S/cm
DO	Winkler Titration	0.10	mg O2/L
BOD5	Dilution-Winkler method	2	mg O2/L
COD	Oxidation with dichromate	2	mg O2/L
Nitrates	Reduction with Cadmium	0.03	mg NO3/L
Coliforms	Membrane filtration	0	UFC/100 mL

A3.2 Water quality results

Table A3.2. Results from the chemical water analysis.

Zone	ID	Sample occasion	pH	T water (°C)	T ambient (°C)	EC (µ S/cm)	DO (mg O2/L)	BOD5 (mg O2/L)	COD (mg O2 /L)	Nitrates (mg NO3/L)	Coliforms (UFC/100 ml)
Chinata	1	1	8,18	21	24	427	7,25	2	21	0,13	655
		2	8,67	20	26	400,5	7,32	<2	45	0,27	694
		3	8,27	19	19	384	7,54	<2	18	0,13	580
Quintanilla	2	1	7,49	23	27	1452,5	<0,05	261	555	<0,03	75000000
		2	8,24	23	20	1817	<0,05	506	713	0,31	53000000
		3	6,72	21	20	1497	<0,05	620	854	0,4	100000000
Puente Cajon	3	1	7,68	25	26	1055	0,2	54	111	0,13	6400000
		2	8,32	24	27	1151	0,2	69	219	0,22	12000000
		3	7,58	18	19	790	2,34	38	85	4,51	12000000
Puente Zofraco	4	1	8,08	27	22	624,5	<0,05	91	156	0,13	10000000
		2	8,22	25	28	1650	<0,05	84	259	0,27	17000000
		3	7,51	20	22	959	<0,05	17	123	0,04	6500000
Puente Pico de Loro	5	1	7,56	19	26	689	<0,05	74	117	0,04	8900000
		2	7,71	16	20	676	<0,05	108	171	0,22	7700000
		3	7,29	19	22	452,5	2,04	24	103	9,39	3300000
Entrada Mallcorancho	6	1	8,54	14	19	1636	<0,05	93	237	0,04	12000000
		2	7,29	17	21	463	1,11	72	190	0,13	2900000
		3	6,98	15	20	437	2,14	60	167	6,25	9500000

A3.3 ICO-index calculation

Table A3.3. Calculated ICO-index (equation 3.1) for each location with the sum of the three sampling occasions, where, n=4 and m=3. The measured dissolved oxygen value was converted to percent saturation regarding elevation and temperature with the converter from University of MN, Natural Resources Research Institute.

Chiñata (ID 1)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO %	116.32	1.31	115.07	1.21	116.10	1.29	
	BOD_5 (mg/L)	2.00	1.33	2.00	1.33	2.00	1.33	
	COD (mg/L)	21.00	2.10	45.00	4.50	18.00	1.80	
	Nitrates (mg/L)	0.13	0.11	0.27	0.18	0.13	0.11	
	Sum		4.85		7.22		4.54	
	Total sum							16.6
ICO Chiñata:	**1.38**							
Quintanilla (ID 2)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO %	0.81	12.06	0.81	12.06	0.78	12.07	
	BOD_5 (mg/L)	261.00	174.00	506.00	337.33	620.00	413.33	
	COD (mg/L)	555.00	55.50	713.00	71.30	854.00	85.40	
	Nitrates (mg/L)	0.03	0.05	0.31	0.20	0.40	0.23	
	Sum		241.61		420.89		511.03	
	Total sum							1173.53
ICO Quintanilla:	**97.79**							
Puente Cajon (ID 3)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO %	3.35	11.45	3.28	11.46	34.04	5.74	
	BOD_5 (mg/L)	54.00	36.00	69.00	46.00	38.00	25.33	
	COD (mg/L)	111.00	11.10	219.00	21.90	85.00	8.50	
	Nitrates (mg/L)	0.13	0,.11	0.22	0.16	4.51	1.08	
	Sum		58.66		79.52		40.66	
	Total sum							178.84
ICO Punte Cajón:	**14.90**							

Puente Zofraco (ID 4)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO %	0.87	12.04	0.84	12.05	0.76	12.07	
	BOD$_5$ (mg/L)	91.00	60.67	84.00	56.00	17.00	11.33	
	COD (mg/L)	156.00	15.60	259.00	25.90	123.00	12.30	
	Nitrates (mg/L)	0.13	0.11	0.27	0.18	0.04	0.05	
	Sum		88.43		94.13		35.76	
	Total sum							218.32
ICO Puente Zofráco:	**18.19**							
Puente Pico de Loro (ID 5)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO %	0.74	12.08	0.70	12.09	30.24	6.28	
	BOD$_5$ (mg/L)	74	49.33	108.00	72.00	24.00	16.00	
	COD (mg/L)	117	11.7	171.00	17.10	103.00	10.30	
	Nitrates (mg/L)	0.04	0.05	0.22	0.16	9.39	1.72	
	Sum		73.16		101.35		34.29	
	Total sum							208.81
ICO Puente Pico de Loro:	**17.40**							
Entrada Mallcorancho (ID 6)	**Parameter**	**Y 1**	**X1**	**Y2**	**X2**	**Y3**	**X3**	
	DO (%)	0.66	12.10	15.75	8.76	29.07	6.45	
	BOD$_5$ (mg/L)	93.00	62.00	72.00	48.00	60.00	40.00	
	COD (mg/L)	237.00	23.70	190.00	19.00	167.00	16.70	
	Nitrates (mg/L)	0.04	0.05	0.13	0.11	6.25	1.33	
	Sum		97.85		75.88		64.48	
	Total sum							238.21
ICO Entrada Mallcorancho:	**19.85**							

Appendix 4: Contraloría del Estado (2017)

Water quality results from the previous study of Contraloría del Estado (2017).

A4.1 Water quality results

Table A4.1. Measured values from 20 points along Rocha River in 2017 (Contraloría General del Estado, 2017).

Point	**Municipality**	**East**	**North**	**UTM**	**EC µS/cm**	**OD %**	**pH**	**T °C**	**NO_3^- mg/L**	**BOD_5 mg/L**	**COD mg O_2/L**	**Fecal coliform cfu/100mL**	**Flow m^3/s**
1	Sacaba	811951	8074208	19K	630.4	0.25	6.85	19.6	83.83	196	326	920000	0.02
2	Sacaba	804826	8076707	19K	740.25	0.2	7.85	20.7	43.6	168	280	420000	0.03
3	Cercado	801288	8075379	19K	1677	58.56	8.18	22.1	15	399	665	590000	0.015
4	Cercado	800222	8072961	19K	1937	2.72	7.8	27.6	17	272	453	170000	0.046
5	Cercado	795259	8071488	19K	2740	2.4	7.54	24.9	39	324	539	300000	0.029
6	Colcapirhua	794834	8072088	19K	2.95	235.6	8.23	23.1	20.6	199	649	130000	-
7	Colcapirhua	793269	8072545	19K	3.11	100.1	8.28	27.6	56.9	324	821	100000	-
8	Colcapirhua	793031	8072719	19K	3.65	85	8.31	19.9	23.3	283	695	390000	-
9	Colcapirhua	791870	8072887	19K	1.96	4	7.79	29.8	22.3	295	492	110000	-
10	Quillacollo	791412	8072969	19K	4070	3	8.03	21.7	187	139	307	510000	-
11	Quillacollo	788598	8071965	19K	1600	2	7.65	27	49.1	373	791	260000	-
12	Quillacollo	786675	8072760	19K	1550	2	7.39	20.4	91	232	204	580000	-
13	Vinto	786303	8072953	19K	1583	3.1	6.8	20.7	62.3	80	200	1000000	0.1
14	Vinto	785318	8073316	19K	1638	41	7.57	25.6	72.1	217	690	2800000	0
15	Vinto	784556	8073463	19K	1649	5.4	7.46	25.4	95	104	770	1000000	0.2
16	Vinto	784332	8072961	19K	848	6.6	6.7	28.7	121	429	920	4400000	0.1
17	Sipe Sipe	784917	8070483	19K	255	3	7.6	24.8	263	442	1008	580000	0.1
18	Sipe Sipe	783630	8066036	19K	14	52	7.5	25	160	90	124	4000	-
19	Sipe Sipe	782886	8064657	19K	1426	96	7.6	21.7	116	210	389	18000	-
20	Sipe Sipe	783421	8055459	19K	166	110	8.1	22.4	83.8	70	117	9000	-

A4.2 ICO-index calculation

Table A4.2 Calculated ICO-index for results from Contraloría del Estado (2017) in Appendix 3 on points correlating to ID 1-6 in this project.

Zone (ID 2017)	**Parameter**	**Y1**	**X 1**	**Y2**	**X2**		
Puente Cajón (ID 4)	DO %	2.72	11.60				
	BOD5 (mg/L)	272	181.33				
	COD (mg/L)	453	45.3				
	Nitrates (mg/L)	17	2.50				
	Sum		240.73				
						ICO Punte Cajon 2017:	**60.18**
Puente Zofráco (ID 6)	DO %	235.6	46.94				
	BOD5 (mg/L)	199	13.67				
	COD (mg/L)	649	64.9				
	Nitrates (mg/L)	20.6	2.82				
	Sum		247.33				
						ICO Zofraco 2017:	**61.83**
Puente Pico de Loro (ID 14, 15)	DO %	41.00	4.89	5.40	10.97		
	BOD5 (mg/L)	217.00	144.67	104.00	69.33		
	COD (mg/L)	690.00	69.00	770.00	77.00		
	Nitrates (mg/L)	72.10	6.22	95.00	7.41		
	Sum		224.78		164.71		
						ICO P. Pico Loro 2017:	**48.69**
Entrada Mallcoranch (ID 17)	DO %	3	11.53				
	BOD5 (mg/L)	442	294.67				
	COD (mg/L)	1008	100.80				
	Nitrates (mg/L)	263	14.10				
	Sum		421.10				
						ICO E. Mallcorancho 2017:	**105.27**

Appendix 5: Documentation of Rocha River

Documentation of river characteristics and field material.

Figure A. Storage for water samples during fieldwork.

Figure B. River sediment at sampling point ID 1

Figure C. River sediment at location ID 2

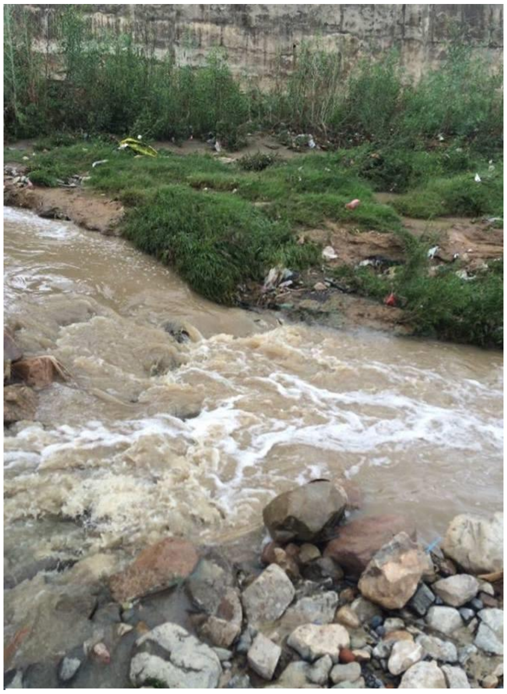

Figure D. River Restoration potential at ID 3

Figure E. The Rocha River at ID 6, showing banks that prevent flooding and solid waste deteriorating

Figure F, Sample containers (ID 1-4) for evaluation of pH and EC at C.A.S.A.