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# Two-dimensional hydraulic modeling for flood assessment of the Rio Rocha, Cochabamba, Bolivia.

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Johanna Myrland

# ABSTRACT

## Two-dimensional hydraulic modeling for flood assessment of the Rio Rocha, Cochabamba, Bolivia.

*Johanna Myrland*

Historically humans have settled in river valleys, which has made flooding a natural hazard for human communities. This is also the situation in the valley of Cochabamba, which is frequently affected by floods. Therefore it is of high relevance to assess and manage the flood risk in order to reduce the impact in the affected areas.

For this purpose hydraulic simulations were performed with the two-dimensional model Iber. The study area includes 17 kilometers of the main river, Rio Rocha, and its tributaries. The data used in the project was elevation data of high resolution and computed hydrographs. Field work and sensitivity analysis were performed to evaluate the result.

The model was used to describe the dynamics of the Rio Rocha and its tributaries during flooding, such as flow path and water levels. The simulations showed that flooding mainly occurs in the tributaries and at eleven other sites without a clear riverbank. Most of the area affected by flooding is agricultural land, but also residential areas and infrastructure were also at risk. The flood duration shown to be longest for agricultural land, which can lead to major crop damage due to anoxic condition. Even though a smaller part of the affected area is residential land, the urbanization in this area is predicted to increase and more land may be settled in the near future.

This thesis, along with other studies, highlights the importance of high resolution mesh to perform a hydraulic simulation with a two-dimensional model and the need of data to validate the result.

*Keyword: Iber, two-dimensional hydraulic model, flood assessment, river dynamics.*

*Department of Earth Sciences. Program for Air, Water and Landscape Science, Uppsala University.*
*Villavägen 16, SE-752 36, UPPSALA. ISSN 1401-5765*

# REFERAT

## Tvådimensionell hydraulisk modellering för att bedöma översvämningsrisken av Rio Rocha, Cochabamba, Bolivia.

*Johanna Myrland*

Människor har i årtusenden bosätt sig vid flodslätter, vilket gjort översvämningar till en naturlig risk för våra samhällen. Detta är även fallet i Cochabamba, en dal i centrala Bolivia som ofta drabbas av översvämningar. Därför är det av stor betydelse att bedöma och hantera översvämningsrisken med syfte att minska påverkan i de drabbade områdena.

För detta ändamål genomfördes hydrauliska simuleringar med den tvådimensionella modellen, Iber. Studieområdet omfattade 17 kilometer av huvudfloden, Rio Rocha och dess bifloder. De data som användes var högupplöst höjddata och beräknade hydrografer. För att utvärdera resultatet utfördes fältarbete och känslighetsanalys.

Modellen användes för att beskriva dynamiken i floderna vid höga flöden. Simuleringarna visade att översvämningar riskerar att inträffa främst i bifloderna och på elva specifika plaster med en otydlig flodbank. Översvämningarna drabbade mest jordbruksmark, men även bostadsområden och infrastruktur. Översvämningens varaktighet var längst för jordbruksmarken, där översvämningen kan leda till stora skador på odlingen på grund av syrebrist. Även om endast en mindre del av översvämningsområdet är bebott i nuläget, förväntas urbaniseringen öka inom studieområdet.

Detta examensarbete, liksom andra studier, belyser vikten av högupplöst numerisktrutnät för att kunna utföra hydraulisk simulering med en tvådimensionell modell samt behovet av data för att validera resultatet med.

*Nyckelord: Iber, tvådimensionell hydraulisk modell, översvämningsriskbedömning, flod dynamik*

*Institutionen för geovetenskaper, Luft-, vatten-, och landskapslära, Uppsala universitet*
*Villavägen 16, SE-752 36, UPPSALA. ISSN 1401-5765*

# PREFACE

This thesis is the final part of the Masters Program in Environmental and Water Engineering at Uppsala University, Sweden. It has been performed as a Minor Field Study (MFS) at the Universidad Mayor de San Simón (UMSS), Bolivia, financed by the Swedish International Development Agency (Sida) on behalf of the Swedish University of Agricultural Sciences (SLU). The supervisor was Abraham Joel at the Department of Soil and Environment at SLU. Subject reviewer was Allan Rodhe, Professor at the Department of Earth Sciences, Program for Air, Water and Landscape Science at Uppsala University.

I would like to thank all the concerned at UMSS for your warm welcome and hospitality during my stay in Bolivia. Thanks to Carmen Ledo, without you I wouldn't have been able to start this project. I would also like to thank the staff at the Hydraulics Laboratory of the Universidad Mayor de San Simón (LHUMSS). A special thanks to Mauricio Villazón for all your help and supervision, and to Ruben Batista and Sofia Fuente for providing the hydrological data for my thesis. I would also like to thank Mauricio Ledezma at the Integrated Watershed Management Program (PROMIC) in Bolivia for providing the elevation data and your help during fieldwork.

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# POPULÄRVETENSKAPLIG SAMMANFATTNING

## Tvådimensionell hydraulisk modellering för att bedöma översvämningsrisken av Rio Rocha, Cochabamba, Bolivia.

*Johanna Myrland*

Översvämningar är ett naturligt fenomen för alla floder, men det blir allt mer uppenbart att översvämningsrisken ökar för det moderna samhället. Numera är en tredjedel av de årliga naturkatastroferna och ekonomiska förlusterna av naturkatastrofer översvämnings relaterade. Därför är det av stor betydelse att bedöma och hantera översvämningsrisken med syfte att minska de negativa konsekvenserna av höga flöden.

För att bedöma och hantera effekterna av höga flöden är det viktigt att förstå flodsdynamiken. För detta ändamål används hydrauliska modeller, vanligtvis en- eller tvådimensionella. Modellerna simulerar en översvämning och ger information om vattennivåer och flödesvägar. Därmed är det möjligt att fastställa områden som drabbas och vilka som bidrar till översvämning. När dessa områden är kända är det möjligt att vidta relevanta åtgärder för att skydda stadsområden.

Cochabamba är den tredje största staden i Bolivia och huvudstad i regionen Cochabamba. Den ligger i en dal i centrala Bolivia och har en befolkning på 1,5 miljoner, men antalet ökar för varje år. Cochabamba har en problematisk urbanisering och nybyggen sker ofta i områden som inte är lämpliga för bosättningar. Ett av dessa områden är flodslätterna till Rio Rocha, en flod som rinner genom hela dalen från öst till väst. Större delen av året är floden torr, men under regnperioden orsakar höga flöden ofta översvämningar. Högst översvämningsrisk finns nedströms flygplatsen, ett flackt område som tar emot stora flöden både från uppströms Rio Rocha och de lokala bifloderna.

Tidigare studier har undersökt översvämningsrisken i Rio Rocha med den endimensionella modellen HEC-RAS. Modellen definierar geometrin med hjälp av tvärsektioner av floden. Resultatet från simuleringarna ger värden för vattennivån vid varje tvärsektion, vilket innebär att flödet endast tillåts att spridas i en dimension, längs med vattendraget.

Nyligen har bättre, högupplöst höjddata publicerats för de översvämningsdrabbade området nedströms flygplatsen. Det ger nya möjligheter att undersöka dynamiken i floden med en mer omfattande och komplex hydraulisk modell. En tvådimensionell modell beräknar inte bara vattennivån längs med vattendraget utan även spridningen av vattnet. Istället för att använda tvärsektioner, är geometrin beskriven med numerisktrutnät, vilket beskriver geometrin noggrant med högupplöst höjddata.

Syftet med det här examensarbetet var att få en förståelse av dynamiken i Rio Rocha och dess bifloder vid höga flöden med den tvådimensionella hydrauliska modellen, Iber. Studieområdet omfattade 17 kilometer av Rio Rocha och dess bifloder. Data som användes var höjddata med hög upplösning, beräknade flöden med olika sannolikhet att inträffa, samt värden på Mannings tal. För att utvärdera resultatet utfördes fältarbete och en känslighetsanalys, där värden på Mannings tal varierades.

Resultatet från simuleringarna visade att översvämningar sker främst i bifloderna. Detta inträffade även för simuleringar när det inte var något tillflöde i bifloderna. Detta kan förklaras med att området där bifloden mynnar mot huvudfåran är väldigt flackt, vilket medför att vattnet stiger upp i biflödet och orsakar översvämning. Översvämningar inträffade även på elva specifika platser där det inte fanns någon tydlig flodbank. Sammanfattningsvis anses resultatet av vilka områden som bidrar till översvämning vara rimligt.

Översvämningarna drabbade mest jordbruksmark, men även bostadsområden och infrastruktur. Resultatet visade att översvämningens varaktighet var längst för jordbruksmarken, vilket kan leda till stora skador på odlingen på grund av syrebrist. Även om endast en mindre del av översvämningsområdet är bebyggt, förväntas urbaniseringen att öka inom studieområdet.

På en bro mättes markeringar från tidigare vattennivåer och jämfördes med de simulerade värdena. Resultatet indikerade att de simulerade vattennivåerna var underskattade, men flera jämförelser skulle behövas för att kunna göra någon fullvärdig validering. Tidigare studier har belyst problemet med att data för att validera hydrauliska simuleringar med ofta är otillräcklig, vilket är fallet också för detta examensarbete.

Resultat från känslighetsanalysen visade att Mannings tal inte har någon större påverkan på resultatet för detta examensarbete. Däremot anses upplösningen på höjddata vara av stor betydelse, eftersom den kunde generera ett numeriskrutnät med hög upplösning i Iber. Följaktligen stämmer detta examensarbete överens med tidigare studier, att beträffande tvådimensionell hydrauliska modellering, har högupplöst numerisktrutnät större betydelse än den vanliga kalibreringsparametern, Manningstal.

Detta examensarbete visar en förnyad metod för att bedöma översvämningsrisken för Rio Rocha genom att använda den tvådimensionella modellen, Iber. Iber är ett användbart verktyg för att utvärdera områden som kan drabbas av översvämning och skulle kunna användas för att ta fram beslutsunderlag till arbetet med en hållbar urbanisering och för att öka säkerheten för invånarna inom studieområdet.

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# 1. INTRODUCTION

Floods are a fundamental part of the dynamics in any river channel. Most flooding occurs when more water is supplied to the stream than can be discharged downstream, which causes the water level to rise and excess water to spread to areas not normally under water. Historically humans have settled in river valleys, which has made flooding a natural hazard for human communities for millennia (Wohl, 2000). Even if floods are a natural phenomenon our society tends to get more vulnerable. Nowadays a third of the annual natural disasters and economic losses are flood related. Hence, it is of high relevance to assess and manage flood risk, with the aim to reduce adverse consequences of flooding (Warchien & Mambretti, 2012).

To assess and manage the impact of high flows it is important to understand the dynamics of a river. For this purpose hydraulic models are widely used, the most common are one- or two-dimensional models. The models simulate flood events and provide information relating to water levels and flow paths, and thereby identifying vulnerable areas (Schumann, 2011). When these areas are known it is possible to develop relevant management strategies and set up suitable regulation in order to safeguard populated urban areas.

Cochabamba is the third largest city in Bolivia and the capital of the department of Cochabamba. It is located in a valley in central Bolivia with a total population of 1.5 million. Through the valley flows the Rio Rocha, a river that frequently is affected by floods. The area most sensitive by flooding is downstream of the airport, a flat area that receives large flows both from the upstream part of the Rio Rocha and from the local tributaries.

Previous studies have assessed the flood risk in the Rio Rocha with the one-dimensional model HEC-RAS (Haddad, et al., 2004, Romero & Urquieta, 2006, Fuente & Batista, 2014). One-dimensional models define the geometry using cross-sections placed perpendicular to the flow direction. The simulated result gives values of the water depth at each cross-section, meaning that the flow will only spread in one dimension, along the watercourse (Tayefi, et al., 2007). Therefore one-dimensional models may describe the in-channel flow satisfactorily but will not take into account the large horizontal spread, which occurs during flooding events (Horritta & Batels, 2002).

Recently upgraded elevation data has been published for the Rio Rocha in the areas most affected by flooding (PROMIC, 2012). This enables us to investigate the dynamics in the river with a more complex and comprehensive hydraulic model. A two-dimensional model not only calculates the water level along the watercourse, but also the spread of the water. Instead of using cross-sections, the geometry is described with a numerical mesh, which thoroughly describes the geometry with high resolution elevation data (Bates, et al., 2003).

## 1.1 Objectives

The purpose of this thesis was to improve the current level of knowledge about flooding in the Rio Rocha downstream of the airport, with a two-dimensional hydraulic model. The specific aims of this thesis were to:

- Perform hydraulic modeling with the two-dimensional model Iber in order to understand the dynamics of the Rio Rocha and its tributaries during flooding, such as flow paths and water levels.
- Identify zones along the riverbanks that contribute to flooding.
- Identify areas directly affected by flooding.

# 2. BACKGROUND AND THEORY

This section gives background to the problems with flooding in Rio Rocha. It will also describe the fundamental parts within flood assessment and give an introduction to Iber, the model choice in this thesis.

## 2.1 Area of interest and previous studies

Cochabamba is the third largest town in Bolivia and the capital of the department of Cochabamba. It is located in a valley in central Bolivia. The department includes seven municipalities; Cochabamba, Quillacollo, Sipe Sipe, Tiquipaya, Vinto, Colcapirhua and Sacaba with a total population of 1,500,000. It is located in the eastern part of the Andes and the valley is surrounded by mountains. The average altitude is 2,500 m a.s.l. and the region has a temperate climate with an average of 20 degrees Celsius all year around. The area is characterized by an ecological diversity with mountains, tropical area, agricultural land and urbanized area. The water drains from the mountains in steep ravines into tributaries which take the water to the main river, Rio Rocha (Ledo, 2013).

**Figure 1** Location of Cochabamba. Map data © 2014 Google, Mapcity.

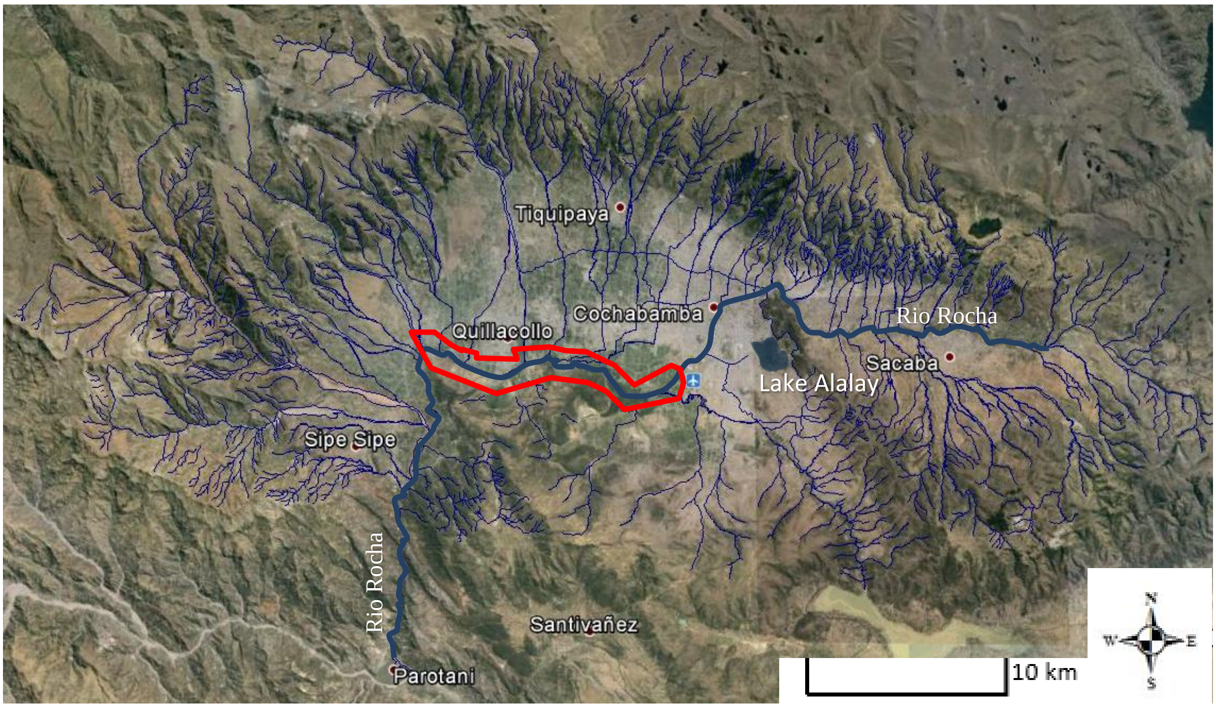

**Figure 2** The catchment of the Rio Rocha. The study area is enclosed by the red line. Figure modified from Google Earth. Map data ©2014 Google, Europa Technologies Image Landsat.

The Rio Rocha flows through the whole valley from east to the west. The river begins up in the mountains in Sacaba. From here the average slope of the river is 1.5 % and in some places the river is 200 meters wide. The river continues through the urbanized area of Cochabamba and Quillacollo where the slope is significantly smaller, about 0.1 %. Through the center of Cochabamba the average width of the river is 45 meters and thereafter it narrows down to 30 meters. Downstream the slope increases to about 0.3 %. From Sacaba to Parotani the length of the Rio Rocha is approximately 60 km and the total drainage area is 2,030 km$^2$. The longitudinal profile of the Rio Rocha is shown in Figure 3 (Romero & Urquieta, 2006).

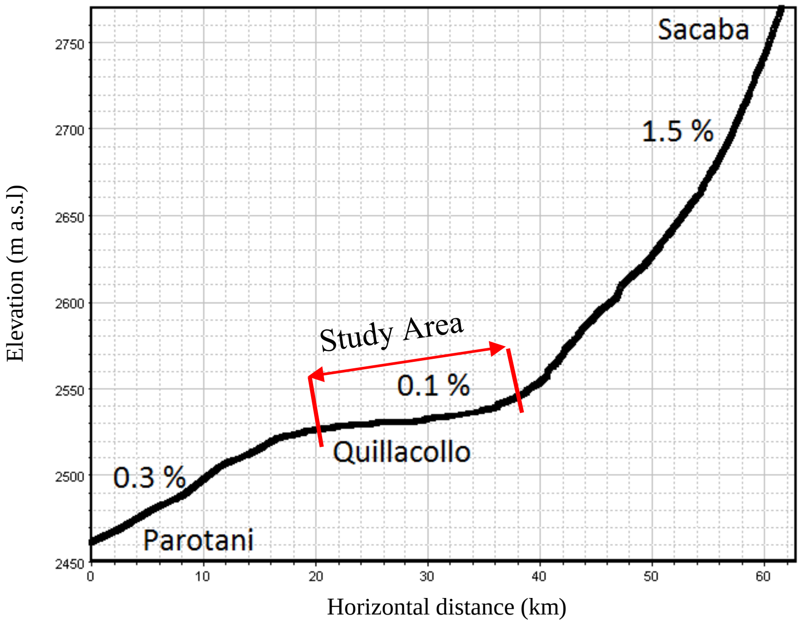

**Figure 3** The longitudinal profile of the Rio Rocha, (Romero & Urquieta, 2006). Permission from the author.

Rio Rocha has contamination problems since it is a recipient of poorly treated waste water from households and industries. According to the environmental report K2/AP06/M11 (2012), the water quality was classified as very poor to bad quality and should not be used for irrigation or human use. However the study informs that water from the Rio Rocha is used for irrigation by various consumers along the river.

**Figure 4** Rio Rocha in Sacaba (Romero & A.Urquieta, 2006).

Most part of the year the rain is scarce and there is almost no water in the rivers and some are completely dry. Average annual rainfall ranges from 440 mm (in Sacaba) to 660 mm (in Quillacollo). Most of the rain falls during the rainy season, November to March. The rainfall rarely covers the entire valley, it is more likely to appear as local rainfall covering only a dozen of square kilometers. This usually generates a high runoff that frequently causes flash flood in the rivers (Romero & Urquieta, 2006).

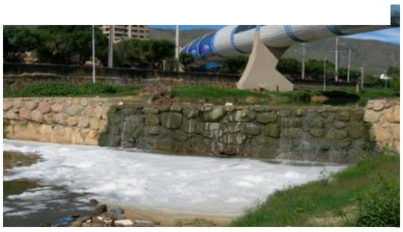

**Figure 5** Rio Rocha in the city center in Cochabamba. The withe foam is due to contamination (PROMIC, 2012).

In order to decrease the risk of flooding in the city center of Cochabamba some measures have been taken. In the 1930's a tunnel was built to lead some of the water from the Rio Rocha to a constructed lake, Laguna Alalay, before it enters the city. Moreover the river is canalized though the city center of Cochabamba to the airport (PROMIC, 2012).

**Figure 6** Rio Rocha in Quillacollo

### 2.1.1 Flooding in the Rio Rocha

The area most sensitive to floods is downstream of the airport through Quillacollo until the sharp turn, Pico del Loro. This is a flat area that receiving much water from the upstream part of Rio Rocha, Figure 3. There are additional water contributions from the local tributaries that drain the area which has the highest annual rainfall in the catchment (Romero & A.Urquieta, 2006). Another reason why this area is so affected could be that measures have been taken in order to decrease the flood risk through the city center of Cochabamba, but less action has been taken downstream the airport to Quillacollo. Although there is a high population in the area a negligible part of the river is canalized (PROMIC, 2012).

The Democracy Center (2014) informs about the vulnerability in Quillacollo due to flooding caused by heavy rain. The most recent event occurred in February 2011 and affected about 1,000 families, 19 houses collapsed completely. In the worst hit areas the water rose above the waist and remained one week in the houses.

**Figure 7** Maria Alonzo is demonstrating with her right hand where the water level rose in her store during the flooding year 2011.

Several studies have assessed the flood risk for the entire Rio Rocha with the one-dimensional model HEC-RAS (Haddad, et al., 2004, Romero & Urquieta 2006, Fuente & Batista, 2014). The studies have used computed flow, elevation data with 30 meters grid and measured cross-sections as input data. Their result shows that the area downstream of the airport is the one most vulnerable to high flows, Figure 8.

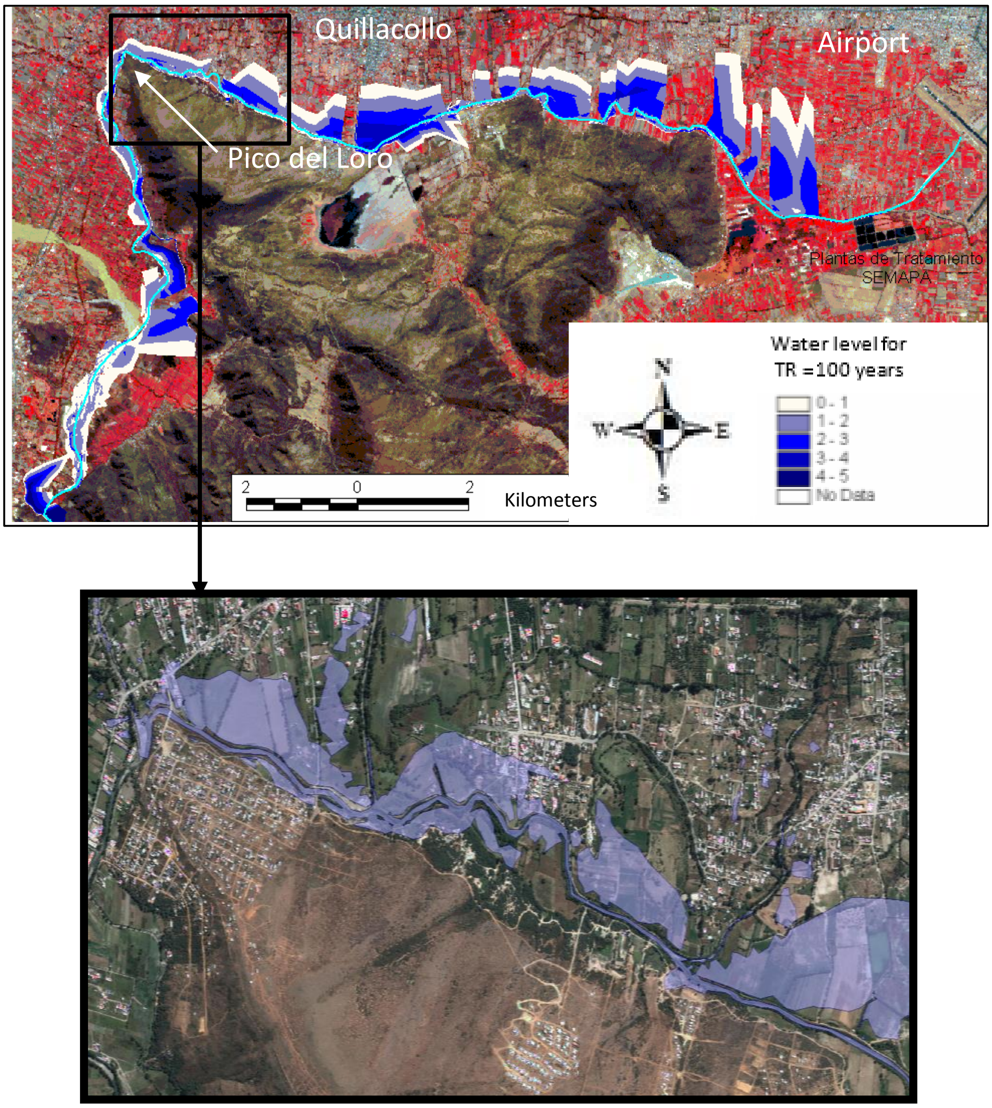

**Figure 8** Previous studies of flooding in Cochabamba. The upper figure is from Haddad, et al., (2004) illustrating a 100 years flood and the lower from Fuente & Batista (2014) illustrating a 50 years flood. The black square in the upper figure shows where the lower figure is located. Permission from the authors.

### 2.1.2 Urbanization problem

The metropolitan area of Cochabamba has increased with a factor of 9 over the past 50 years, from 2,000 hectares in 1962 to 18,900 hectares in 2012. If the growth continues with the same rate, 420 hectares per year, one would expect the urban area to cover about 35,000 hectares in 2036. The high population growth has increased the demand of land around the city and the expansion of the city often occurs without proper planning and regulations in areas that are not suitable for settlements (Ledo, 2013).

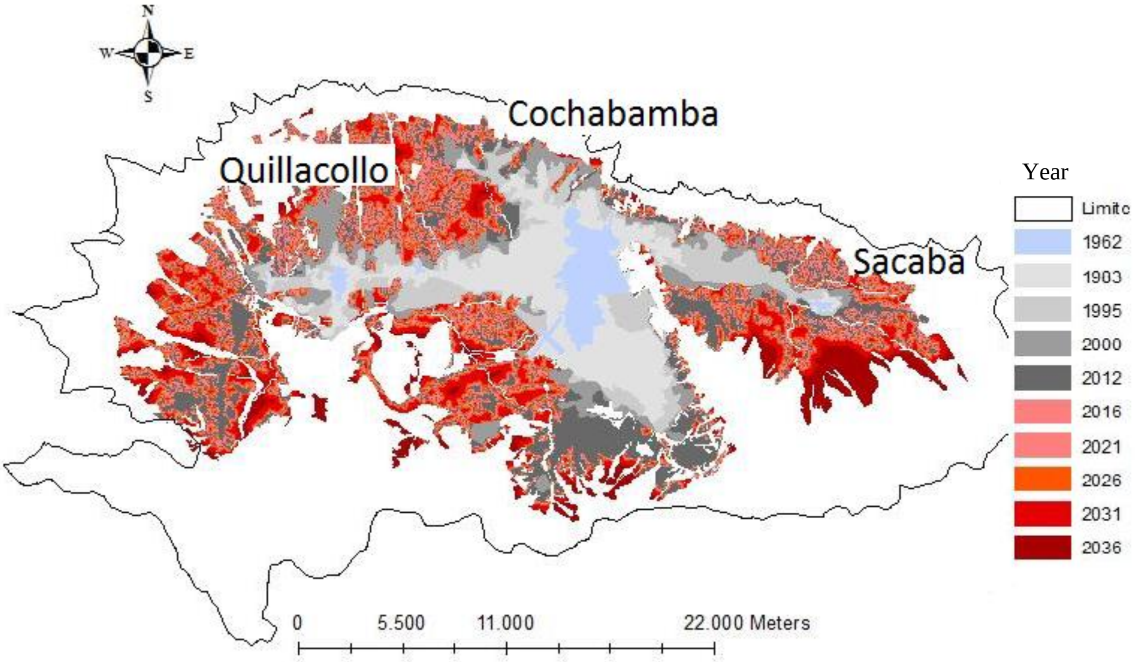

**Figure 9** Historical and the predicted urbanization of Cochabamba (Ledo, 2013). Permission from the author.

When a city grows it replaces vegetation and soil by houses and paved areas. This generates a greater and more momentary runoff which increases the frequency of floods in nearby streams (Konrad, 2014). Montenegro (2013) has analyzed the influence of land use change for the occurrence of flooding in the Rio Rocha. The study concludes that the urbanization process within the catchment has increased the flow and flooding downstream of the airport.

The largest municipalities within in area affected by floods is Quillacollo. It is located 13 kilometers from the city center of Cochabamba. Thereby it provides an affordable option for immigrants from rural areas that search for the economic opportunities a town can offer. This has led to an explosive urbanization during the last decade. Since 2001 the population has nearly doubled and is presently estimated at 300,000. The urbanization is predicted to continue to increase in this area and thereby the vulnerability of flooding will increase if no action is taken (Ledo, 2013).

## 2.2 Flood assessment

In summary, flood assessment begins with hydrological prediction of flood events often using frequency analysis and rainfall-runoff models to compute hydrographs with a given return period. This hydrological data together with data of the river, such as geometry and roughness, are used as input to a hydraulic model in order to understand the dynamics of a river during flooding.

### 2.2.1 Rainfall-Runoff models

In most counties there are plenty of rainfall records, but limited access to stream flow data. Since flow data is a requirement for flood assessment, the relationship between the rainfall over a catchment and the resulting flow in a river is a fundamental part of the hydraulic analysis (Shaw, 2004). There are many methods to estimate the flood peaks and runoff volumes from a catchment. Usually a rainfall-runoff model is used which computes a runoff hydrograph as a response to a rainfall event. Hydrological predictions of a flood events performed with computers have been done since the 1970s and nowadays various rainfall-runoff models are available (Wohl, 2000). Despite extensive experiences, rainfall-runoff simulation often has a lot of uncertainties due to the complexity of the hydrological process. Also the limitation of flow data to calibrate and validate the result makes it hard to assess the efficiency of the model (Willems, 2005).

### 2.2.2 Hydrograph

The graph that describes the whole time history of the changing rate of runoff due to a rainfall event is called a hydrograph. Sherman (1932) introduced the concept of unit hydrograph (UH) which is defined as the direct runoff hydrograph resulting from a unit volume a rainfall of constant intensity, uniformly distributed over the drainage area. The unit volume is usually 1 mm of effective rain. The effective rain is the rain that finds its way to the river, which occurs when the surface and the soil are saturated. The volume of water is given by the area underneath the hydrograph and is equivalent to 1 mm depth of effective rainfall over the catchment (Shaw, 2004).

### 2.2.3 Return period

The concept of the return period is a measure of the probability for an event to occur. A flood with a return period of 100 years, also called 100 year flood has 1/100 = 0.01 or 1 % chance of appearing each year and a 50 year flood has 0.02 or 2 % chance of appearing each year (Wohl, 2000). However the cumulative probability is much greater because of the exposure to the risk over several years. For example the chance for a 100 year flood to appear at least once during 100 years is 63.4 % (Shaw, 2004).

### 2.2.4 Frequency analysis

Frequency analysis is used for hydrological data to estimate how often an extreme event occurs based on the probability distribution. It means that it is carried out on observed historical records with the aim of assessing future probabilities of appearance. It usually assumes that there will not be any temporal changes in the catchment, like changes in land use or climate change (Warchien & Mambretti, 2012).

Frequency analysis is usually a problem in hydrology because sufficient information is seldom available; the records are generally less than 30 years in length (Wohl, 2000). Therefore flood extrapolation is required when determining a 100 year flood. Several probability distributions and methods have been used for this purpose. The two main appoches are to fit a stochastic model to the observed values on the series for maxima annual flow (MAF) or partial duration series of flood (PDF) with values exceeding a specific magnitude (Warchien & Mambretti, 2012).

### 2.2.5 Hydraulic modelling

Understanding the hydraulic dynamics of a river is a key element in managing the impact of flooding. For this purpose hydraulic models are widely used. The model needs hydrological data and spatial resolution information about the terrain, such as elevation and roughness. With this data a hydraulic model uses the differential equation of unsteady flow, known as the Saint Venant equations, to estimate flow rate, velocity and depth of the water (Warchien & Mambretti, 2012).

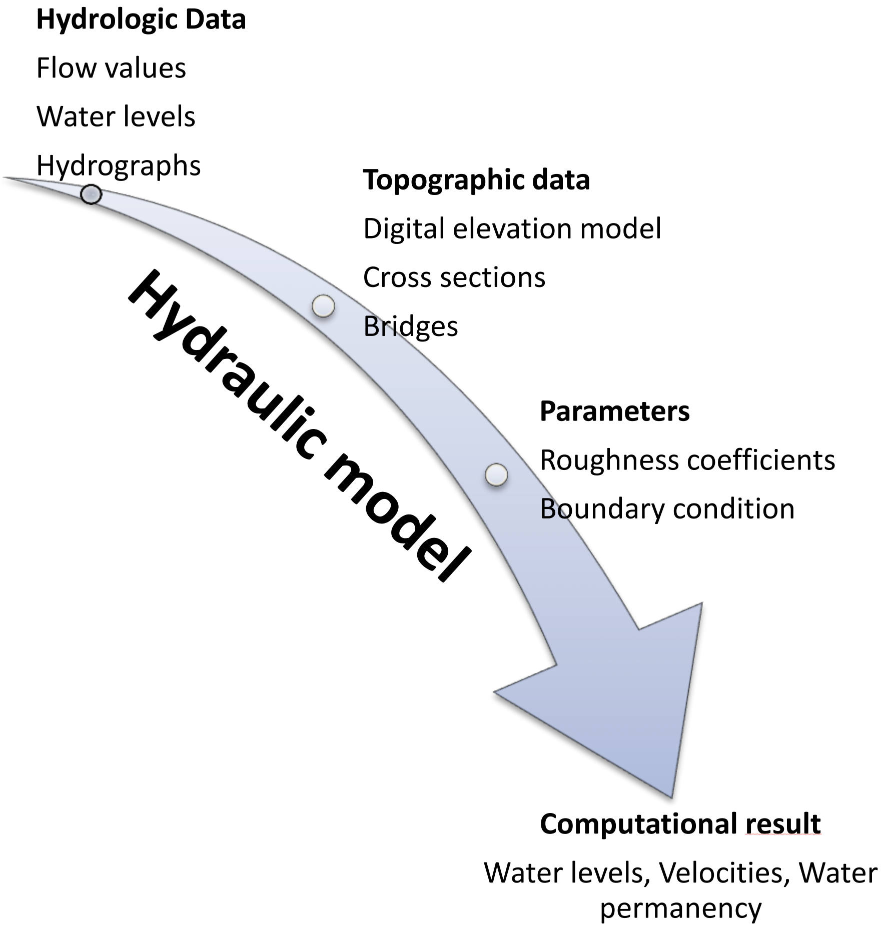

**Figure 10** The components of a hydraulic numeric model. Based on information from Schumann (2011).

## 2.3 Model choice

The choice of model has a big impact on the outcome of the simulation. It is important to choose a model that adapts with the input data since the hydraulic model can never be more accurate than the used data. Recently new elevation data with high-resolution have been released for the study area. This enables the use of a more complex model, hence a two-dimensional model was believed to be the best option.

It would be appropriate to choose a model that the Universidad Mayor de San Simón (UMSS), Bolivia, had former knowledge about in order to increase the usefulness of the project and to receive better tutoring. Therefore the two-dimensional model Iber, a well-used model at UMSS, was chosen for the hydraulic modeling. The following description is based on the hydraulic reference manual for Iber v1.0 (Iber, 2010a).

### 2.3.1 Introduction to Iber

Iber is a two-dimensional mathematical model for simulating free surface flow and environmental processes in river hydraulics. Iber has three main computational modules: a hydrodynamic module, a turbulence module and a sediment transport module. The hydrodynamic module, which is the base in Iber, solves the two-dimensional depth averaged shallow water equations for free surface flows, also known as the 2D Saint-Venant equations.

The equations are solved using the finite volume method, which requires a spatial discretization of the study domain. To do that, the study domain is divided into relatively small cells, a numerical mesh. Iber works with a non-structured mesh, which means that the elements can have 3 or 4 sides and be of different sizes. The main advantage of working with non-structured meshes is the ease of adaptation to any geometry, which makes them especially functional for river hydraulics.

A computation with Iber requires elevation and hydrologic data as well as information on bed friction. The bed friction is defined as a Manning roughness coefficient, which needs to be assigned to each element of the mesh. The result can be visualized and analyzed in multiple options such as water depth, velocity, water permanence etc. It is possible to view the result at each time step or an animation over the course of the event.

# 3. MATERIAL AND METHOD

A hydraulic model was used to compute the flooded area with flow data of different probabilities of appearance. The required data to perform hydraulic simulation are elevation data, hydrologic data and values of Manning’s roughness coefficient. Some of the data needed to be processed in ArcGIS before it could be used in the hydraulic model.

## 3.1 Study area

The study area is located in the valley of Cochabamba, from the airport, through the urbanized area of Quillacollo, to the sharp turn named Pico Del Loro, Figure 2 and 11. The area is frequently affected by floods, since it receives much water both from the upstream part of Rio Rocha and from the tributaries. This part of the river is 17 kilometers, has an average width of 30 meters and an average depth of 2 meters. The floodplains are mainly agricultural land, but also residential area.

## 3.2 Elevation data

The Integrated Watershed Management Program (pers.comm., 2012b) has recently published new elevation data within the catchment of the Rio Rocha. The elevation data is within the mentioned study area 17 kilometer downstream of the airport, one kilometer upstream the eight main tributaries and 150 meter on each side of the rivers, Figure 11. The data was given in elevation points with 2 to 50 meters distance between the points. Based on these points contour lines with half meter equidistance had been created by the Integrated Watershed Management Program.

It was possible to see in an early stage that the areal extent of the elevation data was very limited. Therefore attempts were made to expand the study area, but with an unsuccessful result. The problem was not to find more elevation data, but to adapt it to the existing data because of the variation in difference between the data. In some places the difference was 40 meters higher and in other 5 meters lower. An adaption with this data would create a higher uncertainty and the data was therefore not used. Since it was not possible to expand the study area it ends abruptly and causes a significant impact on the result of the flood modeling.

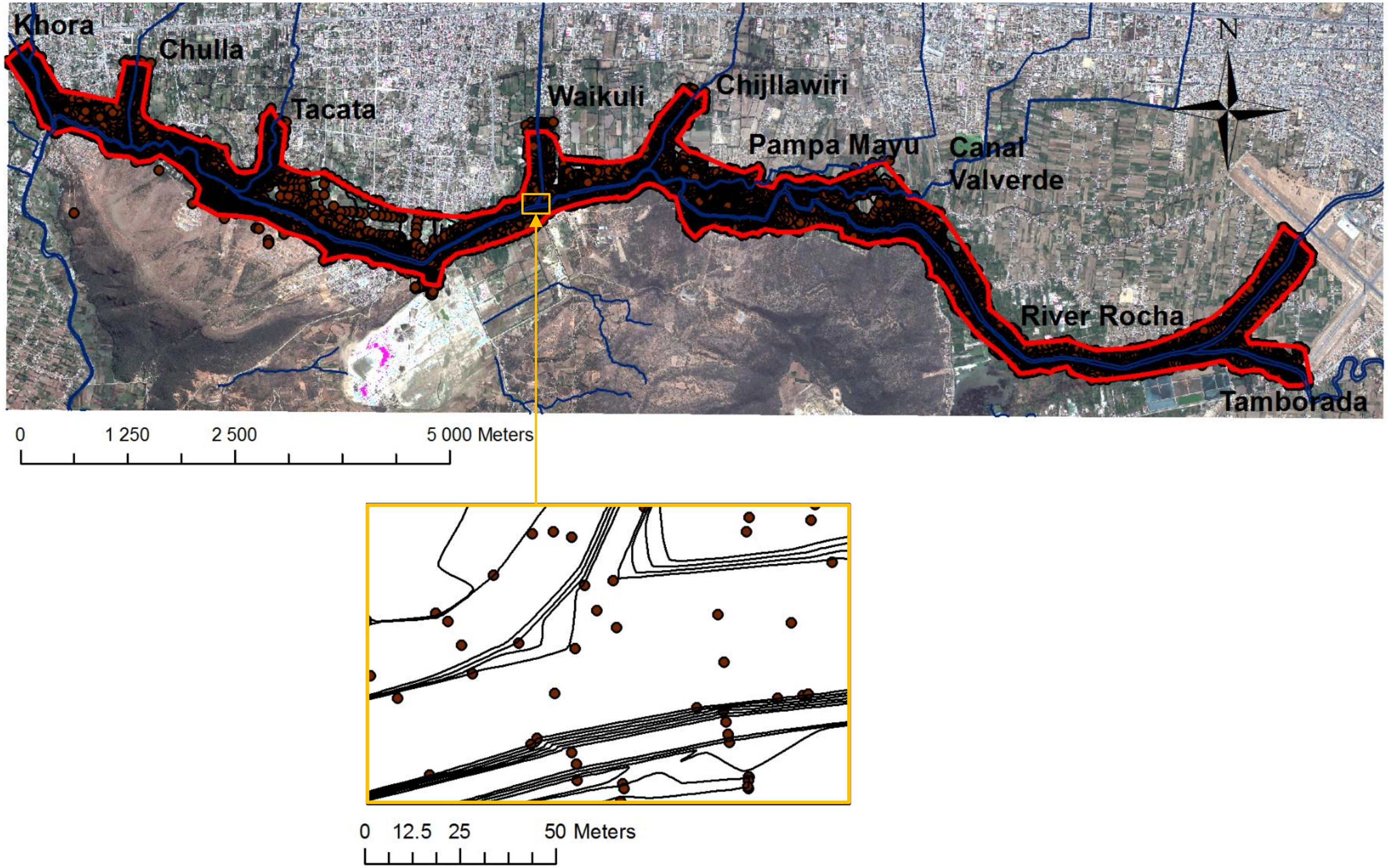

**Figure 11** The elevation data used in the project. The enlarged figure demonstrates the variation in density of the elevation points. The black lines are contour lines with 0.5 meters equidistance. The study area is enclosed by the red line.

## 3.3 Hydrologic data

The hydrological data was hydrographs taken from a study by Fuente & Batista (2014). The hydrographs were compared with data from study made by Haddad, et al., (2004). The comparison identified errors in the hydrographs and a modification was done in order to improve the data.

### 3.3.1 Hydrologic modeling by Fuente & Batista

The hydrologic data used in this thesis was obtained from a recent study performed by Fuente & Batista (2014), who computed hydrographs for the Rio Rocha and the main tributaries with the software HEC-HMS. The Hydrologic Modeling System (HMS) is designed to simulate the rainfall-runoff processes of dendritic catchment systems. The software allows the user to choose from several mathematical methods to perform the simulation. The main methods used by Fuente & Batista (2014) to compute the hydrographs are described in the in the following points.

- The catchment for the Rio Rocha was divided into 14 sub-catchments, Figure 12.
- Precipitation data was taken from 22 measurement stations that had daily data for at least 10 years period. The method of Thiessen polygons[1] was used for each sub-catchment to assign a weight factor of the total precipitation for each station proportional to the area represented by the station.
- Frequency analysis was performed in order to generate rain with certain return periods. Rain data for return periods of 10, 20, 50 and 100 years were computed with the method of partial duration series (PDF)[2].
- Each sub-catchment was assigned a value of the time of concentration, $T_c$, which is the time needed for the water to flow from the most remote point in a catchment to the catchment outlet. The values were estimated with the method of Kirpich[3] using only geometric conditions as input data.
- To estimate the losses from infiltration the Soil Conservation Service (SCS) method[3] was used. The method requires a Curve Number (CN) for each sub-catchment, which is an empirical parameter based on the soil group, land use and hydrological condition of the area. The values were obtained from the Integrated Watershed Management Program.
- Flood routing was also performed, which is the process of following the behavior of hydrographs downstream from one point to another along the river. This allows the model to compute both a hydrograph for the contribution from each sub-catchment and a total hydrograph for the Rio Rocha at the junctions of the tributaries. The Muskingum Cunge method[1] was applied for this purpose.
- The Clark Unit Hydrograph method[3] was used to transform the precipitation data to runoff hydrographs. The study performed four different simulations in HEC-HMS and gave results for 10, 20, 50 and 100 year return periods.

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[1] Information of the method (Shaw, 2004).

[2] Information of the method (Warchien & Mambretti, 2012).

[3] Information of the method (Maidment, 1993)

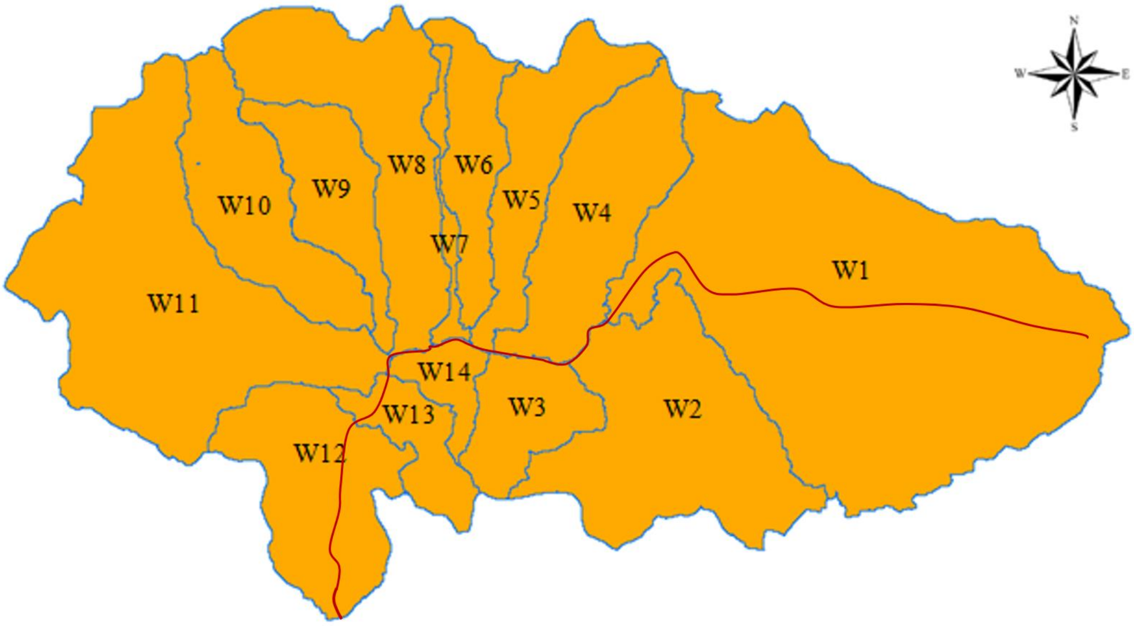

**Figure 12** The whole catchment area for Rio Rocha divided into 14 sub-catchments. The red line illustrates Rio Rocha. Further description in Table 1. (Fuente & Batista, 2014). Permission from the authors.

**Table 1** The required information to perform the hydrologic simulation; Area, Curve Number (CN) and Time of Concentration ($T_c$). (Fuente & Batista, 2014).

| Sub-catchment | Name | Area (km$^2$) | CN | $T_c$(h) |
|---|---|---:|---:|---:|
| W1 | Sacaba | 450.9 | 78.2 | 10.4 |
| W2 | Tamborada | 165.3 | 76.5 | 6.0 |
| W3 | Laguna Pampa | 49.4 | 80.1 | 3.0 |
| W4 | Canal Rocha | 107.1 | 74.6 | 5.1 |
| W5 | Pampa Mayu | 76.5 | 73.7 | 8.1 |
| W6 | Chijllawiri | 54.3 | 72.1 | 4.6 |
| W7 | Waikuli | 15.3 | 76.0 | 4.0 |
| W8 | Tacata | 125.3 | 76.1 | 4.1 |
| W9 | Chulla | 59.2 | 71.6 | 4.8 |
| W10 | Khora | 90.6 | 71.3 | 5.5 |
| W11 | Viloma | 249.7 | 79.1 | 8.4 |
| W12 | Khullkumayu | 36.8 | 78.2 | 3.2 |
| W13 | Seco | 105.6 | 74.5 | 8.1 |
| W14 | s/a | 21.6 | | |

### 3.3.2 Comparison and modification of the hydrological data

Observed flow data for validating the hydrographs computed by Fuente & Batista (2014) was somewhat limited, and therefore the results was compared with a previous study (Haddad, et al., 2004). That study had measured the cross-sections for seven tributaries to the Rio Rocha and based on that calculated the maximum flow that could pass through the sections. These maximum values were compared to the maximum values obtained from the hydrographs of a 10 and 20 year return period given by Fuente & Batista (2014), Table 2. It was shown that most of the flow values correlate with each other, except for the River Tacata where the simulated flow value is almost 10 times greater than the calculated maximum flow that could pass through. The previous study (Haddad, et al., 2004) and aerial photo approve that the Rivers Tacata and Waikuli are two branches from the same river and therefore should be in the same sub-catchment. Fuente & Batista divided Waikuli (W7) and Tacata (W8) into two different sub-catchments and assumed Waikuli to be the smaller catchment, see Figure 12. However aerial photo confirms that Waikuli is larger than Tacata and the computed hydrographs are not realistic.

With this in consideration the computed hydrographs for these two rivers could not be used as they were. Therefore weight factors were assumed using the calculated maximum flow that could pass through and compute the contribution from respective river. The weight factors were multiplied with the total simulated flow from Waikuli and Tacata, giving a new more realistic distribution, Table 3. For example, Waikuli contributes with 12.5/ (12.5+6.4) = 66.1 %. The new contribution for a 10 year return period was given from 0.661x 54.4 =35.9.

**Table 2** Comparison with maximum flow of different return periods (TR) from different tributaries to the Rio Rocha. The unit for the flow $Q_{Max}$ is $m^3/s$. Result taken from **a)** Haddad, et al., (2004) and **b)** Fuente & Batista (2014).

| | PAMPAMAYU | CANAL ROCHA | CHIJLLAWIRI | WAIKULI | TACATA | CHULLA | KHORA |
|---|---|---|---|---|---|---|---|
| $Q_{Max}$ calculated **a)** | 3.6 | 16.2 | 17.3 | 12.5 | 6.4 | 10.6 | 29.8 |
| $Q_{Max}$ TR = 10 **b)** | 5.4 | 11.0 | 6.0 | 3.6 | 50.8 | 19.4 | 15.0 |
| $Q_{Max}$ TR = 20 **b)** | 8.0 | 16.8 | 9.1 | 5.2 | 71.9 | 26.1 | 28.2 |

**Table 3** Calculated weight factor for River Waikuli and Tacata. Old and new maximum flow ($Q_{max}$) having a 10 year return period.

| | $Q_{Max}$ calculated | Weigh factor, % of total | Old $Q_{Max}$ | New $Q_{Max}$ |
|---|---|---|---|---|
| WAIKULI | 12.5 | 66.1 | 3.6 | 35.9 |
| TACATA | 6.4 | 33.9 | 50.8 | 18.4 |
| Tot | 18.9 | 100 | 54.4 | 54.4 |

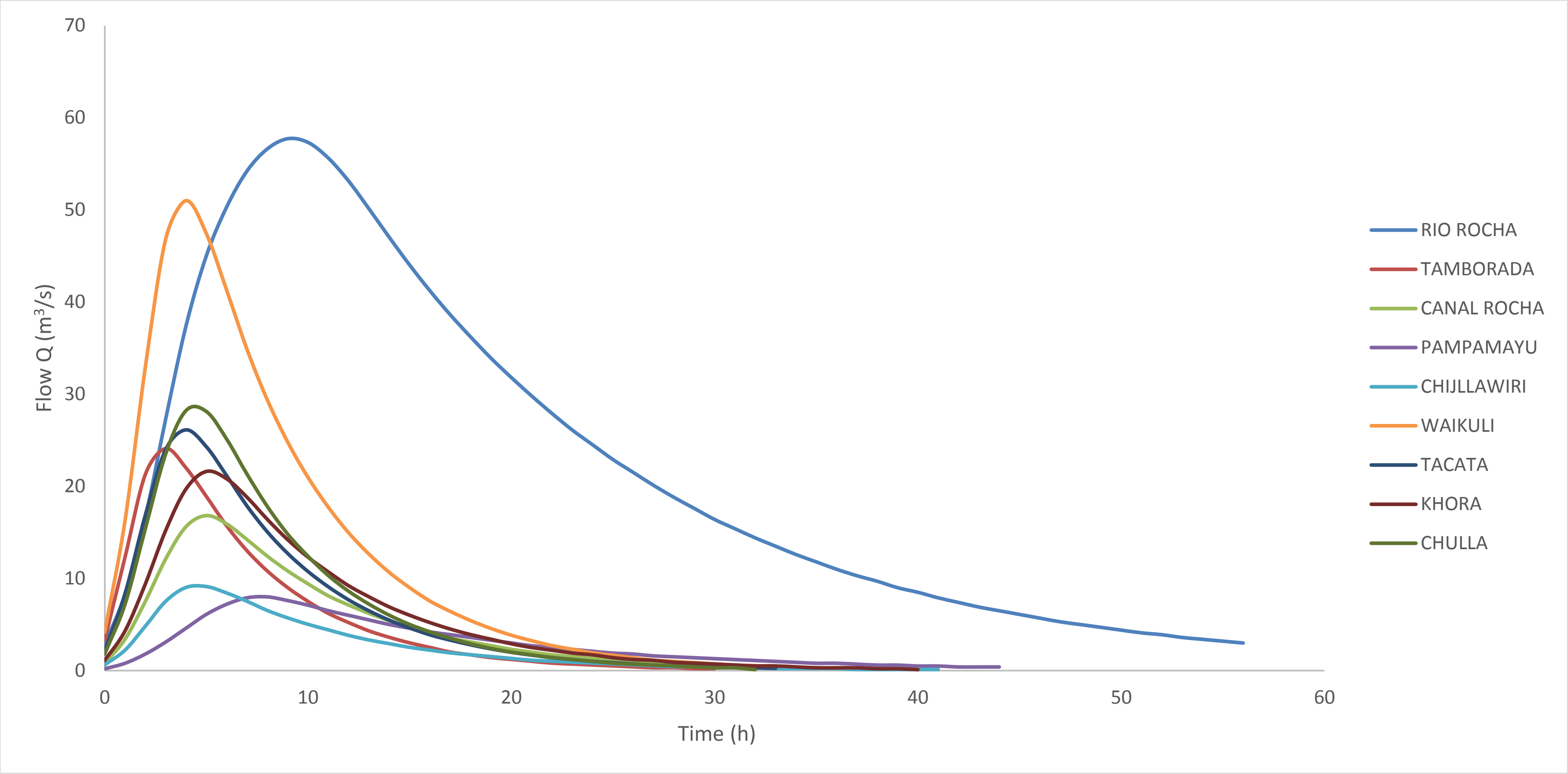

**Figure 13** Hydrographs used for 20 year return period for the Rio Rocha at the airport and all the local tributaries. Data from Fuente & Batista (2014). Modified hydrographs for River Waikuli and Tacata.

## 3.2 Working process in ArcGIS

ArcGIS is a geographic information system (GIS) for working with maps and geographic information. The version 10.0 was used for this thesis (Esri, 2014a). The work performed in ArcGIS was to interpolate the elevation data, delimit the study area and ascribe different roughness values for the study area.

### 3.2.1 Creation of digital elevation model

The elevation data consisting of points and curves were merged together by interpolation to create a digital elevation model (DEM). Even if the curves were based on the points it was believed that they would improve the interpolation. To delimit the study area a *polygon* was created carefully in ArcGIS so there was no area without elevation data and the inlets were perpendicular to the flow direction, Figure 11. With the elevation data and the polygon the interpolation tool *Topo to Raster* was used and the result was converted into an ASCII text file with the tool *Raster to ASCII*. Topo to Raster was used since it is specifically designed to generate a connected draining system and an accurate representation of ridges and streams from contour lines. A DEM can also be represented as a Triangulated Irregular Network (TIN), but due to the complex data structure of a TIN a raster turned out to be more efficient and generate a smother interpolation than a TIN (Esri, 2014b).

The spatial resolution has been shown to have a great impact on the result of a hydraulic simulation. Schumann (2011) suggests that the number of calculation cells should be increased up to the point of exact imaging of the elevation data, which will result in a finer discretization of the numerical mesh in the two-dimensional model. Hence the cell size was set to 2 meters, the same size as the densest elevation points.

### 3.2.2 Roughness assignment

Values of the Manning roughness coefficient had to be assigned to the entire study area. This was done in ArcGIS using a background picture with high resolution and dividing the study area manually with a polygon into *river*, *grass* and *residential*. Only three types were considered sufficient since the process was time consuming and the area relatively homogenous with little urbanization.

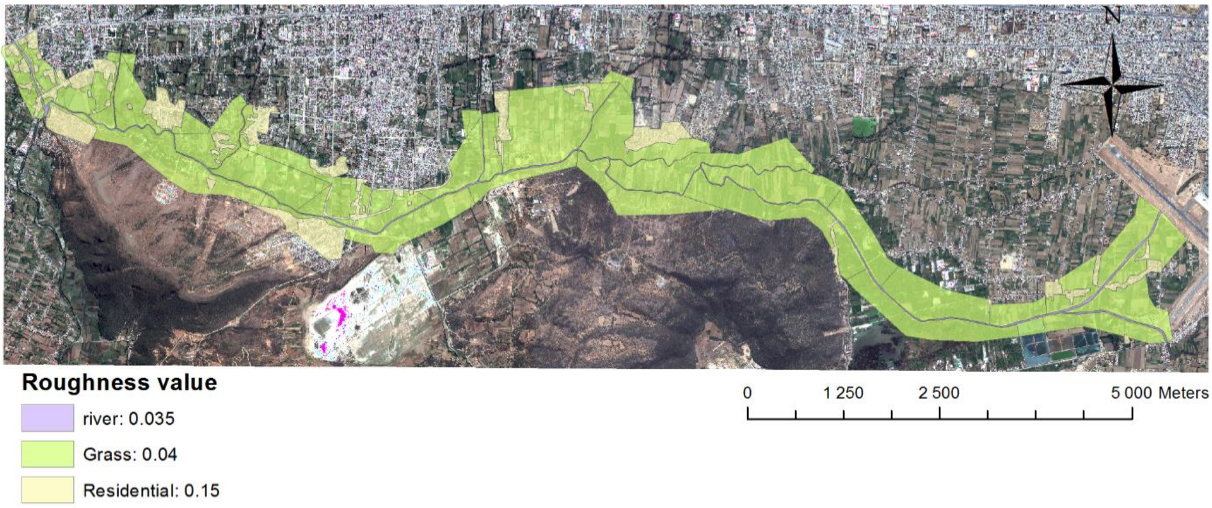

**Figure 14** Roughness values used in the simulation.

The Manning roughness coefficient, is denoted as *n* and has the unit s/m$^{1/3}$. The value for *river* was taken from Romero & Urquieta (2006) who had calibrated the Manning roughness coefficients for the entire Rio Rocha using HEC-RAS and performing flow measurements in the field. The values obtained for this study area were between 0.03 and 0.04, hence an average value of 0.035 was used. This value was also confirmed from Dingman (2002) for major streams with irregular section. The area marked *grass* was mainly agricultural land and set as mature field crops, 0.04, taken from the same source. Iber had preset values which were used for the *residential* area, 0.15.

### 3.3 Working process in Iber

A calculation in Iber required the following steps;

- Create the geometry.
- Assign boundary conditions, bed roughness and initial conditions.
- Generate a mesh.
- Set calculation parameters and start simulation.

The first step was to create the geometry. Different options were tried and the most suitable for this thesis was to create an RTIN with the Iber tool; ***create RTIN***. As input data the DEM was selected. The *Minimum length of the triangles* was set to 2 meters, the same value as the cell size of the DEM, and he *Maximum length of the triangles* was set to 100 meters, a large value that reduced the accuracy in the flat areas and thereby also a reduction in the computational cost.

Thereafter the different conditions were set. The outlet condition was set by assigning the outlet of the river. Since the model simulated flooding, the flow condition was set to subcritical. The inlet conditions were set by assigning the inlets to the model and allocating the corresponding hydrograph. This was a difficult working process and it was important to be very accurate. A background picture of the DEM was used to ease the problem, as shown in Figure 15. The darker colors signify higher elevation, thereby the brown squares show the riverbanks. A Manning roughness coefficient was assigned to each element of the geometry by importing the polygon created in ArcGIS. The value for the initial water depth was set to 0.2 meters.

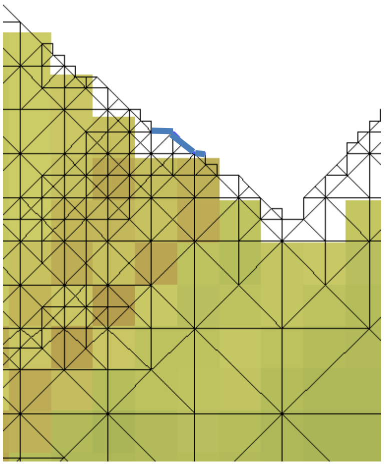

**Figure 15** The assigned inlet to the tributary Chijilawiri marked with a blue line. This inlet was assigned a flow having a 20 year return period. The background picture is the DEM, where different colors represent different elevation:

Green: low elevation
Yellow
Brown: high elevation

The meshing process transfers the assigned conditions and the geometry into nodes of a new numerical mesh. The preference for meshing was changed in order to reduce the computational time without affecting the result. The changes and values were obtained from a tutorial by Iber (2013b) with the same state of problem. In Figure 16 it is possible to see the smaller mesh around the river where elevation data was denser and larger mesh for the flat areas. By having longer mesh where it was possible to reduce the computational time.

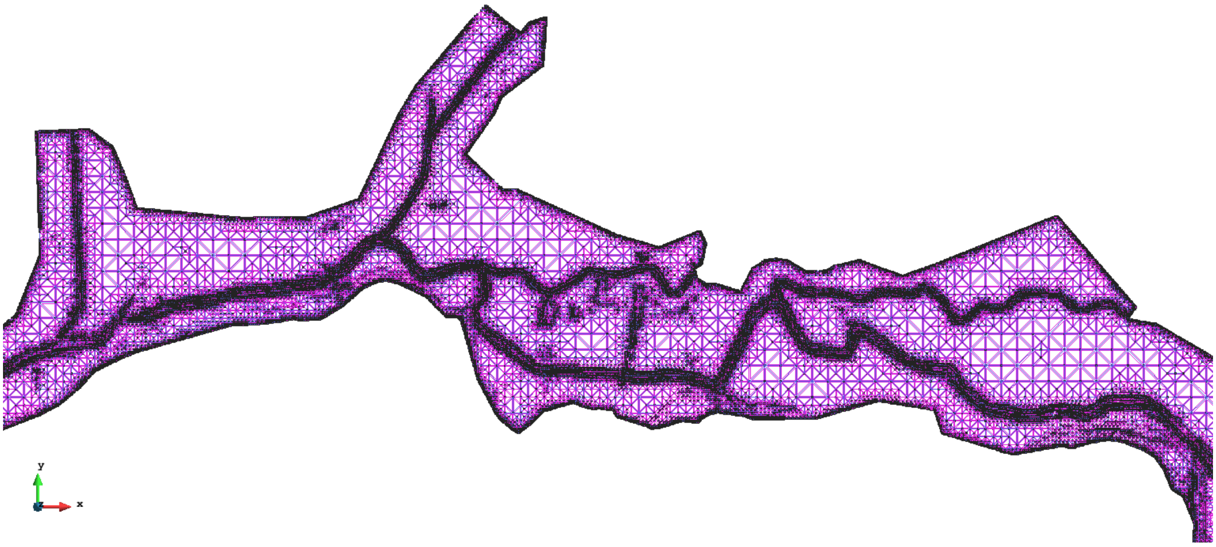

**Figure 16** A part of the mesh generated in Iber.

Lastly, the calculation parameters were set. The *Maximal simulation time* was set to 40 hours, since this was the time at which all hydrograph had ended.  For two of the simulations the *Result time interval* was set to 600 seconds. This generated a limitation and due to lack of data space the simulation stopped after 3 days. Then the two simulations had only completed 20 respective 23 hours of the 40 hours that were set as the maximal simulation time. Therefore the value for Result time interval was increased to 1,800 seconds, which alleviated the problem. That simulation completed 27 hours in 7 days, when the simulation was stopped manually. Even though the simulations were not finished completely, the result was sufficient since most of the hydrographs had ended after 20 hours, Figure 13.

Three different simulations were performed. Since the purpose with this thesis was to understand the dynamics of the rivers, the Rio Rocha and all its tributaries were given flow data for two of the simulations. For the third simulation only the Rio Rocha was assigned a hydrograph in order to simulate an extreme runoff with the contribution from only the upstream part of the main river.

**Table 4** The simulation performed in the project.

| Simulation | Flow data | Assigned rivers | Simulated flow time | Computational time |
|---|---|---|---|---|
| 1 | 10 year return period | All | 27 hours | 7 days |
| 2 | 20 year return period | All | 20 hours | 3 days |
| 3 | 20 year return period | Only Rio Rocha | 23 hours | 3 days |

## 3.4 Fieldwork

There was no data of water levels at different flows for calibrating or validating the model. However fieldwork was performed for some validation and to get an overview for the study area and the rivers.

During the project time in Bolivia only one day was spent in the field. It was attempted to visit the study area more times, but because of time limitation and for safety reasons that was not possible. The field study was done on the 6 of December 2013, in the beginning of the rain season. The previous week have had precipitation, which generated a higher water depth than average. Therefore it was possible to validate the initial condition of water depth for flooding simulation. During the fieldwork the water depth was estimated in three places along the river and historical water level mark on one bridge was measured.

## 3.5 Sensitivity analysis

A sensitivity analysis is the study how the uncertainty of the result can be apportioned to different sources of uncertainty in the model inputs. It also gives a better understanding of the relationship between input and output variables. In its simplest form it is performed by varying one variable at a time. For this thesis the values for the Manning roughness coefficient were varied. Three different simulations were performed, where the roughness values were changed ether to the minimum or maximum value for river respective grass (Dingman, 2002), Table 5.

**Table 5** Values of Manning's coefficient for the sensitivity analysis.

| | Original | Test 1 | Test 2 | Test 3 |
|---|---|---|---|---|
| River | 0.035 | 0.025 | 0.035 | 0.035 |
| Grass | 0.04 | 0.04 | 0.04 | 0.05 |
| Residential | 0.15 | 0.15 | 0.15 | 0.15 |

# 4. RESULTS

The result of the simulation is presented in three sections. Firstly the dynamics of the river identify flow path and thereby the zones that contribute to flooding. These zones where further investigated with the elevation data and presented in the next section. Thereafter the final result of each simulation and area affected by flooding is presented. Lastly the results from the fieldwork and sensitivity analysis are presented.

## 4.1 Dynamics of the rivers during flooding

To understand the dynamics of the river during flooding, simulated results from different simulated flow times are illustrated in this chapter. To make it easier to understand the result there is no background map in the figure and the time given in the figures is the simulated flow time.

### 4.1.1 Inflow from all rivers

The simulation when all rivers had an inflow with a 10 year return period shows that the main bank overflow occurs in the tributaries. It is possible to observe in an early state that the overflow water from river Pampa Mayu and Chijllawiri moves towards the boundary of the study area, which can be seen as a wall in the simulation and the water level begins to rise up against it. Later on the water also starts to overflow along some sites in the main river, as shown in Figure 18.

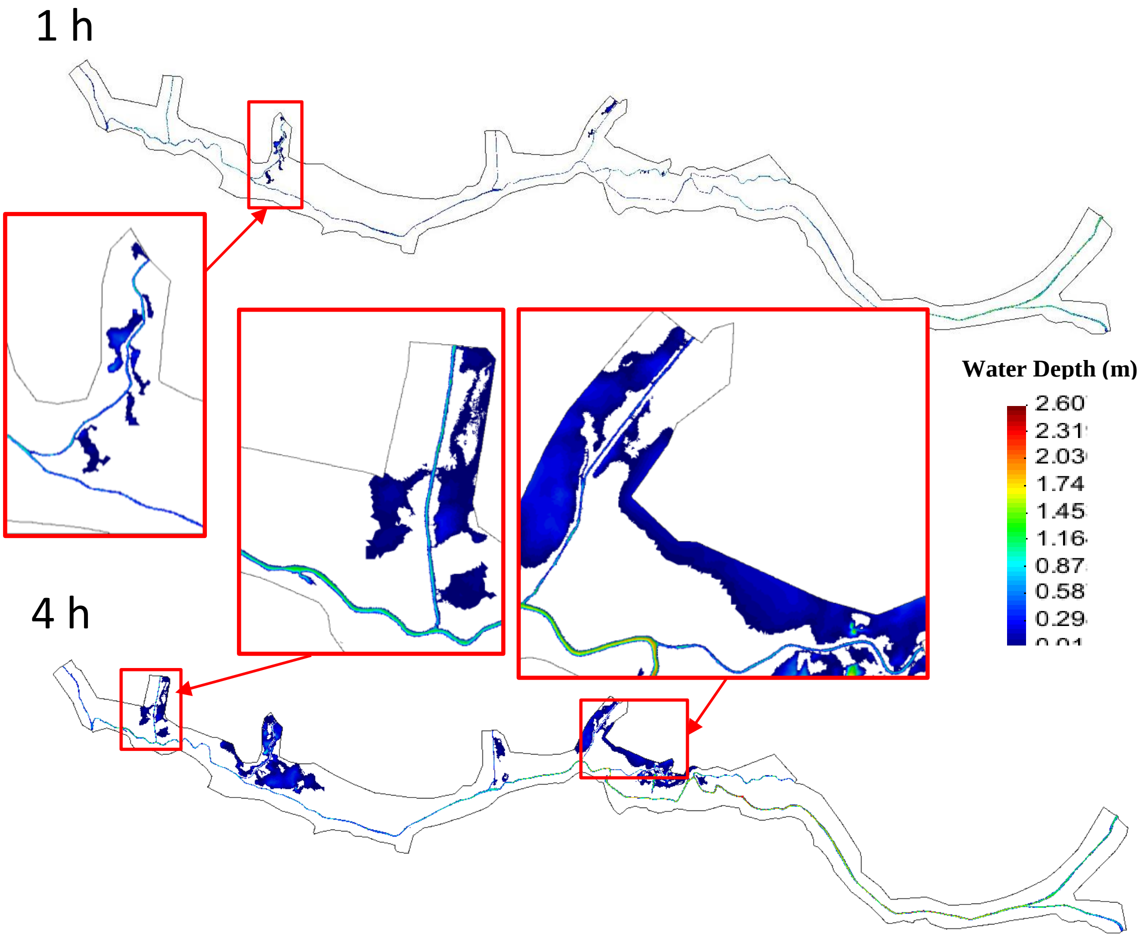

**Figure 17** Flooding at 1 and 4 hours after the onset of a flow with a return period of 10 years.

For the simulation when all rivers had an inflow with a 20 year return period the flooding begins from the inlet of the rivers. This could be an example of the mentioned problem with the assignment of the inlet to model. Thereafter flooding occurs in the same problematic zones as mentioned above, along the tributaries and some specific zones along the Rio Rocha. Already after 7 hours almost the entire study area is flooded.

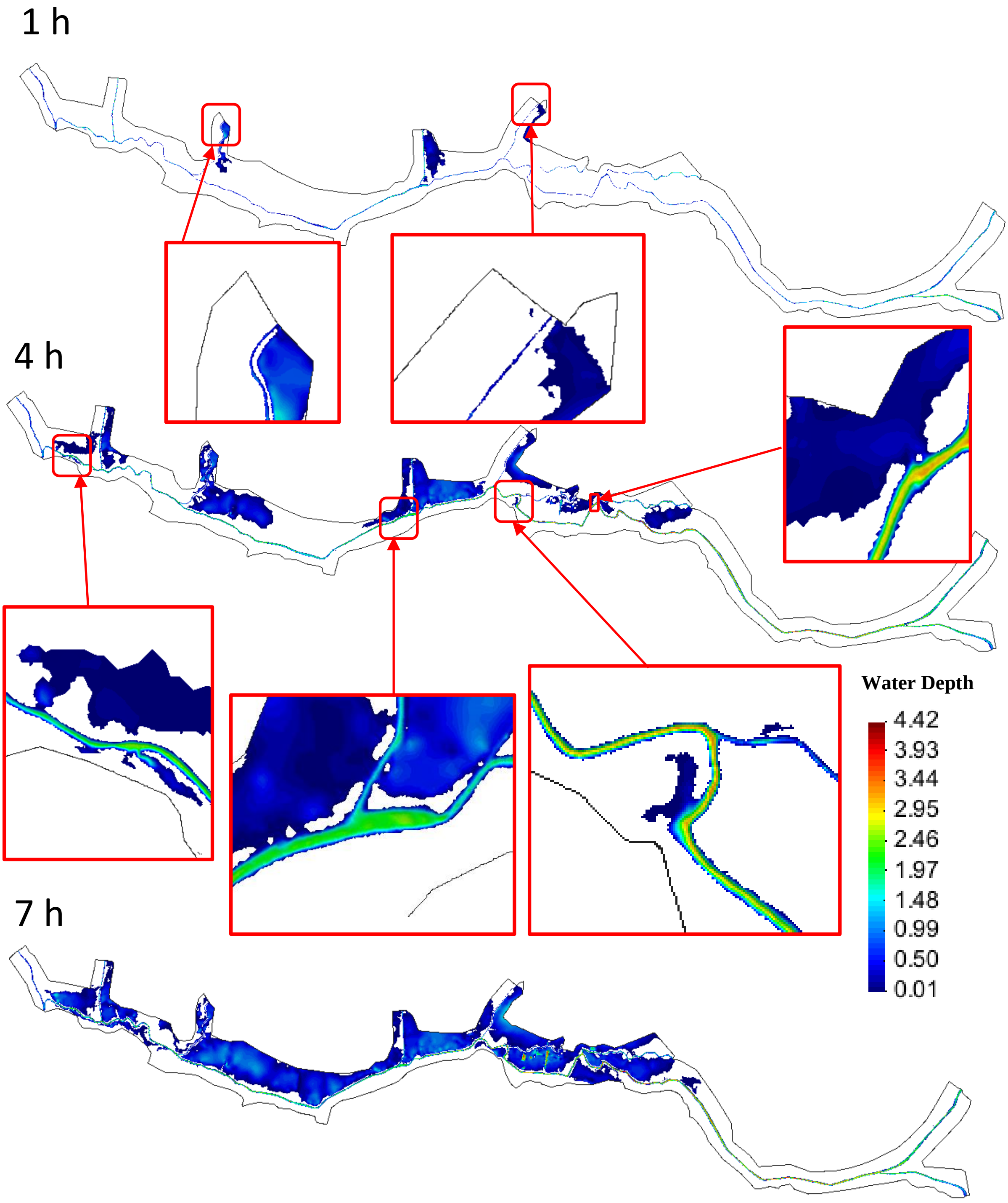

**Figure 18** Flooding at 1, 4 and 7 hours after the onset of a flow with a return period of 20 years.

### 4.1.2 Inflow only from the Rio Rocha

For one of the simulations only the main river, Rio Rocha had an inflow with a 20 year return period. The flooding begins after 4 hours along some sites in the Rio Rocha, the same as shown in Figure 18. After two more hours of simulation time, flooding takes place in the tributaries Canal Valverde, Pampa Mayu and Wiakulli. Shortly after also Tacata River starts to bank overflow and it is possible to observe that the water level has risen, in some places up to 2.5 meter, in all the tributaries except for the two farthest downstream, river Chulla and Khora. By analyzing the velocity in the same time step it is seen that bank overflow often occurs where the velocity is high. The velocity analysis also shows that the water rises up in the tributaries and causes flooding. For example is it possible to observe a higher velocity in Canal Valverde, since the water overflows the bank there, even though this tributary did not have any inflow in this simulation, Figure 19.

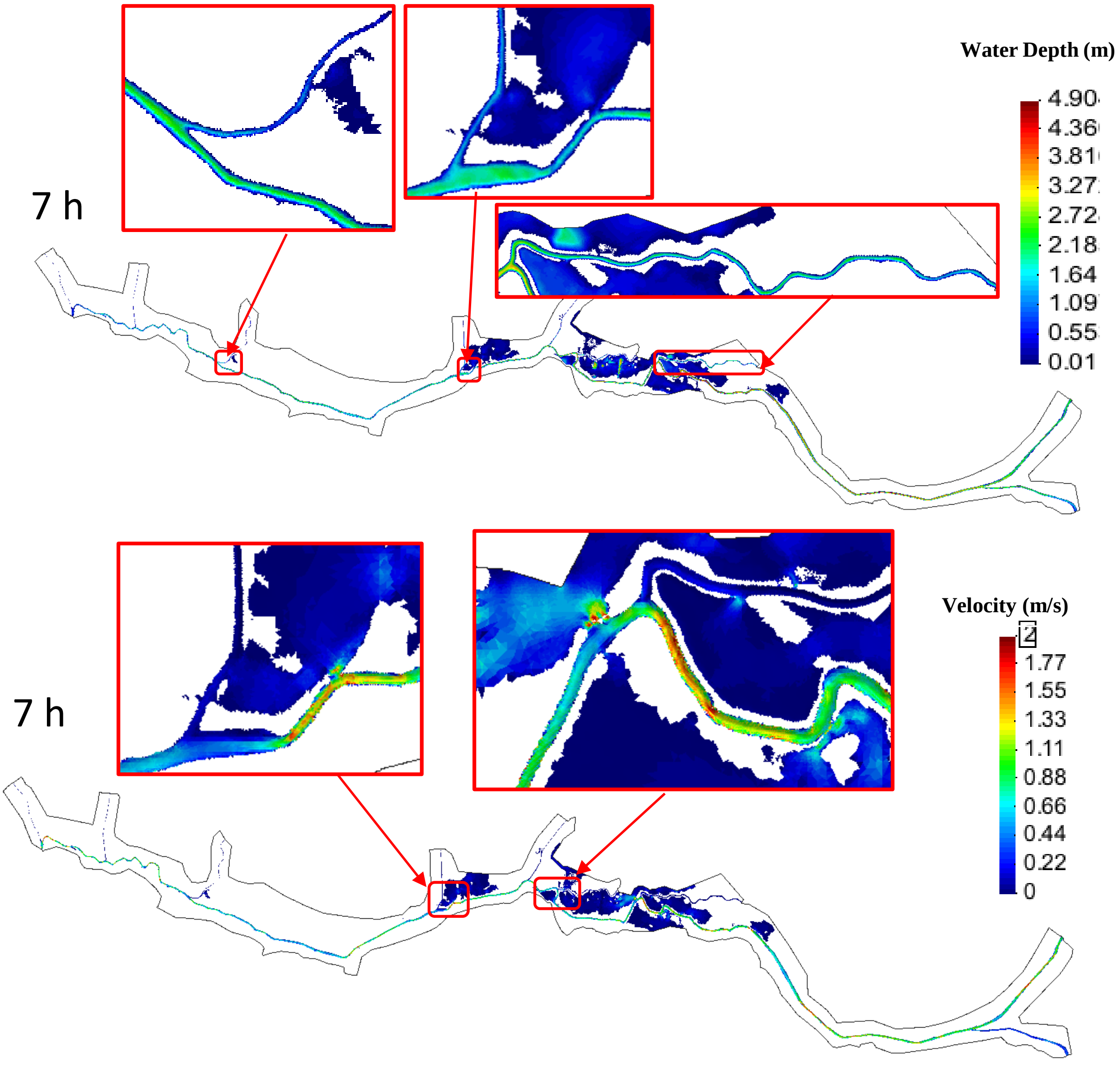

**Figure 19** The water level and velocity after 7 hours for a simulation when only Rio Rocha had an inflow with a 20 year return period.

## 4.2 Zones that contribute to flooding

Zones that contribute to flooding are defined as the riverbanks where overflow occurs. Those zones were investigated in detail in order to get a better understanding why bank overflow occurs. In this manner the results from the simulated floods were analyzed with the DEM and contour lines. This identified eleven specific zones where overbank flow occurred which are immersions or very flat without a clear riverbank. The four tributaries Chulla, Tacata, Waikuli and Pampa Mayu, also contribute to flooding. These zones were more diffuse and hard to specify and are marked with a red line in Figure 20. The more specific zones are marked with a red arrow in the same figure.

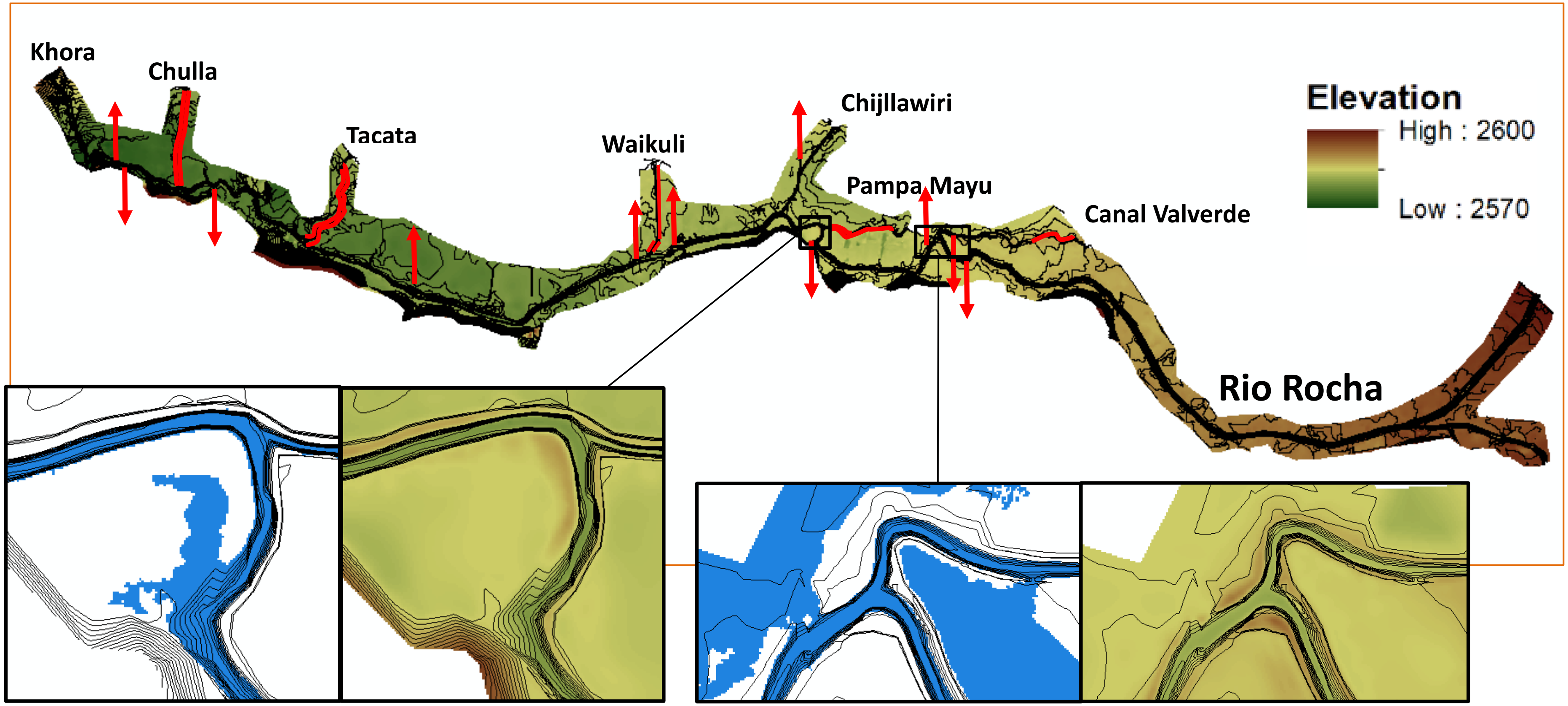

**Figure 20** The red lines and arrows indicate zones that contribute to flooding. The enlarged figures show some examples of the zones without a clear riverbank, which contribute to flooding. The black lines are height contours with 0.5 meters equidistance.

## 4.3 Areas affected by flooding

Almost the entire study area gets flooded in all three simulations. This occurs at an early time step and thereafter the water level continues to increase until the simulation ends. Most of the area affected is agricultural land, but also infrastructure and urbanized areas are flooded. Figure 22 shows the final result for a simulation when all rivers had an inflow with a 20 year return period. The affected urbanized area is marked with red squares and some of the squares are shown enlarged.

The result from Iber also provided water permanency. The areas where the flooded water remains for the longest time is agricultural land. In order to improve the understanding of this result, the simulated water levels were analyzed with the elevation data, Figure 21. This indicates that the agricultural land and the river are separated by a large riverbank and that the area is very flat.

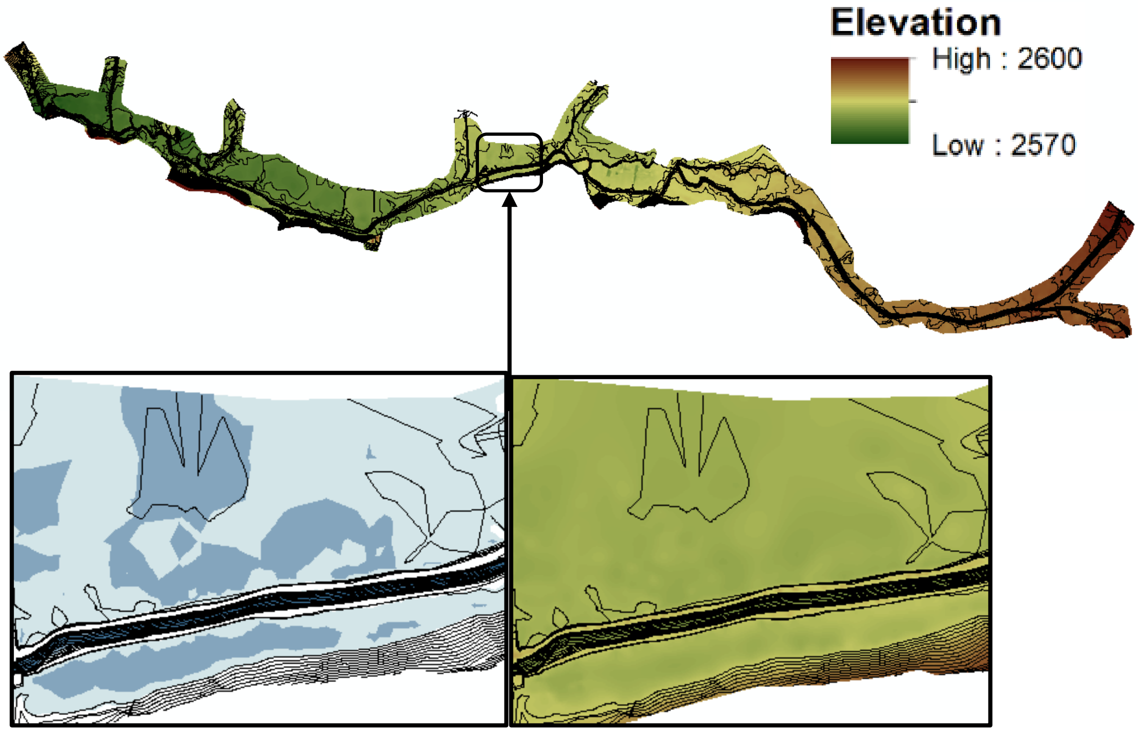

**Figure 21** The lower left figure shows flooded agricultural land and one next to it shows the DEM of the same area. The location of the area is marked with a square in the upper figure. The black lines are height contours with 0.5 meters equidistance.

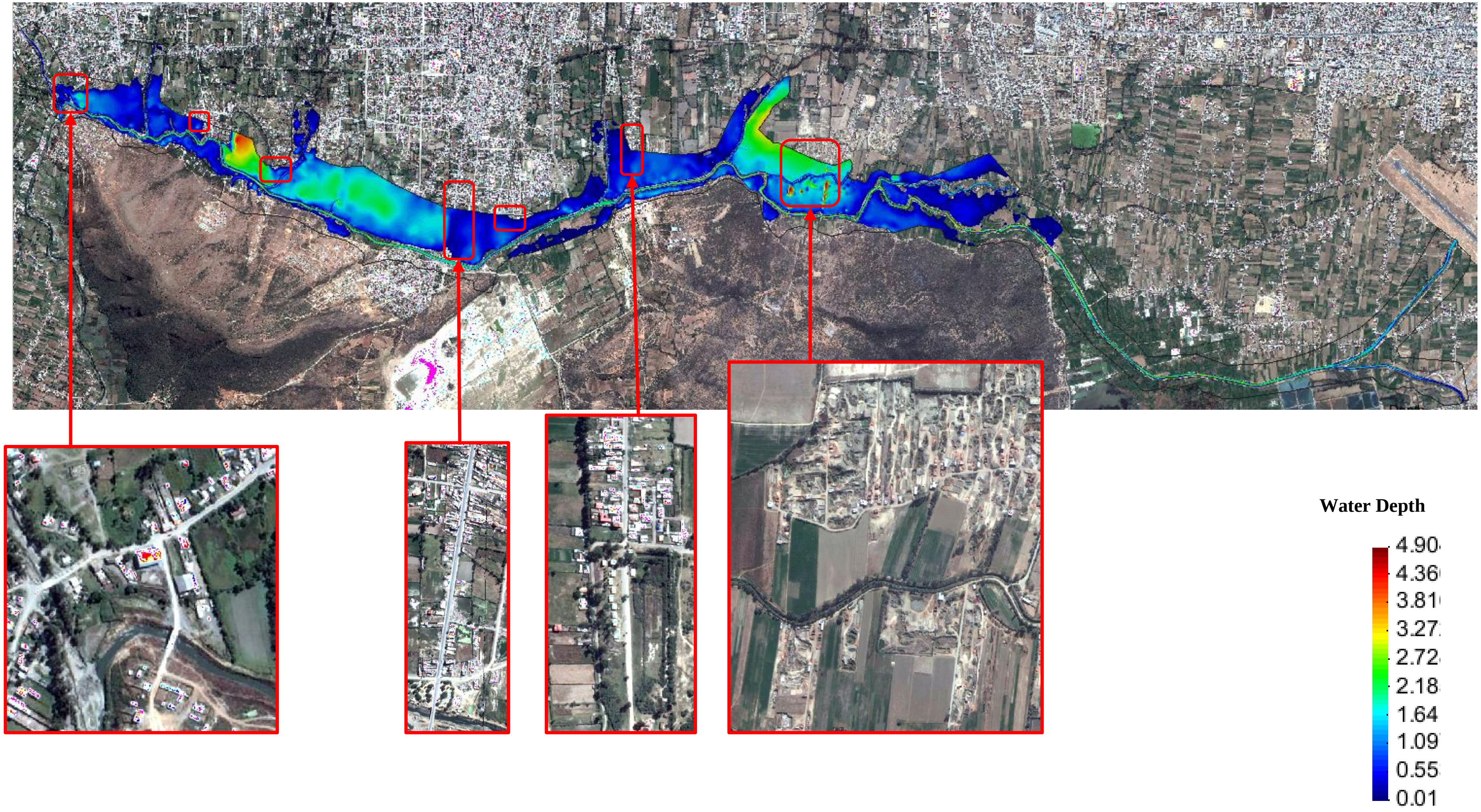

**Figure 22** Final result of water level for the simulation when all rivers had an inflow of 20 year return period. The residual areas affected by flooding are marked with a red square and some are shown in enlargement. Simulated flow time was 20 hours.

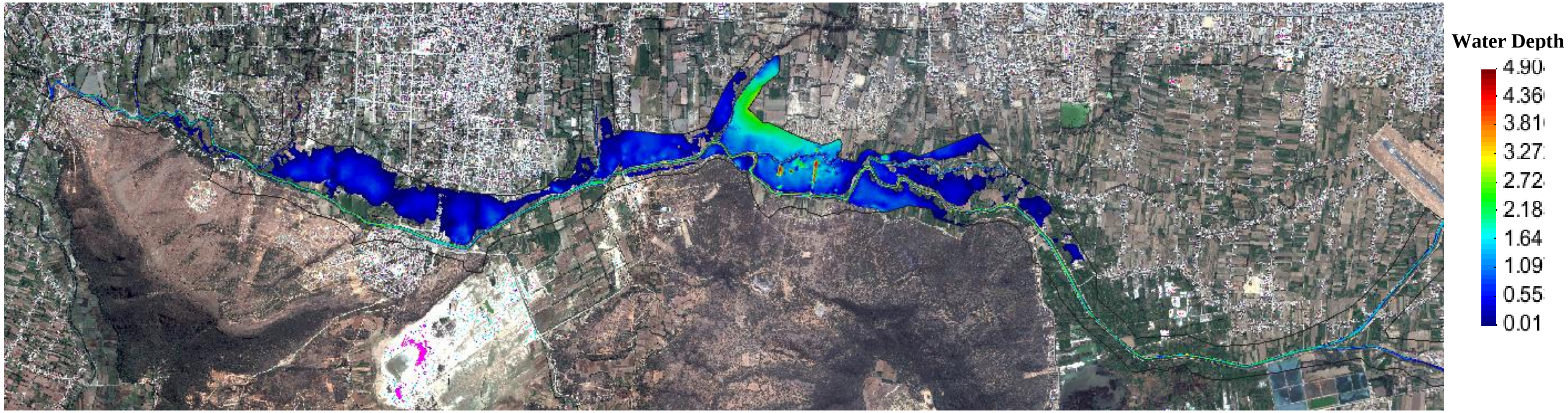

**Figure 23** Final result of the water level for the simulation when only Rio Rocha had an inflow of 20 year return period. Simulated flow time was 23 hours.

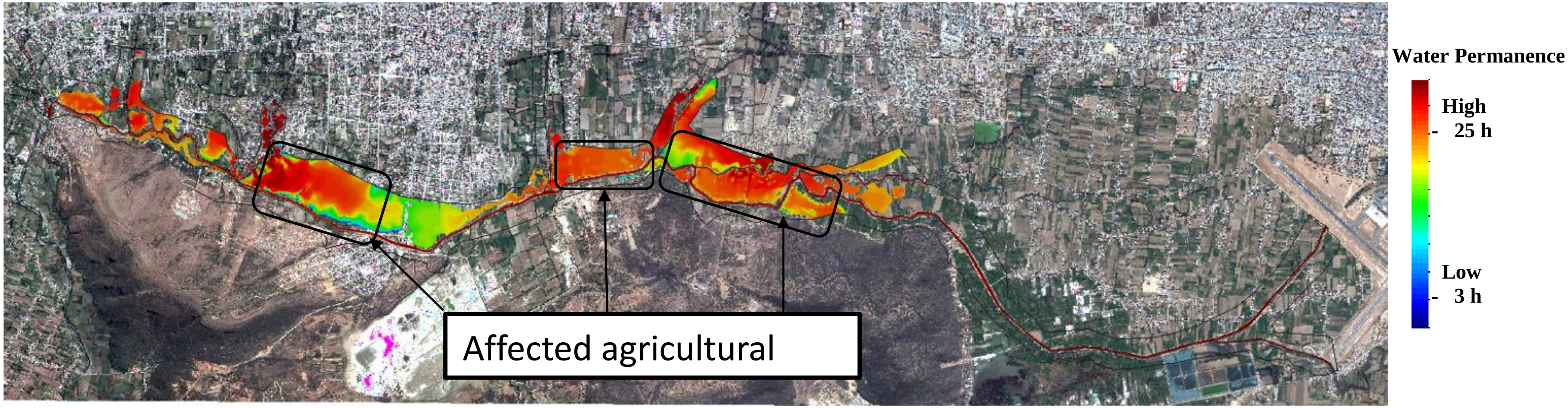

**Figure 24** The duration of the flooding for the simulation when all rivers had an inflow of 10 year return period. Simulated flow time was 27 hours.

## 4.4 Fieldwork

During the fieldwork the water depth in the Rio Rocha was estimated to 0.2 meters along two places near the bridge Cotapachi and at one place at bridge Siles. This value was thereafter used as the initial condition for water depth in the simulations.

On the bridge Cotapachi one historical mark was measured and thereafter compared with the simulated water level, Table 6.

**Table 6** Comparison of water level at the Cotapachi bride.

| | Maximal historical mark | Flow having a 10 year return period for all rivers | Flow having a 20 year return period for all rivers | Flow having a 20 year return period for only the Rio Rocha |
|---|---|---|---|---|
| Water level at the bridge Cotapachi (m) | 3.0 | 1.72 | 2.02 | 1.88 |

**Figure 25** Historical water level mark on the Cotapachi Bridge, measured to 3 meters.

## 4.5 Sensitivity analysis

The sensitivity analysis was performed by varying the values of Manning roughness coefficient in the simulation when all rivers had an inflow with a 10 year return period. As previously mentioned, the study area was divided into three roughness values; river (0.035), grass (0.04) and residential area (0.15), Figure 14.

The value for the river was varied to 0.025, which indicates a cleaner and straighter river and to 0.045, which indicates a river with more stones, weed and ineffective slopes (Dingman, 2002). Thereafter the simulations were compared by plotting how the water level changes with time at one specific site, Figure 26. The site was located in the Rio Rocha near the junction of the river Canal Valverde and was a local immersion with extreme water levels. The value of grass was varied to 0.05, the maximum value of field crops (Dingman, 2002), and compared to the original simulation, Figure 27. For grass the comparison site was located on the floodplain near the junction of the rivers Rio Rocha and Khora.

A higer value of Manning Roughness coefficient resulted in a slower increase, but higher maximum water levels, Figure 26 and 27. A lower value gave the opposite response, faster increase and lower maximum values, Figure 26. However the average change in water depth was only 0.1 meter for the river (Figure 26) and 0.01 meters for the floodplain (Figure 27).

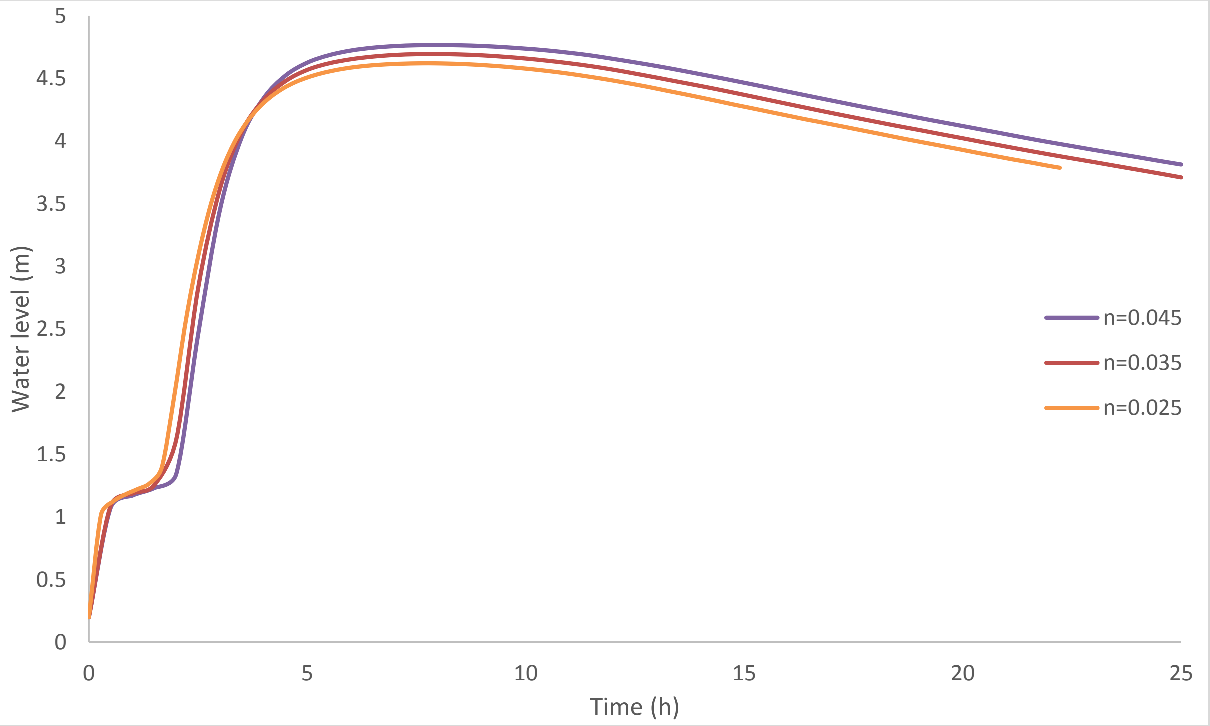

**Figure 26** Simulated water levels with different values of Manning's coefficient for the rivers. All rivers were assigned hydrographs of 10 year return period. The comparison site was located in Rio Rocha, GPS cord: 793770, 8072500.

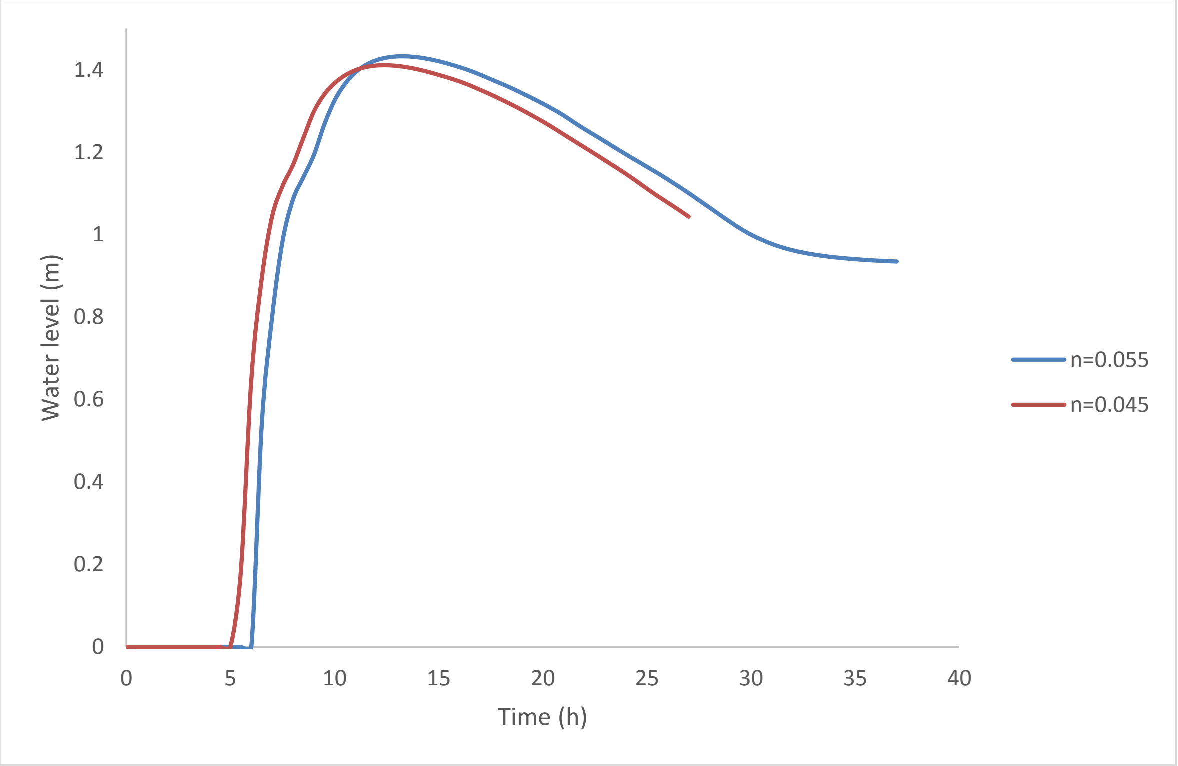

**Figure 27** Simulated water levels with different values of Manning's Coefficient for grass. All rivers were assigned hydrographs of 10 year return period. The comparison site were located on the floodplain, GPS cord: 789810, 8072500.

# 5. DISCUSSION

Hydraulic simulation using the two-dimensional model Iber gave a good understanding of the dynamics in the Rio Rocha during flooding. Flooding was shown to occur at eleven specific zones as well as in the tributaries Chulla, Tacata, Waikuli, Pampa Mayu and Canal Valverde. Most of the area affected by flooding is agricultural land, but infrastructure and urbanized areas were also at risk.

The simulated result shows that the main bank overflow occurred along the tributaries to the Rio Rocha. Even for the simulation with inflow only from the main river, the result showed that the water level increases within the tributaries and causes overbank flooding. This seems reasonable since the area near the junction of tributaries and the main river is flat, which causes the water to rise up within the tributaries. Bank overflow also occurs in the eleven specific zones identified as immersions or very flat without a clear riverbank. Moreover, the water velocity was often higher for those zones, hence the result could be realistic.

The result showed that water remains for a long time on the flooded agricultural land. This is confirmed by field studies and topography analysis, both showing that the river and agricultural land are at the same elevation level separated by a large riverbank. This indicates that when water floods agricultural land (mainly from overbank flooding of the tributaries) it may stay there for a long time, since there is no active driving force for flow towards the main river. This could cause significant damage to crop production since water saturated soil causes anoxic conditions and increases the risk of plant disease and insect infestation (Rosenzweiga & Tubiellob, 2002).

The result also clarifies the problematic situation with settlements along riverbanks. Even though a smaller part of the area affected by flooding is residential, urbanization is predicted to increase and therefore extra land may be required for developing new housing in the future.

A historical mark at a bridge was measured and compared to the simulated water levels at the same site. The simulated result is almost one meter below the historical mark, however there is a lot of uncertainties in this comparison. The maximum historical mark is from an unknown flow, and it is most likely to have originated from a larger flow than a flow of a 10 or 20 year return period. Another reason for discrepancy could be the difference in river bed elevation at the historical mark compared to that of the simulated values for the water level. This could have a significant impact but it is difficult to assess to what extent. The water level is also expected to rise near bridge pillars, one aspect that model Iber did not take into account. This does however, indicate that the simulated results are perhaps an underestimation, but for a full validation more historical marks need to be investigated, which was not possible in this thesis.

The sensitivity analysis showed a small change of the water level for the different values for the roughness coefficient (average change of 0.1 meter in the river). Since the purpose of the thesis was to understand the dynamics of the river and identify vulnerable areas, a small difference in the water level does not have a big impact on the result of the thesis. Consequently the uncertainties in Manning roughness coefficient is not believed to create a great uncertainty in the result. This finding was also seen by Harley, et al., (2007) who stated that for a two-dimensional hydraulic model the resolution of the mesh has a greater impact than the usual validation parameter, the roughness coefficient.

The resolution of the mesh was of high significance in this thesis, as has previously been demonstrated in several studies (Hardly, et al., 2004, Tayefi, et al., 2007, Schumann 2011). To get a fine mesh begins with the resolution of the elevation data. For this thesis, the elevation data was sufficient. But in order to utilize the high-resolution elevation data, different parameters had to be set carefully. Primarily the cell size when creating the DEM in ArcGIS and thereafter the minimum length of the triangles when creating the RTIN in Iber.

The main limitations and weakness in this thesis can be divided into three categories;

i) Elevation data: extent and quality
ii) Hydrological data: quality
iii) Technical model aspects: computational time and assigning inlets to the model

The narrow boundary of the model is the main limitation in this project. Due to the limited extent of the elevation data the model area was too small and the model water rose up against the boundary causing high water levels. These values should not be considered realistic. In reality the water would keep on spreading outside the model area and cause greater floods. This is confirmed by local authorities who acknowledge that flooding has indeed occurred outside the study area. Consequently, the narrow boundary limited the identification of areas affected by flooding and therefore it was not possible to fulfill a complete flood assessment.

As previously mentioned, the resolution of the mesh was sufficient but it was hard to evaluate the accuracy of the elevation data. Even if the data was only two years old, the quality was ambiguous in some areas. Such examples are found south of the tributary Pampa Mayu. There are two immersions where the water level rises up to 4.8 meters, which it is the highest water level outside the river. The aerial photo shows that the area is settled with houses and roads, but gives no specific explanation of these extreme values. In order to gain a better understanding I attempted to visit this area during the fieldwork, unfortunately with no success.

Another weakness in the project was the quality of the hydrological data. The hydrological data was taken from a recent study performed by Fuente & Batista (2014). Considering that the catchment was large, the method they chose to compute the flow is relatively simple and contains a lot of uncertainties. However a comparison to other studies within the same catchment (Haddad, et al., 2004, Romero & Urquieta, 2006), showed that the hydrological data from Fuente & Batista (2014) appeared to be larger and the quality is questionable. A great disadvantage is the lack of measured flow values, since it would give an indication on how reasonable the computed hydrographs were.

The long simulation time is a consequence of the high-resolution mesh. Schumann (2011) acknowledges that an increase in calculation cells will increase the computational time, but decrease the model errors. In this thesis it was highly important to achieve high accuracy of the mesh and the result, which lead to a long computational time. However, parameters were adjusted in order to decrease this time. The most important parameter to adjust was the maximum length of the triangles when creating the RTIN and thereafter the properties when creating the mesh. These changes gave some reduction in computational time. Several researches conclude that the only way to retain the efficiency of a two-dimensional model but still reduce the computational time, is to use a one-two-dimensional-linked model approach (Schumann 2011, Tayefi, et al., 2007)

The assignment of the inlet to the model was a crucial working process and difficult to perform. If the area for the inlets in the model was too wide, so that some of the water went directly to the floodplains, it would cause inaccuracy, such as unrealistic flooding and too little flow in the river during the simulation. This explains the initial flooding from the inlets to the model for the simulation when all rivers had an inflow with a 20 year return period. It should also be considered that another explanation for this flooding could be that the used hydrographs gave a flow that is larger than the maximum flow that could pass through the inlet. Since the problem occurred for the greater flow values, this could be a reasonable explanation. However flooding from the inlets should be considered as a problem with the modeling or data, not as a trustful result.

Three simulations were completed and in two of them all rivers had inflow to the model area. According to Romero & Urquieta (2006) rainfall rarely covers the entire valley, as these two simulations suggest. However, the purpose of this thesis was to understand the dynamics of the river and to analyze the zones that contribute to flooding, and this justifies why all rivers should have an inflow. The third simulation is more realistic since it represents an extreme runoff from the upstream part of the main river, even though this simulation showed that almost the entire study area got flooded. Therefore other more realistic simulations in which not all rivers have an inflow would most likely give similar result and give no further information. For the same reason it was not valuable to perform simulations with higher flow data, although hydrographs with 50 and 100 year return periods were available.

Several studies have performed hydraulic simulation with the one-dimensional model HEC-RAS in order to assess the flood risk in the Rio Rocha (Haddad, et al., 2004, Romero & Urquieta 2006, Fuente & Batista, 2014). In comparison with these studies, this thesis showed a larger flooding, with higher water levels and wider spread, especially for the two simulations with inflow from all rivers. As previously mentioned, the higher flow values and narrow boundary, could also explain the higher water levels predicted in this thesis.

As compared to the previous studies, the two-dimensional model Iber gave an improved knowledge of flooding in this area, primarily since it identifies flow paths and thereby identifies the zones that contribute to flooding. The result from Iber also provides more information for each simulation step, such as water velocity in different directions and water permanence, which is not possible to achieve from a one-dimensional model.

# 6. CONCLUSION

Flooding occurred along the tributaries; Chulla, Tacata, Waikuli and Pampa Mayu and at eleven other sites without a clear riverbank. Nine of the specific sites were located along the Rio Rocha and two were located in the tributaries Canal Valverde and Chijllawiri.

A major part of the area affected by flooding is agricultural land, which is often liable to damage due to the high water permanency. Even though a smaller part of the affected land is residential area, urbanization is predicted to increase and therefore more land may be settled in the near future.

The high resolution of the elevation points was of high relevance for this thesis since it enables the use of a two-dimensional hydraulic model.

This study showed a renewed approach for assessing the flood risk in the Rio Rocha using the two-dimensional hydraulic model, Iber. Iber is a convenient tool and could be used to aid decision processes to promote sustainable urbanization.

# 7. RECOMMENDATIONS

Field validation and further investigations should be performed for the zones that contribute to flooding, and appropriate measures taken to reduce flooding in the area.

To decrease the vulnerability of the inhabitants in the area it is of high relevance to develop relevant management strategies and set up suitable regulations.

The reliability of the hydrological data is questionable and continuous flow measurements should be taken to calibrate a hydrological model, which could compute more realistic flow data.

The narrow boundary of the model area was a great limitation in this project. Expansion of the elevation data is an important and a necessary improvement for flood assessment in this area.

The long computational time is another limitation. To decrease the problem without effecting the efficient result, a one-two-dimensional-linked model could be a possible approach for further studies within this study area.

The two-dimensional model Iber thoroughly describes the dynamics of the Rio Rocha during flooding. Therefore a further study could be to investigate the effectiveness of measures to decrease flooding.

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