University of Zurich[UZH]

Impact of climate change on water availability in Tropical Andean catchments: a case study in the Vilcanota catchment, Peru

GEO 511 Master's Thesis

Author
Selina Meier
15-701-055

Supervised by
Randy Muñoz Asmat

Faculty representative
Prof. Dr. Christian Huggel

26.01.2021
Department of Geography, University of Zurich

Abstract

Water scarcity is increasingly becoming a problem in many regions of the world. On the one hand, this can be attributed to changes in precipitation conditions due to climate change. On the other hand, this is also due to population growth and changes in consumer behaviour. In this study, an analysis is carried out for the highly glaciated Vilcanota River catchment (9808 km2 – 1.2% glacier area) in the Cusco region (Peru). Possible climatic and socioeconomic scenarios up to 2050 were developed including the interests from different water sectors, i.e. agriculture, domestic and energy. The analysis consists of the hydrological simulation at a monthly time step from September 2043 to August 2050 using a simple glacio-hydrological model. For historic conditions (1990 to 2006) a combination of gridded data (PISCO precipitation) and weather stations was used. Future scenario simulations were based on three different climate models for both RCP 2.6 and 8.5. Different glacier outlines were used to simulate changes in glacier surface through the time for both historic (from satellite data) and future (from existing literature) scenarios. Furthermore, future water demand simulations were based on the SSP1 and SSP3 scenarios. Results from all scenarios suggest an average monthly runoff of about 130 m^3/s for the Vilcanota catchment between 2043 and 2050. This represents a change of about +5% compared to the historical monthly runoff of about 123 m^3/s. The reason for the increase in runoff is related to the precipitation data from the selected climate models. However, an average monthly deficit of up to 50 m^3/s was estimated between April and November with a peak in September. The seasonal deficit is related to the seasonal change in precipitation, while the water demand seems to have a less important influence. Due to the great uncertainty of the modelling and changes in the socioeconomic situation, the data should be continuously updated. In order to construct a locally sustainable water management system, the modelling needs to be further downscaled to the different subcatchments in the Vilcanota catchment. To address the projected water deficit, a new dam could partially compensate for the decreasing storage capacity of the melting glaciers. However, the construction of the dam could meet resistance from the local population if they cannot be involved in the planning.

Zusammenfassung

Wasserknappheit wird in vielen Regionen der Welt zunehmend zu einem Problem. Dies ist zum einen auf veränderte Niederschlagsverhältnisse durch den Klimawandel zurückzuführen, zum anderen auf das Bevölkerungswachstum und ein verändertes Verbraucherverhalten. Diese Studie fokussiert auf das stark vergletscherte Vilcanota Einzugsgebiet (9808 km2 - 1,2% vergletschert) in der Region Cusco (Peru). Es wurden mögliche klimatische und sozioökonomische Szenarien bis 2050 entwickelt. Die Analyse bestand aus der hydrologischen Simulation in monatlichen Zeitschritten zwischen September 2043 und August 2050 unter Verwendung eines einfachen hydrologischen Modells. Für die historischen Bedingungen (1990 bis 2006) wurde eine Kombination aus gerasterten Daten (PISCO) und Wetterstationen verwendet. Die zukünftigen Simulationen basierten auf drei verschiedenen Klimamodellen für die beiden RCP 2.6 und 8.5. Für Veränderungen der Gletscheroberfläche im Laufe der Zeit wurden sowohl für historische (aus Satellitendaten) als auch für zukünftige (aus vorhandener Literatur) Szenarien modelliert. Die Simulationen des zukünftigen Wasserbedarfs basieren auf den Szenarien SSP1 und SSP3 und decken die Interssen der Sektoren Landwirtschaft, Haushalte und Energieproduktion ab. Die Ergebnisse aller Szenarien deuten auf einen durchschnittlichen monatlichen Abfluss von etwa 130 m^3/s zwischen 2043 und 2050 hin, etwa +5% im Vergleich zum historischen monatlichen Abfluss (123 m^3/s). Der Grund für den Anstieg des Abflusses hängt mit dem modellierten Niederschlag zusammen. Es wurde ein durchschnittliches monatliches Defizit von bis zu 50 m^3/s zwischen April und November mit einer Spitze im September prognostiziert. Das saisonale Defizit hängt mit der saisonalen Veränderung des Niederschlags zusammen, während der Wasserbedarf einen weniger wichtigen Einfluss zu haben scheint. Aufgrund der grossen Unsicherheit und möglichen Änderungen sollten die Daten kontinuierlich aktualisiert werden. Um ein lokal nachhaltiges Wassermanagementsystem aufzubauen, sollte die Modellierung auf die verschiedenen Teileinzugsgebiete skaliert werden. Um das mögliche Defizit zu verringern, könnte ein neuer Damm die abnehmende Speicherkapazität der schmelzenden Gletscher teilweise kompensieren.Falls die lokale Bevölkerung nicht ausreichend in den Plaungsprozess eingebunden wird, könnte der Bau jedoch auf Widerstand stossen.

Acknowledgements

I would like to thank all the following people for their support and flexibility in this turbulent time during my master thesis, especially my supervisors Randy Muñoz Asmat and Prof. Dr. Christian Huggel. Furthermore Prof. Dr. Jan Seibert for the short introduction into hydrological modelling, Dr. Javier Fluixá Sanmartín for the help in the field of RS MINERVE, Ing. Dax Warthon Riveros for the support on the part of EGEMSA and Elsbeth Mäder for the proofreading.

The greatest thanks go to the people who have accompanied and supported me all my life, even though they could not always fully comprehend what I was doing in the course of my life: my parents. Just as important are my sister's creative chaos and my brother, my calming influence. In addition, I would like to mention my boyfriend and my mother's partner, who helped out where help was needed. And Nightwish for the soundtrack.

Contents

List of Figures

List of Tables

Introduction

Water shapes the everyday life of every person, so everyone has their own idea of the term or water is so self-evident that no further thought is given to it. In view of climate change, however, water is no longer taken for granted everywhere. Two terms strongly shape this discussion: Drought and water scarcity. There are different definitions for both terms, depending on the area of application.In the case of drought, for example, a distinction can be made between a meteorological (focus on precipitation), a hydrological (focus on streamflow) and an agricultural drought (focus on soil moisture). All in all, drought is generally defined as a water shortage with reference to a specified need for water in a conceptual supply and demand relationship (Dracup et al. 1980). Water scarcity in turn can broadly be understood as the lack of access to adequate quantities of water for human and environmental uses. Water scarcity is frequently used by the media, in government reports, by nongovernmental organisations (NGOs), the international organisations such as the United Nations (UN) and the Organisation for Economic Co-operation and Development (OECD), as well as in academic literature, to highlight areas where water resources are under pressure. Still there is no consensus on how water scarcity should be defined or how it should be measured. One possible approach is the ‘water poverty index’, which takes into account (1) the level of access to water; (2) water quantity, quality, and variability; (3) water used for domestic, food and productive purposes; (4) capacity for water management; and, (5) environmental aspects (White 2014). With a very high confidence it can be said that the risk of water scarcity is a consequence of climate change (IPCC 2014). However, it is just as important to include power relations between water stakeholders, political priorities, and market-driven choices when creating different scenarios in the distribution of water (Drenkhan et al. 2015).

Various scenarios try to quantify the extent of the consequences of climate change. There are four different Representative Concentration Pathways (RCPs), which show up to 2100 different scenarios ranging from greenhouse gas emissions heat the top of the atmosphere up to 2.6 or 8.5 W/m^2 . From these scenarios, climate models calculate, on the one hand, climate change and, on the other hand, the emissions (including all feedback from the carbon cycle) required to cause these concentrations. These scenarios are named after the change in radiative forcing by 2100 compared to pre-industrial forcing (1850). RCP2.6, for example, stands for a radiative forcing by anthropogenic greenhouse gases of 2.6 W/m^2 in 2100. However, the negative anthropogenic forcing by aerosols and land use changes must still be deducted from the value 2.6 W/m^2. The main driver of the different scenarios is the development of the total population and the Gross Domestic Product (GDP) (Figure 1.1). Primary energy consumption in RCP8.5 is about twice as high as in RCP2.6, with coal providing the largest share of energy (Figure 1.2). The scenarios have different degrees of influence on climate-related changes, whereas RCP8.5 with the largest emissions is having the greatest impact on the climate (van Vuuren et al. 2011). The fifth report assumes that the surface temperature increases in all scenarios. It is likely that more and longer heat waves will be the consequences, and more extreme precipitation events will be more intense and more frequent in many regions. The precipitation events would also continue to warm up and acidify, and cause global mean sea level to rise (IPCC 2014). For the tropical Andes there is growing evidence, that glaciers will retreat due to rising temperature, which in turn results in a seasonal change in runoff (Magrin et al. 2014).

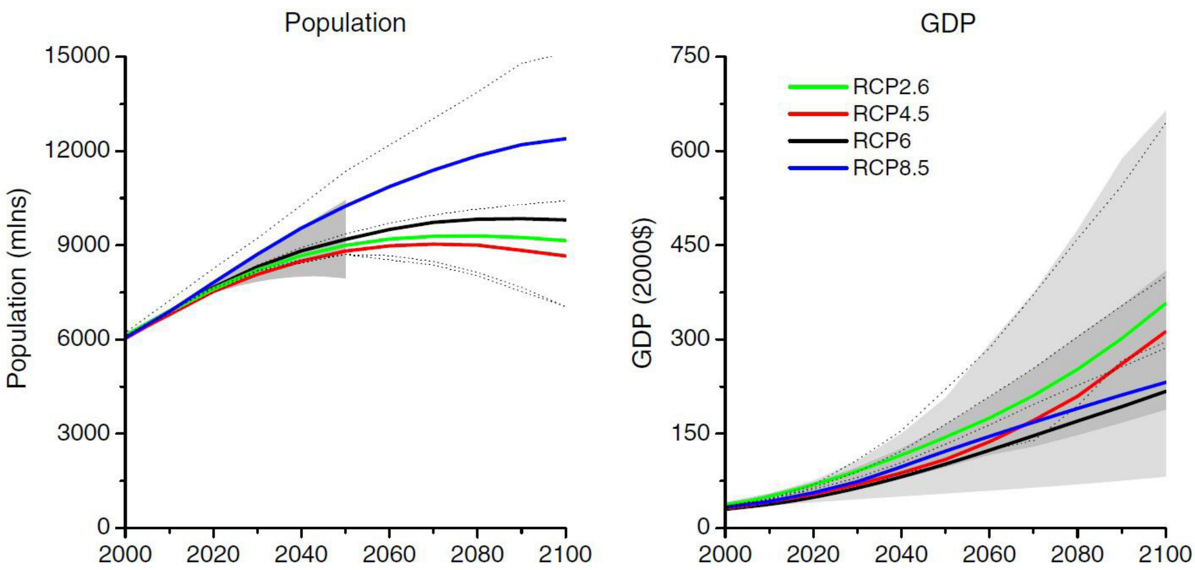

Figure 1.1.: *Global population and GDP of the different RCP scenarios (van Vuuren et al. 2011).*

Future greenhouse gas emissions are highly dependent on economic, social and political developments. However, the RCP scenarios are not very informative for socio-economic developments, which is why, for example, shared socioeconomic pathways (SSPs) are included in this study (van Vuuren & Carter 2014).

The SSP narratives were developed independently from the RCP scenarios and were designed to be complementary. Whereas the RCPs set of pathways model greenhouse gas concentrations and the effective warming that could occur by the end of the century, the SSP scenarios have the focus on which reductions in emissions will – or will not – be achieved. The SSP scenarios basically consist of two types of scenarios. The basic scenarios deal with adaptive strategies, i.e. possible social and economic developments without new climate policy measures over and above those already in place. The migration scenarios include a future active climate policy. Overall, the scenarios consist of five socio-economic development paths (SSP1 to SSP5), which can be seen in the overview of figure 1.3. Where SSP1 stands for a green and sustainable path

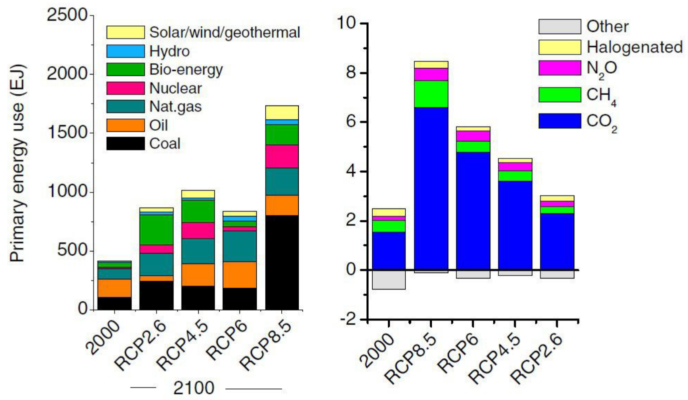

Figure 1.2.: *Global primary energy use and different gas emissions of the different RCP scenarios. (van Vuuren et al. 2011)*

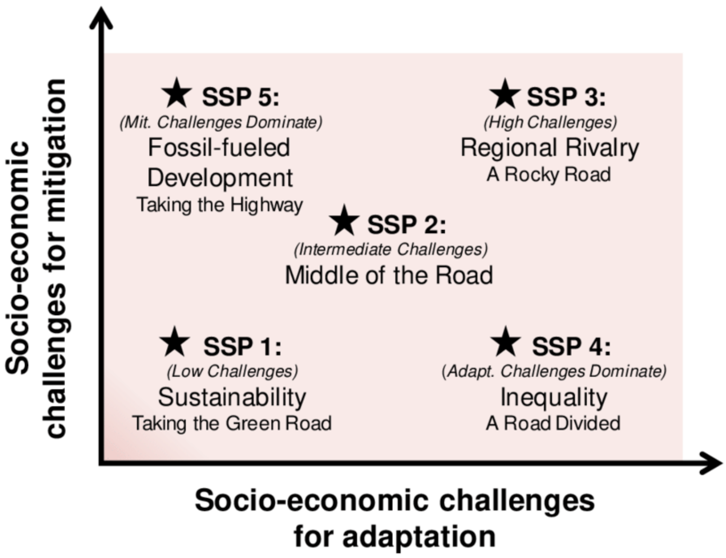

Figure 1.3.: *Overview of the different SSP scenarios. (O'Neill et al. 2017)*

and SSP2 for a middle path, SSP3 takes regional rivalries into account, SSP4 assumes that global inequalities will increase and SSP5 stands for fossil development (O'Neill et al. 2017). No literature about SSP scenarios for the region of the Andes or Peru could be found so far.

The effects of climate change can already be observed in various climatological but also socio-economical areas. It is likely that they will be exacerbated by climate change, or that new ones will emerge, thus creating new risks for the natural and human systems. Countries in South America meet 60% of their energy demand through hydropower, while at the same time land use change for food production and bioenergy exerts pressure on water resources (IPCC 2014). Vulnerability to water-related impacts of climate change is also high in rural areas, with climatic factors limiting economic options and driving out-migration (Water 2020). Regions in higher altitudes which have steep slopes, are particularly at risk for droughts. Other influencing factors are agricultural land use, soil properties, the presence of dams, access to water sources, population density and the Human Development Index. Drought is one of the biggest natural disasters in Southern Peru, where the Vilcanota catchment is located and causes enormous economic losses, mainly in the agricultural sector (Vega Jácome & Acuña Azarte 2016). Future scenarios can help to support decision makers in different fields of expertise in future projects. They help to estimate both the supply of water and demand for water.

The supply of water is strongly influenced by precipitation. As mentioned before, the precipitation regime will change due to climate change. Mountain areas provide a disproportionally high runoff in many parts of the world. One-third of the global lowland area equipped for irrigation is currently located in regions that both depend heavily on runoff contributions from mountains. The importance of ice melt contributions to total runoff decreases with increasing distance from glaciers (Viviroli et al. 2020). In the immediate vicinity, the glacial contribution shapes the runoff regime of a catchment area significantly. The reduction of the total glacier volume due to climate change will have an influence on the total runoff and the seasonality of the runoff. With the retreating of the glaciers, the storage capacity of water in the catchment will decrease and therefore, the contribution to runoff by melting water, especially in dry months and in the upstream catchment areas (Drenkhan et al. 2015, Kronenberg et al. 2016). The transition of the hydrological response from a glaciated to a deglaciated area starts with an increase in the runoff until a maximum is reached ('peak water'). Afterwards the runoff decreases and varies more in quantity (Drenkhan et al. 2015).

The demand for water is influenced by the size of the population living in the catchment or surroundings and their need for fresh water, agricultural goods and energy. Climate-induced changes in energy demand are expected, especially in tropical regions. Low- and middle-income countries in these regions are particularly affected, which allows the question if climate change could exacerbate energy poverty (De Cian & Sue Wing 2019). With regard to climate change, sustainable and resource-saving energy production is required. In this context, however, a dilemma arises with energy production by hydropower. Energy production through hydropower is highly dependent on the availability of water. The paradoxe concerning this situation is that sustainable energy supply can only be guaranteed if there are sufficient water reserves. However, climate change is endangering precisely this water availability, which would be important for sustainable energy supply, which in turn could reduce the effects of climate change (Johnson 2015). The security of fresh water, food and energy is essential for human well-being, poverty reduction and sustainable development. Due to the pressures of population growth and mobility, economic development, international trade, urbanisation, diversifying diets, cultural and technological changes as well as climate change, the demand for fresh water, food and energy will increase significantly over the next decades (Hoff 2011). The increased demand for water is also expected to lead to greater competition for the resource water (Water 2020).

In order to identify possible future conflicts, it is necessary to record the regional actors and their needs as well as the way water is handled as accurately as possible. Therefore, several scenarios regarding input and output of the water amount in a certain catchment are needed. The climate scenarios of RCP and socio-economic scenarios of SSP are usually available primarily globally or regionally (continents or countries), but not locally, where the actors have to deal with the consequences of climate change. Locally, conditions can vary greatly on a large scale, especially in mountainous areas (Huggel et al. 2015). Water demand estimates have already been made for the water demand in the Vilcanota-Urubamba catchement. However, these are only rough estimates for some regions in the catchment and only a single scenario exists

(Drenkhan et al. 2019), not several as in the SSP scenarios.

The aim of this study is to quantify the demand for water as accurately as possible in order to provide the actors with a basis for discussion to approach the future water scarcity with the best possible solutions, which include all actors on an equal footing. Therefore different hydrological scenarios for the future period 2025-2050 in the Vilcanota-Urubamba catchment will be made. The scenarios for water supply (RCPs) are developed separately from the socio-economic scenarios (SSP), which allows the different water supply and socio-economic scenarios to be combined. Based on these scenarios, various theses can be derived as to how the supply and distribution of water might look and where possible controversial issues could arise. The focus of this master's study is on the study area of the Vilcanota catchment, which is located in the departement of Cusco (Peru) and is described in more detail in the next chapter 2. For this study the following research questions were formulated:

1. How large is the current runoff in the Vilcanota catchment and how would it change in the future in a climate change context?
2. How large is the current demand for water from the various users in the Vilcanota catchment and how would it change in the future by 2050?
3. How large is the current energy demand in the Vilcanota catchment and how would it change in the future by 2050?
4. What could be the possible water management scenarios for electricity production and other water demands in the Vilcanota catchment?

Study Area

The focus of this study is on the Vilcanota catchment in the department of Cusco, Peru. Most of the literature is about Vilcanota-Urubamba catchment of which the Vilcanota catchment is part, in the study a distinction is made between the Upper and Lower Vilcanota catchment (see section 3.1) . The Lower Vilcanota catchment is the output of the whole Vilcanota catchment and it can be seen as the summation of the whole hydrological balance in the Vilcanota catchment. The Cusco region, where is the Vilcanota catchment (9,808 km^2) and study area located, is a social space that has historically attracted national and international tourism (Flores Moreno 2016). The rapidly growing population (INEIa 2017) and increasing energy demand (MEM 2014) have led to an increased development of hydroelectric power and mining in recent years (Flores Moreno 2016). The regional leading hydropower company EGEMSA (Empresa de Generación Eléctrica Machu Picchu, S.A.) must also deal with this problem. As a proposed solution, a new dam is to be built in one project (Castro Alvarez 2019). At the same time, there are still farming communities in this region that, in these areas and their goods, find conditions for the possibility of reproducing their way of life and their social identities. In recent years, both processes have led to an intensification of socio-ecological conflicts at regional and national level, which in the context of climate change could be further aggravated by the pressure of population and economic activities that impede the use and control of water of glacial origin (Flores Moreno 2016). As an example, the two provinces of Canchis and Urubamba with a high risk of droughts can be considered (Vega Jácome & Acuña Azarte 2016).

2.1. Climate and hydrology

Climate change primarily influences the following hydrological parameters: temperature and precipitation, which in turn influence evaporation and the glaciated area.

The current temperature per month is about 7.8°C in the dry season (June, July and August),

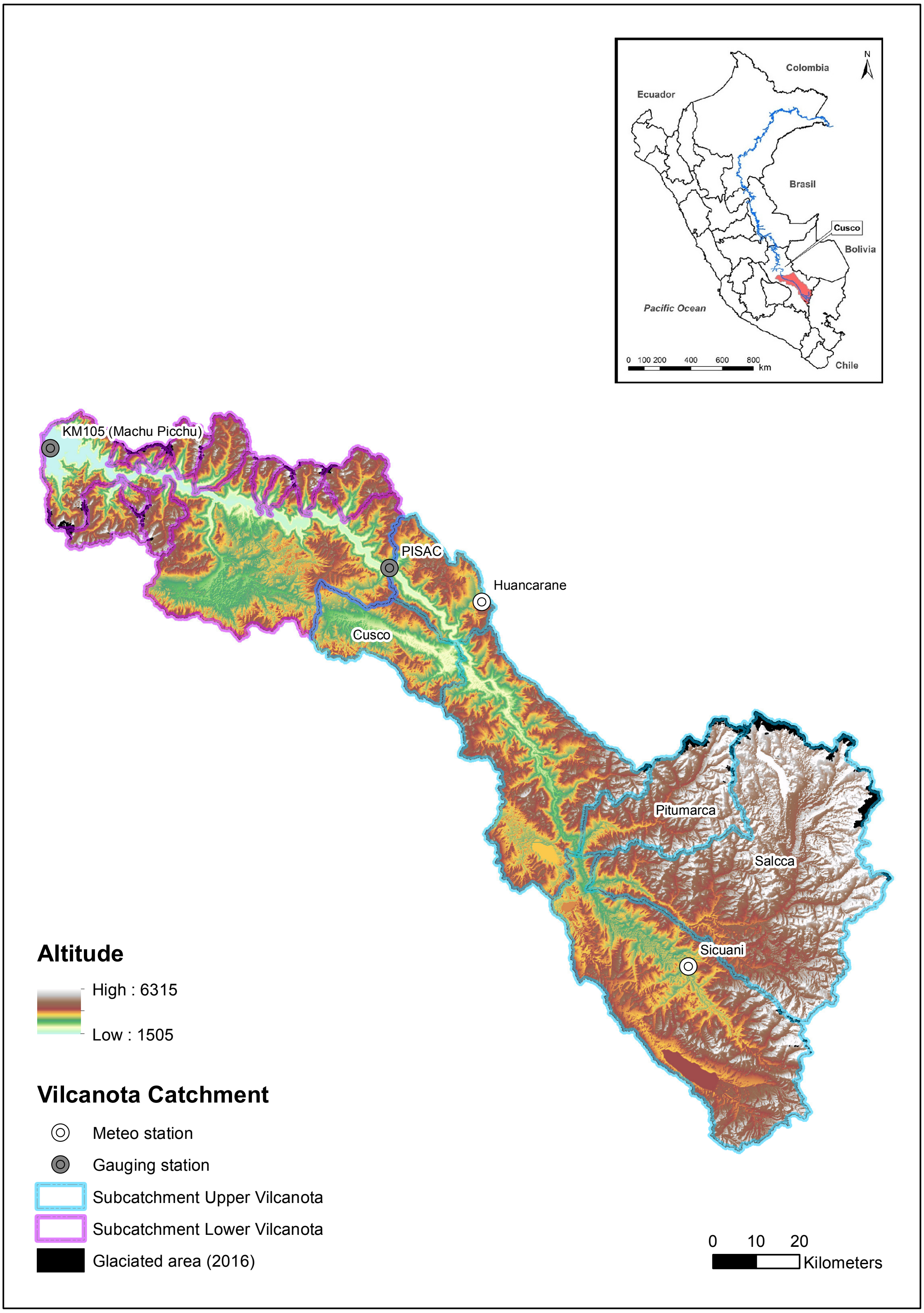

Figure 2.1.: *Overview map of the Vilcanota catchment with its subcatchments Lower and Upper Vilcanota. The gauging station KM105 can be located at Pisac. Source Inset Map: Drenkhan et al. (2019)*

10.5°C in the wet season (December, January and February) and averaged over the whole year about 9.6°C (Drenkhan et al. 2019). In the report of EGEMSA in the year 2003 an average annual temperature of 7.73°C was measured in Huancarane at 3910 m.a.s.l. (Figure 2.1) and a temperature gradient of 0.8°C per 100 meters was observed (Olivos Aranda 2003). In the tropical Andes an increase in temperature of approximately +0.5°C to +1.5°C in the RCP2.6 and approximately +4°C to +4.5°C in the RCP8.5 until 2100 was modeled in the regional IPCC report for Central and South America (Magrin et al. 2014).

The current precipitation per month is about 9.9 mm in the dry season (June, July and August), 138.5 mm in the wet season (December, January and February) and over the whole year averaged about 66.0 mm (Drenkhan et al. 2019). A rough graphical overview of the seasonal variation of Peru can be found in Figure 2.2. In Huancarane (Figure 2.1) an average annual precipitation of 859 mm was observed (Olivos Aranda 2003) In the tropical Andes a decrease in the precipitation of approximately -10% in the RCP2.6 and approximately -19% to -33% in the RCP8.5 until 2100 is expected (Neukom et al. 2015).

At the highest station in Sicuani (3550 m.a.s.l., Figure 2.1) there is an annual evaporation rate of 1277.1 mm. The trend of evaporation in relation altitude is a decrease for higher altitudes (Olivos Aranda 2003). It is expected that with increasing temperature, also the evaporation rate will increase. If evaporation increases, this would have a direct impact on runoff, as the snow would evaporate before it melts and feeds the runoff (Singh & Bengtsson 2005).

The current extent of glaciers of the year 2000, made by Global Land and Ice Measurements from Space (GLIMS) inventory, of Cordillera Vilcanota in the wet season, can be quantified with 374 km^2. It is expected that the glaciers in RCP2.6 will retreat to an area of 155 km^2 by the end of 2100. In RCP8.5, this would still be an area of 13 km^2. (Schauwecker et al. 2017) For the period until 2050 it is expected that the glaciated area substantially decreases between 40.7% (RCP 2.6) and 44.9% (RCP8.5) from current levels (2016). The glacier volume is expected to decrease between 41.6% (RCP 2.6) and 45.0% (RCP8.5). These assumptions are based on Freezing Level Heights (FLH) at 5276 m.a.s.l. for RCP 2.6 and 5307 m.a.s.l. for RCP8.5 until 2050. It is expected that the strongest glacier volume loss is reached before 2050 (Drenkhan et al. 2018).

Changes in precipitation, evaporation and glaciated areas lead to lower runoffs and different runoff peaks, which in turn has an impact on potable water use, hydropower production, agriculture, industries and ecosystems, with increasing impact on headwaters (Drenkhan et al. 2015, Kronenberg et al. 2016). The department of Cusco has the highest number of districts in Peru, after the department of Puno, with a very high risk of drought. Nationwide, the provinces of Canchis and Urubamba are considered as areas of high climatic danger and high vulnerability and will be subject to drastic changes in the future. The two provinces are very vulnerable to the risks caused by climate change and especially by the retreat of the glaciers (Flores Moreno 2016, Vega Jácome & Acuña Azarte 2016).

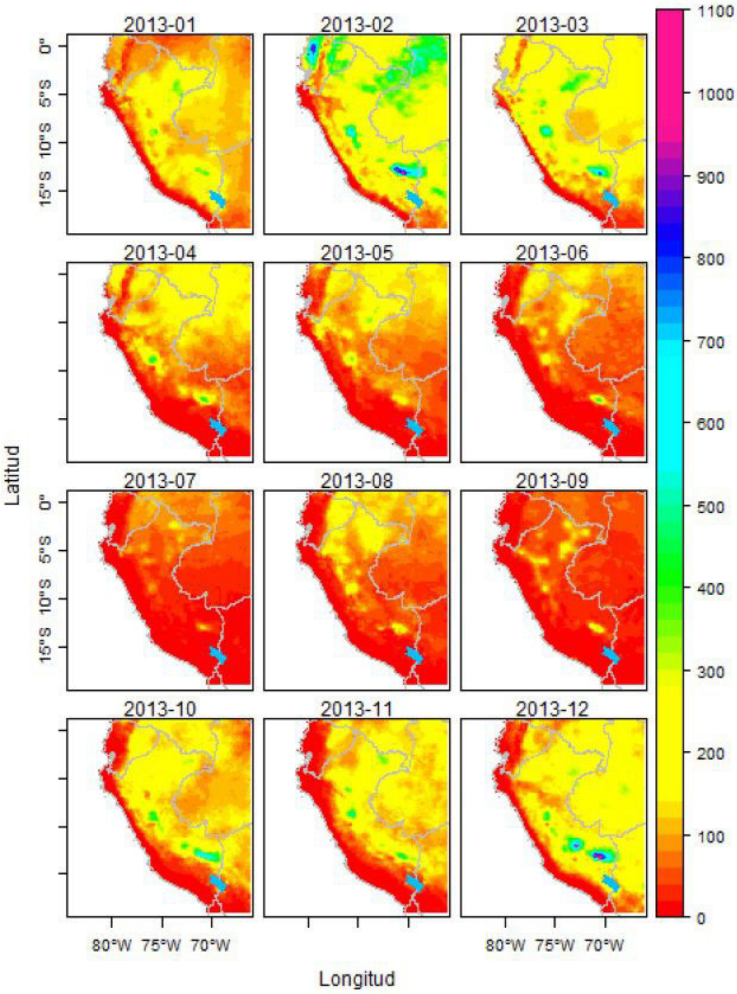

Figure 2.2.: *Maps of monthly precipitation grids [mm] for the months of 2013 of Peru (Díaz Pabló et al. 2015).*

2.2. Socio-economic situation

The Vilcanota-Urubamba catchment area is characterised by both urban and rural areas. There are therefore demands and dynamics which differ in these two areas. In terms of economic dynamism, Licona Licona et al. (2006) divide the department into different zones. A map with the overview of the following places and provinces can be found in the appendix (see Figure A.1).

High dynamic zone, medium dynamic zone and low dynamic zone. The city of Cusco is in the high dynamic zone which has high economic development and is a touristic hotspot. It therefore has a good infrastructure and is well served by a railway and an airport. The zone of high economic dynamism also has a high level of agricultural production. Therefore, parts of the lower La Convencion to Urubamba, Cusco, Calca and Canchis also belong to it. Moreover, the quality of life is highest in this zone. This zone is characterised by urban features and is highly dynamic in terms of the economic and population situation. Cusco, in particular, with its metropolitan characteristics and heart of national and international tourist attraction is the centre of development in the region. The Human Development Index (HDI) of 0.61 in the year 2012 is higher than in rural areas as for example in Paucartambo with an HDI of 0.18 and increases faster. Vulnerability to food insecurity is therefore significantly lower than in rural areas. Other parameters like educational level, access to health system and water are also higher in the high dynamic zone. In the medium dynamic zone there is mainly intensive, low-yield agriculture, mainly of traditional crops like potatoes, coffee or maize and more. This area is often difficult to access, and the agricultural units are smaller than 0.5 hectares. Here there are also some mining sites. The provinces concerned are Espinar, Quispicanchi and parts of Upper Anta and La Convencion and Calca. The population living in extreme poverty is concentrated in the low dynamic zone. They live mainly from small-scale or Andean agriculture, which is practised on marginal soils of the sierra and selva. The road infrastructure at departmental level is inadequate, as are services for the production and marketing of products. The lack of improvements in social indicators is leading to increasing inequality between the various zones. The provinces of Canas, Acomayo and Paucartambo are located in this zone (Licona Licona et al. 2006). This zone is an example of a rural lifestyle, which is dependent on agriculture and therefore needs the water from the glaciers for the irrigation system in order to maintain their way of life (Flores Moreno 2016). Most of the inhabitants do not want to give up agricultural activity, as it is intended to ensure the livelihood of future generations. At the same time, there is also a desire that the next generation should have more choices in how to make a living, including outside agriculture and livestock breeding. The agricultural activities should provide their children with education and professionalization and pay for access to industrial products. The money that the people receive through these economic activities is mainly invested into inputs and maintenance of productive activities or into school education and the professionalisation of their children. In addition, this money serves as a supplement to income and serves to reduce possible losses due to fluctuations in market prices, climate change or family emergencies (Castro Alvarez 2019).

In the regional competitiveness index, the department of Cusco is in the middle compared with the other departments of Peru in the period 2013-2014. This indicator is used at national level to measure the development of the economy and the estimation is made by the national competitiveness council. Progress has been made in the categories of institutionality, health and economic performance. However, issues such as corruption, lack of planning and management of investments are not reflected in the index (Licona Licona et al. 2006). In general, the population is aware of the drastic climate changes due to the rise in temperature, the increase in intensity and the alternation of seasons of frost, rain, thunderstorms (high basins), hail and snowfall, which affect the inhabitants economic activities. Some of them see a chance in the developments, others are afraid of it. Communication channels between public and private institutions and municipalities often have gaps, which results in limited access to information for residents. Consequently, there is a general distrust of outsiders, including non-local institutions. The missing information concerns technical assistance or training at community level that could help the population to better deal with the consequences of climate change. Inhabitants of the two catchment areas of Pitumarca and Salcca, for example, think that future water resource management projects should be financed by local or regional governments (Castro Alvarez 2019). In the department of Cusco about 92% of the water is used for irrigation and 6% are needed for the domestic demand. Others like livestock, as well as mining and other industries only have low demand on the water resources (Licona Licona et al. 2006). In future projects to organise and manage community water, the population prefers local and regional governments to private and external actors. The management of livestock water is organised at family level and not at municipal level. This in turn requires several different reservoirs in the upper catchment area (Castro Alvarez 2019).

Method

This section explains the data preparation and methods used to perform hydrological modelling for the historical (1990-2006) and the future period (2025-2050). Due to data availability, only the period from 2043 until 2050 could be used for further analysis. The input parameters can be divided into catchment parameter information, hydrological parameters and different water demands.

3.1. Definition of the catchment parameter

The catchment of Vilcanota can be divided in subcatchments of Upper Vilcanota from the headers up to the Pisac gauging station including Cusco city, and Lower Vilcanota between the gauging stations Pisac and Machu Picchu (km105). A map of the catchment parameter can be found in Figure 2.1. The stations are important as reference points for runoff in the historical modelling. In summary, the following subcatchments can be distinguished in the models: Lower Vilcanota (2,780 km^2), Upper Vilcanota (4,009 km^2), Salcca (2,334 km^2) and Pitumarca (685 km^2). This is a total area of 9,808 km^2 with 1.2% glaciated area, where the largest part of the glaciated area is in Salcca and Pitumarca. The dam of lake Sibinacocha is located in the catchment of Salcca. The data for the two catchments Salcca and Pitumarca were modelled separately and included into the calculations of Upper Vilcanota. The Upper Vilcanota discharge was included in the Lower Vilcanota model. Both the historical modelling and all scenarios were made separate for both subcatchments. The EGEMSA hydropower plant is located near the Machu Picchu monitoring point. Two other small power plants are located in the Upper Vilcanota subcatchment, as well as the city of Cusco.

3.2. Quantification of water availability

To model the water availability for the future, the current situation must first be known. Based on the current (historical) situation, scenarios for the future can be developed. For the climatically variable parameters, two different scenarios of RCP were applied on historical precipitation data. Scenarios from SSP were applied for parameters that are influenced by socio-economic factors, such as water demand. Since the RCP's and the SSPs scenarios are not linked to each other, it is suggested to combine the RCPs and the SSPs in a two-dimensional RCP/SSP matrix. These suggestions are based on an older version of socioeconomic development SRES (Special Report on Emission Scenarios, 2000) and combine for example the scenarios RCP8.5 and SSP3 but not RCP2.6 and SSP1 (van Vuuren & Carter 2014). In this study the combinations mentioned in the sentence before were selected to cover at least one best and one worst possible scenario. In total six different scenarios made of combinations with the two RCP scenarios 2.6 and 8.5 and the three SSP scenarios SSP1, SSP2 and SSP3 were used in this study. Further descriptions of the different RCP and SSP scenarios can be found in subsection 3.2.1 and subsection 3.2.2. These six scenarios were made for each of the two subcatchments Lower Vilcanota and Upper Vilcanota. The RCP scenarios were carried out with three different RCMs (Regional Climate Models) so that they are more widely supported. The RCM were bias-corrected with historical runoff data from the two gauging stations Pisac and Machu Picchu.

The hydrological balcance of the subcatchments Salcca and Pitumarca was modelled with RS Minerve, which is based on a semi-distributed approach with HBV (Bergström 1976). RS Minerve was developed by CREALP (Hernández et al. 2020) and simulates runoff in a system with open channel flow. It can be used to calculate several hydrological processes such as surface and subsurface runoff, snow and glacier melt. Furthermore, it is able to integrate regulated or non-regulated structures like reservoirs, gates, spillways, water intakes, turbines and pumps, tunnels, and many more. RS Minerve allows a more detailed modelling, which is useful for the complex area of Salcca and Pitumarca including the reservoir of Lake Sibinacocha. The resulted balance of Salcca and Pitumarca was implemented as supply to the model of Upper Vilcanota. The availability of water in the remaining Upper Vilcanota and Lower Vilcanota catchment was quantified with an extended version of the hydrological model developed by Témez (1977). Compared to RS Minerve, the extended version of Temez needs less input parameters. This model is a lumped model which simulates water supply from glaciers, groundwater and superficial runoff, while integrating water demand from agriculture and domestic use (Motschmann et al. 2020).

In the following paragraphs the modelling process with Temez, which was the main part of the study, will be explained in more detail. The modelling process in Temez was divided into the following time periods, with calibration and validation counting towards the historical period (1990-2006):

- Calibration period: between the years 1990-2000
- Validation period: between the years 2000-2006
- Future scenarios: between the years 2025-2050

The following parameters were adjusted in Temez, the respective sources of the parameters or the paragraphs with a more detailed description can be found in the brackets: Areas of the catchment (GIS layer), the lakes (ANA 2014), the reservoirs (only a value for Salcca, no values for the other catchments) and the glaciers (see subsection 3.2.1, paragraph *Glacial contribution*) were needed. Data for evaporation (Olivos Aranda 2003), evapotranspiration (ANA 2015) and kc value (Drenkhan et al. 2019) were included in the calculations. Different RCP scenarios were created for precipitation (see subsection 3.2.1, paragraph *Precipitation*) and glacial discharge (see subsection 3.2.1, paragraph *Glacial contribution*). Agricultural and domestic scenarios for water demand were created based on SSP scenarios and the environmental flow was estimated (see subsection 3.2.2, paragraphs *Agricultural demand* and *Domestic demand*). It was also necessary to adjust backflow of the agricultural and domestic demands and the evaporation through agriculture needed adjustments based on SSP scenarios (see subsection 3.2.2, paragraphs *Agricultural demand* and *Domestic demand*).

The demand for energy production through hydropower is not included in the Temez model and is compared with the total runoff from Temez in the results in subsection 4.3.3. The reason for this is that the hydroelectric power plants do not consume the water, but instead return the water to the river.

3.2.1. Water supply with hydroclimatic data

For the future modelling of precipitation and glacial contribution, it was decided to use the two extreme scenarios (RCP2.6 and RCP8.5) to have a full range of water supply. The supply is composed of the following parameters:

- Precipitation
- Evaporation
- Evapotranspiration
- Kc value
- Glacial contribution
- Supply of Salcca/Pitumarca (in Upper Vilcanota) and Upper Vilcanota (in Lower Vilcanota)

Precipitation

The PISCO ("Peruvian Interpolate data of the SENAMHI's Climatological and hydrological Observations") data set provides daily and monthly gridded data of precipitation and evapotranspiration for Peru. These climate maps have been developed with bivariate geostatistical techniques, which combined observed (in situ) hydroclimatic data and remote sensing satellite data or data from digital elevation models, depending on the hydroclimatic variable being studied (Aybar Camacho et al. 2017). To simulate the precipitation (historical period 1990-2006) of the Upper Vilcanota with RS Minerve, all the grid points from PISCO that cover the catchment were used. For the simulation of the precipitation (historical period 1990-2006) in the Lower Vilcanota catchment with Temez, the weighted average of all grid points and the percentage of grids that were not completely in the catchment was included in the precipitation amount of one grid cell.

To simulate the precipitation of the future scenarios (2025-2050), the historical data of PISCO was bias corrected with the historical data of the regional climate models (RCM) from CORDEX[1]. The three climate models are EARTH, MIROC5 and NCC. It is important to note that not all models cover the full period 2025-2050 and also differ among themselves. The modelled period was therefore set at 01.01.2041 to 31.12.2050. The program CMhyd provides a bias correction procedures with a transformation algorithm for adjusting climate model output. Altitude was not taken into account in the bias correction. This method can be used to minimise the discrepancy between observed and simulated climate variables on a daily time step. Thus, hydrological simulations driven by corrected simulated climate data are in reasonable agreement with the observed climate data. In contrast to the required monthly precipitation data in Temez, CMhyd only works with daily precipitation data. Therefore, the data were modelled in a daily rhythm and then aggregated again on a monthly basis. The selected bias-correction method was "Distribution mapping of precipitation and temperature", which has been designed to work with precipitation data (Rathjens et al. 2016). Using these three models, two RCP scenarios each (RCP2.6 and RCP8.5) were modelled. In total, these are six different future scenarios for precipitation.

Glacial contribution

The glacial contribution was estimated for the subcatchments Lower Vilcanota and Upper Vilcanota (without Salcca and Pitumarca). As the area of the glaciers in the catchment differs greatly between the historical and future period, the models were calculated using different areas. For the historical period,free multi-spectral optical satellite images were used from Landsat 5 (1984) and Landsat 7 (2004) missions, downloaded from the USGS Earth Explorer. Images with minimum cloud cover were selected within the dry season (Jun and July) to avoid temporal snow cover leading to confusion of glacier discrimination. Glacier outlines were obtained through a semi-automatic approach based on the Normalized Difference Snow Index (NDSI) (Hall & Riggs 2011). NDSI thresholds were iteratively assessed, ranging between 0.55 to 0.65. Glacier fragments were filtered using a minimum surface threshold of > 5000 m^2 (similar to the Peruvian Glacier Inventory from ANA (2014)) and then manually edited to merge or discard residual areas (such as water bodies or cast shadows). For the future period different areas for the RCP2.6 and RCP8.5 scenarios were used (Schauwecker et al. 2017). The glacial contribution can be estimated with the following equation (Duan et al. 2018):

$$Q_g[m/s] = Area_g[km^2] \times MF[mm/d] \tag{3.1}$$

The melting glacial area ($Area_g$) is obtained by multiplying the total glacial area, which is obtained from the satellite images, by the Ablation Area Ratio (AAR). The AAR indicates the fraction of the total glacial area that is in ablation. The AAR value (0.7) that was used is from the region of the Cordillera Blanca for tropical glaciers (Kaser & Georges 1997) and is assumed the same in all scenarios. In RCP2.6, an area of 9.6 km^2 was assumed for Lower Vilcanota and

[1]https://climate4impact.eu/impactportal/data/esgfsearch.jsp#project=CORDEX&

1.6 km^2 for Upper Vilcanota. In RCP8.5, 9 km^2 was used for Lower Vilcanota and there was no input area for Upper Vilcanota, as all the remaining glaciated area is in Salcca or Pitumarca and was calculated separately.

The melting factor (MF) indicates how much water comes out of a glacier in a day and includes variables like temperature, latent heat, evaporation. Generally, the maximum melting factor (9 mm/d) for tropical glaciers occurs in December and the minimum melting factor (7 mm/d) in June (Kronenberg et al. 2019). To calculate the melting factor values for each day of the year, the sinusoidal equation (Duan et al. 2018) was used and is assumed the same in all scenarios. Finally, the Temez model works at a monthly rate, so the daily runoff was averaged for each month.

Streamflow measurements

For the validation and calibration of the model, measured streamflow was used. For Lower Vilcanota the gauging station KM105 (data from EGEMSA) and for Upper Vilcanota the gauging station PISAC (data from SENHAMI) were used as reference (see Figure 2.1). For KM105, data was available for the period from 1965 to 2016 and for PISAC from 1965 to 2006. Since the Sibinacocha dam was built in 1994, it can be observed that the discharge at Pisac varies less and is less large in the dry season (see Figure 3.1). The discharge in KM105 has not changed much due to the construction of the dam.

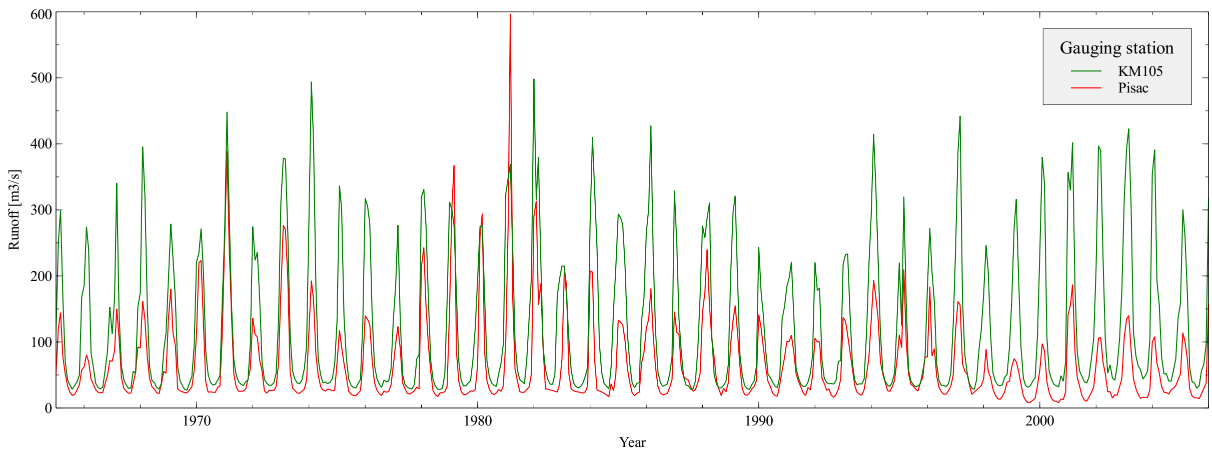

Figure 3.1.: *Runoff measurements for Pisac and KM105 between 1965 and 2006.*

3.2.2. Water demands with socioeconomic data

In the construction of the future socioeconomic scenarios three of the five scenarios were included. The SSP1, SSP2, SSP3 scenarios were selected because they balance each other out in the mitigation and adaptation challenges. The following paragraphs provide a short description of the used scenarios from Riahi et al. (2017):

SSP1: The world is gradually following a sustainable path. Global public goods are being taken seriously and preserved, and the limits of nature are being respected. Instead of economic growth, the focus is increasingly on human well-being. Income disparities between and within states are being reduced. Consumption is oriented towards low material and energy consumption. There is a relatively low growth of the population with a high leveled and well managed urbanization and a high growth per capita. The access to health facilities, water and sanitation is high. The development of technology is rapid and therefore, improvements in agricultural productivity and rapid diffusion of best practices can be expected. The land use is strongly regulated to avoid environmental tradeoffs.

SSP2: The past development continues into the future. Developments in income in the individual countries vary widely. There is a certain degree of cooperation between countries, but it is only marginally developed. Global population growth is moderate and will slow down in the second half of the century. Environmental systems are experiencing some deterioration. This is the middle-of-the-road scenario.

SSP3: A revival of nationalism and regional conflicts are pushing global issues into the background. Politics is increasingly focusing on national and regional security issues. Investment in education and technological development is declining. Inequalities are growing. In some regions there is severe environmental degradation. There is a high growth of the population with a low leveled and poorly managed urbanization and a slow growth per capita. The access to health facilities, water and sanitation is low. The development of technology is slow and therefore, little improvements in agricultural productivity and restricted trade can be expected. The land use has hardly any regulation and a continued deforestation due to competition over land and rapid expansion of agriculture will be the consequence.

In the modelling process for water demand in the agricultural and domestic sectors, SSP data sets[2] of cropland development in Latin America and population development in Peru were used (Riahi et al. 2017).

Agricultural demand

To get the total amount of water demand for each of the subcatchments Lower Vilcanota and Upper Vilcanota, the following equation was used:

$$Demand_{agr}[m^3/s] = Area_{irr}[m^2] \times Irrigation[m^3/s] \tag{3.2}$$

The irrigated area differs in the historical period and the different scenarios whereas the monthly irrigation demand is the same over both periods. The values per month were used for all the scenarios, because the possible technical advance of irrigation systems was included in the backflow. The monthly irrigation demand was quantified with the program of CROPWAT for different irrigation groupings (ANA 2015). All groupings which lay in the subcatchments Lower Vilcanota and Upper Vilcanota were summarized and divided by the actual irrigated area from the fourth National Agricultural Census (INEI 2013) in the subcatchments. For the entire Vilcanota catchment, an annual water withdrawal of 0.0158 hm^3/ha was calculated. A detailed overview of the individual months can be found in Table 3.1.

[2]https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=20

Table 3.1.: *Irrigation in the Vilcanota catchment per month* $[hm^3/ha]$.

Month	Irrigation per month $[hm^3/ha]$
January	0.0001
February	0.0004
March	0.0009
April	0.0016
May	0.0015
June	0.0015
July	0.0017
August	0.0022
September	0.0024
October	0.0020
November	0.0010
December	0.0005

For the historical period, a linear growth of agricultural area was assumed and the irrigated area was extended for the whole period 1990-2006 with a change rate of +0.19% per year (Drenkhan et al. 2019). The size of the irrigated area of the year 2012 in the historical modelling of the various districts is taken from the fourth National Agricultural Census (INEI 2013).

To quantify the approximate percentage of the irrigated area laid in the districts of the subcatchments Lower Vilcanota and Upper Vilcanota, global cropland data with a resolution of 30m recorded from satellites (USGS, 2015) was overlapped with the districts. It was assumed that the area classified as cultivated land above 4000 m.a.s.l. was misclassified. The area was therefore not included in the calculation. For the year 2012, an irrigated agricultural area of 50823 ha was assumed. Divided into the different subcatchments, these are 15,569 ha for Lower Vilcanota, 32,735 ha for Upper Vilcanota and 2,519 ha for Salcca and Pitumarca.

Unlike historical modelling, three different scenarios (SSP1, SSP2 and SSP3) of agricultural land growth have been developed for the future period. It should be noted that in SSP1 the agricultural area decreases from 2010 to 2030 and only increases from 2030 to 2050. In the other two scenarios, it increases constantly from 2010 to 2050. The adjusted agricultural area of the fourth National Agricultural Census (INEI 2013) is again used as reference area in the scenarios. The growth rates differ depending on the SSP scenario (Riahi et al. 2017). In a first attempt the growth rates, which are intended for the whole of Latin America, were adapted to the local historical development. The change rate created with the census data was about 4.9 times higher than the original from SSP. An overview of the different scenarios can be found in Table 3.4. However, it was found that this would represent unrealistically strong growth. Therefore, the change rate from Latin America was used to quantify the irrigated area. The

Table 3.2.: Weighting of the physical parameter altitude and slope to estimate the maximum of agricultural area.

Weighting	Altitude [m.a.s.l.]	Slope [°]
1	2000-2500	0-20
2	3000-3500	20-40
3	4000-4500	40-60
Excluded	4500 and higher	60 and steeper

Table 3.3.: Weighting of the vegetation coverage by the different SSP scenarios to estimate the maximum of agricultural area.

Weighting	SSP1	SSP2	SSP3
1	Coastal and Andean agriculture	Coastal and Andean agriculture	Coastal and Andean agriculture
2			Forests, wetlands, bushes, grassland
3		Forests, wetlands, bushes, grassland	
Excluded	Rest	Rest	Rest

demands for Lower Vilcanota were calculated with 6.4 [m^3/s] in SSP1, 7.3 [m^3/s] in SSP2 and 7.7 [m^3/s] in SSP3. For Upper Vilcanota the demands were calculated with 18 [m^3/s] in SSP1, 20 [m^3/s] in SSP2 and 21.1 [m^3/s] in SSP3.

The backflow of agricultural demand is represented through the efficiency of the irrigation system and the agricultural evaporation. The agricultural evaporation indicates the amount of water that evaporates from the irrigation system, because in an open channel the evaporation is higher than in a tube. The value of 50% backflow was estimated by an expert from the Peruvian Agricultural Agency. It was tried to quantify the development of the three different SSP scenarios, which resulted in an assumption of a value of 30% for the SSP1 scenario and 40% for the SSP2 scenario. For the SSP3 scenario, 50% is assumed as for the historical period because a small technical progress is assumed. For agricultural efficiency, the same value of 40% as in the historical period is also assumed for SSP3. The value improves to 50% in SSP2 and to 60% in SSP1.

An analysis of the maximum area, where agriculture could be possible in the future, was made as described in the following paragraph. A weighted overlay analysis with GIS was made for the three SSP scenarios (maps can be found in the Appendix A.2). Physical parameters like altitude and slope are the same for all the scenarios. An overview with the corresponding weighting points can be found in Table 3.2. For the altitude a maximum value of 4500 m.a.s.l.

Table 3.4.: *Difference of change rate, irrigated area and water demand of the different SSP scenarios with and without correction through historical change rate for the year 2050 in the catchment Vilcanota without Salcca and Pitumarca. In SSP1, the first change rate is for the period between 2010 and 2030, the second for the period between 2030 and 2050. The demand is averaged per month.*

	Without correction			With correction INEI		
	Change rate [%]	Area [ha]	Demand [m^3/s]	Change rate	Area [ha]	Demand [m^3/s]
SSP1	-0.003, +0.006	51,559	24	-0.016, +0.029	66,009	30.7
SSP2	+0.005	58,794	27.3	+0.026	125,762	58.5
SSP3	+0.007	62,004	28.8	+0.032	162,383	75.5

for cultures like barley and natural pastures can be expected (Gamarra Molina et al. 2011). Due to the hillside agriculture with terraced cultivation in the Andean culture, the cultivation of crops would be possible up to a slope of 60° (Blossiers Pinedo et al. 2000). The vegetation cover, which depends strongly on human behaviour, is different for the three scenarios and therefore, in the corresponding weighting points (see Table 3.3). Since deforestation is not an option in scenario SSP1, the forests as well as wetlands, bushes and grassland are not included in the overlay analysis. The following tables show the criteria with the corresponding weightings. In the total overlay with GIS, a minimum of 5 points (SSP1 and SSP2) and 4 points (SSP3) out of a maximum of 9 were required to assess the suitability of soils for agriculture. For the SSP3 scenario, fewer points were assumed, as strong technological progress is expected. Areas with a total score of 5 (or 4) to 6 points were given the rating "additionally possible". Areas with more than 6 points were given the rating "good".

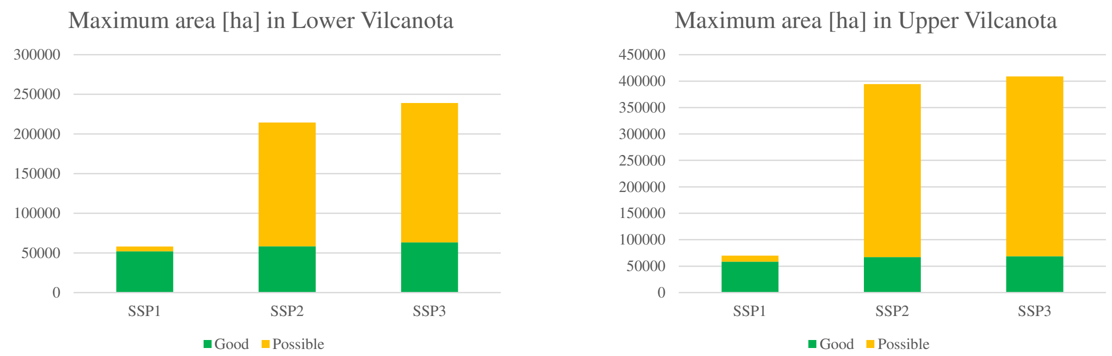

Figure 3.2.: *Maximum agricultural area in Lower and Upper Vilcanota, divided in the ratings good and possible aptitude.*

In total 110,678 ha were classified as good aptitude in the whole Vilcanota catchment, further 17,311 ha were classified as possible aptitude in SSP1. In the SSP2 scenario 125,432 ha were classified as good aptitude and further 483,635 ha were classified as possible aptitude. In the SSP3 scenario 131,724 ha were classified as good aptitude and further 516,211 ha were classified as possible aptitude. A big jump in the possible area can be noted especially between SSP1 and SSP2 in both subcatchments, the change in the good area is more constant (see Figure 3.2). Lower Vilcanota has a greater proportion of land with good aptitude for agriculture compared to the total area than Upper Vilcanota. This can be explained by the large plain in the catchment. In contrast, Upper Vilcanota has the greater proportion of possible aptitude, which is strongly dependent on technical progress. For a more detailed spatial distribution of the areas, maps of the different scenarios can be found in the appendix (see Figure A.2).

Domestic demand

In order to get an overview of household water use, the following parameters were considered necessary: Population, urbanization rate, access to water, consumption of water per person and the efficiency of the system.

Table 3.5.: *Parameter for the two reference years 1993 and 2016 totalled for the subcatchments Lower Vilcanota and Upper Vilcanota (without Salcca and Pitumarca).*

Year	1993	2016
Population in the catchment [pop]	501,850	685,455
Urban population [$\%$, pop_u]	46	60.7
Access to water [$\%$, pop_{acc}]	60	80
Urban consumpt./pers. [l/day, con_u]	150	150
Rural consumpt./pers. [l/day, con_r]	50	50
Urban system efficiency [$\%$, eff_u]	60	60
Rural system efficiency [$\%$, eff_r]	40	40

The population was surveyed at the provincial level for the years 1993, 2007 and 2017 (INEI 2008, INEIa 2017) and had to be adjusted in some cases to the subcatchments Lower Vilcanota and Upper Vilcanota, as these two perimeters do not correspond. To this end, GIS was used to estimate the percentage area of overlap between the province and the catchment and to determine the settlement centre of the province. If the settlement centre of the province was within the catchment, 20% was added to the percentage overlap. The provinces of Calcca and Canchis also had to be subdivided again so that the calculations for Lower Vilcanota and Upper Vilcanota could be carried out separately. No adjustments to the catchment were made for the urbanization rate, which is for the department of Cusco (INEIb 2017) and the percentage of people with access to water divided in urban and rural population for the provinces of the catchment (ANA 2019). For the access to water, only values for the year 2017 are available and on provincional level. Therefore, values on a provincional level are only available for the year 2017 for the other years an averaged value was used. The parameters for the consumption of water per person (in which a distinction was made between rural and urban households) as well as the urban and rural system efficiency were based on a reference value (Apaéstegui & Espinoza V. 2017), which was adjusted to the Cusco region.

For the reconstruction of the historical period 1990-2006, the years 1993 and 2016 were used as reference years, as most statistics could be found for these years. For the population, a linear growth between the reference years 1993 and 2017 as well as the extent to 1990 was assumed. The total values for both subcatchments Lower Vilcanota and Upper Vilcanota are in Table 3.5 (without Salcca and Pitumarca). For the year 2016 access to water is divided in provinces (with an avergage of 80%), because it is the only year with literature values (ANA 2019). For the year 1993 a linear decrease was assumed, similar to the developement of Peru (UNICEF & WHO 2020).

To estimate the domestic demand (see Equation 3.3), in a first step it was necessary to know the total population with access to water [pop_{acc}] which is calculated by multiplying the total population by the percentage with access to water.

$$Demand_{dom}[m^3/s] = (pop_{acc} \times pop_u \times con_u \times (1 + 1(1 - eff_u))) + ((pop_{acc} - pop_{acc} \times pop_u) \times con_r \times (1 + (1 - eff_r)) \tag{3.3}$$

With these input parameters a total demand of 0.078 $[m^3/s]$ for Lower Vilcanota and 0.384 $[m^3/s]$ for Upper Vilcanota in the year 1993 were calculated. For the year 2016 a total demand of 0.166 $[m^3/s]$ for Lower Vilcanota and 0.917 $[m^3/s]$ for Upper Vilcanota were calculated. Domestic demand has no monthly fluctuations but remains the same throughout the year. A linear increase of 3% per year was assumed between the two reference years.

To make the calculation of the future scenarios more efficient, only the demand per person was taken into account (in comparison to the historical period), which was then multiplied by the total population. The demand per person for the different scenarios was calculated the same way as in the historical period. For the demand per person the same equation was used like in the historical modelling (see Equation 3.3) and divided by the corresponding population size. A linear change was assumed for the demand per person in the years between 2025 and 2050. For both subcatchments the three scenarios of the SSPs were made for the population. These growth rates are not linked to the development of the demand per person. The population scenarios from the SSP are for Peru itself and had to be adjusted for the regional scaling of Cusco. The same rates of change were used as for the different SSPs (Riahi et al. 2017), but the reference value was the 2017 population (INEIa 2017). For estimating the population in the respective subcatchment, the same methodology was applied as in the historical period. Again, the subcatchments Salcca and Pitumarca were calculated separately. The changes of the other parameters were made as described in the following part and are listed in the Tables 3.6 for SSP1, 3.7 for SSP2 and 3.8 for SSP3.

Urbanisation and access to water have no increase during the years of the future period compared to historical scenario and the same parameters were used for the whole period. The urbanisation rate was taken from UNCTAD for Peru (UN 2019)and the reference value is from the year 2017 of the department Cusco (INEIb 2017). The percentage of people with access to water was compared with data from the World Bank (UNICEF & WHO 2020). The consumption per person in urban as well as in rural areas is constant. It is assumed that with future technical development and the threat of water scarcity, water will be used more efficiently despite more versatile applications. It is assumed that with future technical development and the threat of water scarcity, water will be used more efficiently despite more versatile applications. Indications of this can be seen in the development of per capita consumption in Switzerland, where consumption is falling (SVGW 2017). The efficiency of the systems in rural and urban areas was adjusted according to the technical advance in the SSP scenarios (Riahi et al. 2017). Due to slow technical development, efficiency improves by only 5 percentage points in SSP3, while it improves by 10 percentage points in SSP2 and 15 percentage points in SSP1.

The result of the domestic demand $[m^3/s]$ is a linear growth in demand per person between the two reference years 2025 and 2050, multiplied by the different population scenarios of SSP for the period 2025 to 2050. For domestic demand in Lower Vilcanota between 2025 and 2050, a range of 0.19 m^3/s and 0.17 m^3/s for SSP1, 0.18 m^3/s and 0.19 m^3/s for SSP2 and 0.19 m^3/s and 0.24 m^3/s for SSP3 was calculated. For Upper Vilcanota a range of 1.01 m^3/s and 0.84 m^3/s for SSP1, 0.99 m^3/s and 0.95 m^3/s for SSP2 and 1.01 m^3/s and 1.16 m^3/s for SSP3

Table 3.6.: *Parameters for the SSP1 scenario totalled for the subcatchments Lower Vilcanota and Upper Vilcanota without Salcca and Pitumarca (LV = Lower Vilcanota, UV = Upper Vilcanota).*

SSP1	2025	2050
Population in the catchment [pop]	LV: 111,342, UV: 605,630	LV: 102,951, UV: 559,991
Urban population [$\%$, pop_u]	67.4	67.4
Access to water [$\%$, pop_{acc}]	96	96
Urban consumpt./pers. [l/day, con_u]	150	150
Rural consumpt./pers. [l/day, con_r]	50	50
Urban system efficiency [$\%$, eff_u]	75	75
Rural system efficiency [$\%$, eff_r]	55	55

Table 3.7.: *Parameters for the SSP2 scenario totalled for the subcatchments Lower Vilcanota and Upper Vilcanota without Salcca and Pitumarca (LV = Lower Vilcanota, UV = Upper Vilcanota).*

SSP2	2025	2050
Population in the catchment [pop]	LV: 112,467, UV: 611,752	LV: 120,793, UV: 657,038
Urban population [$\%$, pop_u]	64.9	64.9
Access to water [$\%$, pop_{acc}]	91	91
Urban consumpt./pers. [l/day, con_u]	150	150
Rural consumpt./pers. [l/day, con_r]	50	50
Urban system efficiency [$\%$, eff_u]	70	70
Rural system efficiency [$\%$, eff_r]	50	50

Table 3.8.: *Parameters for the SSP3 scenario totalled for the subcatchments Lower Vilcanota and Upper Vilcanota without Salcca and Pitumarca (LV = Lower Vilcanota, UV = Upper Vilcanota).*

SSP3	2025	2050
Population in the catchment [pop]	LV: 118,165, UV: 642,746	LV: 150,626, UV: 819,312
Urban population [$\%$, pop_u]	62.3	62.3
Access to water [$\%$, pop_{acc}]	86	86
Urban consumpt./pers. [l/day, con_u]	150	150
Rural consumpt./pers. [l/day, con_r]	50	50
Urban system efficiency [$\%$, eff_u]	65	65
Rural system efficiency [$\%$, eff_r]	45	45

Table 3.9.: Required capacity of the installed and planned hydropower plants [m^3/s] .

Hydropower plant	Lower Vilcanota	Upper Vilcanota
Central Hidroelectrica Langui S.A		6.3
Electro Sureste S.A.A (planned)		0.7
Salcca Pucará (planned)		64
EGEMSA	30	
Primavera (planned)	62	
Machu Picchu III (planned)	10	

was calculated. In general, the demands for Upper Vilcanota are higher can be explained by the settlement of the city of Cusco and surroundings. In SSP1 the trends of both subcatchments are decreasing. In SSP2 a increasing demand in Lower Vilcanota can be observed and a decreasing trend in Upper Vilcanota. Increasing trends for both subcatchments can be seen in SSP3. The different starting values in 2025 can be explained by the reference value of population in the year 2017. The years between 2017 and 2025 were not used in the future scenarios.

The domestic backflow of 80% (Muñoz 2017) is the same in the historic scenario and in all the scenarios, because the technical advance is already included with the efficiency of the system in the demand of water per person.

Hydropower

Hydroelectric power plants are not equated with agricultural and household demand, as they do not take water from the river, but directly reintroduce it. Nevertheless, they are dependent on the river having a certain water level in order to fully utilise the capacity of the turbines. In addition to the existing required capacities of the power plants in the subcatchments (ANA 2015), the planned projects (Vergara Rojas 2017) for the future period until 2050 are included.

In the historical period the total required water capacity for the hydropower plants in the Lower Vilcanota subcatchment is 30 m^3/s and 7 m^3/s for the Upper Vilcanota subcatchment. In the future period the total required water capacity for the hydropower plants in the Lower Vilcanota subcatchment is 102 m^3/s and 64 m^3/s for the Upper Vilcanota subcatchment. It is noticeable that the planned projects rely on a higher runoff as the already installed ones, especially Salcca Pucará in Upper Vilcanota and Primavera in Lower Vilcanota (see Table 3.9).

Environmental flow

The environmental flow was only included in water demand for the future scenarios and is the same for all scenarios. However, a distinction is made between the two catchments Vilcanota and Upper Vilcanota. With the environmental flow a demand is included, which represents the required minimum of runoff that is necessary for sustainable ecological processes. It is assumed as a demand of 5% of total streamflow (Drenkhan et al. 2019). In this study, a total outflow was assumed, which was averaged over the measured period between 1990-2006. This should represent the normal conditions of the whole period. Furthermore, the environmental flow is the same throughout the year and has no monthly fluctuations.

3.3. Deficit

When talking about a deficit in this study, a hydrological drought (Dracup et al. 1980) is assumed. In addition to water supply (precipitation and glacial contribution) and water demands from the agricultural, domestic and environmental sectors, the demand from the energy sector for hydropower production was included in the scenarios of possible deficits. In energy production with a hydropower plant, for example, the runoff would not be large enough to use the turbines at full capacity. Energy production is included in the deficit because it relies on a certain amount of runoff and should be included in the distribution of water. In an equation, where the total demand ($Demands_{tot}$) includes the agricultural, domestic and ecological demands and the energy production is represented with $Demand_{prod}$ this looks like this:

$$Deficit[m^3/s] = Supply_{tot}[m^3/s] + Demands_{tot}[m^3/s] + Demand_{prod}[m^3/s] \tag{3.4}$$

In this study, a distinction is made between the terms balance and deficit. Balance refers to the outflow that includes the demand for hydropower production, as opposed to the total runoff. In the case of the deficit, only those months are considered that have a negative balance.

Results

4.1. Water supply

4.1.1. Precipitation

In general the majority of the models and scenarios show more annual precipitation in the period between 2025 and 2050 compared to the historical period as can be seen in table 4.1. All models show more annual precipitation in RCP8.5 as in RCP2.6 except NCC in the Upper Vilcanota. The positive trend until 2050 can be seen in data with and without bias correction (see graphs 4.1 and 4.2 and deviates from the literature precipitation values for this region. In the cited literature is showing a negative trend (Magrin et al. 2014, Neukom et al. 2015). The results of the models have a higher annual variation than recorded in the historical period.

The EARTH model differs from MIROC5 and NCC in several aspects. Compared to the historical period, it shows a significant maximum precipitation in October and November in an averaged year in the Lower Vilcanota. In the historical period, the maximum precipitation in the months of December, January and February is at the same time as the maximum precipitation of the MIROC5 and NCC models in the Lower Vilcanota. Furthermore, the precipitation trends between Lower and Upper Vilcanota are the furthest apart of the three models, with 41.4 percentage points in RCP2.6 and 45.2 percentage points in RCP8.5 (see table 4.1). This difference can be assumed to be too large, as the geographical distance between the two catchments is relatively small. Due to these differences, EARTH was omitted from the further modelling of runoff and deficit.

Averaged over both RCP scenarios and the models MIROC5 and NCC a monthly precipitation of 65 mm (change -0.3%) for Lower Vilcanota and 64 mm (change of 13.6%) for Upper Vilcanota is expected. The two subcatchments thus equalise in the amount of monthly precipitation. The MIROC5 and NCC models differ in terms of monthly precipitation, with MIROC5 gen-

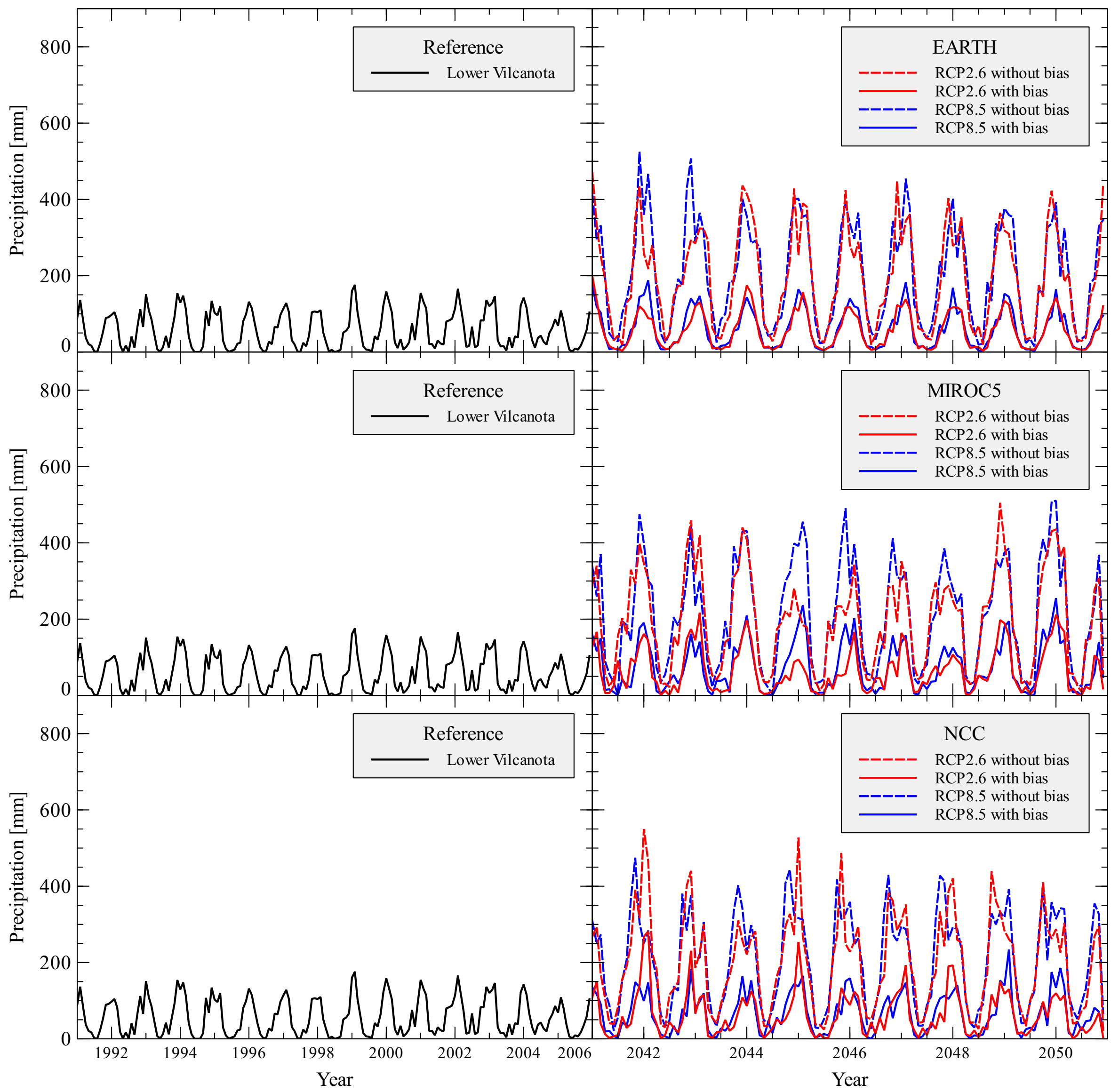

Figure 4.1.: *Comparison of the models with and without bias correction in the Lower Vilcanota and observed data on the left.*

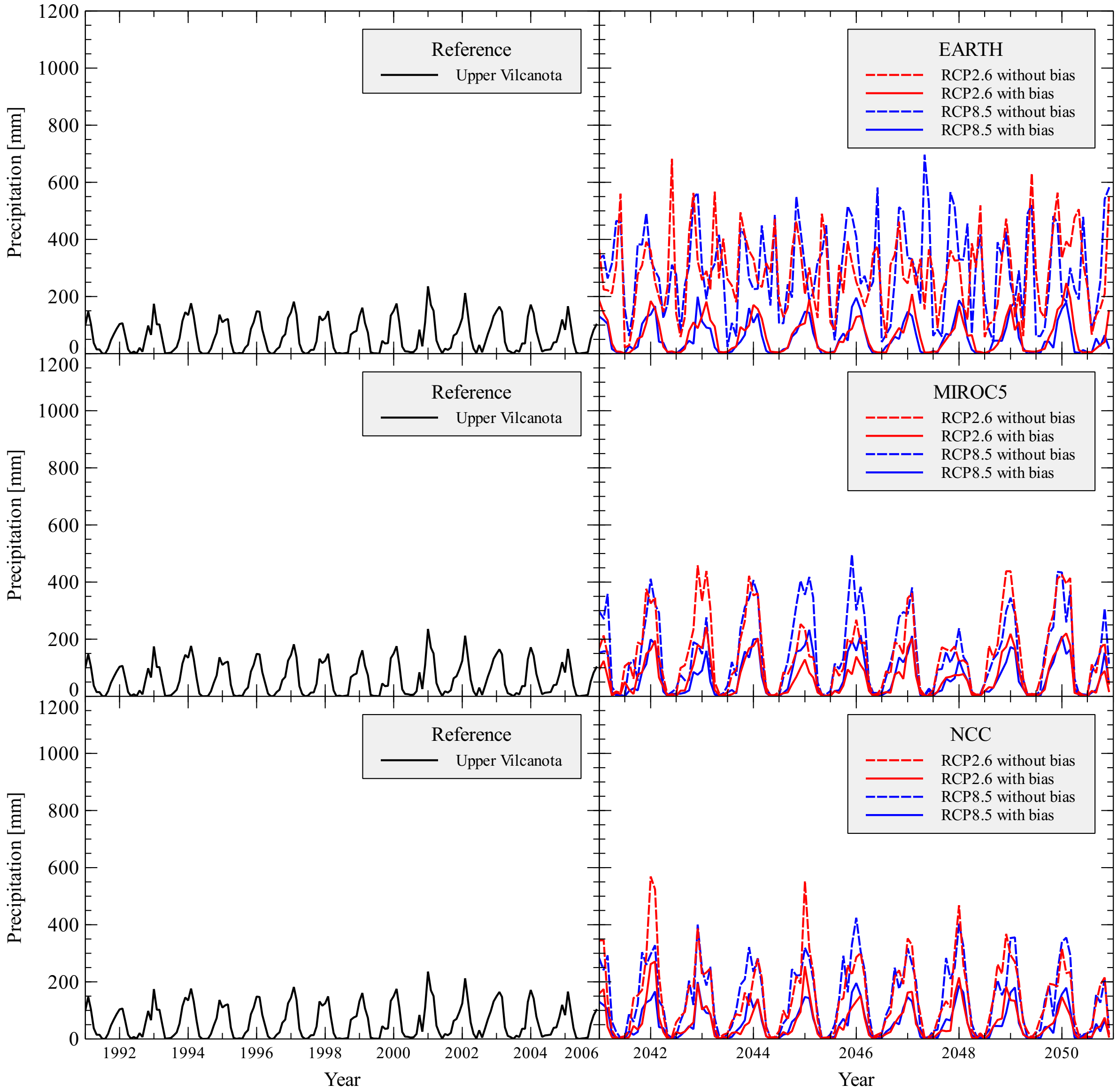

Figure 4.2.: *Comparison of the models with and without bias correction in the Upper Vilcanota and observed data on the left.*

Table 4.1.: Monthly precipitation [mm] and change compared to historical period [%] of the different models (bias-corrected) in the Lower and Upper Vilcanota catchment.

	Lower Vilc.		Upper Vilc.	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
MIROC5	66	75	64	68
Change M	2	14	13	27
NCC	57	61	64	58
Change N	-11	-6	14	2
EARTH	39	53	58	69
Change E	-39	-17	3	29

Table 4.2.: Annual glacial contribution in RCP2.6 and RCP8.5 in the Lower and Upper Vilcanota catchment (without Salcca and Pitumarca).

	Lower Vilc.		Upper Vilc.	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Total per year [m^3/s]	3.20	3.00	0.53	0.00
% of averaged runoff	0.20	0.19	0.06	0.00

erally showing higher precipitation. NCC, like EARTH, has a different precipitation trend in Lower (negative) and Upper Vilcanota (positive), but the range is smaller. MIROC5 shows a positive trend in both subcatchments (see table 4.1). In the graphs 4.1 and 4.2 the following differences in Lower and Upper Vilcanota can be seen. In Lower Vilcanota there are fewer months with very little rainfall over the whole period than in Upper Vilcanota. The best variant is the MIROC5 model together with the RCP8.5. The variation within a year is stronger in Lower Vilcanota than in Upper Vilcanota for both models. In Upper Vilcanota, the annual change in precipitation is therefore more constant. Especially in December, January and February, there is more dispersion across all models in Upper Vilcanota than in Lower Vilcanota (see graph A.3), although the averaged annual amount of precipitation in the two catchments does not differ significantly (see table 4.1).

4.1.2. Glacial contribution

The glacial contribution was only modelled for both of the subcatchments (Lower and Upper Vilcanota) but the significant contribution of the glaciers in the Upper Vilcanota are in the catchments of Salcca and Pitumarca, which were modelled with RS Minerve. In Table 4.2 the averaged annual runoff from models MIROC5 and NCC was used to calculate the percentage of the glacial contribution to the total runoff. Due to very small runoff, the annual runoff is listed as overview in Table 4.2 for Lower and Upper Vilcanota.

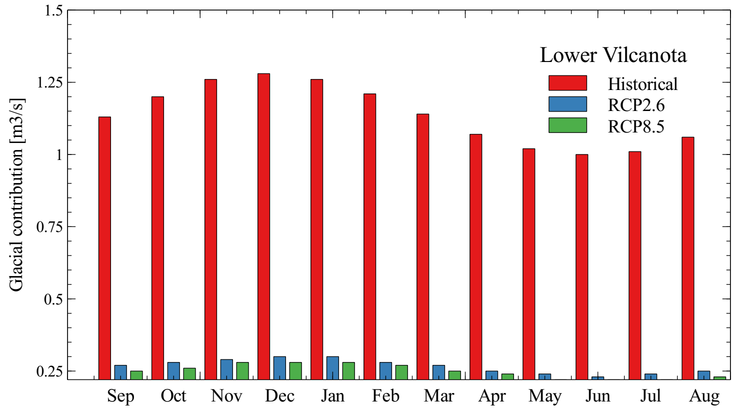

Figure 4.3.: *Comparison of the historical glacial contribution with RCP2.6 and RCP8.5 scenarios in Lower Vilcanota.*

It is to be expected, that the future contribution from glaciers will be significantly lower, about -77% in Lower Vilcanota compared to the historical contribution. For Lower Vilcanota in RCP2.6 this would be 0.24 m^3/s between June and August and 0.29 m^3/s between December and February. In RCP8.5 for Lower Vilcanota 0.23 m^3/s between the months June and August and 0.27 m^3/s between December and February can be expected. Since the glaciated area in Lower Vilcanota was already rather small, the difference between the two scenarios RCP2.6 and RCP8.5 is not significant. Over a whole year, it is 0.2 m^3/s (see Table 4.2. The glacial contribution of Upper Vilcanota is projected to be close to zero runoff because the large part of the glaciated area is in the subcatchments Salcca and Pitumarca, which are included in the separate model of RS Minerve and therefore, not mentioned in this paragraph.

4.1.3. Total supply

The averaged monthly supply of Lower Vilcanota is 138 m^3/s, 78 m^3/s for Upper Vilcanota and 43 m^3/s for Salcca and Pitumarca. A detailed overview can be seen in Table 4.3. The supply of Lower Vilcanota is a lot higher than in Upper Vilcanota, which can be explained with the summation of all subcatchments inclusive Upper Vilcanota at the gauging station from Machu Picchu. The change in the supply increases upstream. While Lower Vilcanota still has a +14% increase in supply, Upper Vilcanota has an increase of only +5% and Salcca/Pitumarca a decrease of -65% as it can be seen in Table 4.3. In Lower and Upper Vilcanota, a decrease of supply was only predicted in RCP8.5 of the NCC model. All the other scenarios show an increase. The biggest increase is expected in Lower Vilcanota in RCP2.6 with the MIROC5 model. Because of the reasons described in subsection 4.1.1 the EARTH model is not included in the overview of the following different supply scenarios. The annual fluctuation in supply compared to the historical period can be seen in Figure 4.7. Supply is highest in December, January and February. The lowest is in June, July and August.

Table 4.3.: *Monthly supply [m^3/s] and change compared to historical period [%] of the models MIROC5 and NCC for the scenarios RCP2.6 and RCP8.5 in Lower Vilcanota, Upper Vilcanota and Salcca/Pitumarca catchment.*

	Lower Vilc.		Upper Vilc.		Salc./Pit.	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
MIROC5	148	147	90	79	52	38
Change M	22	21	17	3	-57	-69
NCC	137	120	81	62	49	33
Change N	13	-1	5	-20	-59	-73

Table 4.4.: *Monthly water demands [m^3/s] of the Lower and Upper Vilcanota catchment between 2025 and 2050.*

	Low. Vilc.			Upp. Vilc.		
	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Agriculture						
Demand [m^3/s]	6	7	7	17	20	20
Change [%]	46	67	75	1125	1301	1368
Domestic						
Demand [m^3/s]	0.2	0.2	0.2	0.9	1	1.1
Change [%]	71	88	119	62	78	108
Ecology						
Monthly demand [m^3/s]	6	6	6	4	4	4

4.2. Water demands

The water demands were separated into the three categories agriculture, households and ecology. In Figure 4.4 it can be seen that domestic demand and demand for ecological flow do not change seasonally, but agricultural demand has large seasonal fluctuations. Agricultural demand is quantitatively the largest of the three demands. The greatest demands are in the months of February to November, when precipitation is low. It is interesting to note that there are two peaks in agricultural demand (March and September). The higher peak of irrigation in September intersects with the time of sowing, the peak in March is in the harvest season (Gamarra Molina et al. 2011). The peak around March is considered to be higher in Upper Vilcanota because already in the historical period, the peak around March is higher compared to the other. The difference in the historical period is lower in Lower Vilcanota.

According to table 4.4, averaged over all scenarios a monthly agricultural demand of 7 m^3/s (change of 63%) is expected for Lower Vilcanota and 19 m^3/s (change of 1265%) for Upper Vilcanota. A maximum value of 22 m^3/s in September (SSP3) and a minimum value of 0 m^3/s in December (all scenarios) can be expected in Lower Vilcanota. In Upper Vilcanota a maximum value of 37 m^3/s in September (SSP3) and a minimum value of 1 m^3/s in January (all scenarios) can be expected.

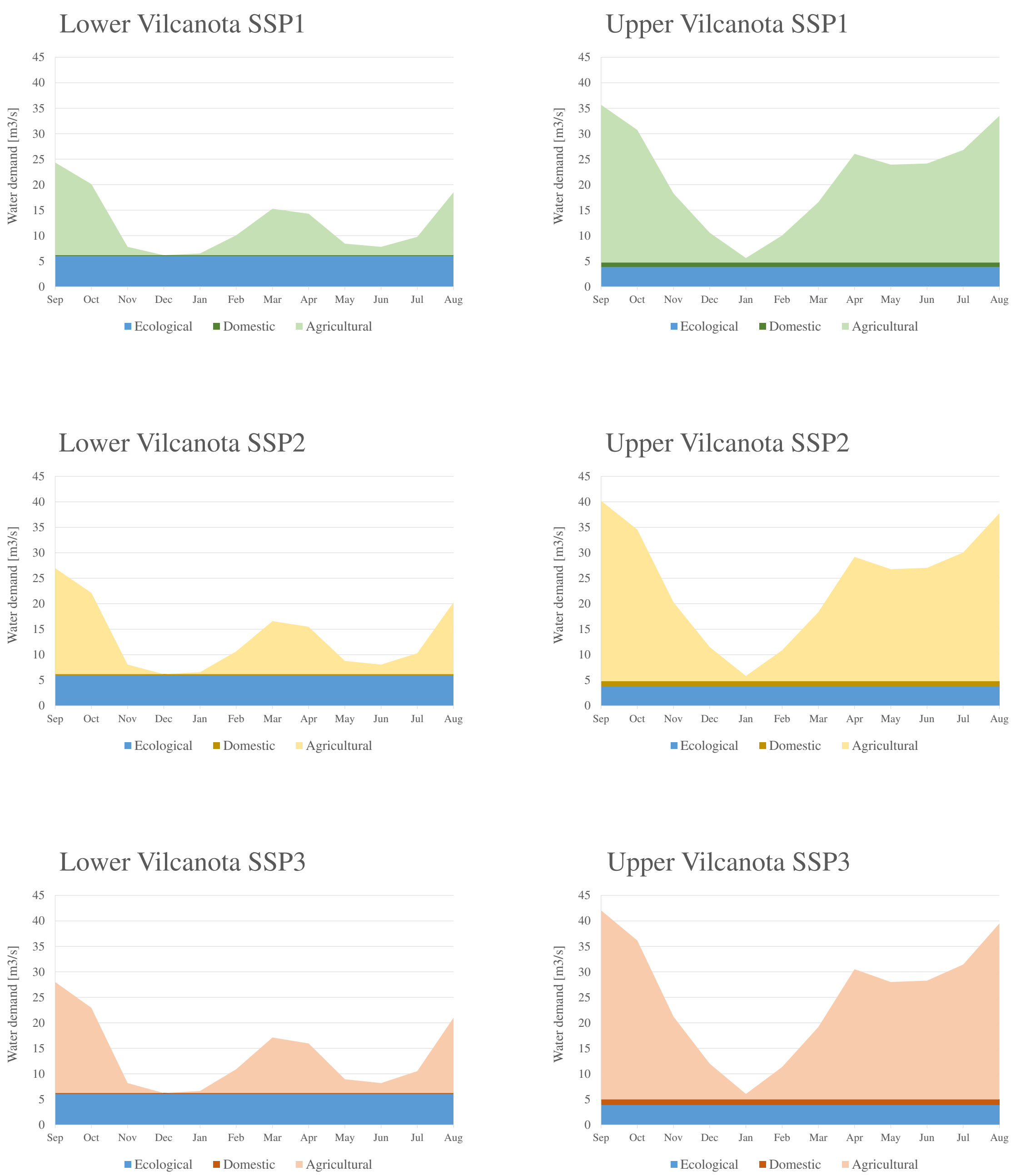

Figure 4.4.: *Averaged monthly cummulation of the different water demands of the subcatchments Lower and Upper Vilcanota between 2025 and 2050.*

Table 4.5.: Statistical values of the Temez model for Lower and Upper Vilcanota

	Lower Vilcanota		Upper Vilcanota	
Period	Calibration	Validation	Calibration	Validation
NASH	0.80	0.77	0.83	0.71
NASH-LN	0.84	0.85	0.74	0.73
R2	0.90	0.91	0.90	0.86
Error	±52.7 m^3/s		±32.8 m^3/s	

For the monthly domestic demand an amount of 0.2 m^3/s (change of 93%) for Lower Vilcanota and of 0.8 m^3/s (change of 83%) is expected. The domestic demand is constant over the whole year. Additional to these demands a monthly constant ecological demand of 6 m^3/s for Lower Vilcanota and 4 m^3/s was included in the hydrological modelling.

After agricultural demand, ecological demand is the second largest demand, while household demand has a smaller impact on total demand. In Figure 4.4 a cummulation of all demands was made for the different SSP scenarios for Lower and Upper Vilcanota. In Upper Vilcanota, agricultural and household demand generally increase more than in Lower Vilcanota. A correlation can be assumed with the stronger population growth around the city of Cusco, which is located in Upper Vilcanota. The difference in agricultural demand is greater between the SSP2 and SSP3 scenarios than between the SSP1 and SSP2 scenarios 4.4. This can be explained by the fact that in the SSP1 scenario, the farmed agricultural area decreases slightly until 2030 before it increases again. In the other two scenarios, SSP2 and SSP3, continuous growth is assumed over the entire period.

4.3. Total Runoff simulation

4.3.1. Model performance

In Temez, the models were calibrated using the following coefficients: Nash-sutcliffe efficiency coefficient for peak flows (Nash & Sutcliffe 1970), the logarithmic Nash-sutcliffe efficiency coefficient for low flows (Oudin et al. 2006) and the coefficient of determination R2 for the average pattern. The main focus of calibration was on the low flows because the aim was to assess the dry season for water availability. For the calibration and validation period, the logarithmic Nash-sutcliffe efficiency coefficient was set as close as possible to 1. A standard error averaged over the year of ±32.8 m^3/s was calculated for Lower Vilcanota and ±52.7 m^3/s for Lower Vilcanota in the calibration period. An overview of the different statistical values of the calibration and validation period in Lower and Upper Vilcanota can be found in Table 4.5.

Overall, the simulations at both catchments show acceptable model performance. In general, better statistical values were achieved in the Lower Vilcanota subcatchment. The worst values are for peak flows, the average pattern achieves good values. Lower Vilcanota, however, has a

Table 4.6.: *Averaged monthly runoff [m^3/s] and change compared to historical period [%] of the models MIROC5 and NCC for RCP2.6 and RCP8.5 over the years 2043 until 2050 in the Lower and Upper Vilcanota catchment.*

	Lower Vilc.		Upper Vilc.	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
MIROC5	133	144	81	75
Change M	8	16	24	14
NCC	125	115	78	58
Change N	1	-7	19	-11

larger standard error. Significant uncertainties can be observed at high runoff in January, February and March in Lower Vilcanota. In Upper Vilcanota, no significant variability in uncertainty in the annual course is discernible.

4.3.2. Total runoff

The total runoff is the balance of the water supply and the different water demands and is therefore the amount of water passing the two gauging stations. The analysed runoff in this section are all illustrated with the SSP2 scenarios to have a clearer presentation of the different models and scenarios, as it is known as the middle-of-the-road scenario (see Figure 4.5). The difference between the SSP scenarios is compared to the differences between the RCP scenarios and models insignificant. The runoff peak is earlier than in the historic period in all scenarios. In the RCP8.5 scenario the peak is even later than in RCP2.6. The decrease in glacier contribution is seen as the reason for this. Due to the decrease in glacier volume, the storage volume also decreases, which delays the runoff. In the RCP8.5 the runoff is more abrupt as in RCP2.6 (see Figure 4.5). There are bigger differences between the models MIROC5 and NCC in RCP8.5. The RCP8.5 NCC scenario is the only scenario with a negative runoff compared to the historical period (see Table 4.6. Most of the negative runoff comes from the months with little precipitation (especially in March and April). In the RCP8.5 The MIROC5 scenario is similar but not negative because of more runoff in January and February (see Figure 4.5). From table 4.6 a runoff of 129 m^3/s for Lower Vilcanota can be expected, which would be a change of +5% compared to the historical period. For Upper Vilcanota a runoff of 73 m^3/s, which would be a change of +12%. It should be noted that the trend of the outflow is opposite to the trend of the supply. So far, no explanation could be found for this. A distribution of the extreme values of the runoff of both subcatchments for the months with high and low discharge can be seen in the figures A.5 and A.6 in the appendix.

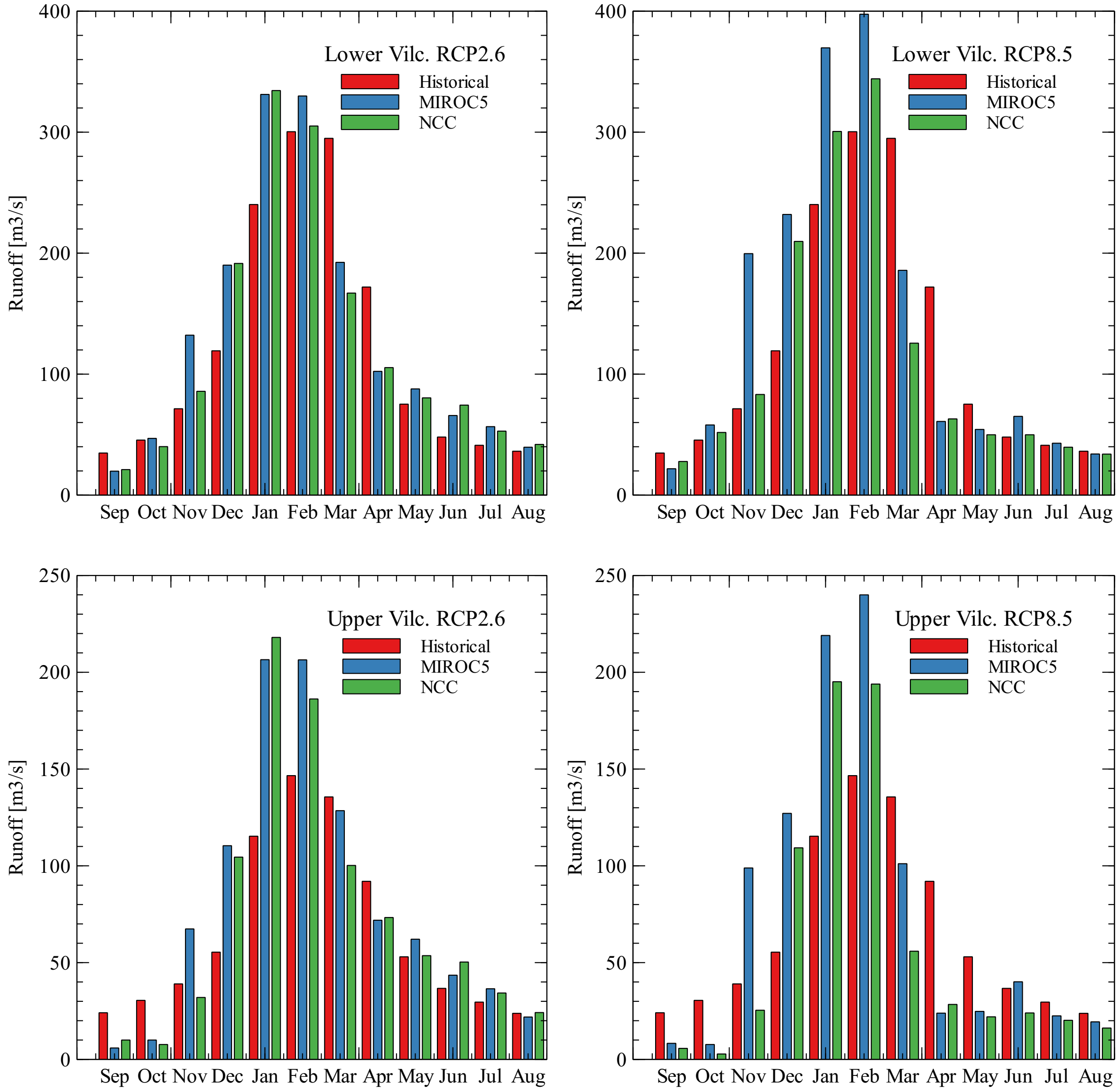

Figure 4.5.: *Comparison of the annual variation in runoff between MIROC5 and NCC (both with SSP2 scenario) in the Lower and the Upper Vilcanota.*

Table 4.7.: *Periods of deficits of the different scenarios in Lower and Upper Vilcanota regarding Figure 4.7.*

	Lower Vilcanota		Upper Vilcanota	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
MIROC5	May - Oct.	Apr. - Oct.	May - Nov.	Apr. - Oct.
NCC	May - Nov.	Apr. - Nov.	May - Nov.	Mar. - Nov.

4.3.3. Possible deficit for water users

In order to obtain an overview of the extent of the possible deficit of the Vilcanota catchment, the following parameters were included in the analysis: duration of deficit, magnitude (average water deficiency) and severity over years (cummulative water deficiency) (Dracup et al. 1980). The future demand for energy production through hydropower was assumed to be 102 m3/s for Lower Vilcanota and 71 m3/s for Upper Vilcanota in the future period until 2050 (see Figure 3.9). These values were added to the modelled runoff of each scenario.

However, an average monthly deficit of up to 50 m^3/s for Lower Vilcanota was estimated between April and November with a peak in September and 46 m^3/s for Upper Vilcanota between March and November with a peak between September and October. As it can be seen from table 4.8, an average of all scenarios predicts a monthly water balance of 28 m^3/s for Lower Vilcanota and 4 m^3/s for Upper Vilcanota. The term balance refers to the positive and negative streamflow, which also include the demand of the hydropower plants. This demand is not included in the total runoff of subsection 4.3.2. In the case of the deficit, only the negative outflows are considered (with the exception in Figure 4.6). The only scenario with a negative balance averaged over the whole year is the NCC model in RCP8.5. All others have a positive monthly balance. In general, the monthly balances associated with MIROC5 are higher than those associated with NCC. It is noticeable that the model MIROC5 in RCP2.6 the monthly balance in SSP2 is smaller than in SSP3. In RCP8.5, however, the development is linear.

The highest deficits are visible in the months of August, September and October (see Figure 4.7). This is about a two-month delay to the low-peak of the supply and can be explained by the water demand of the agricultural sector, which is subject to seasonal fluctuation and peaks in these months. In the months of March to September, the RCP scenarios are more similar in the forecasts, in the months of September the MIROC5 and NCC models. The dimensions of water demand are small compared to supply and the SSP scenarios do not differ significantly from each other. The deficit seems quite high compared to the modelled demands with the SSP scenarios. The reason for this is that energy production through hydropower does not consume the water, but only uses it, and it is therefore still usable for users further downstream. It is paramount to analyse the annual fluctuations in more detail. Table 4.7 shows that in all scenarios of the Lower and the Upper Vilcanota catchment, a deficit is expected in the months from April until October. March and November vary in the different scenarios. The longest deficit is in RCP8.5 in relation to the NCC model.

To find out if water users are facing a deficit, the monthly average cut is not enough. This paragraph takes a closer look at the extreme deficits in the months of August, September and October. As seen in Figure 4.6, the deficits in Upper Vilcanota have less outliers of extreme deficit and less variation between the months of August, September and October. This figure contains the values of both scenarios RCP2.6 and RCP8.5, a separate representation of all months can be found in the figures A.7 and A.8 in the appendix. Whereas values without a deficit also appear in Lower Vilcanota in October. Higher values are also assumed to have greater uncertainty. In Upper and Lower Vilcanota, the highest deficits have been calculated in September. For Lower Vilcanota this is a deficit of -115 m^3/s and for Upper Vilcanota a deficit of -95 m^3/s. In August, this is a deficit of -82 m^3/s for Lower Vilcanota and -60 m^3/s for Upper Vilcanota. In Lower Vilcanota, the highest deficit of October is -113 m^3/s, almost the same as in September. In Upper Vilcanota, however, it is much lower at -87 m^3/s.

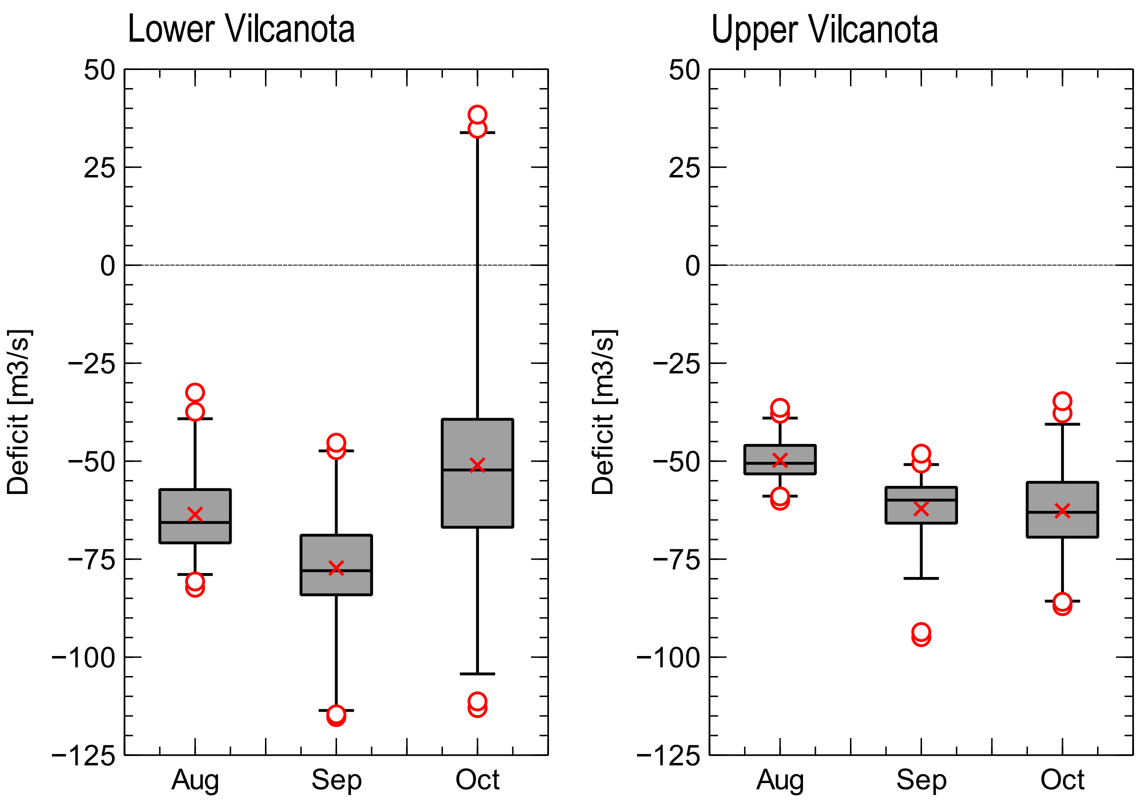

Figure 4.6.: *Extreme values of deficit for Lower and Upper Vilcanota for the months August, September and October.*

To conclude, the deficit is strongly related to the seasonal change in precipitation, while the water demand seems to have a less important influence. The worst scenario the one of RCP8.5 of the model NCC. In general, MIROC5 predicts a smaller deficit in a shorter period.

Table 4.8.: *Monthly water balance $[m^3/s]$ including future hydropower projects of Lower and Upper Vilcanota catchment.*

Lower Vilcanota												
	RCP2.6						*RCP8.5*					
	MIROC5			NCC			MIROC5			NCC		
	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Balance $[m^3/s]$	35	31	37	22	23	25	41	42	43	11	13	15
Upper Vilcanota												
	RCP2.6						*RCP8.5*					
	MIROC5			NCC			MIROC5			NCC		
	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Balance $[m^3/s]$	14	10	15	2	4	5	7	7	8	-4	-13	-11

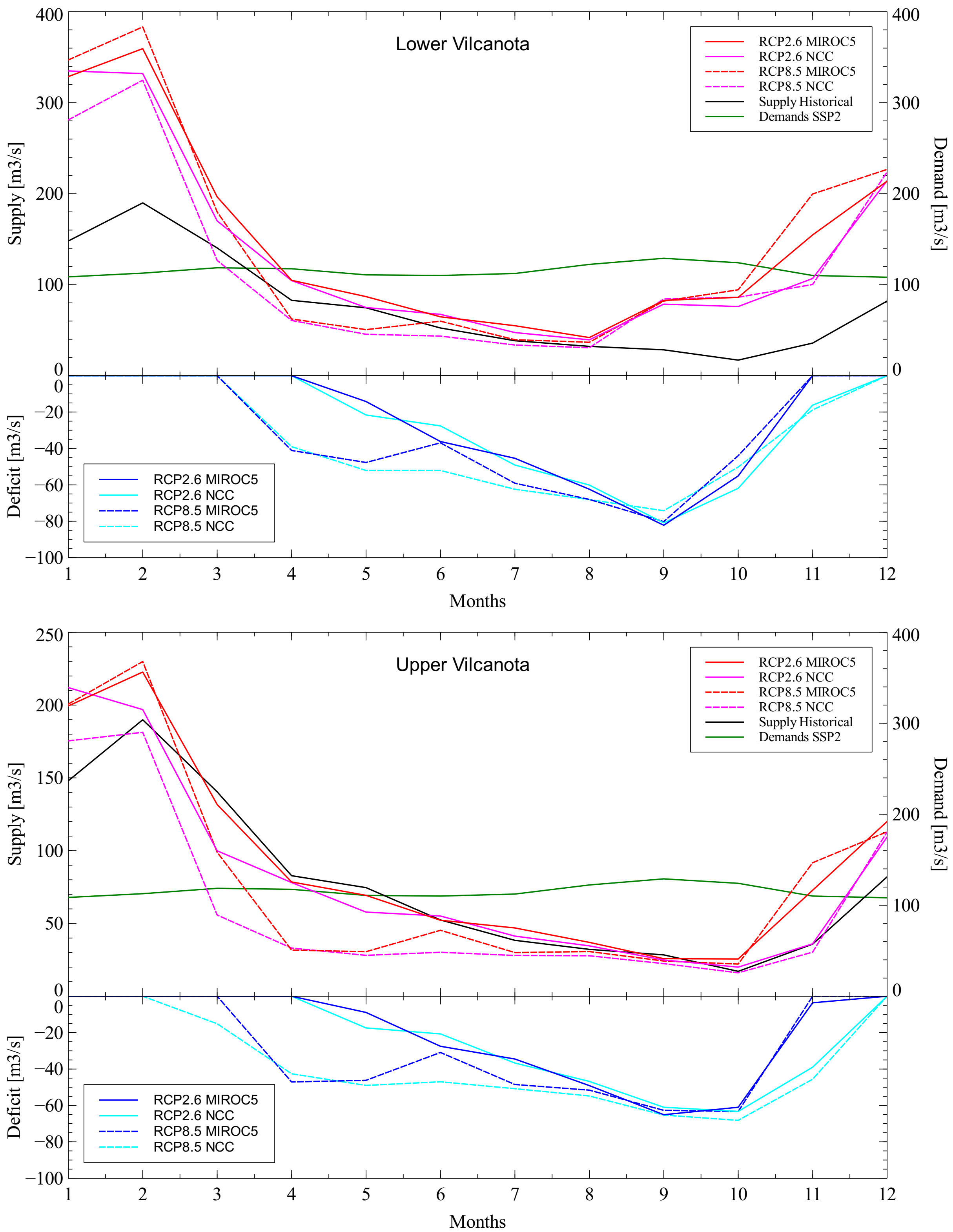

Figure 4.7.: *Annual variation of the monthly deficit of the different scenarios in Lower and Upper Vilcanota between 2043 and 2050. In the upper part of the respective graph, the supply of the different scenarios and models can be read out (red lines), whereby the black line stands for the historical comparison, and the SSP2 demand (green line). These two parameters form the deficit, which is compared between the different scenarios and models in the lower part of the graph (blue lines).*

4.4. Energy consumption and production

The quantification of energy demand and the type of production play a major role in the enrolment of a sustainable water management system of a region (De Cian & Sue Wing 2019). Energy demand depends strongly on the gross domestic product (GDP) and its development in the future. In addition, the development of energy efficiency must be observed; this can reduce the energy demand despite the same services.The following graph shows values of energy consumption for GDP growth of 4.5% and 6.5% with and without energy efficiency (MINEM n.d.).

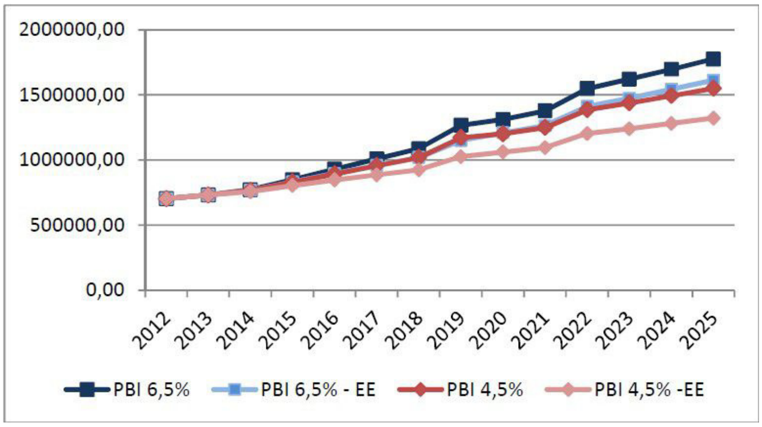

Figure 4.8.: *Energy consumption of Peru with and without energy efficiency. (MINEM n.d.)*

Access to energy influences the consumption of electrical energy. It is a national aim to improve access to electrical energy mainly by closing the electricity grid and increasing the consumption of electricity in the main cities (MINEM n.d.). It is assumed that in the Vilcanota catchment, the city of Cusco consumes most of the region's energy. For 2013, the energy consumption of the city of Cusco was calculated to be 216,444,788 kW/h and an average growth of 3.09% was assumed until 2033. The Centro Histórico has the largest share of electricity consumption with 25.79%, the Centro Médico the smallest with 0.34%. (Silva Lovón & Cruz Alfaro 2014).

In general, energy production is trending away from fossil fuels towards renewable energy sources. In Peru, 54.3% of electrical energy is produced with renewable energy sources, of which 53.26% with water, 0.5% with the sun, 0.49% with bagasse and 0.08% with biogas. Of the hydropower plants, 51.8% produce more than 20 MW (MINEM n.d.). However, the large hydropower plants often harbour great potential for discussion in the destruction of environmental spaces like in the Vilcanota catchment (Castro Alvarez 2019). Nonetheless, reservoirs in particular have great potential to store water and energy for electricity production for times with little precipitation or general power shortages, which in turn can have a negative impact on economic growth. In this study, an annual increase in precipitation was modelled until 2050. This would mean that the hydropower plants in the Vilcanota catchment could produce energy at full capacity in the future. However, these results should be viewed with caution, as other models from the literature forecast negative trends. The localisation of the individual power plants is important to find out whether the full capacity can also be utilised with the new power plants and whether new storage lakes would be necessary.

Discussion

5.1. Possible sources for uncertainties

5.1.1. Water supply

Precipitation

Precipitation has the highest influence on water supply and at the same time shows the greatest uncertainties. Neukom et al. (2015) predict a decrease of precipitation of approximately -10% in the RCP2.6 and approximately -19% to -33% in the RCP8.5 until 2100. The modelling of precipitation in this study only extends to 2050, but shows a slight positive trend of about +5% in RCP2.6 and about +9% in RCP8.5 over the whole catchment (average of the models MIROC5 and NCC). The PISCO precipitation input data includes an uncertainty of bias about ±20%, root mean square error about ±15 mm/month related to the merge and interpolation of the global dataset CHIRPS and quality-checked in-situ stations (Aybar Camacho et al. 2017). Since the trend is positive both with and without bias correction, it is assumed that the reason lies with the models MIROC5 and NCC. Altitude was not taken into account in the bias correction of CMhyd but can have an influence on the behavior of precipitation, especially in areas with large differences in altitude. Trends in total or solid precipitation at high elevation remain highly uncertain, due to intrinsic uncertainties with in situ observation methods, and large natural variability (Hock et al. 2019). Similarly, it is possible that conditions will change again in the period between 2050 and 2100, which were not considered in this study. Interestingly, in the years 2045 and 2046 MIROC5 has a precipitation which is high in RCP8.5 and low in RCP2.6 in Lower and Upper Vilcanota All the other years do not have such a significant difference (see graph 4.1 and 4.2). One possibility would be to carry out a consistency analysis in a further step, as has already been done for the Pisac outflow.

Glacial contribution

The decrease in glacial contribution in Lower Vilcanota is significant at -77%, but it will only contribute about 0.2% to the total runoff in 2050 and thus has a less strong influence than precipitation. The two heavily glaciated subcatchments Salcca and Pitumarca were modelled and inserted separately. Therefore, no detailed information of the glacier contribution in Upper Vilcanota is available. For the resident population in Upper Vilcanota, this glacier contribution is of great importance and should therefore be analysed in more detail in further studies. Drenkhan et al. (2019) assume a glacier contribution for 2050 of 4.4 m^3/s for the months of December, January and February and of 0.9 m^3/s for the months of June, July and August over the entire Vilcanota catchment. For Lower Vilcanota, averaged values of 0.24 m^3/s between June and August and 0.28 m^3/s between December and February were calculated in this study across the RCP scenarios.

Groundwater contribution

Another uncertainty regarding water supply can be found in the groundwater contribution. In most of the Andean basins, and therefore, in the Vilcanota catchment, groundwater contribution and flow characteristics are not yet sufficiently quantified and comprehensively understood in order to enable the inclusion of groundwater processes in the modelling process (Drenkhan et al. 2019).

5.1.2. Water demands

Some of the data used for the reconstruction of current demand is no longer particularly up-to-date, which can also lead to a distortion in the future scenarios. For example, the data on monthly irrigation dates from 2015 at the earliest, the data on agricultural area from 2012 and the data on population from 2017. These parameters all carry a lot of weight in the future scenarios. With the help of the scenarios, an attempt was made to show a range of possible demand up to 2050. However, the SSP scenarios are also only adapted to local conditions to a limited extent (Latin American scenario for agriculture and national scenario of Peru for population development). Comparative values could only be found to a limited extent so far and are often only suitable for a current analysis. Licona Licona et al. (2006) and Drenkhan et al. (2019)'s forecasts are very general and not adapted to the parameter of the whole catchment area. Moreover, Licona Licona et al. (2006)'s forecasts only extend to the year 2030 and not to 2050 as desired.

Agricultural demand

Agricultural demand has the largest proportion of water demand in the Vilcanota catchment and due to its seasonality the biggest influence on a possible deficit. Agricultural demand is also higher in months when there is less supply of water. Upper Vilcanota is more affected by this problem than Lower Vilcanota. There are basically three important parameters in the modelling

Table 5.1.: *Suitable and moderately suitable ground for maiz (Marangani) and bean (San Salvador) in literature compared to own calculations [ha].*

	Historical (INEI)	Literature	SSP1	SSP2	SSP3
Marangani (maiz)	406.56	14596.67	3695.26	18875.77	19667.28
San Salvador (bean)	603.88	5990.97	2662.83	11544.51	12666.27

of agricultural demand: the cultivated area, the growth rate of the area in the future and the irrigation rate.

The only representative values for the Vilcanota catchment for the agricultural area come from the official census from the years 1994 and 2012. The year 2012 is therefore also the reference year for the future scenarios and corresponds to an irrigated area of 50,823 ha for the Vilcanota catchment. There is an uncertainty in the used values of INEI, as these correspond to the perimeters of the districts and do not coincide with the perimeter of the catchment. The values were therefore adjusted with the geographical distribution of the cropland from NASA's layer. Misclassifications were found in the layer, as cropland at altitudes above 4000 m.a.s.l. was classified as cropland, which seemed impossible due to agroclimatic conditions (Gamarra Molina et al. 2011). After subtracting this area, a cultivated area of 34,825 ha resulted, which was significantly smaller than the area of INEI and therefore not integrated into further modelling. However, the data give an idea of the spatial distribution of agricultural land.

In order to obtain an initial assessment of the possible spatial distribution of future agricultural land, a GIS analysis was made with parameters of altitude, slope and current vegetation cover. There is already an analysis of suitability for different crops in the districts of Marangani and San Salvador (Gamarra Molina et al. 2011). A comparison is made with the crop that has the greatest potential to spread on suitable (San Salvador) and moderately suitable ground (Marangani and San Salvador). The estimated values from the literature for the districts of Marangani and San Salvador can be placed between the SSP1 and SSP2 scenarios. The estimated suitable areas for different crops are close to each other in San Salvador. It is assumed that the values are a little lower than in the calculated scenarios, because in addition to altitude and slope, climate (temperature and precipitation) and soil parameters were also included in the analysis. To replace these parameters, the land cover was used, which, however, has a lower level of detail. For a more realistic analysis, a field visit as well as a precise analysis of the desired crops and their preferred environments is indispensable (Gamarra Molina et al. 2011).

The second parameter with uncertainties is the growth rate. There are no future growth rates in the literature for the Vilcanota catchment at this time. The growth rate calculated with the Census between the years 1994 and 2012 (0.02% per year) is very high compared to the Latin American growth rate of SSP2 scenario (0.005% per year). The growth rate from the Census is based on real figures, but these come from a period with very rapid growth of cultivated land (Drenkhan et al. 2019, INEI 2013) and can therefore not be directly applied to the future period. The cropland classified by the satellite (NASA) as well as Google Earth show that most of the flat areas are already occupied. What can be used are areas with a higher slope, which would make agricultural growth slower. In conclusion, it seems that the uncorrected rate of the SSP is more realistic than the corrected rate.

The maximum value for agricultural demand is in September and is 49.4 m^3/s for the year 2012. For this purpose, the estimated demand values for the Urubamba catchment (ANA 2015)] were averaged and further used as irrigation per hectare. No adjusted values or scenarios for the future in the catchment perimeter were found in the literature. The same values were used as reference for the future scenarios, although it is not certain whether and how the demand values will change. Uncertainties in the future irrigated area can also be caused by parameters that were not of great importance in the quantification of the water demand for irrigation, such as technological progress, market demand for local agricultural goods or the spatial distribution of the agricultural area and thus the accessibility of the area. Depending on the crop and terrain, a different amount of water is needed and at different times (INEI 2013). The importance of the individual parameters in the modelling process can certainly be questioned, especially at a larger scale in the modelling process.

Domestic and other demands

With a higher GDP, an increase in the industrial sector can be assumed, which in turn could result in a surge in demand for water. However, industrial water use is only partially linked to a country's level of industrialization and, for example around the Mediterranean Sea, seasonal water demands from the tourism industry (comparable to the Cusco region and its tourist trade) increase annual water demand by an estimated 5%-20% (Water 2020). The demand for domestic water depends strongly on population growth and changes are smoother. However, non-permanent residents or those who are not officially registered and were not taken into account in the study should not be disregarded.

5.2. Impact of COVID-19

The current economic crisis, which the IMF dubbed the "Great Lockdown" in its April 2020 semi-annual report and which is already the worst since the Great Depression of the interwar period, is hitting poor countries the hardest (IMF 2020). The national GDP has a significant influence on sustainable investments (Riahi et al. 2017) and therefore, it can be expected that investments on innovative, sustainable and climate-friendly green-energy projects and climate change actions will decrease (Farand 2020, UNCTAD 2020). The current global political and economic situation can best be compared to SSP3 (assuming the worst possible scenario), where politics are increasingly focusing on national and regional security issues (for example the closed borders). Investments in education (for example closed educational institutions) and technological development are declining and inequalities are growing. The equity within the population and the societal participation will be low, which will not bring any approval for the hydropower projects that are already viewed critically by the local population. (Riahi et al. 2017).

Noticeable at the local level are also impacts reflected in less or regionally changed consumption patterns in water and energy, for example. The changed mobility behaviour and few to no tourists in a region heavily influenced by tourism are to be highlighted. However, these dramatic changes should not only be viewed negatively, as they also contribute to sustainable changes and offer an opportunity to reposition oneself for example in the tourism sector. This in turn can help move away from the path of the SSP3 scenario.

5.3. Possible scenarios of water management

Economic inequality also translates into inequality in access to water and sanitation, and vice versa. Therefore, with climate change, increasing risks of waterborne diseases have a greater impact on poor people. In the face of economic development priorities, water is needed to meet both sectoral (domestic, agriculture, energy) and ecosystem needs (Water 2020). The provinces of Canas, Acomayo and Paucartambo (all in Upper Vilcanota) have the greatest vulnerability in the Vilcanota catchment and should be the focus of particular attention. The provinces of Urubamba, Cusco, Calca and Canchis, which are in the high dynamic zone, need less attention (see Section 2.2). The provinces in Upper Vilcanota are also more exposed to changes in runoff due to the reduction of glaciers. Also, the increase in irrigated agricultural land is greater in Upper Vilcanota than in Lower Vilcanota. All these points lead to the conclusion that in the Vilcanota catchment, Upper Vilcanota is more jeopardized to water scarcity than Lower Vilcanota.

The important parameter of precipitation, which is strongly influenced by changes in the global system, can hardly be influenced on a local scale. However, it is important to understand how water supply will change in the future so that a concept for the distribution of water can be developed on this basis. It is proposed to work with a multi-level system to set a water management system which is consistent for all stakeholders. For stakeholders with a large demand for water, such as energy producers, a large-scale concept should be developed. For stakeholders with a small demand of water, such as individual households or farms, small-scale and local concepts of small-scaled catchments should be developed. On the one hand, the indigenous population seems to be more vulnerable to water stress, on the other hand, there is a long tradition of adapting to a harsh and dynamic environment. It can be assumed that climate change will bring too rapid a change in the environment for the indigenous population to evolve with it. Adverse policies and the pervasive effects of non-climatic stressors could also lead to them being overwhelmed. Nevertheless, they and their knowledge should be integrated into the strategies of the government and development agencies, especially at the small-scale and local level (Postigo 2020).Furthermore, it is important at this level, that the individual stakeholders are interlinked and that there is equal communication among the stakeholders. Only a well-interlinked stakeholder group will have a chance to negotiate on an equal footing with stakeholders of a high demand for water, like energy producers. To counteract water scarcity, on the one hand, technical progress could be used to use the available water as efficiently as possible, for example in energy production, the water consumption of individual households or in agricultural irrigation systems. On the other hand, traditional methods can be increasingly used in agriculture, which can be further developed with newly acquired knowledge to meet the changed needs. The focus could be on the various crops, but also on the time of cultivation or the spatial expansion of cultivation.

The demand for energy will also increase, as section 4.4 shows. This in turn can increase the demand for hydropower production if the trend for renewable energy production continues.

The economic losses from reduced electricity production due to water scarcity in deficit months could be significant as Vergara et al. (2007) show, but also depends strongly on the actual energy price. In order to make a detailed forecast, further studies specifically in this direction would be necessary. As hydropower causes many conflicts in the Vilcanota catchment (Drenkhan et al. 2015) and the conflicts might not decrease in the future with the predicted water scarcity, it would be a possibility to look for alternative renewable energy production. One possibility would be solar power, which recent studies have shown to perform better over the whole year in areas of higher altitude than in areas of lower altitude (Anderegg et al. 2020). The existing hydropower plants could be used for electricity storage and water regulation (multi-purpose project) and, if necessary, converted. This would prevent an even greater burden on water resources in the future. These possibilities would certainly have to be examined more closely in further studies to determine their feasibility in the area of the Andean Alps.

One way to create a systemwide optimal solution which is consistent over various sectors and scale is to work with the Extended Continental-scale Hydro-economic Optimization (ECHO) model (Kahil et al. 2019). ECHO is subjected to resource constraints, technical constraints, sustainability and policy constraints. As a further step, the costs for individual parameters, which were modelled in this study would have to be quantified. In addition, further parameters will be necessary for the analysis, such as information on groundwater (Kahil et al. 2019). At this point in time, the data basis is still very scarce. It is also important not to neglect the temporal component of the change, as the modelling and data basis are constantly changing.

Conclusion

In this study, an attempt was made to quantify the water supply and demand in the Vilcanota catchment. Different models were used in both areas, RCP in the area of water supply and SSP in the area of water demand. The modelled precipitation deviates with a positive trend of +7% over the whole catchment from the literature values (-10% up to -33%), which leads to a large uncertainty in the runoff of the Vilcanota catchment. It can be assumed that the RCM models are the main reason for the positive trend of +5% of total runoff, which is a total of 130 m^3/s per month. For the water demands, different scenarios were developed and can therefore only be compared with the literature values to a limited extent, but they are within the range of the previous modelling. However, a seasonal monthly deficit of up to 75 m^3/s in Lower Vilcanota was estimated between April and November with a peak in September. The deficit is related to the seasonal change in precipitation, while the water demand seems to have a less important influence. In order to construct a locally sustainable water management system, the modelling needs to be further downscaled to the different subcatchments in the Vilcanota catchment. It is also paramount to involve the local actors in order to cover the whole water-energy-food nexus (FAO 2014). This becomes visible, for example, in the scenarios of possible future agricultural areas, where field inspection and soil analysis are unavoidable. Due to the great uncertainty of the modelling in water supply and changes in the economic situation, the data should be continuously updated. A new dam could partially compensate for the decreasing storage capacity of the melting glaciers. However, the construction of the dam could meet with resistance from the local population if multiple use of the new dam cannot be clearly promised and communicated to them. Sustainable water management requires the cooperation of all stakeholders and all stakeholders should be able to benefit from it so that they will support future projects.

Appendix

A.1. Economic zones of the department Cusco

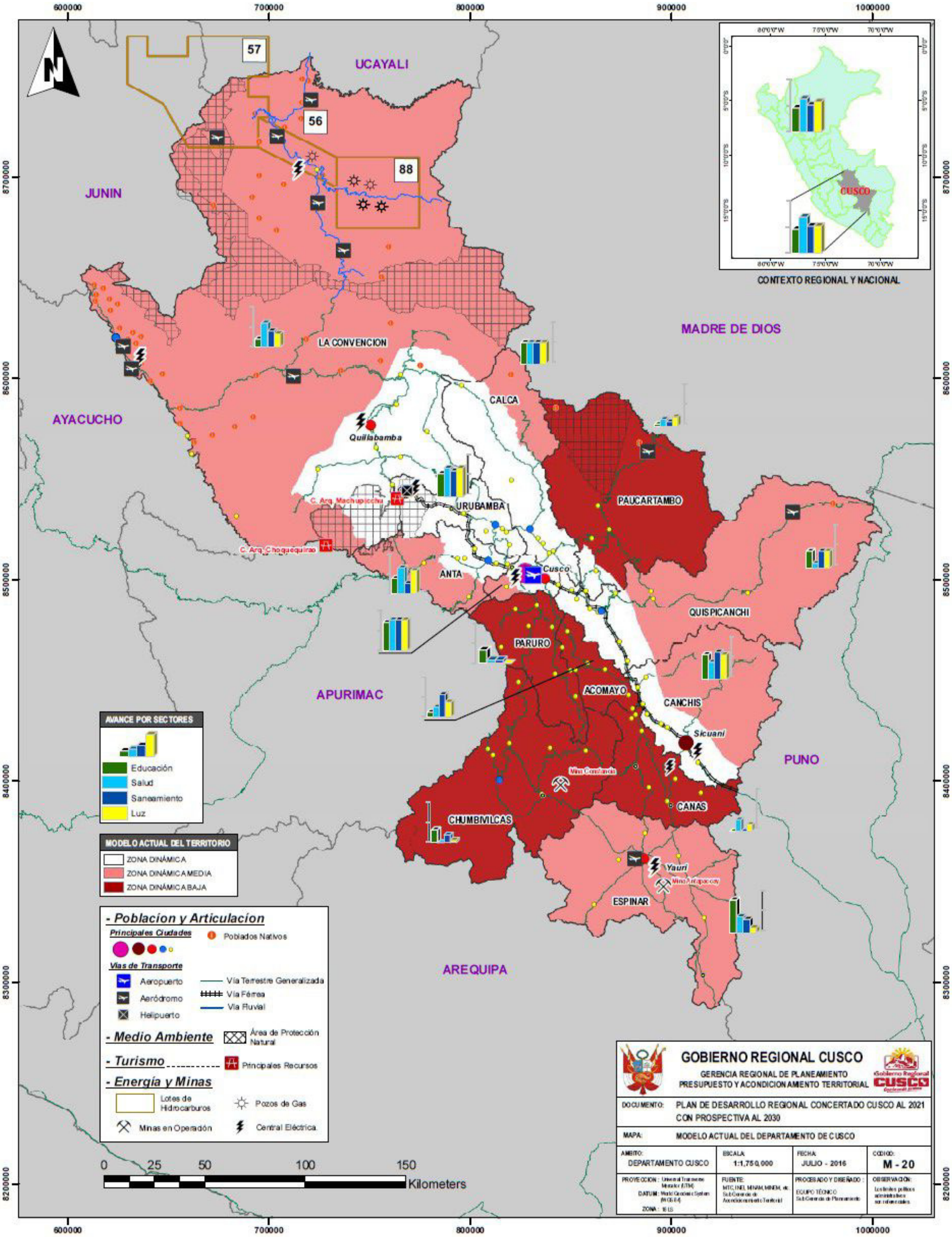

Figure A.1.: *Map of the economic zones of the departement Cusco (Licona Licona et al. 2006).*

A.2. Maximum agricultural area

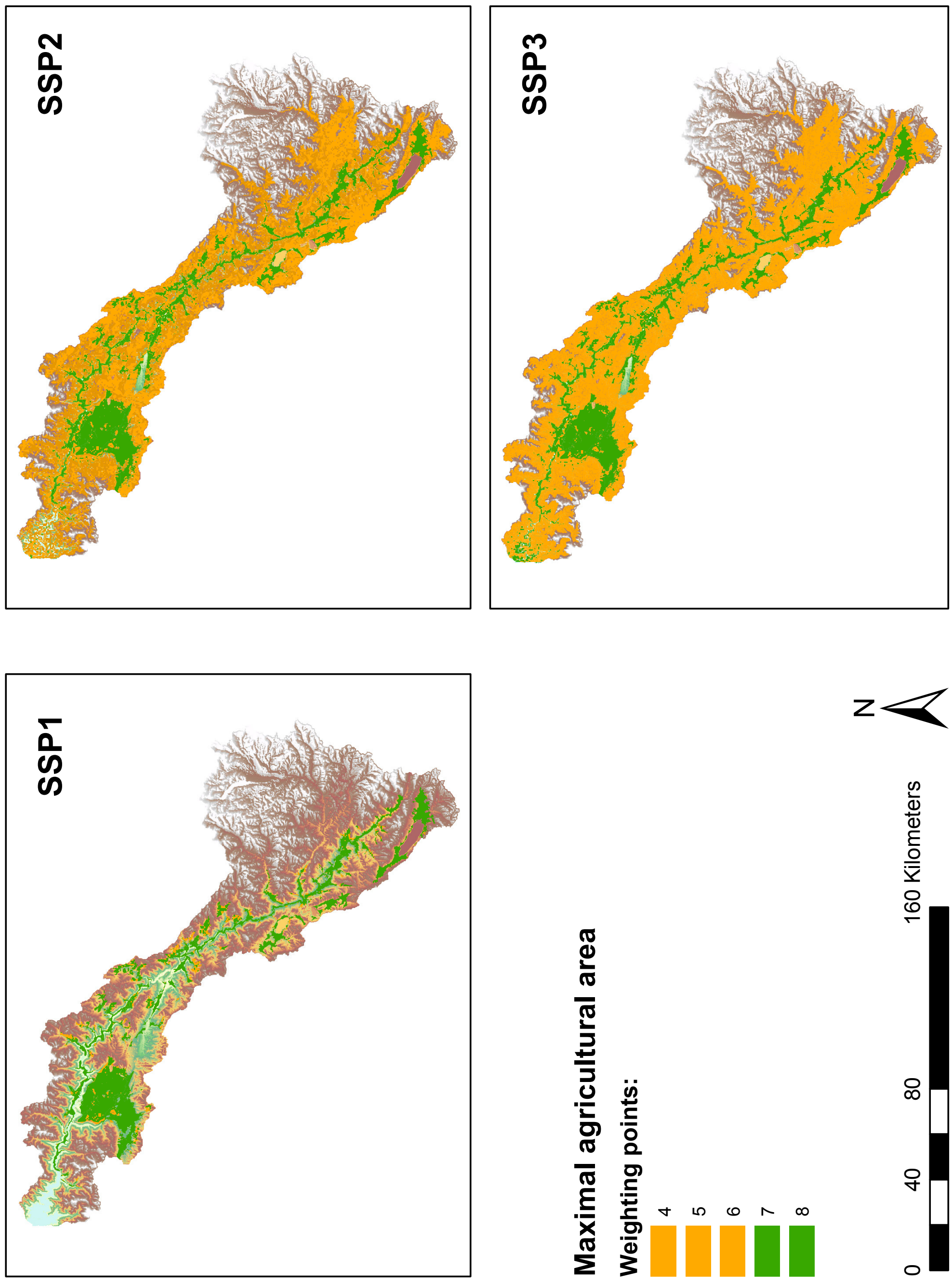

Figure A.2.: *Map of maximal agricultural area of the SSP scenarios SSP1, SSP2 and SSP3.*

A.3. Precipitation

For the boxplots (9/91 percentile) the data of all models (MIROC5, NCC and EARTH) of the individual months between September 2043 and December 2050 were used to have a complete data series of all models.

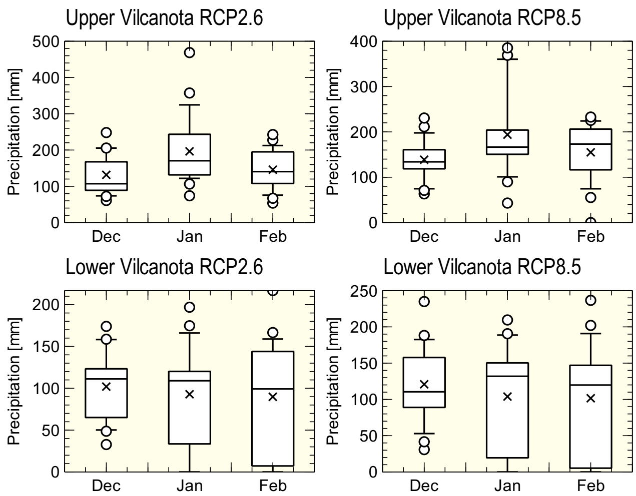

Figure A.3.: *Distribution of precipitation over all models of the months December, January and February in Lower and Upper Vilcanota.*

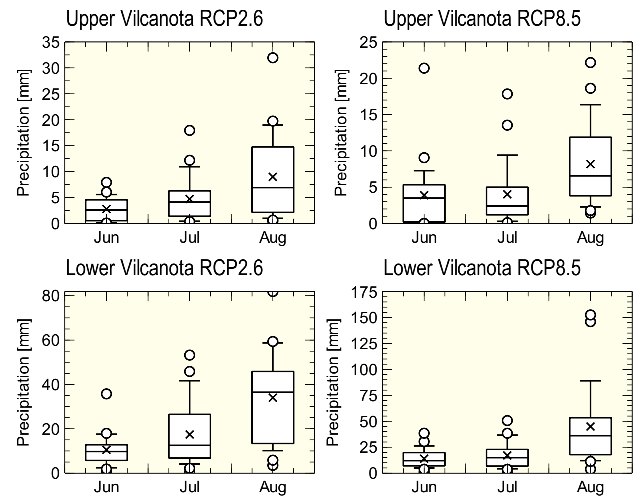

Figure A.4.: *Distribution of precipitation over all models of the months June, July and August in Lower and Upper Vilcanota.*

A.4. Runoff

For the boxplots (9/91 percentile) the data of all models (MIROC5, NCC and EARTH) of the individual months between September 2043 and December 2050 were used to have a complete data series of all models.

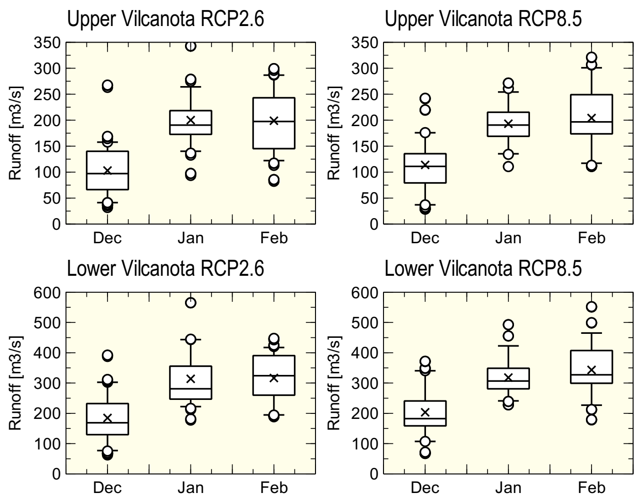

Figure A.5.: *Distribution of runoff over all models of the months December, January and February in Lower and Upper Vilcanota.*

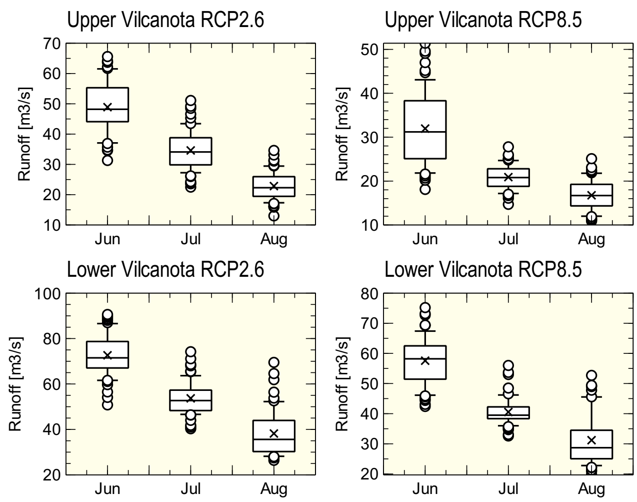

Figure A.6.: *Distribution of runoff over all models of the months June, July and August in Lower and Upper Vilcanota.*

A.5. Deficit

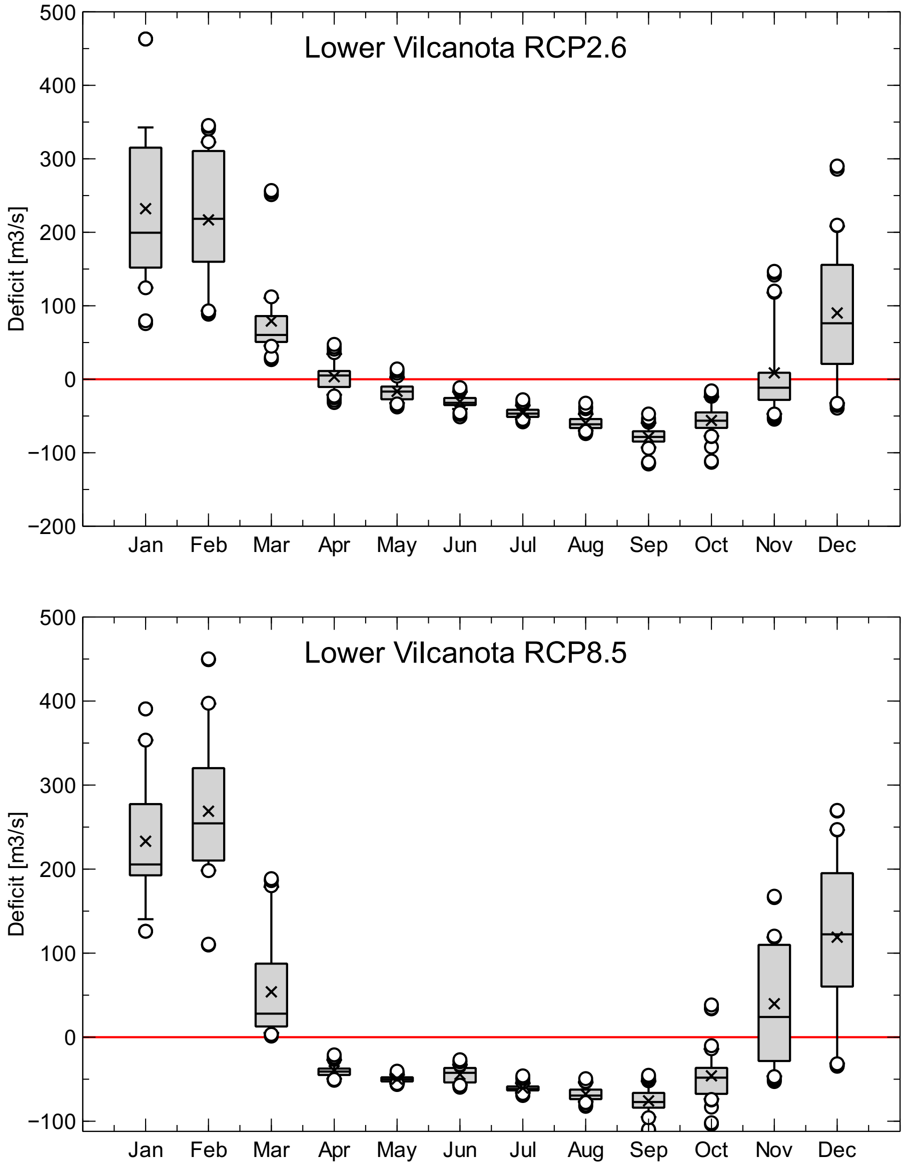

Figure A.7.: *Annual variation of the extreme deficit values of the different scenarios in Lower Vilcanota (9/91 percentile boxplots).*

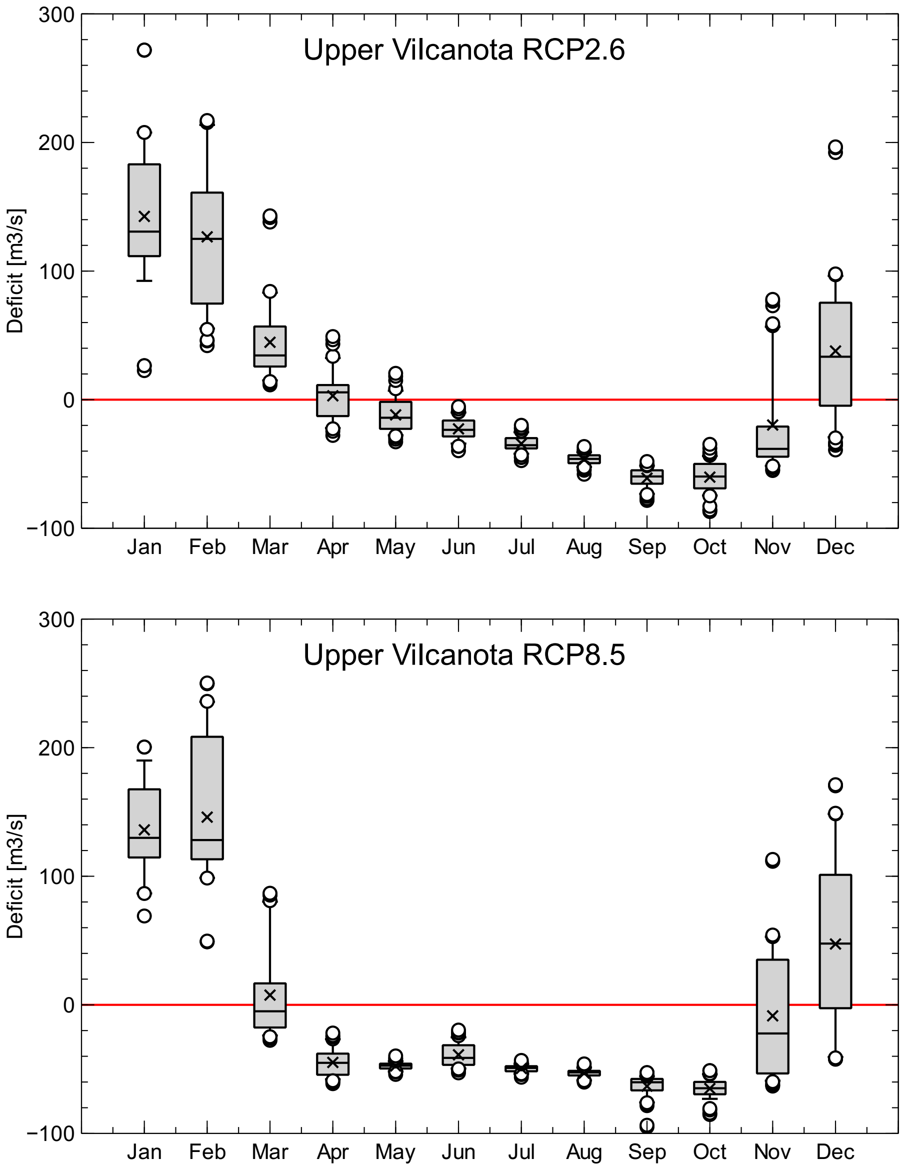

Figure A.8.: *Annual variation of the extreme deficit values of the different scenarios in Upper Vilcanota (9/91 percentile boxplots).*

Bibliography

ANA (2014), INVENTARIO DE LAGUNAS GLACIARES DEL PERU, Technical report, Huaraz, Peru.

ANA (2015), Evaluación de Recursos Hídricos en la cuenca Urubamba, Technical report.

ANA (2019), 'Consejo de recursos hídricos (cuenca interregional Vilcanota-Urubamba) - Variables Socioeconómicas'.

Anderegg, D., Strebel, S. & Rohrer, J. (2020), Winterstrom mit alpiner Photovoltaik.

Apaéstegui, J. & Espinoza V., R. (2017), 'Estimación, evaluación y análisis de la demanda hídrica en la cuenca del río Quillcay (Ancash, Perú) desde un enfoque de Gestión Integrada de los Recursos Hídricos', pp. 0–59.

Aybar Camacho, C., Lavado, W., Huerta Julca, A., Fernández Palomino, C., Vega Jacome, F., Sabino Rojas, E. & Felipe Obando, O. (2017), Uso del Producto Grillado "PISCO" de precipitación en Estudios, Investigaciones y Sistemas Operacionales de Monitoreo y Pronóstico Hidrometeorológico, *in* 'Nota Técnica 001 SENAMHI-DHI-2017', Lima, Perú, p. 22.

Bergström, S. (1976), Development and Application of a Conceptual Runoff Model for Scandinavian Catchments, PhD thesis.

Blossiers Pinedo, J., Deza Pineda, C., León Huaco, B. & Samané Mera, R. (2000), 'Agricultura de laderas a través de andenes, perú', *Manual de Capacitación y Aprovechamiento del Agua de Lluvia. Experiencias en América Latina* pp. 195–216.

Castro Alvarez, M. A. (2019), Reporte y descripción de los resultados: Recopilación de información para la caracterización del uso del agua y el análisis de medios de vida en las zonas altas de las subcuencas de Pitumarca y Salcca., Technical report.

De Cian, E. & Sue Wing, I. (2019), 'Global Energy Consumption in a Warming Climate', *Environmental and Resource Economics* **72**(2), 365–410.

Díaz Pabló, A., Villegas Paredes, E., Ovando, O. G. F. & Lavado Casimiro, W. (2015), Generación De Baso De Datos De Precipitación Mensual Grillada De Alta Resolución A Nivel Nacional 1981-2013, Technical report, SENAMHI, Lima, Perú.

Dracup, J. A., Lee, K. S. & Paulson, E. G. (1980), 'On the definition of droughts', *Water Resources Research* **16**(2), 297–302.

Drenkhan, F., Carey, M., Huggel, C., Seidel, J. & Oré, M. T. (2015), 'The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru', *Wiley Interdisciplinary Reviews: Water* **2**(6), 715–733.

Drenkhan, F., Guardamino, L., Huggel, C. & Frey, H. (2018), 'Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes', *Global and Planetary Change* **169**(November 2017), 105–118.

Drenkhan, F., Huggel, C., Guardamino, L. & Haeberli, W. (2019), 'Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin', *Science of the Total Environment* **665**, 465–483.

Duan, Y., Liu, T., Meng, F., Luo, M., Frankl, A., De Maeyer, P., Bao, A., Kurban, A. & Feng, X. (2018), 'Inclusion of modified snow melting and flood processes in the SWAT model', *Water (Switzerland)* **10**(12).

FAO (2014), The water-energy-food nexus A new approach in support of food security and sustainable agriculture, Technical report, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Farand, C. (2020), 'Coronavirus slows developing nations' plans to step up climate action in 2020'.
URL: *https://www.climatechangenews.com/2020/03/18/coronavirus-slows-developing-nations-plans-step-climate-action-2020/*

Flores Moreno, A. (2016), La sociedad puesta a prueba por el cambio climático: Una apreciación crítica de los actores principales de Canchis y Urubamba (Cusco), y su relevancia para la intervención del proyecto Glaciares +, Technical report, University of Zurich, Zurich, Switzerland.

Gamarra Molina, W., Silvestre Espinoza, E. & Alarcón Velazco, C. (2011), Caracterización Agroclimática De La Región Cusco, Technical report, SENAMHI, Lima, Peru.

Hall, D. K. & Riggs, G. A. (2011), Normalized-Difference Snow Index (NDSI), *in* V. Singh, P. Singh & U. Haritashya, eds, 'Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series.', Springer Netherlands, Dordrecht.

Hernández, J. G., Foehn, A., Fluixá-Sanmartín, J., Roquier, B., Brauchli, T., Paredes-Arquiola, J. & De Cesare, G. (2020), RS Minerve - Technical Manual v2.25, Technical Report April, CERALP, Sitzerland.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. & Steltzer, H. I. (2019), 'Chapter 2: High Mountain Areas. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate', *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* pp. 131–202.

Hoff, H. (2011), 'Understanding the Nexus. Background paper for the Bonn2011 Nexus Conference:', *Stockholm Environment Institute* (November).

Huggel, C., Scheel, M., Albrecht, F., Andres, N., Calanca, P., Jurt, C., Khabarov, N., Mira-Salama, D., Rohrer, M., Salzmann, N., Silva, Y., Silvestre, E., Vicuña, L. & Zappa, M. (2015), 'A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes', *Environmental Science and Policy* **47**, 80–94.

IMF (2020), *World Economic Outlook: The Great Lockdown*, number May, International Monetary Fund, Washington, DC.

INEI (2008), 'Perfil sociodemografico del Peru', *Encuesta Demografica de Salud (ENDESA)* p. 474.

INEI (2013), IV Censo Nacional Agropecuario 2012: Informe Final de Actividades, Métodos y Documentos, Technical report.

INEIa (2017), 'Censos Nacionales 2017: XII de Población, VII de Vivienda y III de Comunidades Indígenas'.

INEIb (2017), 'Características de la Población', *Perú: Perfil Sociodemografico 2017* pp. 12–94.

IPCC (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Technical report, IPCC, Geneva, Switzerland.

Johnson, K. (2015), 'Hydropower and the Challenge of Climate Change'.
URL: *https://foreignpolicy.com/2015/03/16/hydropower-and-the-challenge-of-climate-change/*

Kahil, T., Albiac, J., Fischer, G., Strokal, M., Tramberend, S., Greve, P., Tang, T., Burek, P., Burtscher, R. & Wada, Y. (2019), 'A nexus modeling framework for assessing water scarcity solutions', *Current Opinion in Environmental Sustainability* **40**, 72–80.

Kaser, G. & Georges, C. (1997), 'Changes of the equilibrium-line altitude in the tropical Cordillera Blanca, Peru, 1930-50, and their spatial variations', *Annals of Glaciology* **24**, 344–349.

Kronenberg, M., Huggel, C. & Frey, H. (2019), Modelling melt from glaciers located the tropical Andes Background and practical considerations, Technical report, Department of Geography, University of Zurich, Zurich, Switzerland.

Kronenberg, M., Schauwecker, S., Huggel, C., Salzmann, N., Drenkhan, F., Frey, H., Giraáldez, C., Gurgiser, W., Kaser, G., Juen, I., Suarez, W., Hernaández, J. G., Sanmartín, J. F., Ayros, E., Perry, B. & Rohrer, M. (2016), 'The Projected Precipitation Reduction over the Central Andes may Severely Affect Peruvian Glaciers and Hydropower Production', *Energy Procedia* **97**, 270–277.

Licona Licona, E., Vargas Salinas, R. F., Baca Sánchez, Y. & Díaz Velazco, E. (2006), Plan de desarollo regional concentrado Cusco al 2021 con perspectiva al 2030, Technical report, CEPLAN (Centro Nacional de Planamiento Estratégico), Gobierno Regional Cusco, Cusco, Peru.

Magrin, G. O., Marengo, J. A., Boulanger, J.-P., Buckeridge, M. S., Castellanos, E., Poveda, G., Scarano, F. R. & Vicuña, S. (2014), Central and South America, Technical report, Cambridge University Press, Cambridge, United Kingfdom and New York, USA.

MEM (2014), 'National Energy Plan 2014 - 2025 | Peru'.

MINEM (n.d.), Plan Energético Nacional 2014-2025.

Motschmann, A., Huggel, C., Muñoz, R. & Thür, A. (2020), 'Towards integrated assessments of water risks in deglaciating mountain areas: water scarcity and GLOF risk in the Peruvian Andes', *Geoenvironmental Disasters* **7**(1).

Muñoz, R. (2017), Impacto del Cambio Climático en los Recursos Hídricos de la Sucuenca Quillcayhuanca, Perú, PhD thesis.

Nash, J. E. & Sutcliffe, J. (1970), 'River flow forecasting through conceptual models part I — A discussion of principles', *Journal of Hydrology* **10**(3), 282–290.

Neukom, R., Rohrer, M., Calanca, P., Salzmann, N., Huggel, C., Acuña, D., Christie, D. A. & Morales, M. S. (2015), 'Facing unprecedented drying of the Central Andes? Precipitation variability over the period AD 1000-2100', *Environmental Research Letters* **10**(8).

Olivos Aranda, A. Z. (2003), Estudio de Naturalizacion de la Informacion Hidrológica del Rio Vilcanota, Technical report, EGEMSA.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. & Solecki, W. (2017), 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change* **42**, 169–180.

Oudin, L., Andréassian, V., Mathevet, T., Perrin, C. & Michel, C. (2006), 'Dynamic averaging of rainfall-runoff model simulations from complementary model parameterizations', *Water Resources Research* **42**(7), 1–10.

Postigo, J. C. (2020), 'The role of social institutions in indigenous Andean Pastoralists' adaptation to climate-related water hazards', *Climate and Development* **0**(0), 1–12.
URL: *https://doi.org/10.1080/17565529.2020.1850409*

Rathjens, H., Bieger, K., Srinivasan, R. & Arnold, J. G. (2016), CMhyd User Manual Documentation for preparing simulated climate change data for hydrologic impact studies, Technical report.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. & Tavoni, M. (2017), 'The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview', *Global Environmental Change* **42**, 153–168.

Schauwecker, S., Rohrer, M., Huggel, C., Endries, J., Montoya, N., Neukom, R., Perry, B., Salzmann, N., Schwarb, M. & Suarez, W. (2017), 'The freezing level in the tropical Andes, Peru: An indicator for present and future glacier extents', *Journal of Geophysical Research* **122**(10), 5172–5189.

Silva Lovón, J. L. & Cruz Alfaro, G. (2014), Análisis de mercado del sistema eléctrico de la ciudad del Cusco en un horizonte de 20 años, PhD thesis, Universidad Nacional De San Antonio Abad Del Cusco.

Singh, P. & Bengtsson, L. (2005), 'Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region', *Journal of Hydrology* **300**(1-4), 140–154.

SVGW (2017), 'Der Wasserbedarf in der Schweiz sinkt'.
URL: *http://wasserqualitaet.svgw.ch/index.php?id=874*

UN (2019), 'World Population Prospects 2019: Data Booklet', *Department of Economic and Social Affairs Population Division* pp. 1–25.

UNCTAD (2020), World Investment Report 2020: International production beyond the pandemic, Technical report, UNCTAD, Geneva, Switzerland.

UNICEF & WHO (2020), State of the World's Sanitation, Technical report, New York, USA.

van Vuuren, D. P. & Carter, T. R. (2014), 'Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the ol', *Climatic Change* **122**(3), 415–429.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. & Rose, S. K. (2011), 'The representative concentration pathways: An overview', *Climatic Change* **109**(1), 5–31.

Vega Jácome, F. & Acuña Azarte, J. Y. (2016), Análisis del riesgo de sequías en el sur del Perú, Technical report, Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), Lima, Peru.

Vergara Rojas, R. (2017), Potencial hidroelectrico de la cuenca del rio vilcanota en la region cusco y mejoras en la operación de cc hh con grupos pelton y francis.

Vergara, W., Deeb, A. M., Valencia, A. M., Bradley, R. S., Francou, B., Zarzar, A., Grünwaldt, A. & Haeussling, S. M. (2007), 'Economic impacts of rapid glacier retreat in the Andes', *Eos* **88**(25), 2–4.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. & Wada, Y. (2020), 'Increasing dependence of lowland populations on mountain water resources', *Nature Sustainability* **3**(11), 917–928.

Water, U. (2020), WWAP (UNESCO World Water Assessment Programme), 2019, United Nations World Water Development Report 2020: Water and Climate Change, Technical report.

White, C. (2014), Understanding water scarcity: Definitions and measurements, *in* R. Q. Grafton, P. Wyroll, C. White & D. Allendes, eds, 'Global Water: Issues and Insights', ANU Press, Canberra, Australia, pp. 161–165.

Personal declaration:

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

S. Meier

Selina Meier

Wetzikon, 31st January 2021