Climate Change Adaptation Case Studies

Climate Change Impacts During Droughts on the City of Trujillo, Peru

Inter-American Development Bank
Case Study Report
December 2012

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Climate Change Impacts During Droughts on the City of Trujillo, Peru

Prepared for Inter-American Development Bank

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1 Introduction

1.1 Background

Inter-American Development Bank (IADB) has contracted DHI to conduct this study under a project called "Knowledge and Capacity Building Product".

The overall objective of the project is the development of an initial portfolio of adaptation case studies allowing IADB to respond to requirements and needs of its member countries in establishing specific policies of adaptation to climate change with respect to impacts on water resources.

The case studies are based on on-going IADB activities in the Latin American region and they are aiming at providing local information and analyses assisting the local water resources managers in coping with the climate change challenges but also to prepare guidelines on how to mainstream adaptation to climate change into implementation of Bank-funded projects and to recognise explicitly the impact of adaptation measures.

The case study described in the present report forms part of this projects and concerns:

Climate Change Impacts During Droughts on the City of Trujillo, Peru

The specific objectives of the case study are:

i. Contribute to strengthen the capacity of water and sanitation company SEDALIB in Trujillo and the City's authorities to adaptively respond to climate change in terms of their needs and vulnerability requirements.

ii. Define, in terms of measurable quantitative variables, the vulnerability of the water and sanitation sector in LAC to climate change for different types of projects.

iii. Contributing to the establishments of guidelines for "best practices" in adaptation to climate change in the water and sanitation sector in Latin America and the Caribbean (LAC).

iv. Contribute to the Bank's across-the-board efforts to classify, monitor and evaluate its investments in reducing the vulnerability of climate change in the region.

In addition to Trujillo three other cities have been selected to serve as cases of different types of climate change impacts, namely:

1. Montevideo, Uruguay (increased hydrological extreme events)
2. Port-of-Spain, Trinidad and Tobago (sea level rise)
3. Quito, Ecuador (Mountain hydrology/Glacier retreat)

As a strategic partner of the City of Trujillo and SEDALIB, the Inter-American Development Bank has during the recent years developed several basic water and sanitation infrastructure investment projects in the city, and currently the Bank's Water and Sanitation Division, under which this project resides, is working with Trujillo under the umbrella "Sustainable Cities" to improve the sustainability of the City on a very broad scale including enhancement of the institutional capacity for efficient management.

1.2 The Case Study

The City of Trujillo is located at the bank of the Moche River (see Figure) and the city receives its waters from two different sources:

1. The local groundwater aquifer in the Moche Valley, and

2. The trans-basin water transfer via the Chavimochic Canal. This canal conveys water from the perennial Santa River and distributes it along the coast. The water is mainly used for cash crop irrigation. At present, the supply to Trujillo from the canal (1.25 m3/s) has the highest priority (higher than irrigation) and amounts only a small fraction of the capacity of the canal.

The assessment of the vulnerability of the City of Trujillo to Climate change will therefore deal with the possible climate impacts on both of these sources and the consequences for supply of the City. From hydrological and climate points of view the two sources are quite different.

The Moche River is fed by a basin of 2700 km2 predominately located in the arid or semiarid part of the country (see Figure). There are no glaciers in the basin and the flow varies significantly over the year and is often quite low (below 1 m3/s) in parts of the dry season. The only climate change assessments available for the Moche basin is the overall national assessments based on the global circulation models with a very coarse resolution. Furthermore, the hydrological information and studies of the river are sparse. The case study has analysed the possible changes in the recharge to the Moshe aquifer on the basis of the available information

The Santa River Basin has a total area of about 12,200 Km2, making it the second largest and most regularly flowing Peruvian river to reach the Pacific Ocean (see Figure). The Santa River is fed by the glaciers of the Cordillera Blanca, which define the basin´s eastern boundary. The Cordillera Blanca contains the world´s largest concentration of tropical glaciers, most of which flow westward toward the Pacific Ocean along the Santa River. The Santa River is better investigated than the Moshe. Regional models for downscaling climate change projections have been established and assessments of climate change impacts are available both for the river flows and for the glacier flows. These existing studies have been used to quantify the possible climate change effects for the city of Trujillo. The allocation of the water resources in the Santa River is politically sensitive, and with competition for the resources, particularly in the dry season, other pressures than the pure climatic ones may have to be taken into account in the evaluation of the future supply to the City of Trujillo.

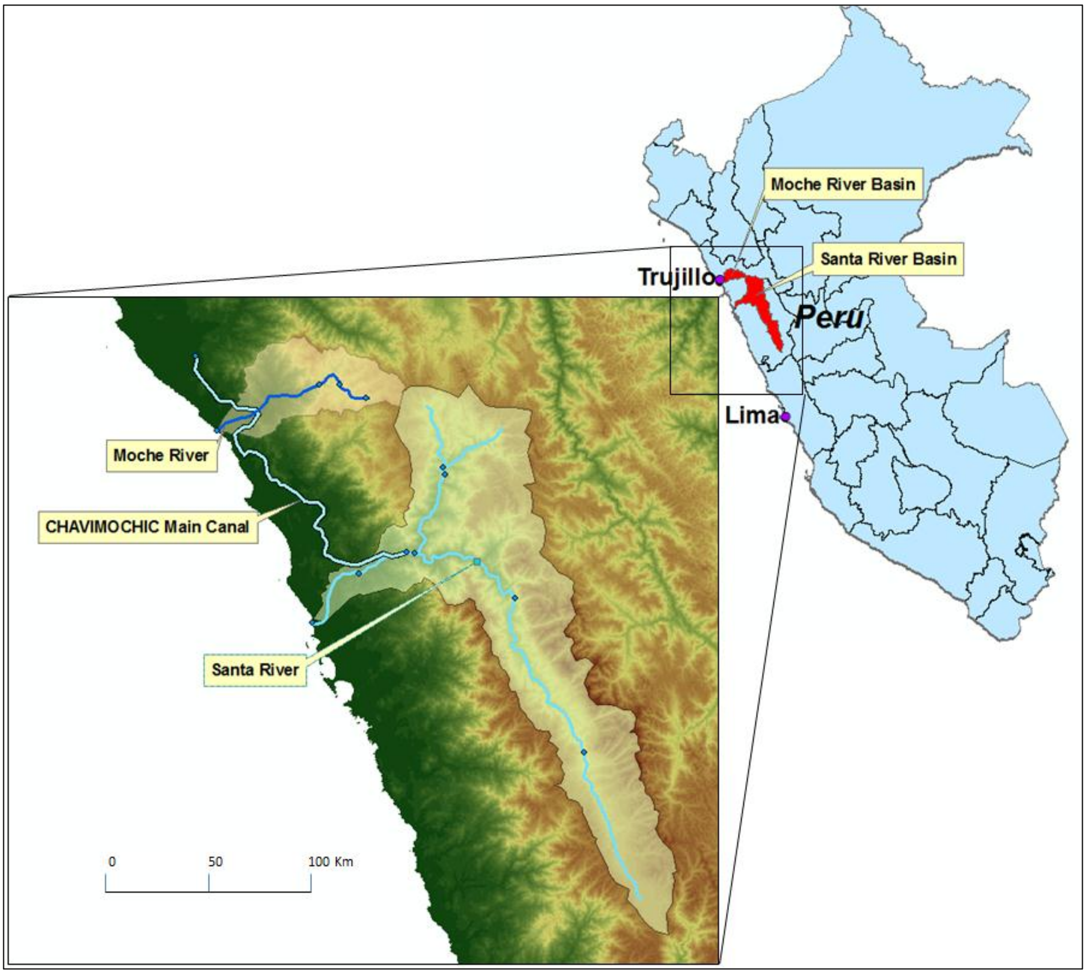

Figure location of the Moche and Santa River basins

In addition to the supply of domestic water to the City of Trujillo, the Chavimochic project also supplies water to irrigation along the coast and in the Moche valley. Farmers in the valley previously pumped their irrigation water from the Moche aquifer, but many of them now make use of the surface water from Chavimochic. Due to the losses from the irrigation this change in water source means a net import of water to the aquifer that has in recent years raised the groundwater levels in Trujillo to levels causing troubles for the foundation of buildings and roads as well as drainage congestion in the downstream parts of the valley. Hence, the water resources challenges faced by Trujillo seem to be more related with drainage congestion than with droughts.

Since SEDALIB still pumps parts of its raw water from upstream in the Moche aquifer and wish to expand this pumping, this case study includes a sustainability analysis of such pumping under a changed climate.

On the basis of assessment of the climate change impacts on the Chavimochic canal flow and of Moche aquifer, possible adaptation measures have been identified and preliminarily ranked to form an initial outline adaptation plan with focus on the proximate future. The initial findings on the adaptation options will be presented to and discussed with the stakeholders in Trujillo before a revised case study report is produced.

1.3 Approach to the Case Study

The approach used in the case study is inspired by a stepwise approach to incorporate Climate Change Adaptation and Resilience into development projects, as developed by USAID. The approach has, however, been modified to fit this project, both in terms of scope and focus. Where the original approach seems to focus on primarily on new infrastructure projects, the present case study considers the sustainability of the existing water supply and drainage systems of Trujillo and their adaptation to future climate conditions. The approach is illustrated in Figure 1..

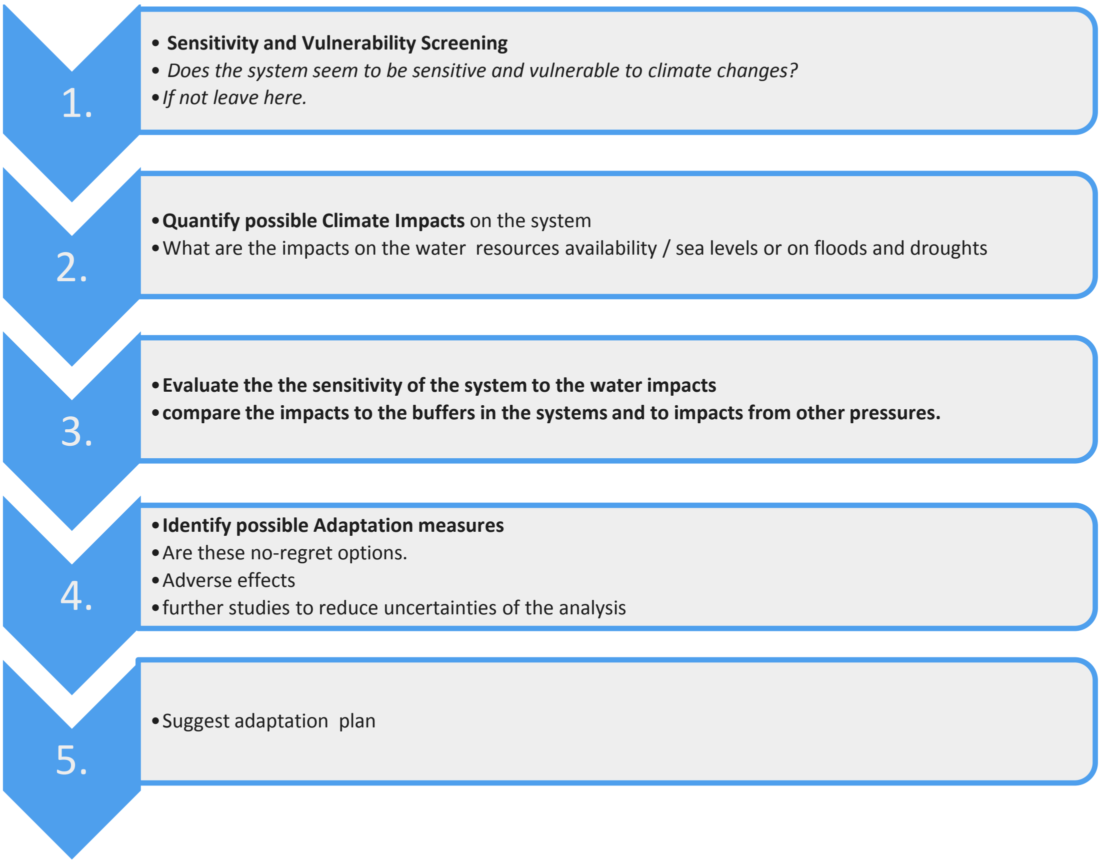

Figure 1. Stepwise approach used in the case studies under this project.

2 Summary, Conclusions and Recommendations

2.1 Vulnerability Screening

The domestic water supply from Rio Santa to Trujillo via the Chavimochic canal is not likely to be affected by climate change. The annual supply to Trujillo is only 4% of the irrigation supply from the canal and the domestic supply has priority over irrigation. Furthermore, the capacity of the Chavimochic canal has been designed for servicing a larger area than today. Hence, there should be a buffer in the Chavimochic project even to increase the supply to the city, if it turns out to be necessary.

Part of the supply is based on pumping from the Moche aquifer and this pumping may be sensitive to droughts. The impacts on the aquifer of proposed pumping under dry and wet future climate scenarios have therefore been analysed with an existing groundwater model.

The City of Trujillo could be indirectly vulnerable to climate change through its possible impact on the irrigation sector that, in essence, is the basis for the City´s economic sustainability. The climate change impacts on the flows in the Santa River, as assessed by other studies (Ref.), has therefore been discussed and used to analyse the impacts on the Chavimochic canal flows.

An assessment of the possible changes in irrigation water demands, under a dry climate change scenario, has also been carried out and included in the analyses to investigate the sensitivity of the irrigation sector to the predicted climate change.

The analyses indicate that Trujillo is vulnerable to drainage congestion under a possible wet future climate scenario, but that the City could be short of water to meet the domestic demands after 2020 under a possible dryer climate. However, the analyses also suggest that adaptation measures to both situations exist.

2.2 Climate Change Prediction

The water to the City of Trujillo originates from two different sources: the Rio Moche catchment and the Santa River (through the Chavimochic canal). The climate change predictions for these two areas are dealt with separately.

2.2.1 Climate change prediction for the Moche River basin

The best climate change assessment available for the Moche River Basin is the one made in the Second National Communication on Climate Change (Ref.). The assessment is based on the global climate scenarios, using dynamical and statistical downscaling methodologies recognised by the IPCC for the A2 high rate emission scenario.

From this national assessment the following local future climate scenarios have been elaborated and analysed in the present case study:

- A Dry climate change scenario assuming a temperature rise of 1.2 degrees in the Moche basin and a corresponding 10% *decrease* in the basin rainfall.

- A Wet climate change scenario assuming a temperature rise of 0.4 degrees in the Moche basin and a corresponding 10% *Increase* in the basin precipitation.

- A climate change scenario for the coastal areas assuming a temperature rise of 0.8 degrees and no changes in rainfall, which is negligible in these desert areas.

2.2.2 Climate change prediction for the Santa River basin

Climate change projections for the Santa River basin and their impacts on water availability was modelled and reported by MINAM and SENAMHI in 2012(Ref.). This report is the most up to date study of the area and forms the basis of the information presented here. The report assesses changes for the time horizon 2030-2039.

Climate change projections for Santa were simulated for the A1B future scenario of greenhouse gas emissions. The A1B scenario is based on the assumptions of rapid economic growth and low population growth, with a rapid introduction of a new and more efficient technology.

Two climate model results are analysed: The Japanese MRI model with high spatial resolution (20km x 20 km) and NCAR model, which the result of dynamic downscaling of the CCSM3 Global climate model with a resolution of 5km x 5km.

For the period 2030-2039 the two models both project that rainfall in the wetter months would increase and rainfall in the drier months of July and August would decrease slightly. However, the NCAR model also projects a decrease in rainfall in January and February. *The models predict the annual precipitation to increase by 3.2% and 16.1%* for the NCAR and MRI models, respectively.

Both climate models show an increase in temperature in the Santa Basin for all months. *The increases in temperature range between 0.9 and 1.7 degrees C* for both models.

2.3 Climate Change Impacts on the Water Use and on the Groundwater

2.3.1 Impacts on the Moche aquifer

Based on rainfall runoff analyses of the Upper Moche basin, carried out under this case study, the 75% probable monthly runoff at Quirihuac, upstream of the aquifer, has been found to change by factors of 1.37 and 0.57 for the wet and dry climate scenarios, respectively. The corresponding factors for 75% probable base flow (groundwater contribution) are 1.41 for the wet scenario and 0.55 for the dry one.

An increased pumping pattern from Chavimochic's wells has been suggested by a previous study (Chavimochic, Ref.) to combat drainage congestion. *A combination of this pumping and the present extraction by SEDALIB for domestic supply has been analysed under the dry climate scenario and the present pumping rates has been found to be sustainable*. Due to the lower groundwater inflow to the aquifer and the dryer river, the groundwater levels will be lower under the future dry climate scenario. In general the results are an average drop of 0.9 m in the part of the aquifer presently having depths to groundwater less than 5 meters.

For the wet climate scenario and the above-mentioned pumping the groundwater levels will rise all over the aquifer because both the river flows and the groundwater inflow will increase. The average rise has been calculated 0.32 m for the area, in which the groundwater is already less than 5 m under terrain. *Increasing the pumping for domestic use to 1500 l/s as suggested by SEDALIB in the 2005 master plan (*Ref. *) has, however, been found to be sufficient to control the water level rise* and even lower the groundwater by 0.64 m in average under the essential parts of the city. *This future pumping scenario seems to be sustainable under the wet future conditions.*

The increase of domestic extraction to 1500 l/s has also been analysed under the dry climate scenario. In this case the results are substantial lowering of the groundwater by around 4.5 m in average under the essential parts of the city. *The pumping scenario still seems to be sustainable* but groundwater levels along the coast line approach zero although they are still positive. *To prevent possible salinity intrusion into the aquifer the scenario should* therefore *be investigated in larger details and, if implemented, accompanied by intensive groundwater monitoring in the coastal fringe*.

Hence *the analyses, carried out under this study with the existing groundwater model, suggest that the proposed increase in pumping, to meet the domestic demand until 2018, seem to be sustainable for both climate scenarios, and it seems to be necessary and sufficient to control groundwater rise under the city in the wet scenario.*

2.3.2 Impacts on the water availability for the Chavimochic project

The real variable of interest for Trujillo is the future change in available water for the Chavimochic project in the Santa River.

On the basis of rainfall-runoff and glacier modelling, MINAM and SENAMHI have assessed the changes in flow at Condor Cerro, just upstream of the CHAVIMOCHIC intake. Results for both climate models *show an increase in flow in all months and increases of around 15% for the drier months*, relative to the period 1969-1989. *This suggests that for the time horizon 2030-2039, the climate induced changes in flow alone will not cause problems for CHAVIMOCHIC water supply.*

The projected flow increase includes a component of extra runoff from loss of ice mass in the basin. This component will dry out over time as the glaciers disappear. A quick analysis of the experienced melting rates suggests, however, that the glaciers are not likely to disappear within the considered time horizon (until 2039).

2.3.3 Impacts on the Irrigation sector

The irrigation sector is very important for Trujillo's economy and its social sustainability. Climatically the coastal plains around Trujillo are virtually deserts. The average annual rainfall in Trujillo is negligible and the uncertainty in the rainfall estimates therefore has little effect on the climate change impacts on the irrigation. With no indication of reduced water availability for CHAVIMOCHIC until 2039, the impact assessment has been confined to a rapid analysis of changes in reference evapotranspiration. The analysis suggests that the change in annual irrigation demands in the Trujillo area may be around +6 % under a future climate and that the changes in the most critical month may be +7%. If such impacts materialise it may be compensated by reducing the planned future expansion in the third stage of the project by 26%. Alternatively, the Irrigation demand may be reduced to a new (sustainable) level by investing in water saving irrigation equipment or by adjustment in cropping and irrigation patterns. Further planning of such measures and quantification of their possible effects will, however, require more detained analyses than those possible under this study.

2.4 Outline Adaptation Plan

Due to the high uncertainties embedded in the assessments of the climate change impacts, the adaptation measures identified and ranked in this case study give preference to:

- win/win scenarios (scenarios that benefits the system in other ways that just climate change adaptation),
- no-regret options (developments that will be good investments independently of how the climate develop) and
- studies that increase knowledge and assist in reducing some of the encountered uncertainties.

A number of adaptation measures have been identified, and preliminarily ranked using a multi criteria scoring matrix focusing, among others, on the above mentioned criteria. Ranking options through such multi criteria analyses will always be subjective and may be changed by altering the criteria and the weights assigned to them. The suggested adaptation measures are listed below in a sequence following the initial ranking. Both the suggested adaptation options and their ranking shall be discussed with the stakeholders in Trujillo and the list adjusted in the final version of this report.

2.4.1 General adaptation measures

1.1 *Detailed climate change assessment* of the Moche River basin and surrounding areas in line with the work carried out on the Santa basin should be started. The aim is to reduce the considerable uncertainty on the climate predictions and, as a minimum, to constrain the impact to either a flow decrease or flow increase at the Quirihuac station. The work should involve several climate models and dynamic downscaling.

1.2 *Establishment of a groundwater modelling team* conducting more detailed groundwater and surface water inaction studies of the Moche aquifer. The team should enable the city, SEDALIB and Chavimochic *to respond dynamically to possible changes in the climate and in the pumping pattern* aiming at improving the drainage congestion measures without running the risk of over pumping

2.4.2 Adaptation to a drier climate.

2.1 *Conduct detailed modelling studies* to reveal with larger accuracy the sustainable pumping from the aquifer. The rapid assessments of this study have indicated that planned increase in pumping rates up to 2018 seems to be sustainable under the predicted drier climate.

2.2 *Negotiate options for increasing the delivery of domestic water from Chavimochic* to be effectuated in case new climate assessment point to a dryer scenario, than the one analysed in this study, or if detailed analyses find the planned pumping rates to be unsustainable.

2.3 *Start planning for increased irrigation demands.* The assessed increase in irrigation demands of 6% annually and 7% in the most critical month (December) does not seem to be alarming Since the Chavimochic project is not fully developed, it still has surplus of water resources to accommodate such changes. However, the predictions have to be refined, and taken into account in the planning of further development, or compensated by changes in cropping patterns or water savings

2.4 *Monitor the groundwater levels* in the aquifer, particularly along the coast line to trigger possible over extraction and alter pumping scenarios accordingly.

2.5 *Reducing the gross demands* by minimising losses in the distribution system (pressure reduction and /or replacement works.

2.6 *Demand management initiatives* aiming at reducing the net demand by awareness raising, price policies or by restrictions in water use. The planned pumping scenarios will only meet the demands up to 2020 reducing the demand could prolong the time until further sources will be needed.

2.7 *Expansion of the extraction from the Chavimochic canal and increase of the treatment plant.* To be effectuated if further studies of the 2018 pumping scenario shows to be unsustainable. An extension of 750 l/s is suggested to compensate the difference between present pumping and proposed future pumping rates.

2.4.3 Adaption to a wetter climate

3.1 *More detailed groundwater and surface water interaction studies* of the Moche aquifer to confirm the findings of the present study and to plan further abatement of the drainage congestion.

3.2 *Investigation of the opportunities* of further expansion of the development plans for the Chavimochic project opened by a larger availability of water.

3.3 *Increase SEDALIB's pumping to the planned 1500 l/s* and use this for supply of the city if the water quality so allows. The pumping scenario seems to be capable of compensating for the negative effects of a wetter climate.

3.4 *Increase the pumping for irrigation in the Valley,* as suggested by Chavimochic in Scenario 3 of the previous study (Ref.)

3.5 *Abstraction of water from the river for export out of the basin.* This may help the drainage congestion but needs further investigation and quantification.

3.6 *Restricting irrigation in certain areas of the valley.* If the drainage congestion cannot be controlled by other measures, it may be necessary to restrict the irrigation in certain areas of the valley to certain crop types with lower water consumption and leakage to groundwater.

2.5 Lessons Learned by this Case Study

In situations where the uncertainties in climate change assessments point in different hydrological directions (towards either a wetter or a drier future climate) structural no-regret options may be difficult to define, before more precise climate predictions agree on the trend direction. Hence, improving local climate predictions is a priority.

Implementation of increased groundwater pumping under dry climate scenarios would require detailed and dynamic assessment, planning and management.

3 Sensitivity and Vulnerability Screening of the System

3.1 General

The rationale of the rapid vulnerability assessment described in this section is to evaluate whether Trujillo's water supply system seems to be robust to climate changes, particularly with respect to droughts.

The vulnerability of a system to climate change not only depends on the local climate change or its impacts on the water resource; it also depends on the system's sensitivity to such changes and on its capacity to adapt to a changed situation.

Water supply systems taking their water from an abundant source, e.g. extracting an insignificant fraction of the flow of a major river, are not likely to be sensitive to even large changes in river flows. In such cases it might therefore not be necessary, from a water supply point of view, to invest large efforts in climate adaptation planning.

In principle, a system may also have a built-in readily available capacity to adapt to large changes in the resource availability. Also in such cases the system can be said to be robust to climate changes and further adaptation analyses may be avoided or postponed. Water supply systems are, however, normally designed to supply a population of a certain size (often close to the present size) with sufficient amounts of water under the present hydrological conditions. As the serviced population are likely to increase in future, and initiatives for reducing the per capita consumption are often undertaken on an "as needed" basis; few systems, in fact, have a significant extra capacity to be mobilised as protection against possible decreased water availability.

In basins where the water resources are shared by several sectors (e.g. domestic and industrial supply, energy production, agriculture and the environment) the supply of drinking water is often given a higher priority than supply to other uses. This may in fact lead to domestic supply not being directly vulnerable to a change in climate, because large water extractions from other sectors (often irrigation) could provide a sufficient buffer protecting the domestic supply against the impacts from a changed climate. However, a system in which some sectors are suffering to protect others could easily generate political problems. The need for adaptation would still exist; it would just be passed from one sector to another.

3.2 Could Trujillo's Water Supply be vulnerable to Climate Change?

With large predicted increases in the urban population and its demand for water in coming decades and the system's present supply capacity matching the present demand, the water supply system of Trujillo is likely to be both sensitive and vulnerable to changes in the water availability at the surface water intake in the Chavimochic Canal and in the Moche aquifer.

SEDALIB are already covering more than one third (750l/s) of Trujillo's domestic water supply (2000 l/s) from wells in the Moche aquifer and have plans to increase this pumping to meet the projected future increases in the water demand (Ref.) . This plan may be sensitive to climate change impacts on the aquifer.

At present, the high groundwater levels in Moche valley are causing problems for the infrastructure in Trujillo. The drainage congestion already experienced today may be further aggravated if the climate in the Upper Moche Valley changes to a wetter regime causing larger groundwater inflows and recharge from the river into the aquifer.

The case study will, therefore, investigate the impacts on the groundwater levels in the Moche Aquifer from predicted climate changes in the Upper Moche Basin. Since the present rainfall in Trujillo constitutes less than 1% of the potential evapotranspiration (Ref.) even larger climate changes in the city area itself are not likely to have any significant effect on the local water resources and will therefore not be studied further.

Although the flow in the Chavimochic canal will be sensitive to future changes in the flow regime of the Santa River, the Domestic Supply to Trujillo may not be under threat from such changes, since it is protected by having the first priority to the water and since the present domestic extraction demands only a small fraction of the canal flow. The irrigation activities are therefore acting as a buffer that protects the domestic supply against climate change effects. This study will, nevertheless, analyse the predicted changes in the Santa River flows to reveal if the flows are predicted to decrease, which could make it more difficult for SEDALIB to acquire additional water from the canal in future.

4 Climate Change Impacts on Water Availability and Groundwater Conditions

4.1 Projected Climate Change for Trujillo and the Moche River Basin

No specific predictions of the changes in temperatures and precipitation over the Moche River Basin (and Trujillo) have been available for this case study. The scenarios of climate change over the Moche River Basin used in this case study are therefore extracted from the mapped information at national scale from the Second National Communication (Ref.) which is the latest available climate change assessment. The assessment is based on the global climate scenarios (A2 high rate emission scenarios), using dynamical and statistical downscaling methodologies recognised by the IPCC.

4.1.1 Changes in precipitation

The predicted precipitation changes until 2030 have been assessed from the national map of temperature changes (Figure 4., Ref.). The map is at national scale and therefore rather coarse for making assessments on the Moche River Basin, which constitutes only 0.2 % of the national territory. It has, nevertheless, been used for the assessment as it is the only information available for the area at the moment.

For the area of interest, indicated by the blue rectangle on the figures, the average precipitation around year 2030 is seen to deviate between -10% and +10% from today's annual precipitation. In this case, study change factors of 0.9 and 1.1 have been applied on the observed precipitation series to represent dry and wet precipitation scenarios, respectively.

4.1.2 Changes in temperature

Similar to the precipitation changes, the only information on the expected changes in temperatures is in the form of maps on a national scale. Figure 4. shows the predicted changes in maximum annual temperature until year 2030 while a similar map of changes in minimum annual temperature is shown in Figure 4.. For the area of interest, indicated by a blue rectangle on the two figures, the minimum temperature may rise by 0.4-0.8 degrees C and the maximum temperature by 0.4-1.2 deg. C.

Assuming that the development of maximum and minimum temperatures is representative for the trend in monthly average temperatures, increases in the Moche River Basin temperatures until 2030 have, in this case study, been assessed at 0.4 dig C and 1.2 dig C representing dry and wet future scenarios, respectively. The maps show smaller temperature rises for the Chavimochic service area close to Trujillo along the pacific coasts. For this area, temperature rise estimates of 0.4 and 0.8 dig C for the period up until 2030 seem to be more realistic.

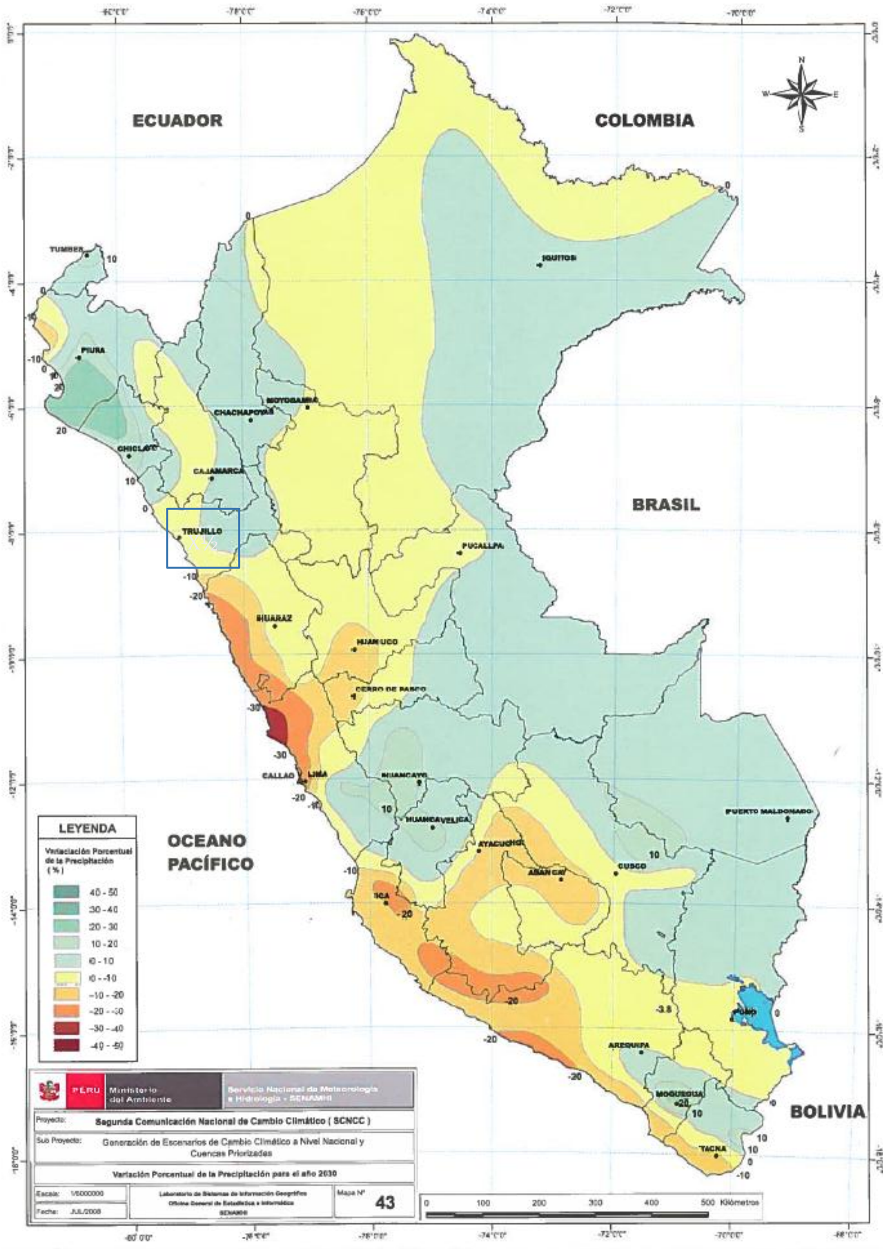

Figure 4. Predicted change in precipitation (as a per cent of present values) up to 2030 for Peru. Source: Second National Communication (Ref.).

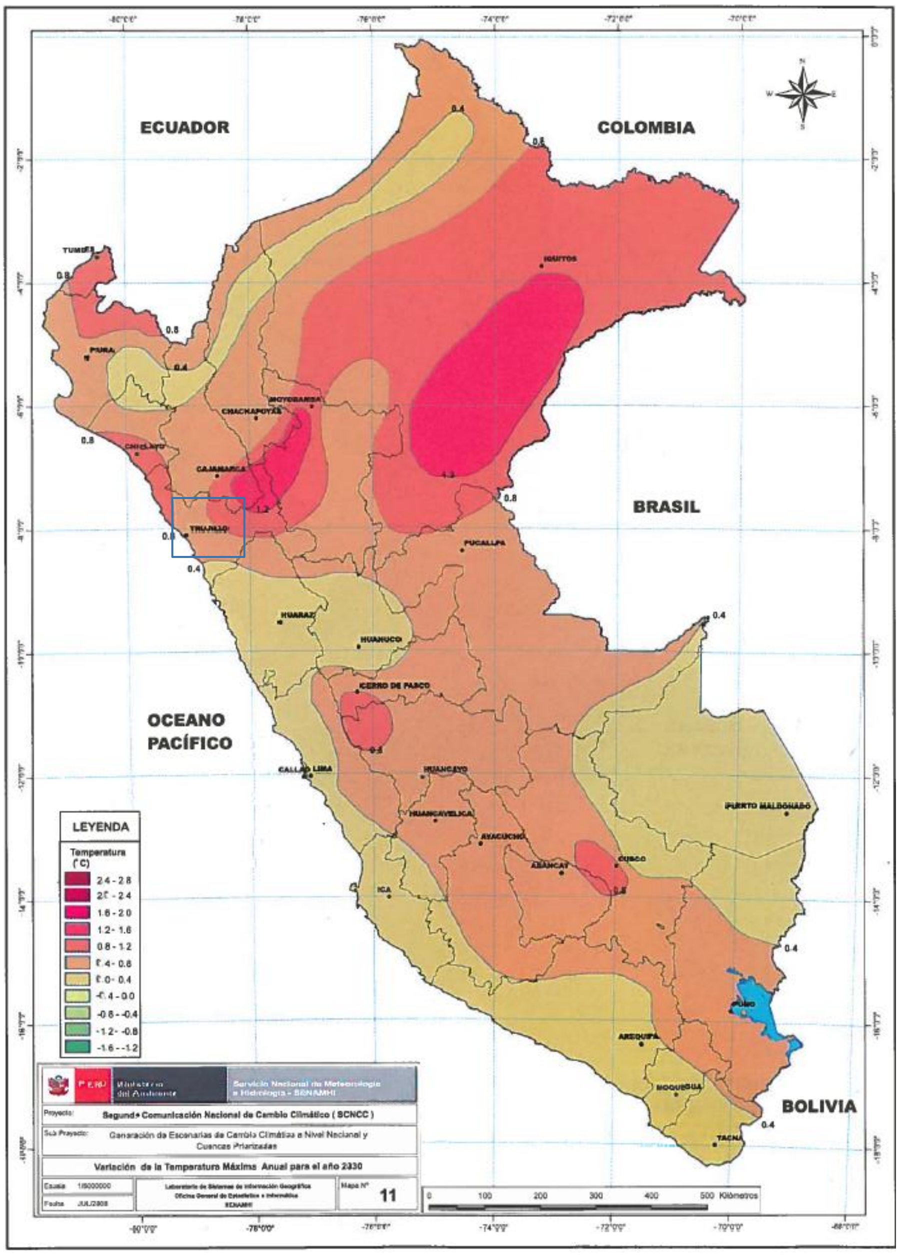

Figure 4. Predicted change in daily maximum temperature up to 2030 for Peru. Source; Second National Communication (Ref.)

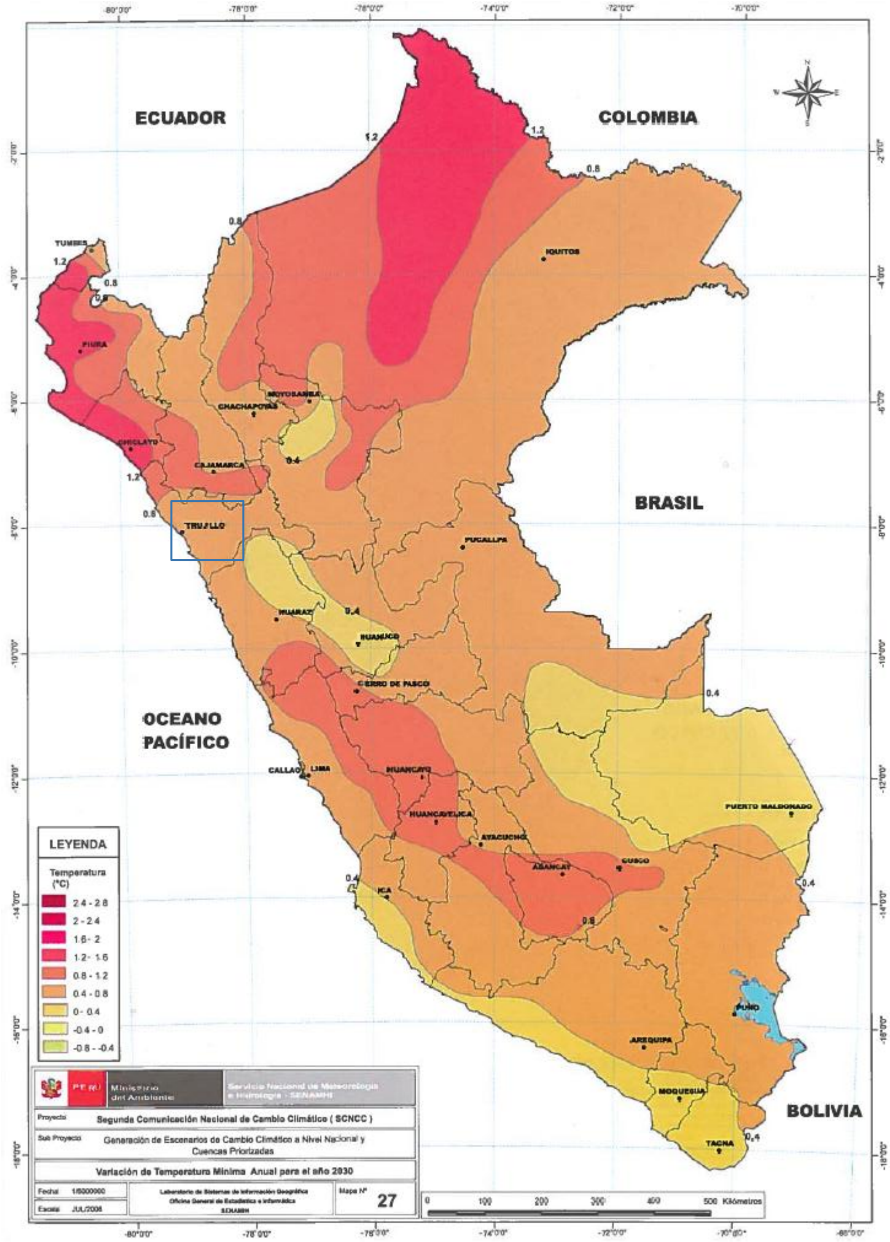

Figure 4. Predicted change in daily minimum temperature up to 2030 for Peru. Source; Second National Communication (Ref.)

4.1.3 Climate Change Impacts on Moche River flows and Aquifer Recharge

4.1.3.1 Approach

Although the City of Trujillo is located in a desert, the biggest water related problems faced by the city at present seems to be water logging and drainage congestion rather than water shortage and droughts. The raw water for supply to the city is taken partly from ground water in the Moche aquifer and partly from surface water canalised by the Chavimochic Project from the Santa River in the south.

The water supply to Trujillo is protected from droughts by:

a) having the highest priority among the water users supplied by the Chavimochic canal;

b) current groundwater abundance (rising water levels) in the Moche Aquifer and

c) only a small fraction of the aquifer inflows originating from the discharge from the upstream Moche River Basin.

The water logging in Trujillo seems to originate from the water transferred to the aquifer through seepage from canals and irrigation fields which, at least partly, use water from the Chavimochic Canal (transferred surface water).

The present case study analyses the sensitivity of the water balance of the Moche aquifer to the climate changes in Upper Moche Basin. The analysis is carried out as an assessment of the climate change impacts on the Moche River flows using a rainfall-runoff model of the whole upstream basin and further simulation of the groundwater conditions in the Moche aquifer using a groundwater model to reveal the aquifer's response to the changed river flows and projected future increased domestic demands. The applied model has previously established by Chavimochic to study possibilities for improving the drainage congestion (Ref.).

Sea Level Rise

A detailed assessment of impacts from the sea level rise has not been within the scope of this case study and this paragraph therefore only summarises the possible issues from such rise. A special case study under this project from Trinidad and Tobago (Ref.) is dedicated to sea level rise impacts and describes possible adaptation measures in more details.

The local sea level rise at Trujillo will be a combination of the general regional rise, which is as a function of the heat expansion of the sea water and of the melting of the polar ice caps, the local hydro-graphic conditions and the local tectonic changes in terrain levels. Ref. quotes the latest projections of the global sea level rise at around 40 cm by 2050 and up to around 2 m by the end of the 21st century.

Unless compensated by tectonic rise of the local terrain, sea level rise will have an impact both on the drainage congestion and on the salinity levels in the groundwater close to the present coastline. The location of the coastline itself may also retreat as a consequence of the seal level change.

The terrain slope near Trujillo's coast line is in the order of 1 %, and terrain elevation is around 10 m above the present sea level about one km from the coast. Although a rise in the sea level can affect the ground water levels further inland the groundwater levels are already quite close to the terrain in the coastal areas (see Appendix B). If necessary it should therefore be possible to confine the impacts from sea level rise to the coastal fringe by establishment of drains parallel to the coast either by canals draining by gravity or by pumping.

Salinity intrusion in the aquifer close to the coast has already been observed and may be aggravated by sea level rise. According to SEDALIB groundwater pumping close to the coast has, however, already been stopped due to salinity problems. Consequently, the supply to the City should not be threatened by this effect.

Possible salinity intrusion through the river mouth is deemed not to be a problem, since fresh water is not extracted close to the sea. Problems with such intrusion may be combatted by salinity barriers if this shows to be a problem in future.

4.1.3.2 Climate change impacts on the Moche River flows

To analyse the possible consequences of the predicted climate changes on the river flows in Moche, a conceptual rainfall-runoff model (The NAM model, Ref.) has been established and calibrated on the Moche River basin upstream of Quirihuac flow gauging station (see Figure 4.). The Upper Basin has a total area of 1830 km2 with an average altitude of 2680 m.a.s.l.

The NAM model can be characterised as a deterministic, lumped, conceptual and moisture accounting model with moderate input data requirements. The NAM model has been selected because it has been proven capable of simulating short-term climatic variations such as a series of dry or wet years and should therefore also be capable of simulating the climatic changes predicted in the Moche Basin. The NAM model is a well-proven engineering tool that has been applied to a very large number of catchments around the world, representing many different hydrological regimes and climatic conditions including the Peruvian Andes.

Using series of daily rainfall from local stations in the basin as input, the model has been calibrated on daily flow records from the Quirihuac Station for the period 1992-2004. It has been possible to calibrate the model to fit the long-term water balance of the calibration period within 1%, and the model simulates most of the years in the calibration period well with a good performance in both dry and wet years. A comparison between average monthly simulated and observed flows for the calibration period is shown in Figure 4..

Appendix A to this report has more details on the model setup and the calibration.

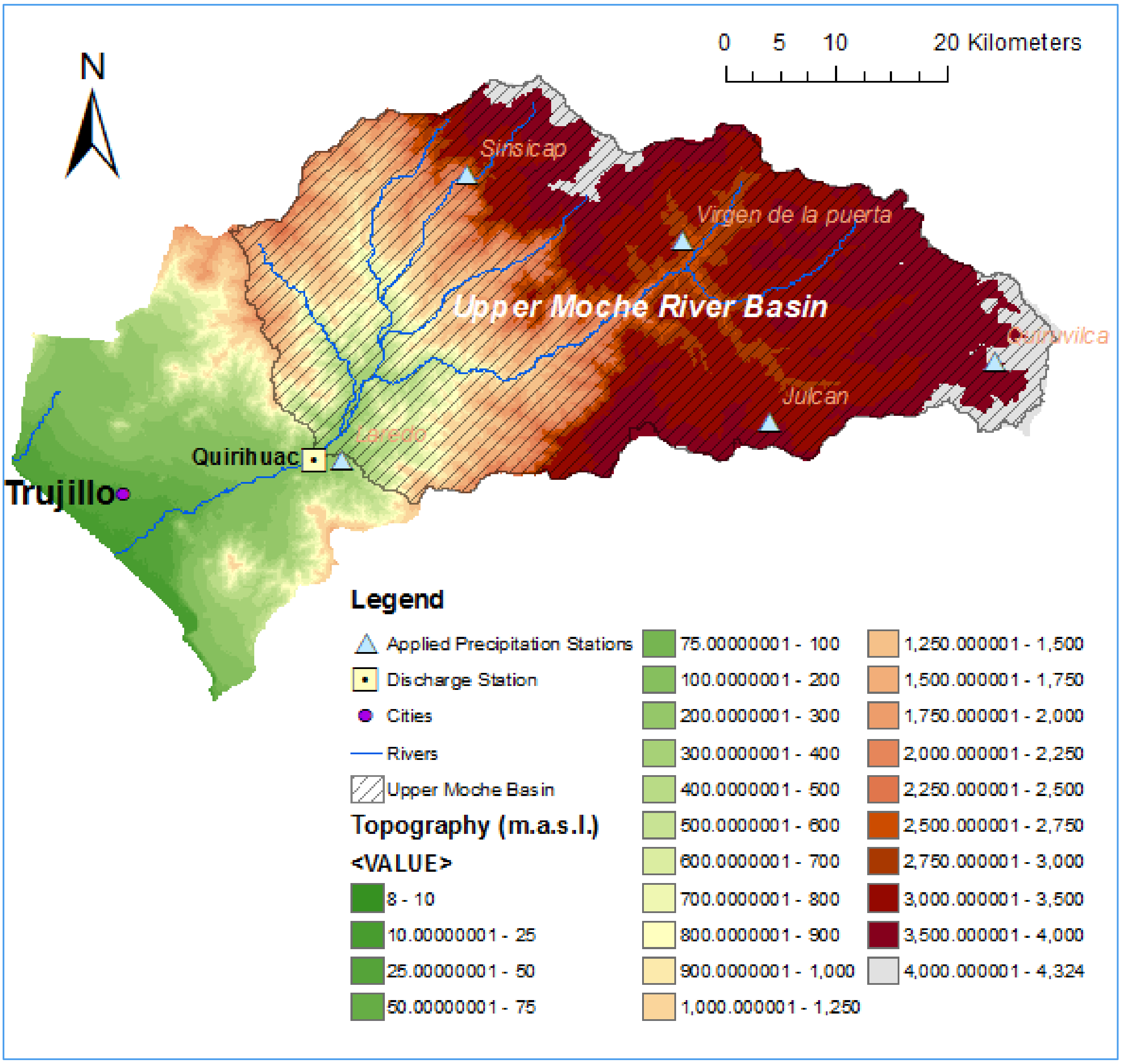

Figure 4. Location of hydrological stations used in the Rainfall runoff modelling of the upper Moche River Basin

Simulation of Climate Change Impacts

The calibrated model has been used to simulate two climate change scenarios:

- A wet scenario that combines a low temperature increase (0.4 deg. C) with a high increase in rainfall (+10%) and
- A dry scenario combining a high temperature increase (+1.2 deg. C) with a decrease on rainfall of 10%.

The analysed scenarios are listed in Table 4. and constitute the most extreme of the four scenarios emerging from combining the range limits of the climate change scenarios described in Section 4.1.

The 75% probable monthly runoff at Quirihuac has, through these analyses, been found to change by factors of 1.37 and 0.57 for the wet and dry climate scenarios, respectively. The corresponding factors for 75% probable base flow (groundwater contribution) are 1.41 for the wet scenario and 0.55 for the dry one.

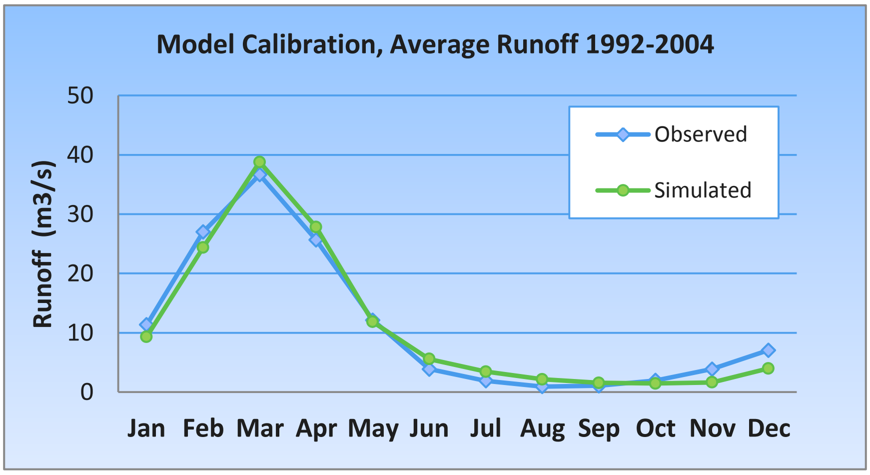

Figure 4. Calibration of the NAM model for the Moche River catchment. Average monthly simulated and observed runoff at Quirihuac

Table 4. Simulated climate change scenarios

Change in Temperature	Precipitation Change Factor	Calculated ET0 Change Factor	Included in analysis
Deg. C	Fraction	Fraction	-
+0.4	1.1	1.02	Yes, Wet estimate
+0.4	0.9	1.02	No
+1.2	1.1	1.04	No
+1.2	0.9	1.04	Yes, Dry estimate

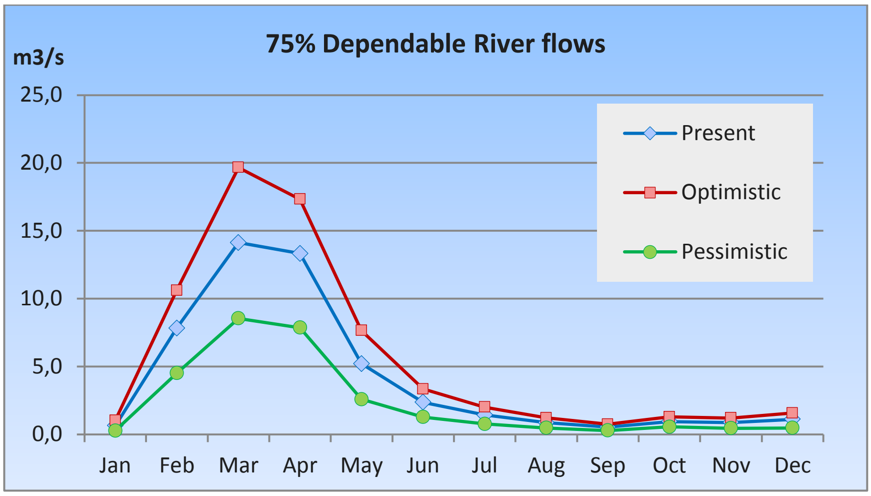

Figure 4. Simulated 75% dependable Monthly flows in the Moche River at Cuirihuac, for the present situation as well as for optimistic and pessimistic scenarios of the future climate.

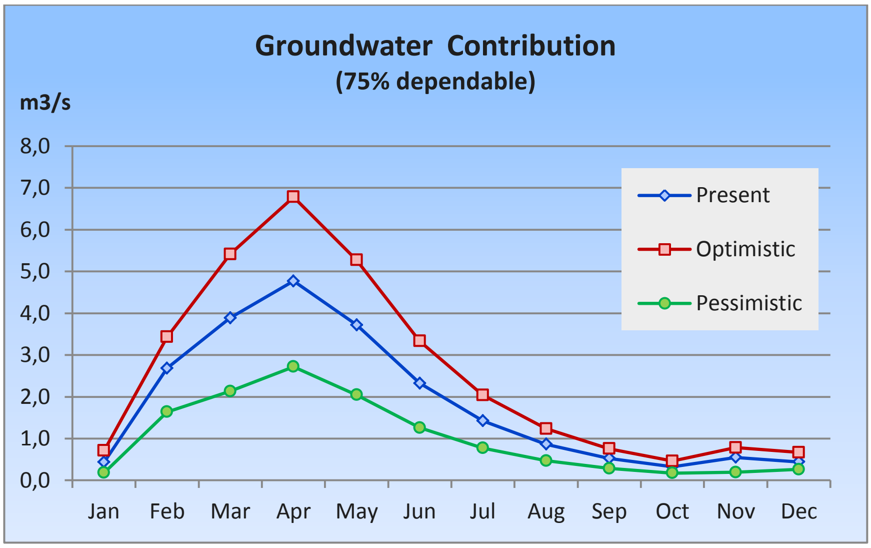

Figure 4. Simulated 75% dependable groundwater contributions to the Moche River upstream of Cuirihuac, for the present situation as well as for optimistic and pessimistic scenarios of the future climate.

4.1.3.3 Climate change impacts on the Moche aquifer

The climate effects on the sustainable pumping from the aquifer have been analysed using an existing groundwater model (Ref.). The model was originally established for Chavimochic to analyse pumping scenarios for drainage congestion alleviation and is based on the Visual MODFLOW groundwater simulation system (Ref.). It is a two-dimensional finite difference model of the Moche aquifer from the approximate location of the Quirihuac gauging station at the upstream end and to the coast at the downstream end. The city of Trujillo is located centrally in the model area covering large parts of the modelled aquifer. The extension of the model is indicated by the blue rectangle in Figure 4. with the aquifer being indicated by the yellow area on the maps. The aquifer is phreatic and consists of alluvial quaternary deposits.

The model includes all the pumping wells in the area with their present or suggested pumping rates. The previous simulations suggest that 9.7% of the inflow to the aquifer is from seepage from Moche River, 13.6% is groundwater inflow from the upper pates of the aquifer while the remaining 76.7% is seepage from the irrigation schemes.

The local precipitation over lower part of the Moche valley is negligible as explained in Section 3.2. The climate change impacts on the aquifer have therefore been modelled by changing the upstream boundary inflow to the model and changed leakage from the river.

The scope of the present study has neither allowed for a review of the calibration of the model nor for a recalibration. Hence, it is simply assumed that the existing model reflects the behaviour of the aquifer in a satisfactory manner.

The following paragraphs describe the results of the analyses of the groundwater conditions under the two projected climate scenarios. More details of these analyses are given in Appendix B to this report.

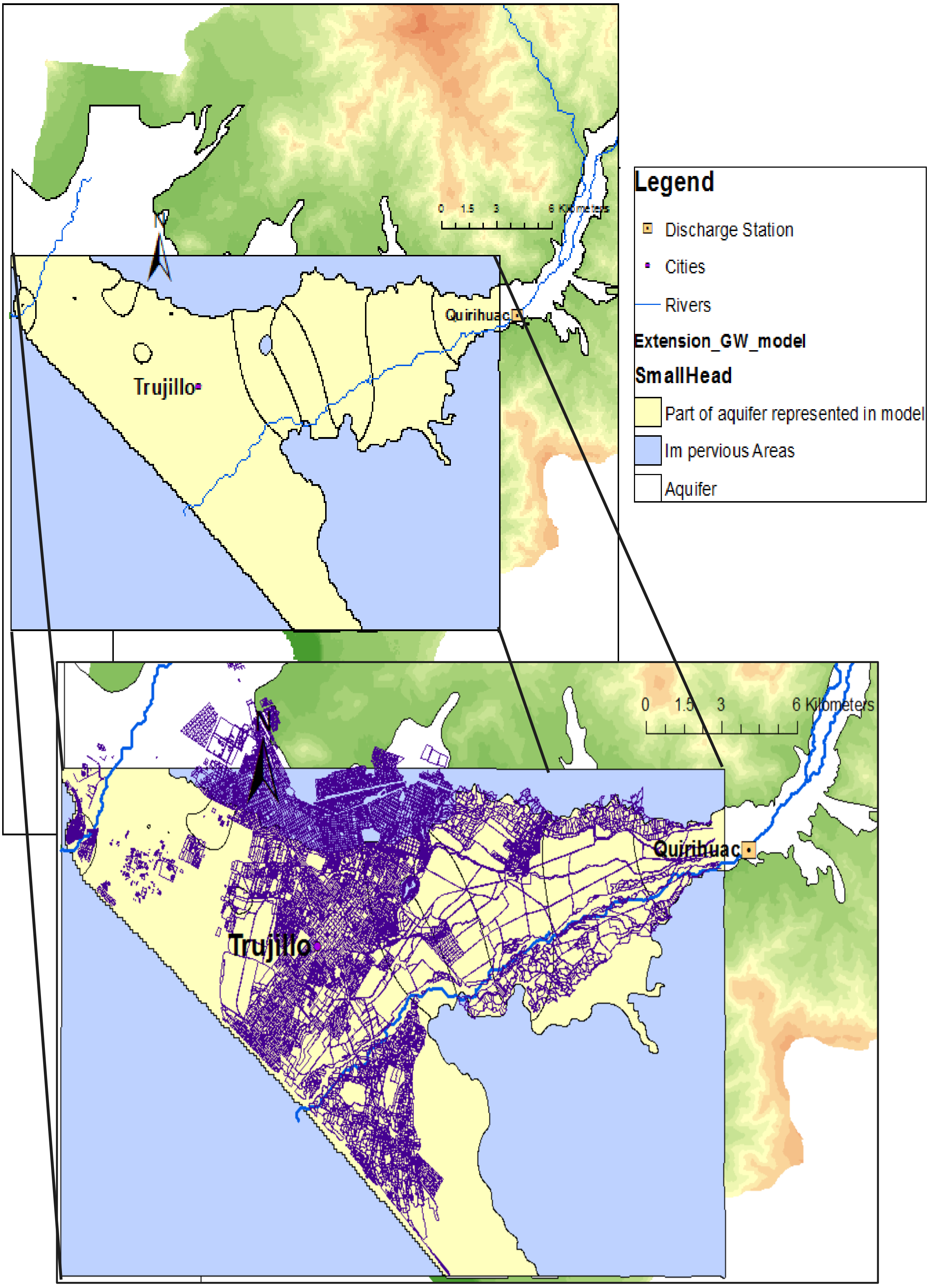

Figure 4. The Extension of the Chavimochic Model of the Moche Aquifer.

4.1.3.4 Present groundwater extraction under future climate scenarios

The groundwater levels have been simulated for the two future climate scenarios and compared to a simulation of the present conditions. The simulated rise in the groundwater table relative to the present conditions is shown in Figure 4. for the dry future climate scenario and in Figure 4. for the wet future climate scenario.

Dry future climate

Due to the lower groundwater inflow to the aquifer and the drier river, the groundwater levels will be lower under a future drier climate (Figure 4.). The aggregated impacts on the groundwater levels are listed in Table 4. and show an average drop of 1.2 m for the aquifer as a whole and an average drop of 0.9 m in the part of the aquifer presently having depths to groundwater of less than 5 metres. The aggregation areas are shown in Figure 4..

The water levels in the figures are taken from the model after 6 years of simulation, once the levels have stabilised. Since no indication of decreasing levels has been identified, it can be concluded that the present pumping is sustainable even under a future drier climate.

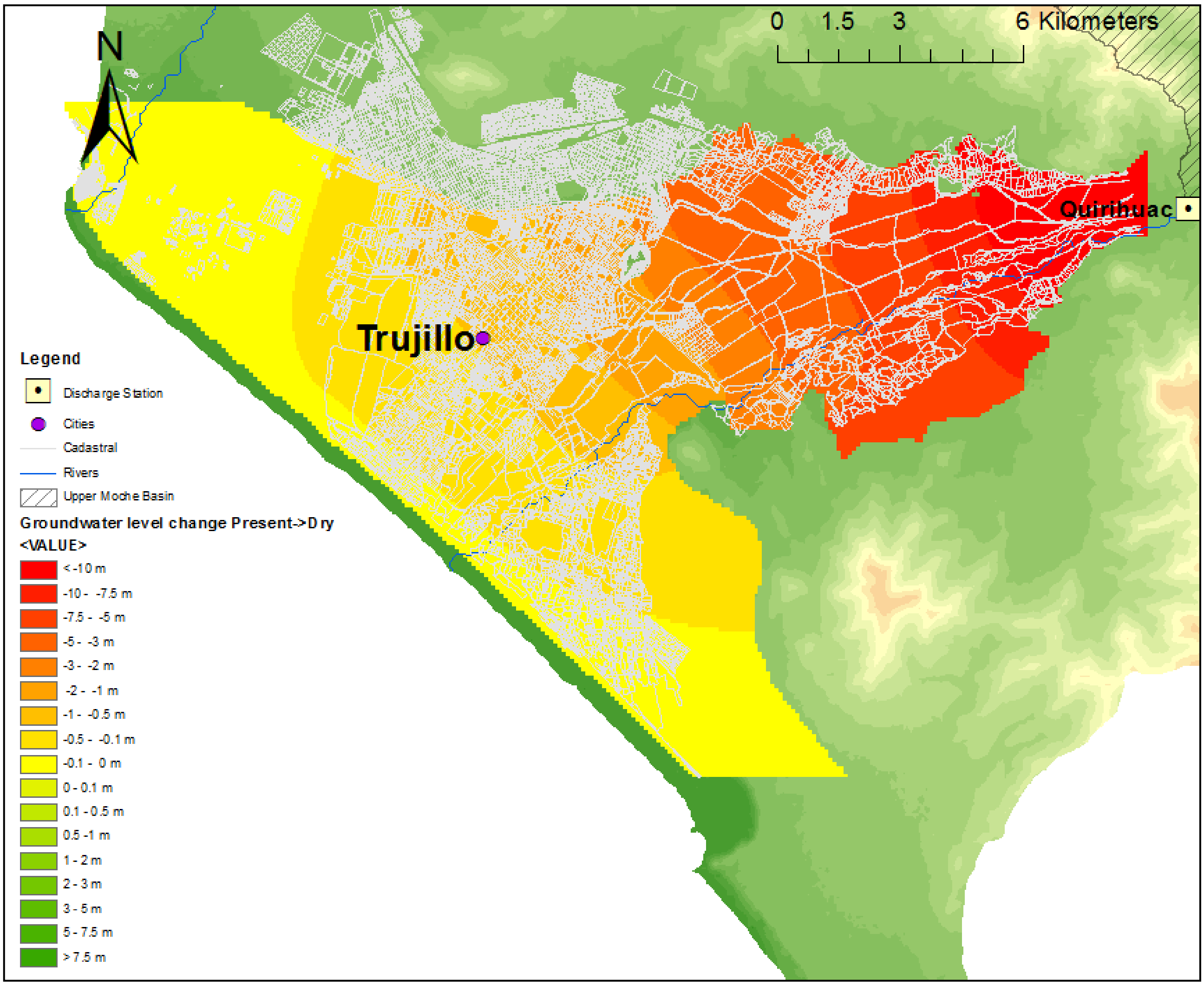

Figure 4. Simulated groundwater rise from the present conditions to conditions under the dry climate scenario. Negative values indicate lowering of the groundwater table

Wet future climate

For the wet climate scenario (Figure 4.) the groundwater levels will rise over the entire aquifer because both the river flows and the groundwater inflow will increase. The average rise has been calculated as 0.52 m for the aquifer as a whole and 0.32 m for the area, in which the groundwater is already less than 5m below the surface (Table 4.)

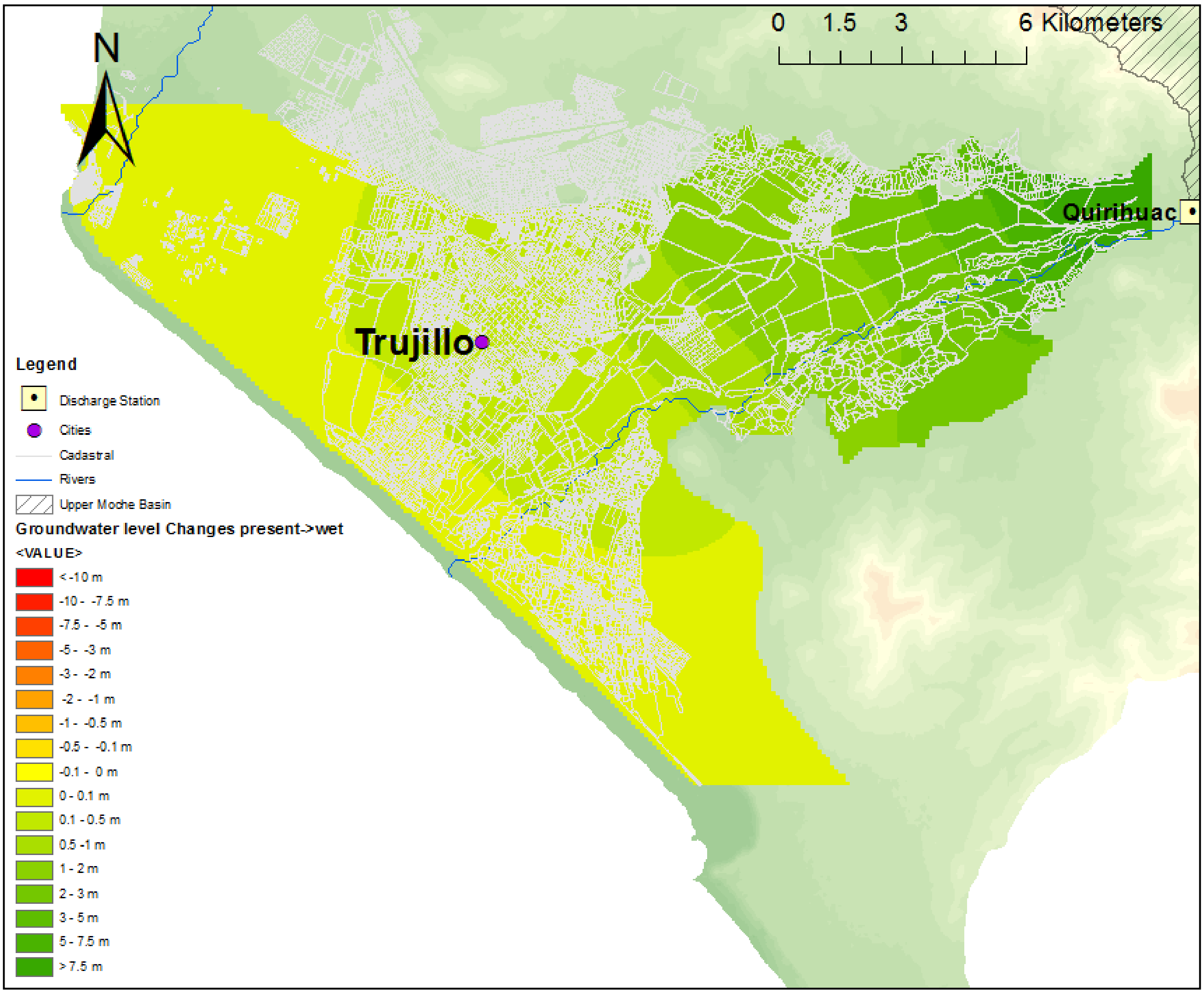

Figure 4. Simulated groundwater rise from present conditions to conditions under the wet climate scenario. Negative values indicate lowering of the groundwater table

Table 4. Simulated increases in groundwater water levels of the Moche aquifer (present pumping) under a future climate. The changes are given as maximum, minimum and average over the aquifer as a whole and over the part of the aquifer with simulated depths to groundwater of less than 5 m. The two aggregation areas are indicated in Figure 4..

Future Climate	Sampling area	MIN	MAX	MEAN
Dry	Whole Aquifer (195.2 km2)	-11.34	0.00	-1.19
Dry	Depths to groundwater < 5m (58.4 km2)	-5.14	0.00	-0.88
Wet	Whole Aquifer (195.2 km2)	0.00	7.73	0.52
Wet	Depths to groundwater < 5m (58.4 km2)	0.00	2.21	0.32

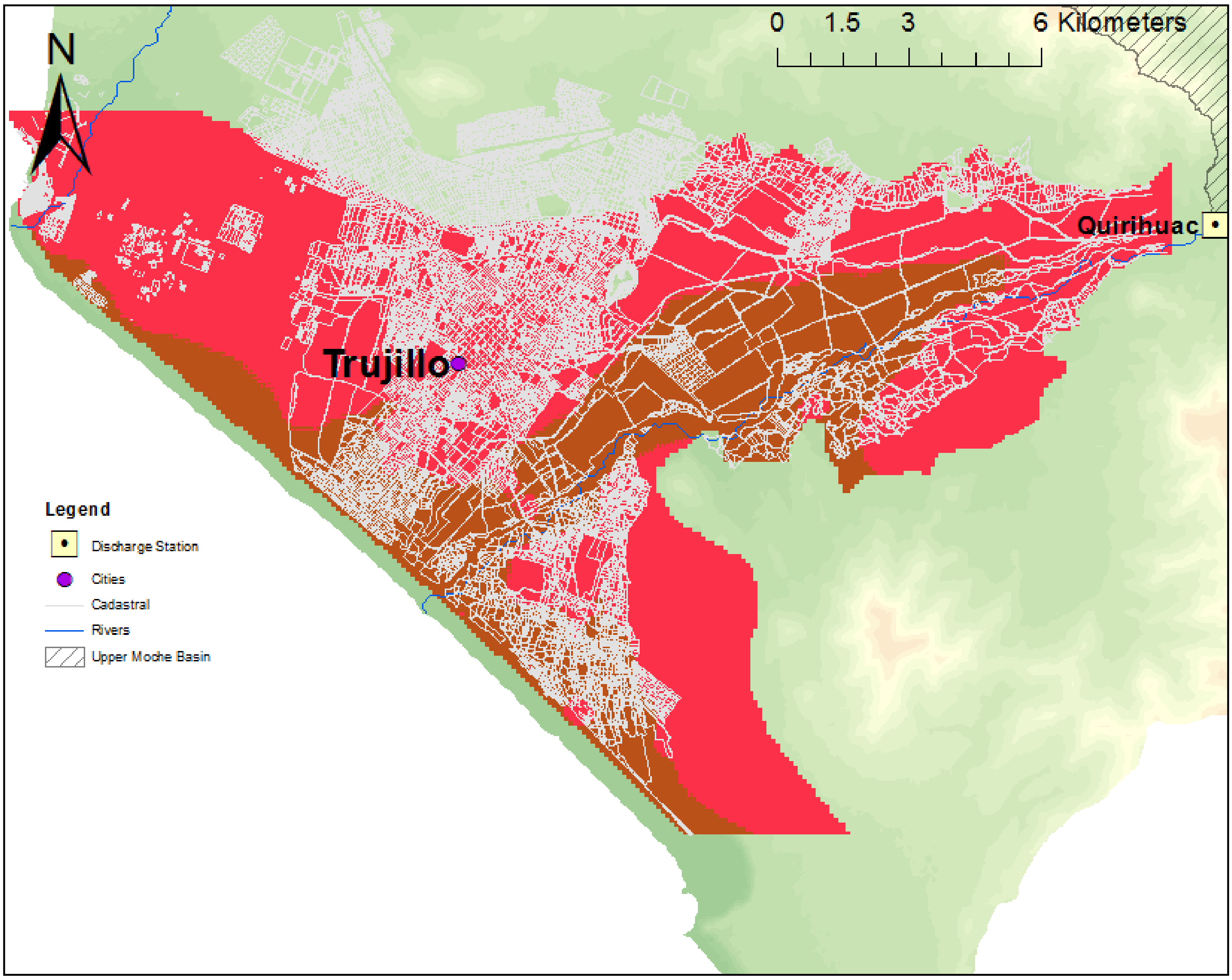

Figure 4. Aggregation areas: Whole aquifer (red) and area with simulated depths to groundwater of less than 5 m in scenario 3 (Brown).

4.1.3.5 Future pumping under future climate scenarios

The SEDALIB Master plan from 2005 (Ref.) includes a projection of the future water demand for Trujillo and a proposed increased pumping from the Moche Aquifer to meet this demand (Figure 4.). To meet the demand up to 2018 it is suggested that pumping is increased from the 2005-rate of 520 l/s to 1500 l/s in 2018.

The climate change scenarios used in this case study are for the period up until 2030 and it is therefore unlikely that full climate change reported here would occur within the time horizon of the projected pumping scenario 2005-2018. Nevertheless, we have found it appropriate to investigate if the proposed extended pumping rates will be sustainable under the projected future climates and analyse their impacts on the groundwater levels.

The pumping rates of the SEDALIB wells in the present pumping scenario have therefore been increased to the proposed pumping of 1500 l/s using the same factor of increase on all wells and the pumping scenario has been subjected to the dry and the wet future climate scenarios. The results are shown in Figure 4. and Figure 4. representing changes in groundwater levels under the wet and the dry climate scenarios, respectively.

It is interesting to note that the increased groundwater levels introduced by a wetter future climate can be controlled by increasing the pumping from the SEDALIB wells to a total of 1500 l/s and that the groundwater level under the city would even decrease relative to the present scenario under such conditions. The average level changes are calculated to be +0.74m for the whole aquifer but -0.64 for the areas with high groundwater levels today (Table 4.).

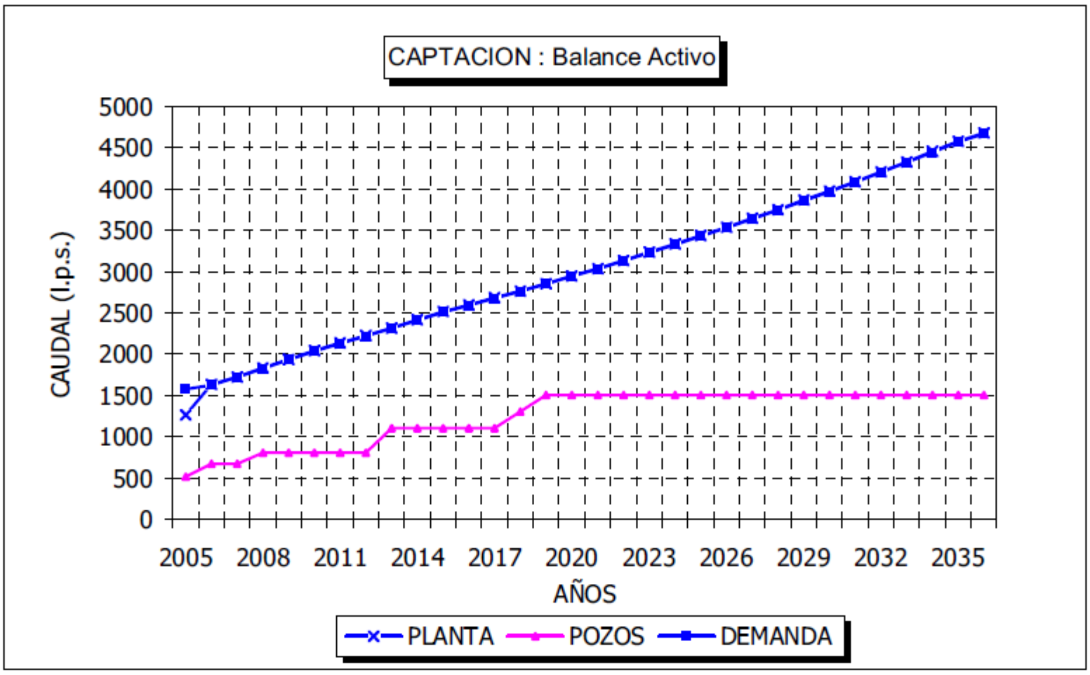

Figure 4. Planned increased pumping from the Aquifer to meet the rising demand From SEDALIB 2005 (Ref.)

Not surprisingly, a dry future climate combined with an increased pumping rate of 1500 l/s will cause the groundwater levels to drop. On average over whole aquifer the levels are predicted to decrease by 5.8 m and by 4.5 m on average over the area with present groundwater depths of less than 5 m. It is noteworthy that the new levels seem to stabilise within the simulation period of 6 years, and that the increased pumping rates therefore seem to be sustainable under the dry climate scenario. It is also noted that even though the changes in levels are small close to the coast line, the predicted levels are very close to 0 m.a.s.l. in this zone. Levels should therefore be monitored carefully in future in order to reduce pumping locally to prevent salinity intrusion if groundwater levels start falling further in this area.

Table 4. Simulated increases in groundwater water levels of the Moche aquifer from the present pumping and climate conditions to a future dry climate with a pumping of 1500 l/s . The changes are given maximum, minimum and average over the aquifer as a whole and over the part of the aquifer with simulated depths to groundwater less than 5 m. The two aggregation areas are indicated in Figure. 4.11.

Future Climate	Sampling area	MIN	MAX	MEAN
Dry	Whole Aquifer (195.2 km2)	-41.96	0.00	-5.76
Dry	Depths to groundwater < 5m (58.4 km2)	-14.92	0.00	-4.46
Wet	Whole Aquifer (195.2 km2)	-7.10	20.48	0.74
Wet	Depths to groundwater < 5m (58.4 km2)	-2.58	1.57	-0.64

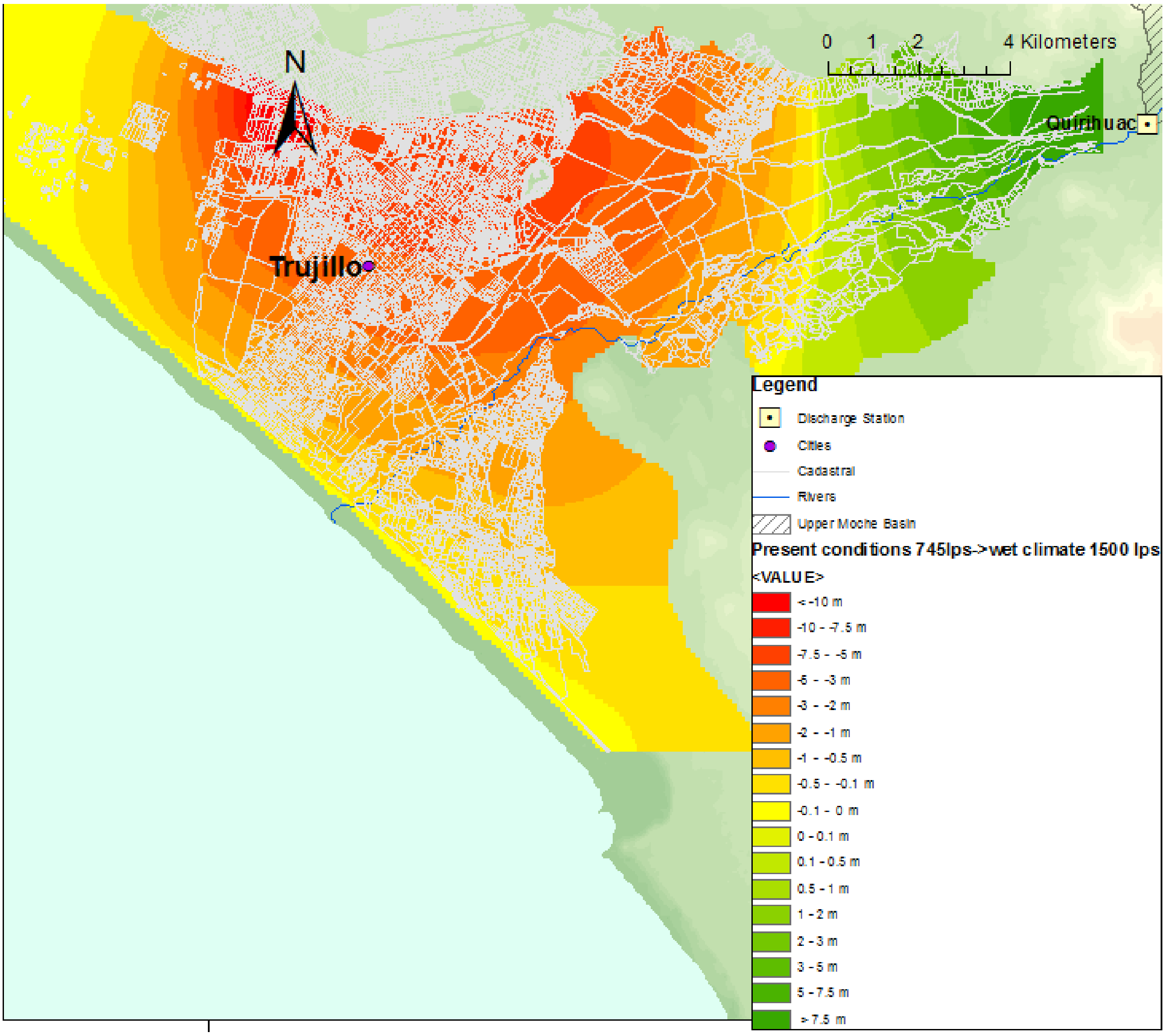

Figure 4. Changes in depth to groundwater from present conditions to a wet future climate with a pumping from SEDALIB's wells of 1500 l/s

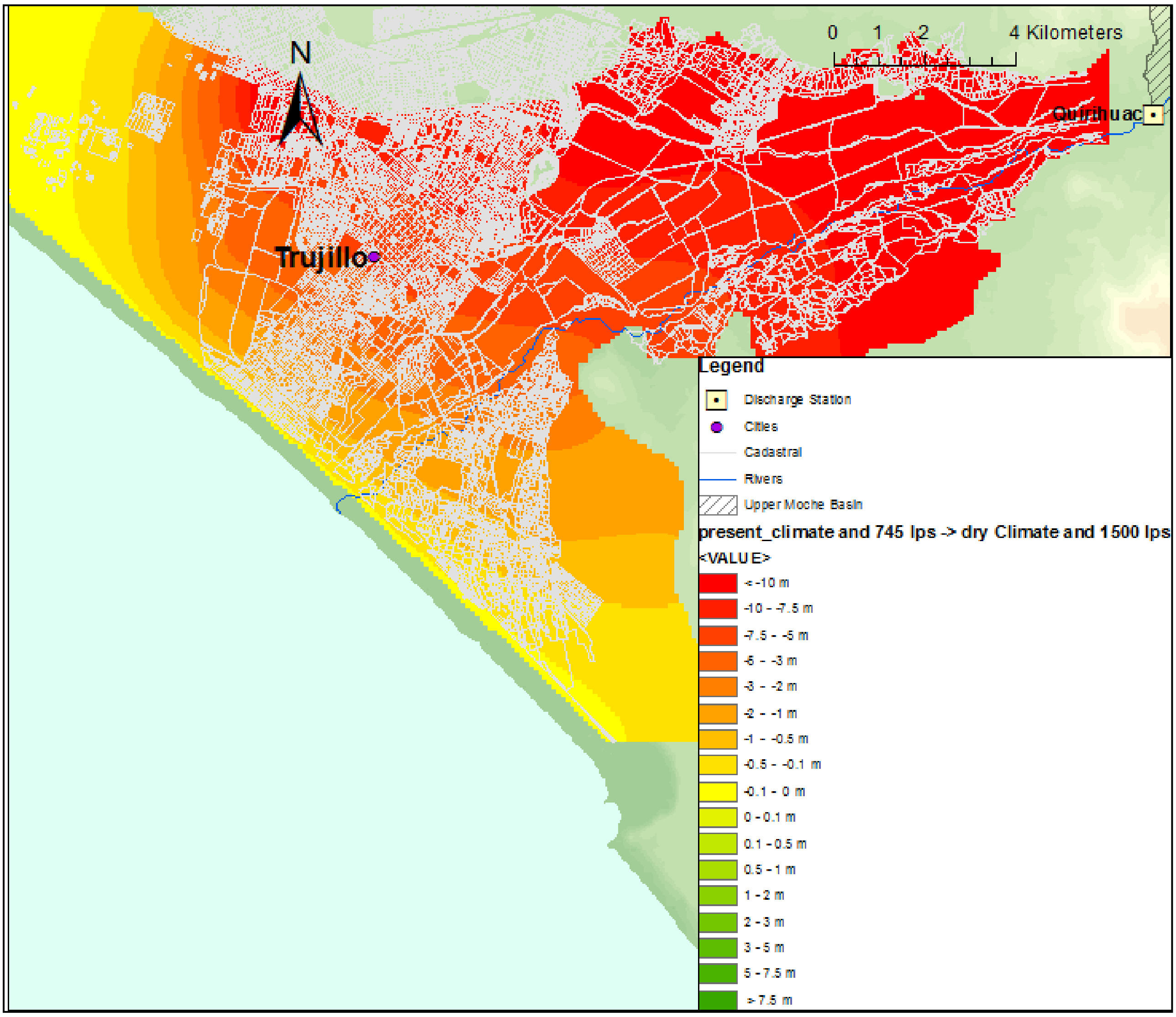

Figure 4. Changes in depth to groundwater from present conditions to a dry future climate with a pumping from SEDALIB's wells of 1500 l/s

4.2 Climate Change Prediction for the Santa River Basin

Climate change projections for the Santa River basin and their impacts on water availability was modelled and reported by MINAM and SENAMHI in 2012 (Ref.). This report is the most up to date study of the area and forms the basis of the information presented here. The report assesses changes for the time horizon 2030-2039.

Climate change projections were taken from two global climate models which were using the A1B future scenario of greenhouse gas emissions. The A1B scenario is based on the assumptions of rapid economic growth and low population growth, with a rapid introduction of a new and more efficient technology.

Two climate model results are investigated: MRI and NCAR. The MRI model is a global climate model developed in Japan which is run at a very high resolution (20km squared) compared to most other global climate models (100-200km squared). The NCAR model is the result of dynamic downscaling of the CCSM3 Global climate model with a resolution of 5km squared (Ref.).

There are many sources of uncertainty in climate change projections, such as the emissions scenario, the choice of climate model, and the internal variability of the variable being projected (the natural inter-annual variability of temperature or precipitation). Although only one greenhouse gas emission scenario is investigated here, studies of uncertainty in climate projections show that, in general, for the shorter-term (20-year lead time) the choice of emissions scenario is not the most important source of uncertainty (Figure 4. and Figure 4.). The largest uncertainty for the horizon 2030-2039 comes from the choice of climate model. Although it is preferable to analyse results from a large number of different climate models it is not always practical. Here, the results from two models are presented but it should be noted that these do not represent the full range of possible future projections.

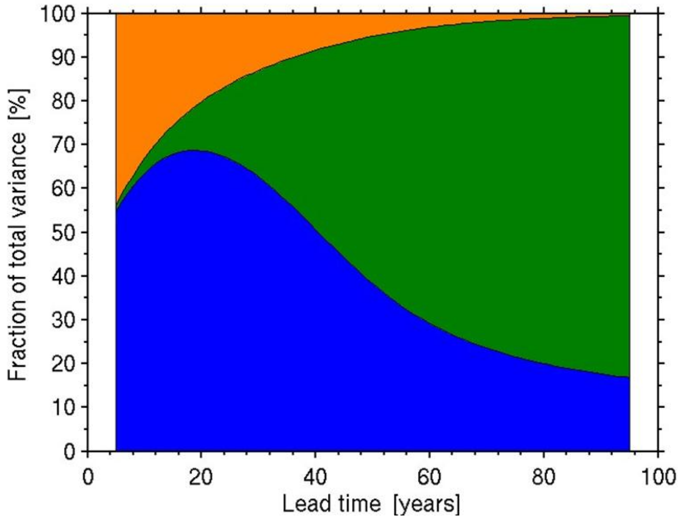

Figure 4. Relative of importance of factors contributing to the uncertainty in 10-year average temperature projections in South America. **Orange:** Internal natural variability of temperatures. **Blue:** Model uncertainty. **Green:** Scenario uncertainty. Choice of climate model is the most important factor for the 2030-2039 time horizon. Source: Ref.

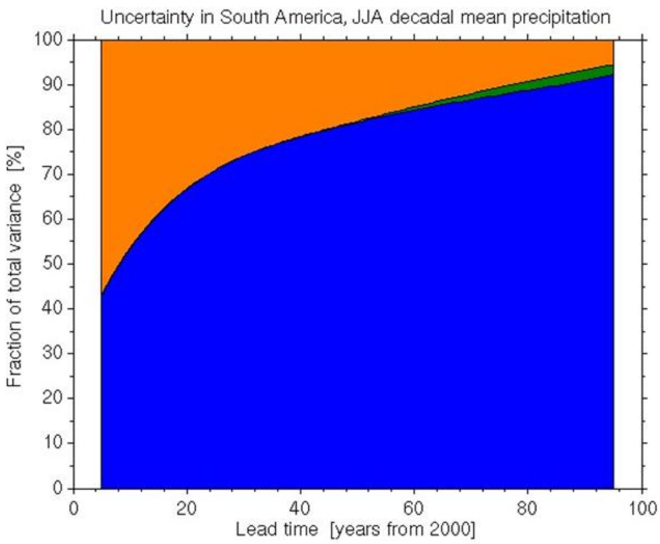

Figure 4. Relative of importance of factors contributing to the uncertainty in climate change projections for June July August Rainfall in South America. Orange: Internal natural variability of precipitation. Blue: Model uncertainty. Green: Scenario uncertainty. Projections are more sensitive to choice of climate model than choice of emissions scenario. Source: Ref.

The projected changes in climate impact the water balance in the basin as precipitation, and evaporation are changed. Changes in temperature and precipitation also affect glaciated areas and the melting back of glaciers impacts the available water in the river for the CHAVIMOCHIC transfer.

4.2.1 Assessed changes in precipitation

Precipitation changes in the Santa basin from the two models for the period 2030-2039 both project that under the A1B scenario, rainfall in the wetter months would increase and rainfall in the drier months of July and August would decrease slightly (Figure 4.). However, the NCAR model projects a decrease in rainfall in January and February. The models predict the annual precipitation to increase by 3.2% and 16.1% for the NCAR and MRI models, respectively (Table 4.).

Table 4. Projected changes in rainfall in the Santa River basin, from two different climate models under the assumption of a A1B greenhouse gas emission scenario. Source: Ref. .

	Santa				
	referencia (1969-89)	MRI (2030-39)	NCAR (2030-39)	MRI	NCAR
	mm	mm	mm	Δ %	Δ %
ene	121.9	150.6	112.2	23.6	-7.9
feb	138.4	169.0	136.2	22.2	-1.5
mar	149.2	173.5	168.5	16.2	12.9
abr	98.9	119.5	106.1	20.8	7.3
may	33.6	45.7	43.0	35.9	28.1
jun	12.7	18.8	18.7	47.8	46.8
jul	6.6	3.9	6.3	-40.3	-3.8
ago	12.2	10.5	11.6	-13.5	-4.9
sep	39.7	38.2	39.6	-3.8	-0.3
oct	70.1	75.2	73.4	7.3	4.7
nov	80.6	88.5	79.4	9.7	-1.5
dic	104.0	114.2	100.6	9.9	-3.3
Total	867.8	1007.6	895.6	16.1	3.2

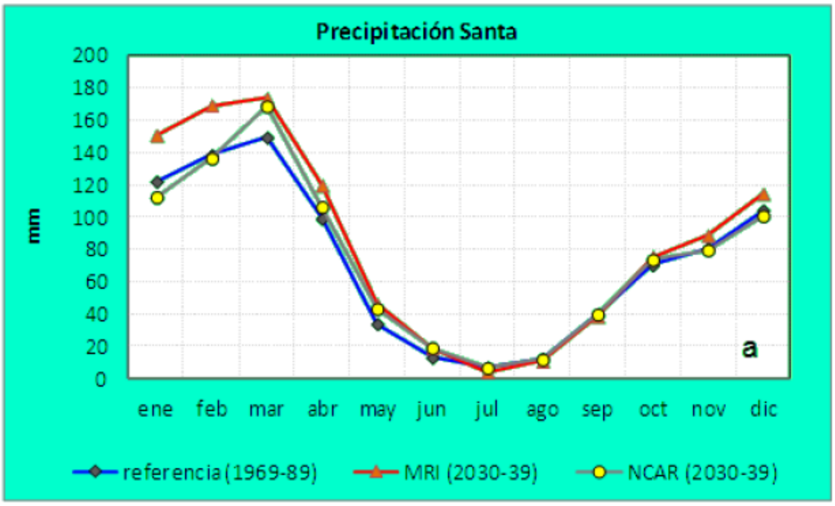

Figure 4. Changes in precipitation over the Santa Basin for the period 2030-2039 as predicted by the MRI and NCAR models. (Source: Ref.)

4.2.2 Assessed changes in temperature

Temperature changes from both climate models in the Santa Basin show an increase in temperature in all months (Table 4. and Figure 4.). There is greater agreement between the two climate models in the temperature projections compared to the precipitation projections. This is to be expected as temperature is a variable which can be modelled more simply than precipitation as it relies on fewer underlying atmospheric processes.

Table 4. Temperature changes projected for the Santa River basin from two climate models. Source: Ref.

	Santa				
	referencia (1969-89)	MRI (2030-39)	NCAR (2030-39)	MRI	NCAR
	°C	°C	°C	Δ °C	Δ °C
ene	12.7	13.7	13.8	0.9	1.1
feb	12.5	13.7	13.9	1.2	1.3
mar	12.4	14.0	13.6	1.7	1.2
abr	12.7	14.2	13.9	1.5	1.1
may	12.4	14.1	13.5	1.7	1.0
jun	12.0	13.3	13.0	1.3	0.9
jul	11.8	13.2	12.8	1.4	1.1
ago	12.3	13.7	13.3	1.4	1.0
sep	13.0	14.2	14.4	1.2	1.4
oct	12.9	14.4	14.3	1.4	1.4
nov	12.9	14.1	13.9	1.2	1.0
dic	13.1	14.4	14.8	1.3	1.7
Total	12.6	13.9	13.8	1.4	1.2

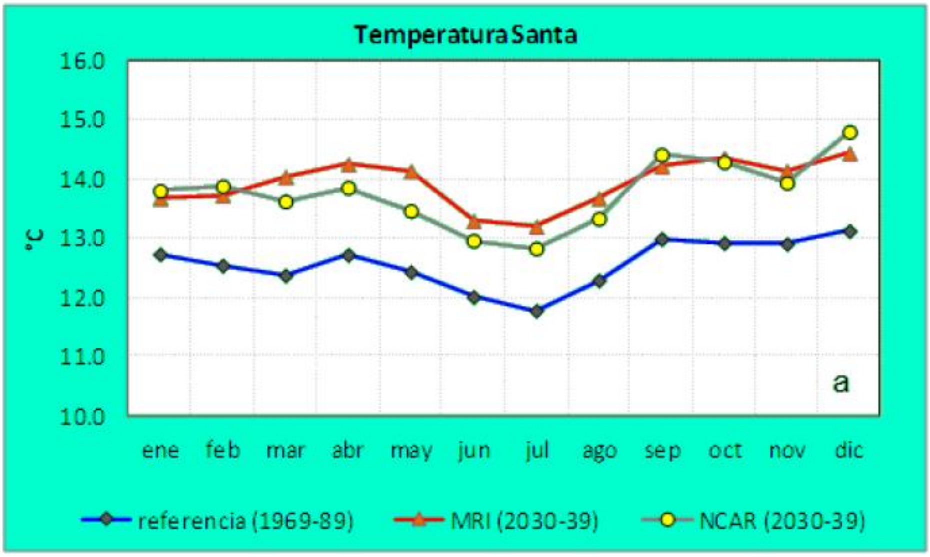

Figure 4. Projected temperatures in the Santa Basin for 2030-2039 compared to the reference period, from two climate models, MRI and NCAR, under the A1B emissions scenario. Source: Ref 1.

4.2.3 Projected changes in the water availability for the Chavimochic canal

The real variable of interest for Trujillo is the change in available water for the Chavimochic project. This depends not only on climate changes and their impacts on the river but also on changes in water use within the Santa basin and on the water allocation agreement with the Chavimochic project.

4.2.3.1 Climate-induced impacts on river flow

The climate models project and increase in temperatures and a change in the rainfall distribution throughout the year. To assess how these changes affect the flow in the river, a water balance model was used to simulate river flows under the future scenarios (Ref.).

The changes in flow were assessed at Condorcerro, just upstream of the CHAVIMOCHIC intake. Results for both climate models show an increase in flow in all months and increases of around 15% for the drier months, relative to the period 1969-1989 (see Table). This suggests that for the time horizon 2030-2039, the climate induced changes in flow alone will not cause problems for the CHAVIMOCHIC water supply.

Table 4. Projected changes in flow in the Santa River at Condorcerro, upstream of the CHAVIMOCIC intake. Reproduced from Ref.

Past and Future Flows in Santa at Condorcerro (m3/s)			
Month	Reference (1969-1989)	MRI (2030-2039)	NCAR (2030-2039)
Jan	207.7	248.9	227.7
Feb	299.4	351.0	320.0
Mar	307.4	337.1	350.6
Apr	231.8	234.8	240.2
May	109.5	119.4	131.2
Jun	71.2	89.2	100.6
Jul	57.3	64.8	76.6.
Aug	56.0	65.5	77.0
Sep	70.4	89.3	107.4
Oct	99.5	138.6	142.5
Nov	124.8	139.7	151.9
Dec	162.5	218.1	205.6

Glacial retreat

Some of the increase in flow is derived from the melting of glaciers, which releases water into the river, which was previously stored as ice. Projections of glacial melt are reported in Ref. , and show the reduction in the area covered by glaciers for each year between 2030 and 2039. Results for the year 2030 based on MRI climate projections produce a glaciated area of 324.2km^2 and using the NCAR climate outputs, results in an area of 391.3km^2. However, the report also states that in 2006 there was a glacial area of 343.6km2 in the Santa basin. This suggests that modelling glacial retreat using the NCAR climate projections cannot melt the ice quick enough as the projected area for 2030 under NCAR climate (391.3km^2) is larger than the observed area in 2006 (343.6km2). The MRI projections result in a smaller glacial area (324.2km2) for 2030 than the NCAR projections, but it is still not very much smaller than the area measured in 2006 (343.6km2) which suggests the MRI projections too do not result in fast enough glacial retreat.

Table 4. Glacial area as projected by a glacier model using the two climate model projections as input. See Ref 1.

		Area Glaciar (Km^2)										
		Referencia	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Santa	Referencia (1967)	510.2										
	MRI		324.2	319.4	314.5	309.7	304.4	299.0	295.8	292.6	289.3	284.8
	NCAR		391.3	382.8	375.9	369.2	362.6	357.4	352.3	346.9	341.9	337.2

There is a lot of uncertainty in the climate projections and also in how the change in climate will affect the ice cover. However, even if the glaciers melted more rapidly than projected, in the short-term this could only lead to more flow in the river, as more of the water stored as ice would be released from storage. If the glaciers melt completely, however, a decrease in flows would be expected, as there would then be no more water being released from storage to supplement precipitation contributions, and all flow would be derived from precipitation alone.

For the period 2030-2039 the results of the glacier modelling suggest an annual loss of glacier areas of -4.4 km2/year and -6.0 km2/year, for the climate predicted by the MRI and NCAR models, respectively. Using these melting rates from the observed 2006 glaciered area of 343.6 km2 would result in remaining glaciered area of 199 km2 and 145 km2 for the MRI and NCAR predictions, respectively. Since these numbers correspond to 40%-60% of the glaciered areas in 2006, a complete loss of glaciated areas is not expected to occur within the time horizon 2012-2039.

4.2.4 Other pressures on river flow

Although, the climate models project an increase in the flow of water in the river, this water may not necessarily still be available for the CHAVIMOCHIC transfer project as other changes in the basin may increase pressures on the water supply.

The population of Peru is expected to rise by 16%, between 2010 and 2025 but the population in Ancash is expected to rise by about 8% over the same period (Ref.). If the population in the Santa basin was to rise by about 10% by 2030 (taking the population rise in Ancash and extrapolating roughly to 2030), this additional population would put added pressure on water resources in the catchment and likely result in lower flows in the river at the point of the CHAVIMOCHIC intake than would otherwise be expected from changes in climate.

Around a 15% increase in flow in the dry season is projected as a result of climate change in 2030-2039 relative to 1969-1989, but this increase in flow will be at least partly offset by those projected increases in population. A 19% increase in population in the Ancash province is projected over a similar but shorter time period 1995-2025 (Ref.).

Table 4. Population estimations and projections for Peru and the Ancash region. (Ref.)

Area	1995	2000	2005	2010	2015	2020	2025
Peru	23,926,300	25,983,588	27,810,540	29,461,933	31,151,643	32,824,358	34,412,393
Ancash Department	1,012,624	1,049,379	1,084,038	1,116,265	1,148,634	1,177,080	1,201,465

In addition to population increases, water use in the Santa basin may change. Higher temperatures and lower precipitation in the dry season could lead to more of the flow in the dry season being extracted for irrigation purposes.

Economic development in the Santa basin may also increase pressure on the water supply, especially if agriculture in the basin is developed and new intakes for irrigation are planned from the river upstream of the CHAVIMOCHIC intake.

5 Climate Change Impacts on the Irrigation Demands in the Trujillo Area

The irrigation sector is very important for Trujillo's economy and its social sustainability. and an analysis of the Climate change impacts on the sector is therefore relevant.

A thorough analysis of the sector's water demands, possible water-saving initiatives, and development potential is a large study in itself and therefore out of the scope of the present case study. However, it is still relevant to make an overall assessment of the possible impacts on the sector's water demand from the predicted climate change until 2030, which is dealt within this section.

Climatically, the coastal plains around Trujillo are virtually deserts. The average annual rainfall in Trujillo is only 7 mm, which is less than one per cent of the reference evapotranspiration (Et0) of 1070 mm (Penman-Monteith estimate, Ref.). Hence, the predicted changes in rainfall of +/- 10% will not have any significant influence on the future water demand for irrigation, which may, consequently, be estimated solely from the changes in Et0.

In Section 4.1.1 the rise in temperature in the area was predicted to be in the range of 0.4 – 0.8 deg. C. The impact of such change on Et0 is illustrated in Figure 5.. and the impacts on Chavimochic´s irrigation demands are assessed in Table 5.. From the table it appears that the annual change in irrigation demands may be around +6 %. The most critical change seems to occur in December where the irrigation demand may increase from 73.8 mill. m3 to 78.9 mill. m3, or from 27.5 m3/s to 29.5 m3/s (7%). The demands originate from 'Estudio de Prefactibilidad del Proyecto Chavimochic Tercera Etapa – Primera Fase' which also indicates that 27% of the irrigation demand 187.5 mill m^3 is for new irrigation areas.

Since there is no indication of a climate-generated decrease in the low flows in Rio Santa, which are, in fact, more likely to increase until 2039, the main source of irrigation water is likely to still be available in future. Hence, it is likely that the climate change impacts on the irrigation sector will be limited to the changes in the evapotranspiration (7% in the most critical month). If such a change materialises it may adapted to by adjusting the planned future expansion in the third stage of the project by 26%. It may also be adapted to by investing water-saving irrigation equipment or by adjustment in cropping or irrigation patterns. Planning of such measures and quantification of their possible effects and costs requires detailed analysis of the various irrigation schemes and practices in the area which beyond the scope of this project. Suggested components of such a study are attached as Appendix C to this report.

At the present stage of development Chavimocic has abundant irrigation water. This situation may, however, change if the system's service area is expanded to the Chicama Valley north of Moche. If water extraction from the Chao, Virú and Moche rivers or from their aquifers will be needed to service such expansion of the system, the climate change impacts on the water availability in these valleys should be taken into account in the feasibility calculations of the expansion. The flows in Moche have been found to be sensitive to climate change (Section 4.1.3) and the Chao and Virú Rivers are likely to show similar sensitivity to climate changes as the Moche.

Considering the scale of investment related to such an expansion more detailed assessments of the changes in rainfall and temperature in the basins should be initiated if the water availability is critical for the feasibility. Subsequently the impacts on the local resources can be assessed following approaches similar to the ones used in this study or the refinements suggested in Section 6.1.

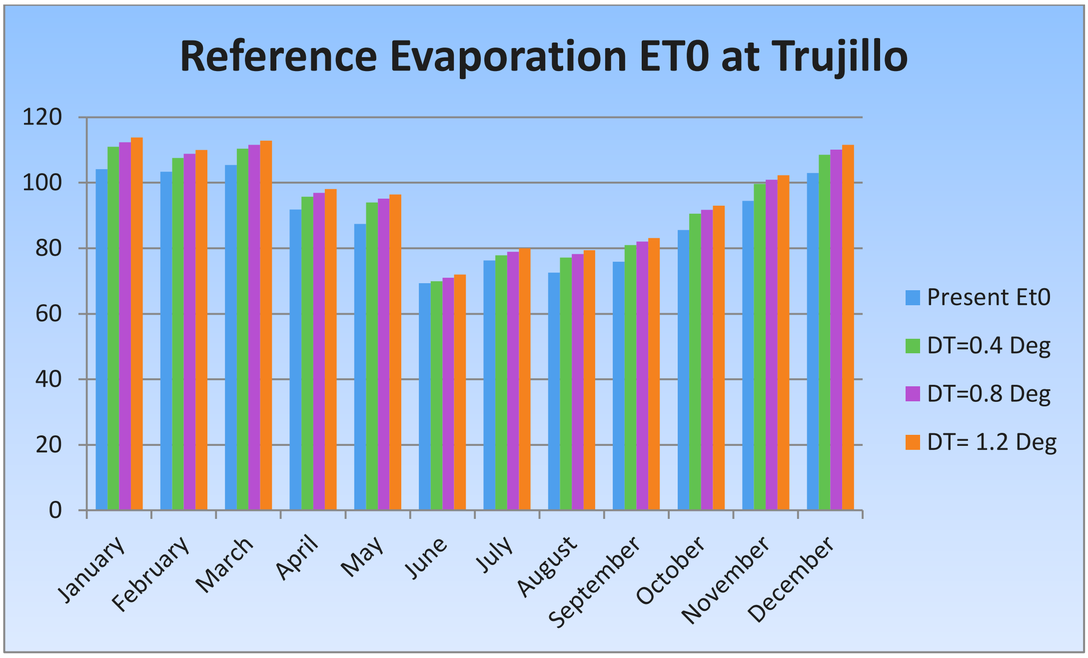

Figure 5. Change in reference evaporation in Trujillo, calculated by changing the temperature component in Penman-Monteith estimates and maintaining the rest of the parameters at the present level.

Table 5. Calculated Change factors in reference evaporation and future irrigation demand for predicted future temperature changes

Temperature change (dig C)	0.4	0.8	-	-	-	0.4	0.8	0.4	0.8
Variable	Et0		Present Chavimochic Demands*			Future Demand		Demand Change	
Sector			Total	Domestic	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation
Unit	factor	factor-	MCM	MCM	MCM	MCM	MCM	MCM	MCM
January	1.07	1.08	67.2	2.4	64.8	69.0	69.9	4.2	5.1
February	1.04	1.05	61.4	2.2	59.2	61.6	62.3	2.4	3.1
March	1.05	1.06	66.1	2.5	63.6	66.6	67.3	3.0	3.7
April	1.04	1.06	67.4	2.5	65.0	67.7	68.6	2.8	3.6
May	1.07	1.09	59.6	2.5	57.1	61.4	62.2	4.3	5.1
June	1.01	1.02	47.3	2.3	44.9	45.3	46.0	0.4	1.1
July	1.02	1.03	40.6	2.4	38.2	38.9	39.5	0.8	1.3
August	1.06	1.08	44.7	1.9	42.7	45.5	46.1	2.7	3.4
September	1.07	1.08	51.2	1.8	49.4	52.7	53.4	3.3	4.0
October	1.06	1.07	62.6	1.9	60.6	64.2	65.0	3.5	4.4
November	1.05	1.07	74.1	2.2	71.9	75.8	76.8	3.9	4.9
December	1.05	1.07	76.1	2.3	73.8	77.8	**78.9**	4.0	**5.1**
Annual	**1.05**	**1.06**	**718.2**	**27.0**	**691.2**	**726.5**	**736.1**	**35.3**	**44.8**

* Source: Chavimochic. Explotación de Aguas Subterráneas en los Valles de Chao, Viru and Moche, Proyecto Chavimochic, Región La Libertad (Ref.). Estudio de Prefactibilidad del Proyecto Chavimochic Tercera Etapa – Primera Fase

6 The Adaptation Process

From the previous sections it should be clear that the prediction of the climate change impacts on the water supply to Trujillo, the groundwater levels in the Moche Aquifer, and the water supply to the Chavimochic canal are, at present, related with large uncertainties. For the Moche Aquifer the two analysed climate scenarios even point in opposite directions. Hence, the feasibility or even relevance of certain adaptation measures could be questioned.

Particularly when uncertainties are large, it is important, without stalling the adaptation process, to launch activities aiming at addressing and reducing the uncertainties and subsequently to revolve to the adaptation process with better knowledge.

Since some adaptation measures could, however take considerable time to implement, just postponing the decision on implementing them might not be acceptable. The UK Climate Impact Program suggests a stepwise yet cyclic approach to adaptation planning as indicated in Figure 6.. To avoid stalling of the process it is important at an early stage to identify win-win and no-regret scenarios i.e. scenarios that will benefit the system in other ways than just climate adaptation and scenarios that would be beneficial independently of how the climate actually will develop. Therefore, the adaptation measures outlined below will focus on studies aiming at reducing uncertainty, win-win scenarios and no-regret measures.

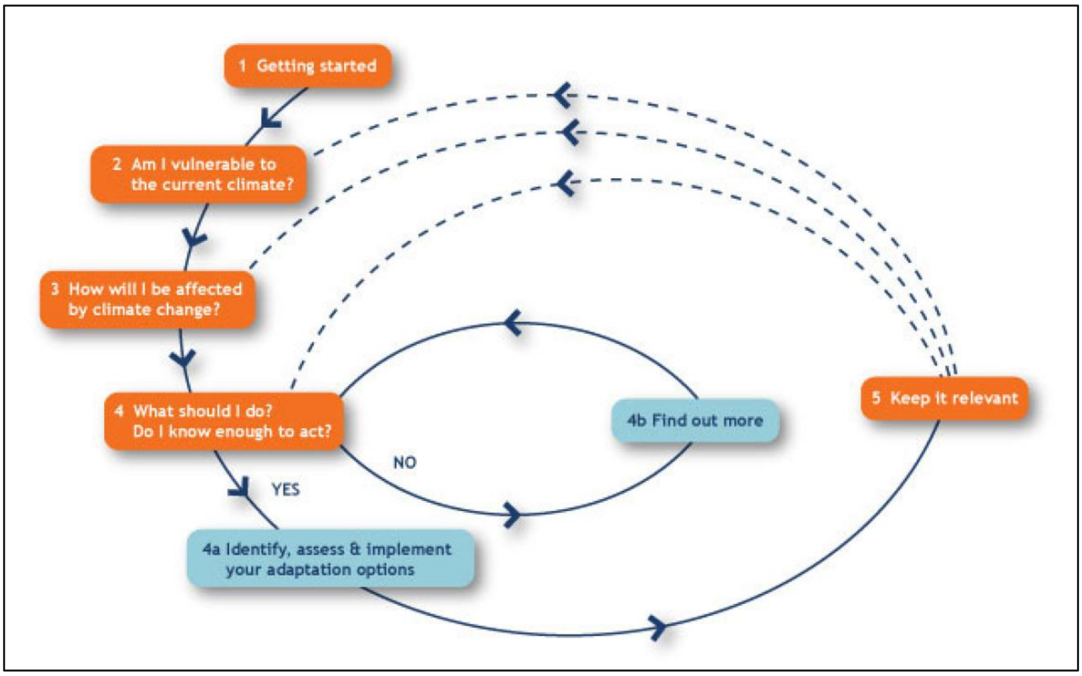

Figure 6. The UKCIP Adaptation Wizard v 2.0. UKCIP, Oxford (UKCIP, 2008).

6.1 Possible Adaptation Measures

A preliminary set of adaptation options have been identified. The various options have been subjectively evaluated in a scoring matrix and ranked to form an outline adaptation plan.

It should be emphasised, that the list of options is preliminary and that the final list of options and their ranking is a detailed and longer process, beyond the scope of this case study. The adaptation plan will need to be revisited and revised when more detailed predictions or evidence of the local climate change become available or when changes in the forecasted demand make this relevant. In this respect, the climate change adaptation process does not differ from normal water resource planning or water supply management.

The preliminary list of options and the ranking is included here to serve as reference and can, hopefully, assist in starting the process of climate adaptation and the development of a climate change adaptation plan.

The following adaptation measures have been identified:

General

1 No Action. Although the analysis made in this case study does not reveal any alarming vulnerability to the climate change impacts, the uncertainty of the possible changes is still so large that, as a minimum, the situation should be monitored intensively and studied further.

2 Detailed climate change assessment of the Moche River Basin and surrounding areas in line with the work carried out on the Santa Basin should be started. The aim is to reduce the considerable uncertainty on the climate predictions as a minimum to constrain the impact to either a flow decrease or flow increase at the Quirihuac Station. The work should involve several meteorological models and dynamic downscaling to reduce the uncertainty on the climate predictions, as a minimum, to constrain the impact to either a flow decrease or flow increase at the Quirihuac Station.

3 Establishment of a groundwater modelling team conducting more detailed groundwater - surface water interaction studies of the Moche aquifer. The team should enable the city and Chavimochic to respond dynamically to possible changes in the climate and in the pumping pattern from the aquifer aiming at improving the drainage congestion measures without running the risk of over pumping, particularly along the coastline. The team should establish a groundwater decision support tool with upgraded modelling capability to reflect the seasonal variation of inflow and irrigation application, more direct modelling of the influence of the inflows to the aquifer, possible salinity intrusion, impacts from changed pumping and an assessment of groundwater quality. The established tool should be calibrated with particularly attention to the depth to the groundwater table.

Adaptation to a Drier Climate.

4 Conduct detailed modelling studies to reveal with greater accuracy the sustainable pumping from the aquifer. The rapid assessment in this study has indicated that planned increases in pumping rates up to 2018 seem to be sustainable under the predicted drier climate, but this has to be confirmed by more detailed studies. The activity will address water shortage due to climate change as well as drainage congestions. Win-Win.

5 Demand management initiatives aiming at reducing the net demand by pricing policies or by restrictions in water use. The planned pumping scenarios will only meet the demands up to 2020.

6 Reducing the gross demands by minimising losses in the distribution system (pressure reduction and /or replacement works).

7 Monitor the groundwater levels in the aquifer, particularly along the coastline to trigger warnings of possible over extraction and alter pumping scenarios accordingly.

8 Negotiate options for increasing the delivery of domestic water from Chavimochic to be effectuated in case new climate assessments point to a drier scenario than the one made in this study or if detailed analyses determine the planned pumping rates to be unsustainable.

9 Start planning for increased irrigation demands. Although the assessed increase in irrigation demands of 6% annually and 7% in the most critical month (December) does not seem to be alarming, the projection of the temperature rise that causes this increase is more certain than the rainfall predictions dominating the predicted flow changes in the local rivers. Since the Chavimochic project is not fully developed it still has surplus of water resources to accommodate such changes. However, the projections have to be refined and taken into

account if further development is planned, or compensated by changes in cropping patterns or water savings.

10 Expansion of the extraction from the Chavimochic canal and increase of the treatment plant. To be effectuated if further studies of the 2018 pumping scenario show it to be unsustainable. An extension of 750 l/s is suggested to compensate for the difference between present pumping and proposed future pumping rates

Adaptation to a Wetter Climate

11 More detailed groundwater and surface water interaction studies of the Moche aquifer to confirm the findings of the present study and to plan further abatement of the of the drainage congestion.

12 Increase SEDALIB's pumping to the planned 1500 l/s and use this for supply of the city if water quality so allows. The pumping scenario investigated in the previous sections seems to compensate for the negative effects of a wetter climate.

13 Increase the pumping for irrigation in the Valley, as suggested by Chavimochic in Scenario 3 of the previous study (Ref.)

14 Restricting irrigation in certain areas of the Valley. If the drainage congestion cannot be controlled by other measures it may be necessary to restrict the irrigation in certain areas of the valley to certain crop types with lower water consumption and leakage to groundwater.

15 Investigation of the opportunities of further expansion of the development plans for the Chavimochic project made possible by a greater availability of water.

16 Abstraction of water from the river for export out of the basin. This may help the drainage congestion but needs further investigation and quantification.

6.2 Screening Matrix

All possible adaptation measures are put in the screening matrix and are subject to initial evaluation, based on general knowledge and site-specific conditions. This is a qualitative evaluation, where each measure is evaluated against the following criteria:

- Win/Win
- Regret/No regret
- Flexibility
- Resilience improvement
- Urgency
- Political acceptability
- Costs

The narrative evaluations are complemented by "points" ranging from '+ + +' for the best positive score, through '0' as neutral, to '- - -', as the worst score. Positive and negative "scores" are summarized separately with the following meanings:

- High positive score = high priority in implementation
- High negative score = a high level of controversy, high cost or otherwise doubtful measure.

The currently evaluated measures, the evaluation criteria and the actual scores might be incomplete and may not reflect the actual situation in a fully objective manner. Therefore, the screening matrix needs to be updated and/or extended appropriately through interactive participation of local stakeholders.

ID	Adaptation measure	Win/Win	Regret / No Regret	Flexible	High Resilience	Urgency	Political Acceptability	Costs	Score	Ran k
	General									
0	No Action	--- no wins	-- Some measures takes time to implement. no action could be regretta-ble	-- Waiting will in this case not make the options later on more flexible	-- by doing nothing vulnerabil-ity will grow	0 Not relevant	-- Not addressing identified problems is normally not a good political strategy	-- No costs now could lead to larger costs later.	0+/12-	-
1.1	Detailed climate change assessment of the Moche River Basin and surrounding areas	++ Improves calibration possi-bilities for meteorological and hydrological models Improves the knowledge for design of new structures	++ expanding knowledge is never regrettable	++ It will open for more adap-tation ideas	0 It will not in itself improve resilience.	+++ it is urgent in order to assist future decisions.	++ Politically acceptable	+++ low costs	+14/-0	1
1.2	Establishment of a groundwater modelling team.	++ Improves adaptation to both present, drier and wetter climate. Provide evidence for adaptation measures	++ expanding knowledge is never regrettable	++ It will open for more adap-tation ideas	++ It will improve resilience opening for a more dynam-ic response to encountered problems	+ it is urgent in order to assist future decisions.	+++ Politically acceptable	+ rather low costs	13+/-0	2
	Adaptation to a Drier Climate									
2.1	More detailed Assessment of the sustainable pumping	++ Protection of Aquifer, supply to the City and combatting drainage con-gestion	++ no regret	++ it will improve rather than constrain decisions	0 It will not in itself improve resilience.	+ Rather urgent in order to assist future decisions	++ Politically acceptable	++ low costs	11+/0-	3
2.2	Demand Management initiatives aiming at reduc-ing the net demand by pricing or restriction in water use	++ Reducing the need for pumping or investment in surface water treatment to fulfil increased future demands	++ No regret.. Savings are always good.	++ Can be implemented and changed at any time but need time to work	0 will not in itself improve resilience	+ May be implemented at any time but preferably sooner than later	- - May be politically sensitive.	++ low costs	9+/2-	8
2.3	Reducing the gross demands by minimising losses in the distribution system	++ will benefit both water availability and running costs	++ No regret. Savings are always good.	++ Implementation may start at any time	+ An effective distribution is more resilient	+ May be implemented at any time but preferably sooner than later	+ not politically sensitive	- - Rather High costs	10+/2-	7
2.4	*Monitor the groundwater levels* in the aquifer	+ Will benefit both drainage congestion and pumping sustainability	++ No regret	++ Implementation may start at any time	+ it may improve resilience by opening for higher pumping during shorter	+ Rather urgent in order to assist future decisions	+ not politically sensitive	+ Rather low costs	9+/0-	6
2.5	Negotiate options for increasing the delivery of domestic water from Chavimochic	0	++ No regret	++ Implementation may start at any time	+ it will lead to higher re-source flexibility	+ Rather urgent in order to assist future decisions	++ Politically acceptable	++ low costs	10+(0-	4
2.6	Start planning for increased irrigation demands.	0	++ No regret	++ Implementation may start at any time	+ it should lead to a higher resilience of the irrigation systems	+ Rather urgent in order to assist future decisions	++ Politically acceptable	++ low costs	10+/0-	5
2.7	Expansion of the extraction from the Chavimochic canal and increase of the treat-ment plant	0 will benefit only the water supply	0 Could be regrettable if the climate prediction shows to be too conservative	+ Implementation takes time and should not be stated before more solid evidence of the climate and the sustainable pumping rates are available	++ it will to a higher resilience of the irrigation systems	0 not very urgent	++ Politically acceptable	- - High Costs	5+/2-	9

	Adaptation to a wetter Climate									
3.1	More detailed groundwater and surface water interaction studies of the Moche Aquifer	+ Benefit the adaptation to both a wetter and to a drier climate	++ not regrettable	++ Implementation may start at any time.	+ it should lead to a higher resilience	+ Rather urgent in order to assist future decisions	++ Politically acceptable	+ low costs	10+/0-	3
3.2	Increase SEDALIB's pumping to the planned 1500 l/s	++ will benefit both water availability and drainage congestion	++ No regret	+ Gradual Implementation may start at any time	++ Resilient it leads to larger resource flexibility	0 May be implemented at any time but not later than required by the demand development	++ not politically sensitive	- - High costs	9+/2-	5
3.3	Increase the pumping for irrigation in the Valley,	++ will benefit both water availability and drainage congestion	++ No regret	+ Gradual Implementation may start at any time	++ Resilient. It leads to larger resource flexibility	+ Rather urgent	- Could be politically sensitive	- - High costs	8+/3-	6
3.4	*Restricting irrigation in certain areas of the Valley*	0 Not Win /win	0 Could be regrettable	+ Quite flexible	0 will not in itself improve resilience	0 not urgent	- - Politically sensitive	- Could be costly	1+/3-	8
3.5	Investigation of the opportunities of further irrigation expansion	+ Benefit mainly the irrigation sector but also the general development of the area	++ not regrettable	++ Implementation may start at any time.	0	+ Rather urgent in order to assist future decisions	++ Politically acceptable	+ low costs	9+/0-	4
3.6	Abstraction of water from the river for export out of the Basin	++ benefits both the drainage congestion and the irrigation of other areas	0 Depends on the Climate prediction	+ Need further studies	++ Resilient it leads to larger regulation capacity	0 not urgent	+ Politically acceptable	- - High Costs	5+/2-	7

ID	Adaptation measure	Win/Win	Regret / No Regret	Flexible	High Resilience	Urgency	Political Acceptability	Costs	Score	Ran k
	Additional sources									
10	Ríos Orientales Expansion	+++ Win/win it boosts water availability and makes the water supply less vulnerable to mud flows (destruction of pipelines) and produces power	+ No regret This project seems to be needed even when Climate change is not considered. But technically challenging and big investment could suggest possible regrets	- - Not very flexible	+++ Improves resilience to volcan eruptions (Mud-flows)	+ Somewhat urgent	++ Not politically sensitive	- - high costs	10+/4-	9

7 Outline Adaptation Plan

The identified options have been prioritized according to the rankings in the screening matrix. This outline plan has to be discussed with the City of Trujillo, SEDALIB and Chavimochic who will have to further elaborate on it before implementation.

The preliminary ranked list of measures is divided into three sections of which the last two, adaptation to a drier and adaptation to a wetter climate are ranked in parallel.

7.1 General Adaptation Measures

1.1 Detailed climate change assessment of the Moche River Basin and surrounding areas in line with the work carries out on the Santa Basin should be started. The aim is to reduce the considerable uncertainty on the climate predictions as a minimum to constrain the impact to either a flow decrease or flow increase at the Quirihuac Station. The work should involve several meteorological models and dynamic downscaling to reduce the uncertainty on the climate predictions, as a minimum, to constrain the impact to either a flow decrease or flow increase at the Quirihuac Station.

1.2 Establishment of a groundwater modelling team conducting more detailed groundwater and surface water interaction studies of the Moche aquifer. The team should enable the City and Chavimochic to respond dynamically to possible changes in the climate and in the pumping pattern from the aquifer, aiming at improving the drainage congestion measures without running the risk of over pumping, particularly along the coastline. The team should establish a groundwater decision support tool with upgraded modelling capability to reflect the seasonal variation of inflow and irrigation application, more direct modelling of the influence of the inflows to the aquifer, possible salinity intrusion, impact from changed pumping and assessment of groundwater quality. The established tool should be calibrated with particularly attention to the depth to the groundwater table.

7.2 Adaptation to a Drier Climate

2.1 Conduct detailed modelling studies to reveal with larger accuracy the sustainable pumping from the aquifer. The rapid assessments of this study have indicated that the planned increase in pumping rates up to 2018 seems to be sustainable under the predicted drier climate, but this has to be confirmed by more detailed studies. The activity will address water shortage due to climate change as well as drainage congestion. It is a Win-Win, no-regret and low-cost option that can initiated at any time.

2.2 Negotiate options for increasing the delivery of domestic water from Chavimochic to be effectuated in case new climate assessments point to a drier scenario than the one made in this study or if detailed analyses determine that the planned pumping rates are unsustainable. It is a Win-Win, no-regret and low-cost option that can initiated at any time.

2.3 Start planning for increased irrigation demands. Although the assessed increase in irrigation demands of 6% annually and 7% in the most critical month (December) does not seem to be alarming, the projected temperature rise that causes this increase is more certain than the rainfall projections dominating the projected flow changes in the local rivers. Since the Chavimochic project is not fully developed it still has surplus of water resources to accommodate such changes. However, the projections have to be refined, and taken into account if planning of further development, or compensated by changes in cropping patterns or water savings. It is a Win-Win, no-regret, resilience-increasing and low-cost option that can initiated at any time.

2.4 Monitor the groundwater levels in the aquifer, particularly along the coastline to trigger warnings of possible over extraction and alter pumping scenarios accordingly. It is a

Win-Win, no-regret, resilience-increasing and low-cost option that can initiated at any time.

2.5 Reducing the gross demands by minimising losses in the distribution system (pressure reduction and /or replacement works). It is a Win-Win, no-regret, and low-cost option that can initiated at any time. It may, however, be rather costly.

2.6 Demand management initiatives aimed at reducing the net demand by pricing policies or by restrictions in water use the planned pumping scenarios will only meet the demands up to 2020. It is a Win-Win, no-regret, resilience-increasing and low-cost option that can initiated at any time. It may, however, take time to generate results and be politically sensitive.

2.7 Expansion of the extraction from the Chavimochic canal and increase of the treatment plant. To be effectuated if further studies of the 2018 pumping scenario show it to be unsustainable. An extension of 750 l/s is suggested to compensate for the difference between present pumping and proposed future pumping rates. Could be regrettable and is costly but could show to be necessary in the long run.

7.3 Adaptation to a Wetter Climate

3.1 More detailed groundwater and surface water interaction studies of the Moche aquifer to confirm the findings of the present study and to plan further abatement of the of the drainage congestion.

3.2 Investigation of the opportunities of further expansion of the development plans for the Chavimochic project made possible by a greater availability of water.

3.3 Increase SEDALIB's pumping to the planned 1500 l/s and use this for supply of the city if water quality so allows. The pumping scenario investigated in the previous sections seems to compensate for the negative effects of a wetter climate.

3.4 Increase the pumping for irrigation in the valley, as suggested by Chavimochic in Scenario 3 of the previous study (Ref.)

3.5 Abstraction of water from the river for export out of the basin. This may help the drainage congestion but needs further investigation and quantification.

3.6 Restricting irrigation in certain areas of the valley. If the drainage congestion cannot be controlled by other measures it may be necessary to restrict the irrigation in certain areas of the valley to certain crop types with lower water consumption and leakage to groundwater.

8 References

Ref. Min. de Ambiente, SENAMHI (2012): DISPONIBILIDAD HIDRICA SUPERFICIAL EN LAS CUENCAS DE LOS RIOS SANTA, RIMAC Y MANTARO BAJO CONTEXTO DE CAMBIO CLIMATICO PARA EL HORIZONTE 2030-2039.

Ref. Min. of Environment, SENAMHI (2009): Climate Change Scenarios for Peru to 2030, Second National Communication on Climate Change, Executive Summary.

Ref. Min. del Ambiente, SENAMHI (2010) Segunda Comunicación Nacional del Peru a la convención MArco de las NAciones Unidades sobre Cambio Climatico

Ref. MIKE BY DHI (2011).MIKE 11 a Modelling System for Rivers and Channels, Reference Manual

Ref. SEDALIB (2005): Plan Maestro Optimizado 2005-2035

Ref. Chavimochic(2008?): Proyecto especial de Chavimochic. Modelo Matemático de Simulación del Acuífero Moche

Ref. Visual Modflow(2012): http://www.swstechnology.com/groundwater-modeling-software/visual-modflow-flex

Ref. SEDALIB 2012:PLAN MAESTRO OPTIMIZADO, EPS SEDALIB S.A. PERIODO 2012 - 2042

Ref. SEDALIB (2005): Plan Maestro Optimizado 2005-2035

Ref. FAO 2005: Climwat 2.0 for Cropwat

Ref. Chacimochic (200?): Explotacion de Aguas Subterreneas en los Valles de Chao, Viru and MocheProyecto Chavimochic, Region La Libertad

Ref. INEI, 2010. Estimaciones y Projecciones de población por departamento, sexo y grupos Quinquenales de Edad 1995-2025. Boleti n de Analisis Demografico No. 37. Online http://www.inei.gob.pe/biblioineipub/bancopub/Est/Lib0846/index.htm Accessed 22/06/2012.

Ref. Hawkins, Ed, Rowan Sutton, 2009: The Potential to Narrow Uncertainty in Regional Climate Predictions. Bull. Amer. Meteor. Soc., 90, 1095–1107. doi: http://dx.doi.org/10.1175/2009BAMS2607.1

Ref. Hawkins, Ed, Rowan Sutton, 2011 The potential to narrow uncertainty in projections of regional precipitation change. Climate Dynamics, 2011, Volume 37, Numbers 1-2, Pages 407-418

Ref. IADB 2012: Climate Change Adaptation Case Studies

A P P E N D I C E S

A P P E N D I X   A

Rainfall-Runoff and Climate Change Modelling of the Upper Moche Basin

A Climate Change Impacts on the Moche River Flows

Table of Contents

A.1 Introduction

To analyse the possible consequences of the above climatic changes on the river flows in Moche a conceptual rainfall runoff model, the NAM model, has been established and calibrated on the Moche River basin upstream of Quirihuac flow gauging station (see Figure A. 5). This Upper Basin has a total extension of 1830 km2 with an average altitude of 2680 m.a.s.l.

A.2 Establishment of the NAM Rainfall-Runoff Model for the Upper Moche Basin

The NAM model is one of several rainfall-runoff models included in the MIKE 11 river modelling system. It simulates the rainfall-runoff process at a catchment scale and represents the various components of this process by continuously accounting for the water content in four different and mutually interrelated storages. Each storage represents different physical elements of the catchment. The NAM model can be characterised as a deterministic, lumped, conceptual model with moderate input data requirements. The HBV Model, The Stanford Model, The Sacramento Model all belong to the same family of models along with many others. These models are strong tools for assessing impacts from changed climate parameters The NAM model has been selected because it has been proven capable of simulating shorter term climatic variations such as series of dry or wet years and is therefore also capable of simulating the climatic changes predicted in the Moche Basin. The NAM model is a well-proven engineering tool that has been applied to a very large number of catchments around the world, representing many different hydrological regimes and climatic conditions. I Peru it has been successfully applied for simulating the Mantaro, the Chaglla and the Marañon basins. For more detailed information on the NAM Model and references to applications please consult Ref. 4.

Weighted historical daily data from the five rainfall stations listed in Table A.1 have been used as input to the model in the calibration period. In the selection of stations emphasis have been given to availability and continuity of daily data as well as to spatial coverage of the basin. The weights applied to the various records have been calculated using the Thiessen polygon method and are also included in Table A.1. The locations of the stations are shown on Figure A. 5.

Table A.1 Rainfall stations with daily records used in the established hydrological model of the upper Moche Basin and the Thiessen areas and weights applied to the records.

Name of Station	Area (Km^2)	Thissen Weight
Sisincap	518.78	0.283
Julcan	301.54	0.165
Virgin del Puerta	498.25	0.272
Quiruvilca	269.27	0.147
Laredo	238.74	0.130

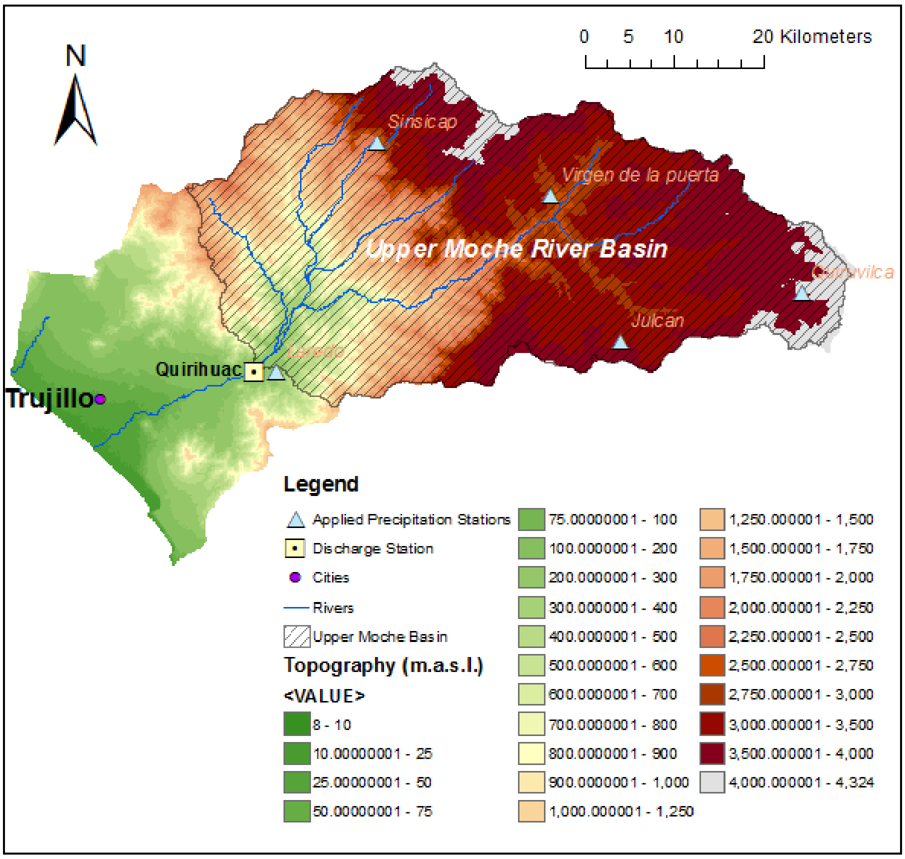

Figure A.1 Location of hydrological stations used in the Rainfall runoff modelling of the upper Moche River Basin

In addition to the catchment rainfall the model also need potential evapotranspiration input. The model is not as sensitive to this input as it is to the rainfall. Hence, in this case average monthly Penman-Monteith estimates from the Chachapoyas Station have been applied. The Chachapoyas Station is located at an altitude of 2540 m.a.s.l. and deemed to be representative for the basin.

A.2.1 Model Calibration

The model has been calibrated on the discharge records from the Quirihuac station for the period 1992-2004. The results are shown in Figure A. 4 and Figure A. 5. It is noted that the long term water balance is well simulated with a deviation of only 1 % from the observations. Although the water balance is good for most of the individual years, it is for some years, such as 1998 and 1999, only acceptable. The seasonal water balance in Figure A. 7 shows a bit underestimation in the start of the wet season (November and December) and a corresponding overestimation of the start of the dry season (June-August) the rest of the months are very well simulated. It is noteworthy that the model handles both very dry and wet years quite well (se Figure A. 5). For this reason and because the deviations from the simulated and observed discharges are assumed to be small as compared to the uncertainties imbedded both in the assessment of the climate change factors and in the assessed recharge to the Moche aquifer, the calibrated model is deemed to be capable of simulating the impacts of a changed climate with a sufficient accuracy for this case study.

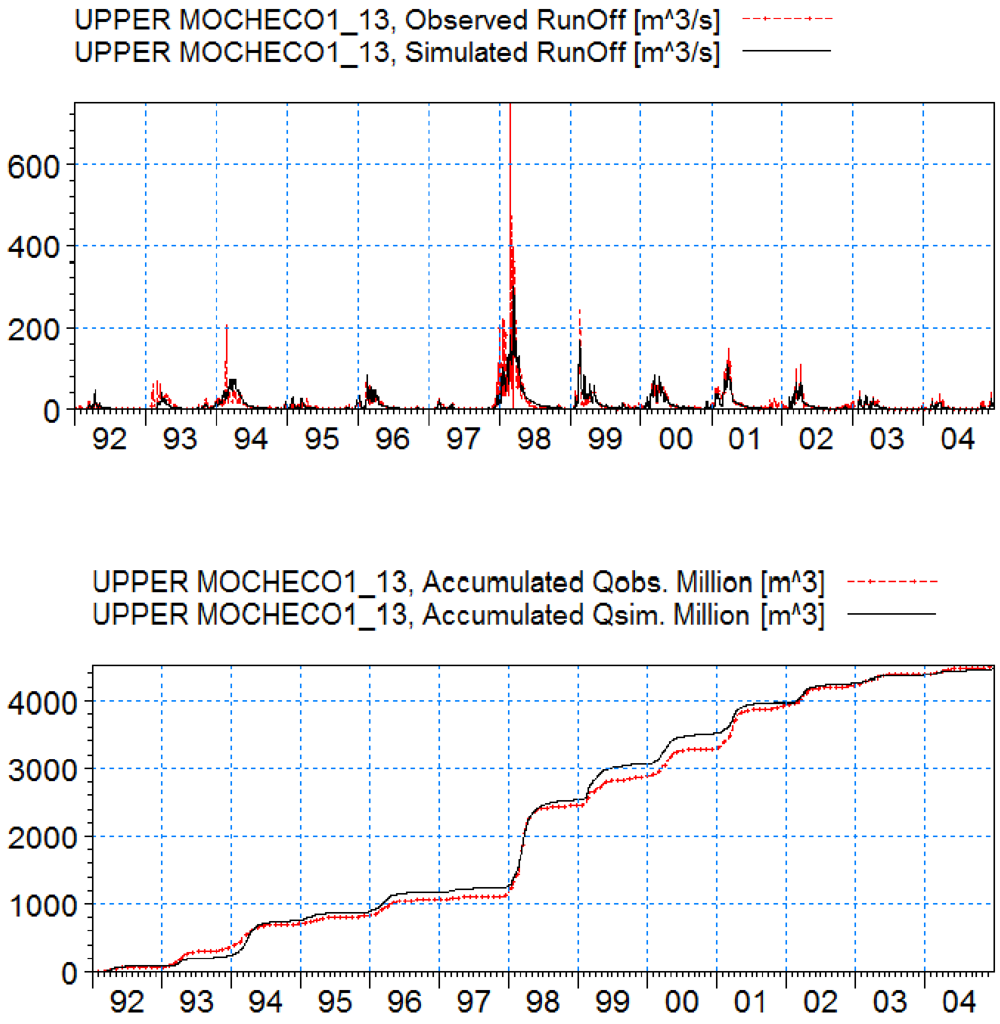

Figure A. 2 Calibration of the nam catchment for the Moche River basin full period 1992 -2004. WB error 1% (observed discharge = 190 mm/year, simulated discharge= 188 mm/year), R2 = 0.64

DHI

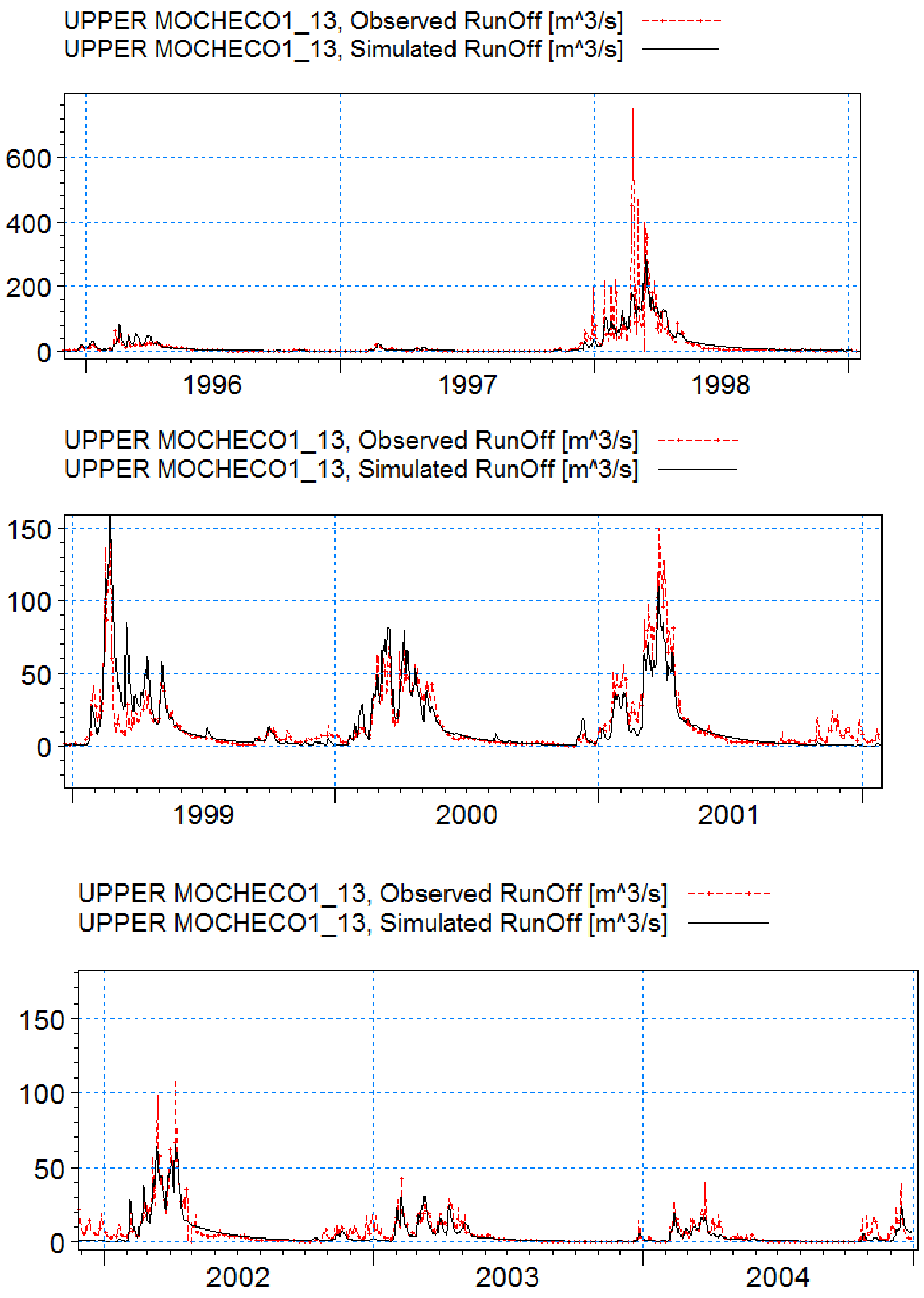

Figure A. 3 Calibration of the _NAM model for the Moche River basin , Details of calibration of certain years including both wet dry and average years.

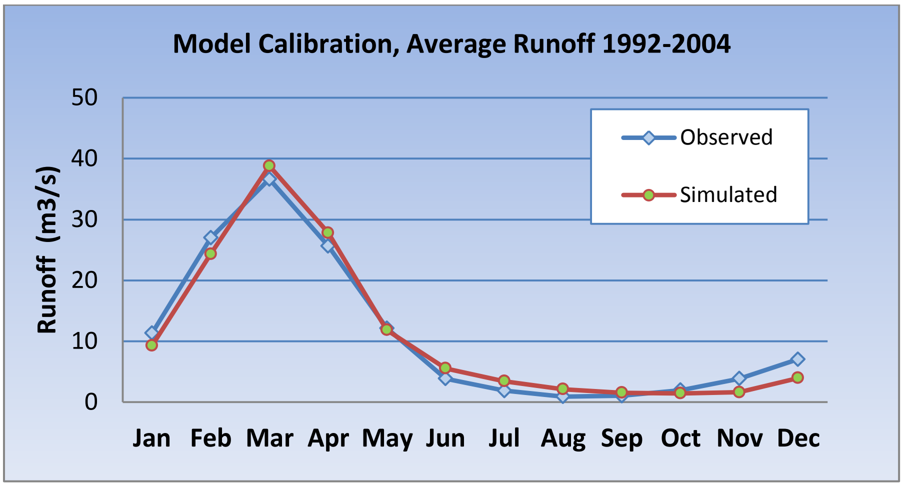

Figure A. 4 Calibration of the NAM model for the Moche River catchment. Average monthly simulated and observed runoff

A.3 Simulation of Climate Change Impacts

The calibrated model has been used to simulate two climate change scenarios. An optimistic scenario, seen from a water supply point of view, assuming a low temperature increase (0.4 deg. C) in combination with a high increase in rainfall (+10%); and a more pessimistic one consisting of a combination of a high temperature increase (+1.2 deg. C) and a decrease on rainfall of 10%. The analysed scenarios are listed in **Error! Reference source not found.** and are the most extreme of the four scenarios emerging from combining the range limits of the Climate change scenarios described in Section **Error! Reference source not found.** of the main report. The potential evapotranspiration values are shown for the present climate as well as for the wet and dry estimates of the future climate. The average changes in potential evapotranspiration are listed in Table A. 2and the monthly changes are illustrated in Figure A5.

Since the inflow to the downstream groundwater model of the Moche Aquifer, which has been established under a previous study (Ref. 5), is based on 75% dependable monthly flows (the flows exceeded during 75% of the time, these flows have been extracted from the hydrological model for the present climate as well as for the dry and wet estimates of the future climate. The extracted results are listed in Table A. 3 and illustrated for surface water in Figure A.6 and for groundwater contributions in Figure A. 7. Average annual change factors have been computed for use in the further analyses and are included in Table A. 3. The Flow Change factors Fof and Fbf for overland flow and groundwater flow, respectively, are defined as:

Fof = Q75pres/Q75 CC

Fbf= BF75pres/BF75cc

Where:

Q75pres is the 75% dependable runoff simulated by present climatic input,

Q75cc is the 75% dependable runoff simulated changed climate input,

BF75pres is the 75% dependable baseflow simulated by present climatic input and

BFcc is the 75% dependable baseflow simulated changed climate input

Table A. 2 Simulated climate change scenarios

Change in Temperature	Precipitation Change Factor	Calculated ET0 Change Factor	Included in analysis
Deg. C	**Fraction**	**Fraction**	**-**
+0.4	1.1	1.02	Yes, optimistic estimate
+0.4	0.9	1.02	No
+1.2	1.1	1.04	No
+1.2	0.9	1.04	Yes, pessimistic estimate

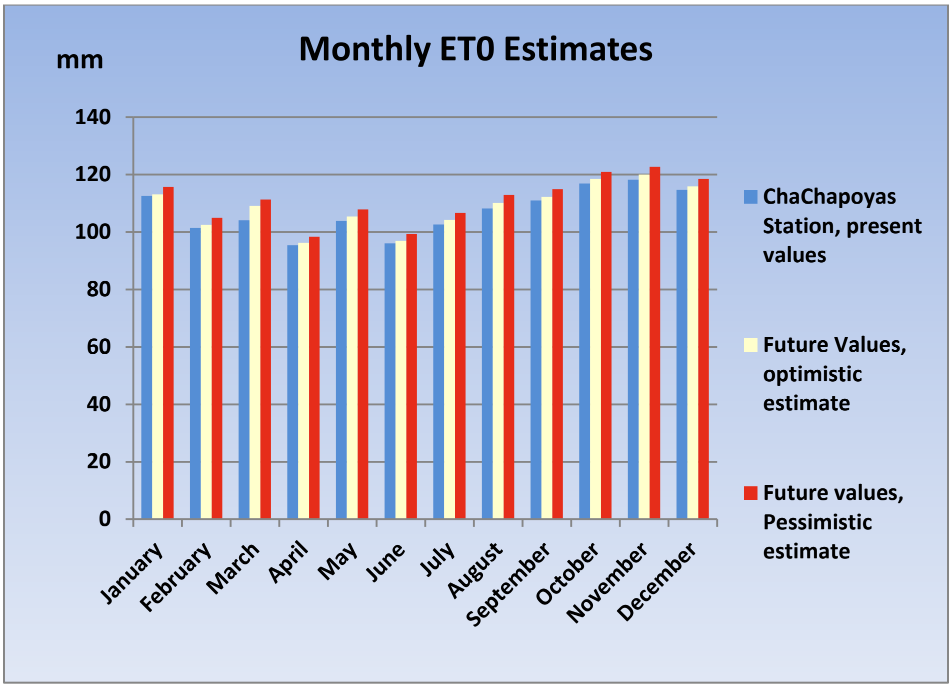

Figure A. 5 Penman Monteith Estimates of monthly reference evapotranspitation for the Moche River Basin given as present, future optimistic and future pessimistic values assuming 0, +0.4 and +1.2 deg. higher temperature , respectively.

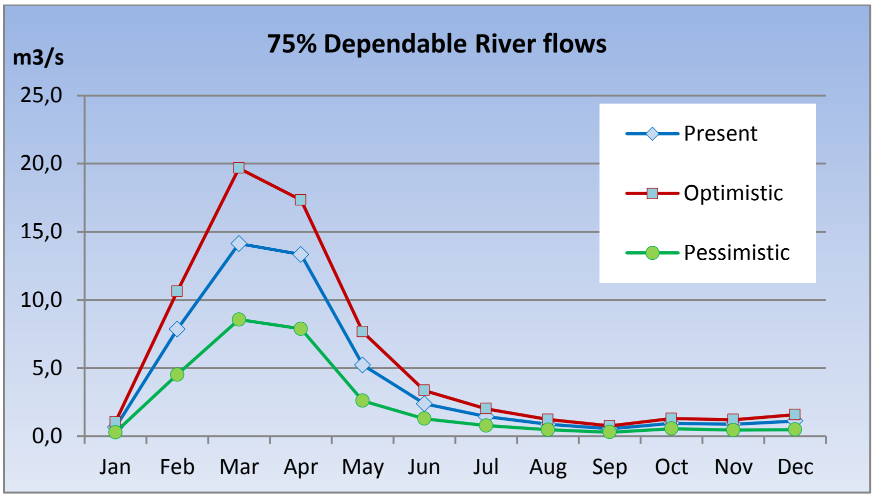

Figure A. 6 Simulated 75% dependable Monthly flows in the Moche River at Cuirihuac, for the present situation as well as for optimistic and pessimistic scenarios of the future climate.

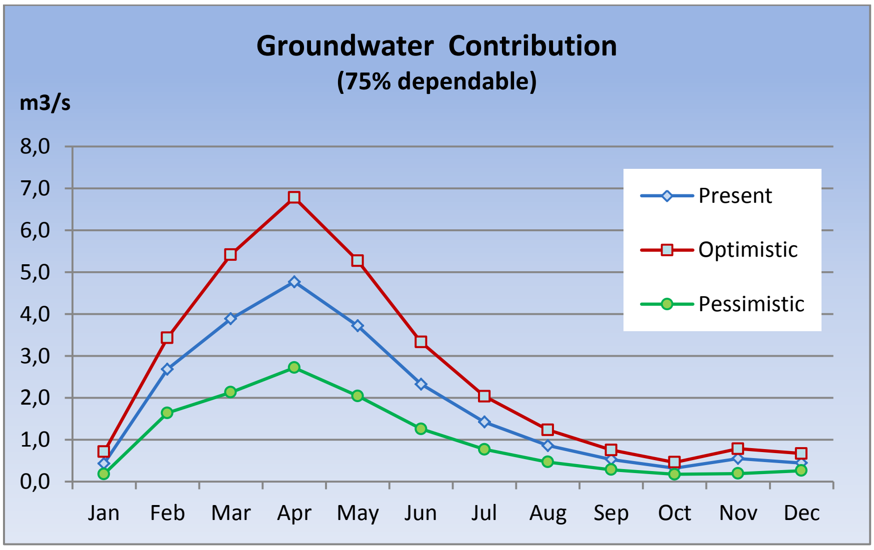

Figure A. 7 Simulated 75% dependable groundwater contributions to the Moche River upstream of Cuirihuac, for the present situation as well as for optimistic and pessimistic scenarios of the future climate.

Table A. 3 Simulated changes in river flows and ground water contributions at the Chuirihuac Station on the Moche River for the present situation and for the two climate scenarios. The average change factors relative to the present situation are listed in bold.

River Flows															
Scenario		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly	Change factor
Present	Average	9.8	26.2	41.0	28.9	12.2	6.0	3.7	2.3	1.7	1.5	1.6	3.0	11.5	1.00
Wet	Average	13.1	33.4	51.3	36.0	15.6	7.7	4.8	2.9	2.2	2.2	2.4	4.4	14.7	1.27
Dry	Average	6.0	18.2	29.7	20.2	8.2	4.2	2.6	1.6	1.1	0.8	0.8	1.6	7.9	0.69
Present	Q75	0.6	7.8	14.1	13.3	5.2	2.4	1.4	0.9	0.5	0.9	0.9	1.1	4.1	1.00
Wet	Q75	1.0	10.6	19.7	17.3	7.6	3.3	2.0	1.2	0.7	1.3	1.2	1.6	5.6	***1.37***
Dry	Q75	0.3	4.5	8.5	7.9	2.6	1.3	0.8	0.5	0.3	0.6	0.4	0.5	2.3	***0.57***
Base flow															
Scenario		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly	Change factor
Present	Average	2.5	6.6	12.4	13.6	9.3	5.9	3.6	2.2	1.4	1.0	0.8	0.9	5.0	1.00
Wet	Average	3.4	8.3	15.4	17.1	11.9	7.6	4.7	2.9	1.8	1.3	1.2	1.3	6.4	1.28
Dry	Average	1.4	4.3	8.8	9.6	6.5	4.1	2.5	1.5	1.1	0.6	0.4	0.5	3.4	0.69
Present	Q75	0.4	2.7	3.9	4.8	3.7	2.3	1.4	0.9	0.5	0.3	0.6	0.4	1.8	1.00
Wet	Q75	0.7	3.4	5.4	6.8	5.3	3.3	2.0	1.2	0.8	0.5	0.8	0.7	2.6	***1.41***
Dry	Q75	0.2	1.6	2.1	2.7	2.0	1.3	0.8	0.5	0.3	0.2	0.2	0.3	1.0	***0.55***

A.4 References

Ref. 1 Min. de Ambiente, SENAMHI (2012): DISPONIBILIDAD HIDRICA SUPERFICIAL EN LAS CUENCAS DE LOS RIOS SANTA, RIMAC Y MANTARO BAJO CONTEXTO DE CAMBIO CLIMATICO PARA EL HORIZONTE 2030-2039.

Ref. 2 Min. of Environment, SENAMHI (2009): Climate Change Scenarios for Peru to 2030, Second National Communication on Climate Change, Executive Summary.

Ref. 3 Min. del Ambiente, SENAMHI (2010) Segunda Comunicación Nacional del Peru a la convencionMArco de las NAciones Unidades sobre Cambio Climatico

Ref. 4 MIKE BY DHI (2011).MIKE 11 a Modelling System for Rivers and Channels, Reference Manual

Ref. 5 Chavimochic(2008?): Proyecto especial de Chavimochic. Modelo Matemático de Simulación del Acuífero Moche

APPENDIX B

Climate Change Impacts on the Moche Aquifer

B Climate Change Impacts on the Moche Aquifer

B.1 Introduction

The Moche Aquifer is being used as of one of the sources of water for SEDALIB's water supply to Trujillo and for the irrigation in the Moche Valley. In this case study the climate effects on the sustainable pumping from the aquifer have been analysed using an existing groundwater model.

The scope of the present study has neither allowed for a review of the calibration of the model nor for a recalibration. Hence, it is simply assumed that the model reflect the behaviour of the aquifer in a satisfactory manner.

B.2 The Groundwater model Established by CHAVIMOCHIC

The model was originally established for Chavimochic (Ref. 1) to analyse pumping scenarios for drainage congestion alleviation and is based on the Visual MODFLOW groundwater simulation system (Ref. 2). The established models is a two-dimensional finite difference model of the Moche Aquifer from the approximate location of the Quirihuac gauging station in the upstream end and to the coast in the downstream end. The city of Trujillo is located centrally in the model area and the urbanised areas cover substantial parts of the modelled aquifer. The extension of the model is indicated by the blue rectangle in Figure B.1 with the aquifer being indicated by the yellow area on the maps. The discretization of the model is 25m x 25 m.

The Aquifer is phreatic and consists of alluvial quaternary deposits. The formations bordering and under layering the alluvial aquifer is modelled as impermeable. The model has been elaborated using hydrogeological information from June 2004 and has been calibrated on the data from that year.

In the original study (Ref. 1) several scenarios were investigated with the objective of lowering the ground water levels at strategic locations under the City. The most promising of these scenarios (Scenario3) involved a total pumping from SEDALIB's wells of 0.520 m3/s. along with pumping from other wells suggested by Chavimochic. The scenario lead to lowering of the ground water levels in the order of 0.5-3.5 m. The scenario was recommended by Chavimochic, and has been used in this case study as template for the scenario representing the present conditions. The analyses made in this case study have only considered changes in the pumping pattern from SEDALIB's wells. The remaining pumping has been maintained unchanged from the original scenario (Scenario 3).

In the model the aquifer is recharged through three sources:

1. The infiltration from the Moche River, this recharge depends on the river flow. And has been calculated as a fraction of the 75% dependable river flows at the Quirihuac Station.

2. The subterranean inflow from the upper part of the aquifer assessed in the modelling report (Ref. 1) at 15.23 MCM/y (=0.48 m3/s).

3. The Recharge in the form of leakage from the irrigation canals and seepage from the fields in the valley. Although this recharge is the dominant inflow to the aquifer, it is almost

constant in the analysed scenarios this a range of only 2.73-2.78 m3/s. This implies an assumption of full irrigation supply at any time independently of the climate, which is a reasonable assumption in a desert.

For more information on the setup and calibration of model as well as on the previous scenarios please refer to (Ref. 1).

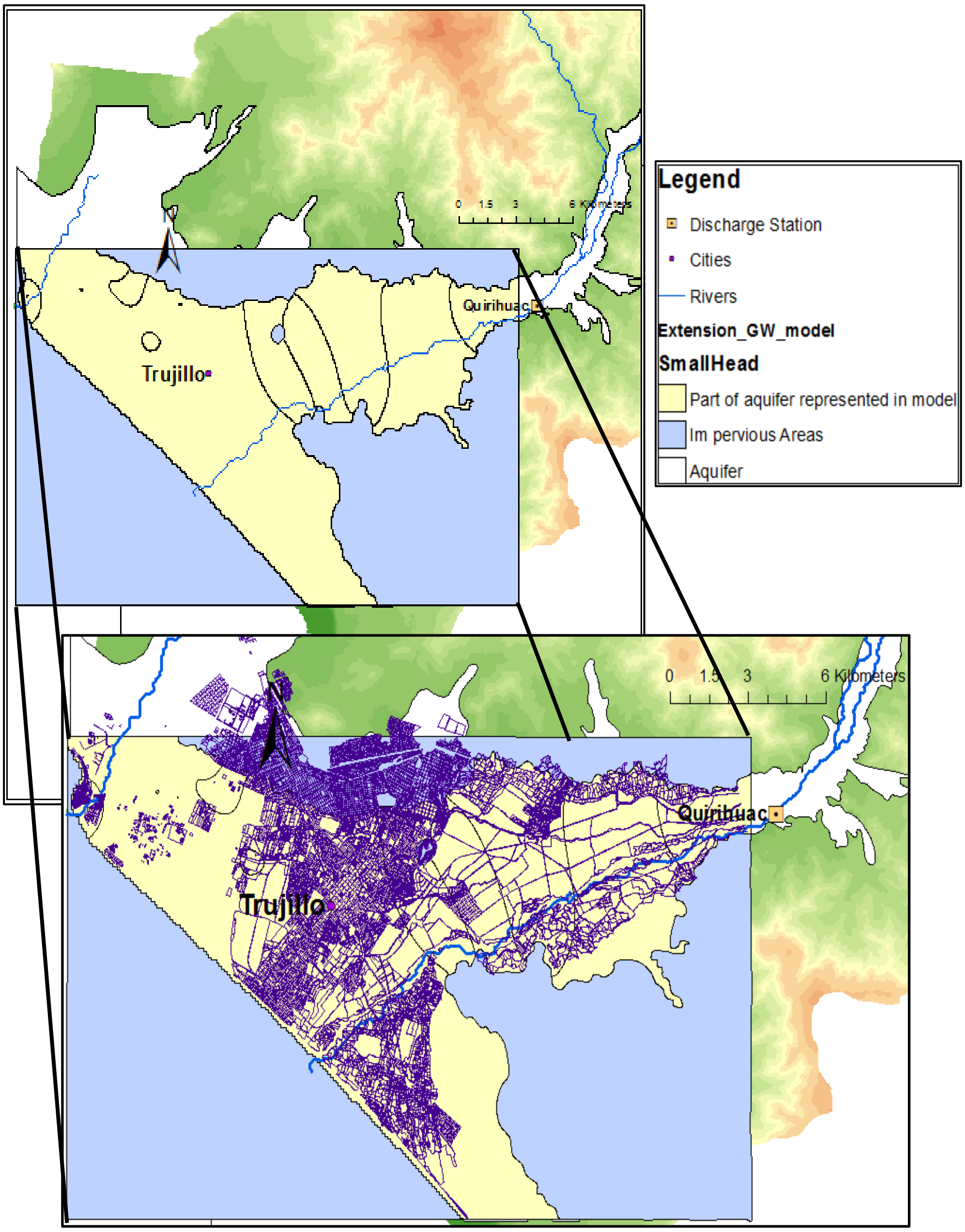

Figure B.1 The Extension of the Chavimochic Model of the Moche Aquifer.

B.2.1 The Pumping Scenario Representing Present Conditions

A detailed distribution of the present pumping from SEDALIB's wells has not been available. Hence, in the model the present pumping conditions have been introduced by modifying the pumping from the SEDALIB wells in Chavimochic's Scenario 3 from the original total of 0.52 m3/s, originating from SEDALIB's master plan from 2005 (Ref. 4), to the present total of 0.745 m3/s as indicated in the SEDALIB's master plan from 2012 (Ref. 3). The SEDALIB wells have been identified by their names and the pumping from the identified wells have all been increased by the same factor to arrive at the present total. This approximation is deemed to be sufficiently accurate for the analyses in this case study.

B.3 Modelling of the Climate Change Impacts on the Aquifer

The impacts on the aquifer under climate change have been analysed by simulating the present pumping scenario subjected to the inflows of the wet and dry climate scenarios, respectively. The results of these two scenarios have been compared to a reference scenario of the present pumping under present hydrological conditions, i.e. the original inflows from Chavimochic's Scenario 3.

The local precipitation over lower part of the Moche Valley is negligible and a possible smaller increase in potential evaporation in the lower Moche Valley is deemed to be balanced by increased import of irrigation water. The climate change impacts on the aquifer have therefore been modelled by changing the groundwater inflow at the upstream boundary of the model and the leakage from the river.

The original recharge from the river was calculated by assuming a water depth in the river of 2 m and the conductivity between river and aquifer was calibrated until the assessed infiltration was reached. This is a long calibration process and a repetition is out of the scope of this study. Instead the water depth of the river has been assumed to vary linearly with the flow. This is not strictly correct, but the assumption seems justified by the large uncertainty imbedded both in the climate assessment and in the rather coarse description of the groundwater - surface water interaction in this type of groundwater model. Hence, in the two climate change scenarios the river depth has been altered using the change factors found in the rainfall –runoff analyses for the 75% dependable flows (See Appendix A). Likewise, the original groundwater inflow along the upper model boundary was altered using the change factors for 75% dependable groundwater contributions. The resulting parameters are listed in Table B.1

Table B.1 Parameters applied for alteration of the inflow to the groundwater model of the Moche Aquifer for the present and the wet and dry climate change assessments.

Scenario 3		Present	Wet	Dry
Groundwater inflow	m3/s	0.47	0.66	0.26
River Depth	m	2	2.81	1.09

B.3.1 The Present Situation

The simulated depths to the groundwater table as simulated for the present conditions is illustrated in Figure B.2, where the darkest blue area represents areas with a calculated depth to groundwater of less than one meter and the lightest blue represent areas with large depth to groundwater (> 10m).

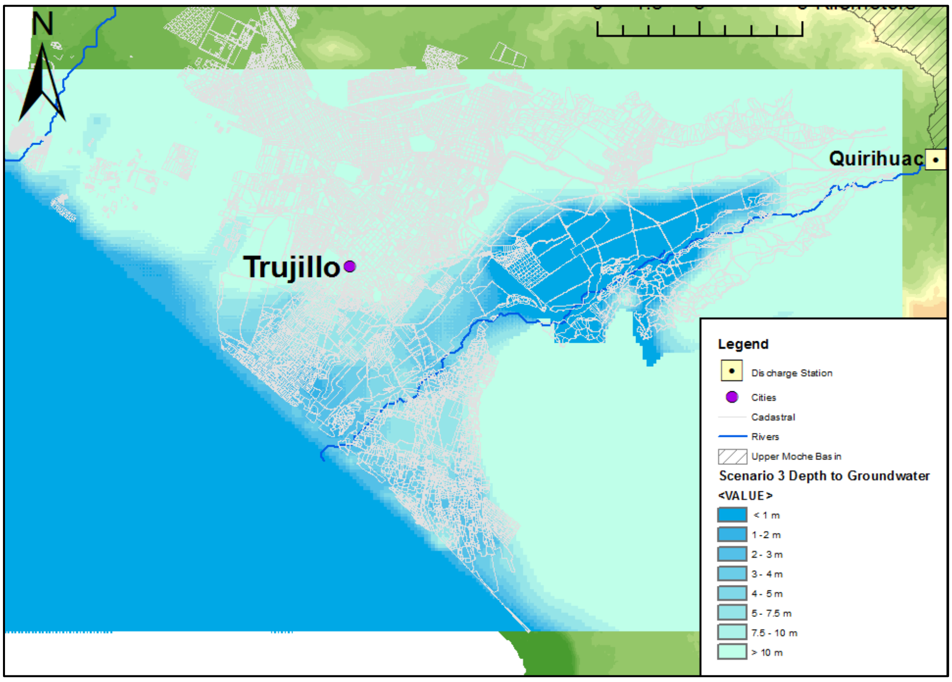

Figure B.2 Depth to Groundwater as simulated in the original pumping scenario 3, made by CHAVIMOCHIC (Ref. 1) and used in this Case study as a reference.

B.3.2 Groundwater Conditions under the Predicted Future Climate Scenarios

B.3.2.1 Present Pumping under Future Climates

The groundwater levels have been simulated for the two future climate scenarios and rise in the groundwater table relative to the present conditions are shown in Figure B.3 for the dry future climate scenario and in Figure B.4 for the wet future climate scenario.

Due to the lower groundwater inflow to the aquifer and the drier river, the groundwater levels will also be lower under a future drier climate (Figure B.3). The aggregated impacts on the groundwater levels are listed in Table B.2 and shows an average drop of 1.2 m for the aquifer as a whole and an average drop of 0.9 m in the part of the aquifer presently having depths to groundwater less than 5 meters.

The Water levels in the figures are taken from the model after 6 years of simulation at a time where the levels have stabilised. Since no indication of decreasing levels has been found it must be concluded that the present pumping is sustainable even under a future drier climate.

For the wet climate scenario (Figure B.4) the groundwater levels will rise all over the aquifer because both the river flows and the groundwater inflow will increase. The average rise has been calculated to 0.52 m for the aquifer as a whole and 0.32 m for the area in which the groundwater is already less than 5 m under terrain (Table B.2)

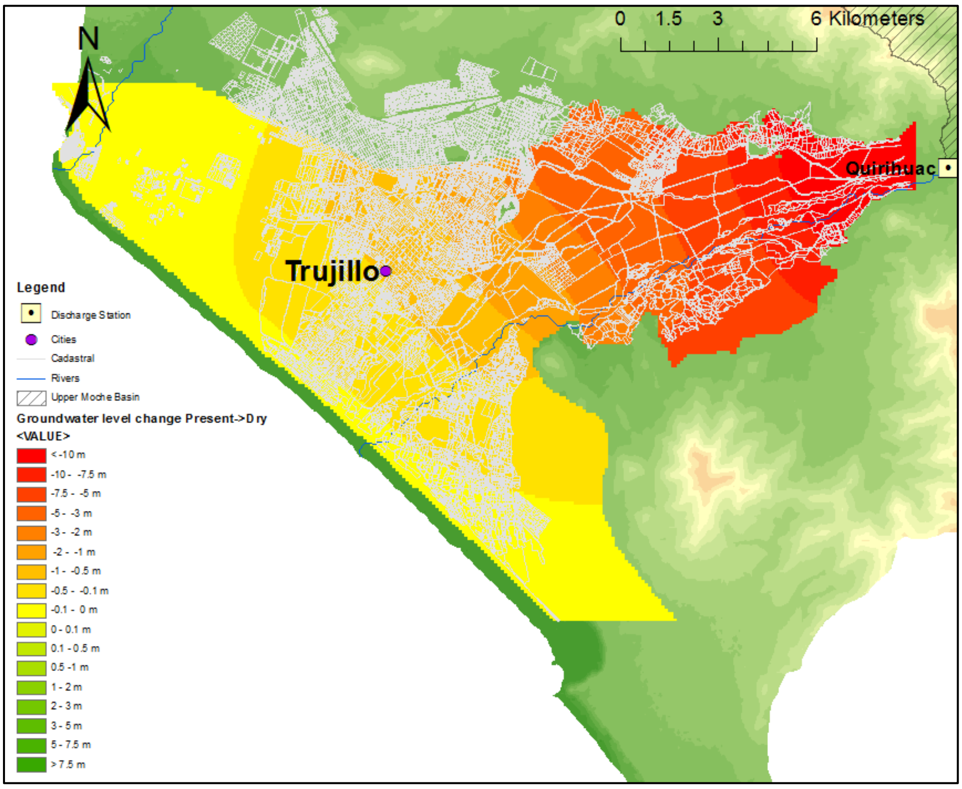

Figure B.3 Simulated groundwater rise from the present conditions to conditions under the dry Climate scenario. Negative values indicate lowering of the groundwater table)

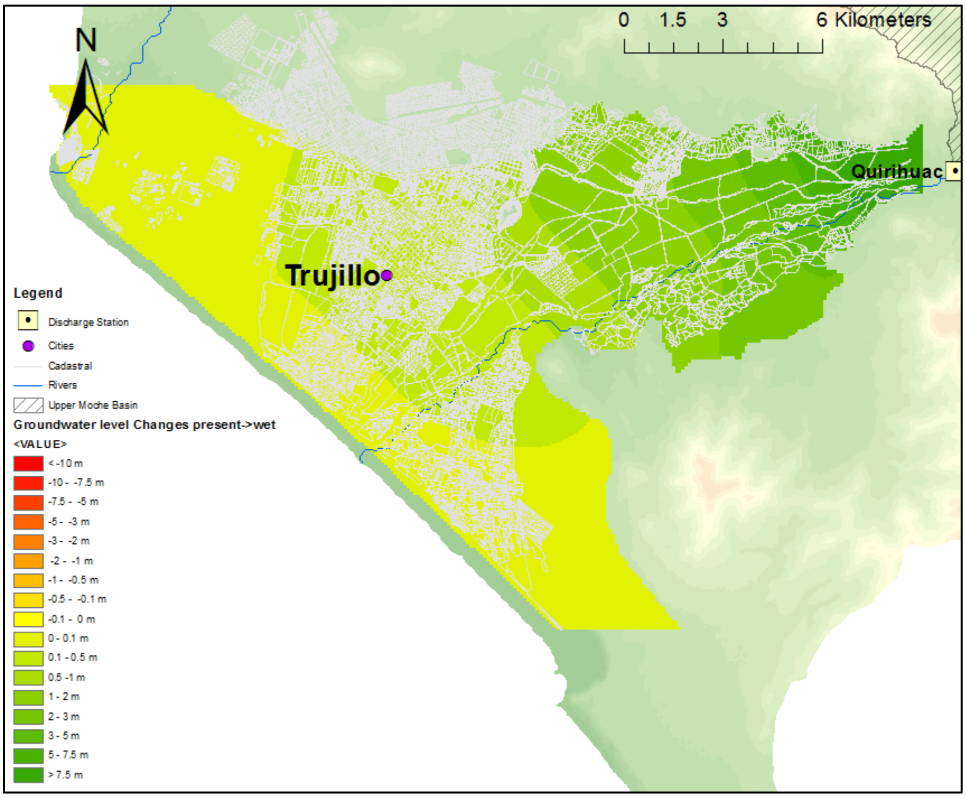

Figure B.4 Simulated groundwater rise from the present conditions to conditions under the dry Climate scenario. Negative values indicate lowering of the groundwater table)

Table B.2 Simulated increases in groundwater water levels of the Moche aquifer (present pumping) under a future climate. The changes are given maximum, minimum and average over the aquifer as a whole and over the part of the aquifer with simulated depths to groundwater less than 5 m. The two aggregation areas are indicated in Figure B.5

Future Climate	Sampling area	MIN	MAX	MEAN
Dry	Whole Aquifer (195.2 km2)	-11.34	0.00	-1.19
Dry	Depths to groundwater < 5m (58.4 km2)	-5.14	0.00	-0.88
Wet	Whole Aquifer (195.2 km2)	0.00	7.73	0.52
Wet	Depths to groundwater < 5m (58.4 km2)	0.00	2.21	0.32

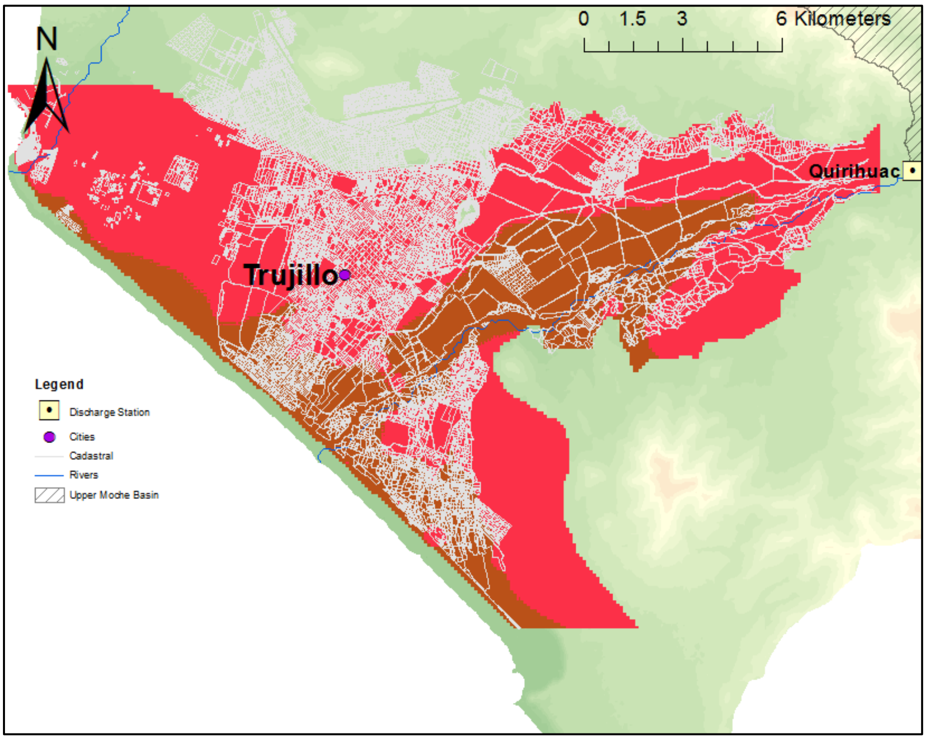

Figure B.5 Aggregation Areas: Whole aquifer (red) and area with simulated depths to groundwater less that 5 m in scenario 3 (Brown).

B.3.2.2 Future pumping under future climates

The SEDALIB Master plan from 2005 (Ref. 4) includes a projection of the future water demand for Trujillo and a proposed increased pumping from the Moche Aquifer to meet this demand (Figure B.6). To meet the demand up to 2018 it is suggested to increase the pumping from the 2005-rate of 520 l/s to 1500 l/s in 2018.

The climate change scenarios used in this cases study is for the period until 2030 and it is therefore unlikely that full climate change would occur within the time horizon of the projected pumping scenario 2005-2018. Nevertheless, we have found it appropriate to investigate if the proposed extended pumping rates will be sustainable under the projected future climates and analyse their impacts on the groundwater levels.

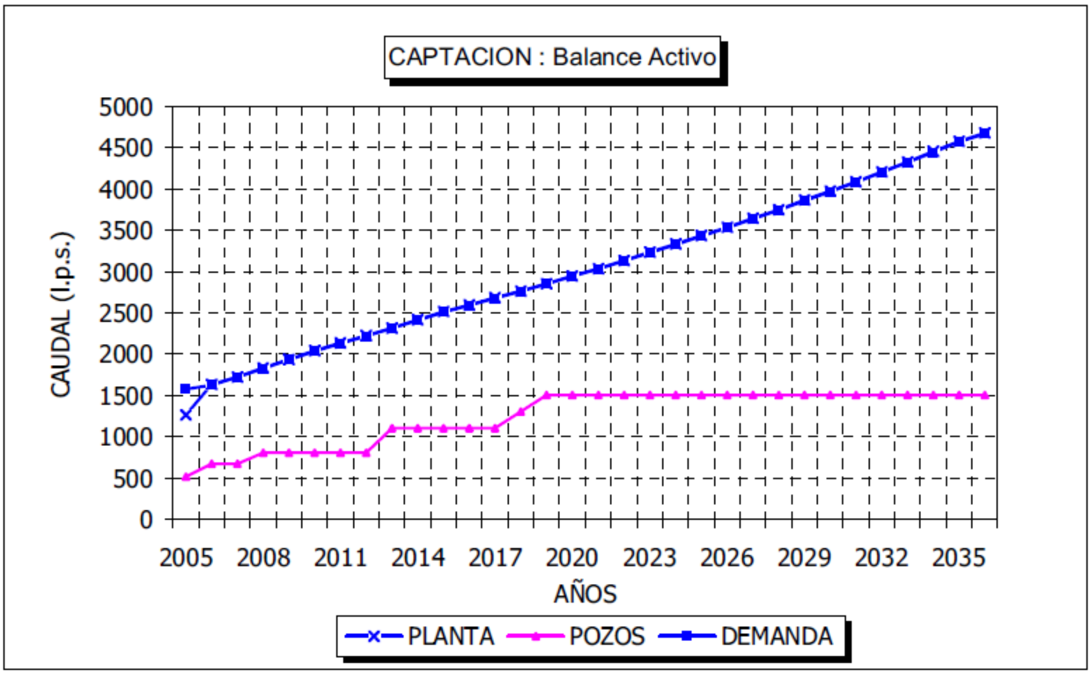

Figure B.6 Planned increased pumping from the Aquifer to meet the rising demand From SEDALIB 2005 (Ref. 4)

The pumping rates of the SEDALIB wells in the present pumping scenario have therefore been increased to the proposed pumping of 1500 l/s using the same factor of increase on all wells and the pumping scenario has been subjected to the dry and the wet future climate scenarios. The results are shown in Figure B.7 and Figure B.8 representing changes in groundwater levels under the wet and the dry climate scenarios, respectively.

It is interesting to note that the increased groundwater levels introduced by a wetter future climate can be controlled by increasing the pumping from the SEDALIB wells to a total of 1500 l/s and that the groundwater level under the City would even decrease relative to the present scenario under such conditions. The average level changes are calculated to be +0.74m in average for the whole aquifer but -0.64 for the areas with high groundwater levels today (Table B.3).

Not surprisingly, a dry future climate combined with an increased pumping rate of 1500 l/s will cause the groundwater levels to drop. In average over whole aquifer the levels are predicted to decrease by 5.8 m and by 4.5 m in average over the area with present groundwater depths less than 5 m. It is noteworthy that the new levels seem to stabilise within the simulation period of 6 years, and that the increased pumping rates therefore seems to be sustainable under the dry climate scenario. It is also noted that even though the changes in levels are small close to the coast line, the predicted levels are very close to zero in this zone. Levels should therefore be monitored carefully in the future in order to reduce pumping locally to prevent salinity intrusion if groundwater levels start falling further in this area.

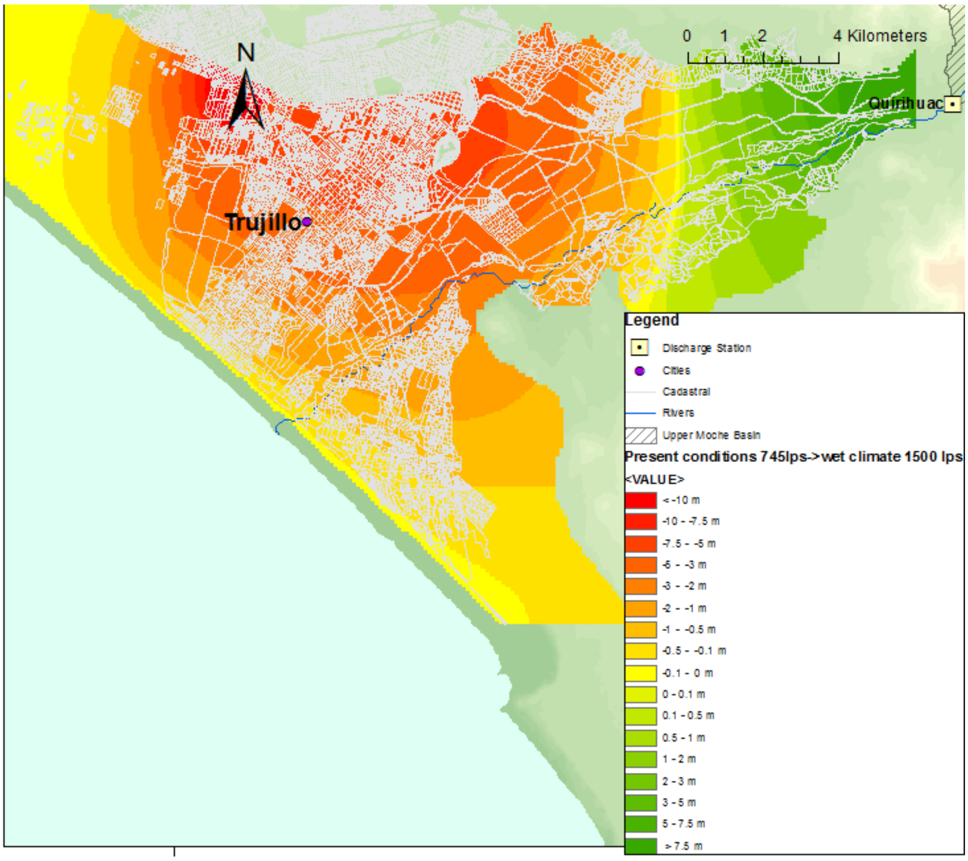

Figure B.7 Changes in Depth to groundwater from present conditions to a future wet climate with a pumping from SEDALIB's wells of 1500 l/s

Table B.3 Simulated increases in groundwater water levels of the Moche aquifer from the present pumping and climate conditions to a future dry climate with a pumping of 1500 l/s . The changes are given maximum, minimum and average over the aquifer as a whole and over the part of the aquifer with simulated depths to groundwater less than 5 m. The two aggregation areas are indicated in Figure B.5

Future Climate	Sampling area	MIN	MAX	MEAN
Dry	Whole Aquifer (195.2 km2)	-41.96	0.00	-5.76
Dry	Depths to groundwater < 5m (58.4 km2)	-14.92	0.00	-4.46
Wet	Whole Aquifer (195.2 km2)	-7.10	20.48	0.74
Wet	Depths to groundwater < 5m (58.4 km2)	-2.58	1.57	-0.64

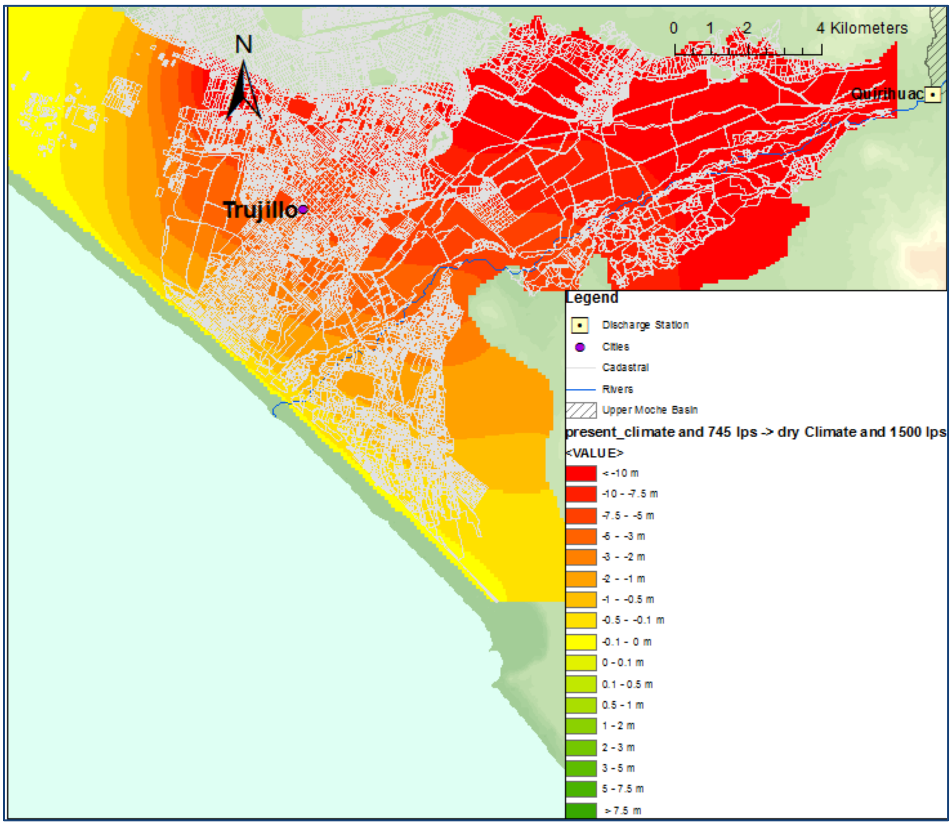

Figure B.8 Changes in Depth to groundwater from present conditions to a future dry climate with a pumping from SEDALIB's wells of 1500 l/s

B.4 References

List of references used in this Appendix

Ref. 1 Chavimochic(2008?): Proyecto especial de Chavimochic. Modelo Matemático de Simulación del Acuífero Moche

Ref. 2 Visual Modflow(2012): http://www.swstechnology.com/groundwater-modeling-software/visual-modflow-flex

Ref. 3 SEDALIB 2012:PLAN MAESTRO OPTIMIZADO, EPS SEDALIB S.A. PERIODO 2012 -2042

Ref. 4 SEDALIB (2005): Plan Maestro Optimizado 2005-2035

APPENDIX C

Climate Change Adaptation in the Irrigation Sector
Suggested Project Components

Climate Change Adaptation in the Irrigation Sector, Suggested Project Components

C.1 Background

The irrigation sector is a very important factor for Trujillo's economy and its social sustainability. An analysis of the climate change impacts on the sector is therefore relevant.

A thorough analysis of the sector's water demands, possible water-saving initiatives, and development potential is a large study in itself. This appendix contains a summary of relevant aspects to consider in such a study.

Climatically, the coastal plains around Trujillo are virtually deserts. As shown in Section 5 of the Main Report even large percentage changes in the precipitation will not have significant impact on the crop water demand in this area. The increased temperature is, however, likely to increase the crop water demands by 6 % annually and 7 % in the most critical month (December).

It should be emphasised that a detailed analyses of adaptation measure is only relevant if the irrigation sector seems to be sensitive to the projected climate change. In a situation with abundant resources, such as the present one, a detailed analysis may not be needed although drainage congestion may become a problem that needs further attention. This situation may change if the system is expanded. More water will be needed and the resource may become scarce. In such cases a more detailed analysis should indeed be considered.

C.2 Components

A more detailed climate change adaptation study of the irrigation sector should include, but not be limited to the below aspects. It will require extensive involvement of stake holders at all levels both from Chavimochic, from the local farmers and from the irrigation companies.

C.2.1 Climate Change impacts on the Local River Flows

There is no indication of a climate-generated decrease in the low flows in Rio Santa in the near future. If water from the local rivers Chao, Virú, Moche and Chicama or the aquifers fed by those rivers is to be used for irrigation, a more detailed assessment of the climate change in their upstream catchment areas should be made, since the Moche River has been found to be sensitive to the projected climate changes in its upper catchment.

The impacts from such changes on the river flows and the recharges to the aquifers may be assessed using a hydrological modelling approach similar to the one applied in this study. It is recommended, though, to apply groundwater models with a more integrated description of groundwater and surface water to improve the rather coarse seepage and infiltration assessment used here.

C.2.2 Inventory of the Irrigated Crops

An inventory of the types and extents of crops grown in the irrigation schemes should be made. This may be based on remote sensing analysis in combination with consultation with local stake holders. The rationale for the selection of the various crop types such as profitability, tradition, soil and climate suitability, resilience, market aspects etc. should be clarified.

C.2.3 Present Water Demands and Losses

The various irrigation technologies in use should be analysed. The crop water demand and irrigation demands should be determined. The actual water allocation along with the losses (operational, conductive and application) should be revealed along with the recipients of the lost water and possible reuse of these losses.

The overall water balance of the irrigation systems and the interaction between the various sub elements should be analysed by integrated water allocation and irrigation models accounting for both surface water and ground water aspects.

C.2.4 Present Costs and Benefits in the Production

In order to further understand the present system and to form the basis for proposing realistic adaptation measures the costs and benefits, constraints and opportunities related to the present production should be clarified. This analysis should be differentiated on crop types and irrigation technology and, if necessary, access to finances.

C.2.5 Trends in the Market

Market aspects of the present production along with possible trends and opportunities in the market should be assessed by stake holder consultation and by local and international market analyses.

C.2.6 Possible new Water Saving Technologies and their Costs

The possibility for water savings or improved drainage by introduction of more advanced technology should be investigated and discussed. Cost benefit analyses of the implementation of such technology should be made and its applicability assessed (technical, economically, sociologically, financially and environmentally) Local and global experience may be used to supplement this analysis

C.2.7 Possible Water Saving Crop Changes

Similarly it should be investigated if changes to alternative crop types could be useful adaptation measures and if such changes would be feasible and sustainable.

C.2.8 Social and Financial Aspects, Willingness to change

The local perception of the vulnerability to climate change and the willingness and capacity to change should be revealed and discussed.

C.2.9 Proposed Adaptation Plan

Possible adaptation measures should be identified and ranked and an adaptation plan should be proposed, discussed with the local stake holders, and revised according to the feedback received.