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Potential outcomes of multi-variable climate change on water resources in the Santa basin, Peru

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Abstract

Water resources in the Santa basin in the Peruvian Andes are increasingly under pressure from climate change and population increases. Impacts of temperature-driven glacier retreat on stream flow are better studied than those from precipitation changes, yet present and future water resources are mostly dependent on precipitation which is more difficult to predict with climate models. This study combines a broad range of projections from climate models with a hydrological model (WaterWorld), showing a general trend towards an increase in water availability due to precipitation increases over the basin. However, high uncertainties in these projections necessitate the need for basin-wide policies aimed at increased adaptability.

Keywords: Water resources, climate change, WaterWorld, tropical glaciers, uncertainty, Peru

Introduction

Water resources in many regions of the world are increasingly under pressure from climate change with precipitation changes affecting water availability and runoff directly and temperature, radiation and humidity impacting on evapo-transpiration (Solomon, 2007; Buytaert, 2010) and snow and ice dynamics. In the Peruvian Andes, climate change pressure on water resources is considered to be exacerbated by the retreat of glaciers that act as seasonal water stores, providing freshwater during the dry season (Vuille, 2008). More than 99% of all tropical glaciers are located in the Andes (Kaser and Georges, 1999) of which nearly 70% are located in Peru (Vuille et al., 2008). Most water resources on the Pacific slopes of Peru originate from snow and ice in the Andes according to Vuille et al., (2008).

Pressures of climate change and glacier retreat are particularly pertinent for Peru’s Rio Santa basin where a growing water demand has resulted from increases in human population, export agriculture, mining and hydropower production leading to increased competition for water (Lynch, 2012). This competition and developing strategies for better sharing the benefits of available water was the focus of the CGIAR Challenge Programme on Water and Food (CPWF) Project AN3 (COMPANDES) under which the research for this paper was carried out (CGIAR WLE, 2014).

Most studies on the impacts of climate change on water resources in the Peruvian Andes focus on glacier retreat and associated impacts on streamflow. For example, Pouyaoud (2005) using an increase in temperature of 0.1 °C/decade projected increases in stream flow for the next 20-50 years under melting glacier conditions in the Llanganuco river basin after which stream flow will become rain and snowmelt dominated. Juen et al (2007) obtained similar results using a more sophisticated tropical-glacier-hydrology model driven by four IPCC AR4 (Fourth Assessment Report; Solomon et al, 2007) emission scenarios which resulted in reduced dry season runoff because of diminishing glacier size but increased wet season runoff due to enhanced direct runoff as a result of increased rainfall. Generally, these studies show that overall discharge may not change very much but there are significant changes in seasonality under climate change due to the loss of water stored and released seasonally by glaciers. There are however significant differences between the various climate change projections that lead to large differences in glacier discharge between scenarios (Vuille, 2008) and these are a key uncertainty associated with assessing the impacts of climate change on water resources, particularly in the Peruvian Andes. These uncertainties derive from a number of sources associated with the General Circulation Models (GCM), most importantly the emission scenario but also difficult to model mechanisms such as rainfall and cloud behaviour and sub-grid heterogeneity associated with simplified representation of topography. This can result in different GCMs producing very different projections. Even more uncertainty is introduced when combining these GCMs with hydrological models as the GCM outputs will need to be downscaled. Due to the typically coarse resolution of GCMs, natural gradients in precipitation and temperature are smoothed out and this is particularly problematic in mountainous regions as their hydrology is characterised by strong elevational gradients (Wilby et al., 2004; Buytaert et al., 2010).

This paper aims to evaluate the potential outcomes of climate change on the water resources of the Santa basin by combining a range of statistically downscaled climate models using scenarios from the IPCC AR4 with a physically based spatial hydrological model

(WaterWorld, Mulligan, 2013a) which is capable of simulating snowfall and snowmelt dynamics (WaterWorld version 2, Mulligan, 2013b). This allows for the assessment of some of the uncertainty in future discharge projections and water resource availability in the basin and especially the relative role of changes in different fluxes (particularly, rainfall, snowfall and melt water) on water resources at different scales.

Study area

Study location and topography

The Rio Santa basin is located in Peru, in the Ancash region about 400 km north of the capital Lima (Figure 1). The basin has a total drainage area of around 12,200 km^2 and a total length of 316 km which makes it the second largest river and most regular flowing Peruvian river to flow into the Pacific ocean (Mark et al., 2010). The river originates at Lake Conococha at an altitude of 4080 m.a.s.l. and then runs north in the Callejón de Huaylas valley which is located between the Cordilleras Blanca and Negra, it then turns west at the confluence with the Rio Manta towards the city of Chimbote at the Pacific coast (McKinney, 2011). The Cordillera Blanca towards the east of the Rio Santa has about one quarter of all tropical glaciers (more than 600 km^2) and over 30 peaks that are higher than 6000 m.a.s.l. (Kaser et al., 2003; Vuille et al., 2008). Of the 23 tributary streams of the Rio Santa, 20 originate from the glaciers of the Cordillerra Blanca, making glacier melt an important contributor to the Rio Santa discharge, particularly in the dry season (McKinney, 2011). Conservative estimates of this contribution by Mark et al., (2005) indicate that about two-thirds of the dry season flow of the Rio Santa in the Huaylas valley originates in the Cordillera Blanca with 40% of the total flow in the dry season coming from glacier melt. Annual and wet season contributions were not assessed in this study.

< insert figure 1 around here>

Current and recent climate

Temperature in the area is dominated by the Intertropical Convergence Zone (ITCZ) and trade winds leading to only small variations in annual air temperature seasonally (Mark et al., 2005; Maurer, 2009). Mean annual temperature in the basin based on WorldClim (Hijmans et al., 2005) data is 9.6°C with a mean monthly minimum of 8.2°C in August and a mean monthly maximum of 10.9 °C in March.

More than eighty percent of precipitation falls in the wet season between October and May when the ITCZ is in the region (Mark et al., 2005; Mark et al., 2010). The Cordillera Blanca acts as a barrier between the humid Amazon and the extremely dry coastal region with the Amazonian side being up to three times wetter than the Pacific side (Racoviteanu et al., 2008). Average precipitation for the basin amounts to 548 mm a year according to WorldClim data. However, this is extremely spatially variable with the highest precipitation found along the Cordillera Blanca and the lowest in the dry coastal region.

Recent and projected climate changes

A temperature increase of around 0.35°C-0.39°C per decade has been found in central Peru between 1951 and 1999 based on 29 temperature stations (Mark et al., 2005) while Vuille et al., (2008) using 279 temperature stations found 0.10°C increase per decade between 1939 and 2006 for the tropical Andes between 1 deg N and 23 deg S, leading to an overall temperature increase of nearly 0.7°C since 1939. No clear trends in precipitation have been found, partly as a result of the lack of long period, high-quality precipitation records. Vuille et al., (2003) analyzed 42 precipitation stations in the region and only found five with a significant increase and two with a significant decrease in annual precipitation. There was no clear dependence on elevation. Some other studies have found clear precipitation increases from mostly the Eastern slopes of the Andes (Vuille et al., 2003). Projected changes in climate for the region under the IPCC AR4 emission scenarios point to a warming of between 3-3.5 deg C for the 2041-2071 period as well as a consistent pattern of increasing precipitation up to 10%. However, for the precipitation projections, there is relatively low agreement between climate models (Met office, 2011).

Water resources and land use

The basin can roughly be divided into three zones based on elevation: the high mountains above 2000 metres, the Callejón de Huaylas valley between 1000 and 2000 metres and the coastal region below 1000 metres. The highland areas mostly support subsistence farming and grazing. Land use in the Callejón de Huaylas valley mostly consists of small irrigated farming and the coastal region is dominated by large commercial irrigated agriculture in the Chavimochic and Chinecas project areas. Furthermore, the coastal cities of Chimbote and Trujillo further north are dependent on water from the Rio Santa for their drinking water supplies.

Methods

To assess the implications and uncertainties of climate change for water supply in the Santa basin we used the WaterWorld hydrological model (Mulligan, 2013a) with a total of six multi-model ensemble climate change scenarios in order to capture the widest range of possible futures. Changes in melt water contribution, total stream flow and melt water generated stream flow were analysed at the basin level and for two of the largest, most populous, high altitude cities in the basin: Caraz, with a population of circa 13,000 and Huaraz with a population of circa 96,000.

The WaterWorld hydrological model

WaterWorld is a fully distributed, process-based hydrological model that utilises remotely sensed and globally available datasets to support hydrological analysis and decision-making at national and local scales globally, with a particular focus on un-gauged and/or data-poor environments, which makes it highly suited to this study. The model (version 2) currently runs on either 10 degree tiles, large river basins or countries at 1-km^2 resolution or 1 degree tiles at 1-ha resolution utilising different datasets. It simulates a hydrological baseline as a mean for the period 1950-2000 and can be used to calculate the hydrological impact of scenarios of climate change, land use change, land management options, impacts of extractives (oil & gas and mining) and impacts of changes in population and demography as well as combinations of these. The model is ‘self parameterising’ (Mulligan, 2013a) in the sense that all data required for model application anywhere in the world is provided with the model, removing a key barrier to model application. However, if users have better data than those provided, it is possible to upload these to WaterWorld as GIS files and use them instead. Results can be viewed visually within the web browser or downloaded as GIS maps. The model’s equations and processes are described in more detail in Mulligan and Burke (2005) and Mulligan (2013b). The model parameters are not routinely calibrated to observed flows as it is designed for hydrological scenario analysis in which the physical basis of its parameters must be retained and the model is also often used in un-gauged basins. Calibration is inappropriate under these circumstances (Sivapalan et al., 2003). The freely available nature of the model means that anyone can apply it and replicate the results shown here.

Snow and ice model

A number of studies have modelled water resources under future climate scenarios in the tropical Andes using various approaches and models for capturing snow and ice responses. For instance, Chevallier et al., (2011) used a simple temperature-discharge correlation approach to project future discharges given temperature increases. Condom et al., 2011 extended the Water Evaluation and Planning (WEAP; Yates et al., 2005) model with a glacier module based on a degree-day model approach while Andres et al., (2014) used a semi-distributed hydrological model (PREVAH; Viviroli, 2009). While the latter type of model provides good results, such models are calibrated to current conditions and require large amounts of (daily) input data which is generally lacking in this region and for the future (Huggel et al., 2015). Within WaterWorld, the snow and ice dynamics are resolved in a fully distributed, integrated approach without the need for additional parameterisation data and applicable at the wider basin scale.

WaterWorld's (V2) snow and ice module is capable of simulating the processes of melt water production, snow fall and snow pack, making this version highly suited to the current application. The model component is based on a full energy-balance for snow accumulation and melting based on Walter et al., (2005) with input data provided globally by the SimTerra database (Mulligan, 2011) upon which the model relies. In particular, initial monthly snow cover is based on Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data processed by Mulligan (2006) and precipitation that falls where ground level temperature is below 0°C is assumed to fall as snow. Changes in melt water production and snow pack as a result of climate change are based on changes in seasonal and spatial patterns of temperature and precipitation for scenario conditions. Increased temperature leads to less precipitation falling as snow and to more snow and ice melt while increased precipitation can lead to more snowfall. Both snow melt and glacier melt are governed by temperature with temperatures above 0°C leading to melting conditions. This means that on days with temperatures above 0°C and no snow pack available, glacier melt will occur. WaterWorld takes into account diurnal temperature ranges by iterating through four diurnal time-steps that represent the mean diurnal cycle for each of the 12 monthly time-steps represented by the 50 year climatology.

Glaciers are represented by the World Glacier inventory of World Glacier Monitoring Service (WGMS) and National Snow and Ice Data Center (NSIDC) (2012) whose water equivalent are added to the initial snowpack water equivalent in the model. Changes in glacier extent under scenario conditions are accounted for by allowing the model to spin up. The database identifies some 390 km^2 of glacier within the Santa basin (2.8 % of the surface area) with a mean water equivalent of 0.9 mm but ranging up to 146 mm on a 1-km grid cell basis.

Model validation

In order to test model performance in the basin, simulated stream flow was compared with observed flow. Data for observed stream flow were obtained through the COMPANDES project with original data supplied by the Peruvian Institute of Natural Resources (INRENA) with data available for 16 sub-catchments for measurement periods ranging from 9 to 57 years. Two input precipitation datasets were used in the validation, the WaterWorld default WorldClim data (Hijmans et al., 2005) based on 15 precipitation stations in and around the basin for observation periods up to 50 years and a TRMM (Tropical Rainfall Measuring Mission) monthly precipitation climatology based on the TRMM 2B31 dataset for the years 1997-2006 developed by Mulligan (2006). According to Condom et al., (2013) there are 39 precipitation stations in the Santa watershed which is more than are included in the WorldClim dataset, hence this underrepresentation of stations may account for uncertainty in the precipitation input data. However, Ward et al., (2011) showed that observational climatology data products such as the CRU CL 2.0 and WorldClim datasets compare well with Thiessen interpolated averages of observed data for long-term mean annual precipitation in two Andean basins, mainly due to these products being generated from very similar observed datasets although differences may be attributed to availability of precipitation data and averaging time period.

Table 1 shows the results for the stream flow validation for both precipitation climatologies for all available observed stream flow stations and for stations that have an average flow of at least 5 m^3s^{-1} (8 stations). Modelled annual stream flow shows a good fit with observed data for all stations (R^2 = 0.84) but particularly for the stations with higher flow rate (R^2 = 0.99) using WorldClim precipitation. Validation results for TRMM climatology show a slightly weaker fit which is likely due to an underestimation of precipitation for TRMM data. This underestimation of TRMM precipitation has also been shown by Ward (2011) and Lavado Casimiro (2009) for a number of basins in the Andes and Andes-Amazon.

<Table 1>

Climate change scenarios

In order to better understand the high uncertainties in projections of climate change, the full available range of GCMs from IPCC AR4 downscaled to 1-km spatial resolution by CCAFS

(Research Program on Climate Change Agriculture and Food Security of the CGIAR) (Ramirez and Jarvis, 2008) using the delta method for the 2050s is used in this study. Two AR4 emissions scenarios were used. The SRES A2A scenario represents high growth and a global 3.5°C warming (relative to 1900) by 2100 and the SRES A1B scenario which is a more balanced scenario, representing moderate growth and a global 2.5°C warming by 2100 (Nakicenovic et al., 2000). Individual monthly downscaled GCM output (Ramirez and Jarvis, 2010) for temperature and precipitation were combined by WaterWorld into multi-model ensemble per-pixel mean scenarios using 17 available GCM for the A2A scenario and 24 GCM for the A1B scenario (see table S1 for more details on GCM used). Using ensembles of GCMs is advocated as a way to obtain reliable information on the range of possible regional changes and associated uncertainties (Murphy et al., 2004; Solomon, 2007). More recent downscaled GCM data is currently available (e.g. WorldClim Coupled Model Intercomparison Project phase 5, CMIP5) using the Representative Concentration Pathways (RCP) scenarios (Van Vuuren, 2011). At the time of analysis however these were not yet incorporated in the WaterWorld model but analysis of mean monthly precipitation and temperature changes for 17 GCM under the RCP 4.5 scenario for the basin for 2050 resulted in similar directions of change and model disagreement as for the A2A and A1B scenarios.

Figure 2 shows the range of monthly GCM projections for the Santa basin for precipitation and temperature for both A2A and A1B emission scenarios. Clearly between-model differences are significant, particularly for precipitation which differs between GCMs in the direction of projected change (i.e. positive or negative relative to baseline) as well as the magnitude of change for nearly all months. To capture this wide range of possible futures, as well as the multi-model mean for A2A and A1B, the multi-model mean plus (+) and minus (-)

the inter-model standard deviation for both temperature and precipitation were also used as scenarios to drive the WaterWorld model resulting in a total of 6 ensemble scenarios (mean, mean-1SD, mean+1SD for two emissions scenarios). The mean-1SD can be considered the cool, dry end of projections whilst the mean+1SD is the warm, wet end of projections.

< Figure 2>

Results and discussion

Basin wide changes

Table 2 shows the annual contributions of the different fluxes to projected change in water balance derived from WaterWorld as averages for the Rio Santa basin for the 6 multi-model climate change scenario-ensemble metric combinations as well as the proportion of the basin that contributes to that direction of change (a metric calculated by WaterWorld to better understand spatial variability when examining basin mean changes). The mean and mean+1SD scenarios result in increases in water balance, in all cases because change is dominated by increases in rainfall (Figures 2a and 2b). Temperature-driven change in actual evapo-transpiration (ET) increases for all scenarios but in all cases this is only a marginal increase compared to increases in rainfall (change in ET is between 5-6% of change in rainfall for the mean of all GCM scenarios).

Changes in annual total fog inputs are only significant in the A2A +1 SD scenario as a result of changes in lifting condensation level due to increased temperature which results in more fog capture on exposed ridges in the band between the former and new maximum lifting condensation levels while a decrease in fog interception occurs at lower elevations as a result of a rise in the cloud base level. Annual total snow and ice melt decreases for all scenarios as a result of precipitation falling as rain instead of snow due to increased temperature and this is reflected in the observed decrease in the snowfall model output. Therefore, in all scenarios except A1B-1SD, the water balance becomes more rainfall dominated (with less influence of snowmelt). Under baseline conditions around 60% of the water balance derives from rainfall which increases to between 70-75% for the mean of all models and mean+1SD scenarios. It should be noted that melt water production in the model combines melt from new snow fall as well as glacial and snowpack melt. The contribution of glacial melt is not output as a separate variable. Declines in melt water production are mostly attributable to reductions in snow fall. This means that reductions in snowmelt are as much a function of changes in precipitation as they are of changes in temperature in the short term, until an equilibrium with the new temperature has been established. Given the uncertainties in precipitation projections by GCM for this - and any other high mountain - area (Buytaert et al., 2010; Ramirez and Jarvis, 2010), the resulting impacts on changes in melt water are also highly uncertain.

< Table 2 >

Seasonal changes

The results in Table 2 describe the annual impacts of climate change on the water balance but since the supply of water resources in this region is highly seasonal, it is necessary to assess changes in seasonality of the various fluxes. Under baseline conditions the hydrology in the basin is governed by highly seasonal precipitation with 80% of rainfall falling in the wet season (Oct-Apr) meaning that stores such as glaciers are required to sustain stream flow in the dry season. However, changes in precipitation under climate change could either increase or reduce this seasonality. To assess shifts in seasonality for the Rio Santa basin for all water balance fluxes, the seasonality index of Walsh and Lawler (1981) modified to handle negative values (by offsetting by the minimum so that all negatives become positive) was calculated using WaterWorld for the baseline and for the climate change scenarios for comparison. An index value of greater than 0.4 is considered seasonal, >0.8 marked seasonal with a long dry season and >1.2 extreme seasonal with almost all water available in 1-2 months. Table 3 shows the basin-average index values as well as the direction of change from the baseline indicated by up and down arrows. Changes in water balance seasonality are minor at the basin scale with three scenarios showing an increase and three scenarios showing a decrease although none of the values are considered highly seasonal. In general, small increases in water balance seasonality can be found in the uplands and small decreases at lower elevations. Rainfall seasonality however, is already seasonal under the baseline and this seasonality is projected to decrease at the basin scale for the multi-GCM mean scenarios as well as the multi-GCM mean +1SD scenarios. This effectively means that the increase in basin average precipitiation as seen in Table 2 and Figure 3a is more evenly distributed throughout the year than current precipitation.

Snowfall and melt water are extremely seasonal but are projected to become more so under all climate change scenarios since snowfall and snowmelt occur over a shorter time-period with significant melt on average only occuring in two to three months compared to six in the baseline. However, their impact on catchment average water balance is low so their impact on catchment average water balance seasonality is also low. Figures 3c and 3d show the impacts of the changing water balance fluxes on runoff at the outlet of the basin for the A1B and A2A mean scenarios respectively with the mean+1SD and -1SD scenarios representing the boundaries of the potential range of runoff under these scenarios. Figures 3a and b show the variability of precipitation (a) and temperature (b) projections for all scenarios. Both A1B and A2A mean scenarios result in increased runoff from the basin for nearly all months with A1B showing more uncertainty in the wet season while the A2A scenarios have a wider range in the dry season. The majority of the range of projections for both A1B and A2A scenario sets show a tendency towards increased runoff in the dry season as a result of increased precipitation in those months.

< Table 3 >

Implications for water resourcesSo far all results have been presented as basin wide averages. However, water resource availability varies significantly throughout the basin, as does demand. To assess the implications of climate change for water supply including: changes in melt water contribution, total stream flow and melt water generated stream flow, two of the largest, most populous, high altitude cities in the basin were identified; Caraz (population of circa 13,000) and Huaraz (population of circa 96,000). For these locations, runoff and contributions to it for the baseline and for the climate change scenarios were analysed (see Figure 1 for locations). Furthermore, to assess the impact of changes in melt water contribution to basin outflow, modelled stream flow and melt water contribution near the outflow of the Santa river into the Pacific was analysed. Table 4 shows the annual total stream flow, melt water generated stream flow and the proportion of total streamflow derived from melt water for these areas. The results show that the contribution of melt water to total stream flow diminishes for all scenarios but overall stream flow volume is projected to increase for all mean and mean+1SD scenarios. Under baseline conditions, the proportion of snow and ice melt to the stream flow at Huaraz and Caraz is more than 10% while for all climate change scenarios this decreases to below 10% for the A2A scenarios (2.7% and 6.5% for Huaraz and Caraz respectively for the mean of all models scenario) and well below 10% for the A1B scenarios (2.6% and 1.2% for Huaraz and Caraz respectively for the mean of all models scenario). Baseline melt water contribution to stream flow at the basin outlet is around 5% which decreases to a maximum of 1.6% under projected climate change.

< Table 4>

Policy implications

The results of this analysis are a clear indication that projected climate change across a wide range of scenarios generally leads to increased water availability for the Rio Santa basin and shows a trend towards runoff being more rainfall dominated, particularly in the dry season. Though snowmelt increases, rainfall increases more so the relative contribution of snowmelt lessens. However, projections of precipitation by GCMs are highly uncertain, particularly for a highly heterogeneous landscape such as the Andes mountain range (Buytaert et al., 2009; Ramirez and Jarvis, 2010). This is clear from our different ensemble summaries (mean, mean+1SD and mean-1SD), which show very different results. Therefore, to best deal with this unpredictability and uncertainty in future stream flow, more and better-distributed storage and distribution systems alongside efficient water use are essential.

Our analysis did not take into account groundwater stores, even though a number of studies have demonstrated that groundwater contributions in small glacier dominated sub-watersheds of the Santa basin are proportionally equally important as glacier melt for dry season stream flows (Mark et al., 2010; Baraer et al., 2015; Gordon et al., 2015). WaterWorld assumes groundwater stores to be in equilibrium in the long term as it uses a long term climatology and groundwater resources at these timescales are controlled by the long term water balance. In reality, a projected reduction or increase of water balance because of the combined impacts on precipitation, evapotranspiration and snowmelt will thus affect both runoff and groundwater stores in the same direction. Therefore, under those scenarios that project overall increases in water balance (four of the six scenarios), it is likely that groundwater stores will be adequately replenished and can thus act as seasonal buffers whereas the reverse might be true for scenarios projecting a decrease in water balance.

While groundwater stores are important for freshwater resources in the region, they cannot replace the storage function of current snow and ice. With the disappearance of these stores, new storage solutions that can provide a buffer against seasonal shortage should be considered. This could include small reservoirs, modified lakes and household-scale water storage systems (Vuille, 2008; McKinney et al., 2011). A recognition of the potential of natural infrastructure for harnessing and storing glacial and snow meltwater, particularly at high altitudes is therefore required within policy and implementation institutions. In addition, targeted investments in physical water infrastructure can increase resilience to uncertain climate changes by regulating water flows. On the demand side, policies aimed at changes in irrigation practices and shifts in crop types and varieties could potentially lead to diminished water demand and less competition in times of low supply. The continuing population growth however, will increase domestic demands year round, as will agricultural, hydropower and mining water users who are all dependent on reliable water flows throughout the year. To balance these competing demands between all water users in the basin necessitates the need for watershed level dialogue between all upstream and downstream water users, The range of possible outcomes of climate change highlighted in this study require policies aimed at creating capacity to respond to such changing and unpredictable conditions and strategies that are robust under the full range of possible future scenarios: in short a focus on adaptability rather than a specific adaptation *per se*.

Conclusions

Impacts of climate change on water resources are extremely difficult to project, particularly in a highly heterogeneous landscape such as the Peruvian Andes. The uncertainties in projections by GCM, particularly for precipitation lead to a wide range of possible outcomes for water resources even for the same emissions scenario. Model simulations with the WaterWorld model and climate change scenarios that encompass a very broad range of projections for the Santa basin show a general trend toward an increase in water availability as a result of projected increases in precipitation. This is in contrast to previous studies that examined the impact of temperature increases on snow and ice alone (Pouyaud, 2005; Chevallier et al., 2011). Although the level of uncertainty around glacial retreat with warming is already high, if studies do not examine the impact of precipitation change then impacts on water resources are not fully accounted for. Although impacts on precipitation change are even more uncertain, they have to be considered alongside snow and ice melt in basins like the Santa. Increased temperature leads to decreases in snow fall (more precipitation falls as rain) and thus less snowpack accumulation ultimately producing decreases in snow melt volume (even though the per unit-area rate of melting of the snowpack may increase with warming, the extent of the snowpack - and thus total snowmelt -

declines). This leads to a more rainfall-dominated hydrological system at the basin scale and also at critical sites of water demand (for example key cities). A more rainfall dominated system is more prone to short-onset drought in response to monthly rainfall receipt than one fed from snow and ice stores that respond to longer term accumulation and melt dynamics. Seasonal water availability is likely to be affected but the projected decreases in water storage in glaciers and snowpack are potentially offset by an increase in direct runoff from greater rainfall in the dry season.

The very high uncertainties associated with climate change in these environments necessitates basin-wide policies aimed at increased adaptability, and the development of adaptive capacity to respond to such changing conditions including through demand-side management. Simplistic notions of climate change leading to drying-up of Andean water supplies as a result of de-glaciation have to be considered within the context of projected changes in precipitation and in the partitioning of precipitation between rain and snow as well as the commonly studied impact of warming on snow and ice melt. Without the former, studies on the latter alone can be highly misleading.

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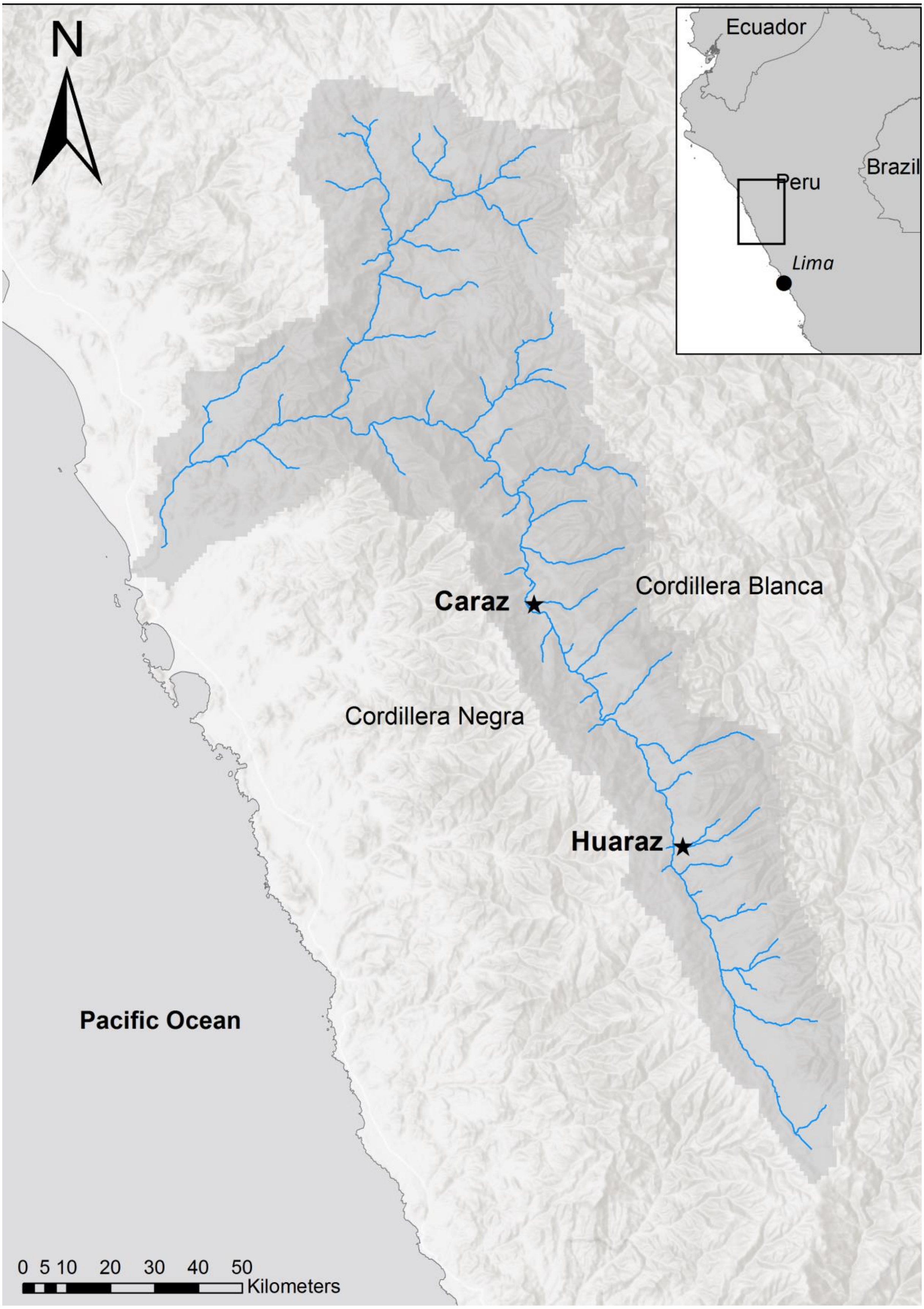

Figure 1 Rio Santa Basin in Peru with main rivers and location of two largest high altitude cities Caraz and Huaraz.

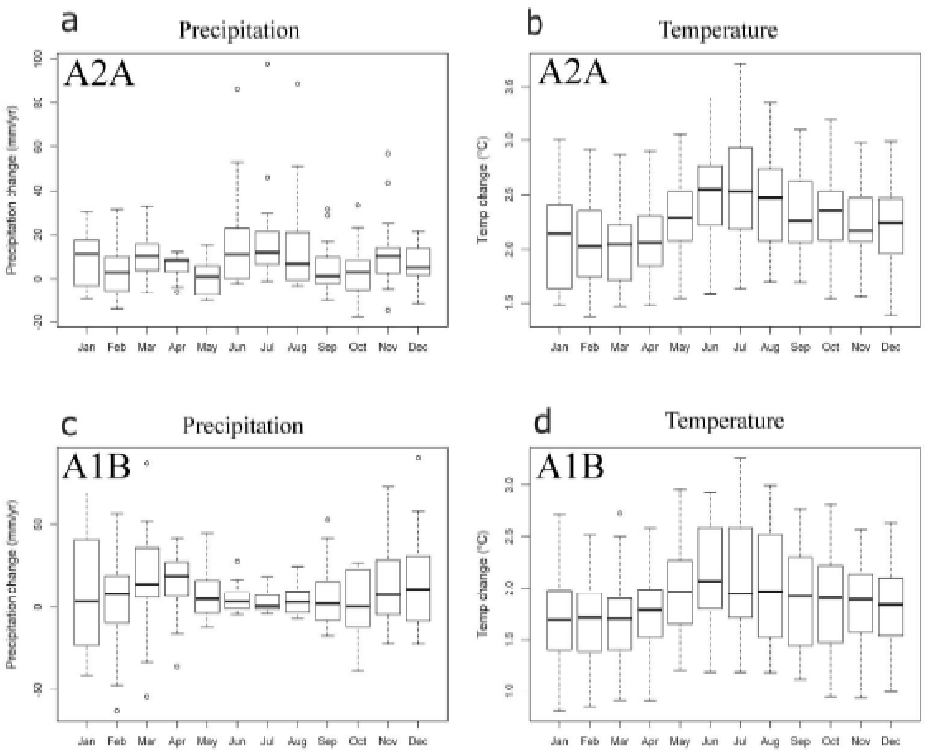

Figure 2 a-d: between scenario variability for precipitation and temperature projections for the Santa basin for 17 GCM under A2A scenario (a,b) and 24 GCM under A1B scenario (c,d). Boxplots show median, quartiles and range of the data. Outliers, shown on the plots as hollow circles, are defined as extreme values > 1.5 times the interquartile range.

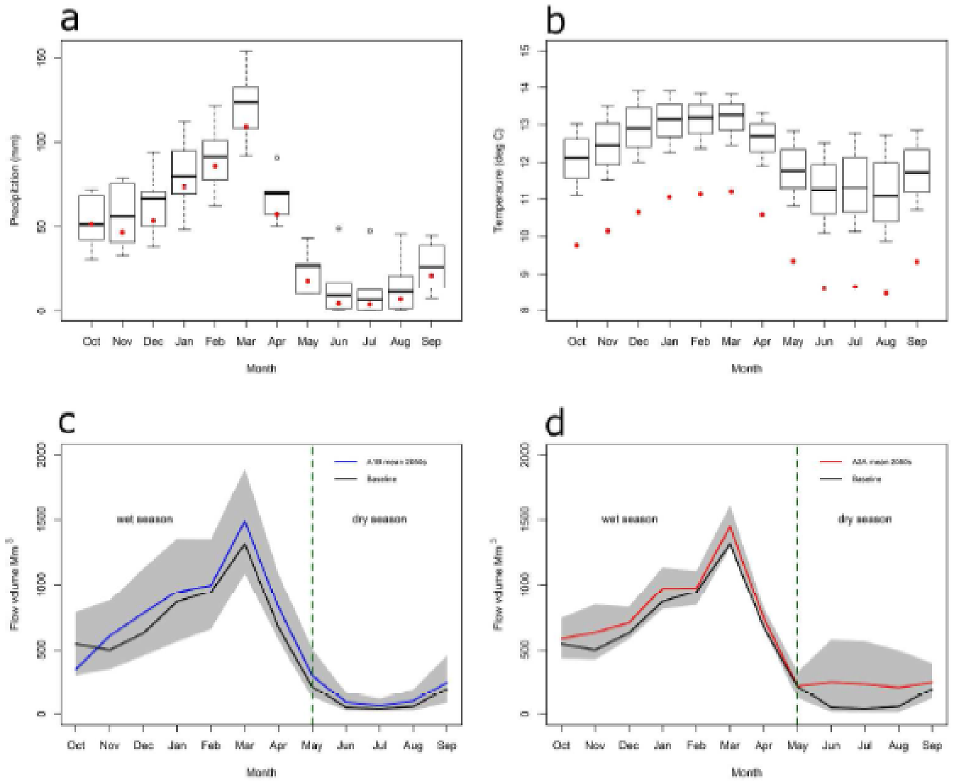

Figure 3 a-d: Seasonal distribution and variability of a) precipitation, b) temperature and the basin runoff the ensemble climate change scenarios c) A1B and d) A2A. Red dots (a and b) represent the baseline precipitation and temperature. Grey areas (c and d) represent the range between the upper (+SD) and lower (-SD) scenarios for basin runoff.

Table 1 WaterWorld stream flow validation for WorldClim and TRMM rainfall climatologies.

	Annual WorldClim		**Annual TRMM**		**Wet season WorldClim**	**Dry season WorldClim**
Statistics	Q total	Q>5	Q total	Q>5	Q total	Q total
Observed mean (m^3s^{-1})	34.5	46.3	34.5	46.3	35.0	14.4
Modelled mean (m^3s^{-1})	29.9	48.9	24.8	40.1	43.0	7.5
Modelled SD (m^3s^{-1})	54	71.6	47	58.1	85.9	13.6
Bias (m^3s^{-1})	4.6	2.5	9.7	6.2	-7.2	6.7
Mean Absolute Error (MAE)	8.5	3.6	10.7	17.9	7.2	6.7
Root mean Squared Error (RMSE)	318.7	32.9	373.8	274.1	14.2	18.7
R^2	0.84	0.99	0.80	0.73	0.96	0.98

Table 2 Contribution of annual change in different fluxes to the change in mean basin wide water balance and overall outcome of the ensemble mean.

Scenario	Outcome	Change in water balance (mm/yr)	%	Change in wind driven rainfall (mm/yr)	%	Change in ET (mm/yr)	%	Change in fog inputs (mm/yr)	%	Change in snowmelt (mm/yr)	%	Change in snowfall (mm/yr)	%
Baseline	-	-	-	-	-	-	-	-	-	-	-	-	-
A2A all	Positive	+100	98	+127	98	+8.5	81	+0.47	63	-14.5	29	-14.8	29
A2A +1SD	Positive	+272	100	+309	100	+13	89	-6.7	95	-17.5	31	-17.3	31
A2A -1SD	negative	-65	94	-47	78	+3.5	71	-0.15	44	-14.5	30	-18.8	30
A1B all	Positive	+81	84	+108	89	+8.5	76	-0.21	47	-18.7	27	-18.8	27
A1B +1SD	Positive	+325	97	+355	98	+11	81	-0.087	46	-18.9	28	-18.8	28
A1B -1SD	negative	-157	93	-131	84	+6	70	-0.327	48	-19.4	28	-19.7	28

Table 3 Seasonality statistics for baseline and scenarios and direction of change. All increases compared to baseline indicated in grey.

Scenario	Water balance seasonality		Rainfall seasonality		ET seasonality		Snowfall Seasonality		Melt water seasonality		Snow pack seasonality	
Baseline	*0.21*	-	*0.73*	-	*0.41*	-	*1.20*	-	*1.17*	-	*1.31*	-
A2A all	0.19	↓	0.53	↓	0.41	↑	1.27	↑	1.23	↑	1.26	↓
A2A +1SD	0.15	↓	0.40	↓	0.41	↓	1.27	↑	1.23	↑	1.00	↓
A2A -1SD	0.25	↑	0.84	↑	0.41	↑	1.52	↑	1.48	↑	1.54	↑
A1B all	0.24	↑	0.59	↓	0.41	↑	1.37	↑	1.35	↑	1.28	↑
A1B +1SD	0.30	↑	0.52	↓	0.41	↑	1.38	↑	1.36	↑	1.21	↓
A1B -1SD	0.20	↓	0.91	↑	0.41	↑	1.50	↑	1.48	↑	1.45	↑

Table 4 Percentage of snow melt generated runoff at cities of Caraz and Huaraz and at Santa outflow under different multi-model climate change scenarios. All increases compared to baseline indicated in grey.

	Huaraz			**Caraz**			**Santa outflow**		
Scenario	**Total Q (m^3 s^{-1})**	**Melt Q (m^3 s^{-1})**	**%**	**Total Q (m^3 s^{-1})**	**Melt Q (m^3 s^{-1})**	**%**	**Total Q (m^3 s^{-1})**	**Melt Q (m^3 s^{-1})**	**%**
Baseline	**5.3**	**0.7**	**11.1**	**2.9**	**0.45**	**13.5**	**165.6**	**8.5**	**4.9**
A2A all	6.1	0.2	2.7	3.5	0.24	6.5	198.6	3.2	1.6
A2A +1SD	7.6	0.1	1.6	4.3	0.16	3.5	256.4	2.1	0.8
A2A -1SD	4.7	0.2	3.5	2.7	0.27	9.3	147	3.2	1.6
A1B all	5.9	0.2	2.6	3.1	0.04	1.2	193	1.6	0.8
A1B +1SD	7.8	0.2	1.9	4.2	0.04	0.9	275	1.6	0.6
A1B -1SD	3.9	0.1	3.2	1.9	0.03	1.6	118	1.4	1.1

Table S1 GCMs used in analysis for A1B and A2A emission scenarios

Climate Model	**Developing Institute**	**Scenario**	
		A1B	**A2A**
E20/Russell	NASA Goddard Institute for Space Studies	X	
INMCM3.0	Institute for Numerical Mathematics, Russia	X	
CM2.1	NOAA Geophysical Fluid Dynamics Laboratory	X	X
CM2.0	NOAA Geophysical Fluid Dynamics Laboratory	X	X
ECHO-G	Meteorological Institute of the University of Bonn	X	X
CGCM3.1 T47	Canadian Centre for Climate Modelling and Analysis	X	X
FGOALS1.0_g	LASG, Institute of Atmospheric Physics, China	X	
Mk3.0	CSIRO, Atmospheric Research, Australia	X	X
Mk3.5	CSIRO, Atmospheric Research, Australia	X	
ECHAM5 /MPI OM	Max Planck Institute for Meteorology, Germany	X	X
CCSM3.0	National Center for Atmospheric Research	X	
CM3	Centre National de Recherches Meteorologiques, France	X	
C4x3	NASA Goddard Institute for Space Studies	X	
BCM2.0	Bjerknes Centre for Climate Research, Norway	X	X
HadCM3	Hadley Centre for Climate Prediction, Met Office, UK	X	X
E20/HYCOM	NASA Goddard Institute for Space Studies	X	
MIROC3.2 High Res	CCSR/NIES/FRCGC, Japan	X	X
CM4 V1	IPSL/LMD/LSCE, France	X	X
ECHAM4.6	INGV, National Institute of Geophysics and Volcanology, Italy	X	
HadGEM1	Hadley Centre for Climate Prediction, Met Office, UK	X	
CGCM3.1 T63	Canadian Centre for Climate Modelling and Analysis	X	X
PCM1	National Center for Atmospheric Research	X	X
MIROC3.2 Med Res	CCSR/NIES/FRCGC, Japan	X	X
CGCM2.3 2a	Meteorological Research Institute, Japan	X	X
CGCM2.0	Canadian Centre for Climate Modelling and Analysis		X
CNRM-CM3	Centre National de Recherches Meteorologiques, France		X
AO	NASA Goddard Institute for Space Studies		X