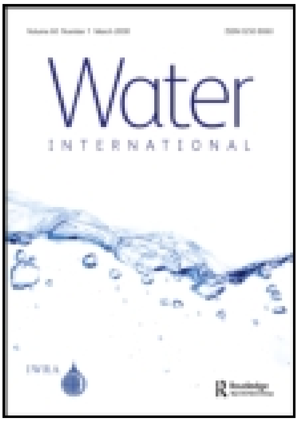

Water International
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rwin20

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Version of record first published: 21 Aug 2012

To cite this article: Thomas Condom, Marisa Escobar, David Purkey, Jean Christophe Pouget, Wilson Suarez, Cayo Ramos, James Apaestegui, Arnaldo Tacsi & Jesus Gomez (2012): Simulating the implications of glaciers' retreat for water management: a case study in the Rio Santa basin, Peru, Water International, 37:4, 442-459

To link to this article: http://dx.doi.org/10.1080/02508060.2012.706773

Water International
Vol. 37, No. 4, July 2012, 442–459

Routledge
Taylor & Francis Group

Simulating the implications of glaciers' retreat for water management: a case study in the Rio Santa basin, Peru

Thomas Condom[a]*, Marisa Escobar[b], David Purkey[b], Jean Christophe Pouget[c], Wilson Suarez[d], Cayo Ramos[e], James Apaestegui[d], Arnaldo Tacsi[f] and Jesus Gomez[f]

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(*Received 29 March 2012; accepted 24 June 2012*)

This paper presents a model of Andean glacier hydrology which can be used to assess the water management implications of possible future glacier retreat. The approach taken uses the Water Evaluation and Planning (WEAP) system and integrates both hydrologic processes and representations of the operations of built infrastructure. The model is applied in the Rio Santa watershed in Peru to illustrate how alternative water management strategies can be simulated. The WEAP platform built for this study has been used to engage with local stakeholders for water management.

Keywords: glacier retreat; climate change adaptation; hydropower; irrigation; conflict; Cordillera Blanca

Introduction

Approximately 99% of the world's tropical glaciers are found in the Andes of South America. Of these, 71% are located in Peru (Kaser and Osmaston 2002). The Cordillera Blanca, located in the western branch of the Andes in Peru, is the highest and most extensive expanse of tropical glaciers in the world, representing approximately 35% of the total area of Peruvian glaciers (Zapata *et al.* 2008). Analysis of remotely sensed images testifies that glaciers in the Cordillera Blanca are retreating. The glaciated area is estimated to have changed from 728 km^2 in 1960 to 536 km^2 in 2003 (Ames *et al.* 1989, Zapata *et al.* 2008). A recent study by Racoviteanu *et al.* (2008), based on analysis of high-quality SPOT5 satellite data from 2003, estimated the total glaciated area for the Cordillera Blanca at 569.6 ± 21 km^2. Among the primary causes of glacier retreat some name changes in temperature and humidity (Vuille *et al.* 2003) or regional-scale precipitation variability linked to large-scale atmospheric circulation (Vuille *et al.* 2008b). Overall, the combined impact of all changing climatic forcing variables contributes to retreat (Vuille *et al.* 2008a). The water management implications of these changes are worrisome. Vergara *et al.* (2007) estimated the consequences of observed glacier retreat on the power and water supply sectors in

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ISSN 0250-8060 print/ISSN 1941-1707 online

http://dx.doi.org/10.1080/02508060.2012.706773
http://www.tandfonline.com

Peru, indicating large future costs to the Peruvian economy in the absence of adaptation measures in response to continued glacier retreat. They estimate that the average yearly energy output for the Cañon del Pato hydropower plant on the Rio Santa would drop from 1540 GWh to 1250 GWh (±10.9%) with a 50% reduction in effective glacier runoff, and would be reduced further to 970 GWh (±14.2%) once the glacier contribution disappears. The economic consequences of this last estimated result (disappearance of the glaciers) could cost US$144 million per year. The performance of various water management adaptation strategies associated with implications of possible Andean glacier evolution under future climate scenarios needs to be evaluated. This paper uses a simulation model and the Rio Santa basin on the western slope of the Cordillera Blanca as an example to illustrate the evaluation of the model. Mark and Seltzer (2003) evaluated the glacier melt in the larger Rio Santa watershed and concluded that the peak of glacier melt occurs in spring, and that 10–20% of Rio Santa upper-watershed discharge comes from melting glaciers. However, they did not consider that more than 50% of the total watershed area downstream of La Balsa, including the coastal region, is characterized by substantial irrigation growth (Pouyaud *et al.* 2005, Juen *et al.* 2007, Mark and McKenzie 2007, Suarez *et al.* 2008). These studies also do not include transient simulations of glacier retreat and associated river flows, which brings into question the usefulness of this information for water managers. Further, at a catchment scale, groundwater plays a significant role in the river's flow regime because roughly half of the dry-season discharge is provided by aquifers (Kaser *et al.* 2003, Mark *et al.* 2005, Barear *et al.* 2009), a resource not commonly analyzed in previous studies.

In the Himalayas, some studies have been done to compute the hydrological response to climate change in glaciated catchment with a combined cryospheric hydrological model at daily time step without the consideration of the different water uses (Immerzeel *et al.* 2012). Another example of a hydro-glaciological model with a conceptual semi-distributed model based on temperature index has been used in Himalayan watersheds (Rees and Collins, 2006). In the present case, only monthly hydrological and meteorological data are available and the intention is to develop and test a methodology to quantify the role of glacier evolution and associated hydrologic change relative to the current and future challenges and opportunities confronting water managers in the Rio Santa system. The approach taken uses the Water Evaluation and Planning (WEAP) system, developed by the Stockholm Environment Institute (Yates *et al.* 2005a, 2005b, Yates 1996). The research seeks to refine the existing WEAP software, which integrates both hydrologic processes and representations of the operations of built infrastructure, to capture changing hydrologic and water management conditions in a heavily glaciated Andean watershed. What is original in this work is that the Rio Santa application spans the climate–glacier–hydrology–water management continuum to respond to the planning challenges facing water managers and decision makers in a relatively data-poor and highly vulnerable region. Given the importance of hydropower operations in the system, this sector was the focus of early application of the tool presented here.

Water management and policy context

In Peru, the most important consumptive water use sectors are agriculture (80%), followed by urban (12%), industrial (6%) and mining (2%) (IADB 2012). While not consumptive, hydropower is responsible for substantial manipulation of hydrologic regimes. The economic sectors showing rapid growth are mining, energy, agriculture and water supply, all of which are intensive in water use. These development trends are creating tensions between sectors. For instance, there are shortages in water supply near the coastal regions where most of the population concentrates. Migration from rural to urban zones and degradation of water quality increase the pressure on the resource. Consequently, conflict has grown over the last few years.

In response, there has been change in Peruvian law. In 2008 the legal and institutional framework for water management was improved through the release of several acts from the Ministry of the Environment, the ANA (Autoridad Nacional del Agua), and the National System for Water Resources. In 2009, a new water resources law created a National System for Water Resources Management, which is implemented by a council within the ANA with participation from several ministries and representatives from economic sectors. The main mandate from the ANA is the development of a strategy for water resources management and the establishment of watershed-specific management plans. At the local level, the ANA is represented by AAAs (Administrative Water Authorities) and ALAs (Local Water Authorities), which are in charge of the development of the specific watershed management plans.

Because of the complexity of managing competing uses – including the third-largest hydropower facility in the country, large irrigation districts, small-holder agriculture, urban demands and a population of over one million people – the Rio Santa is a basin of focus for water resources management investments channelled through the ANA, and efforts to develop a watershed management plan have been launched. Obviously, achieving the establishment of a solid water management strategy requires the involvement of a wide set of actors that need to interact to resolve the existing conflicts. For instance, water rights to manage the glacial Lake Parón were given to the hydropower company without consideration of the water uses upstream, causing local residents to block access to the lake beginning in 2008. To date, it has not been possible to reach agreement between local actors and hydropower interests through a water benefit sharing strategy.

In addition to the existing social and institutional vulnerabilities, climate change constitutes a source of additional uncertainty (Kundzewicz *et al.* 2008). The Foro Agua Santa, which involves a wide set of actors interested in supporting the implementation of the ANA mandate for a watershed plan, seem poised to tackle the challenge. Still, initiatives such as these require information about current and potential climate and water distribution scenarios. Through the CGIAR Challenge Program for Water and Food, the authors are supporting this initiative by building local capacity to use and implement the enhanced WEAP platform that includes glacier routines. Although these efforts are nascent, and the evaluation of the final outcome may take several years, the tool has been positively evaluated by the local scientists and stakeholders. This type of model could be used to contribute in the resolution of water-related conflicts in the future. Important actors are collaborating to assemble a modelling platform that can be used to evaluate different water management strategies.

Model description

General structure of the WEAP model

Within the existing version of WEAP, rainfall-runoff processes are simulated by dividing a watershed into sub-watersheds within variable land cover. For each band, climatic time-series can be imposed. Land cover variability is captured by subdividing the area into land cover types that are parameterized individually. Rainfall-runoff processes are simulated using a two-bucket formulation and the groundwater flow reaching the river network is the sum of the baseflow and interflow (Yates *et al.* 2005a, Yates 1996).

In cold regions, WEAP can simulate the accumulation and melting of snow. In addition to considering the rainfall-runoff processes, WEAP has a water management algorithm that allows for the analysis of current and projected scenarios of water allocation under a user-defined set of demand priorities and supply preferences (Yates *et al.* 2005a, 2005b).

In this study, both the rainfall-runoff and water management algorithms in WEAP were used to represent conditions across the entire Rio Santa watershed. Given the importance of hydropower production in the system, special attention was paid to calibrating the application at the primary diversion to the Cañon del Pato hydropower plant.

Glacier Module

The WEAP glacier module simulates the dynamics of glacier surface extension and glacier meltwater contribution to the outflow from each glaciated sub-watershed. Each elevation band in a given sub-watershed was divided into glaciated and non-glaciated areas, with the glaciers being conceptualized via a modification of an existing degree-day model into a degree-month model. Some studies, for example Sicart *et al.* (2008) and Kaser (2001), point out that the degree-day approaches are not well adapted for simulating glacier meltwater contributions to river flow at daily time step in tropical zones. Others, however, successfully used the same approach with a monthly time step to make long-term projections of changes in glacier mass balances caused by climate change (Braithwaite and Zhang 1999, Suarez *et al.* 2008). In general, the degree-day factor may change depending on the climatic conditions. Recent studies in the region, however, indicate no significant decrease or increase in annual precipitation, and an increase in annual air temperatures on the order of 0.5 °C per decade (Racoviteanu *et al.* 2008). Consequently, for simplification purposes, it is assumed here that the degree-month factor is constant. This same goal of generality shaped the decision not to use a full energy balance model that would have explicitly captured all key glacier processes, such as sublimation (Winkler *et al.* 2009), as energy balance models are difficult to apply at large scales and in the absence of detailed information.

Initial glacier areas were derived from 1969 data that was available for each of the 17 sub-watersheds in the Rio Santa WEAP application. Based on an empirical relationship that relates glacier ice volume (V, expressed in km^3) to glacier area (Bahr *et al.* 1997), the initial glacial volume in each sub-watershed was estimated.

For each monthly time step, the volume of surface runoff within a sub-watershed was the sum of the contribution of melting snow and ice for the glaciated portion of the sub-watershed and the runoff coming from the simulation of rainfall-runoff processes in non-glaciated portions of the sub-watershed. The monthly time step was chosen considering the availability of meteorological and hydrological data.

At the end of a hydrological year, a mass balance was carried out to assess changes in the overall volume of glacier ice within a sub-watershed. The model is described in detail in the Appendix. The WEAP glacier module uses only three parameters: T_0, the threshold temperature for glacial fusion, and a_{ice} and a_{snow}, the degree-month factors for ice and snow.

Policy options modelling

In addition to modelling the hydrology and glacier dynamics, in WEAP it is possible to model elements of the water management system, including reservoirs, canals and hydropower production. WEAP allocates water according to assigned priorities. Once the infrastructure is represented, it is also possible to change the hydropower, irrigation and urban requirements and priorities. The WEAP platform built for this study has been used to engage with local stakeholders for water management. Through the process of engagement, the tool is being used to support the development of the watershed management plan. Because of the current dominant role of hydropower production in the Rio Santa, this study focused on the influence of water availability (from glacier melting, groundwater and surface) on the hydropower system and associated climate change vulnerabilities.

Case study: the Rio Santa and the Cordillera Blanca

Study area and water resources for human uses

The Rio Santa watershed covers an area of 12,300 km^2. The basin reaches 6768 m (the Huascaran peak) and discharges to the Pacific Ocean. Glaciers within the Rio Santa watershed are located at high elevations of the western side of the Cordillera Blanca. The water from the Rio Santa, which relies on both glacial and non-glacial sources, is vital for the economy and livelihoods in the region. The economic activities in the watershed include the following, starting at the highest elevation and moving down to the ocean (Chevallier *et al.* 2011).

- Above 5000 m, the glaciers themselves and the mountain tops above them are a tourist attraction for mountaineers from all over the world.
- Between 2000 and 4000 m, for centuries the Quechua peasants have used irrigated slope agriculture which entails a complex system of small channels called *acequias* that are contoured to the slope of the mountains.
- Below 2000 m, taking advantage of the extraordinary natural site of the Canõn del Pato, a hydropower project converts the waters of the Rio Santa into electrical energy. The hydropower production facility has been in operation since 1954 and was substantially expanded in 1998.
- Below the Cañon del Pato powerhouse, at the foot of the Andes, water from the Rio Santa is used to irrigate huge agricultural areas recently created in the barren coastal zone. Two significant water diversions send water out of the basin towards irrigation districts to the north and south of the Rio Santa's mouth: Chavimochic (144,385 ha, www.chavimochic.gob.pe) and Chinecas (44,220 ha, www.pechinecas.gob.pe).

Based on the presence of either a flow measurement gauge with available data or known water management control points, the Rio Santa watershed was divided into 17 sub-watersheds as shown in Figure 1. The population in centres in the upper watershed ranges from 390,171 in Santa to 7786 in Corongo, according to the 2005 census. Water demand in these centres was approximated in WEAP by assuming a total per capita water demand for urban and rural populations in each area.

Climatic settings

In the tropical Andes the main sources of precipitation are the Atlantic Ocean and the Amazon Basin. The latter plays the role of recycling water via intense evapotranspiration; the principal mechanism of transport of this humidity into the Andes is the seasonal easterly wind (Johnson 1976, Aceituno 1998). This seasonality allows the development of one wet season centred during the austral summer, December-January-February (DJF), and a dry

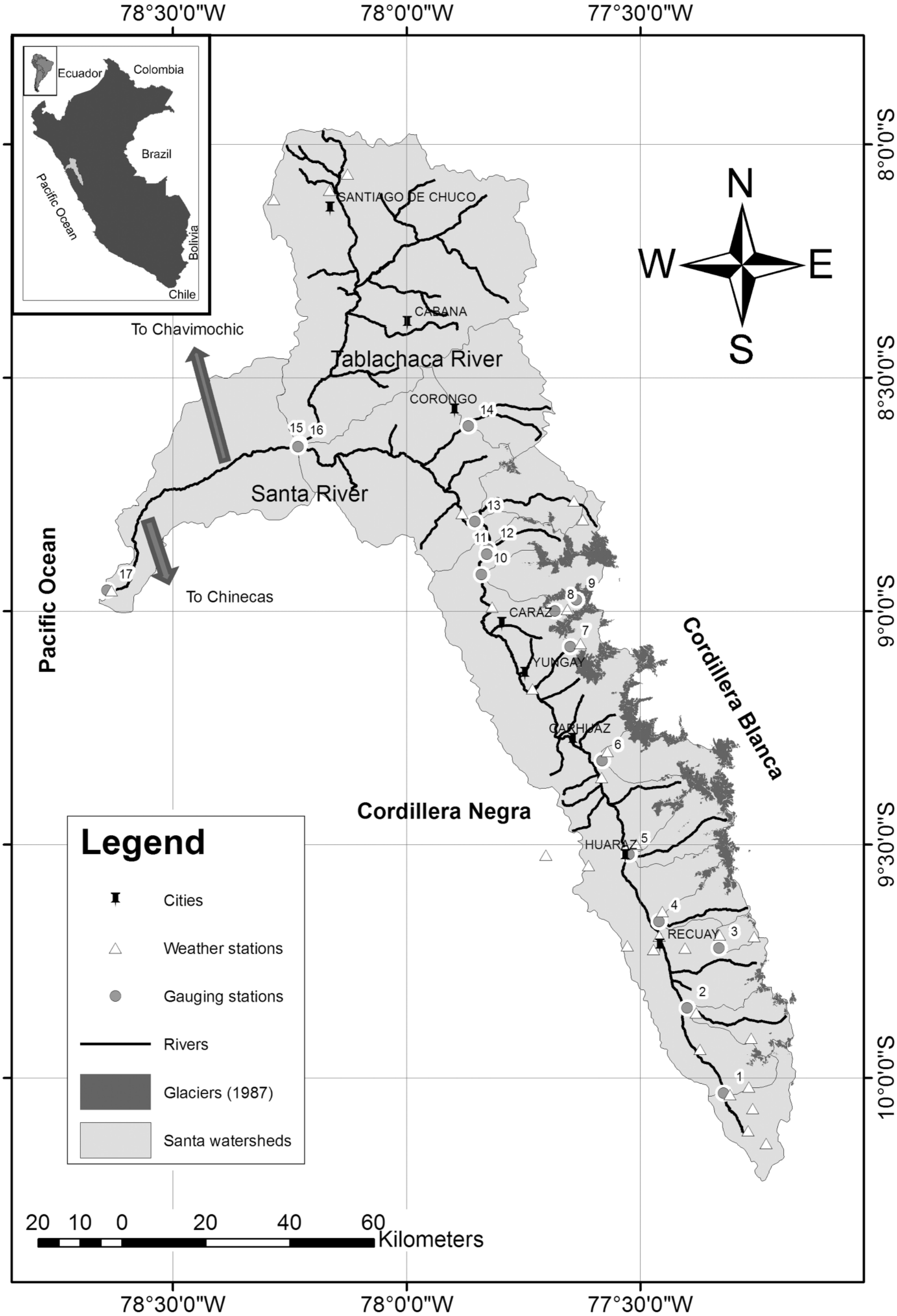

Figure 1. Study area, with delimitation of watersheds, position of the modern glaciers, cities, principal rivers, weather stations and gauging stations. Numbers indicate sub-watersheds: 1. La Recreta; 2. Pachacoto; 3. Querococha; 4. Olleros; 5. Quillcay; 6. Chancos; 7. Llanganuco; 8. Paron; 9. Artesoncocha; 10. Colcas; 11. Los Cedros; 12. Quitaracsa; 13. La Balsa; 14. Corongo (Manta); 15. Chuquicara; 16. Condorcerro (Tablachaca); 17. Puente Carretera.

season during the austral winter, June-July-August (JJA). Along South America's western coastal strip, the proximity of the South Pacific anti-cyclone and its subsidence, reinforced by the cold Humboldt current, generate a dry climate. Garreaud *et al.* (2003) give a detailed description of climate in the tropical Andes.

At the scale of the Cordillera Blanca, longitudinal and a latitudinal gradients of precipitation are present. For the dry Pacific coast and the humid summits the mean annual values ranged between 93 to 1542 mm/y for the period 1967–1998. The weighted average for the entire Rio Santa watershed was 868 mm/y. Concerning temperature, the inner-tropic location of the watershed (Kaser and Osmaston 2002) makes the annual variation less important than the diurnal variation. Nevertheless, seasonal variation is observed and the range of mean annual temperature values fall between −7 °C at elevations and 30 °C on the lower floodplain for the period 1967–1998, with a weighted mean value of 8 °C. In summary, both mean annual temperature and precipitation for the Rio Santa watershed show strong latitudinal, longitudinal and altitudinal gradients. These gradients offer a great contrast between the hot arid zone to the west and the cold and wet high-elevation zone to the east, with an average annual precipitation of approximately 1500 mm/y for the period 1967–1998 at the Huascarán summit with the interpolation of the precipitation data from the meteorological stations (Figure 1). In this tropical zone, no permanent snow cover occurs on the ground of the non-glaciated part of the sub-watersheds. Flow from interannual snowpack is limited in this tropical watershed (Viviroli *et al.* 2011).

Input data

The Digital Elevation Model (DEM) issued by the National Geographic Institute of Peru (IGN) (scale 1/100000) was used to define sub-watersheds (IGN, 2005). The DEM (cell size 100 m) was also processed to define elevation bands within each sub-watershed, with a range of 700 m in the lower parts and 300 m in the higher parts of the basin to afford greater detail in the zone occupied by glaciers. The intersection between sub-watersheds and elevation bands constituted a WEAP catchment, for which areas and land cover types were estimated using a data-set obtained from the Chavimochic project (ATA-INADE 2002) and reclassified into tundra, coastal plain, shrub and agriculture categories.

Three data-sets, for the years 1969, 1987 and 1999, on the spatial evolution of glaciated area were derived from Landsat images and from an inventory published by Ames *et al.* (1989) based on analysis of 168 aerial photos. The latter set was used to define initial glaciated area conditions. The different glaciated areas in the Rio Santa watershed are shown in Figure 2.

In order to characterize the human and agricultural water consumption in the Rio Santa watershed, water demand nodes were added to represent each province which included information on the number of inhabitants (rural and urban). Total water demands in each province were estimated by multiplying the number of inhabitants by a per capita water use of 300 L/day, which is a rough estimate of the combined urban and agricultural water use in each region.

A total of 39 pluviometric stations are located within the Rio Santa watershed (Figure 1). The time series of available data extended from 1968 to 1999 on a monthly basis. The stations were submitted to the regional vector method (RVM) (Hiez 1977, Brunet-Moret 1979) to assess their data quality and to isolate climatologic regions (see Vauchel 2005 and Espinoza *et al.* 2009 for more details about this method). Although precipitation in this watershed might be controlled by spatial variability due to barrier effects and altitudinal gradient, the interpolation technique used is well suited to maximize utility of the available data. The vertical precipitation lapse rate is +0.03% per metre.

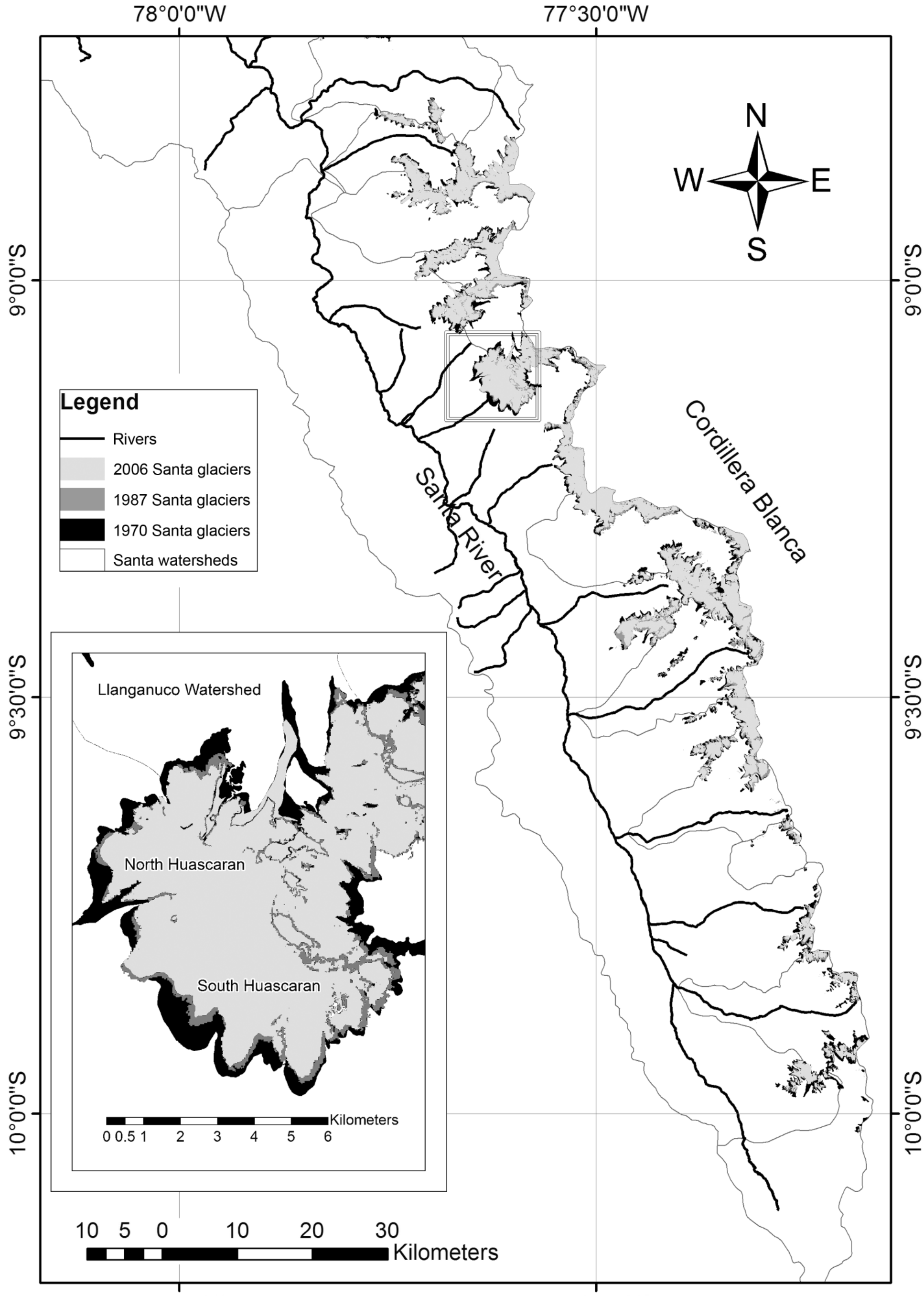

Figure 2. Evolution of the glacier extension between the years 1970, 1987 and 2006 (with detail of the Huascarán Massif).

Concerning temperature and humidity data, only one good-quality, long, continuous time series exists for the Rio Santa watershed: the Recuay station (77°31′W 09°45′S, 4420 m asl). Continuous temperature data for each catchment was obtained using a temperature gradient of 0.6 °C/100 m applied to the temperature observed at Recuay. For humidity and wind speed, the long-term monthly average time series at Recuay was applied to all catchments because of the scarcity of weather station data. At Recuay station for the period 1969–1999, the mid-monthly temperature ranges between 12.3 °C in August and 11.5°C in January; precipitation shows high seasonality between the humid period (190 mm in March) and the dry period (3 mm in July). Concerning the outflow data, 17 gauging stations with a monthly time series for the period 1969–1999 were used (see Figure 1 for locations).

Results

Model calibration and validation for the historical period 1970–1998 for the Rio Santa watershed

For the Rio Santa watershed, the strategy was to calibrate the standard WEAP rainfall-runoff parameters for the Tablachaca and Corongo sub-watersheds, as these lack glacier coverage (Table 1), and then to apply them uniformly to the entire basin. Next, to calibrate the degree-day factors a_{ice} and a_{snow} without access to specific reference values for the Cordillera Blanca we began with the compilations provided by Singh *et al.* (2000) and Hock (2003) with values ranging from 1.3 to 11.6 mm per day per °C for snow and from 5.5 to 20 mm per day per °C for ice. To calibrate T_0, we assumed that the value fell between −2 °C and 2 °C. The optimized parameters obtained were 1.45 °C for T_0, 380 mm per month per °C for a_{snow} and 600 mm per month per °C for a_{ice}. The calibrated glacier parameters were used to run the model for a calibration period (1970–1984) and a validation period (1985–1999). The efficiency criteria – the root mean square error (RMSE), the Bias (difference between observed and simulated values), and the Nash-Sutcliffe parameter

Table 1. Land use parameters for the non glacial part and parameter values for the glacier module for all the watersheds.

Parameter	Unit	Value
Land use parameters (without glaciers)		
Crop coefficient	none	1.1
Root zone capacity	mm	80
Root zone conductivity	mm/month	500
Deep water capacity	mm/month	500
Deep water conductivity	mm/month	50
Runoff resistance factor - crop	none	4
Runoff resistance factor - peat bog	none	3.2
Runoff resistance factor - tundra	none	0.8
Runoff resistance factor - coastal desert	none	0.8
Flow direction - horizontal	%	0.68
Z1	%	35
Z2	%	35
Glacial parameters		
T0	°C	1.45
a_{snow}	mm month^{-1} °C^{-1}	380
a_{ice}	mm month^{-1} °C^{-1}	600

(Ef) (Nash and Sutcliffe, 1970) – for the main watersheds show reasonable values. Figure 3 shows that good agreement between observed and simulated outflows was achieved for the Chuquicara and La Balsa sub-watersheds.

Another important test of model performance is the differentiation of the simulated amount of streamflow that comes from glaciated and non-glaciated portions of the watershed. An analysis of the total simulated water passing through La Balsa for the modelling period 1969–1999 indicates that on an annual basis 38% of the flow comes from melting glaciers (Table 2). This value is similar to the 37% value presented by Vergara *et al.* (2007) based on analysis of observed climatic and hydrologic data. For the Querococha sub-watershed the value is 15%, which is in accordance with the 10% that was calculated in a previous study (Mark and Seltzer 2003). Seasonally, the model suggests that melting glaciers contribute 30% of the streamflow at La Balsa during the wet season (December-January-February) and 67% during the dry season. This result provides insight into the importance of glaciers as water reservoirs during the dry season and the implications of their accelerated melting on water resources management in the region. Table 2 shows the total outflow as well as the proportions of water from melting glacier and from groundwater accretions for each sub-watershed and for each season (wet and dry). The total outflow is always higher during the wet season. If we consider only the sub-watersheds where ice covers more than 20% of the total area, we note that the proportion of glacier meltwater is higher during the dry season. For groundwater, the seasonal importance varies depending on the conditions in each sub-watershed. Considering the mean proportion of groundwater accretions in the total outflow we find 32% during the humid season and 35% during the dry season. Figure 3 shows the annual dynamic of these water balance components for Chuquicara and La Balsa. We recognize that the quality of the modelling would be improved by more spatially continuous information on actual climatic conditions.

Simulation of the glacier area evolution since the 1970s

In addition to simulating river flows, we checked that the glacier module captured observed changes in glaciated area in the Cordillera Blanca. An analysis of the trends in glacier area evolution for the Rio Santa watershed indicated good correspondence between simulated and observed data (Figure 4 and Table 3). The model captured the overall change in area in both 1970–1987 (a period characterized by rapid glacier retreat) and 1987–1999 (less pronounced retreat).

Looking at glacier area evolution of individual sub-watersheds, the model provided good correspondence with observed data (periods 1970–1987 and 1987–1999), particularly for the sub-watersheds with larger initial glacier area cover (Figure 4). One explanation for the lower correspondence for small glaciers is the fact that the observed data has an intrinsic error on the order of $\pm 5\%$ of the total glacier area. In addition, the glacier model, being based on empirically derived relationships, may not represent particular physical characteristics of small glaciers, such slope and aspect, which will tend to have more average aggregate characteristics for larger glaciers. The evolving observed and simulated glacier areas in sub-watersheds with glacier cover >10 km^2 tend to align well with the 1:1 line, while the glacier area of sub-watersheds with glacier cover <10 km^2 tend to diverge from the 1:1 line, sometimes under-predicting and at other times over-predicting. It is likely that any errors created in calibrating the model against sub-watershed runoff and glaciated area observations exist in our estimation of the evolving glacier ice volume, for which there is no regional set of *in situ* observations against which to calibrate.

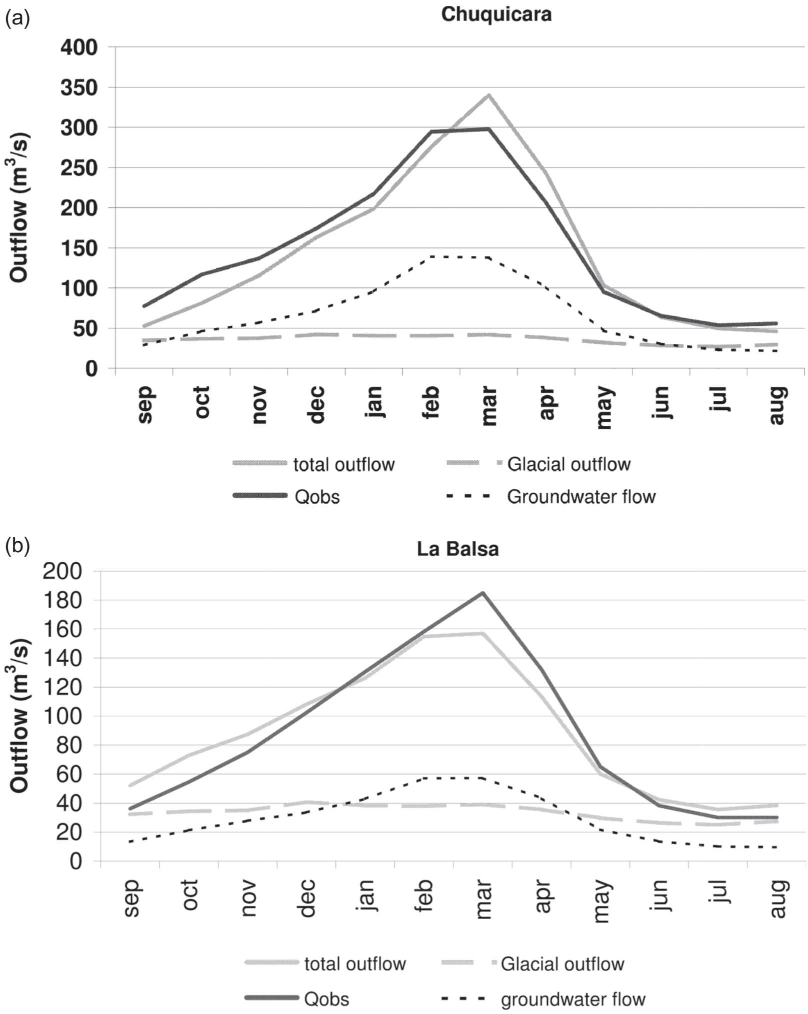

Figure 3. Mid-mensual calculated and simulated streamflows of two sub-watersheds during the period 1969–1998 in (a) Chuquicara, (b) La Balsa.

Simulation of the electric power at Cañon del Pato

Climate impacts are anticipated to change the hydrology in high mountain regions. Understanding these impacts is essential to planning and implementing adaptation measures in the hydropower sector and to understanding the implications of these changes for other water users. The hydropower facilities modelled include a diversion element at La Balsa with a maximum capacity of 82 m^3/s, a fixed generating head of 382 m, a plant factor at Cañon del Pato of 64%, and a diversion logic which sought to divert water at maximum capacity at La Balsa throughout the year. This fairly rough characterization of the hydropower system, which could be improved, nonetheless reasonably reflects the actual management of the system. During the dry winter months all the water in the river is diverted at an average rate of 40 m^3/s, while during the wet summer months flows can exceed the 150 m^3/s maximum diversion capacity (Figure 5).

Table 2. Results for simulated and observed runoff, subterranean part and glacier part for the calibration and the validation period (1969–1999).

Sub-watershed	Area (km^2)	Ice area (km^2)	DJF outflow (m^3/s)	JJA outflow (m^3/s)	DJF ice outflow (%)	JJA ice outflow (%)	DJF groundwater outflow (%)	JJA groundwater outflow (%)	Glacier meltwater (snow + ice) part of annual discharge (%)	Groundwater part of annual discharge (%)
1 La Recreta (Santa)	231	0	7.4	0.8	0	0	30	57	0	34
2 Pachacoto	203	22	5.8	1.6	28	67	30	28	35	30
3 Querococha	58	4	2.6	0.6	11	36	34	50	15	37
4 Olleros	175	19	7.7	2.1	25	61	30	32	32	31
5 Quillcay	245	46	11.0	3.8	41	76	28	21	50	27
6 Chancos	265	71	13.0	5.4	53	84	22	14	61	20
7 Llanganuco	83	36	4.2	2.2	71	93	13	6	77	11
8 Paron	31	20	2.0	1.0	74	93	10	6	79	11
9 Artesoncocha	9	6	no data	no data	no data	no data	no data	no data	no data	no data
10 Colcas	234	46	9.3	3.6	46	80	25	18	53	23
11 Los Cedros	106	23	4.2	1.7	46	75	23	16	52	21
12 Quitaracsa	310	14	12.5	3.6	12	30	25	25	15	25
13 La Balsa (Santa)	4696	421	129.7	38.7	31	68	34	28	38	33
14 Corongo	562	5	13.4	2.1	4	16	52	76	5	55
15 Chuquicara (Santa)	9540	443	228.5	58.0	19	49	44	43	23	44
16 Tablachaca/ Condorcerro	3179	2	56.6	9.1	0	0	67	98	0	71
17 Puente Carretera (Santa)	10776	443	247.3	70.0	18	46	45	43	25	40

DJF: December, January, February (wet season); JJA: June, July, August (dry season). Groundwater outflow is the sum of simulated interflow and baseflow.

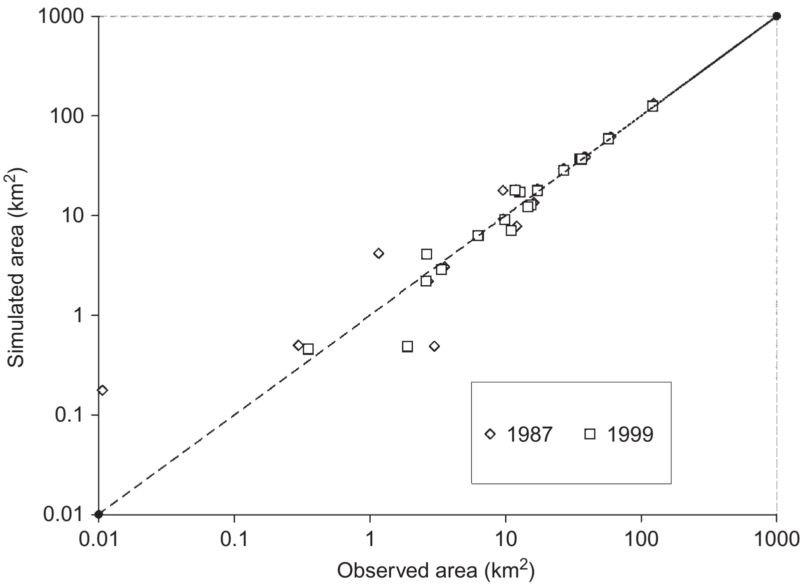

Figure 4. Scatter plot for observed versus simulated glacier areas for 1987 and 1998.

Table 3. Simulated and observed data of glaciers evolution between 1970 and 1999.

	Total area 1970 (km^2)	Total area 1987 (km^2)	Total area 1999 (km^2)	Change 1970–1987 (%)	Change 1987–1999 (%)	Change 1970–1999 (%)
Simulated	none	411	391	−19	−5	−23
Observed (error: ± 25 km^2)	507	396	387	−22	−2	−24

The installed capacity of the Cañon del Pato hydropower plant was expanded in 1997/1998. Since the modelling period is 1969–1998, it is only possible to obtain one year of simulated generation results for comparison to the reported 1484 GWh total plant capacity. The model output for the 1998 water year was 1120 GWh, which corresponds to 75% of the installed capacity. As the actual generation values were not available from the system operator, this correspondence with the installed capacity seems to suggest that the key features of the Cañon de Pato plant are captured. Improving the calibration of actual generation time series will be the focus of future efforts when attention turns to estimating the effects of changes in climate and hydrology on different management objectives in the Rio Santa system as part of watershed management planning efforts.

Implications for the electric power sector in the context of climate change

Having demonstrated the reasonable performance of the new tool, it is possible to demonstrate how the impact of future climate projections and the potential effectiveness of possible water management adaptation strategies can be analyzed as for example for hydropower management. To demonstrate the utility of the model in the study of the effects of climate change on hydropower production, two simplified climate scenarios were developed. Climate data (precipitation and temperature) from the WCRP CMIP3 multi-model

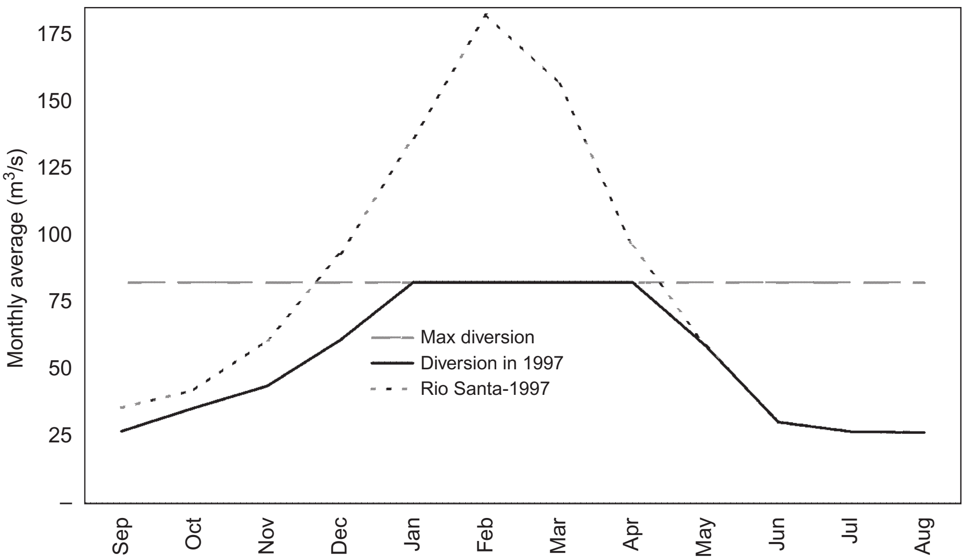

Figure 5. Monthly average streamflow calculated through the Cañon del Pato diversion in 1997/1998. Maximum flow diversion (grey line) is compared to flow diversion in 1997/1998 (black line) and to the average flows in the Rio Santa at the point of diversion of La Balsa for the modelling period 1969–1998 (dotted line).

database project (National Center for Atmospheric Research, n.d.) for the Caraz, Paron, Huaraz and Collota stations, were used. For the year 2030 and for each month the standard deviations between actual values and future values are calculated. The future values come from 16 global models under two carbon emission scenarios, A1b and B1 (32 scenarios). From the 32 scenarios, two scenarios are selected: a wet-warmer scenario (15% increase in precipitation and 0.5°C increase in temperature) and a dry-warmest scenario (10% decrease in precipitation and 2°C increase in temperature). The historic conditions were used as the reference case upon which were imposed the changes anticipated in these two scenarios; the model was run to investigate potential changes in the hydrology of the Cañon del Pato diversion. Both scenarios provided a slight increase in monthly average wet-season flows (summer and fall) with respect to the historical climate for the 30-year modelling period. The increase in monthly flows for the wet-warmer scenario is due to increased precipitation, while the increase in monthly flows for the dry-warmest scenario is due to increased glacier melt linked to increased temperatures. The wet-warmer scenario produced a decrease in base flows during the dry season (winter) because the temperature increase of 0.5 °C decreases watershed yield, while the dry-warmest scenario presented similar base flow magnitudes to the reference scenario because the increase of 2 °C in temperature had the capacity to melt higher-elevation glaciers during the winter.

Conclusion and discussion

Understanding hydrology, and having the capacity to model it, is crucial in Andean tropical mountains as part of efforts to plan and manage water resources. The main challenge in this region is to be able to simulate the hydrology with scarce meteorological and hydrological data and with high spatial variability. Several assumptions need to be made and interpolation methods need to be implemented in order to obtain continuous climate time series that can feed hydrologic models. This paper makes an attempt to respond to these challenges, but certainly more research is needed to define the best approach for developing continuous climate fields in the Andes.

The originality in this work, however, goes beyond the preparation of usable climate input data and rests on the successful linkage of transient climate time series and a model of glacier evolution within a rainfall-runoff modelling framework, to simulate the hydrology of glaciated watersheds and potential water management implications of climate change. The implication of climate change and other stressors can now be captured in an analytical framework that will allow key actors to explore different management strategies as part of the development of watershed plans. The tool is in permanent evolution. To date, the outputs are useful to policy and decision makers; the next step would be its integration for management decisions. Further steps into this modelling exercise should focus on detailing the implications of hydrologic change on water demands, including hydropower and agriculture, and the consequent economic implications. Having developed the basic analytical framework, future research could focus more heavily on the water management impact and adaptation aspects of potential climate change projections.

In Peru, a new basin-centric governance structure is dealing with the complexities in water use. In a system as complex as the Rio Santa, where there is such potential for change, it is necessary to have a modelling tool to support the process of developing watershed water plans. We are continuing to work with stakeholders in the basin to develop more detailed models that respond to their needs for information, and to explore management options that can support their contribution to the reduction of water-related conflicts.

Acknowledgements

We thank the guest editor and the two anonymous reviewers for improving the quality of the paper. This study is part of World Bank project SOF/TF055069(70)-P110305, entitled Assessing the Impacts of Climate Change on Mountain Hydrology: Development of a Methodology through a Case Study in Peru, undertaken at the request of the Government of Peru, and we thank Alejandro Deeb and Adriana Valenciana for their important support. Furthermore, the authors thank the following organization and persons for data gathering: the Unit of Glaciology and Water Resources (UGRH) of the National Authority of Water (ANA) for its great support in the investigations in glaciology, and the hydrology group from the SENAMHI (National Service of Meteorology and Hydrology in Peru), at Lima, Peru.

References

Aceituno, P., 1988. On the functioning of the southern oscillation in the South American sector. Part I: Surface climate. *Monthly Weather Review*, 116, 505–524.

Ames, A., *et al*., 1989. *Inventario de Glaciares del Perú. Fuente: Fotografias aeras de 1962, 1963, 1970, Part 1*. Huaraz, Peru: Hidrandina S.A.

ATA-INADE [company Asesore Tecnicos Asociados, governmental institute Instituto Nacional de Desarrollo], 2002. *Diagnostico Consolidado de la Cuenca de Gestion Chavimochic*. Lima, Peru: Instituto Nacional de Desarollo.

Bahr, D.B., Meier, M.F., and Peckham, S.D., 1997. The physical basis for glacier volume-area scaling. *Journal of Geophysical Research*, 102 (B9), 20355–20362.

Barear, M., *et al*., 2009. Characterizing contributions of glacier melt and groundwater during the dry season in a poorly gauged catchment of the Cordillera Blanca (Peru). *Advances in Geosciences*, 22, 41–49.

Braithwaite, R.J., and Zhang, Y., 1999. Modeling changes in glacier mass balance that may occur as a result of climate changes. *Geografiska Annaler*, 81 A, 489–495.

Brugger, K.A., 2006. Late Pleistocene climate inferred from the reconstruction of the Taylos River glacier complex, southern Sawatch Range, Colorado. *Geomorphology*, 75, 318–329, doi: 10.1016/j.geomorph.2005.07.020.

Brunet-Moret, Y., 1979. Homogénéisation des precipitations. Cahier ORSTOM, *Série Hydrologie*, 16, 3–4.

Chevallier, P., *et al*. 2011. Climate change threats to environment in the Andes: glaciers and water resources. *Regional Environmental Change*, 11 (S1), 179–187, doi: 10.1007/s10113-010-0177-6.

Espinoza, J.C., *et al*., 2009. Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador). *International Journal of Climatology*, 29, 1574–1594, doi: 10.1002/joc.1791.

Garreaud, R., Vuille, M., and Clement, A., 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 194, 5–22, doi: 10.1016/S0031-0182(03)00269-4.

Hiez, G., 1977. L'homogénéité des données pluviométriques. Cahier ORTSTOM, *Série Hydrologie*, 14, 129–172.

Hock, R., 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282, 104–115, doi:10.1016/S0022-1694(03)00257-9.

IADB 2012. Proyecto de modernización de la gestión de los recursos Hídricos (pe-l1070). Propuesta de préstamo. Washington DC: Inter-America Development Bank.

IGN, 2005. Normas Tecnicas Especificaciones tecnicas para la produccion de mapas topograficos a escala de 1:100,000. Lima, Peru: Instituto Geografico Nacional.

Immerzeel, W., *et al*., 2012. Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change*, 110, 721–736.

Johnson A.M., 1976. Climate of Peru, Bolivia, and Ecuador. *In*: W. Schwerdtfeger, ed. *World survey of climatology*, Vol. 12. New York: Elsevier, 147–218.

Juen, I., Kaser, G., and Georges, C., 2007. Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Peru). *Global and Planetary Change*, 59, 37–48, doi: 10.1016/j.gloplacha.2006.11.038.

Kaser, G., 2001. Glacier-climate interaction at low latitudes. *Journal of Glaciology*, 47 (157), 195–204.

Kaser, G., and Osmaston, H., 2002. *Tropical glaciers*. New York: Cambridge University Press.

Kaser G., *et al*., 2003. The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru. *Journal of Hydrology*, 282, 130–144.

Kundzewicz, Z.W., *et al*. 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Science Journal*, 53, 3–10.

Mark, B.G., and McKenzie, J.M., 2007. Tracing increasing tropical Andean glacier melt with stable isotopes in water. *Environmental Science and Technology*, 40 (20), 6955–6960.

Mark, B.G., McKenzie, J.M., and Gomez, J., 2005. Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru. *Hydrological Science Journal*, 50 (6), 975–987.

Mark, B.G., and Seltzer, G.O., 2003. Tropical glacial meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Perú. *Journal of Glaciology*, 49 (165), 271–281.

Nash, J.E., and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part 1: A discussion of principles. *Journal of Hydrology*, 27 (3).

National Center for Atmospheric Research (n.d.) Earth system grid website. Available from: www.earthsystemgrid.org

Pouyaud, B., *et al*., 2005. Avenir des ressources en eau glaciaire de la Cordillère Blanche. *Hydrological Science Journal*, 50 (6), 999–1022.

Racoviteanu, A.E., *et al*., 2008. Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. *Journal of Glaciology*, 54, 186.

Rees, G., and Collins, D. N., 2006. Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. *Hydrological Processes*, 20, 2157–2169.

Schaefli, B., *et al*., 2005. A conceptual glacio-hydrological model for high mountainous catchments. *Hydrology and Earth System Sciences*, 9, 95–109, doi: 10.5194/hess-9-95-2005.

Sicart, J.E., Hock, R., and Six, D., 2008. Glacier melt, air temperature, and energy balance in different climates: the Bolivian Tropics, the French Alps, and northern Sweden. *Journal of Geophysical Research*, 113, D24113, doi: 10.1029/2008JD010406.

Singh, P., Kumar, N., and Arora, M., 2000. Degree-day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas. *Journal of Hydro*logy, 235, 1–11, doi: 10.1016/S0022-1694(00)00249-3.

Smith, C.A., and Sardeshmukh, P. 2000. The effect of ENSO on the intraseasonal variance of surface temperature in winter. *International Journal of Climatology*, 20, 1543–1557.

Suarez, W., *et al*., 2008. Modelling the water balance in the glacierized Paron Lake basin (White Cordillera, Peru). *Hydrological Science Journal*, 53 (1), 266–277.
Vauchel, P., 2005. *HYDRACESS: software for management and processing of hydro-meteorological data* [online]. Available from: http://www.mpl.ird.fr/hybam/outils/logiciels.htm.
Vergara, W., *et al*., 2007. Economic impacts of rapid glacier retreat in the Andes. *Eos*, 88 (25), 261–268.
Viviroli, D., *et al*., 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, 15, 471–504.
Vuille, M., Kaser, G., and Juen, I., 2008a. Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. *Global and Planetary Change*, 62 (1–2), 14–28, doi: 10.1016/j.gloplacha.2007.11.003.
Vuille, M., *et al*., 2003. 20th century climate change in the tropical Andes: observations and model results. *Climate Change*, 59 (1–2), 75–99.
Vuille, M., *et al*., 2008b. Climate change and tropical Andean glaciers: past, present and future. *Earth-Science Reviews*, 89 (3–4): 79–96, doi: 10.1016/j.earscirev.2008.04.002.
Winkler, M., *et al*., 2009. Measured and modelled sublimation on the tropical Glaciar Artesonraju, Perú. *The Cryosphere*, 3, 21–30.
Yates, D., 1996. WatBal: an integrated water balance model for climate impact assessment of river basin runoff. *International Journal of Water Resources Development*, 12 (2), 121–139.
Yates, D., *et al*., 2005a. WEAP21: a demand-, priority-, and preference-driven water planning model. Part 1: Model characteristics. *Water International*, 30, 487–500.
Yates, D., *et al*., 2005b. WEAP21: a demand-, priority-, and preference-driven water planning model. Part 2: Aiding freshwater ecosystem service evaluation. *Water International*, 30 (4), 501–512.
Zapata, M., Arnaud, Y., and Gallaire, R., 2008. Inventario de glaciares de la Cordillera Blanca. *13th IWRA World Water Congress*, 1–4 September, Montpellier, France.

Appendix: Glacier module description

The degree-month glacier evolution routines were implemented at two time scales: a monthly time step t, for estimations of glacier contributions to runoff, and an annual time step y, for annual ice mass balances and glacier area adjustments; therefore the notation for initial conditions is $y = 0$, $t = 0$. The initial spatial extent of glaciers within each elevation band of each sub-watershed is used to allocate the area within each catchment, A_i (in units of km^2) between glaciated and non-glaciated area:

$$A_i = \sum_{j=1}^{2} A_{y=0,\,t=0,\,i,\,j} \tag{A1}$$

The total initial extent of glaciers in a sub-watershed was defined as:

$$A_{glacier,\,y=0,\,t=0} = \sum_{i=m}^{n} A_{y=0,\,t=0,\,i,\,j=1} \tag{A2}$$

where j sums over glaciated and non-glaciated areas, n is the total number of elevation bands within a sub-watershed and m is the lowest elevation band containing glacier ice.

Surface runoff at the sub-watershed level

$$Q_{sub-watershed,\,y,\,t} = \sum_{i=m}^{n} \left(Q_{\mathrm{liq},\,y,\,t,\,i,\,j=1} + Q_{\mathrm{snow},\,y,\,t,\,i,\,j=1} + Q_{\mathrm{ice},\,y,\,t,\,i,\,j=1}\right) + \sum_{i=1}^{n} Q_{\mathrm{WEAP},\,y,\,t,\,i,\,j=2} \tag{A3}$$

For each monthly time-step, the volume of surface runoff within a sub-watershed "$Q_{\text{sub-watershed}}$" is the sum of the contribution of melting snow and ice for the glaciated portion of the sub-watershed and the runoff coming from the simulation of rainfall-runoff processes in non-glaciated portions of the sub-watershed. Q_{WEAP} is the discharge from the non-glaciated area of the sub-watershed; the contribution from the glacier of snow and ice melt (Q_{snow} and Q_{ice}) and the rainfall from the *i*th catchment (Q_{liq}) to surface flow from a sub-watershed and the accumulation of snow on the surface of the glacier were determined by accounting for the surface area of the glacier within the elevation band; $Q_{\mathrm{snow},y,t,i,j=1}$ = *i*th catchment discharge from snow reservoir (m^3/month); $Q_{\mathrm{ice},y,t,i,\,j=1}$ = *i*th catchment discharge from ice reservoir (m^3/month); $Q_{\mathrm{liq},\,y,t,i,j=1}$ = *i*th catchment total monthly precipitation (m^3/month) when the monthly air temperature is superior to the threshold temperature T_0 (limit temperature between snow and liquid precipitation).

To quantify snowmelt, ice melt and liquid runoff from glaciated portions of each elevation band, the degree-day method proposed by Schaefli *et al.* (2005) was used at a monthly time step with three calibrated parameters: a_{snow} (snowmelt degree-month factor in mm per month per °C), a_{ice} (ice melt degree-month factor in mm per month per °C) and T_0 (threshold value for conversion of liquid precipitation into snow and limit to activate the fusion process of snow and ice). When during particular months the snow totally disappeared from a glaciated portion then the ice is submitted to the fusion. Initial efforts to calibrate the parameters a_{snow} and a_{ice} were based on the range of values presented by Hock (2003), Brugger (2006) and Singh *et al.* (2000), who found that the degree-day factor for snow ranged from 1.3 to 11.6 mm per day per °C for snow and from 5.5 to 20 mm per day per °C for ice. For our monthly model, we investigated ranges between 40 and 400 mm per month per °C for snow and between 165 and 600 mm per month per °C for ice.

Annual mass balance and glacier geometry evolutions

The input of water to a band comes either through liquid precipitation or snowfall. Outputs of water include the estimated runoff from melting snow and the melting of glacial ice, which take into consideration runoff associated with liquid precipitation falling on the surface of a glacier within the elevation band. If this balance is positive, the implication is that some portion of the water that has fallen within the elevation band has not been offset by water leaving the band, and as a result, on net, there is a volume of water free within the elevation band at the end of the hydrologic year that would be transformed into ice. From the annual mass balance conducted on each elevation band containing ice at the start of a hydrologic year, the overall change in volume of glacial ice within a sub-watershed was estimated. It was possible to adjust the overall volume and extent of the glacial ice within a sub-watershed. Ideally this would be done by assessing the internal dynamics of ice movement within the glacier, but the simplifying assumption was made that changes in the total volume of ice manifest themselves at the low part or tongue of the glacier. The estimated surface area of the glacier and the change in this surface area at the end of the hydrologic year are given by Bahr's relation (Bahr *et al.* 1997). The final step in the annual adjustment to the glacial extent in a sub-watershed is to compensate for change in the extent of glacial ice in the areas defining the non-glaciated portion of a particular elevation band *i*. The WEAP glacier module uses only three parameters, T_0 (threshold temperature for fusion), a_{ice} and a_{snow} (degree-month factors for ice and snow), and provides a transient modelling framework for simulating the dynamics of glacier surface extension and glacier meltwater contribution to the outflow from each glaciated sub-watershed.