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Modelling the hydrologic role of glaciers within a Water Evaluation and Planning System (WEAP): a case study in the Rio Santa watershed (Peru)

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Abstract

For the past 30 years, a process of glacier retreat has been observed in the Andes, raising alarm among regional water resources managers. The purpose of this paper is to develop a model of the role of Andean glaciers in the hydrology of their associated watersheds, which is appropriate for application at a river basin scale, with an eye towards creating an analytical tool that can be used to assess the water management implications of possible future glacier retreat. While the paper delves deeply into our formulation of a glacier module within a water resources management modelling system, the widely subscribed Water Evaluation and Planning System (WEAP), the originality of our work lies less in the domain of glaciology and more in how we apply an existing reduced form representation of glacier evolution within a model of the climate-glacier-hydrology-water management continuum. Key insights gained pertain to appropriate ways to deploy these reduced form representations in a relatively data poor environment and to effectively integrate them into a modelling framework that places glaciers within a wider water management context. The study area is the Rio Santa watershed in Peru which contains many of the expansive glaciers of the singular Cordillera Blanca. The specific objectives of this study included: (i) adequately simulating both monitored glacier retreat and observed river flows from the last forty years using historical climate time series as model input; (ii) quantifying the proportion of river flow in the Rio Santa produced from melting glaciers during this period; (iii) estimating the historical contribution of groundwater accretions to river flows; and (vi) reproducing a reasonable simulation of recent hydropower operations in the Rio Santa system. In pursuit objective (i), a split sample calibration-validation of the model was conducted by comparing the simulated glacier area to Landsat images taken in 1987 and 1998 and observed and simulated river flow at 16 control points in the Rio Santa watershed. At the global scale of the watershed, the glacier retreat is correctly simulated for the period 1970/1999 with a calculated retreat equals to −23% when the observed retreat is of −24%. Having established that the model can respond to these scientific objectives,

the ultimate goal of the study was to demonstrate how this integrated modelling system can be used as a decision support tool to assist in planning water management adaptation to climate change. This sort of integrated assessment is required to adapt water resources management in the Andes to a range of future climatic conditions, improving the resilience of developing Andean economies such Peru's in the face of a major drive of global change.

1 Introduction

Approximately 99% of the world's tropical glaciers are found in the Andes of South America, of which 71% are located in Peru (Kaser and Osmaston, 2002). The Cordillera Blanca, located in the western branch of the Andes in Peru (South Latitude: 7°57′–10°13′ and West longitude: 77°17′–78°18′), 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 (photographic and satellite) testify to the fact that glaciers in the Cordillera Blanca are retreating. Over a long period from 1960 and 2003 the estimated reduction in glacier area was from 728 to 536 km^2 (Ames et al., 1989; Zapata et al., 2008). Between 1987 and 1996 the spatial extent of all glaciers in the Cordillera decreased from $643 \pm 63\,km^2$ to $600 \pm 61\,km^2$ (Silverio and Jacquet, 2005). 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 was $569.6 \pm 21\,km^2$.

Research has been carried out to understand what may be driving these changes. Some have speculated that the primary causes are changes in temperature and humidity (Vuille et al., 2003). In a more recent paper, however, Vuille et al. (2008a) argued that temperature, which usually co-varies with precipitation, is probably of secondary importance. According to this study, regional-scale precipitation variability linked to large scale atmospheric circulation is the principal factor in glacier mass balances in the Cordillera Blanca. Ultimately, it seems likely that the combined impact of changes

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in all climatic forcing variables is contributing to the retreat (Vuille et al., 2008b), and that 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 Peru, indicating large future costs to the Peruvian economy in the absence of adaptation measures in response to continued glacier retreat.

What is missing from among the currently available tools is a framework that can be used to evaluate the performance of various water management adaptation strategies to climate change while taking into consideration the differential evolution of Andean glaciers under future climate scenarios. Certainly there will be uncertainties associated such a tool, which may come from the lack of sufficient climatic and hydrometric data to calibrate models, uncertainties from the climate models in developing future climate scenarios, and uncertainties within the hydrologic and water resources modelling approaches selected (Kundzewicz et al., 2008). Even acknowledging all the associated uncertainties, however, this type of analytical framework is essential to provide water resources managers with insight into promising water management adaptation strategies (Kundzewickz et al., 2008) in Andean systems where large populations rely on glacier melt to supply water and hydropower (Barnett et al., 2005). There is a critical need to capture the key features of possible future changes in glacier extent and contribution to river flow within a water resources management context, which requires the development of a temporally and spatially appropriate glacier evolution routine, nested within a water resources modelling framework, the subject of this paper.

The western slope of the Cordillera Blanca lies within the Rio Santa Basin, which ultimately discharge into the Pacific Ocean. Many tributaries to the Rio Santa are at least partially fed by the glacier melt water from the Cordillera Blanca and together they provide critical urban and agricultural water supplies for roughly one million people living in the upper portion of the Rio Santa watershed. Below the main population centres of the upper watershed, the Rio Santa passes through the narrow Cañon del Pato where a major river diversion is made to provide water for a critical hydropower production facility that has been in operation since 1954 and which underwent a substantial capacity expansion in 1998. Below the Cañon del Pato powerhouse, close to the coastal plain, two significant water diversions send water out of the basin towards irrigation districts to the north (Chavimochic, 144 385 ha, www.chavimochic.gob.pe) and south (Chinecas, 44 220 ha, www.pechinecas.gob.pe) of the Rio Santa mouth (Fig. 1).

Past hydrologic studies of the Rio Santa Basin reveal the importance of glacier melt water to the overall water supply in the watershed under current conditions. For example, Mark and Seltzer (2003) evaluated the hydrological impact of glacier melt water from the Cordillera Blanca in small glaciated catchments and in the larger Rio Santa watershed. Using a water balance model and hydrochemical analysis to quantify the different sources of water in the Rio Santa, they concluded that: (i) the annual maximum glacier melt occurs during the austral spring; and that (ii) annually, at least 10%, and potentially as much as 20%, of the Rio Santa upper watershed discharge comes from melting glacier ice. The Mark and Seltzer (2003) study, which concentrates on the upper part of the basin down to the "La Balsa" gauge station, the main point of diversion for the Cañon del Pato hydropower project, is typical of a series of studies which do not consider the more that 50% of the total watershed area below La Balsa, including the region characterized by substantial growth in irrigation along the coastal plain (Mark and McKenzie, 2007; Juen et al., 2007; Suarez et al., 2008; Pouyaud et al., 2005). Perhaps more critically, these studies do not included transient simulations of glacier retreat and associated river flows, relying instead on the analysis of observational data. This calls into question how useful this information can be to water managers who want to evaluate the performance of specific, river basin wide, water management adaptations to future climate change. Further, at a catchment scale, groundwater plays a significant role in the river's flow regime as roughly half of dry season discharge is provided by aquifers (Kaser et al., 2003; Mark et al., 2005; Baraer et al., 2009). As with the representation of glacier evolution, the role of groundwater in the Rio Santa river is not commonly analyzed using transient modelling techniques differentiated between the sub-catchments.

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The purpose of this paper is to develop and then test a methodology to quantify the role of Andean glacier evolution and associated hydrologic change relative to the challenges and opportunities that currently confront water managers in the Rio Santa system and those that will takes on increasing importance in the face of potential climate change. The approach taken uses the planning tool Water Evaluation and Planning (WEAP) system which has been under developed by researchers at the Stockholm Environment Institute (SEI) for over 15 years (Yates 1996, Yates et al., 2005a,b) as a point of departure. The research sought to refine the existing WEAP software, which integrates both hydrologic processes and representations of the operations of built infrastructure, so that it could capture changing hydrologic and water management conditions in heavily glaciated Andean watersheds.

The originality of this work does not lie in the formulation of a new conceptual models or analytical routines. The Rio Santa WEAP application joins a glacial module derived from the reduced form degree-day method for simulating glacier evolution, WEAP's existing rainfall-runoff hydrology module of non-glaciated portions of the watershed, and WEAP's existing functionality to represent water management infrastructure and operating regimes. What is original in this work is that the Rio Santa application spans the climate-glacier-hydrology-water management continuum in a manner that is appropriate to respond to the planning challenges facing water managers and decision makers in a relatively data poor and high vulnerable region of the world. The primary objective of this study included accurately simulating both river flows and glacier retreat during a recent forty year period and quantifying the proportion of the water in the different Rio Santa sub-watershed that are directly produced from the melting of glaciers and groundwater accretions. Much of this paper focuses on how we met this specific objective. Having demonstrated the reasonable performance of the new tool, however, it will be possible to demonstrate how the impact of future climate projections and the potential effectiveness of possible water management adaptation strategies can be analyzed.

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2 Model description

2.1 General structure of the WEAP model

Within the existing version of the WEAP software, rainfall-runoff processes are simulated by dividing a watershed into sub-watershed areas above points of river flow measurement or management control. For a WEAP study in a mountainous region, each sub-watershed area is typically divided into elevation bands in order to capture elevation related climatic gradients. Each sub-watershed/elevation band is then represented as a unique WEAP catchment object within which temporally variable land cover and temporally variable yet spatially homogeneous climatic conditions can be imposed on a time step-by-time step basis. Land cover variability in each catchment is represented by subdividing the area into representative land cover types that are parameterized individually. For each catchment, rainfall-runoff processes are simulated using a 2-bucket representation of a root zone layer and a deep layer (Yates 1996; Yates et al., 2005a). Equations (1) and (2) are the mathematical formulation of rainfall-runoff hydrology in WEAP:

$$\mathrm{Sw}_j \frac{dz_{1,j}}{dt} = P_\mathrm{e}(t) - \mathrm{PET}(t) k_{c,j}(t) \left(\frac{5z_{1,j} - 2z_{1,j}^2}{3} \right) - P_\mathrm{e}(t) z_{1,j}^{\frac{\mathrm{RRF}_j}{2}} - f_j k_s z_{1,j}^2 - (1 - f_j) k_s z_{1,j}^2 \quad (1)$$

$$\mathrm{Dw}_j \frac{dz_{2,j}}{dt} = -k_d z_{1,j}^2 + (1 - f_j) k_s z_{2,j}^2 \quad (2)$$

Where Sw (mm) is the soil water capacity of the top bucket, z_1 is the relative soil water storage, and P_e in mm is effective precipitation. The second term in Eq. (1) is evapotranspiration from each fractional area, j where PET is the Penman-Monteith reference crop potential evapotranspiration given in mm/day and k_{cj} is the crop/plant coefficient for each fractional land cover. The third term in Eq. (1) represents surface runoff where RRF is the runoff resistance factor. The fourth and fifth terms are the interflow and

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deep percolation, where the parameter k_j, is an estimate of the upper storage conductivity (mm/time) and f_j is a tuning parameter related to soil, land cover type, and topography that fractionally partitions water as either horizontal, f_j or vertically $(1-f_j)$ drainage. In Eq. (2), Dw is the deep water storage capacity (mm) where the inflow the deep percolation from the upper root zone from Eq. (1), and k_d is the conductivity rate of the lower bucket (mm/time). The second term in Eq. (2) represents the baseflow. The baseflow and interflow are the components of groundwater flow to a river network. Equations (1) and (2) are solved numerically in WEAP using a simultaneous solution routine.

In cold regions the rainfall-runoff routines in WEAP can simulate the accumulation and melting of snow within a catchment as described previously. 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,b).

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 interest in assessing potential impact of climate change on hydropower production, special attention was paid to calibrating the application at La Balsa where the primary diversion to the Cañon del Pato hydropower plant occurs (Fig. 1).

2.2 Glacier module

This section describes the approach used to add a transient representation of evolving glacial melt water contributions into the existing WEAP rainfall-runoff routine. Again, the key innovation in this section is not related to the routines themselves, but rather to how existing reduced form representations of glacier evolution can be configured for integration within an integrated water resources modelling framework. In this formulation each elevation band in a given sub-watershed was divided, into glaciated and non-glaciated areas (Fig. 2) with the glaciers being conceptualized via a modification to an existing degree-day model (DDM). Some studies, for example Sicart et al. (2008) or

Kaser (2001), point out that the degree-day approaches are not well adapted for simulating glacier melt water contributions to river flow at daily time step in tropical zones. However, other studies have successfully changed the temporal resolution of this sort of model to a monthly time step in order to make long term projections of changes in glacier mass balances caused by climate change (Braithwaite and Zhang, 1999; Suarez et al., 2008). We considered that a modified DDM applied using a monthly time step constitutes an appropriate approximation for studies of climate impacts at large temporal and spatial scales such as that of the Rio Santa watershed. This assumption is also consistent with the rainfall-runoff and water allocation routines in WEAP, which are commonly run on a monthly time step.

The degree-day factor in this study is then a degree-month factor. In general, this 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, we assumed that the degree-month factor would be constant. Maintaining the degree-month factor constant for all subwatersheds and during the modelling period provided a robust approach by reducing the degrees of freedom available during model calibration. Here it is worth pointing out that developing a climate driven degree-month factor for the various Cordillera Blanca glaciers in the Rio Santa watershed would be a worthy glaciological investigation. As is the case with many of the assumptions in our model, however, we sought to make the model as general as possible, expecting that the implications of these assumptions would be captured implicitly in a successful model calibration.

This same goal of generality shaped our decision to not use a full energy balance model that would have explicitly captured all key glacier processes and relationships, such as sublimation (Winkler et al., 2009) as energy balance models are notoriously difficult to apply at large scales and in the absence of detail input data. For now, we provide a simplified model that can be applied at large temporal and spatial scales, assuming that the implications of these simplifications will be implicitly captured during

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calibration. WEAP is flexible enough as a modelling platform, however, that these assumptions and simplifications can be revised in future studies.

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. In this notation, a subscript $t=0$ suggests that the expression pertains to conditions at the beginning of a hydrologic year, y, before any of the monthly time step calculations are carried out and as such, y, $t=12$ is the time equivalent to $y+1$, $t=0$. The notation for initial conditions is $y=0$, $t=0$.

2.2.1 Initial conditions

The initial spatial extent of glaciers within each elevation band of each sub-watershed (a unique WEAP Catchment model object) is used to allocate the area within each Catchment, A_i, defined in units of km^2 between glaciated and non-glaciated area:

$$A_i = \sum_{j=1}^{2} A_{y=0,t=0,i,j} \tag{3}$$

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

$$A_{\text{glacier},y=0,t=0} = \sum_{i=m}^{n} A_{y=0,t=0,i,j=1} \tag{4}$$

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. Initial glacier area calculations are feasible in the Peruvian context, and specifically, for the Rio Santa watershed, given that 1969 data was available for each of the 17 sub-watersheds in the Rio Santa WEAP application (see Sect. 3.3.1). Note that Ai is constant but the relative proportion between $A_{j=1}$ (glaciated) and $A_{j=2}$ (non-glaciated) will vary after each hydrologic year.

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Based on an empirical relationship that relates glacier ice volume (V) expressed in km^3 to glacier area for individual glaciers (Bahr et al., 1997), the initial glacial volume in each sub-watershed was estimated as:

$$V_{\text{glacier},y=0,t=0} = c \cdot A^{b}_{\text{glacier},y=0,t=0} \tag{5}$$

Where c and b are scaling factors related to the width, slope, side drag, and mass balance of a glacier. Analysis of 144 glaciers around the world glaciers worldwide suggests that factor values of b=1.36 and c=0.048 (Bahr et al., 1997; Klein and Isacks, 1998). Note that this volume corresponds to the entire initial ice mass within a WEAP sub-watershed. An allocation of this volume between glaciated elevation bands was not attempted.

2.2.2 Surface runoff at the sub-watershed level

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.

$$\begin{aligned} Q_{\text{sub-watershed},y,t} = & \sum_{i=m}^{n} \left(VP_{\text{liq},y,t,i,j=1} + VQ_{\text{snow},y,t,i,j=1} + VQ_{\text{ice},y,t,i,j=1} \right) \\ & + \sum_{i=1}^{n} Q_{\text{WEAP},y,t,i,j=2} \qquad (\text{m}^3) \end{aligned} \tag{6}$$

The contribution of snow and ice melt in volume (V) from the ith Catchment 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.

$$VQ_{\text{snow},y,t,i,j=1} = \left(Q_{\text{snow},y,t,i,j=1} / 1000 \right) \cdot A_{y,t=0,i,j=1} \cdot 1000^2 \qquad (\text{m}^3) \tag{6a}$$

$$VQ_{\text{ice},y,t,i,j=1} = \left(Q_{\text{ice},y,t,i,j=1} / 1000 \right) \cdot A_{y,t=0,i,j=1} \cdot 1000^2 \qquad (\text{m}^3) \tag{6b}$$

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$$VP_{\mathrm{liq},y,i,j=1} = (P_{\mathrm{liq},y,i,j=1}/1000)\cdot A_{y,t=0,i,j=1}\cdot 1000^2(\mathrm{m}^3) \tag{6c}$$

Where for monthly time step, t, during hydrologic year, y:
$Q_{\mathrm{snow},y,t,i,j=1}$=$i$th Catchment discharge from snow reservoir (mm/month)
$Q_{\mathrm{ice},y,t,i,j=1}$=$i$th Catchment discharge from ice reservoir (mm/month)
$P_{\mathrm{liq},y,t,i,j=1}$=Rainfall on glacier surface in ith Catchment (mm/month)

$$= \begin{cases} P_{y,t,i}, & T_{y,t,i} \geq T_0 \\ 0, & T_{y,t,i} < T_0 \end{cases} \tag{6d}$$

$P_{y,t,i}$=ith Catchment total monthly precipitation, also used in j=2 (mm/month)
$T_{y,t,i}$=ith Catchment monthly average temperature, also used in j=2 (°C)
T_0=threshold temperature (°C)

Obviously the amount of monthly precipitation is a key input variable in Eq. (6), along with the estimation of the monthly average temperature. The development of these key input time series is described below (see Sect. 3.3.2). Using Eq. (6) the total runoff volume from a sub-watershed was calculated and compared to actual observed runoff data at the discharge point of each sub-watershed. This comparison constituted the main criterion for calibration of the model.

To quantify snow melt, ice melt and liquid runoff from glaciated portions of each elevation band and simplification of the degree-day method proposed by Schaefli (Schaefli et al., 2005) was used. We should acknowledge that the Schaefli model does not explicitly represent sublimation. A study by Winkler et al. (2008) carried out a very local scale for a glacier in the Andes concludes that sublimation accounts for 60–90% of energy available for ablation in the dry season and 10–15% in the wet season. Here is an example of where in the interest of creating a general modelling framework we assumed that a modified DDM formulation, calibrated against observed glacier area and runoff at an annual scale could implicitly integrate all the energy exchange processes (and so the sublimation process) by the mean of the threshold temperature parameter. It is likely that any errors created in calibrating out model against sub-watershed runoff and glaciated area observations are captured in our estimation of the evolving glacier ice volume, for which there is no regional set of observations against which to calibrate.

The main modification with respect to Schaefli's formulation of snow and ice melt contribution to runoff was the elimination of the exponential autocorrelation factors which for monthly time-step do not have much relevancy (month to month autocorrelation coefficient in observed river flow are typically inferior to 0.6). For a particular elevation band:

$$Q_{\text{snow},y,t,i,j=1} = M_{\text{snow},y,t,i,j=1} \tag{7}$$

where for monthly time step, t, during hydrologic year, y:

$M_{\text{snow},y,t,i,j=1}$=snow melt from glacier surface in ith Catchment (mm/month)

$$= \min \begin{cases} \text{SInitial}_{y,t,i,j=1} \\ M_{\text{pot snow},y,t,i,j=1} \end{cases} \tag{7a}$$

$\text{SInitial}_{y,t,i,j=1}$=snow water equivalent on the glacier surface in ith Catchment (mm)

$$= \text{SFinal}_{y,t-1,i,j=1} + P_{\text{snow},y,t,i,j=1} \tag{7b}$$

$P_{\text{snow},y,t,i,j=1}$=snow accumulation on glacier surface in ith Catchment (mm/month)

$$= \begin{cases} 0, & T_{y,t,i} \geq T_0 \\ P_{y,t,i}, & T_{y,t,i} < T_0 \end{cases} \tag{7c}$$

$M_{\text{pot snow},y,t,i,j=1}$=potential snow melt in the ith Catchment (mm/month)

$$= \begin{cases} a_{\text{snow}}(T_{y,t,i} - T_0), & T_{y,t,i} \geq T_0 \\ 0, & T_{y,t,i} < T_0 \end{cases} \tag{7d}$$

a_{snow}=snow melt degree-month factor (mm/month/°C), a calibration parameter.

T_0 constitutes a threshold value for conversion of liquid precipitation into snow and is a calibration parameter. At the end of each monthly time-step the snow water equivalent accumulated on the surface of the glacier must be update to account for snow melt runoff.

$$\text{SFinal}_{y,t,i,j=1} = \text{SFinal}_{y,t-1,i,j=1} + P_{\text{snow},y,t,i,j=1} - Q_{\text{snow},y,t,i,j=1} \tag{8}$$

When the potential snow melt in a given month, t, exceeds the actual accumulated amount of snow water equivalents on the surface of the glacier within elevation band i. the surface of the glacier ice became exposed. In this case an additional set of equations were executed to estimate the contribution of melting glacier ice to surface flow in the ith Catchment.

$$Q_{\text{ice},y,t,i,j=1} = \text{SFree}_{y,t,i,j=1} M_{\text{potice},y,t,i,j=1} \quad (9)$$

Where $\text{SFree}_{y,t,i,j=1}$ is a weighting factor related to the snow free portion of the month and where the preceding definitions for snow apply for ice with the modifications that $M_{\text{pot ice},y,t,i,j=1}$=potential ice melt from the ith Catchment (mm/month)

$$= \begin{cases} a_{\text{ice}}(T_{y,t,i} - T_0), & T_{y,t,i} \geq T_0 \\ 0, & T_{y,t,i} < T_0 \end{cases} \quad (9a)$$

a_{ice}=ice melt degree-month factor (mm/month/°C), a calibration parameter

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 between 1.3 to 11.6 mm d^{-1} °C^{-1} and between 5.5 to 18.6 mm d^{-1} °C^{-1} for ice. For our monthly model, we investigated ranges between 40 to 400 mm month^{-1} °C^{-1} for snow and between 165 to 600 mm month^{-1} °C^{-1} for ice.

2.2.3 Annual mass balance

At the end of the 12 monthly time steps, t, in a hydrologic year, y, a mass balance was carried out to assess changes in the overall volume glacier ice within a sub-watershed. This was carried for each of the $n-m+1$ elevation bands within a sub-watershed that contained glacial ice at the start of a hydrologic year. The goal was to account for all water that has entered a particular elevation band, i, and had not flowed from the band during the hydrologic year. The input of water to a band comes either through liquid precipitation or snow fall. Outputs of water include the estimated runoff from melting snow and the melting of glacial ice, (Eqs. 7 and 9), which take into consideration runoff associated with liquid precipitation falling on the surface of a glacier within elevation band i, $P_{\text{liq},y,t,i,j=1}$. Considering first the liquid phase, the annual mass balance is:

$$\Delta V_{\text{liq},y,t=12,i} = \sum_{t=1}^{12} VP_{\text{liq},y,t,i,j=1} - \left(\sum_{t=1}^{12} VQ_{\text{snow},y,t,i,j=1} + \sum_{t=1}^{12} VQ_{\text{ice},y,t,i,j=1} \right) \quad (\text{m}^3) \quad (10)$$

If this balance is positive the implication is that some portion of the liquid water that has fallen within the elevation band has not been offset by liquid water leaving the band, and as a result, on net, there is a volume of liquid water free within the elevation band at the end of the hydrologic year. The mass balance for the snow phase at the end of the hydrologic year y is

$$\Delta V_{\text{snow},y,t=12,i} = \text{VSFinal}_{y,t=12,i,j=1} \quad (\text{m}^3) \quad (11)$$

expressed as a water equivalent. The total net accumulation of water within the ith Catchment during hydrologic year, y , expressed as a mass (ΔM) in units of g, is

$$\Delta M_{\text{water},y,t=12,i} = \left(\Delta V_{\text{liq},y,t=12,i} + \Delta V_{\text{snow},y,t=12,i}\right) \cdot \rho_{\text{water}} \cdot 100^3 \quad (\text{g}) \quad (12)$$

where ρ_{water} is the density of liquid water expressed in units of g/cm^3.

At the end of each year, we assumed that all water within a Catchment, i, is frozen and converted to ice. In this case the change in the volume of ice within the ith Catchment during hydrologic year, y, is

$$\Delta V_{\text{ice},y,t=12,i} = \frac{\Delta M_{\text{water},y,t=12,i}}{\rho_{\text{ice}} \cdot 100^3} \quad (\text{m}^3) \quad (13)$$

where ρ_{ice} is the density of frozen ice expressed in units of g/cm^3.

From the annual mass balance conducted on each of the m elevation bands containing ice at the start of a hydrologic year y, the overall change in the volume of glacial ice within a sub-watershed was estimated.

$$\Delta V_{\text{glacier},y,t=12} = \sum_{i=m}^{n} \Delta V_{\text{ice},y,t=12,i} \qquad (\text{m}^3) \tag{14}$$

Based the change in ice volume within each elevation band i in Eq. (14) it was possible to estimate the position of the point where the change in mass is essentially zero for the hydrologic year, or equilibrium line of accumulation (ELA).

2.2.4 Annual glacier geometry evolution

Based on the value of Eq. (14), 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. This is another case where we made a simplifying assumption in the interest of generality, 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 at the end of the hydrologic year y is:

$$A_{\text{glacier},y,t=12} = \sqrt[b]{\frac{V_{\text{glacier},y,t=0} + \frac{\Delta V_{\text{glacier},y,t=12}}{1000^3}}{c}} \qquad (\text{km}^2) \tag{15}$$

The next step was to assess the estimated change in the surface area of the glacier during the hydrologic year using Eq. (16).

$$\Delta A_{\text{glacier},y,t=12} = A_{\text{glacier},y,t=12} - A_{\text{glacier},y,t=0} \tag{16}$$

The assumption is that the change in surface area will be concentrated within the lowest elevation band containing ice, $i=m$, during the hydrologic year, within limits. Depending on the mass balance of the year, the storage in the glacier will be positive, negative or null. The final step in the annual adjustment to the glacial extent in a sub-watershed will be to compensate for change in the extent of glacial ice in the areas defining the non-glaciated portion of a particular elevation band i.

$$A_{y,t=12,i,j=2} = A_i - A_{y,t-12,i,j=1} \tag{17}$$

This WEAP glacier module uses only three parameters, T_0, a_{ice} and a_{snow} and provides a transient modelling framework for simulating the dynamics of glacier surface extension glacier melt water contribution to the outflow from each glaciated sub-watershed driven by time series of climatic input data.

2.2.5 Efficiency criterions

In order to test the validity of the different simulations scenarios and to calibrate the different parameters values, we use three statistics: (a) the Root Mean Square Error (RMSE); (b) the BIAS; and (c) the Nash-Sutcliffe parameter (Nash and Sutcliffe, 1970).

$$\text{RMSE} = \frac{1}{\overline{Q_\text{o}}}\sqrt{\frac{\sum_{i=1}^{n}(Q_{\text{s},i}-Q_{\text{o},i})^2}{n}} \tag{18}$$

$$\text{BIAS} = 100\left[(\overline{Q}_\text{s}-\overline{Q}_\text{o})/\overline{Q}_\text{o}\right] \tag{19}$$

$$E_f = 1 - \frac{\sum\limits_{i=1}^{n}(Q_{\text{s},i}-Q_{\text{o},i})^2}{\sum\limits_{i=1}^{n}(Q_{\text{o},i}-\overline{Q}_\text{o})^2} \tag{20}$$

Where $Q_{\text{s},i}$ and $Q_{\text{o},i}$ are simulated and observed outflow data for each time step i, and n=193 for the calibration period, n=168 for the validation period, and n=120 for the estimation of the monthly average values for either the calibration or the validation. For the RMSE, the smaller the number, the better the performance of the model is considered, with an RMSE of zero indicating a perfect fit between model and observed data.

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For the BIAS, over-prediction is indicated with positive values, while under-prediction is indicated with negative values. For the E_f, although it can range from minus infinity to 1. When E_f are beneath 0, the mean predicts better the variable than the model, when E_f is comprised between 0 and 1 the model is functioning with normal cases and if E_f equals to 1 the model is with the maximum efficiency.

3 Case study: the Rio Santa and the Cordillera Blanca

3.1 Study area

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 use of the water from the Rio Santa, which relies on both non-glacier and the glacier sources, is vital for the economy and livelihoods in the region. The economic activities in the watershed, starting at the high elevation and moving down to the ocean include (Chevallier et al., 2010).

- 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.
- Below 800 m, 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, thus

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considerably increasing the traditional irrigation areas of the main deltas of small coastal rivers.

In the context of both climate change analysis and sustained economic and social development in the basin, it would seem necessary to develop a modelling tool that captures the hydrologic functioning of the watershed along with the water management pursued to support human livelihoods and development.

Based on the presence of either a flow measurement gage for which data was available or a known point of water management control, the Rio Santa watershed was divided into 17 sub-watersheds as shown in Fig. 1. The main population centers in the upper watershed, in order decreasing population, are: Santa (390 171 hab.), Huaraz (143 415 hab.), Santiago de Chuco (57 526 hab.), Yungay (54 489 hab.), Caraz (52 845 hab.), Carhuaz (43 652 hab.), Recuay (18 126 hab.), Corongo (7786 hab.) according to the 2005 census. Water demand in these population centers was approximated in WEAP by assuming a total per capita water demand for urban and rural populations in each area.

3.2 Climatic settings

The regional climate is strongly marked by the mountain barrier of the Andes. In the tropical Andes the main source of precipitation comes from the Atlantic Ocean and the Amazon Basin. The later plays the role of recycling water via intense evapotranspiration and the principal transport mechanism 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 season during the austral winter (JAS). Along the whole South American's western coastal strip, the proximity of the South Pacific anticyclone and its accompanying subsidence, reinforced by the cold Humboldt current which flows parallel to the Pacific coast, generate a dry climate. Garreaud et al. (2003) gives a detailed description of climate in the tropical Andes.

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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^{-1} for the period 1967–1998. The weighted average for the entire Rio Santa watershed was 868 mm y^{-1}. 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 falls between $-7\,^{\circ}C\,y^{-1}$ (higher parts of the watershed) to $30\,^{\circ}C\,y^{-1}$ (lower parts of the watershed) for the period 1967–1998 with a weighted mean value of $8\,^{\circ}C\,y^{-1}$.

In summary, both the 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 more than 1500 mm y^{-1} at the Huascarán Glacier (Fig. 3).

3.3 Input data

3.3.1 Terrain and hydrologic data pre-processing

The DEM issued by the maps of the National Geographic Institute of Peru (IGM) (scale 1/100 000) was used to define sub-watershed above all the points where gauging of streamflow volumes, reservoirs, managed natural lagoons for hydroelectric production, points of water extraction, and points of water return exist. The DEM (cell size of 100 m) was also processed to define elevation bands within each sub-watershed, with a range of 700 m in the lower parts of the basin and 300 m in the higher parts of the basin in order to afford a greater level of detail in the zone occupied by glaciers (Table 1). The intersection between sub-watersheds and elevation bands constituted a WEAP catchment. The area of each catchment was calculated as well as the percentage of various land cover types within the catchment. The land cover data set was obtained from the Chavimochic project (ATA-INADE, 2002) and was reclassified form its original classification scheme into tundra, coastal plain, shrub and agriculture categories.

Two data sets on the spatial evolution of glaciated area were used: one for Artesoncocha sub-watershed alone (2001–2007) derived from Landsat images and another for the whole Rio Santa watershed (1969–1999) from an inventory published by Ames et al. (1989) based on analysis of 168 aerial photos. This later set was used to define initial glaciated area conditions. The different glaciated areas in the Rio Santa watershed are shown in the Fig. 3.

In order to characterize the human and agricultural water consumption in the Rio Santa watershed, we added water demand nodes 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.

3.3.2 Meteorological data pre-processing

Precipitation

As the objective of this study was to obtain a continuous simulation of the evolution of glaciers in the Rio Santa watershed, continuous climate time series were required for each of the catchments in the model. A total of 39 pluviometric stations are located within the Rio Santa watershed. The time-series of available data from the stations 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 Espinoza et al., 2009 for more details about this method). Data from other stations within a group were used to fill gaps in the record of individual stations. From these stations, an inverse distance squared interpolation scheme was used to generate a precipitation time series for each catchment. This analysis was done using Hydracess software (Vauchel, 2005) for the RVM and with ArcGIS for the spatial interpolation. Although precipitation in this watershed

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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 39 stations are evenly distributed in the watershed and thus provide a reliable departure point to obtain a dataset that can approximate the actual spatial variability of precipitation in the watershed.

Temperature, humidity and wind speed

Concerning temperature and humidity data, only one good quality, long, continuous time-series exists for the Rio Santa watershed, the Recuay station (9°50′ S, 76°20′ W). Continuous temperature data for each catchment was obtained using a temperature gradient of 0.6 °C/100 applied to the temperature observed at Recuay. For the humidity and wind speed, we assumed that the long-term monthly average time series at Recuay applied to all catchments. The simplicity of the interpolation of the temperature, humidity and wind speed for each sub-watershed was driven by the scarcity of the weather station data. Although the temperature gradient can vary, the classical range is given between 0.5 to 1 °C/100 m as a function of the atmospheric humidity. In order to simplify the modelling, we assumed that the gradient would be stable and equal to 0.6 °C/100 m as it is classically done for zones where the number of air temperature station is scarce. We recognize that the quality of the modelling would be improved by more spatially continuous information on actual climatic conditions, but the type of analysis we propose cannot wait until a perfect input data set is available.

4 Results

4.1 Calibration of the glacier module for the recent period 2000–2007

The first effort to calibrate the proposed glacier module focused on the well documented Artesoncocha sub-watershed (No. 9 on the Fig. 1). This watershed extends

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over 8.8 km^2 with an initial percentage of glacier coverage equal to 73%. Researchers from the IRD (Institut de Recherche pour le Developpement) in collaboration with the INRENA (Instituto Nacional de Recursos Naturales, a public entity of Peru dedicated on environmental studies) have studied the evolution of the glacier in the Artesoncocha since 2000 (Pouyaud et al., 2005). At the Artesoncocha streamflow gauging station, pluviometers and temperature sensors have been installed and maintained by researchers to continuously monitor the climatic conditions in the watershed. The calibration procedure was structured to understand the role of each glacier module parameter in the simulation of glacier evolution, a critical precursor to the effort to calibrate the glacier module for all of the glaciers in the Rio Santa Watershed.

The Artesoncocha sub-watershed is characterized by a vertical gradient of temperature and precipitation. For the period 2000–2007, conditions at the bottom of the sub-watershed between 4000 and 4400 meters above sea level (m a.s.l.), were on average 900 mm y^{-1} (total precipitation) and 5.9 °C (average temperature). At the top of the watershed between 5900 to 6200 m a.s.l., the annual averages are 1780 mm y^{-1} and −3.7 °C. 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). These suggest that generally the degree-day factor for ice is higher than the degree-day factor for snow and that the ranges are 1.3 to 11.6 mm d^{-1} °C^{-1} for snow and 5.5 to 20 mm d^{-1} °C^{-1} for ice (we scaled these daily values for use in our monthly time step model). To calibrate T_0, we assumed that the value fell somewhere between −2 °C and 2°C.

Monthly comparisons between simulated and observed outflow from the Artesoncocha subwatershed are presented in Fig. 4. Given that the available time-series was relatively short, all the data was used to calibrate the three glacier parameters T_0, a_{ice} and a_{snow} without considering a validation period. The optimized parameters obtained were 1.45 °C for T_0, 380 mm month^{-1} °C^{-1} for a_{snow} and 600 mm month^{-1} °C^{-1} for a_{ice}. The agreement between simulated and observed data is good (the Pearson correlation's coefficient is R^2=0.7 with $p \leq 0.01$) and the seasonal cycle is well represented by

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the model. Some discrepancies occur which are likely due to the fact that the conceptual monthly approach is not able to represent all physical processes involved in the hydrologic cycle of a glaciated area.

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

For the entire Rio Santa watershed, the calibration strategy was to calibrate the standard WEAP rainfall-runoff parameters for the Tablachaca and Corongo sub-watersheds as these lack glacier coverage (Table 2). The parameters obtained for non-glaciated subwatersheds were applied uniformly to the entire basin. Next, the calibrated glacier parameters obtained for Artesoncocha (see Sect. 4.1) were used to run the model for a calibration and a validation period. As monthly time series of precipitation and temperature were available for the period 1968–1999. The period 1970–1984 was set as the calibration period and the 1985–1999 period was used for validation (in some watersheds some years of data were missing, so the calibration and validation periods change accordingly). During the calibration period small adjustments of the Artesoncocha glacier parameters were allowed to capture improve the calibration across the basin. The efficiency criterions results for RMSE, Bias and E_f for all subwatersheds are presented in the Table 3.

Figure 5a shows the correspondence between simulated (continuous think line) and observed (discontinuous thick line) stream flow at La Balsa gauge station between September 1969 and August 1997. La Balsa gauge station includes the aggregated response of most glaciated subwatersheds in the Rio Santa system and it represents a critical water management time series as it lies at the point of diversion to the Cañon del Pato hydroelectric facility. The performance of the model in capturing the structure of the observed hydrograph at La Balsa is notable.

In order to see if the model captures the inter-annual variations in flow, we plotted simulated and observed annual flows for La Balsa gauge station during the years 1969–1997. Comparing simulated and observed values (Fig. 5b), we can be confident of the ability of the model to represent the inter-annual variations. The long term trend is well represented and the magnitude is captured. In Fig. 5b El-Niño events are plotted in grey (Smith et al., 2000). We note that generally, the El-Niño years are associated with high flows as for example the years 70–71 or 82–83 but more average flows can also be observed during these climatic events (90–91). One point should be mentioned, for the extremely high flows (for example during the year 82/83 or 93/94) the observed data is very highly influenced by extreme daily events which are inherently difficulty to measure because of the precision of the calibration curve.

Figure 6 shows that good agreement between observed and simulated outflows was achieved for Chuquicara, Quillcay and La Balsa sub-watershed. Nevertheless, some discrepancies exist for Paron watershed and Puente Carretera sub-watershed (see Table 3). For Paron, the historical operation of the regulated glacier lake was probably not fully captured in the model. For Puente Carretera, the observed hydrologic response likely includes changes in the river geomorphology at this meandering, gravel dominated, lower slope reach which are not present at higher elevation sub-watersheds. Further effort could have been made to develop sub-watershed specific model parameters to improve the calibration on a sub-watershed by sub-watershed basis, but this would by necessity be done in an ad hoc manner that would potentially limit the robustness of the calibration. Again, as the management focus of the study was potential impacts at the Cañon del Pato diversion, no effort was made to correct these more small scale and local discrepancies at this time.

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 4). This value is similar to the 37% value presented by Vergara et al. (2007) based on analysis of observed climatic and hydrologic data. Seasonally, the model suggests that melting glacier contribute 30% of streamflow at La Balsa during the wet season (December, January, February) and 67% during the dry

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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.

The model allows the computation of interflow and baseflow for each elevation band and each sub-watershed. Table 4 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 the ice area covers more than 20% of the total area, we note that the proportion of glacier melt water is higher during the dry season. For groundwater, the seasonal importance varies depending the conditions in each sub-watershed. If we consider the mean proportion of groundwater accretions in the total outflow we found 32% during the humid season and 35% during the dry season. Figure 6 show the annual dynamic of these water balance components for Chuquicara, La Balsa and Quilcay.

The model allows for an estimation of the proportion of river flow originating as glacier runoff (snow and ice melt water) and groundwater accretions. The results are compiled in the Table 4. For groundwater, the sub-watershed with lowest aquifers contribution are LLanganuco and Paron with 11% during the period 1969–1999. These lower values can be explained by the high altitude of these sub-watershed where the aquifers are of small lateral extent. At the scale of the entire Rio Santa watershed, the mean proportion of groundwater accretions is 30% of total annual discharge volume (period 1969–1999). The glacier melt water of annual discharge volume is directly linked with the ice area of the sub-watershed.

The proportion of glacier runoff in the total runoff is comprised between 77% for Llanganuco to 0% for Tablachaca (see Table 4). At La Balsa gauge station and during the period 1969–1999, the glacier melt water was equal to 38% of total annual discharge volume. For the Querococha sub-watershed the value is 15%, which is in accordance with the 10% that was calculated in previous study (Mark and Seltzer, 2003). At the scale of total watershed the results of this study are also in agreement with those

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presented by Mark and Seltzer in 2003 who estimated that more than 20% of the annual discharge volume to the Rio Santa in the Callejon de Huaylas comes from the glacier melt water. Based on all of this information one can consider that the model captures the hydrological setting in the Rio Santa system reasonably well.

4.3 Simulation of the glacier area evolution since the 70's

In addition to simulating river flows, we would like to be confident that our glacier module captures observed changes in glaciated area in the Cordillera Balance. An analysis of the trends in glacier area evolution for the Rio Santa watershed indicates good correspondence between simulated and observed data (Fig. 7 and Table 5). The model captures the overall change in area between both the 1970–1987 (characterized by rapid glacier retreat) and 1987–1999 (characterized by less pronounced retreat). Note that the 1970 glaciated areas are the same for observed and simulated cases since these values were used as the initial conditions for the model runs.

Looking at glacier area evolution of individual sub-watersheds, the model provides good correspondence with observed data (periods 1970–1987 and 1987–1999), particularly for the sub-watersheds with larger initial glacier area cover (Fig. 7). When looking at some of the smaller sub-watersheds like Colca, Pachacoto and Quitaracsa the correspondence between observed and simulated data is reduced. One explanation for the lower correspondence for small glaciers is the fact that the observed data has an intrinsic error on the order of ±5% of the total glacier area. In addition, 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.

This observation is evident in Fig. 7 where 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 some times under-predicting and some other times over-predicting.

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4.4 Simulation of the electric power at Cañon del Pato

Climate impacts are anticipated to change the hydrology in high mountain regions and understanding these impacts is essential to plan and implement adaptation measures in the hydropower sector. Given that one of the most important water management features of the Rio Santa watershed is the use of water for hydropower production at Cañon del Pato, an assessment was made of the ability of the model to simulate hydropower production. 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 is a fairly rough characterization of the hydropower system, which could be improved. Nonetheless, the model seems to reflect the actual management of the system reasonably well. During the dry winter months all of the water in the river is diverted through the canal at an average rate of about 40 m^3/s, while during the wet summer months flows can exceed 150 m^3/s on average with the maximum diversion capacity being utilized (Fig. 10).

The current installed capacity of the Cañon del Pato hydropower plant was put in place in 1998. Since the modelling period is 1969–1998, it as possible to obtain only one year of simulated generation results for comparison to the reported total capacity of 1484 GW-h of the plant. The model output for the 1998 water year was 1120 GW-h, 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 the the key features of the Cañon de Pato plant are being 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.

To demonstrate the utility of the model in the study of the effects of climate change on hydropower production, we developed two simplified climate scenarios under which the calibrated WEAP application could be run. Using climate data from WCRP CMIP3

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multi-model database project (www.earthsystemgrid.org) for the Caraz, Paron, Huaraz, and Collota stations, month by month standard deviations from the mean precipitation and temperature data from 16 global circulation models run under two carbon emission scenarios, A1b and B1, where used to define two scenarios: a wet-warmer scenario (+15% increase in precipitation and +0.5 °C in temperature) and a dry-warmest scenario (−10% decrease in precipitation and +2 °C in temperature). We used the historic conditions as the reference case upon which we imposed the changes anticipated in our scenarios and ran the model to investigate potential changes the hydrology of the Cañon del Pato diversion (not shown here). Both scenarios provide a slight increase in monthly average flows during the wet season (summer and fall) with respect to the reference historical climate for the 30 year modeling 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 increase watershed yield, while the dry-warmest scenario presented similar base flow magnitudes than the reference scenario because the increase in +2 °C in temperature has the capacity to melt higher elevation glaciers during the winter. Looking at the results of these scenarios shows how the WEAP application can be used to evaluate possible adaptation strategies in the region.

5 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 simulate the hydrology with a scarce availability of meteorological and hydrological data which has high spatial variability similar to the temperature and precipitation gradients observed in the Rio Santa watershed. Several assumptions need to be made and interpolation methods need to be implemented in

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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, a model of glacier evolution within a rainfall-runoff modelling framework, to simulate the hydrology of glaciated watersheds and the water management implications. In this paper, glacial melt water and groundwater flows were computed taking into account the spatio-temporal variations in climate at the scale of a fairly large river basins.

This is critical for in addition to the hydrologic dimension of the model, the WEAP software provides the ability to represent and simulate different water uses and water system elements. 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 will focus more heavily on the water management impact and adaptation aspects of potential climate change projections. To accomplish this, the next step will be to simulate the implications of climate change on glaciated watersheds in the tropical Andes using future scenarios derived from global climate models.

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Table 1. Altitude bands for the different sub-catchment and notification of the presence or absence of glacier for each band. The spacing of altitude is accurate for the higher zone (300 m) in order to report correctly the glacier behaviour.

Elevation Bands		Low level (m a.s.l.)	High level (m a.s.l.)	Mid point (m)	Spacing (m)
Land use	1	0	500	250	500
	2	500	1200	850	700
	3	1200	1900	1550	700
	4	1900	2600	2250	700
	5	2600	3100	2850	500
	6	3100	3600	3350	500
	7	3600	4000	3800	400
Land use and Glacier	8	4000	4400	4200	400
	9	4400	4700	4550	300
	10	4700	5000	4850	300
	11	5000	5300	5150	300
Glacier	12	5300	5600	5450	300
	13	5600	5900	5750	300
	14	5900	6200	6050	300
	15	6200	6500	6350	300
	16	6500	6800	6650	300

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Table 2. Land uses parameters for the non glacial part and parameters values for the glacier module for all the watersheds.

Parameter	Unit	Value
Land use parameters (part without glacier)		
Crop coefficient		1.1
Root zone capacity	mm	80
Root zone conductivity	mm/mes	500
Deep water capacity	mm	500
Deep water conductivity	mm/mes	50
Runoff Resistance Factor		
Cultivos		4
Matorral		3.2
Tundra		0.8
Planicie Costera		0.8
Flow Direction	% horizontal	0.68
Z1	%	35
Z2	%	35
Glacier parameters		
T_0	°	1.45
a_{snow}	mm month^{-1} °C^{-1}	380
a_{ice}	mm month^{-1} °C^{-1}	600

Table 3. Criterions for the calibration and the validations periods. The results are given for the principal sub-watersheds.

Sub-watershed	Calibration Period	n	RMSE	BIAS	E_f	Validation Period	n	RMSE	BIAS	E_f
1 – La Recreta	1969–1979	120	0.77	39%	0.63	1979–1989	120	0.87	44%	0.50
2 – Pachacoto	1969–1979	120	0.43	−9%	0.64	1979–1989	120	0.43	−13%	0.55
3 – Querococha	1969–1979	120	0.39	1%	0.72	1979–1989	120	0.36	−20%	0.74
4 – Olleros	1969–1979	120	0.48	12%	0.53	1979–1989	120	0.38	−4%	0.63
5 – Quillcay	1969–1979	120	0.31	9%	0.66	1979–1989	120	0.31	−2%	0.64
6 – Chancos	1969–1979	120	0.44	21%	0.28	1979–1989	120	0.29	−4%	0.63
7 – Llanganuco	1969–1979	120	0.46	36%	0.64	1979–1989	120	0.92	−15%	0.13
8 – Paron	1969–1979	120	1.70	6%	0.25	1979–1989	120	0.33	−16%	0.10
9 – Artesoncocha	*	*	*	*	*	*	*	*	*	*
10 – Colcas	1969–1979	120	0.47	25%	0.19	1979–1989	120	0.44	4%	0.23
11 – Los Cedros	1969–1979	120	0.29	4%	0.33	1979–1989	120	0.38	−18%	0.19
12 – Quitaracsa	1969–1979	120	0.32	−8%	0.65	1979–1989	120	0.42	−24%	0.19
13 – La Balsa	1969–1979	120	0.41	3%	0.70	1979–1989	120	0.39	1%	0.72
14 – Corongo (Manta)	1969–1979	120	0.56	−13%	0.53	1979–1989	120	0.63	−10%	0.41
15 – Chuquicara	1969–1979	120	0.47	5%	0.69	1979–1989	120	0.40	1%	0.77
16 – Tablachaca (Condorcerro)	1969–1979	120	0.79	28%	0.56	1979–1989	120	0.67	16%	0.61
17 – Puente Carretera	1969–1979	120	0.62	2%	0.62	1979–1989	120	0.89	−46%	0.11

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Table 4. Results for simulated and observed runoff, subterranean part and glacier part for the calibration and the validation period (1969–1999). Station on the Santa River are shaded with grey. DJF (December, January, February) – wet season; JJA (June, July, August) – dry season. Groundwater outflow is the sum of simulated interflow and baseflow.

Sub-watershed	Area	Ice Area	% area ice in 1970	DJF total Outflow	JJA total Outflow	DJF ice Outflow	JJA ice Outflow	DJF groundwater Outflow	JJA groundwater Outflow	Glacier meltwater (snow+ice) of annual discharge	Groundwater part of annual discharge volume
	km^2	km^2	%	m^3/s	m^3/s	%	%	%	%	%	%
1 – La Recreta	231	0.12	0.05	7.39	0.83	0.0	0.0	30.4	57.4	0.01	34
2 – Pachacoto	203	21.76	10.72	5.83	1.64	28.0	67.3	29.5	27.9	35	30
3 – Querococha	58	3.55	6.12	2.62	0.57	10.6	36.3	34.2	49.6	15	37
4 – Olleros	175	18.91	10.79	7.70	2.05	25.0	60.8	30.2	32.0	32	31
5 – Quillcay	245	46.17	18.84	10.98	3.76	40.9	76.5	28.0	21.1	50	27
6 – Chancos	265	71.15	26.87	13.04	5.41	53.2	83.8	22.0	14.3	61	20
7 – Llanganuco	83	35.80	43.03	4.21	2.25	70.7	93.2	13.3	6.3	77	11
8 – Paron	31	20.00	64.02	1.95	1.00	73.9	93.4	10.4	5.6	79	11
9 – Artesoncocha	9	6.27	71.41	*	*	*	*	*	*	*	*
10 – Colcas	234	45.89	19.60	9.27	3.58	46.2	79.9	25.1	17.6	53	23
11 – Los Cedros	106	23.00	21.65	4.24	1.74	45.8	74.9	22.8	15.8	52	21
12 – Quitaracsa	310	14.13	4.56	12.51	3.58	11.9	30.2	25.2	25.2	15	25
13 – La Balsa	4696	420.77	8.96	129.69	38.70	30.8	68.0	33.9	28.3	38	33
14 – Corongo (Manta)	562	5.03	0.89	13.40	2.10	3.5	16.2	51.6	76.0	5	55
15 – Chuquicara	9540	442.65	4.64	228.47	57.98	18.8	48.6	44.1	42.6	23	44
16 – Tablachaca (Condorcerro)	3179	1.66	0.05	56.61	9.09	0.1	0.1	66.8	97.5	0	71
17 – Puente Carretera	10 776	443.00	4.11	247.30	70.04	17.8	45.7	44.6	43.2	25	40

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Table 5. Simulated and observed data of glaciers evolution between 1970 and 1999.

Total Areas (km^2)	1970*	1987	1999	% Change 70–87	87–99	70–99
Simulated	507	411	391	−19%	−5%	−23%
Observed	507	396	387	−22%	−2%	−24%

* Observed data error ±25 km^2

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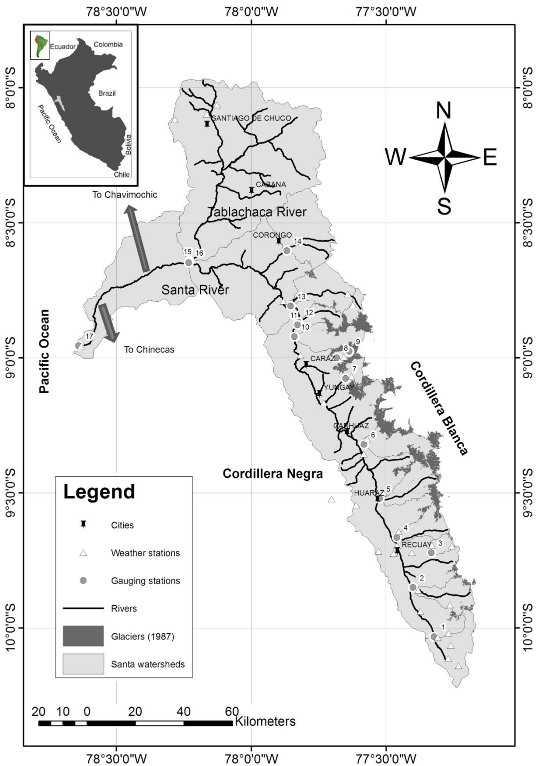

Fig. 1. Study area with the delimitation of the watersheds, the position of the modern glaciers, the cities, the principal rivers, the weather stations, the gauging stations. The numbers indicate each sub-watershed : 1 – La Recreta; 2 – Pachacoto. 3 – Querococha; 4 – Olleros; 5 – Quillcay; 6 – Chancos; 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.

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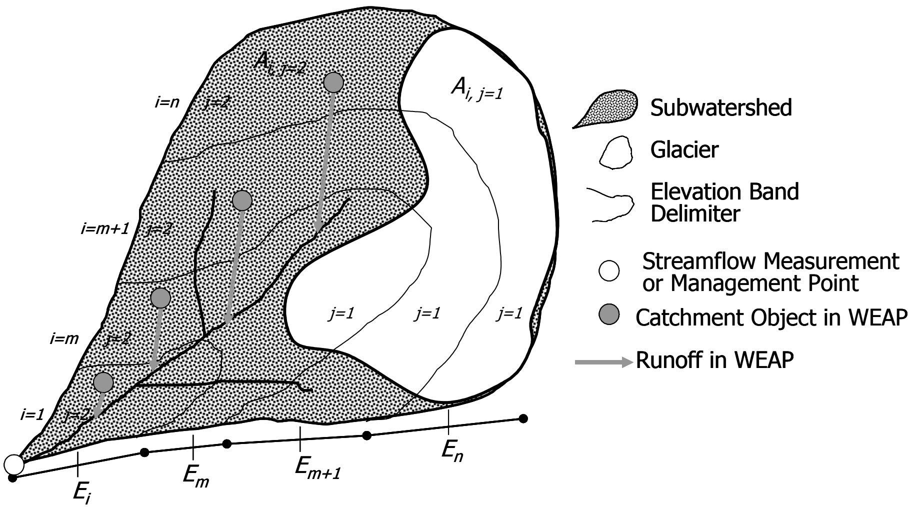

Fig. 2. Schematic of a subwatershed with glacier, dividing each elevation band, i, into either a glaciated ($j=1$) or non-glaciated ($j=2$) portion.

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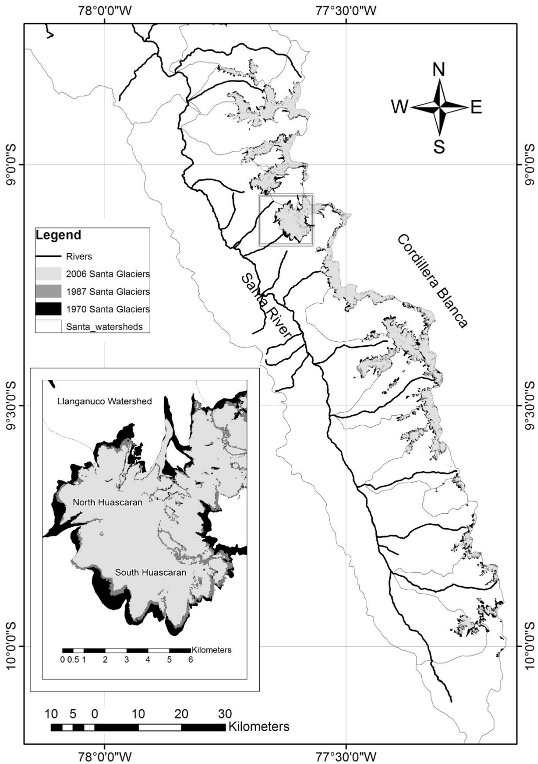

Fig. 3. Evolution of the glacier extension between the 3 periods 1970, 1987 and 2006 (with a zoom on the Huascarán Massif).

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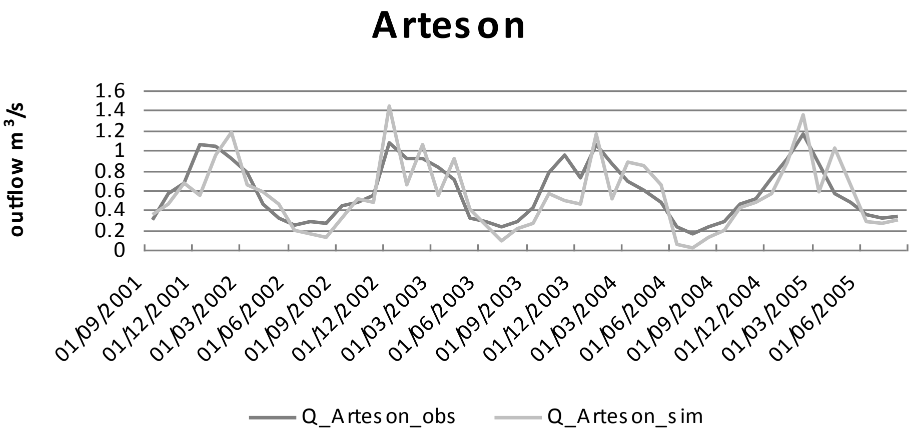

Fig. 4. Outflow at Artesoncocha gauge station: comparison between observed and simulated values between September 2001 and August 2005, Pearson correlation of observed and simulated values: R^2=0.7p≤0.01.

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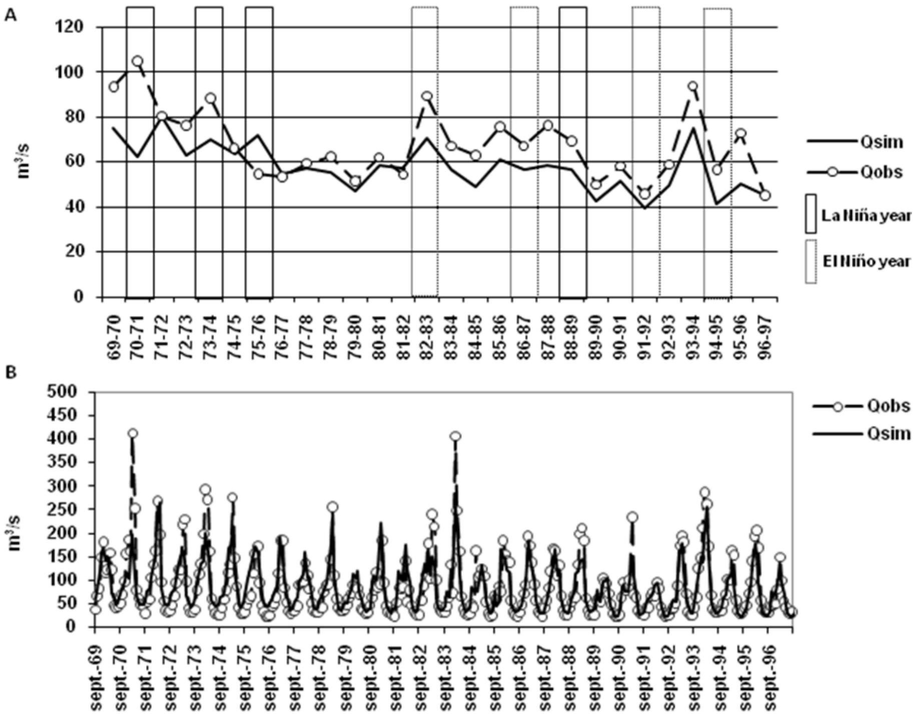

Fig. 5. (A) Correspondence between, simulated (continuous think line) and observed (discontinuous thick line) stream flow at Balsa gauge station between September 1969–August 1997 the lowest pour point before the Cañon del Pato hydroelectric facility, which includes the aggregated response of most glaciated subwatersheds in the Rio Santa basin. Pearson correlation of observed and simulated values: $R^2 = 0.74 p \leq 0.01$. **(B)** Interannual variability of simulated and observed streamflow at La Balsa gauge station between the hydrologic years 1969/1970 and 1996–1997. Distribution of the Niño and Niña events (Smith et al., 2000).

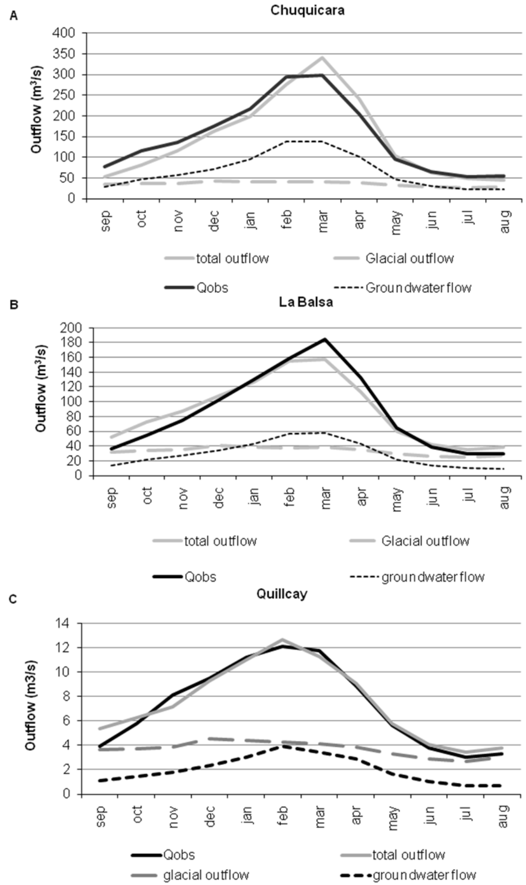

Fig. 6. Mid-mensual calculated and simulated streamflows of 3 subwatersheds (**(A)** Chuquicara, **(B)** La Balsa and **(C)** Quillcay) during the period 1969–1998. For each calculated sub-watershed streamflow are indicated the total streamflow (continuous grey line), the glacial part (dash line) and the groundwater part (black dash lines).

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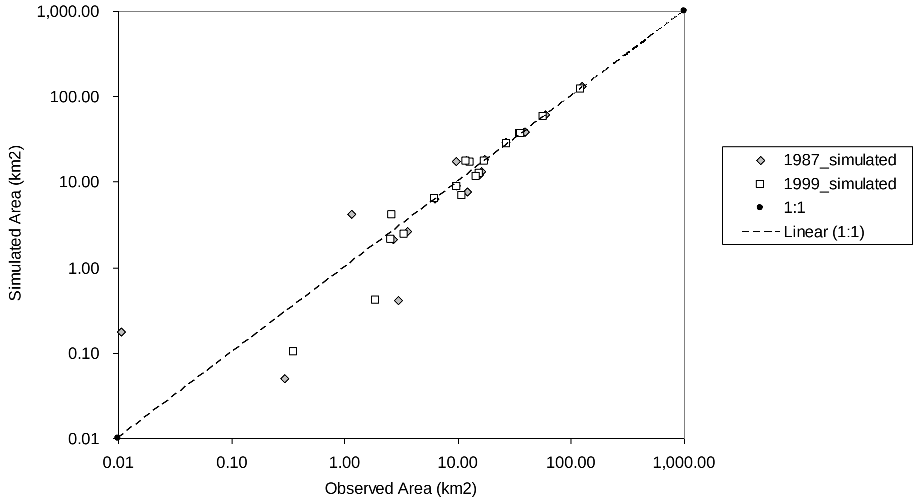

Fig. 7. Scatter plot graph with observed versus simulated glacier areas for the two periods (1987 and 1998).

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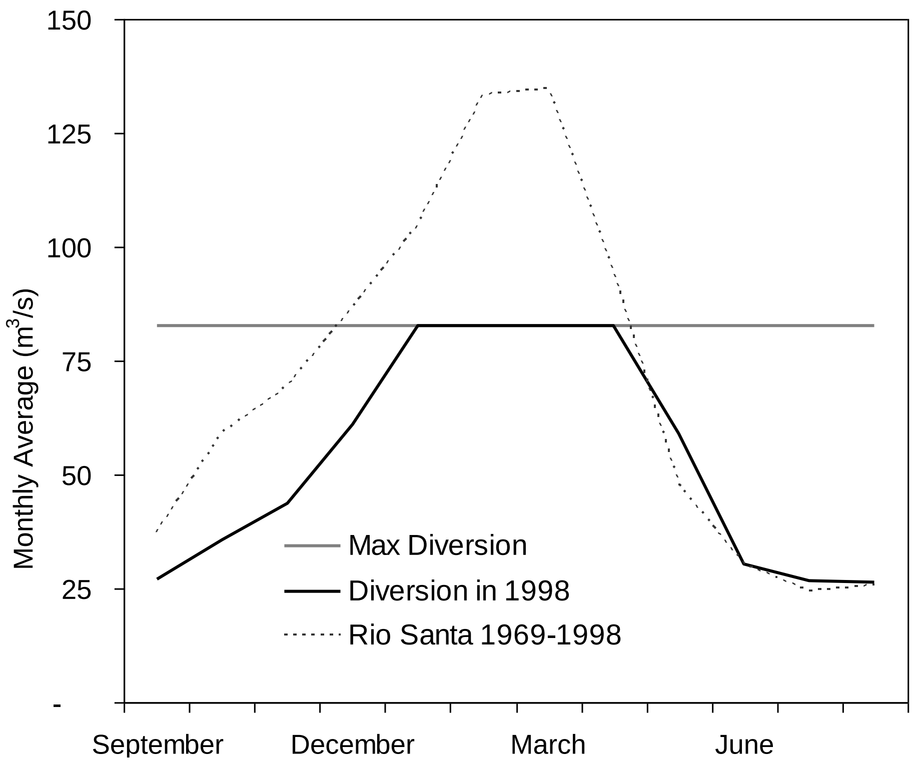

Fig. 8. A. Monthly average streamflow calculated through the Cañon del Pato diversion in 1998. Maximum flow diversion (gray line) is compared to flow diversion in 1998 (black line) and to the average flows in the Rio Santa at the point of diversion of La Balsa for the modelling period 1969–1998 (dotted line).

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