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Modelling the water balance in the glacierized Parón Lake basin (White Cordillera, Peru)

WILSON SUAREZ[1,2], PIERRE CHEVALLIER[2], BERNARD POUYAUD[2] & PAULINA LOPEZ[2]

1 *Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), Dirección General de Hidrología, Jr. Cahuide 785 Jesús María, Lima 11, Peru*
wil_suarez@hotmail.com

2 *IRD, UR Great Ice, Maison des Sciences de l'Eau, BP 64501, F-34394 Montpellier Cedex 5, France*

Abstract The White Cordillera (northern Peru), with a glacial surface of 631 km^2, is the largest glacierized mountain range in the Tropics. Due to the lack of physical data from most of its sub-basins, it is difficult to build a physical model to estimate the water resource flowing from the glaciers at the present time and *a fortiori* for the future. The most recent GCM simulations indicate a significant increase in the temperature and an accelerated shrinking of the glaciers. Consequently, we sought a model that would be based on the data available within instrumented sub-basins. A theoretical/conceptual water model makes it possible to quantify the local glacier contribution, which could then be applied to the other non-instrumented sub-basins. A total of 43.6% of Parón Lake's instrumented sub-basin area (47.4 km^2) corresponds to glacial surfaces. Within this sub-basin, a smaller watershed (8.8 km^2), called Artesón, with 72.9% glacierized area, has been accurately observed over a 5-year hydrological period (September 2000–August 2005). This information allowed us to calibrate the model over the Artesón sub-basin. The parameters obtained were applied to the entire Parón basin using the same modelling approach.

Key words water balance; glacial lake; Peru; snow melting line; tropical glacier; water resource

Modélisation du bilan hydrique du bassin versant englacé du Lac Parón (Cordillère Blanche, Pérou)

Résumé Avec une surface glaciaire de 631 km^2, la Cordillère Blanche (Nord Pérou) est la plus vaste chaîne de montagnes englacée sous les Tropiques. L'absence de données physiques sur la plupart de ses sous-bassins rend toutefois difficile de construire un modèle physique d'estimation des écoulements provenant de ses glaciers, pour la période actuelle et *a fortiori* pour le futur. Les plus récentes simulations des MGCA indiquent une augmentation significative de la température et une diminution accélérée des glaciers. Nous avons donc recherché une modélisation basée sur les données disponibles de sous-bassins instrumentés. Un modèle théorique/conceptuel a d'abord permis de quantifier la contribution locale des glaciers. Dans une étape ultérieure, il sera applicable aux sous-bassins non instrumentés de la région. 43.6% de la surface du bassin instrumenté du lac Parón (47.4 km^2) est englacée. A l'intérieur de ce sous-bassin, le bassin emboîté plus petit d'Artesón (8.8 km^2), avec 72.9% de surface englacée, a été observé avec précision durant cinq années hydrologiques (de Septembre 2000 à Août 2005). Ces informations ont permis de caler le modèle sur le sous-bassin d'Artesón. Les paramètres obtenus ont été appliqués au bassin entier de Parón en utilisant la même approche de modélisation.

Mots clefs bilan hydrique; lac glaciaire; Pérou; ligne de fonte de la neige; glacier tropical; ressource en eau

INTRODUCTION

The presence of glaciers above an average elevation of 4800 m a.s.l. is one of the main characteristics of the high tropical mountain regions. These glaciers produce a perennial glacial runoff throughout the year. During the wet season (December–March for the Southern Hemisphere), the ablation by the melting process is greater than the ablation observed during the dry and cold season by the sublimation process (Kaser, 1999). Taking into account the present conditions induced by the global climate change, because of the permanent ablation process, the tropical glaciers are more affected than glaciers in middle or high latitudes, where ablation alternates with accumulation following the different seasons (Favier *et al.*, 2004). One of the problems faced by high-altitude hydrology in the tropical regions is the quantification of the glaciers' contribution to the overall water resource available for human activities. This issue results mainly from the lack of suitable geographical sites to measure the contribution of the glaciers to the hydrological cycle using accurate recording instruments (Francou & Pouyaud, 2004). For this reason, we decided to study the water balance using a theoretical/conceptual model with the following objectives: (a) to

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quantify the balance, and (b) to analyse the hydrological behaviours of the high-altitude tropical basins.

STUDY AREA AND DATA AVAILABILITY

Description of the study area

The north/south-oriented Rio Santa basin in northern Peru is located between two mountain ranges, the White Cordillera and the Black Cordillera (Fig. 1). It covers a total area of 11 910 km^2. The Black Cordillera, on the west side of the Rio Santa central valley, has a dry climate and no glaciers. On the east side of the Rio Santa central valley, the White Cordillera, higher in altitude and with a more humid climatic influence, contains the largest surface of glaciers within the Tropics, with a total glacial area of 631 km^2. In the White Cordillera, the Rio Santa basin comprises 19 hydrological sub-basins. From these 19 sub-basins, the discharges of only two (Parón and Llanganuco) have been observed over relatively long periods of time since 1971 (Pouyaud *et al.*, 2005).

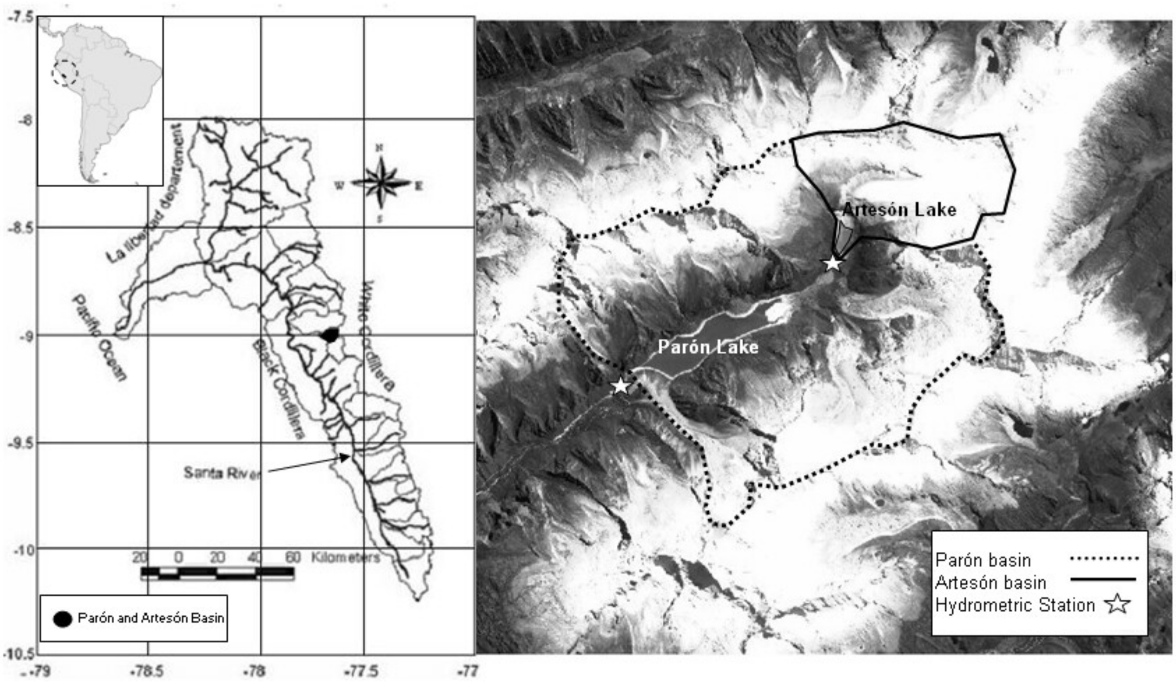

Fig. 1 Location of the Parón and Artesón basins (Spot 5 image, August 2003).

The White Cordillera belongs to a mountain range formed by several basins of glacier origin, most of which have formed lakes as a consequence of glacial retreat. Some of these lakes are controlled artificially for power supply or farming irrigation purposes. The largest of them is the Parón Lake (8°59′S, 77°41′W, 4150/4190 m a.s.l.). Its basin covers an area of 47.4 km^2, 43.6% of which is glacierized. In the upper part of this basin, a smaller lake forms the outlet of a sub-basin, called the Artesón basin. It has an area of 8.8 km^2, 72.9% of which is glacierized (Fig. 1). The overflow of Artesón Lake runs naturally into Parón Lake.

In the White Cordillera, the annual retreat of the glaciers is globally estimated as between 15 and 18 m/year, depending on the glacier (Gomez & Quijano, 2003). For tropical glaciers below an elevation of 5000 m a.s.l., the retreat has been accelerating since the early 1980s (Gaffen *et al.*, 2000).

The outflows of the Parón Lake are regulated by one hatch located at the entry of a tunnel bored through rock in the right bank of the terminal moraine. The water discharges are managed for the generation of electricity at the Huallanca hydropower plant, built downstream on the Rio Santa (Suarez, 2003). The entire structure (hatch + tunnel) artificially maintains the level of the lake several dozen metres below its natural level, and also serves as a protection against a sudden outburst of the terminal moraine and possible catastrophic flooding.

Data collection

The geographical information comes from an accurate local map on the 1/100 000 scale, a digital terrain model with a 50-m resolution (kindly provided by Prof. G. Kaser, Innsbruck University, Austria) and a SPOT 5 satellite image with a 10-m resolution dating from August 2003, provided by the Centre National d'Etudes Spatiales (CNES), France. Table 1 gives the most useful geographical information on the study zone.

Table 1 Geographical information for the basins studied.

	Complete Parón Lake basin	Artesón basin	Parón basin
Total area (km^2)	47.4	8.8	38.6
Glacierized area (km^2)	20.7	6.4	14.2
Non-glacierized area (km^2)	26.7	2.4	24.4
Elevation, max (m a.s.l.)	6395	6025	6395
Elevation, min (m a.s.l.)	4251	4723	4251

Table 2 Temperature gradients for different seasons and for the hydrological year.

	Dry	Wet	Transition	Year
Gradient (°C/100 m)	0.54	0.49	0.53	0.52

The meteorological and hydrological data were collected from September 2000 until August 2005 from three different sources:

(a) the weather station located on the frontal moraine of the lake and owned by the Duke Electric Power Company, which manages of the Huallanca hydropower plant;
(b) several automatic sensors, installed in partnership, by IRD (Institut de Recherche pour le Développement, France) and INRENA (National Institute of Natural Resources, Peru) on the Artesón Glacier and on the outlets of the Artesón and Parón lakes; and
(c) rainfall gauges monitored by SENAMHI (National Meteorology and Hydrology Service of Peru) over the Rio Santa basin.

Most of the data obtained from Duke Energy and SENAMHI are available at a monthly time step. The automatic sensors give data at an infra-daily time step, but daily and monthly averages were used in this study.

In order to extrapolate the temperature data over the whole study area, two meteorological stations were used, located in each basin: at Lake Parón's operational house (elevation: 4200 m a.s.l.) and on Artesón Glacier (4980 m a.s.l.). An interpolation between the two stations allowed us to calculate a temperature gradient, considering the common climatic criteria. With temperature data available since 2000, we used a temperature gradient:

(a) for each seasonal period: wet (November–March), dry (May–August), and transitory (April, September and October); and
(b) for the hydrological year (from 1 September to 31 August).

Table 2 summarizes the values obtained. It is interesting to note that these coefficients are systematically lower than the commonly used values of 0.6°C or 0.65°C/100 m (Francou, 1993; Schaefli, 2005).

For precipitation, the monitoring equipment installed cannot distinguish rainfalls from snowfalls. The good correlation (R^2 = 0.89) between the observed precipitation values at Parón (elevation: 4200 m a.s.l.) and on Artesón Glacier (4980 m a.s.l.) allowed us to extrapolate this data with the elevation. For the period before 2000, when observed data was not available, we used the air temperature values given by the NCEP-NCAR reanalysis data bank, according to the good results obtained by numerous authors in this region (e.g. Francou & Pouyaud, 2004).

For evapotranspiration, we used the values given at a monthly time step for the Rio Santa basin from Tarazona (2005), who assessed the evapotranspiration in the Peruvian Andes applying Penman's method modified by García.

METHODS

In this study, discharges were simulated using the conceptual semi-distributed modelling approach based on Schaefli *et al*. (2005).

A monthly time step was chosen for two reasons: (a) most of the data was available at this time scale; and (b) the monthly time step is quite efficient for the end-users of the water resource (agriculture, water supply and hydropower).

Basically, the Parón and Artesón basins are divided into two areas, glacierized and non-glacierized, with different hydrological processes in each area. The glacierized area was hypothesized to be constant during the study period lasting several years. The two areas were distinguished using a SPOT 5 satellite image from August 2003.

Both parts of the basin were divided into 200-m elevation bands using a digital terrain model. For the Parón and Artesón basins, Fig. 2 shows the distribution of the areas of each elevation band, showing the glacierized area. Precipitation (*P*) and temperature (*T*) were derived for each band, using the interpolation procedure explained in the previous section.

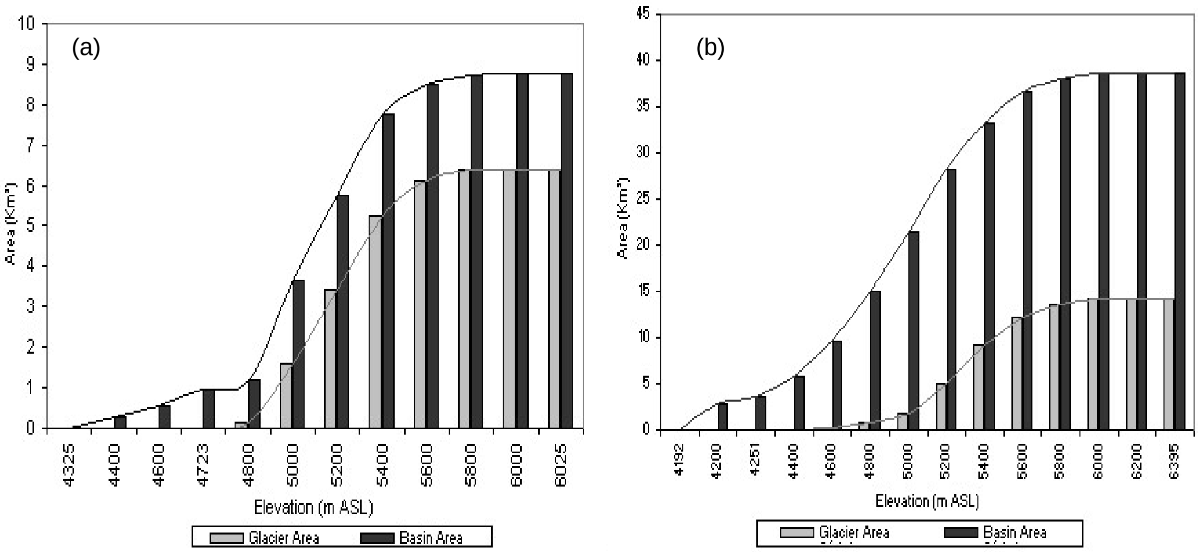

Fig. 2 Hypsometry of the (a) Artesón and (b) Parón basins, built with a discretization of 200 m in elevation. The glacierized areas are represented in grey. The lowest elevations for the glacierized area in the Parón and Artesón basins correspond to 4723 and 4251 m a.s.l., respectively.

Glacierized area

The computation of glacier melt requires knowing the energy exchange at the glacier–atmosphere interface. Empirical models, such as the degree-day or temperature index types of models, would require data that were not available to the authors. Therefore, we decided to use an approach similar to the degree-day method, but dividing the glacier into a contributing (the glacier's lower section) and a non-contributing section (the glacier's upper part). The permanent snowline on the glacier is a significant indicator of the combined effect of variables, temperature and precipitation, and it was used as a limit (Fig. 3), dividing the glacierized area into contributing and non-contributing zones. It is assumed that the division runs along a contour line and depends on the air temperature, which constitutes a parameter of calibration.

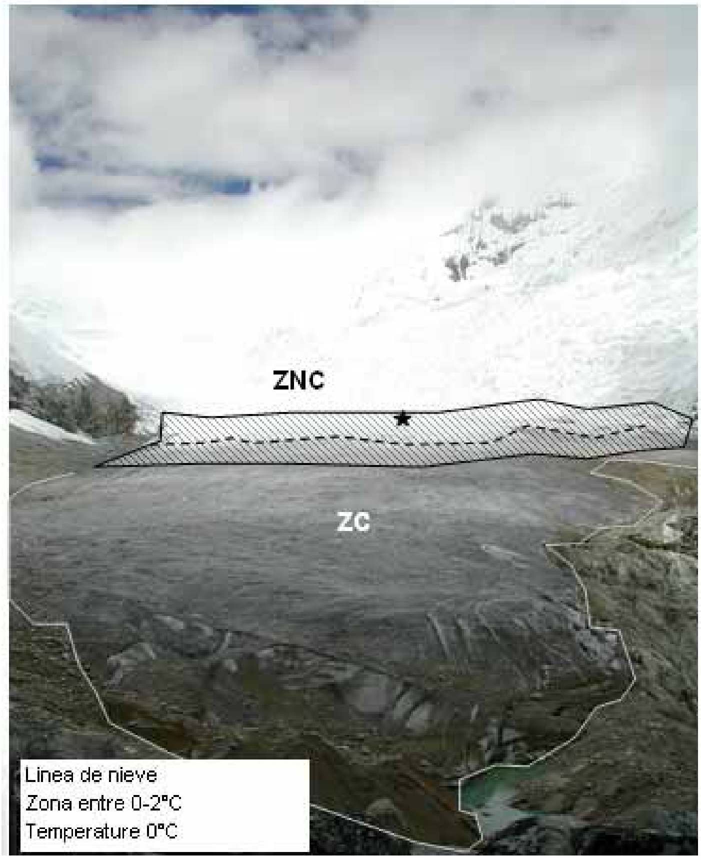

Fig. 3 Artesón Glacier; photo taken in April 2005. The permanent snow line divides the glacier into a contributing (CZ) and non-contributing zone (NCZ) at an elevation close to 5100 m a.s.l.

Schaefli *et al*. (2005) estimated that this temperature, $T_{calibration}$, varies between 0 and 2°C in the Swiss Alps. According to L'Hôte *et al*. (2005), this behaviour can be applied in the Central Andes, which present very similar conditions to the Swiss Alps in terms of the threshold temperature distinguishing rainfall from snowfall.

This limit, characterized by the $T_{calibration}$ value, is also used to separate liquid from solid precipitation. Above the limit, the precipitation is solid (snowfall, P_{liq}) and its contribution to glacial runoff is considered negligible; below the limit, the precipitation is liquid (rainfall, P_{sol}) and it contributes to glacial runoff. Then we have the following relations considering a monthly time step:

$$\begin{array}{lll} \text{If } T_{air} > T_{calibration} & P_{liq} = P & P_{sol} = 0 \\ \text{If } T_{air} < T_{calibration} & P_{liq} = 0 & P_{sol} = P \end{array} \qquad (1)$$

where P (mm/month) is the total amount of precipitation in 1 month (mm/month) and T_{air} (°C) is the air temperature at a given elevation.

In short, we assume that on the glacierized areas of the basin, only the exposed ice section of the glacier contributes to the melt and constitutes the contributing zone of the glacierized area.

Schaefli *et al*. (2005) used the model proposed by Baker *et al*. (1982), which simulated the glacial runoff considering three different parallel reservoirs that represent snow, ice and firn. In our case, with the adopted simplification, only the ice reservoir was considered and the general equation is as follows:

$$Q_{\text{ice}}(\text{ti}+1) = Q_{\text{ice}}(\text{ti}) \cdot e^{-\frac{\text{ti}+1-\text{ti}}{K\text{ice}}} + \left[P_{\text{liq,ice}}(\text{ti}+1) + M_{\text{ice}}(\text{ti}+1) \cdot T(\text{ti}+1)\right] \cdot \left(1 - e^{-\frac{\text{ti}+1-\text{ti}}{K\text{ice}}}\right) \quad (2)$$

where $Q_{\text{ice}}(\text{ti})$ (mm/month) is the glacial discharge during the time ti; K_{ice} is a time constant of the reservoir; $P_{\text{liq,ice}}$ (mm/month) is the liquid precipitation on the glacierized contributing zone; $T(\text{ti})$ (°C) is the average air temperature in the glacierized contributing zone; and M_{ice} (mm/°C) is a factor of ice melting. The parameters K_{ice} and M_{ice} are subject to calibration.

Non-glacierized area

In order to estimate the runoff generated in the non-glacierized areas, two versions of the monthly generic model of the GR family (Edijatno *et al*., 1999), GRM, were used. The two input variables were precipitation (P) and evapotranspiration (E). The global and conceptual monthly GRM generic model was chosen, on the one hand, for its extreme simplicity and heavy-duty applicability, and, on the other hand, for its popularity within the French community of hydrologists.

We decided to test two versions of the model, one with two calibration parameters (GR2M) and the other with only one parameter (GR1M), in large part because the pertinence of applying such models within the context of high tropical mountains was unknown. The double test was an opportunity to observe whether the version with two parameters gave better results than the version with only one parameter.

Figure 4 schematizes the functioning of the GR2M version, with two calibration parameters:

(a) X1, an evapotranspiration adjustment factor;

(b) Kapa, representing the water volume, which can be stored in the basin's soils.

Detailed explanations on the modelling procedure and equations are given in Edijatno *et al*. (1999) and in Schweblin (2004). Figure 4 includes the glacial runoff, which is collected with the runoff of the non-glacierized area directly into the lake, whose outflow discharges were recorded.

The GR1M version uses only the Kapa parameter, with no other adjustment of the meteorological parameter.

APPLICATION

Calibration

Summarizing the explanation given in the previous section, the model proposed needs four or five calibration parameters, depending on the version of GRM used:

(a) a temperature, $T_{\text{calibration}}$ (°C), varying within the interval [0–2]°C;

(b) an ice melting factor, M_{ice} (mm/month °C), varying within the interval 104.6–552.2 mm/month °C, according to the hydrological balance during the 2001–2003 period (Suarez, 2003);

(c) a time constant for the ice reservoir, K_{ice} (expressed in (time unit)$^{-1}$); and

(d) the Kapa and X1 parameters of the GRM model, the second one not used in the one-parameter version.

The most commonly used criterion in hydrological modelling applications is the Nash criterion (Nash & Sutcliffe, 1970). The mass conservation criterion, is also very widely used to assess the error on the total runoff volume during long time steps (Schweblin, 2004).

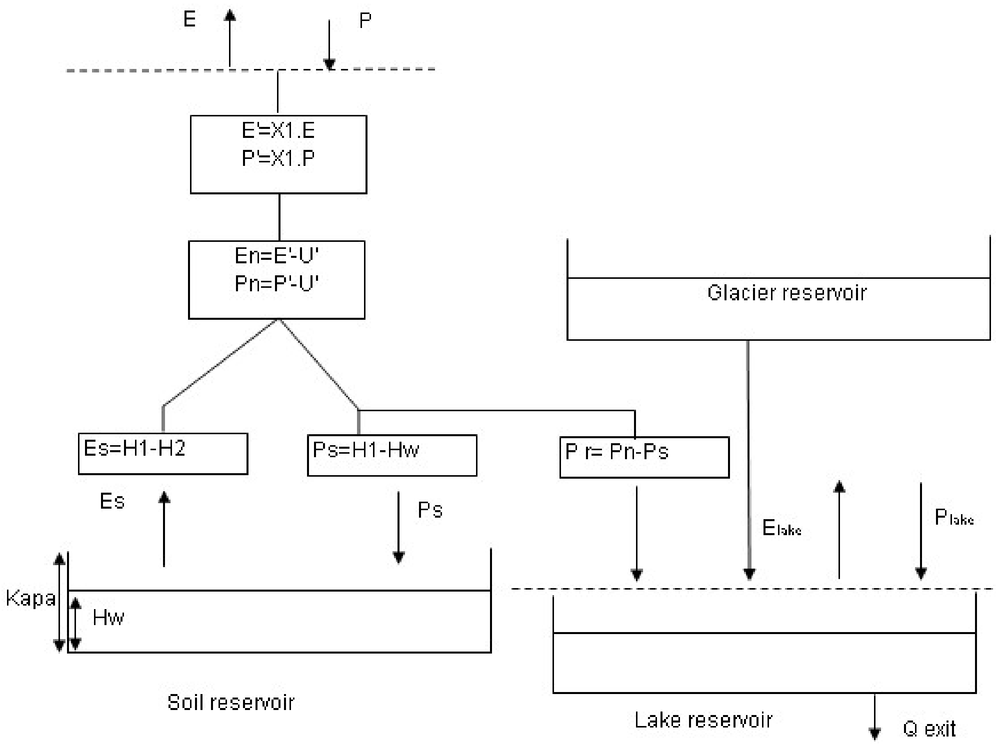

Fig. 4 General chart of the GR2M model variation. The GR1M model is similar but it has variations depending on production (it does not have a data correction parameter) and the drainage of the soil reservoir depends on the fill-up rate of the soil reservoir (Kapa) and net precipitation (Pn).

RESULTS AND DISCUSSION

Artesón basin

The model was first applied to the Artesón sub-basin, with a data series beginning in September 2000 and ending in August 2005, completing five hydrological years.

We carried out 12 runs on this basin, searching for the parameters best simulating the discharges. They were divided into two groups of six runs:

Group (a): the location of the line that separated the contributing zone from the non-contributing zone was considered to vary for each season (wet, dry and transition); and

Group (b): the line that separated the contributing from the non-contributing zone remained at the same location during the entire year, but varied from one year to another.

In each group, three runs (01–03 and 07–09) used the GR1M model and the three others (04–06 and 10–12) used the GR2M model. For each group, four runs were divided into two sections (September 2000–February 2003 and March 2003–August 2005) to calibrate and validate the model. In the two remaining runs, the entire period was used for calibration.

The results of each run are presented in Table 3. The values of the respective parameters obtained for all the runs are collected in Table 4. For both groups, (a) and (b), runs with similar results based on both criteria presented significant differences in the parameter values given in Table 4. However, a physical explanation for those differences does not clearly stand out and the equifinality phenomenon (Beven & Freer, 2001) of the parameter sets is probably the main factor; therefore, we did not attempt a detailed analysis of these parameters.

The Nash criterion ranged within the intervals [0.72; 0.84] and [0.71; 0.88] for the (a) and (b) groups, respectively. The mass balance criterion ranged within the intervals [0.84; 1.17] and [0.77; 1.12] for the (a) and (b) groups, respectively. In general, the values of both criteria were highly significant, but it is difficult to decide which model is more efficient, since these results are so

Table 3 Results of the model runs.

Model		Sep. 2000–Aug. 2005		Sep. 2000–Feb. 2003		Mar. 2003–Aug. 2005	
		Nash	Balance	Nash	Balance	Nash	Balance
Group (a) runs:							
GR1M	01	0.791 c	0.995 c	-	-	-	-
	02	-	-	0.806 c	0.995 c	0.726 v	1.164 v
	03	-	-	0.657 v	0.830 v	0.831 c	1.012 c
GR2M	04	0.800	0.995	–	-	-	-
	05	-	-	0.820 c	0.991 c	0.739 v	1.154 v
	06	-	-	0.716 v	0.862 v	0.836 c	0.999 c
Group (b) runs:							
GR1M	07	0.753 c	0.991 c	-	-	-	-
	08	-	-	0.766 c	0.946 c	0.725 v	1.085 v
	09	-	-	0.713 v	0.774 v	0.882 c	0.989 c
GR2M	10	0.762 c	1.007 c	-	-	-	-
	11	-	-	0.780 c	0.983 c	0.690 v	1.121 v
	12	-	-	0.722 v	0.944 v	0.778 c	0.990 c

c - calibration; v - validation.

Table 4 Values of the parameters.

Run		$T_{calibration}$ (°C)	M_{ice} (mm/month/°C)	K_{ice} (mm)	Kapa	X1
(a)	01	1.48	290	430	1.03	-
	02	1.46	320	500	0.93	-
	03	1.67	310	400	1.25	-
	04	1.55	300	240	1.07	0.40
	05	1.42	305	250	0.93	0.20
	06	1.60	285	250	1.30	0.40
(b)	07	1.52	325	500	0.55	-
	08	1.50	330	500	0.70	-
	09	1.52	300	500	0.50	-
	10	1.50	300	300	0.60	0.38
	11	1.45	320	300	0.76	0.29
	12	1.65	325	250	0.55	0.55

close to each other. To compare the output efficiencies from the different runs, we used a Cartesian diagram where the X axis represents the Nash criterion values and the Y axis represents the mass balance criterion. The optimum point corresponds to Nash = 1 and Balance = 1. The shorter the distance between this optimum point and the point representative of each run, the more efficient the model was (Fig. 5).

Table 5 gathers the distances of each one of these points to the optimal point. It can be concluded that for the (a) group, runs 03 and 06, and for the (b) group runs 09 and 12, showed the best calibration parameters. When analysing only the calibration values, it can be observed that Run 09 (group (b)) produced the best result. For the validations, Run 12 presented the best result and its calibration was quite good compared with the best run (09).

Since Run 09 and Run 12 are in group (b), we can infer that using an annual gradient instead of seasonally adapted gradients does not reduce the simulation's efficiency. It also shows that using the two-parameter version of GRM in the non-glacierized area is preferable.

Figure 6 shows the result of Run 12 in standardized units and the air temperature measured on Artesón Glacier (4980 m a.s.l.) for the following variables: simulated and observed discharge at the Artesón Lake outlet, temperature measured on the Artesón Glacier (4980 m a.s.l.) and precipitation (average rainfall on the ZC area, under the line determined by the value of $T_{calibration}$) over the Artesón basin.

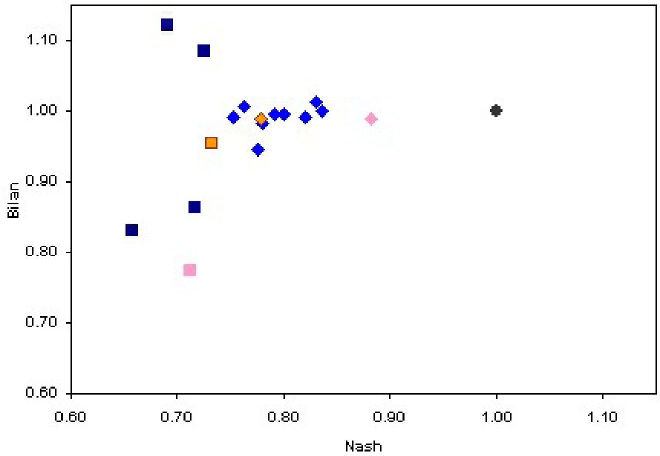

Fig. 5 The Nash criterion *vs* the mass balance criterion. The black circle indicates the point of maximum efficiency (ideal); the diamonds represent the calibrations and the squares the model's validations. Run 09 values are presented in grey (best value for calibration) and Run 12 values in grey outlined in black (best value for validation). For this last run, the distance between calibration and validation is minimal.

Table 5 Distances of each run related to the most optimal point and standard deviation. The best values are in bold.

Run	Calibration	Validation	σ
01	0.21		
02	0.20	0.32	0.08
03	0.17	0.38	0.15
04	0.20		
05	0.18	0.30	0.09
06	0.16	0.32	0.11
07	0.25		
08	0.23	0.29	0.04
09	**0.12**	0.37	0.17
10	0.24		
11	0.22	0.33	0.08
12	0.22	**0.27**	**0.03**

σ: standard deviation.

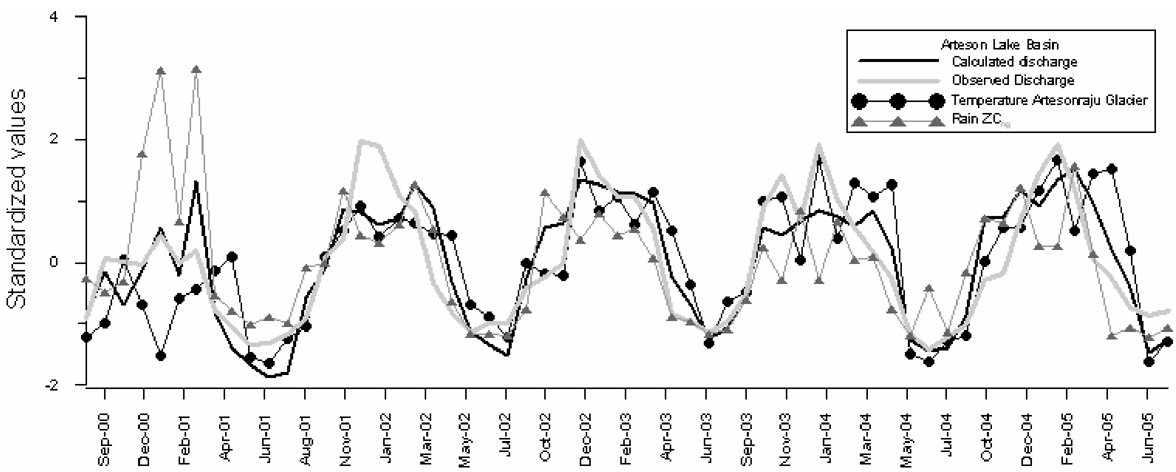

Fig. 6 Results of Run 12. Comparison of standardized values for the following variables: simulated and observed discharge at the Artesón Lake outlet, temperature measured on the Artesón Glacier (4980 m a.s.l.) and precipitation (average rainfall on the ZC area, under the line determined by the value of T calibration) over the Artesón basin.

The monthly outflow discharge observed for Artesón Lake was quite similar to the temperature curve, but the simulated discharge does not follow the peaks very well. This can be attributed mainly to the time variability of the precipitation, which is not well represented by monthly values.

In addition, it is important to note that during the hydrological year 2000–2001, lower discharges were recorded than during the other years studied. This is due to the lower temperatures caused by a La Niña event (Favier *et al.*, 2004) and by the lower elevation of the contour line dividing the contributing zone from the non-contributing zone.

Parón Lake basin

In order to apply the same modelling approach to the discharges entering Parón Lake, which includes the Artesón sub-basin, we used the simplest method: $T_{calibration}$ on an annual basis (group (b)), version GR2M of the model, calibrated over the complete study period. This option corresponds to the parameters obtained with Run 12 on Artesón (Nash = 0.78 and Balance = 0.99).

Nevertheless, the discharges observed at the outlet of Parón tunnel were controlled at the hatch. Consequently, the following observations were used jointly to reconstruct the natural discharges observed entering Parón Lake since September 1992:

(a) the lake water levels, recorded since September 1992;
(b) the hatch opening values, recorded by the operator since September 2000;
(c) the balance (precipitation–evaporation) over the lake;
(d) the measurements of discharges, taken at the outlet of the tunnel to calibrate the entire device.

This analysis resulted in the following equation with a satisfactory correlation coefficient ($R^2 = 0.82$):

$$Qr = -0.70 \times V + 1.29 \quad (3)$$

where Qr is the reconstituted monthly mean natural discharge entering Parón Lake (in m^3/s); and V the variations in the volume of Parón Lake (in m^3/s), excluding the case of a lake's level below the intake level.

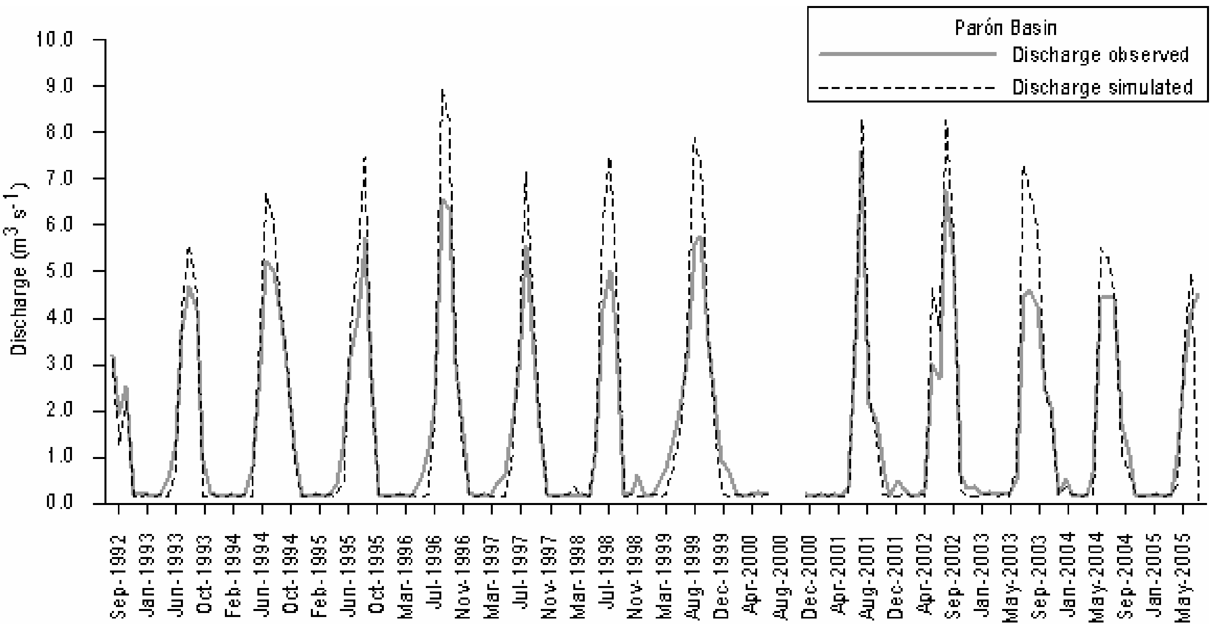

Fig. 7 Comparison between the observed (reconstruction: see explanations in the text) and simulated discharges entering Parón Lake. The simulation is based on the method and parameters obtained with Run 12 on the Artesón sub-basin.

Comparing the reconstructed discharges and the simulated discharges entering Parón Lake, the criterion values are quite good: Nash = 0.80 and Balance = 0.91 over the period November 2000–August 2005, and 0.87 and 1.08 for the period September 1992–August 2005.

Figure 7 compares both curves of monthly discharges during the entire period (September 1992–August 2005). A gap can be noted between July and October 2000, caused by anomalies or missing data on the lake water levels in the Duke Energy Company's operations book. It can be noted that the simulated peak values are always higher than the measured values, which is caused by a permanent leakage problem with the hatch, well identified, but practically speaking, impossible to repair.

CONCLUSIONS

The model's performance is acceptable considering that only two main input variables were used (precipitation and temperature). Though the evapotranspiration parameter, estimated at a regional scale, is essential in the water balance, it is less important here in the modelling process than the other two variables because of the conditions of the high-altitude environment, where its variability has a low significance.

The next steps of this study will attempt to apply this method and its parameterization in two directions:

(a) extending the simulation to the entire Rio Santa basin, taking into account all the glacierized sub-basins of the right bank (Fig. 1);

(b) evaluating the consequences of global warming over the coming decades on the basis of the IPCC scenarios (Gallopín & Rijsbermann, 2000; Nakicenovic & Swart, 2000). The climate data will come from the outputs of the atmospheric models (GCM).

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REFERENCES

Baker, D., Escher-Vetter, H., Moser, H., Oerter, H.,& Reinwarth, O. (1982) A glacier discharge model based on results from field studies of energy balance water storage and flux. In: *Hydrological Aspects of Alpine and High-Mountain Areas* (ed. by J. W. Glenn), 103–112. IAHS Publ. 138. IAHS Press, Wallingford, UK.

Edijatno, Nilo de Oliveira, N., Yang, Z., Mahlouf, Z. & Michel, C. (1999) GR3J: a daily watershed model with three free parameters. *Hydrol Sci. J.* **44**(2), 263–277.

Beven, K. J. & Freer, J. (2001) Equifinality, data assimilation and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *J. Hydrol.* **249** 11–29.

Favier, V., Wagnon, P. & Ribstein, P. (2004) Glaciers of the outer and inner tropics: A different behaviour but a common response to climate forcing. *Geophys. Res. Lett.* **31**(16), L16403.

Francou, B. (1993) *Hautes montagnes, passion d'explorations*. Masson, Paris, France.

Francou, B. & Pouyaud, B. (2004) Metodos de observacion de glaciares en los Andes Tropicales: mediciones de terreno y procesamiento. Report 01, IRD, France.

Gaffen, D. J., Santer, B. D., Boyle, J. S., Christy, J. R., Graham, N. E. & Ross, R. J. (2000) Multidecadal changes in the vertical temperature structure of the tropical troposphere. *Science* **287**(5456), 1242–1245.

Gallopín, G. C. & Rijsberman, F. (2000) Three global water scenarios. *Int. J. Water* **1**(1), 16–40.

Gomez, J. & Quijano, J. (2003) Retroceso del Frente Glaciar Gajap. Pastoruri y Broggi Cordillera Blanca (Perú). Report 01, INRENA, Peru.

Kaser, G. (1999) A review of the modern fluctuations of tropical glaciers. *Global Planet. Change* **22** 93–103.

L'Hôte, Y., Chevallier, P., Coudrain, A., Lejeune, Y. & Etchevers, P. (2005) Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps. *Hydrol. Sci. J.* **50**(6), 989–997.

Nakicenovic, N. & Swart, B. (2000) *Emissions Scenarios*. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

Nash, J. E. & Sutcliffe, J. V. (1970) River flow forecasting through conceptual models. *J. Hydrol.* **10**(3), 282–290.

Pouyaud, B., Zapata, M., Yerren, J., Gomez, J., Rosas, G., Suarez, W. & Ribstein, P. (2005) Devenir des ressources en eau glaciaire de la Cordillère Blanche. *Hydrol. Sci. J.* **50**(6), 999–1021.

Schaefli, B. (2005) Resources: application to a glacier-fed hydropower production system in the Swiss Alps. PhD Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland.

Schaefli, B., Hingray, B., Niggli, M. & Musy, A. (2005) A conceptual glacio-hydrological model for high mountainous catchments. *Hydrol. Earth System Sci.* **9**, 95–109.

Schweblin, M. (2004) Modélisation conceptuelle de dynamiques lacustres sur l'altiplano andin. IRD, France. Mémoire d'Ingénieur école d'Hydraulique et de Mécanique de Grenoble, Grenoble, France.

Suarez, W. (2003) Bilan hydrique d'un système lacustre de haute montagne: le bassin Paron (Cordillère Blanche–Pérou). Mémoire DEA Université Montpellier 2, Montpellier, France.

Tarazona, E. (2005) Generación de descargas mensuales en subcuencas de la cuenca del Rio Santa utilizando el método de Lutz Sholz. PhD Universidad Nacional Agraria La Molina, Lima, Pérou.

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