HYDROLOGICAL PROCESSES
*Hydrol. Process.* **18**, 939–957 (2004)
Published online 3 February 2004 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.1339

# Flow modelling in a high mountain valley equipped with hydropower plants: Rio Zongo Valley, Cordillera Real, Bolivia

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## Abstract:

Water management modelling of a hydroelectric system in a tropical high mountain context is presented. The study zone and the hydraulic network are described and the water management strategy analysed. Three different models are combined to describe the complexity of the specific hydrometeorological context: the spatial distribution of the climatic data over the river basin, the surface energy balance influence on the runoff production of a river basin and the surface flow transfer modelling through a hydraulic system. The atmospheric forcing spatial distribution is derived from the available climatic data records. The runoff production on the catchment's slopes is simulated using the land-surface scheme ISBA. The system dynamics tool Vensim® is used to simulate the hydraulic dynamics in the hydropower plants system. A short description of the three modelling methods is given, followed by the description of the coupled model construction. The simulation results of the ISBA land-surface scheme on both a non-glacial an a glacial sub-basin during a 17 month period are presented. After pointing out the necessity of the water management model to simulate the river discharge at the outlet of the basin, the main reservoirs, simulated water level variations are shown. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS Andes Cordillera; hydraulic and hydrologic modelling; hydropower plant; surface scheme; system dynamics; tropical glacier

## INTRODUCTION

Water management requires understanding both the hydrological processes and the user's management of the hydraulic devices used for the collecting, routing and storage of water resources. To achieve the modelling objective, it was decided to differentiate these two factors from one another and simulate both separately with the level of detail in the method depending on the study context and/or priorities.

To understand better the consequences of glacier volume decrease (Francou *et al*., 1995; Ribstein *et al*., 1995a) and climate variability impact on the high mountain water resources of the Andean Cordillera (Bolivia, Chile, Ecuador and Peru), the French Research Institute for Development (IRD) started a study in close cooperation with the Bolivian Power Company (COBEE) and the Hydrology and Hydraulics Institute of the University San Andres in La Paz. For this purpose, it was of interest to build a water management model in a valley containing several hydropower plants installed in a cascade along the main river. These plants are supplied by a complex hydraulic network made of intakes, channels, tunnels, pressure pipes, siphons and reservoirs for which technical characteristics must be integrated in the model. This paper presents a method to simulate the complex relation between the hydrological processes and the hydraulic dynamics. The ISBA land-surface scheme (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) is combined with a system

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*Received 15 May 2002*
*Accepted 13 February 2003*

dynamics tool called Vensim®. The chosen method allows: (1) the testing of the detailed and well-validated ISBA land-surface scheme in an extreme meteorological context; (2) the construction of an operational tool to optimize the water management strategy.

After a general description of the study zone and the hydroelectric system, the modelling method is detailed in order to show how the hydrological processes and the hydraulic devices (i.e. the ISBA land-surface scheme and the system dynamics tool) have been linked and how their dynamics were simulated. Finally, the modelling results are presented, and both the model's performance and the methodology are discussed.

## GENERAL CONTEXT

### *Geomorphology and climate*

The Rio Zongo Valley (16 °S, 68 °W) is on the eastern part of the Andean chain, about 30 km to the north of La Paz, capital of Bolivia. This chain constitutes a natural barrier between a sedimentary high plateau (Altiplano) and the Amazonian plain. Summits surrounding the valley reach altitudes between 5000 and 6100 m (Huayna Potosi, 6088 m). Small glaciers, whose melting supplies the Rio Zongo, cap some of them.

A metamorphic substratum with granodiorite intrusions is observed. The glacial erosion resulted in moraine formations on the higher part of the valley and fluvio-glacial slope deposits at the slope bottom. These formations control the hydrological processes of the valley (Caballero, 2001; Caballero *et al.*, 2002).

The climate is defined by two regional factors, namely the relief and the position of the intertropical convergence zone (ITCZ), whose oscillations cause a very marked rainy season variability in the eastern Andean area (Aceituno, 1988; Bourges and Hoorelbecke, 1992; Ribstein *et al.*, 1995b; Vuille *et al.*, 2000):

- southern winter—May to September, dry and cold season;
- southern summer—November to March, hot and wet season.

The melt water from several small glaciers (Zongo, Charquini and Huayna Potosi) covering the higher peaks of the basin provokes a seasonal variability of the flow different from that imposed by rain. Tropical glaciers usually provide more water than the rainfall contribution during the rainy season and maintain a continuous discharge even in the dry season. This behaviour is due to the characteristic simultaneous occurrence of ablation and accumulation periods for tropical glaciers (Francou *et al.*, 1995; Ribstein *et al.*, 1995a; Wagnon *et al.*, 1999; Sicart *et al.*, 2001).

### *Power supply equipment*

The morphology of the Rio Zongo valley (3550 m of difference in altitude for a 40 km distance) has allowed the building of a complex hydroelectricity system, operated by the Bolivian Power Company (COBEE), to supply the city of La Paz, where the population exceeds one million inhabitants.

The system is composed of ten hydroelectric power plants, installed in series, with a total capacity of 174·6 MW (Figure 1). The collection of water is done through intakes on the rivers and reservoirs, from which water is routed, by channels or tunnels, towards the pressure pipelines of the hydroelectric power plants.

Several reservoirs located in the high part of the system are used to store water during the rainy season and release it in the dry season to support the hydropower production. These operations drive an efficient but empirical strategy for water management in the system, both at the seasonal and daily scales.

### *The Llaullini basin*

The study zone consists of the upper part of the Zongo Valley, the so-called the Llaullini basin (Figure 1). Its outlet at Llaullini station drains a 95 $km^2$ basin area, and corresponds both to the only water level recorder

 

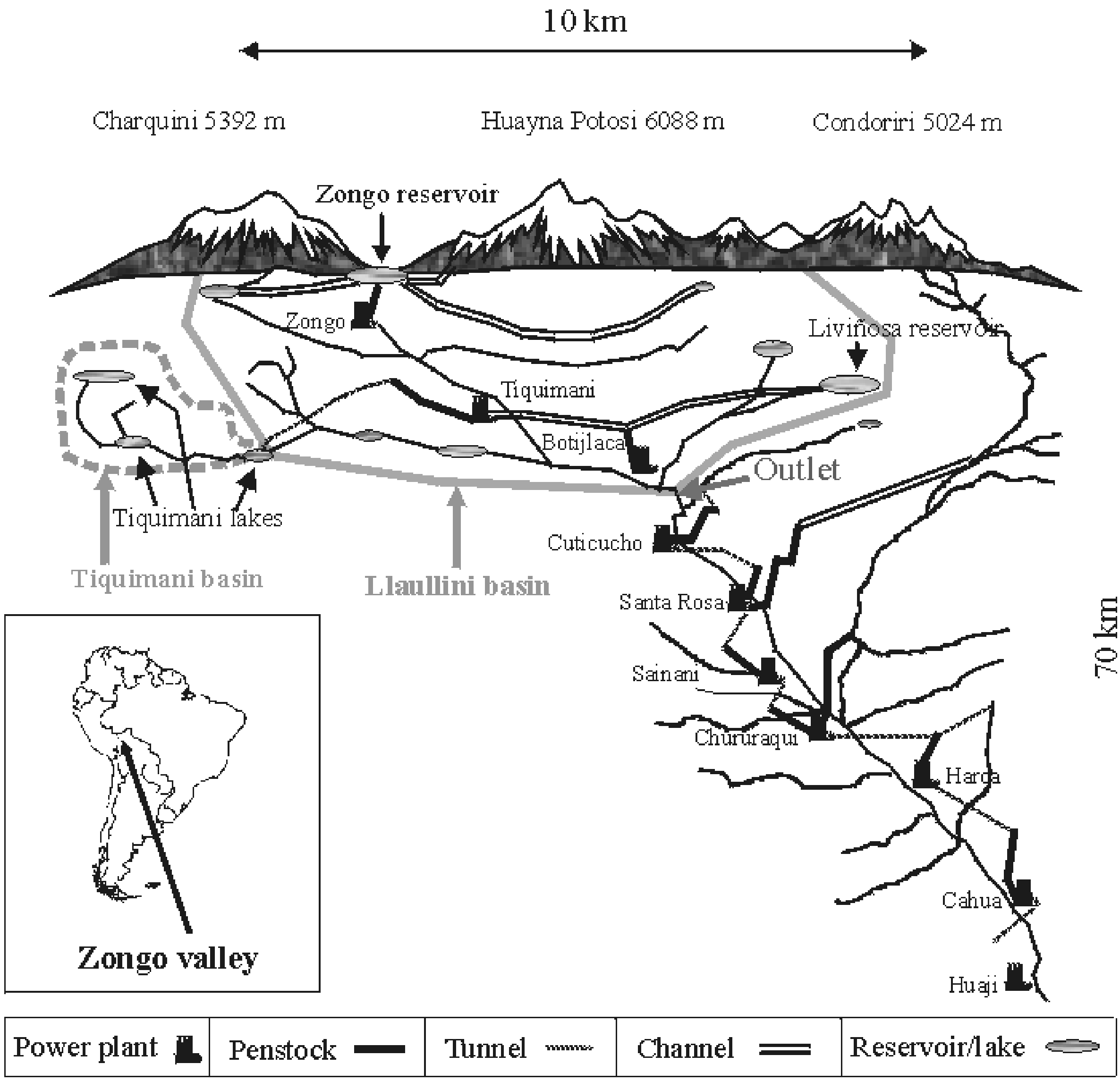


Figure 1. Schematic map of the Zongo valley hydroelectric system (reproduced with permission from COBEE, 1999)

available on the Rio Zongo and to a point where all the upstream water is flowing through (there is no hydroelectric device water uptake). Consequently, it is assumed that this station records the whole of the Llaullini basin flow.

Three hydroelectric power plants are included in this basin: Zongo, Tiquimani and Botijlaca. The first one is supplied by the Zongo reservoir, which mainly drains the glacial catchment's water. The second one uses stored water brought by tunnels and channels to the plant from the contiguous Tiquimani river valley. The third one receives water from the Rio Zongo and from two other valleys (Taypikhuchu and Liviñosa) on the western side of the basin. The three plants' power production depends on the water management in the reservoirs (mainly Zongo and Liviñosa reservoirs) and on the intakes from the river.

 

## MATERIALS AND METHODS

In order to model the outflows of such a basin, it appears to be very difficult and even inappropriate to use classic modelling methods, such as one in the large family of rainfall-runoff distributed or semi-distributed tools. Several reasons justify using a different approach: (i) the incident radiative flux intensity brings a strong atmospheric forcing to the area, which is different from a rainfall-dominated forcing; (ii) the specific spatial and altitudinal variability of precipitation in the tropical high mountain context; (iii) the complexity of the interaction between the 'natural runoff', generated by the precipitation and the glacier or snow melt, and the 'hydraulic flow', resulting from the water transfer (channels), storage (reservoirs) or release (turbine or overflowing).

The Bolivian Power Company (COBEE), which is the main user of the water from the valley, also introduces a constraint. The method employed to combine the climatic input, the hydrologic response and the hydraulic management was made in an attempt to make at transferable (to other basins and operational applications). It should lead, with some adaptation, to a decision support system useful for the water resource operator.

Analysing all these issues, it has been decided to combine three modelling methods:

- the first step is *modelling of the spatial distribution of the climatic data* over the basin,
- the second step is *water cycle production modelling* at the scale of an unmanaged basin (not influenced by the hydraulic system), taking into account the surface energy balance and the surface behaviours;
- the third step is *surface flow transfer modelling* through the basin, taking into account the presence of hydraulic devices and their management.

### *The spatial modelling of the climatic data: elevation gradient*

The precipitation regime depends on the valley's altitude and its orientation (Bourges and Hoorelbecke, 1992; Pouyaud *et al*., 1999; Caballero, 2001). In the rainy season, the eastern intertropical fluxes blow water vapour from the Atlantic Ocean and Amazonian basin, which, when blocked by the eastern Andean chain, produces precipitation. The daily rainfall collected in the rain gauges distributed along the Zongo Valley over a 25 year period was used to calculate the monthly average rainfall. Figure 2 shows the marked seasonal variability of the precipitation (rainy season from November to March, dry season from May to September), as well as the decrease of rainfall with altitude. Two of those rain gauges (Plataforma, near Zongo reservoir, and Botijlaca, near the Botijlaca plant) are located in the Llaullini basin. The daily data available at these rain gauges were used to calculate a monthly elevation gradient (rain decreasing with height) for the rainfall in the Llaullini basin (Table I).

The liquid precipitation intensity (for which the calculation of a time step less than the daily level is needed) was determined using records from three tipping-bucket rain gauges located at different altitudes within the basin. A time step of 30 min was chosen for data processing. The elevation gradient for precipitation (Table I), was used to calculate the precipitation over the whole basin. The basin was sub-divided into sub-catchments and the precipitation was determined for each band using the nearest rain gauge.

The other atmospheric forcing data, such as temperature, pressure, specific humidity, solar radiation and wind speed, were available at the meteorological station located near the Zongo reservoir at 4750 m a.s.l., at

Table I. Monthly rainfall elevation gradient between Botijlaca (near the plant) and Plataforma (near the Zongo reservoir) in mm/100 m

| | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Monthly rainfall elevation gradient (mm/100 m) | −1·7 | −2·1 | −1·8 | −1·7 | −3·6 | −2·7 | −2·8 | −0·4 | −0·3 | −0·3 | −0·3 | −1·4 |

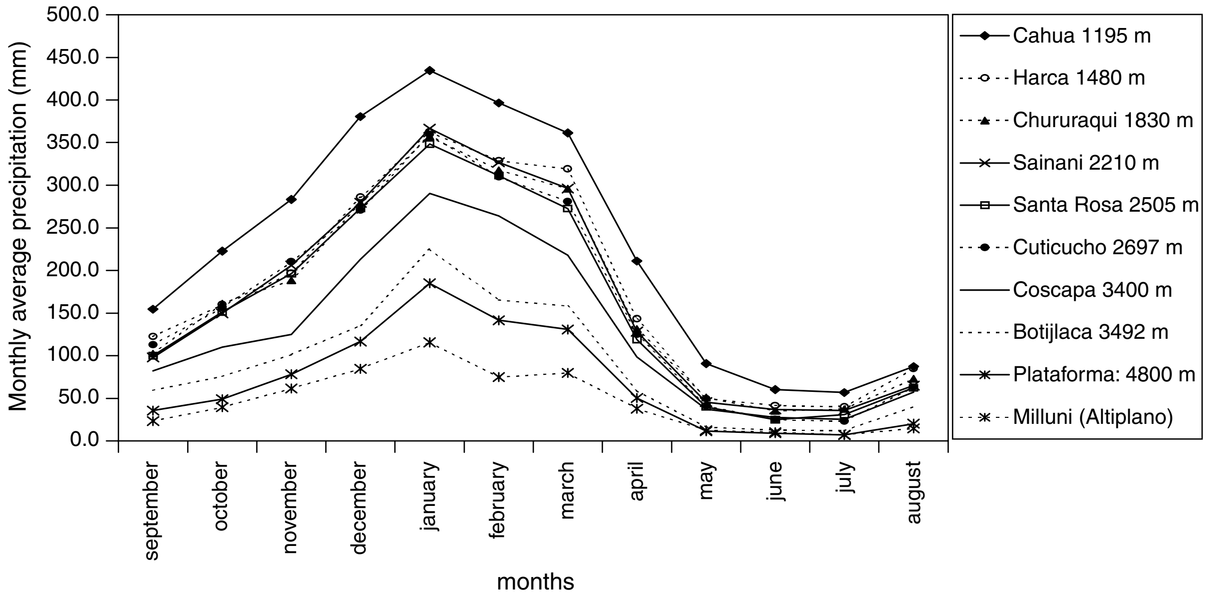


Figure 2. Monthly average precipitation in the Zongo Valley. The influence of altitude and precipitation is shown (Pouyaud *et al.*, 1999)

a 30 min time step. Owing to the lack of climatic observations in other places within the basin, a standard elevation gradient of temperature was adopted: the temperature decreases 0·65 °C per 100 m of elevation (Barry, 1992). This assumption was verified for short periods using temperature stations located near the Zongo glacier. Pressure and humidity were computed based on the temperature. The solar radiation and the wind speed were considered constant over the whole basin. A critical value of the atmospheric temperature was used to determine whether the precipitation fell as snow or rain. This value was set during calibration following a method detailed in Results and discussion section.

*The water cycle production modelling: the ISBA scheme*

In order to represent the local water balance, it was necessary to choose a model that is able to take into account the main meteorological characteristics of a high mountain context: essentially the strong influence of the surface energy balance on the one hand, and the partition between liquid and solid precipitation (and the possible snow cover) on the other hand. For this purpose, the hydrological processes of those catchments that do not contain a glacier surface were simulated with a soil–vegetation–atmosphere transfer (SVAT) land-surface scheme called ISBA (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996).

*General description.* This scheme describes the exchanges of heat momentum and water between the low-level atmosphere, the vegetation and soil surface. As it was designed for meteorological models, and it is based on a generalized force–restore method (Deardorff, 1977; 1978), ISBA is a relatively simple scheme. Nevertheless, it includes the most important components of the land surface processes. We have used the three hydrological layers version of ISBA (Boone *et al.*, 1999), where a thin upper layer is used to calculate the evaporation from the soil surface and two other layers are used to calculate the surface runoff, plant transpiration, infiltration and drainage (Figure 3). The surface runoff is calculated using a sub-grid parameterization based on the work of Dümenil and Todini (1992) and Wood *et al.* (1992). It allows the generation of surface runoff before the soil surface is entirely saturated by considering that, for a given mean soil water content under saturation on a given surface, a fraction of the surface can already be saturated and thereby produce surface runoff. Once the surface runoff and the evaporation are calculated, the remaining

 

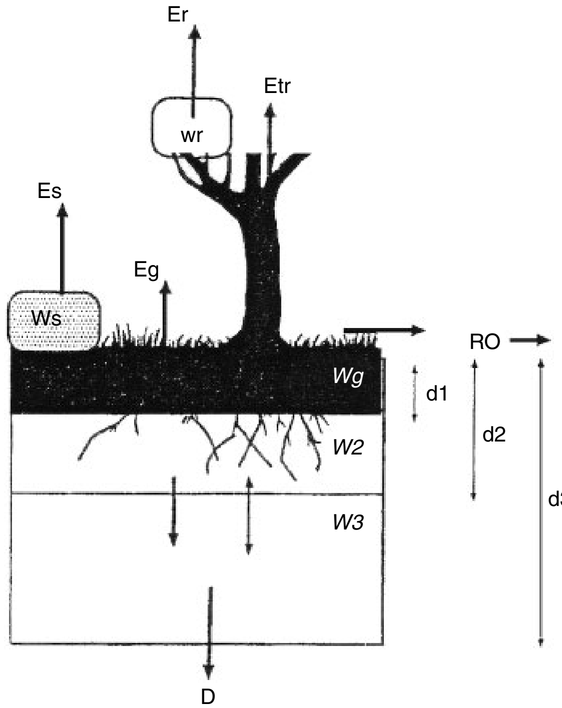


Figure 3. The different terms of the water budget simulated by ISBA (Habets *et al*., 1999c). Respectively, Wg, W2, W3, Ws and Wr represent the volumetric water contents of three soil layers, the total snow cover, water content and the water intercepted by canopy. *E* is the evaporative flux from the vegetation (Etr), the bare ground (Eg), the snow cover (Es) and the water intercepted by canopy (Er). RO is the sub-grid runoff computed by a slightly modified version of VIC (Wood *et al*., 1992), and *D* is the gravitational drainage at the bottom of the soil deep reservoir

water is infiltrated using gravitational drainage and diffusion. The version of the model chosen also includes a three-layer snow scheme (Boone, 2000) that simulates the snow melt resolving a specific energy budget. Tested in a French alpine context, the three-layer scheme was able to represent the hydrological processes satisfactorily, compared to a much more detailed internal processes model (CROCUS).

Recent studies on ISBA coupled with the macroscale hydrological model MODCOU (Ledoux, 1980) in the Adour basin (Habets *et al*., 1999a, b) and the Rhône basin (Habets *et al*., 1999c; Etchevers *et al*., 2001) have shown the ability of the system to model regional-scale hydrology. It was of interest, therefore, to test ISBA in a tropical high mountain context.

The scheme was calibrated on a sub-basin without glacial contribution to the runoff (catchment A in Figure 4), using the 'simple split-sample' method (Klemes, 1986). First, it was partially validated over a 16 month period following the 8 month calibration period. Then it was applied to the entire basin to simulate the total discharge. Some other monitored catchments of the Llaullini basin (mainly catchments D and F in Figure 4) differ from the Liviñosa one and, therefore, provided data for more and different validation tests. Comparison between the simulated and observed runoffs at the outlet of these monitored basins is used to validate the model for both different altitudes and surfaces and a different time period.

*Terrain units for the ISBA application and atmospheric forcing*. Three types of surface were defined in the basin: rock faces, slope deposits and valley bottoms (Figure 5). As ISBA's primary soil parameters are the percentage of sand and clay (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996), a sandy texture (96% sand; 3% clay) was attributed to the rock faces in order to simulate their fast discharge. Granulometry measurements provide 20% sand and 15% clay for the slope deposits and 40% sand and 30% clay for the

 

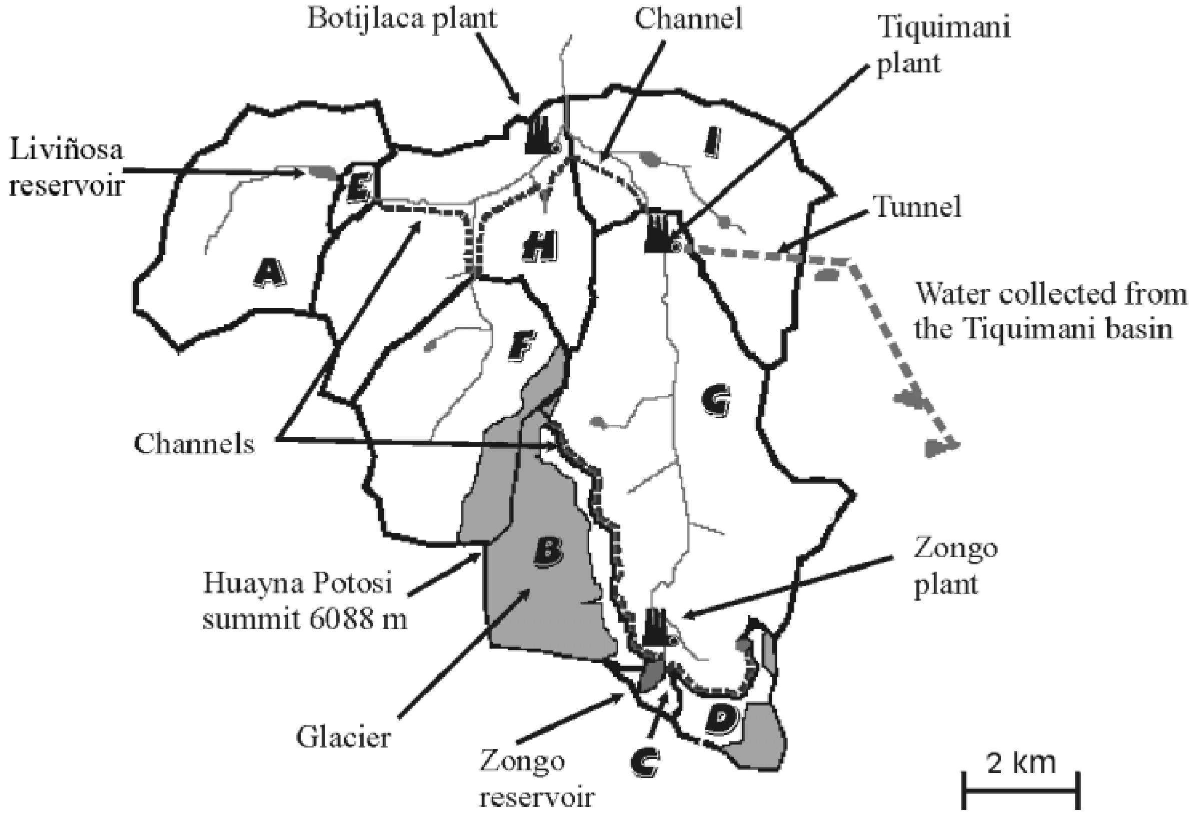


Figure 4. Limits of the nine hydraulic catchments identified by letters A to I, in the Llaullini basin. Channels, tunnels and reservoirs for the hydroelectric power plants are shown

valley bottoms. The remaining model soil and vegetation parameters were either computed from these textures, taken from the literature or measured.

The basin was then subdivided into 300 m elevation bands (Figure 6). The combination of the elevation bands with the three types of surface for each hydraulic catchment determined 79 terrain units. ISBA was applied over each unit using the spatial climatic data input, deduced from the elevation gradient.

*Routing the flow within catchments.* Field observations showed that there is no deep infiltration in the Llaullini basin. Consequently, the runoff and the deep drainage produced by ISBA were summed at each time step and represent the simulated flow production of each terrain unit.

Water was transferred within each catchment using a simple routing method in order to describe, as much as possible, the lateral transfer following the slopes. Briefly, water flow from a rock face unit was introduced in a slope deposit unit of the contiguous inferior elevation band, and water flow from the latter was introduced into a valley-bottom unit. This routing method was found to be similar to the variable contribution area theory used, for example, by Topmodel (Beven and Kirby, 1979), and it gave better results than the simple daily runoff accumulation used for the calibration.

*The glacierized catchments.* Figure 4 shows that the B, D and F catchments, contain glacierized surfaces. Two of them, the B and D catchments, have been monitored since 1990 by the tropical snow and glaciers research program (GREATICE) of the IRD. Their discharge is measured by water level recorders on the 'Prado', 'Tubo' and 'Alpaca' channels that transfer the melt water to the Zongo reservoir. For the F catchment,

 

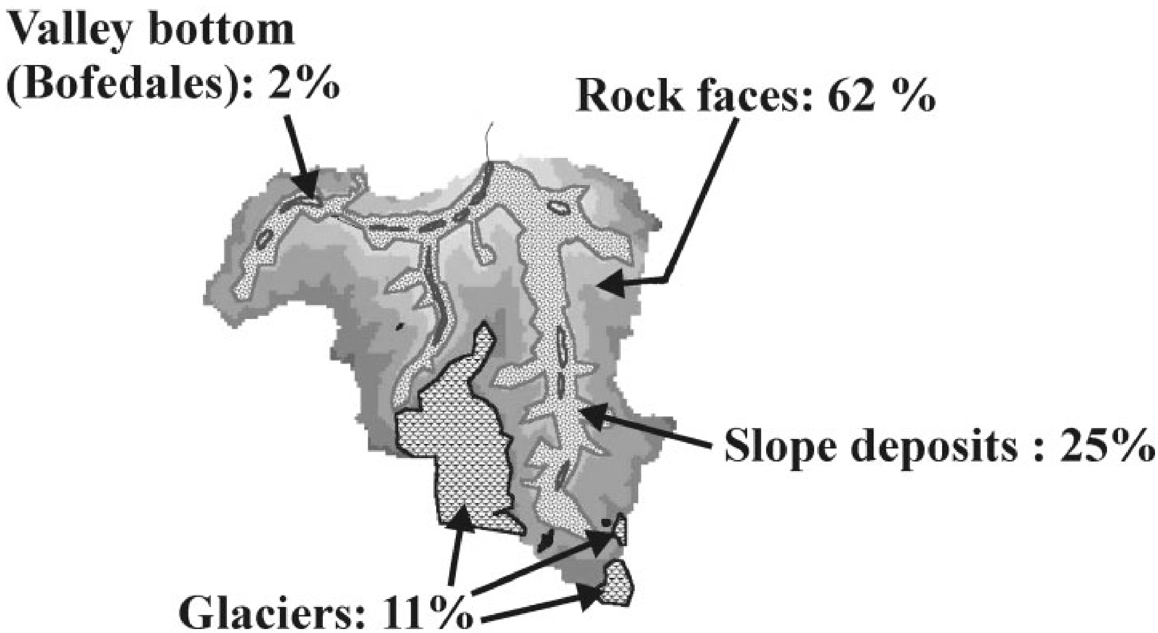


Figure 5. Four types of morphological zone are distinguished in the basin, together with their proportion of the basin area

an estimation of the glacierized area contribution to the discharge was made (Caballero *et al*., 2002) assuming that it's melting dynamics are similar to that of the Zongo glacier, despite their different orientations. In order to minimize the bias introduced by this assumption, we only compared the ablation area of each glacier.

*The transfer modelling: the system dynamics approach*

The system dynamics method was introduced by Forrester (1968) for industrial and urban dynamic-system modelling. It allows the modelling of the dynamic evolution of a complex system by defining it as a set of time-varying interconnected state variables. The system is represented by state-flux diagrams that graphically describe the organization (Lee, 1993). The relations and feedbacks between the state variables are described using differential equations to calculate their instantaneous values (Kositsakulchai, 2001).

Several commercial packages (Vensim®, Ithink®/Stella®, PowerSim®), so-called 'modelling environments', facilitate the construction and handling of dynamic system models. A few studies have applied such tools to water resources management modelling (Lee, 1993; Simonovic *et al*., 1997; Caballero, 2001; Fourcade, 2001; Kositsakulchai, 2001).

In the context of the current evolution of water sciences, where economic criteria are increasingly important, simple and robust tools to model complex dynamic systems are useful (Sasseville and De Marsily, 1998). Moreover, these tools are pedagogic for model building and training. For example, the construction of state-flux diagrams and the definition of the equations that control them oblige the modeller to understand the hydrological processes well before their conceptualization (Lee, 1993).

In this study, the modelling environment Vensim® (Ventana Systems Inc., 1997) was used to build a model for the hydroelectric system of the Llaullini basin.

*Conceptualization of the problem.* A hydroelectric power plant uses hydraulic devices (intakes, channels, reservoirs and pressure pipelines) that are used for the collection, storage and routing of water to the turbines.

In this paper, a *hydraulic system* is defined as the entire collection of sub-basins and hydraulic devices used to supply a given hydroelectric power plant. In such a system, the river flow is tapped by intakes and then

 

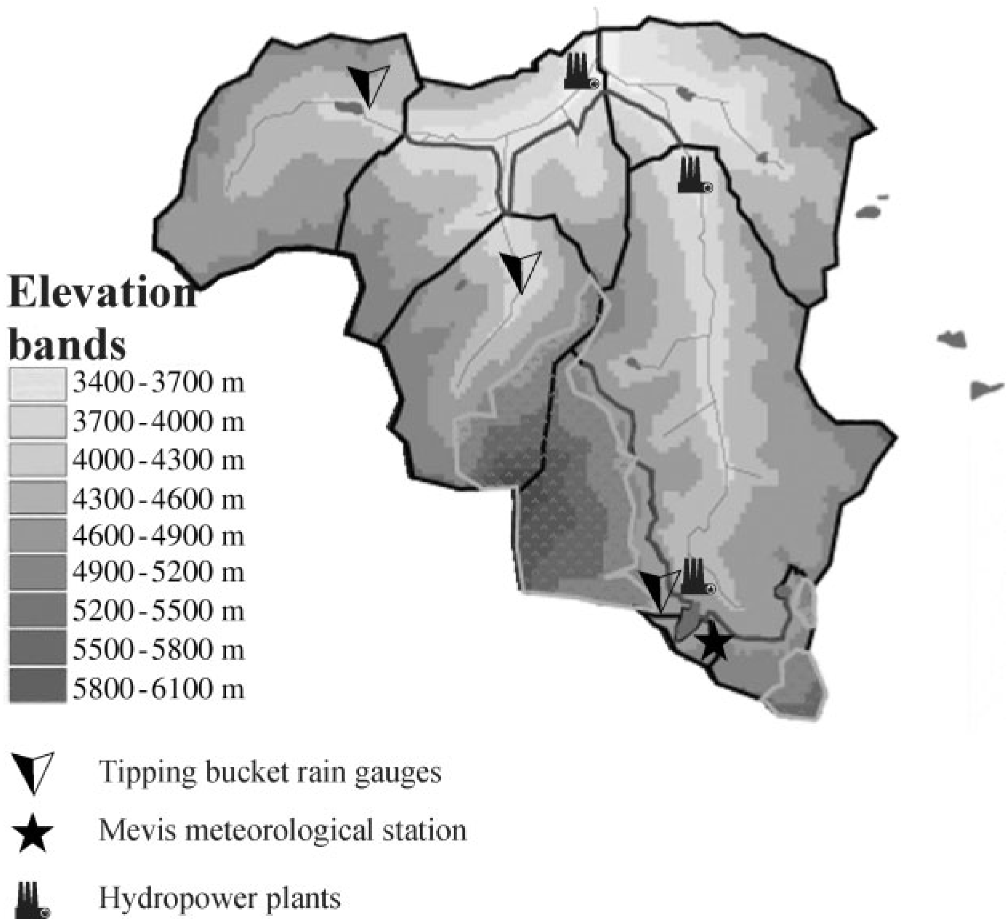


Figure 6. Definition of 300 m elevation bands. The locations of the meteorological station and the tipping bucket rain gauges used to calculate the atmospheric forcing on the basin are shown

routed either directly to the pressure pipelines that supply the hydroelectric power plant or to the reservoirs where the water is stored until it is used to supply the plant.

Figure 4 shows the three hydroelectric power plants in the Llaullini basin (95 $km^2$) corresponding to three above-defined hydraulic systems:

- The Zongo system (12·4 $km^2$) is managed by the Zongo reservoir (3·25 $Mm^3$), which collects water from several sub-basins by way of three channels (units B and C on Figure 4).
- The Tiquimani system is managed by several reservoirs (cumulated volume: 5·9 $Mm^3$), all of which are located outside the Zongo basin (10·2 $km^2$). The flows are transferred into the Zongo basin through a tunnel crossing the mountain crest. Because the reservoir spillways are outside of the basin, the main contribution of this system to the Rio Zongo is the turbinated water by the power plant. The overflow-volume within the basin from the intakes of the pressure pipes is considered to be negligible.
- The Botijlaca system collects water from three different branches: (i) the Zongo main valley, including the Tiquimani and Zongo systems (39·2 $km^2$ within the Zongo basin—units B, C, D and G); (ii) the Liviñosa valley (13·3 $km^2$—units A and E), managed by the Liviñosa Reservoir (0·54 $Mm^3$); and (iii) the Taypikhuchu valley (13·3 $km^2$—unit F).

 

- The last part of the Llaullini river basin (29·8 $km^2$—units I and H) is flowing naturally in the water course. The only artificial runoffs affecting this area are the overflows from the Botijlaca and Tiquimani intakes.

Considering a mean annual inflow at the basin's outlet of 73 $Mm^3$, the ratio of the total system storage to the inflow is less than 15%, caused by the relatively small reservoir systems. This small ratio indicates that the system can be affected by stream flow variations over short time scales. For that reason, it was decided to perform the system simulation modelling at the daily time scale. The water from four hydraulic catchments (units A, B, C and D) is collected by reservoirs, the water from three hydraulic catchments (E, F and G) is used by intakes and the water from two (H and I) is not collected even if measured at the Llaullini station.

Figure 7 shows a schematic view of the hydroelectric system model built at the Llaullini basin scale with Vensim®. A hydraulic system was built for the Zongo plant and linked with the one built for Botijlaca by introducing the output of the upstream Zongo system (reservoir and/or intake's overflows and turbinate water) as an input to the downstream Botijlaca plant. The Tiquimani's turbinated water was also considered as input data to the Botijlaca system.

*Water management in a hydraulic system*

For the water management model described by the above-defined hydraulic system, two equations were used. Equation (1) describes the water management at intakes when they directly supply a plant and Equation (2) describes the water management in the reservoirs.

*Equation (1)—intakes:* The direct supply of a plant from intakes is simulated by comparing the water volume brought by the river to the plant's demand (Equation (1)). Consequently, the overflow (i.e. the non-turbinated and lost water volume for electricity production) always has to be positive.

At each time step the overflow is calculated as

$$O_{(t)} = \mathrm{RW}_{(t)} - \mathrm{TW}_{(t)} \tag{1}$$

where $O$ ($m^3$) is the overflow, RW ($m^3$) is the river water and TW ($m^3$) is the turbinated water.

*Equation (2)—reservoirs:* The water management on the reservoirs is simulated by performing a volume balance for each reservoir belonging to the system. This balance allows the accounting of the natural input (precipitation, water flow from the collected basins) and output (evaporation, overflow) of the reservoir, as well as the electricity production by considering the turbinated water as a loss for the reservoir.

At each time step, the stored water in the reservoir is calculated as

$$\mathrm{RS}_{(t)} = \mathrm{RS}_{(t-1)} + P_{(t)}A + \mathrm{SR}_{(t)} - E_{(t)}A - \mathrm{TW}_{(t)} - O_{(t)} \tag{2}$$

where RS ($m^3$) is the reservoir storage, $P$ (m) is the precipitation (rain or snow), $A$ ($m^2$) is the area of the water surface, SR ($m^3$) is the upstream sub-basin's runoff (including water courses), $E$ (m) is the evaporation over the reservoir, TW ($m^3$) is the turbinated water and $O$ ($m^3$) is the overflow (crest/spillway) or release (bottom gate).

In Equation (2), the reservoir's water volume is a state variable that depends on the input ($P\mathrm{A} + \mathrm{SR}$) and the output ($(EA) + \mathrm{TW} + O$) fluxes. Both are calculated using auxiliary variables that can be treated as an input data ($P$, $E$, SR, TW) or computed in the model ($A$, which varies with the water depth in the reservoir, and $O$).

*Turbinated water volume in a hydroelectric power plant:* A hydroelectric power plant is characterized by its 'plant factor' which depends on the turbine's efficiency and on the pressure height. This efficiency normally varies, as it is related to the instantaneous power production, but it is assumed to be constant in this work.

 

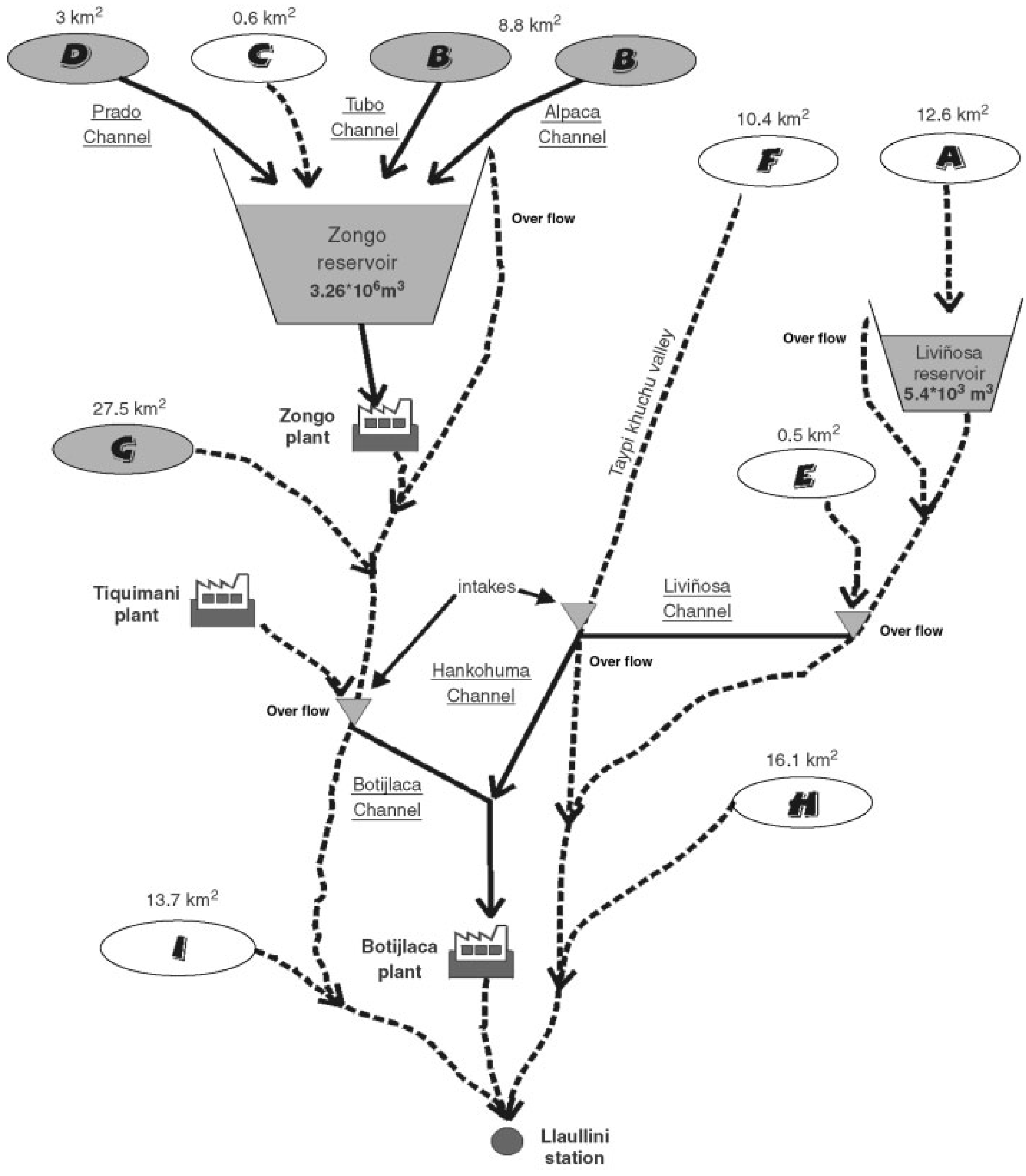


Figure 7. Schematic view of the hydroelectric system model built with Vensim®. The dashed lines represent the rivers and the solid lines represent the channels. The nine hydraulic catchments are integrated in the model. The grey-tinted catchments runoff is monitored and was not simulated with ISBA. Finally, all the water of the basin exits it at the Llaullini station

Indeed, its variation at the daily time step is negligible in comparison with the observed data's precision (Reinhardt, 1997). Thus, the daily turbinated water volume ($m^3$ $day^{-1}$) was calculated by dividing the daily power production (MWh $day^{-1}$) by the plant factor (MWh $m^{-3}$).

 

Equations (1) and 2 provide two ways to control the quality of the simulation. First, a negative value for the calculated overflow means that the water brought by the river is insufficient to supply the plant—as the river drains the sub-basins, this insufficiency points out that the sub-basins' runoff is underestimated. Second, using Equation (2), the variation of the volume stored in the reservoir can be simulated and then compared with the observed variation—the closer the simulated and the observed curves are, the better the water management simulation is.

## RESULTS AND DISCUSSION

Simulations were made for a 17 month period between September 1999 and January 2001. The simulated to observed runoff ratio and the Nash criteria (Nash and Sutcliffe, 1970) were used to quantify the simulation's

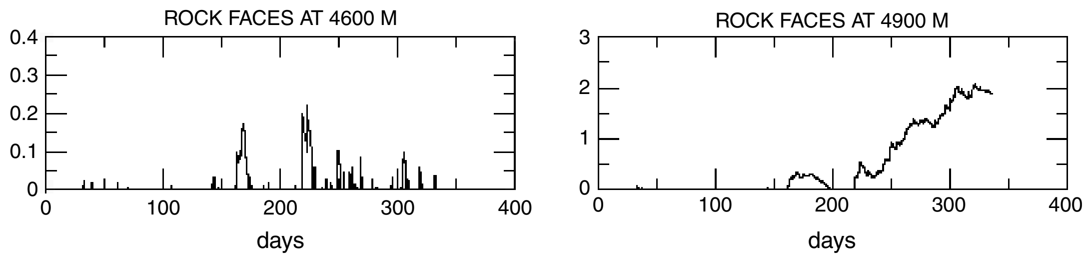


Figure 8. Comparison of the daily snow cover depth (m) on rock face units between 4600 and 4900 m (ROC 4600 m) and between 4900 and 5200 m (ROC 4900 m). The difference between the two simulations shows a threshold around 4900 m linked to the chosen critical value for the temperature

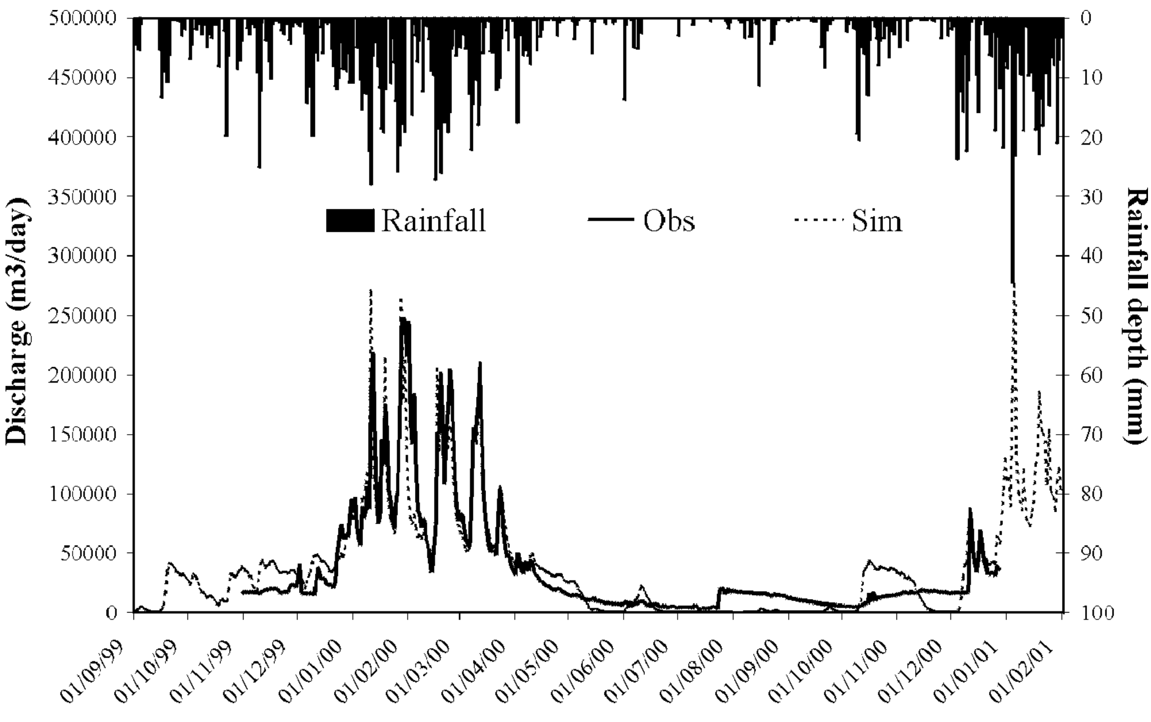


Figure 9. ISBA simulated and observed discharge at the outlet of the A (Liviñosa) sub-basin ($Q_{\text{sim}}/Q_{\text{obs}} = 0{\cdot}99$; Nash criteria: 0·84)

quality. The 16 month period covers an entire hydrological year with a hot and humid summer season from October to March followed by a cold and dry winter season from May to September. The calibration of the model was done during the period between September 1999 and April 2000, on a non-glacial catchment (A catchment in Figure 4). In order to avoid the glacier melt-water flow contribution to the runoff, the observed runoff was corrected by removing the Liviñosa reservoir influence. The 16 month period was found to be long enough to eliminate the effects of the initial conditions, as the sandy texture of the rock faces, covering more than 70% of the catchment, provoked a fast drainage. Details of the calibration can be found in Caballero (2001).

Both the simulation performed on the following period and the application to the other sub-basins of the system provided a good validation test.

ISBA was applied at a daily time step to each unit shown in Figure 7 except for:

- B and D units, which were monitored for several years owing to the study of the glacier;
- all the units producing the Tiquimani's plant turbinated water stored by reservoirs in the contiguous Tiquimani river basin and brought by tunnels and siphons into the Llaullini basin (Figures 4 and 7).

ISBA's model time step (5 min in the current study) is adequate for resolving the key hydrological processes driving the natural runoff on basins that are not affected by water management. The simulated natural runoff was then computed at the daily time step, in order to introduce it into the water management model. This was done in order to take into account the streamflow variations impact on the water management, as the ratio of the storage to inflow is small.

The altitudinal gradient of precipitation and temperature described in section 'The spatial modelling of the climatic data' were used in order to obtain a spatial distribution of the atmospheric forcing over the basin, with only the solar radiation and the wind velocity remaining constant. The snowfall/rainfall altitude limit

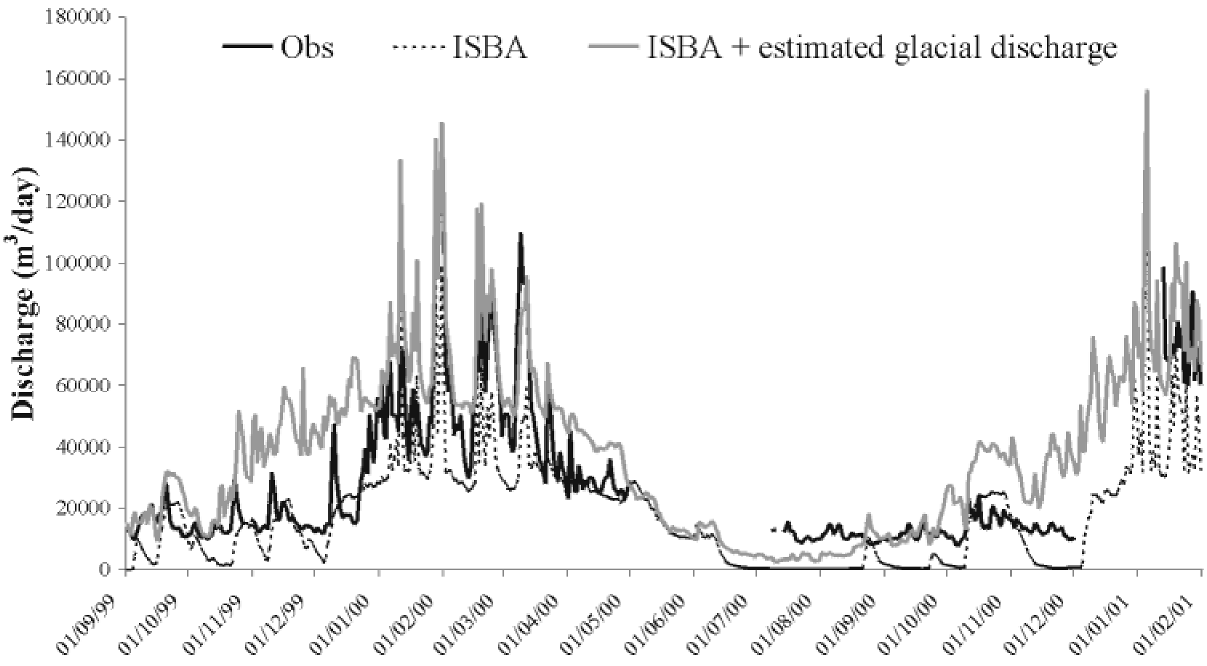


Figure 10. Observed and simulated discharge at the outlet of the F (Taypikhuchu) sub-basin. The glacier surface's discharge of the sub-basin was estimated by comparison with the Zongo glacier surface flow production

also varyied with elevation, as a critical value of temperature was used for rainfall/snowfall partitioning. This value was first found to be roughly contained in the observed interval of [−2°C; −1°C], for which Leblanc (2001) obtained an equal probability for rainfall and snowfall events. The final value was then calibrated by performing nine simulations with the critical value varying in the range [−2°C; +2°C] with 0·5 °C steps. For values above +0·5 °C, the simulation quality strongly decreased because of the overestimated snow cover, wheras it remaining relatively constant for lesser values. The optimum value (according to the runoff ratio and the Nash criteria) was found to be −1·5 °C, where more snowfall than rainfall was simulated at elevations above 4900 m. For this critical value, the visually observed spatial variability of the snow cover was successfully reproduced. Despite the fact that there was no measurement of the snow cover in the basin, it has been widely observed that permanent snow cover remaining more than 2 or 3 days is generally only found above 4900 m. The model clearly reproduces this observation, as shown in Figure 8, where a thin snow cover rapidly melts for the rock face unit under 4900 m and remains several days for the one above 4900 m. Both the difference of the snow cover depth (less than 30 cm below 4900 m and greater than 50 cm above) and the melting intensity show the altitudinal threshold around 4900 m.

The figures presented hereafter show the ISBA simulated discharge at the outlet of two particular catchments, the non-glacial catchment A (Figure 9) and the glacial catchment F (Figure 10). From Figure 9, it can be seen that the ISBA simulated discharge reproduces rather well the observed one, especially during the rainy season. The simulated to observed discharge ratio and the Nash criteria values, calculated for the period between November 1999 and April 2000, are 0·99 and 0·84. Technical problems with the water level gauges prevented the critical evaluation of the simulation during the second rainy season. The results are not as good during the dry season, when the simulated discharge is more sensitive to rainfall events than the observed discharge. This behaviour is mainly caused by both the deep drainage parameterization in ISBA and the presence of a dam upstream of the Liviñosa station. This dam is emptied during the dry season to supply the

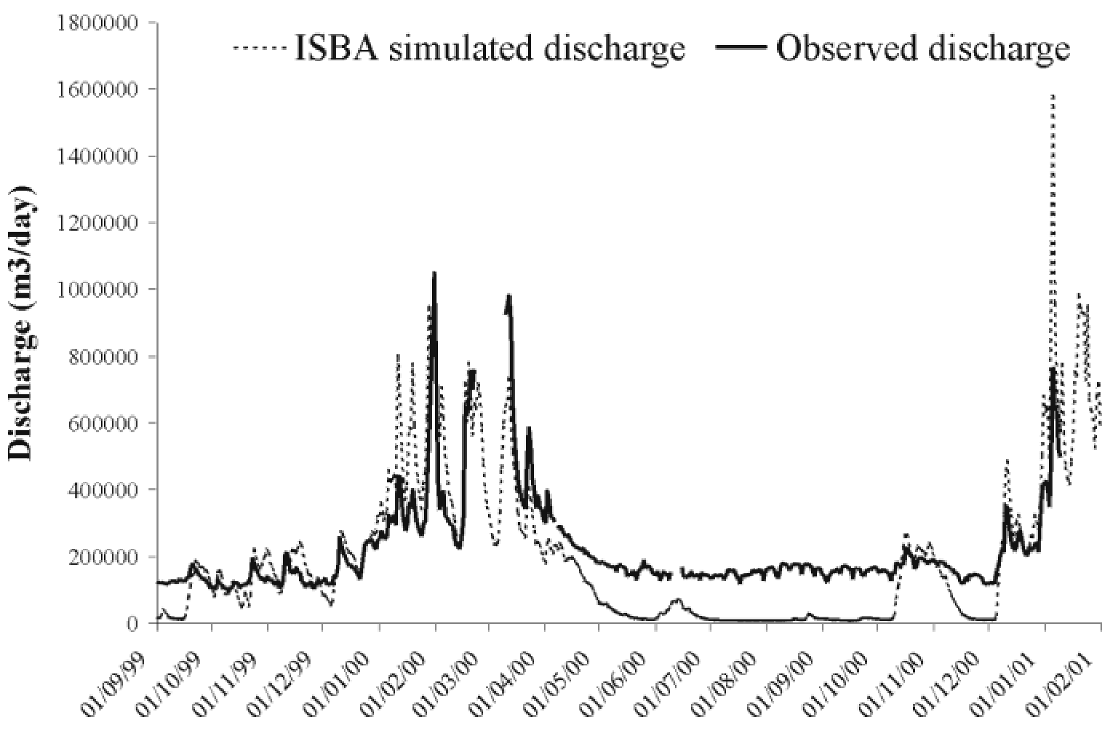


Figure 11. Observed and simulated discharge at the Llaullini station. The simulated discharge corresponds to the addition of the ISBA simulation results at the outlet of each sub-basin without taking into account the water management in the hydroelectric system

Botijlaca plant, which provokes the observed discharge at the beginning of August. The model, which only takes into account the natural processes, simulates a weak discharge. However, the modelling method chosen allows the simulation of the hydrological behaviour of a non-glacial catchment and is useful for correcting the observed discharge from the upstream dam's influence on natural runoff.

Figure 10 shows the influence of the glacial discharge estimation method on the catchment's simulated total discharge. The ISBA simulated discharge corresponding to the dashed curve clearly underestimates the catchment's observed discharge due to the lack of a glacial component in the model. Introducing the glacial contribution causes an increase in the simulated water volume during the whole period. It improves the simulation quality both during parts of the rainy season and the entire dry season. The discharge, however, is overestimated in both the beginning of 1999–2000 and for the 2000–01 rainy seasons. This may be caused by the orientation differences between the Zongo glacier and the F catchment's glacierized area. As this catchment represents less than 10% of the total Llaullini basin surface, this overestimation may not provoke significant errors in the total simulated discharge.

The simulated discharge at the outlet of each sub-basin was then summed in order to calculate the simulated discharge at the Llaullini station, without taking into account the hydroelectric system's influence on the transfer dynamics. Figure 11 compares the observed and the resulting daily simulated discharge at the Llaullini station. During the wet seasons, the calculated and the simulated discharge are roughly the same. However, two facts should be pointed out: on the one hand, at the beginning of the 1999–2000 rainy season, some floods are overestimated, on the other hand, there is a continuous difference between the simulated and the observed discharge all through the dry season. These facts are linked to the water management in the hydroelectric system. During the dry season, the reservoir's stored water is released to supply the hydropower plants of the valley. This provokes a nearly constant flow in the river, which cannot be simulated with ISBA. When the rainy season begins, floods occurring at the time of the first rains are used to fill the empty reservoirs and thus are not observed at the Llaullini river station. It is necessary, therefore, to link the ISBA simulated runoff and the water management model to correct the simulated discharge at the Llaullini station.

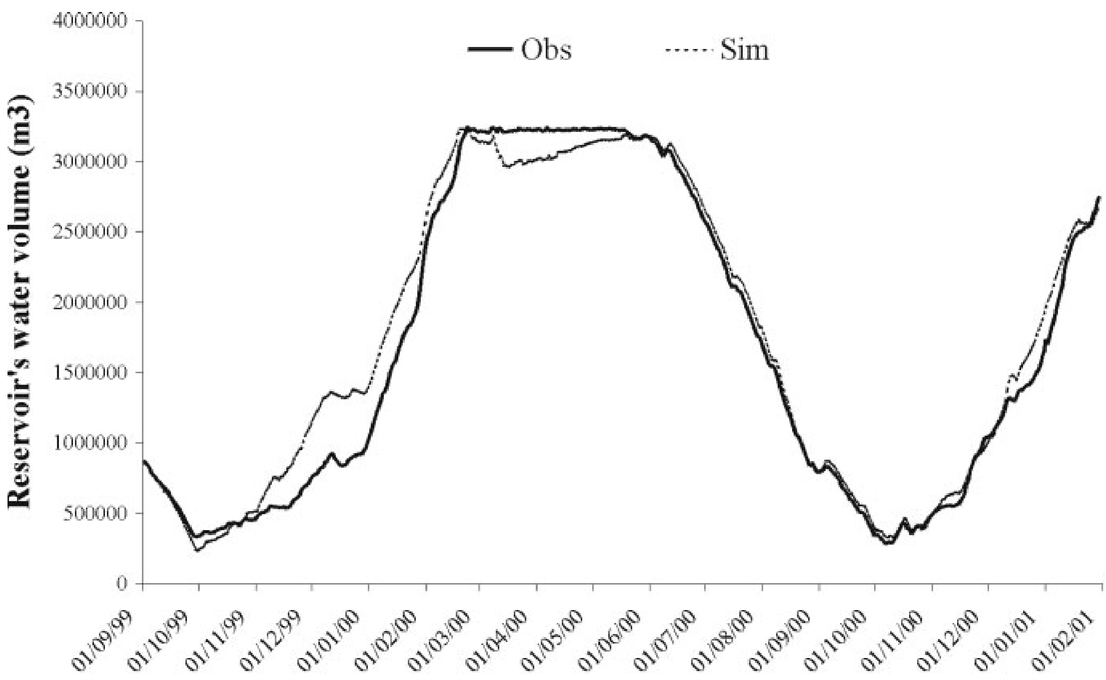


Figure 12. Observed and simulated Zongo reservoir water volume

 

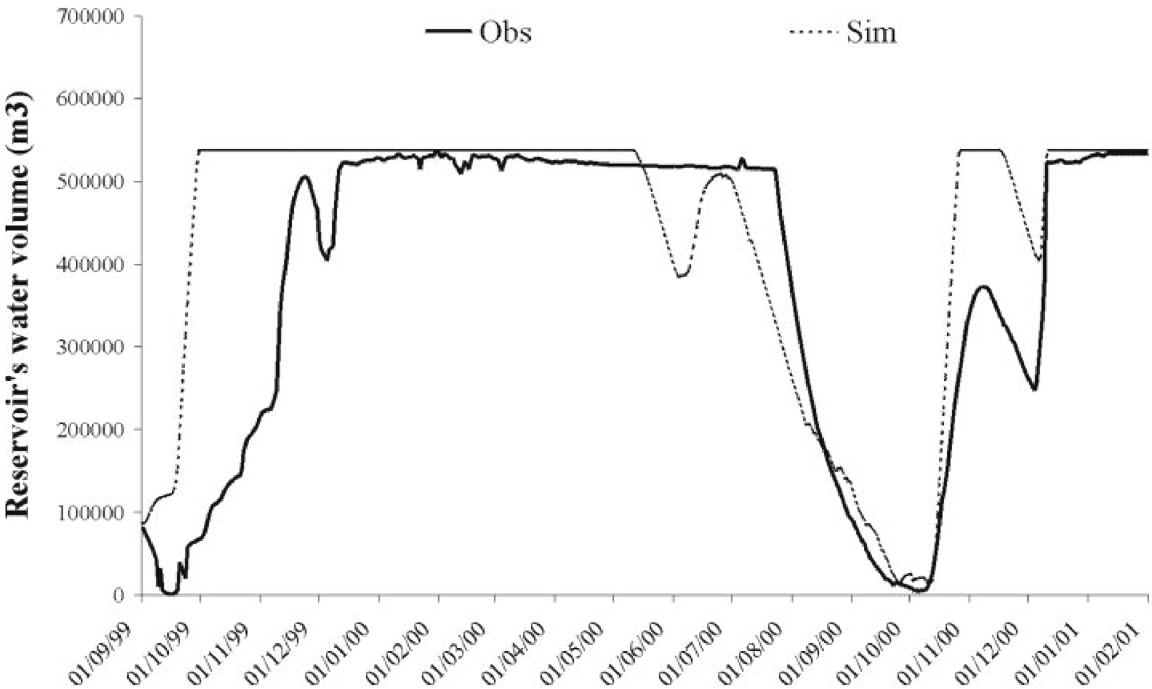


Figure 13. Observed and simulated Liviñosa reservoir water volume

The observed and simulated water volumes of the Zongo and Liviñosa reservoirs are compared in Figures 12 and Figure 13. In both cases, the good quality of the reservoir's simulated dynamics is shown, particularly for the simple Zongo case because of it's direct connection to the Zongo plant. The Liviñosa reservoir is not directly connected to the plant it supplies, but to a much more complicated system, where the E, F and G sub-basins and the Zongo and Tiquimani's turbinated water is managed (Figure 7). In our model, the water from the Liviñosa reservoir is only required when there is insufficient water in the rest of the system. Therefore, the computation of the Liviñosa reservoir water volume integrates all the errors made elsewhere in the model. Consequently, the Liviñosa reservoir simulated dynamics can be considered to be good.

The final result of the simulation is presented in Figure 14, where the simulated discharge integrates both the natural flows and the water management modelling. The simulated to observed discharge ratio and the Nash criteria values are 1·1 and 0·44 respectively. The simulated flood peaks of the wettest rainy season were reduced and are close to the observed peaks. Moreover, the continuous difference observed in Figure 11 was strongly reduced by the water management model. Furthermore, the water management model provoked an increase of the discharge between the end of the dry season and the beginning of the rainy season, probably due to the glacial discharge estimation errors.

## CONCLUSIONS

This study shows that using the system dynamics method to simulate the water management in a complex hydroelectric system is relevant. The ISBA land-surface scheme was chosen to simulate the hydrological processes (energy and water fluxes). Used as a runoff production model, it was successfully adapted to the Andean context (significantly different from an alpine context) during a 16 month period. The simulated discharge at the outlet of each sub-basin was introduced into the water management model. The resulting

 

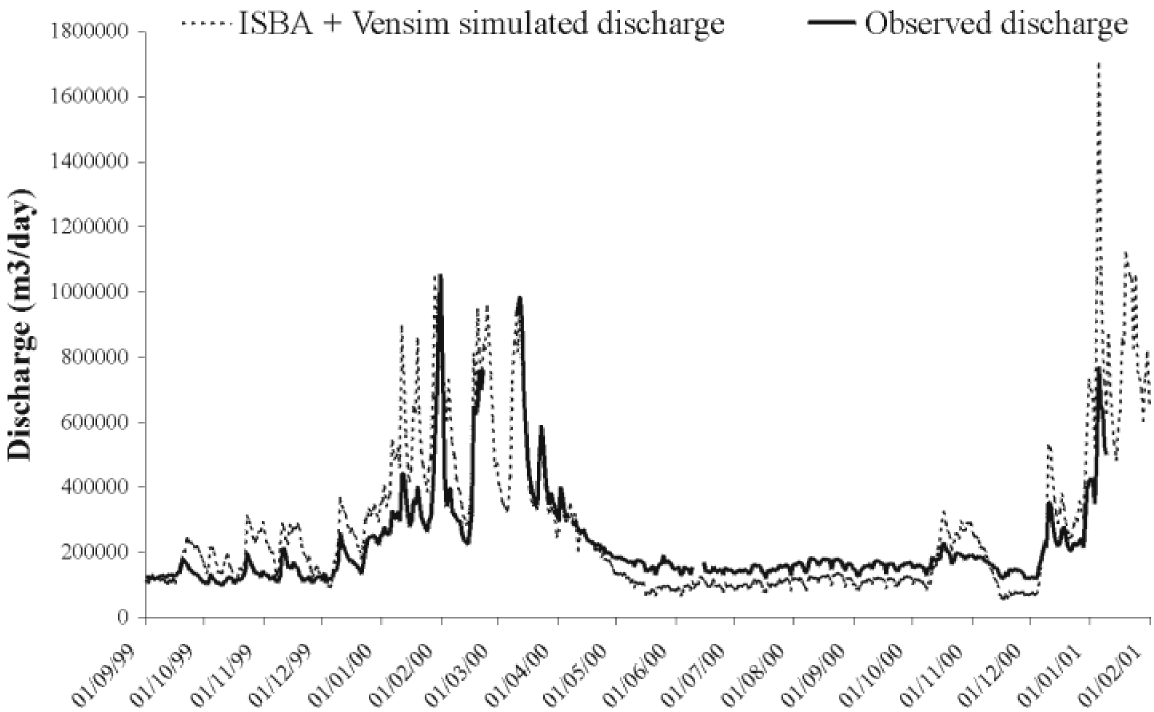


Figure 14. Observed and simulated discharge at the Llaullini station. The simulated discharge integrates the water management model influence ($Q_{\mathrm{sim}}/Q_{\mathrm{obs}} = 1{\cdot}1$; Nash $= 0{\cdot}44$)

coupled model was able to simulate well the reservoir's water volume variation and the Llaullini river station discharge.

This method can be used by the modeller to analyse and qualify the system's dynamics (uptakes, reservoirs and hydroelectric plants) in order to define which kinds of hydraulic device play a significant role in the water management. In this study, intakes and reservoirs were considered to be the main devices to be modelled. For the purpose of the study, only two reservoirs were integrated into the model, because both of them have a significant size and data series do not exist for the remaining reservoirs. This choice was found to produce reasonable results. Available data for the smaller reservoirs would have permitted the simulation of the water management strategy in a more detailed way, but it is quite probable that they would not have provided much better results in terms of the simulated river discharge. Nevertheless, the same method can be applied at a more detailed time and space scale for a more detailed purpose, such as water management for the smaller reservoirs. However, this might necessitate many more surface hydrometeorological stations in order to better describe the complex mountainous atmospheric forcing.

Although the built-model cannot be considered as a decision support system tool (mainly because of the relative complexity and detailed meteorological data input of ISBA), it can be useful for the testing of new water management strategies or the study of the impacts of the construction of new devices, such as reservoirs. Moreover, coupled with a glacier melting model, it could be used to study the impacts of the climatic variability on the water resources, particularly in a global warming context.

## ACKNOWLEDGEMENTS

This study was logistically supported by the Production Department of the Bolivian Company of Electric Power (COBEE). It is the result of a work completed through two postgraduate and PhD theses from the

 

Swiss Federal Polytechnic School in Lausanne (Switzerland) and from Montpellier II University (France). It benefited from infrastructures, material and staff of the GREATICE project in the French IRD and in San Andres University of La Paz (Bolivia). The ISBA code has been furnished by the GMME group from Météo-France. The authors are very grateful to Y. Arnaud, H. Baldivieso, E. Berthier, A. Boone (special thanks for the English corrections), J. P. Chazarin, P. Fraizy, Y. L'Hôte, J. Molina, J. Noilhan, B. Pouyaud, I. Rheinhardt, P. Ribstein, J. C. Salinas, D. Oporto and V. Ticona for useful discussions regarding aspects of this research and helping during field work. Finally, the authors would like to thank the referees for their interesting and useful questions that helped to improve the paper.

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