ELSEVIER

Catena 47 (2002) 101–116

CATENA

www.elsevier.com/locate/catena

Hydrological characteristics of slope deposits in high tropical mountains (Cordillera Real, Bolivia)

Y. Caballero[a], V. Jomelli[b,*], P. Chevallier[a], P. Ribstein[c]

[a]*Maison des Sciences de l'Eau, IRD, BP 5045, 34032 Montpellier Cedex 1, France*
[b]*CNRS UMR 8591, 1 Place Aristide Briand, 92195 Meudon Bellevue, France*
[c]*IRD UMR 7619 Sisyphe, Case 123, 4 Place Jussieu, 75532 Paris Cedex 05, France*

Received 10 December 2000; received in revised form 14 June 2001; accepted 19 July 2001

Abstract

The hydrological processes within slope deposits are not well known, particularly for high tropical mountains with climatic conditions giving seasonal contrasts in the hydrological cycle. Measurements have been taken in a high Andean valley of the Cordillera Real (Bolivia) with the aim to determine the role of the slope deposits in the framework of a hydraulic modelling. Different transfer time measurements combined with morphometrical and sedimentological analysis were carried out on three talus slopes and two moraines during the rainy season. After injection of salt, the electrical conductivity of the water in slope deposits springs is monitored to estimate transfer velocities.

The hydrological behaviour of these slope deposits depends on the season. In the dry season, all the water infiltrates and there is no visible outlet. During the wet season, one part soaks in and gives springs down slope. The lag times estimated by the measurement of tracer velocity demonstrate that these slope deposits delayed the flow depending on the type of deposit. The delay is at least 24 h in the case of the talus slopes and more than 48 h in the case of lateral moraines. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Transfer time; Electrical conductivity; Talus slope; Lateral moraine; High tropical mountain

1. Introduction

The last few years have seen many investigations which aim to define precisely the geometrical and sedimentological characteristics of slope deposits in high tropical

---

[*] Corresponding author.

E-mail addresses: jomelli@cnrs-bellevue.fr (V. Jomelli), Ivan.Caballero@msem.univ-montp2.fr (Y. Caballero).

PII: S0341-8162(01)00179-5

mountains and to propose genetic modelling. In this context, numerous studies were carried out in the case of talus slope deposits (Albjär et al., 1979; Francou, 1988, 1991; Van Steijn et al., 1995; Jomelli and Francou, 2000).

Nevertheless, hydrological processes within slope deposits in high mountains have generated very little interest. Paradoxically, permafrost slope formations, have often been studied, including rock glaciers (Tenthorey, 1992; Hinzman et al., 1993; Barsch, 1996).

Further knowledge of the hydrological processes of slope deposits without permafrost, like talus slopes or morainic deposits is needed. Parriaux and Nicoud (1990, 1993) published on hydrologic processes in glacial and fluvio-glacial deposits. Some specific studies can be mentioned on response times in fluvio-glacial formations (Frohlich and Kelly, 1985; Davit and Looser, 1993) and estimations of groundwater recharge (Johansson, 1987; Harte and Winter, 1995). Jointly, chemical or isotopic observations (Van de Griend et al., 1986; Hamid et al., 1989; Gelhar et al., 1992) made it possible to identify various types of circulation systems and dispersivity within basal moraines and fluvio-glacial deposits. Other studies deal with the influence of a stone cover on the runoff yield of arid talus slopes (Jung, 1960; Yair and Lavee, 1976). From a qualitative point of view, the results of laboratory experiments are not realistic enough to be a substitute for field studies (Gelhar et al., 1992). Studies have mostly been focused on glacial and fluvio-glacial formations. Moreover, no study has been realised in high tropical mountains where the seasonality of the climate gives important contrasts in soil water content. From a quantitative point of view, the lack of systematic analysis based on a large sampling of deposits makes it difficult to apply and extrapolate results on other geographical contexts. The parameters controlling the hydrological characteristics of slope deposits like the length, width, slope, texture or structure have to be precise to understand the variability of the results.

The lack of knowledge on the hydrologic role of slope deposits makes it difficult to model the flow processes within a high altitude valley supplied by glaciers, snow cover and rainfall. All the flow produced by snow and ice melting, as well as, but to a lesser degree, by rainfall, has to pass through the slope deposits although their surface area is much smaller than the upstream basin.

Thus, the aim of this article is to define the influence of the slope formations on the water pathways. Do they play a negligible role or in the case of response mechanisms, how long do they delay the flow? When the daily time step is chosen in the modelling, do we have to consider the influence of slope deposits?

2. The study area

The study is located in the upper Rio Zongo Valley (16°S, 68°W, Fig. 1A) on the Eastern part of the Andean chain, about 50 km north of La Paz, capital of Bolivia. The basin where this study is carried out extends over an area of 95.2 km^2; it is dominated by summits reaching 5000–6000 m asl (Huayna Potosi, 6088 m asl). Some of these are capped by glaciers that supply the Rio Zongo. The slope deposits range between 3500 and

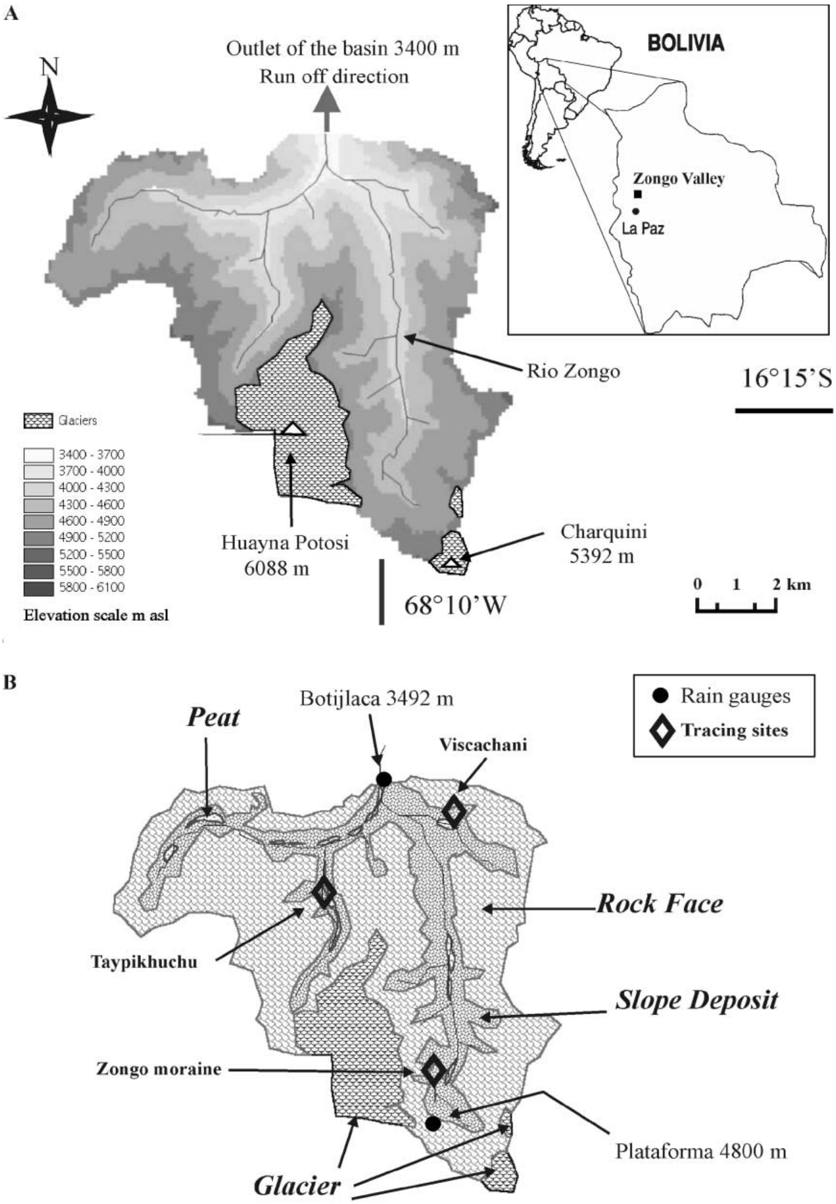

Fig. 1. Location maps. (A) Physical view of the Zongo Valley in Bolivia. (B) The different formations of the valley, with the location of the rain gauges and the tracing sites.

4500 m asl and are under the climatic influence of humid air coming up from the Amazonian basin.

The climate is defined by the position of the Intertropical Convergence Zone (ITCZ), the oscillations of which are responsible for a marked rainy seasonal variability in the

Eastern Andean area (Aceituno, 1988; Roche et al., 1990; Ribstein et al., 1995; Vuille et al., 1998; Garreaud, 1999):

Southern winter: May to September, dry and cold season;
Southern summer: November to March, warm and wet season.

In this tropical altitude context, the valley is located in the high semi-humid Andean stage (Montes de Oca, 1997). Fig. 2 presents the monthly average distribution of the precipitation at two rain gauges located (Fig. 1B) in the valley upstream (Plataforma, 4800 m asl) and downstream (Botijlaca, 3492 m asl). The variations of the monthly average temperatures do not present a large amplitude. Nevertheless, some relatively marked seasonal changes could be noted: temperatures are higher in the rainy season (Leblanc et al., 2000; Sicart et al., 1998). The 0 °C isotherm remains above 4900 m all year.

The precipitation regime is linked to the elevation and orientation of the valley (Pouyaud et al., 1999). Indeed, in the morning during the rainy season, clouds coming up from the Amazon plain can be observed (Wagnon et al., 1998; Wagnon et al., 1999). This phenomenon generates decreasing rainfall all along the valley, with intensities less than 10 mm/h above 3500 m asl. This infiltrates into the slope deposits and saturates the bottom of the valley and generates a surface flow reaching a daily average specific discharge of approximately 0.225 $m^3/s/km^2$ at the outlet of the basin (Caballero, 2001).

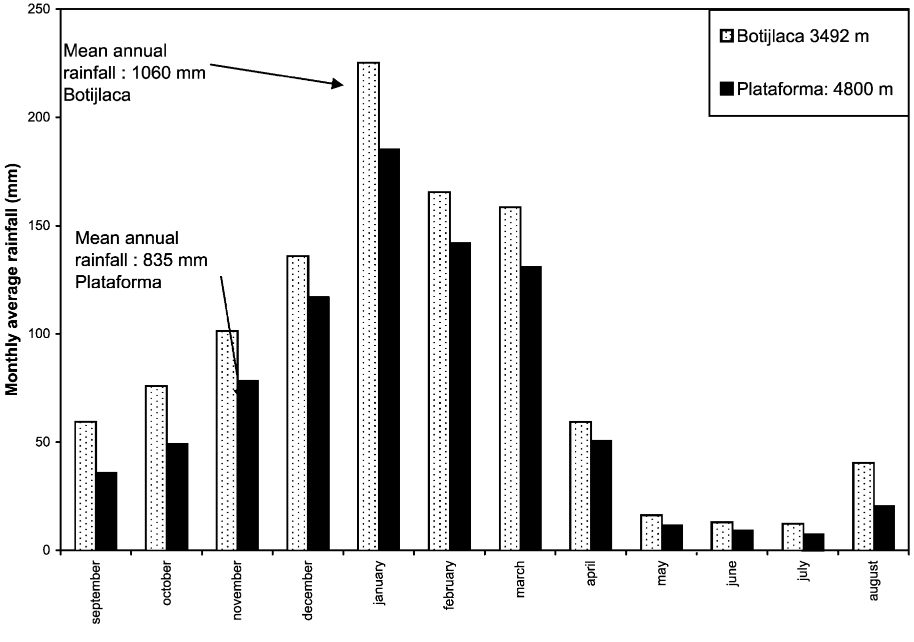

Fig. 2. Monthly average and mean annual rainfall for a 27-year period (1971–1997) at the two rain gauges of the studied basin showing the seasonal variability of precipitation, as well as the influence of altitude.

Three types of morphological zones according to the elevation can be distinguished (Fig. 1B).

- Rock faces, made of massive batholiths (granite with biotite and muscovite) and metamorphic rock (quartzites), represent more than 60% of the total surface of the basin in a horizontal projection. This medium intercepts the snow and rainfall and transfers the water in sheet or concentrated surface runoff.
- Slope deposits, constituted by lateral moraines, and talus slopes that may or may not overlie them, can reach depths in excess of 10 m from observations in closed gullies and cuts. These slope deposits represent approximately 20% of the basin area. For the most part, they are densely vegetated with humid "paramic" high mountain meadow (*Festuca* sp., *Stipa* sp.). The geographic distribution of these slope deposits is almost continuous and surrounds the entire valley forcing the flow coming from the rock faces to pass through the slope deposits (Fig. 1B). They are also subject to rainfall but rarely to snowfall and frost due to their altitude between 3500 and 4500 m asl.
- The "bofedales," local name of valley bottom formation, is composed of basal moraine and fluvio-glacial deposits overlaid by peat. They receive the upstream water coming from the slope deposits and remain saturated for much of the year.

The Zongo River forms the hydrological axis of the valley. The stream is an upstream tributary of the Amazon River. The melt waters of several small glaciers (Zongo, Charquini, Huayna Potosi) supply the Rio Zongo all year long maintaining an important discharge even in the dry season (Ribstein et al., 1995). For that reason, the seasonal variability of the flows differs from the variability of the rainfall.

3. Methods

Some tracing methods into aquifers are good estimates of hydraulic characteristics (Freyberg, 1986; Leblanc et al., 1991; Gelhar et al., 1992). However, these methods cannot be used here because of difficult field conditions (high elevation) and locally poor analysis support and facilities. The use of salt (NaCl) as tracer seemed to be adequate for our purpose. It is cheap, easily carried and with low impact on the environment and humans when dilute. In order to determine the role of these slope deposits on the water transfer times, experiments were carried out to measure the time needed by a salt water tracer, injected at one point, to flow through the formation and appear in controlled springs at the base of the slope deposits. Measurements are taken in the springs in order to register the variation of the electrical water conductivity. A survey of the water temperatures allows calibration of the conductivity values. These measurements have also been made on springs that are not connected to the injection point to be used as reference.

Some requirements were necessary to carry on the experiments: proximity of surface water to prepare the salt mixture at the injection point and to force the infiltration (see below) and presence of springs linked to the monitored slope deposit. According to field investigations, three sites were selected (Fig. 1B): (i) "Viscachani" (talus slopes), (ii) "Zongo Moraine" (lateral moraine), and (iii) "Taypikhuchu," (talus slope, and moraine). They are representative of the deposit characteristics covering the entire valley (Fig. 3a and b).

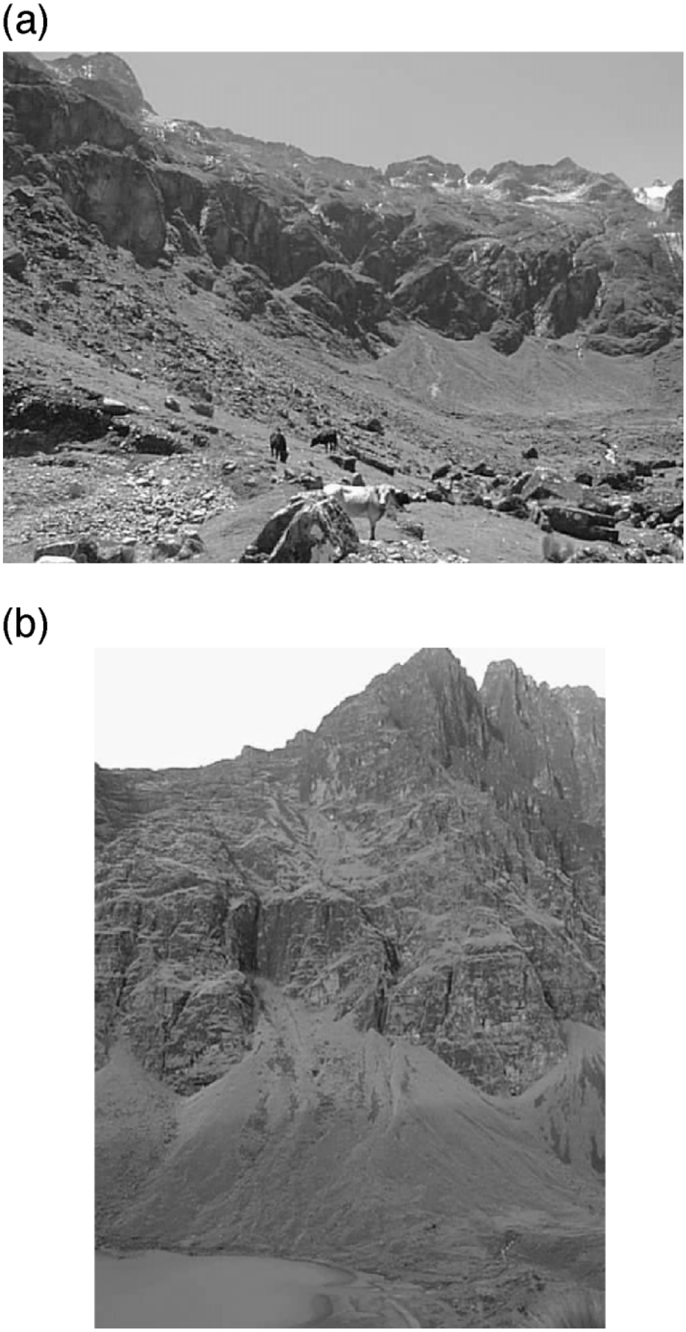

Fig. 3. Photos of (a) Taypikhuchu site and (b) Viscachani site showing the nature of the slope deposits.

Table 1
Details of the 11 experiments and morphological characteristics of studied slope deposits

Name	Type	Weather	Date	Elevation (m asl)	Length (m)	Estimated depth (m)[a]	Mean slope (°)
Taypikhuchu	moraine	rainy	19–21/01/2000	4000	130	< 5	39
Taypikhuchu	moraine	rainy/sunny	23–25/01/2000	4000	130	< 5	39
Taypikhuchu	talus slope	rainy	26–29/01/2000	4000	75	< 5	31
Taypikhuchu	talus slope	rainy	03–05/02/2000	4000	75	< 5	31
Viscachani	talus slope	rainy	01–02/02/2000	3850	240	10	31
Viscachani	talus slope	rainy/sunny	23–25/02/2000	3850	190	10	33
Viscachani	talus slope	rainy	25–27/01/2000	3850	190	10	33
Zongo	moraine	rainy/sunny	04–07/02/2000	4250	230	10	41
Zongo	moraine	rainy	27/04–03/05/2000	4250	230	10	41
Zongo	moraine	rainy	09–11/05/2000	4250	50	10	41
Zongo	moraine	rainy/sunny	14–18/05/2000	4250	50	10	41

[a] Values giving a rough estimate measured on the gullies hollowed out by the concentrated flows.

Each site is injected first with 0.1 l/s of water salted at 100 g/l during 50 min then with clear water at the same discharge of 0.1 l/s until the end of the measurements, i.e. until significant variation of the electrical conductivity of water at the spring outlets is observed, confirming the passing of the salted water. In the case of the moraines, at the Zongo moraine site, the experiment was repeated three times with a concentration of 200 g/l and for a shorter distance between the injection point and the spring in order to determine variation of the electrical water conductivity of the water more accurately.

Experiments were carried out in the rainy and dry seasons in order to understand the hydrological dynamics when the runoff is plentiful and scarce (Table 1). We also measured the mean slope of these slope deposits with a clinometer. An estimation of their minimum depth was made by extrapolating the observed depth of the gullies. To complete the analysis cuts of 1 m maximum depth were made and soil samples were taken on the surface and at different depths to analyse the texture and fabrics in the proximal and distal zone of the deposits. To better understand the internal texture of the slope deposits, all the large cuts located near the studied places resulting from stream erosion or road construction works were systematically observed.

4. Results

The results of the experiments consist in two complementary approaches: (i) a field observation of the flow processes identifying the flow path, and (ii) the computing of the time needed by the tracer to flow through the slope deposit.

4.1. The water flow path

The waterflow processes vary according to the season.

During the rainy season (October to March), water from rainfall, icemelt and snowmelt flows on the rock faces in two forms (Fig. 4), either while concentrating in the form of

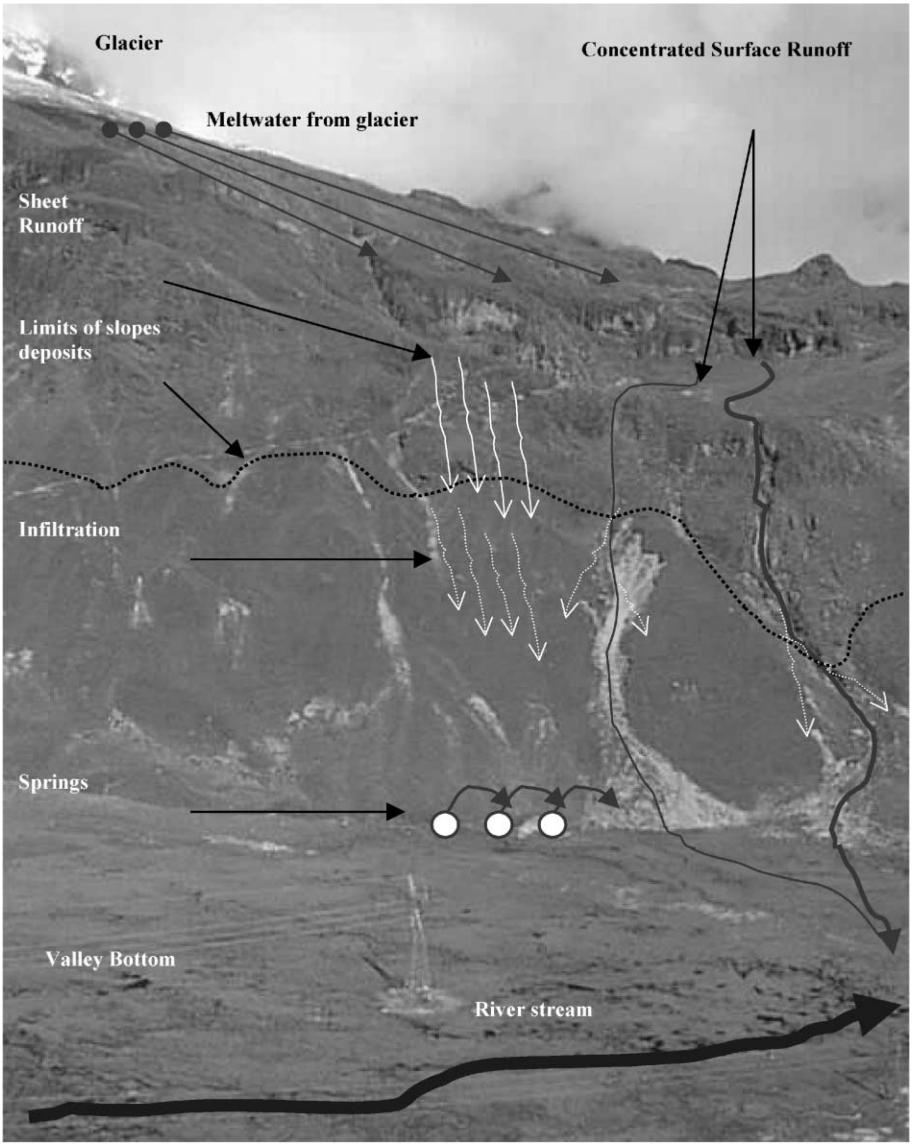

Fig. 4. Description of the flowing type on the rock faces and the observed hydrological behaviour of the slope deposits and valley bottom during the rainy season.

concentrated waterfalls or in sheet flow. When the concentrated waterflow reaches the slope deposits at the contact zone with the rock face, one part infiltrates and the rest continues as surface flow (Fig. 5). The sheet flow constitutes a much smaller part of the total runoff and totally infiltrates at the contact zone. The observations show that, because of the very low rainfall intensities, the water content of the soil always stays below

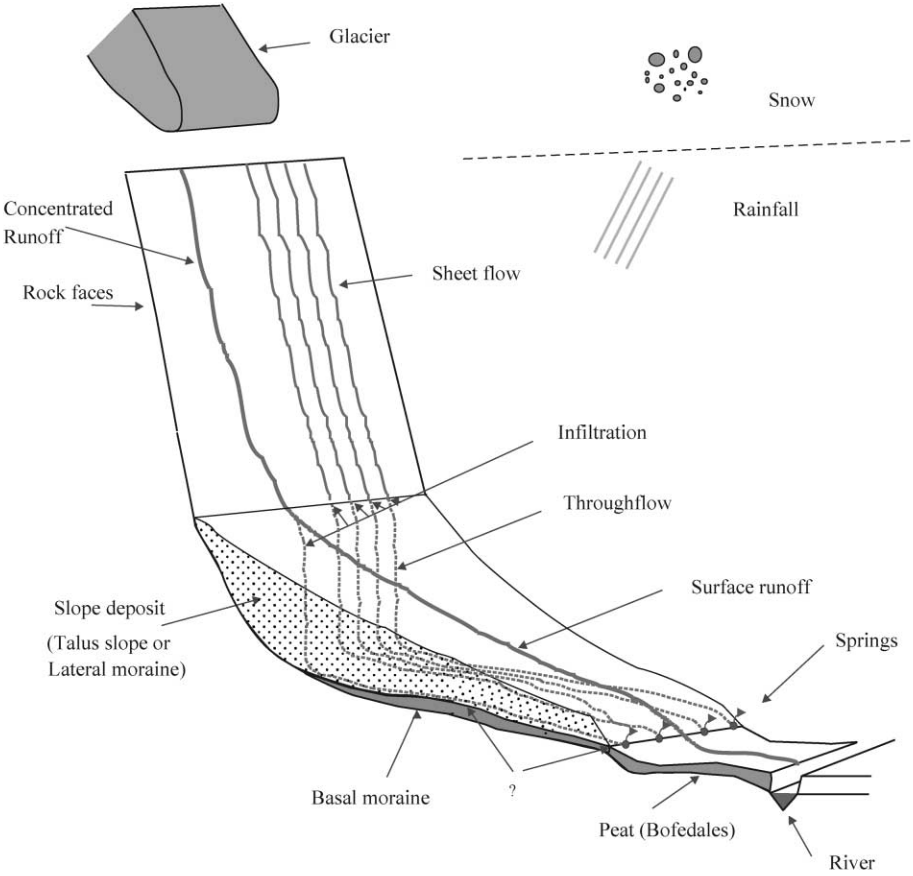

Fig. 5. Schematic description of the hydrologic behaviour of a slope deposit: infiltration and interflow diffusion.

saturation: the hydraulic conductivity remains higher than the cumulated intensity of the rainfall and infiltrated inputs, except in the concentrated surface streams or in the saturated valley bottom (bofedales).

During the dry season, the runoff come only from the glaciers as concentrated flows with several consequences:

the runoff reaching the slope deposits decreases sensibly,
the springs run dry,
the soil water content decreases.

Consequently, the flow reaching the deposit totally infiltrates making the soil water content control the flow dynamic.

A transitional regime takes place between both seasons: (i) before the rainy season, the soil water content is at its lowest value and the soil accumulates the water coming from the first rainfalls until the springs become active; (ii) after the rainy season, the slope deposits release the water in excess until the springs become dry. Thus, the continuous surface flow in the hydrographic network is established at least one month after the beginning of the rainy season (summer), and becomes discontinuous about one month after the end. These two periods are important in terms of daily waterflow modelling at the basin scale.

4.2. Response times, rising times and lag times

The results of the tracer experiments carried out indicate different ranges of response times depending on the type of slope deposit.

In this study, the "response time" is defined as the time needed by water entering the slope deposit to reach the spring. Practically, in the tracer experiment, the "response time" corresponds to the time between the beginning of the injection and the beginning of the significant increase of conductivity at the outlet. Another time, called "rising time," is defined and corresponds to the time between the increase and the peak of conductivity. Finally, we define the "lag time" as the sum of both response and rising time.

An example of electrical conductivity curves according to time on Viscachani and Taypikhuchu talus slopes is shown in Figs. 6 and 7. Following the injection of salted water, the curves present two phases: (i) a rather steady (but slow) increase of the electrical conductivity, and (ii) a sudden increase confirming the arrival of the bulk salted water. The first phase gives, for both sites, a response time of 15.5 h for Viscachani and 17.5 h for Taypikhuchu; the second phase gives a rising time of 5.5 and 12.5 h, respectively.

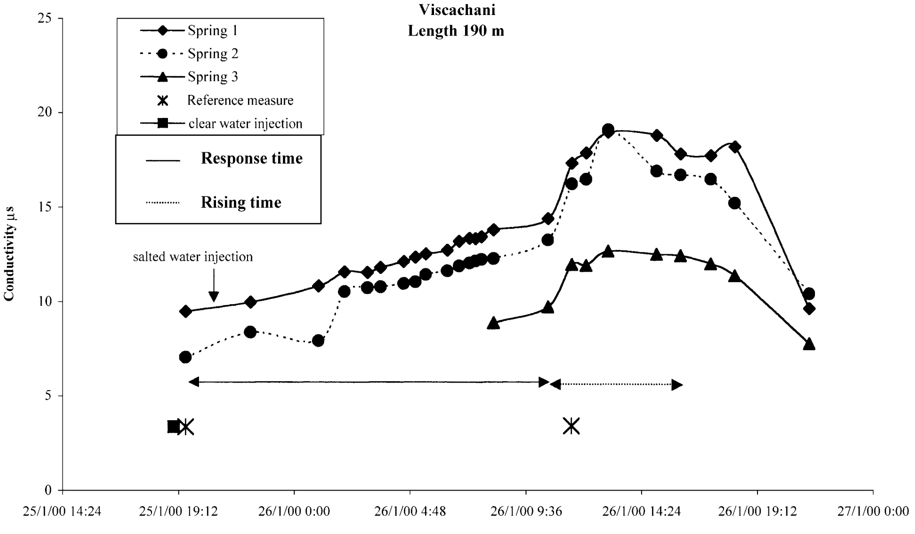

Fig. 6. Conductivity measurements on Viscachani talus slope.

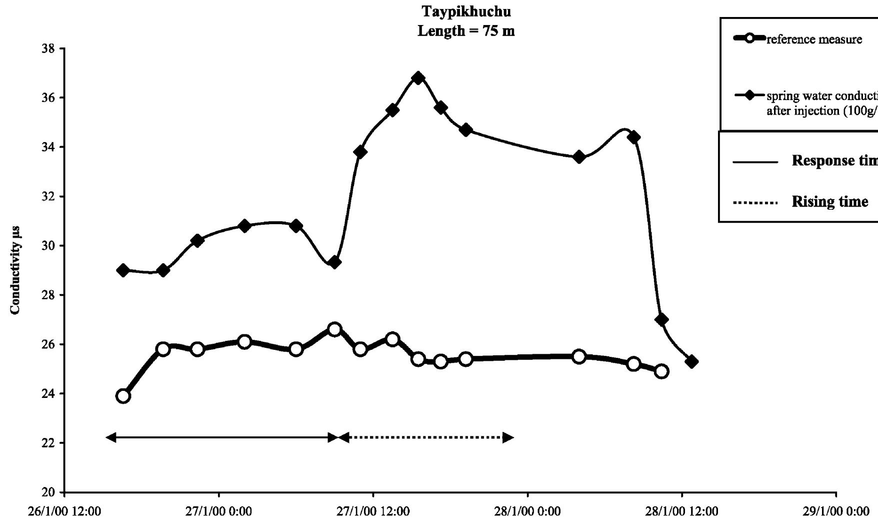

Fig. 7. Conductivity measurements on Taipikhuchu talus slope.

After the peak, in both cases, we note a rapid decrease of the signal that can be attributed to the low conductivity value of the clear water input. Meanwhile, no variation is observed in the measurements at the reference springs.

It is noted that the results obtained in the Viscachani (Fig. 6) case are clearly distinct from those obtained with Taypikhuchu's (Fig. 7). Contrary to what was expected, the

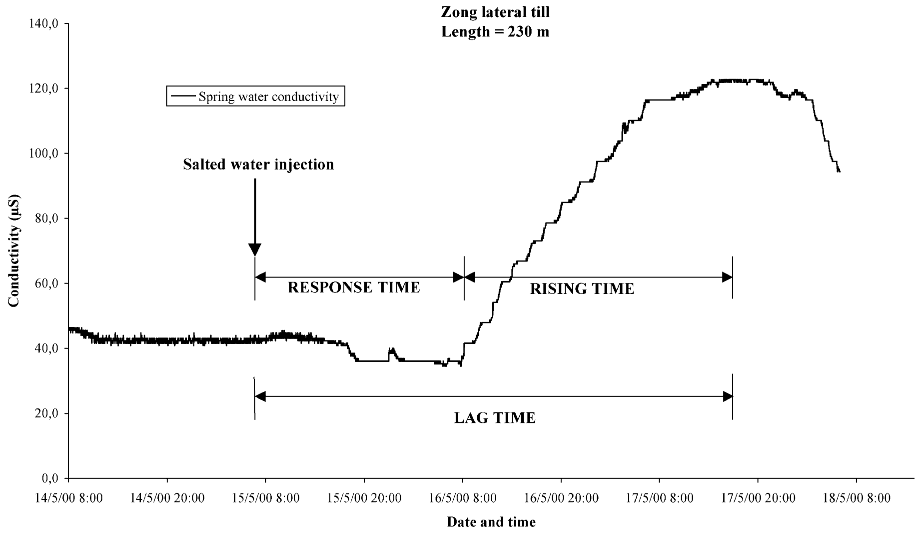

Fig. 8. Conductivity measurements on Zongo lateral till.

phases are shortest on the longest talus slope. This result will be discussed below. Finally, the three springs in Fig. 6 have an almost simultaneous response. This indicates that the throughflow within the slope deposit uses different preferential pathways.

The electrical conductivity of water in the lateral moraine at Zongo site is shown in Fig. 8. The response of the moraine is clearly different to what we could observe with the talus slopes. Although both phases described before are observed, they are noticeably different: 24 h for the response time, more than 48 h for the rising time. The end of the salt transfer was recorded in a very similar way on many springs set a few meters apart. The repetition of these experiments on different moraines did not reveal significant variations in the hydrological behaviour.

5. Discussion

Four points emphasised by the method used and by the results of the experiments have to be discussed: (i) the role of the clear water injected continuously after the salt mixture; (ii) the two phases of the response (response time and rising time); (iii) the differences between talus slopes and lateral moraines, and (iv) the transfer velocities within the slope deposit.

5.1. Clear water continuous injection

The objective of the continuous injection of local clear water after the salt mixture is to simulate the water flow mechanism during the rainy season, when the surface runoff coming from the rock faces reaches the slope deposit. Furthermore, it allows the through flow to remain uninterrupted during the transit within the slope deposit. Therefore, it is an acceptable simulation of the central part of the rainy season when the soil water content is sufficient to further the interflow, allowing observation of the faster transit.

5.2. Response time and rising time

We interpret the first phase of the response (response time) as the time interval necessary for the bulk salted water to reach the outlet. The slow increase of the electrical conductivity can be interpreted as evidence that certain flows are faster than others. The simultaneous responses of the springs shown in Fig. 6, demonstrate a throughflow diffusion. This lateral diffusion seems to be more important (9 m in 24 h) than those measured in other formations (outwash) (Leblanc et al., 1991). The second phase represents the time needed by the whole mass of salt injected to go through the measuring point.

5.3. Talus slope and lateral moraine

Our results highlight an obvious difference in the hydrological behaviour between the talus slope and the lateral moraines. Firstly, the pattern of the response time is different between the talus slopes and the moraines where there is no slow increase of the electrical conductivity of the water. This is explained by their different sedimentological pattern. From a granulometrical aspect, the moraine grain size distribution is very wide, from blocks to silts and clays. In soil samples (Table 2), silts and clays represent between 40–60% without significant variation with depth or down slope. On the opposite, the grain size distribution of the rock debris found in the talus slopes is smaller. Silts and clays represent only around 30% of the deposits in the distal zone. However, this percentage decreases near the surface or in the up slope direction. Differences in fabric and structure are generally observed. Talus slopes in the place studied are not stratified and present an open-work structure at the surface and semi open-work at a deeper level at around 0.6 m deep in the distal zone. According to large cut observations in the valleys, the morainic deposits are sometimes roughly stratified, dipping irregularly towards the flanks of the valley. This occurs even if the layers are very discontinuous and some have a texture that varies from clast-supported to matrix-supported as observed before (Benn and Evans, 1998). Consequently, the large proportion of silt and clay in lateral moraine delays the salted water transfer, thus increasing the rising time and response time.

Based on the sedimentological characteristics and on the continuous increase of conductivity, we can compare the flow within the moraines to a flow within porous medium. The presence of a large proportion of silt and clay involves capillary forces, which diffuse and homogenise the flow. This can explain the continuous increase and decrease of the conductivity curve.

Table 2
Granulometric results for samples from the upper Rio Zongo Valley

Name	Type	Sample location	Depth (m)	Percent sand	Percent silt and clay
Taypikhuchu	moraine 1	proximal	0.2	45.0	8.0
Taypikhuchu	moraine 1	distal	0.7	36.8	57.2
Taypikhuchu	moraine 2	proximal	0.3	25.7	18.1
Taypikhuchu	moraine 2	distal	0.3	21.7	15.5
Taypikhuchu	talus slope 1	proximal	0.5	11.1	13.0
Taypikhuchu	talus slope 1	distal	0.6	17.5	5.5
Taypikhuchu	talus slope 2	proximal	0.4	5.6	6.4
Taypikhuchu	talus slope 2	distal	0.3	13.1	26.6
Viscachani	talus slope 1	proximal	0.3	2.5	4.2
Viscachani	talus slope 1	proximal	0.6	5.6	11.8
Viscachani	talus slope 1	distal	0.3	14.1	11.0
Viscachani	talus slope 1	distal	0.9	15.8	12.4
Viscachani	talus slope 2	proximal	0.4	6.2	8.4
Viscachani	talus slope 2	distal	0.4	17.5	32.6
Zongo	moraine 1	proximal	0.35	35.9	19.7
Zongo	moraine 1	distal	0.8	45.9	22.1
Zongo	moraine 2	proximal	0.5	38.3	42.0
Zongo	moraine 2	distal	0.6	49.3	21.7
Zongo	moraine 3	proximal	0.3	30.9	7.2
Zongo	moraine 3	distal	0.4	34.7	14.5

On the contrary, the talus slopes can be compared to fractured medium in which the flow, following the gravity potential, is more heterogeneous and fast. This could explain the fact that response times and rising times are longer for the lateral moraines than for the talus slopes. The shorter response and rising time observed for the longest talus slope of the Viscachani site could be explained by the differences in morphology and sedimentology that exist between the two sites. We can suppose that the talus slopes of Taypikhuchu overlie older lateral moraines, which would be eroded for the Viscachani talus slope. Dates from Heine (1995) support this hypothesis. Lateral moraines in the Taypikhuchu valley date from the Holocene while moraines located at lower elevation in the Viscachani valley are much older (> 25 ka). It is likely that these slope deposits have been largely eroded to the point that they disappear in places. Moreover, this type of sedimentation has been observed in a large cut in the Taypikhuchu valley, which shows under large angular blocks a lateral moraine with a discontinuous slanting stratification overlying a basal moraine. The contact between the layers is sometimes transitional when the stratification is absent and sometimes abrupt when it is present.

The longer response of the Taypikhuchu formation can be explained by the delayed transit of the salted water within the covered lateral moraine that changes the response of the formation in comparison with the Viscachani talus slope.

5.4. Transfer velocities

Considering the lag time (response time + rising time) as a good index to represent the transfer process and knowing the surface length of the slopes, it is possible to calculate average transfer velocities. In the Zongo case (lateral moraine), we obtain a value close to 2.9×10^{-4} m/s (25 m/day). In the Taypikhuchu case (talus slope which could cover a lateral moraine), we obtain a value close to 6.9×10^{-4} m/s (59.6 m/day), 2.4 times the lateral moraines velocity. For the Viscachani case (talus slopes), we obtain about 2.5×10^{-3} m/s (216 m/day), 8.6 times the velocity of the lateral moraines. We observe that our values of transfer time are a little higher than those found in scientific literature for comparable formations (from 0.3 to 23–27 m/day) (Parriaux and Nicoud, 1990, 1993; Gelhar et al., 1992). This is probably due to the steep slopes which increase natural gradient and sedimentological characteristics.

6. Conclusion

The conductivity experiments undertaken on three talus slopes and two lateral moraines in high tropical mountains without permafrost lead to the following conclusions.

- These formations play a significant role in the waterflow transfer modelling towards the outlet. Surrounding the rock faces with summits capped by snow and glaciers, they are the only way for all the water flowing down the valley. The minimum delay is at least 24 h in the case of talus slopes with a length of 200 m, which represents a very frequent situation in the basin. During the dry season, the very low soil water content should cause a more significant delay.

- This infers that the quick transfers due to significant gradients, characteristic of this high mountain environment, are disturbed by the delay effect due to these slope deposits.
- The hydrologic behaviour of talus slopes can be clearly distinguished from the behaviour of the lateral moraines. Regarding these, the assumption that assimilates the moraines to a semi permeable porous medium explains the slow continuous increase in the electrical conductivity of the water as well as the important delay. The talus slope behaviour, where the transit is faster, can be modified by the presence of a subjacent lateral moraine.

Acknowledgements

We would like to thank O. Slaymaker, H. Van Steijn and an anonymous referee for their constructive comments.

This study was conducted within the framework of the IRD Programme GREAT ICE, at University San Andres of La Paz (Bolivia), Maison des Sciences de l'Eau (Montpellier, France) and Laboratoire de Géographie Physique de Meudon (Paris, France). The authors are very grateful to J.P. Chazarin, R.C Salinas, R. Fuertes, R. Pillco, J.M. Leblanc, T. Condom, C. Santana, C. Pacena, T. Treuil for useful discussions regarding aspects of this research and helping during field work. I. Sentenac is also acknowledged for her English writing comments.

References

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

Albjär, G., Rehn, J., Strömquist, L., 1979. Notes on talus slope formation in different climates. Geografiska Annaler 61A, 179–185.

Barsch, D., 1996. Rock-Glaciers. Indicators for Present and Former Geoecology in High Mountain Environments. Springer, Heidelberg, 319 pp.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, 598 pp.

Caballero, Y., 2001. Modélisation des écoulements d'origine pluvio-nivo-glaciaires en haute montagne tropicale. PhD thesis in progress.

Davit, A., Looser, M., 1993. Le cône fluvio-glaciaire de Montricher (Vaud, Suisse). Quaternaire 4, 61–67.

Francou, B., 1988. L'éboulisation en haute montagne. Andes et Alpes. Editec, Caen, 2 Vols. 696 pp.

Francou, B., 1991. Pentes, granulométrie et mobilité des matériaux le long d'un talus d'éboulis en milieu alpin. Permafrost and Periglacial Processes 2, 175–186.

Freyberg, D.L., 1986. A natural gradient experiment on solute transport in a sand aquifer: 2. Spatial moments and advection and dispersion of nonreactive tracers. Water Resources Research 22, 2031–2046.

Frohlich, R.K., Kelly, W.E., 1985. The relation between hydraulic transmissivity and transverse resistance in a complicated aquifer of glacial outwash deposits. Journal of Hydrology, 215–229.

Garreaud, R.D., 1999. Multi-scale analysis of the summertime precipitation over the Central Andes. Monthly Weather Review 12, 3157–3171.

Gelhar, L.W., Welty, C., Rehfeldt, K.R., 1992. A critical review of data on flied-scale dispersion in aquifers. Water Resources Research 28, 1955–1974.

Harte, P.T., Winter, T.C., 1995. Simulations of flow in crystalline rock and recharge from overlying glacial deposits in an hypothetical New England setting. Ground Water 33, 953–964.

Hamid, S., Dray, M., Ferhi, A., Dorioz, J.M., Normand, M., Fontes, J.Ch., 1989. Etude des transferts d'eau à l'intérieur d'une formation morainique dans le bassin du Léman: transfert d'eau dans la zone non saturée. Journal of Hydrology, 369–385.

Heine, K., 1995. Bedded slope deposits and late quaternary glacial sequence. In: Slaymaker, O. (Ed.), Steepland Geomorphology. Wiley, Chichester, pp. 257–278.

Hinzman, L.D., Kane, D.L., Everett, K.R., 1993. Hillslope hydrology in arctic setting. Proceedings of the Sixth International Conference on Permafrost, Beijing, China, vol. 1, pp. 267–271.

Johansson, P., 1987. Estimation of groundwater recharge in sandy till with two different methods using groundwater level fluctuations. Journal of Hydrology 90, 183–198.

Jomelli, V., Francou, B., 2000. Comparing the characteristics of rockfall talus and snow avalanche landforms in an Alpine environment using a new methodological approach: Massif des Ecrins, French Alps. Geomorphology 35, 181–192.

Jung, L., 1960. The influence of the stone cover on runoff and erosion on slate soil. International Association of Scientific Hydrology. General Assembly of Helsinki, Commission of Land Erosion Publication, Oslo University Press, vol. 53, pp. 143–153.

Leblanc, D.R., Garabedian, S.P., Hess, K.M., Gelhar, L.W., Quadri, R.D., Stollenwerk, K.G., Wood, W.W., 1991. Large scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts: 1. Experimental design and observed tracer movement. Water Resources Research 27, 895–910.

Leblanc, J.M., Sicart, J.E., Gallaire, R., Chazarin, J.P., Ribstein, P., Pouyaud, B., Francou, B., Baldivieso, H., 2000. Mesures météorologiques, hydrologiques et glaciologiques sur le glacier du Zongo. Année hydrologique 1997–1998. IRD Bolivie, Rapport no. 1, 100 pp.

Montes de Oca, I., 1997. Geografia y Recursos Naturales de Bolivia. Edobol, La Paz, 613 pp.

Parriaux, A., Nicoud, G., 1990. Hydrological behaviour of glacial deposits in mountainous areas. Hydrology of mountainous areas. IAHS Publication 190, 291–312.

Parriaux, A., Nicoud, G., 1993. Les formations glaciaires et l'eau souterraine: exemple du contexte nord alpin occidental. Quaternaire 4, 61–67.

Pouyaud, B., Ribstein, P., Gallaire, R., Chevallier, P., Caballero, Y., Berthier, E., 1999. Régimes hydrologiques des hauts bassins nivo-glaciaires boliviens et variabilité pluviométrique des vallées andines en conditions El Niño et La Niña. Manaus'99. Hydrological and Geochimical Processes in Large Scale River Basins, IRD Brasillia, Nov. 15–19.

Ribstein, P., Tiriau, E., Francou, B., Saravia, R., 1995. Tropical climate and glacier hydrology: a case study in Bolivia. Journal of Hydrology 165, 221–234.

Roche, M.A., Aliaga, A., Campos, J., Penna, J., Cortes, J., Rocha, A., 1990. Hétérogénéité des précipitations sur la Cordillère des Andes boliviennes. In: Lang, A., Musy, A. (Eds.), Hydrology in Mountainous Regions. IAHS Publication, Wallingford IAHS publications, vol. 193, pp. 381–388.

Sicart, J.E., Wagnon, P., Gallaire, R., Francou, B., Ribstein, P., Pouyaud, B., Baldiviesco, H., 1998. Mesures météorologiques, hydrologiques et glaciologiques sur le glacier du Zongo. Année hydrologique 1996–1997. Orstom Bolivie, Rapport no. 57, 119 pp.

Tenthorey, G., 1992. Perennial névés and the hydrology of rock glaciers. Permafrost and Periglacial Processes 3, 247–252.

Van de Griend, A.A., Seyhan, E., Engelen, G.B., Geirnaert, W., 1986. Hydrological characteristics of an alpine glacial valley in the North Italian Dolomites. Journal of Hydrology 88, 275–299.

Van Steijn, H., Bertran, P., Francou, B., Hétu, B., Texier, J.P., 1995. Models for genetic and environmental interpretation of stratified slope deposits: review. Permafrost and Periglacial Processes 6, 125–146.

Vuille, M., Hardy, D.R., Braun, C., Keimig, F., Bradley, R.S., 1998. Atmospheric circulation anomalies associated with 1996–1997 summer precipitation events on Sajama ice cap, Bolivia. Journal of Geophysical Research 103, 11191–11204.

Wagnon, P., Ribstein, P., Schuler, T., Francou, B., 1998. Flow separation on Zongo Glacier, Cordillera Real, Bolivia. Hydrological Processes 12, 1911–1926.

Wagnon, P., Ribstein, P., Francou, B., Pouyaud, B., 1999. Annual cycle of energy balance of Zongo Glacier, Cordillera Real, Bolivia. Journal of Geophysical Research 104 (D4), 3907–3924.

Yair, A., Lavee, H., 1976. Runoff generative process and runoff yield from arid talus mantled slopes. Earth Surface Processes 1, 235–247.