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Hydrological Sciences Journal

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t911751996

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Bohumír Janský[a]; Zbyněk Engel[a]; Jan Kocum[a]; Luděk Šefrna[a]; Julius Česák[a]
[a] Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Czech Republic

Online publication date: 13 February 2011

To cite this Article Janský, Bohumír , Engel, Zbyněk , Kocum, Jan , Šefrna, Luděk and Česák, Julius(2011) 'The Amazon River headstream area in the Cordillera Chila, Peru: hydrographic, hydrological and glaciological conditions', Hydrological Sciences Journal, 56: 1, 138 — 151

To link to this Article: DOI: 10.1080/02626667.2010.544257

URL: http://dx.doi.org/10.1080/02626667.2010.544257

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The Amazon River headstream area in the Cordillera Chila, Peru: hydrographic, hydrological and glaciological conditions

Bohumír Janský, Zbyněk Engel, Jan Kocum, Luděk Šefrna & Julius Česák

Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Prague 2, Czech Republic
jansky.b@seznam.cz

Received 12 January 2010; accepted 5 October 2010; open for discussion until 1 August 2011

Citation Janský, B., Engel, Z., Kocum, J., Šefrna, L. & Česák, J. (2011) The Amazon River headstream area in the Cordillera Chila, Peru: hydrographical, hydrological and glaciological conditions. *Hydrol. Sci. J.* **56**(1), 138–151.

Abstract The source of the world's largest river has fascinated scientists and adventurers for a long time. Extensive studies have been undertaken in the unexplored Llogueta River valley, Cordillera Chila, to identify the main stream of the Amazon River. Analysis of the Lloqueta River network and measurements of its hydrographic and hydrometric characteristics are presented in this study. On the basis of the acquired data, the northern hillside of the Cordillera Chila massif, concretely the basins of four mountainous courses—the Carhuasanta, Apacheta, Ccaccansa and Sillanque rivers—should be regarded as the headwaters territory of the Amazon River. Factors influencing the river system—glaciers and soils—were examined for each catchment. Glacier retreat in the last 50 years has left perennial snowfields only in the highest part of the study area, resulting in modification of the headwater runoff regimes. Preliminary results are afforded by the continual automatic water-level monitoring of the Lloqueta River since June 2008. Our investigations have determined that all types of soil in the area could be classified into two main categories: hydromorphic soils or poorly developed cryic soils.

Key words Amazon River sources; headwaters; Cordillera Chila; deglaciation; runoff regime; automatic water-level gauge; discharge measurement

La région source du Fleuve Amazone dans la Cordillère Chila, Pérou: conditions hydrographiques, hydrologiques et glaciologiques

Résumé La source du plus grand fleuve du monde a fasciné les scientifiques et les aventuriers pendant longtemps. Des études approfondies ont été menées dans la vallée inexplorée de la Rivière Llogueta, dans la Cordillère Chila, afin d'identifier le cours principal du Fleuve Amazone. L'analyse du réseau de la Rivière Lloqueta, et la mesure de ses caractéristiques hydrographiques et hydrométriques sont présentées dans cette étude. Sur la base des données acquises, le versant nord du massif de la Cordillère Chila, concrètement les bassins de quatre cours d'eau de montagne—les rivières Carhuasanta, Apacheta, Ccaccansa et Sillanque—doivent être considérés comme étant le territoire supérieur de l'Amazone. Les facteurs ayant une influence sur le système hydrographique—les glaciers et les sols—ont été examinés pour chaque bassin versant. Le recul des glaciers au cours des 50 dernières années n'a laissé des champs de neige pérennes que dans la partie haute de la zone d'étude, ce qui entraîne la modification des régimes d'écoulement amont. Des résultats préliminaires sont permis grâce à la surveillance hydrométrique automatique continue de la Rivière Lloqueta depuis Juin 2008. Nos enquêtes ont établi que tous les types de sols de la région peuvent être classés en deux catégories principales: des sols hydromorphes et des sols peu développés cryiques.

Mots clefs sources du Fleuve Amazone; têtes de bassin; Cordillère Chila; déglaciation; régime d'écoulement; mesure hydrométrique automatique; mesure des débits

INTRODUCTION

Up until the 1950s the Amazon River headstream area was primarily thought to be in the Marañon River basin (Fig. 1). Since 1707, the map drawn by the Czech Jesuit, Samuel Fritz, had been widely recognized as valid, locating the Amazon River headwaters at Lauricocha Lake, Cordillera Raura, part of the Peruvian western Andes (Gicklhorn & Gicklhorn, 1943; Janský *et al*. 2008). This lake is also stated as the main source of the

ISSN 0262-6667 print/ISSN 2150-3435 online

doi: 10.1080/02626667.2010.544257
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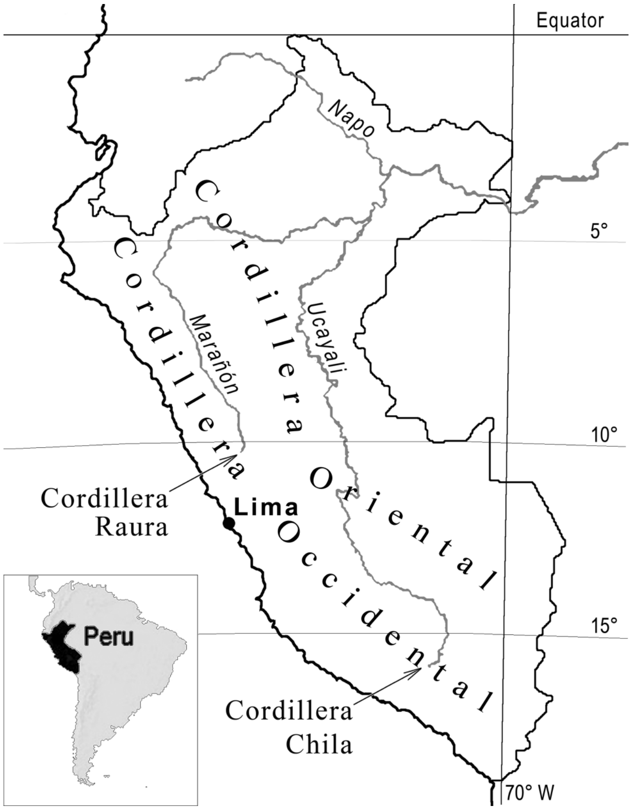

Fig. 1 Location of the Cordillera Chila in the Peruvian Andes.

Amazon River in the 2001 edition of the *Encyclopaedia Britannica* (Encyclopaedia Britannica, 2001).

In the 1950s, large-scale measurements on topographic maps (1:200 000 and 1:100 000), revealed that the Ucayali River is significantly longer than the Marañon River (Fig. 1). The Apurímac River, with its spring at the foot of the Huagra Mountain in the Cordillera Chila, was designated as the longest Ucayali River headstream (Fig. 2). Further progress in accurate delineation was achieved by Peñaherrera del Águila (Peñaherrera, 1969), who designated the Carhuasanta River, at the northern foothills of Nevado Mismi, as the source of the Apurímac River (Figs 2 and 3); the source spring is located at 71°40′36″W, 15°30′49″S. This designation was supported by research results obtained by the National Geographic Institute (Instituto Geográfico Nacional) in Lima, Peru; nevertheless, it was questioned by an international expedition to the sources of Amazon River in 1996. In 1999 and 2000 Czech and Czech-Peruvian expeditions were organized to determine the main headstream of the Apurímac River (Table 1).

Although the Cordillera Chila comprises part of the source area of the world’s largest river, it has not yet been extensively explored. The first scientific results of the region emerged in the 1980s, based on geological mapping techniques (Davila, 1988; Palacios, 1991). Several papers about this area followed in the 1990s when source streams of the Amazon River were studied (Goicochea, 1997; Palkiewicz, 1997). Preliminary results of the 1999 and 2000 Czech and Czech-Peruvian expeditions were published more recently (Janský, 2001; Šefrna, 2001; Engel, 2002).

The main research goal in this study was to investigate the earlier opinions relating to the main source of the Amazon River, and to formulate a novel theory about the headwater territory of the largest river in the world. The findings presented herein were formulated based on analyses of aerial and satellite images, and of detailed geodetic measurements carried out within the field survey. The main source of the Amazon River was determined on the basis of hydrological criteria which regarded (in descending order of importance): river length, catchment area, and discharge.

STUDY AREA

The Amazon source area is situated in the Cordillera Chila, extending between 15°19′–15°31′S and 71°39′–72°13′W, which is a part of the western mountain range (the Cordillera Occidental) of the southern Peruvian Andes (Fig. 1). The study area (15°26′44″–15°31′38″S; 71°40′35″–72°47′38″W) was delimited to include the catchment area of Carhuasanta and Apacheta rivers, sources of the larger Lloqueta River, one of the main sources of the Apurímac River (Figs 2 and 3, Table 2). Western and southern borders of the study area coincide with the main continental divide between the Pacific and Atlantic Oceans. In its southern part, the study region adjoins Nevado Mismi (5628 m a.m.s.l.), the highest peak of the Cordillera Chila. The lowermost region (4712 m a.m.s.l.) is situated at the confluence of Carhuasanta and Apacheta rivers on the northern boundary of the studied region. The study area extends over a region of 57.2 km^2.

Geology and geomorphology

The regional geology is largely connected with the Upper Tertiary to the Pleistocene Andean orogenic phase, which coincides with the culmination of volcanic activity in this region (Hardolph *et al.*, 1995). The study area consists of three different volcanic series (Davila, 1988): Miocene rhyolitic lavas (the Ichocollo Formation of the Tacaza Group), which dominate in the region; Pliocene pyroclastics (the Sencca Formation); and andesitic lavas of the Plio-pleistocene Barroso Group that are exposed in higher elevations of the region.

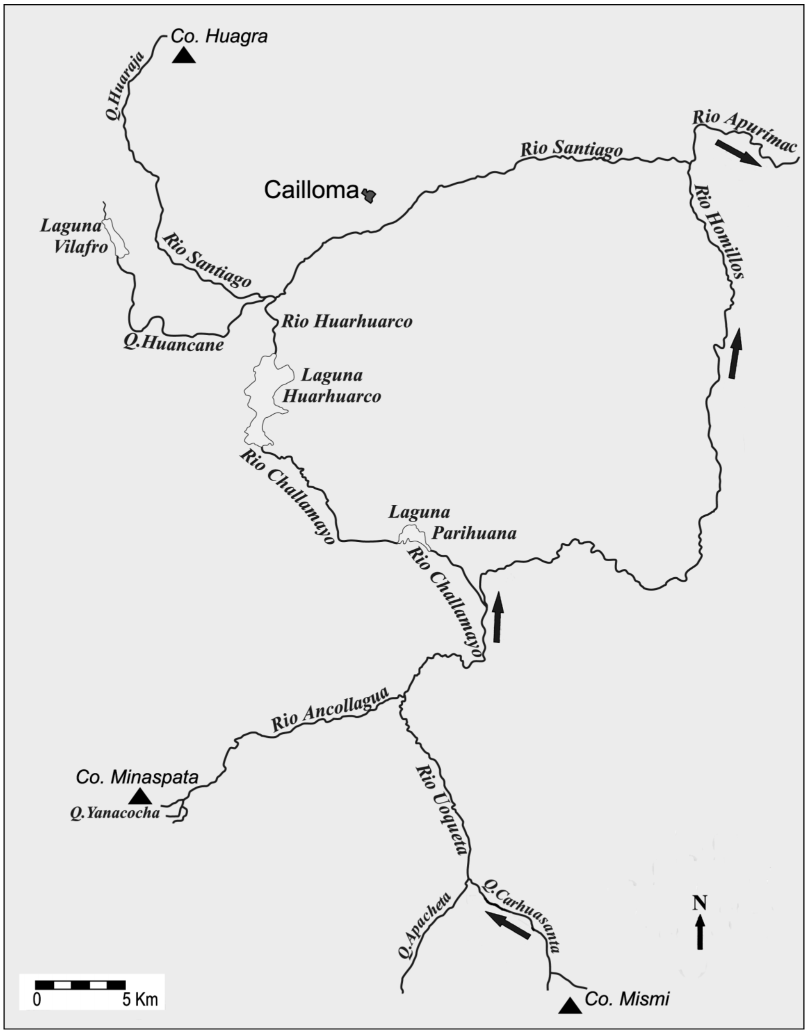

Fig. 2 Schematic map of the Amazon River headstream area.

The overall relief pattern is largely determined by glacial erosion. Deep, glacially transformed valleys and morphologically pronounced peaks and ridges interchange either with elongated flat elevations linked to volcanic plateaus or with dissected rock steps on almost horizontally bedded layers of tuffs. Recent geomorphological processes in the study area reflect the climatic conditions, with diurnal temperature variation and annual precipitation being the decisive factors. Year-long low air temperature, contingent on the high altitude of the study area, and frequent fluctuation around freezing point create good conditions for the development and action of periglacial processes (Engel, 2002).

Climatic setting

Because the Cordillera Chila is located in the western mountain range of the Andes (Cordillera Occidental), the climate of the study area is relatively dry compared to locations of the same latitude in the Cordillera Oriental. Mean annual precipitation at the SENAMHI (National Institute of Meteorology and Hydrology, Peru) climatic station La Angostura (4150 m a.m.s.l.; 30 km to the north of the headwater territory) for the 2004–2009 period reached 775 mm on average (maximum 950 mm in 2006, minimum 643 mm in 2008). The aridity is due to the relatively constant Southeast-Pacific anticyclone that inhibits moisture transport from the Pacific Ocean, and due to the barrier effect of the Central and Eastern Andes against the humid influx from Amazonia (Lettau, 1976). Most precipitation falls from November to March when the nearby Intertropical Convergence Zone enables an increased transport of humid air from the east (Johnson, 1976).

Apart from small seasonal variation, the annual range of temperature is considerably low. This is

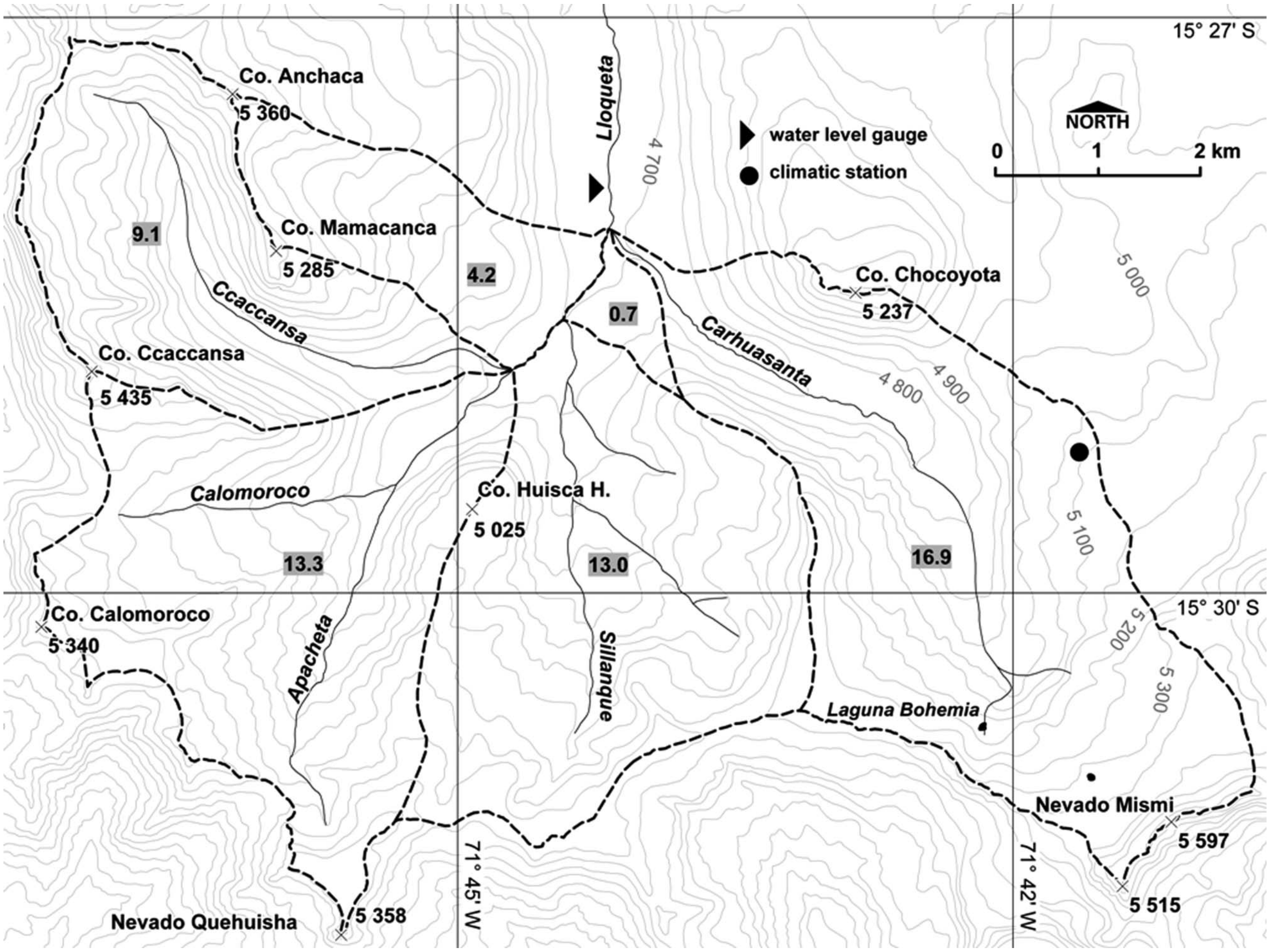

Fig. 3 River network in the Amazon River headwaters, showing enhanced sub-basin borders (in km^2) and location of the Charles University water-level gauge and climatic station.

Table 1 Summary of opinions and suggestions concerning the Amazon River headstream area (edited according to Goicochea, 1997).

Author	Year	Source
S.J. Santos García	1935	Laguna Vilafro
Michel Perrin	1953	Cerro Huagra
Gerardo Diánderas	1953	Cerro Huagra – Río Monigote
Helen a Frank Schreider	1968	Laguna Vilafro
Nicholas Asheshov	1969	Nevado Minaspata
Carlos Peñaherrera del Águila	1969	Nevado Mismi – Carhuasanta River
Loren Mc Intyre	1971	Nevado Choquecorao
Walter Bonatti	1978	Río Huarajo
Jean Michel Cousteau	1982	Nevado Choquecorao
Jacek Palkiewicz, Zaniel I. Novoa Goicochea	1997	Nevado Quehuisha – Apacheta River
Bohumír Janský et al. (Czech exp.)	1999	Nevado Mismi – Carhuasanta
Bohumír Janský *et al*. (Czech-Peruvian expedition)	2000	Nevado Mismi – headwaters of Carhuasanta, Ccaccansa, Apacheta and Sillanque Rivers

due to the low latitude, the high altitude of the study area that varies from 4710 to 5628 m a.m.s.l., and its location in the classic outer tropical climate. Diurnal temperature amplitude displays much greater range of variability, which is the result of the sensitivity of the dry alpine environment to radiation. During the austral summer (October–March), diurnal temperature amplitude reaches 25–30°C (Kastner,

Table 2 Hydrographic parameters of the Amazon River headstream area.

Stream	Length (m)	Length to the beginning of Lloqueta River (m)	Source to spring elevation (m a.m.s.l.)	River basin area (except for other inter-catchments) (km^2)	Source to catchment boundary distance (m)	Source/spring coordinates
Carhuasanta River source from Bohemia Lake	8138.4	–	5150	16.9	2130	15°30′43″S; 71°42′05″W
Apacheta River downstream of the confluence with Carhuasanta River	8134.2	–	5169	35.4	1050	15°31′15″S; 71°45′42″W
Ccaccansa River downstream of the confluence with Apacheta River	6772.2	8926.1	5177	9.1	590	15°27′26″S; 71°46′55″W
Sillanque River down to the confluence with Apacheta River	4683.6	5920.2	5039	13.0	1200	15°30′25″S; 71°44′41″W

2008), and is even greater during the winter season (April–September).

METHODS

The lengths of all streams forming the Lloqueta River network (the Ccaccansa, Apacheta, Sillanque and Carhuasanta rivers, Fig. 3) were measured using a Jenoptik LEM TM 30 laser distance gauge. Measurements were taken up the river towards the major spring in order to reflect all meanders. The length of the streams was determined along the channel centre line, i.e. the centre of the river bed. Based on the measured elevations, longitudinal profiles were constructed to allow analysis of the gradient ratios of particular streams and rivers. Geographical coordinates and elevation marks of all springs and sources were determined using GPS and a barometric altimeter.

River discharges were measured using the OTT Messtechnik C20 and C31 hydrometric propellers. A discharge regime was calculated based on actual daily measurements and correlated with ambient temperature changes. The same measurements were performed in the aforementioned profiles to determine the flow rate. The climatic conditions and hydrological regime of the studied areas was described and assessed using the measuring set from Fiedler-Mágr Company including registering and controlling unit and hydrostatic pressure sensor from June 2008. Hydrological gauges continually monitor water levels at 30-min intervals with 1 mm accuracy. The climatic station (observing precipitation, air temperature and humidity, solar radiation, wind speed and direction, and soil temperature) included a satellite module for data transmission of daily sums. Data transmission allowed an operative solution of meteorological and hydrological situations and also a regular control of the whole measuring set function. In given profiles with installed water-level gauges, periodical discharge measurements were carried out, using the above-mentioned hydrometric propellers, in order to construct accurate rating (stage–discharge) curves and to calculate corresponding discharges. The runoff regime within a day was also determined for both research periods.

The field survey and investigations in 1999, 2000, 2007, 2008, 2009 and 2010 were carried out mainly during the winter time of the Southern Hemisphere. Apart from the fact that, during this period, temperatures fall to the lowest values, precipitation also reaches its lowest volume. These conditions are important for the hydrographic analysis, as any water stream with a permanent flow rate in the driest seasons could be considered as a perennial stream.

The extent of glaciers was reconstructed for four different periods. The oldest one was created using aerial photographs acquired by the National Aerographical Institution (Instituto Aerofotográfico Nacional), Peru, in 1955. Glacier positions from 1986, 1999 and 2007 were constructed from satellite images taken by the LANDSAT 5, and the QuickBird, respectively. Mapping the extent of glaciers for these periods enabled an evaluation of the rate of glacier retreat since 1955.

Soil mapping, description, and sampling were carried out within the field survey using standard analytical methods. Laboratory analyses were used for quantification of gravel content, porosity and water-holding capacity of soils. Radiocarbon dating (^{14}C) was applied to organic matter from buried soil horizons at the valley-floor of Apacheta and Caccansa river valleys.

RESULTS

Hydrography

Carhuasanta River The Carhuasanta River basin has a drainage area of 16.9 km^2 (Fig. 3) which represents approximately 30% of the entire headwater area. An average slope of the river basin is 22.3%. The Carhuasanta River has two sources. The highest point both in the Carhuasanta River basin and in the entire headstream area, Nevado Mismi, is 2130 m from both the left branch and the fissure spring. The overall length of the Carhuasanta River, from its right source down to the confluence with the Apacheta River, is 7799.3 m. The Carhuasanta River runs through a symmetrical valley representing an advanced erosion cycle (with one of the valley closures formed by cliffs at the northern hillside of Nevado Mismi and a stone field at its foot) due to the middle stream accumulation and downstream intensive erosion. The erosion effect forms a balanced gradient profile of the stream.

The left stream springs from Lake "Bohemia" (accepted by the National Geographic Institute, Lima, Peru) with its level at the altitude of 5150 m a.m.s.l. The water runs over a rock step 15 m high. The overall length of the Carhuasanta River from the left headwaters stream to the confluence with the Apacheta River is 8138.4 m. The lake basin has been curved by a glacier into the compact andesite lava at the northwest foothills of the Nevado Mismi massif. Due to intensive frost weathering, landslides and avalanches, the lake basin is blocked. Apart from mechanical blocking, the lake basin volume is also decreased by intensive growth of the vegetation called "champa" (*Distichia muscoides*). Depth measurements verified that champa grows through the entire water column down to the lake basin bed. According to the results of bathymetric measurements in July 2000, verified in October 2009, the lake area reaches up to 1554.30 m^2, on average, in both studied years, while the maximum depth in the centre of the lake basin reached a value of 4.1 m in 2000 (3.9 m in 2009). However, within 9 years, the lake basin volume of retained water decreased by 135.4 m^3 (4.8%) as a result of the above mentioned causes (2795.5 m^3 in 2000, reported by Česák & Janský, 2008, and 2660.1 m^3 in 2009).

The right sourcing stream of the Carhuasanta River springs out under a 36-m-high cliff at an altitude of 5155 m a.m.s.l. The cliff is penetrated by a significant vertical fissure which stretches far up the hill. The spring is clearly fed by melting ice and snow at the northern foothills of the Nevado Mismi massif. At present, after the total glacier disappearance, the spring is fed only by snow (see Table 2).

Apacheta River The length of the Apacheta River from its confluence with the Carhuasanta River to the spring is 8134.2 m. The area of the Apacheta River basin upstream of the confluence with the Ccaccansa River amounts to 13.3 km^2, comprising approximately 23% of the entire headwater area. However, if the overall area of the river basin, including the tributaries, the Sillanque and Ccaccansa rivers, is taken into account, then the resultant figure amounts to 35.4 km^2. The average slope of the river basin down to the confluence with the Ccaccansa River is 18.8%.

Ccaccansa River The Ccaccansa River has the longest regular stream (8926 m) and the highest elevated spring (5177 m a.m.s.l.). In contrast to the other sources, the Ccaccansa River is defined as a spring area because a single unique spring cannot be defined unambiguously. The watershed area of the Ccaccansa River basin alone, down to the confluence with the Apacheta River, is only 9.1 km^2, which makes up only 16% of the entire headwater area (the smallest river basin among the four sources of the Lloqueta River). Significant differences in elevation between the watershed ridge and the valley floor are also implied by the large average gradient of the river basin of 22.8%, the highest gradient throughout the Lloqueta River headwaters. As regards the volume of water flow, the Ccaccansa River is the smallest river in comparison with the other Lloqueta sources.

Sillanque River The spring of the Sillanque River lies at 5039 m a.m.s.l. and is located in the basin of a former glacial lake whose floor is covered with mass wasting debris. The lake basin was also likely clogged by aeolian activity which transported low-resistant volcanic tuffs. At present, the former lake bottom is inhabited by champa-type vegetation which retains a large amount of water in the headwaters. The Sillanque River catchment area extends up to 13.0 km^2. The average slope of the basin (15.9%) represents the lowest value within the entire headstream area.

Runoff regime

Besides the hydrographic analysis, determination of the basic characteristics of the runoff regimes was carried out to compare the runoff balance of each source and to assess the runoff reaction to recent deglaciation. All sources of runoff in the study area are included: rainfall, glaciers and perennial snow cover, periodical snow cover and underground water.

In order to assess the hydrological regime in the Amazon River headwaters, two automatic water-level gauges and one climatic station were installed in the study area in June 2008. Situated about one kilometre downstream in the Lloqueta River, the closing profile of the studied basin was determined (see Fig. 3). A time series of almost one and a half years of water level (discharge) data taken at 30-min intervals was accumulated; this represents a unique database of the rivers natural characteristics and was used for detailed runoff phase analysis. On the basis of these measurements, mean daily and monthly data were calculated in order to evaluate general features and characteristics of the runoff conditions (Fig. 4). Extreme climatic conditions in this area resulted in partial destruction of the climatic station; therefore the data were discontinued (Fig. 5).

In order to obtain corresponding discharges from water-level values, a number of discharge measurements in the Lloqueta River profile were carried out to construct an accurate discharge curve. In addition, discharge monitoring was carried out in chosen profiles within the whole study basin for the purpose of hydrological balance description. In total, about 65 discharge measurements were obtained, both for 1999 and for the 2008–2009 period. Key differences were observed from the above mentioned phases of research.

The course of mean daily and monthly discharge represented in Fig. 4 shows significant runoff increase between mid-December 2008 and April 2009, whereas the absolute highest discharges are characteristic for the February–March period. Mean monthly discharges in these periods reached up to 0.575 m^3 s^{-1}, resp. 0.581 m^3 s^{-1} ($Q_{m,\max}$) in 2009 and to 0.352 m^3 s^{-1}, resp. 0.274 m^3 s^{-1} in 2010. Mean monthly discharges in the driest part of the year (October–December) fell below the value of 100 L s^{-1} ($Q_m = 0.070$ m^3 s^{-1} in December 2009). The driest part within the observed period was recorded during May 2010 ($Q_{m,\min} = 0.035$ m^3 s^{-1}. In terms of mean daily discharge, the highest runoff variability was concentrated in the period with discharge higher than the level of its study-period average ($Q_{\mathrm{avg}} = 0.198$ m^3 s^{-1}). Maximum mean daily discharge was reached on 2 March 2009 ($Q_{d,\max} = 1.221$ m^3 s^{-1}; maximum instantaneous discharge 1.499 m^3 s^{-1}), and the minimum on 19 May 2010 ($Q_{d,\min} = 0.014$ m^3 s^{-1}; minimum instantaneous discharge 0.008 m^3 s^{-1}). The year 2010 was generally drier compared to 2009, while a linear

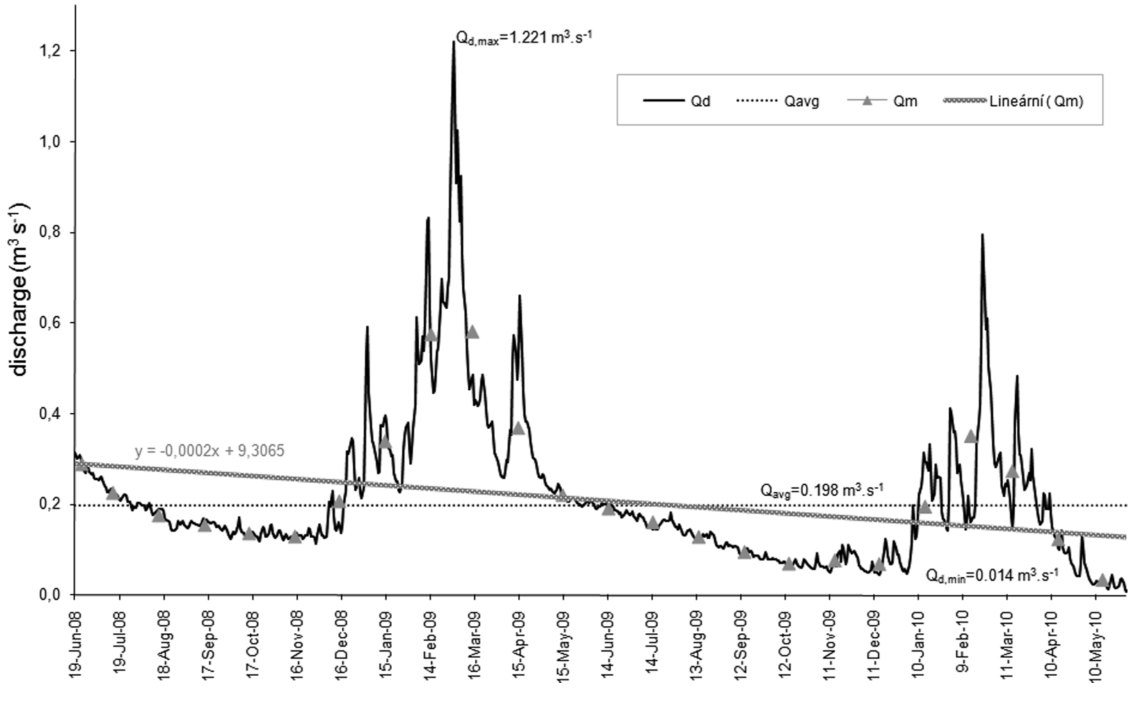

Fig. 4 Mean daily and monthly discharge measured at the Charles University water-level gauge in the period 19 June 2008–31 May 2010. The study period average and trend line of the Lloqueta River profile are shown.

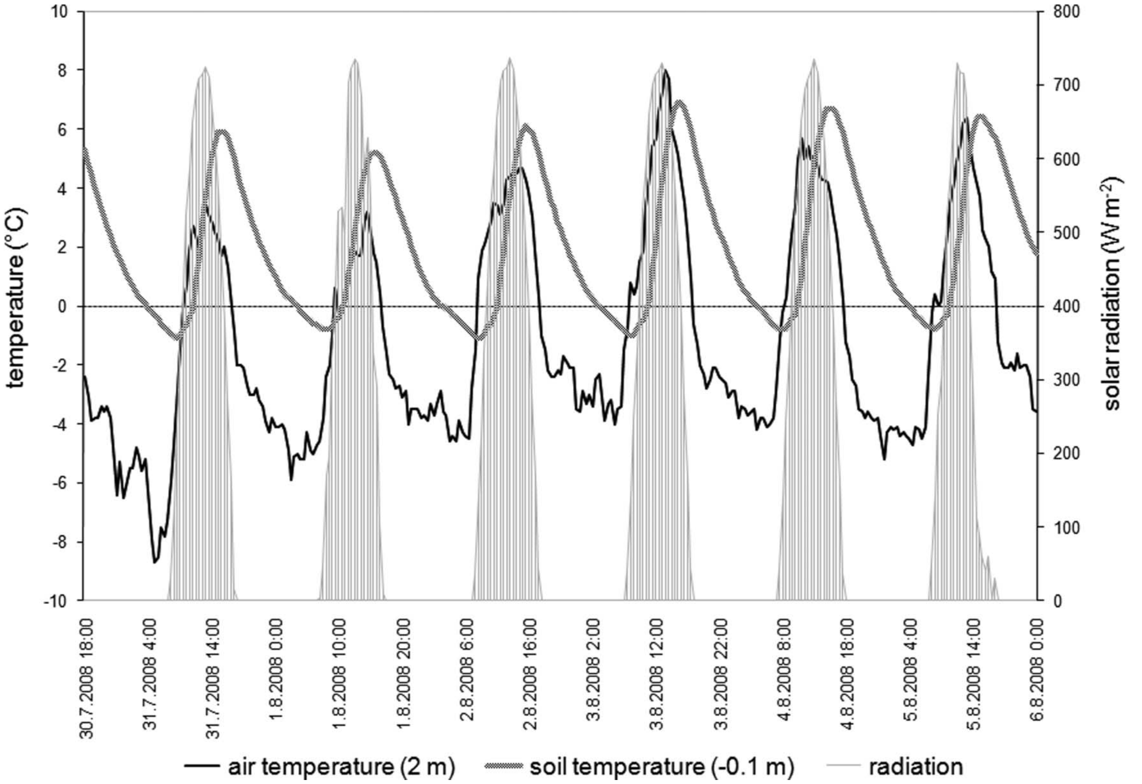

Fig. 5 Instantaneous values of air temperature, soil temperature and solar radiation in the Amazon River headstream area (5075 m a.m.s.l.; Charles University climatic station) for the 30 July–6 August 2008 period.

trend of decreasing daily and monthly discharges was observed throughout the study period. This effect in a runoff hydrogram is probably caused by variations in a seasonal snow cover and in precipitation character within a year. It could also suggest a runoff reaction to recent deglaciation and snow line recession in the area of the Nevado Mismi massif. It is provable that this deglaciation was finished in 2007. Of course, a relatively short discharge time series has to be considered when stating final findings. Deglaciation of the study area resulted also in the disappearance of outflow from Lake Bohemia in 2009, while, ten years ago, a discharge of almost 10 L s^{-1} was measured. However, the strength of the fissure spring (right source of the Carhuasanta River) had been almost constant and had fluctuated around 10 L s^{-1}, depending on the season.

Based on the hydrometric measurements for the 1999 and 2008–2009 periods, the Carhuasanta River has gradually become a more significant stream in comparison to other water courses in this area, in terms of discharge rate. Runoff conditions of the two main sources of the Lloqueta River, the Carhuasanta and the Apacheta rivers (see Fig. 3), and its variations in recent years, were analysed in order to compare their importance for the runoff formation in the study area. Hydrometric characteristics (such as specific runoff) of water streams in the headstream area, calculated in 1999, 2000 and the 2008–2009 period, show a significant balancing character of the Carhuasanta River runoff throughout the year (see Table 3). Importantly, this fact was confirmed during the driest period of the year which is the most critical assumption for a runoff permanency assessment. Insofar as the lack of glacier or perennial snow cover occurs in the study area, this fact leads to the assumption of a very marked flattening effect of champa (Fig. 7) on runoff conditions. In comparison to other streams in the study area, the existence of considerable humolites in the Carhuasanta River basin (see below) results in higher water retention, despite the less favourable elongated shape of this catchment. In 1999 and 2000, the Apacheta River showed higher values of instantaneous discharge in comparison to the Carhuasanta River. In recent years, absolute Carhuasanta River discharges have equalled those of the Apacheta River, while specific discharge is much higher compared to other parts of headstream area. In addition, the present existence of artificial irrigation channels results in the drainage of greater amounts of water from the Carhuasanta River

Table 3 Chosen instantaneous values of discharge and specific runoff measured in the Lloqueta River water-level gauge profile and in different profiles of its sources in 1999, 2000, 2008 and 2009.

Stream	Profile	Date	Time	Discharge (L s^{-1})	Specific runoff (L s^{-1} km^{-2})
Lloqueta River	Water-level gauge	21.06.1999	13:00	535.9	9.08
		13.07.2000	09:15	234.4	3.97
		13.07.2000	12:30	381.0	6.46
		19.06.2008	11:10	257.5	4.36
		14.10.2009	13:30	56.6	0.96
Carhuasanta River	Confluence with Apacheta River	24.06.1999	09:30	168.6	9.98
		06.07.2000	10:15	161.4	9.55
		19.06.2008	11:45	109.0	6.45
		14.10.2009	14:15	33.9	2.01
Apacheta River	Confluence with Carhuasanta River	23.06.1999	09:10	205.9	5.11
		06.07.2000	10:45	280.4	6.96
		19.06.2008	12:00	141.8	3.52
		14.10.2009	14:30	28.1	0.70
	Confluence with Ccaccansa River	08.07.2000	10:50	115.3	8.67
		14.10.2009	15:40	25.2	1.89
Sillanque River	Outfall	08.07.2000	11:50	83.2	6.55
		14.10.2009	15:10	2.2	0.17
Ccaccansa River	Outfall	08.07.2000	10:25	45.0	4.95
		14.10.2009	15:30	5.4	0.59

basin compared to the Apacheta River (12.5 L s^{-1}, resp. 7.4 L s^{-1} on 14 October 2009). That is why in July 2000, the discharge of the Carhuasanta River decreased by 30–50 L s^{-1}.

In the 18 June–9 September 2008 period, partial meteorological data were acquired from the climatic station (operated by the Charles University in Prague) located on the slightly inclined (10°) western slope of Nevado Mismi at an altitude of 5075 m a.m.s.l. (see Fig. 3). The outcome of the air temperature, soil temperature and solar radiation monitoring (Fig. 5) shows the course of these parameters for the period 30 July–6 August 2008. Characteristic air temperature fluctuation within a day (amplitude 8–12°C) is accompanied by very significant soil temperature fluctuation at 10 cm below surface (amplitude 7–8°C). At night (between 20:00 and 06:00 h) the air temperature was varying around –4°C, while the highest values were up to 4–6°C at around 14:00–15:00 h (mean air temperature in the studied period was 0.7°C). The highest soil temperatures were deferred by approximately 1–2 h, and reached up to around 6°C, the lowest values of around –1°C occurred between 08:00 and 09:00 h (mean soil temperature was 3.4°C). The course of soil temperature was generally more gradual. The lowest temperature in the studied period (–8.7°C) occurred on 31 July 2008 in the morning, the highest one on 21 August 2008 in the afternoon (11.3°C). Solar radiation fluctuated between 0 and 956 W m^{-2} (average value was 184.7 W m^{-2}) and showed a typical daily course. The wind of 0–16 m s^{-1} speed was mostly in a 184° direction.

Glacier recession

In 1955 there were six glaciers in the study region, covering about 3.8 km^2 (Table 4). These were small glaciers of irregular shape without typically developed cirques. The glaciers were restricted to the highest parts of mountain slopes and structural plateaus oriented to northern and southern quadrants. A surface covered by firn and glaciers was almost

Table 4 Development of glaciation in the Amazon River headwaters between 1955 and 2007.

Glacier	Area (km^2):				Maximum altitude (m)	Orientation
	1955	1986	2000	2007		
Mismi	0.57	0.50	0.45	–	5628	NW
Chayco	0.72	–	–	–	5200	NW
Quehuisha	0.97	0.20	0.20	–	5358	N
Calomoroco	0.42	–	–	–	5340	NE
Ccaccansa	0.66	0.60	0.51	–	5435	S
Cututi	0.50*	0.40	0.38	–	5360	S
Total	3.84	1.70	1.54	0.00		

*Estimation from the aerial photo; other data from 1955 are adapted from Ames (1989). All characteristics are related to those parts of the glaciers that are situated within the studied area.

continuous along the continental dividing range. In addition, limited glaciers have been distinguished on Cerro Mamacanca and Cerro Chocoyota peaks (Fig. 3). In 1955, firn and glaciers covered almost the entire area above 5200 m a.m.s.l.

Over the following 30 years (1955–1986), the glaciated area rapidly decreased. Initially, the nearly continuous firn and ice cover of the divide fell into small centres of glaciation, and those from Cerro Mamacanca and Cerro Chocoyota vanished completely. The Calomoroco and Chayco glaciers diminished substantially; however, the remainder still supplied water to the tributaries of the Apacheta and Sillanque rivers. On the major part of the Nevado Quehuisha summit plateau (Fig. 3), a glacier still existed in this period. Extensive fields of firn also appeared on the dividing range between the Nevado Quehuisha and Nevado Mismi summits (Fig. 3). The Mismi Glacier with adjacent snowfields covered an area between Nevado Mismi and Cerro Ajocolluna.

During the period 1986–1999, the glaciated area has continued to decay. The largest decrease occurred within the Calomoroco and Chayco glaciers. These had persisted only on favourably oriented southern slopes that are located beyond the study region boundary. The Quehuisha Glacier had decreased significantly, and the glaciated area in the Nevado Mismi has disintegrated into two parts. The total area of glaciers in 2000 was about 1.5 km^2. The snowline was determined at 5300 m a.m.s.l. using the glaciation-threshold method (Engel, 2002).

Progressive glacier recession at the beginning of the 21st century and subsequent deglaciation in the study region is consistent with the global trend. Glaciers have disappeared completely and fields of perennial snow persist in the highest areas only. The largest firn and ice surface (0.3 km^2) appears on the northern slope of Nevado Mismi, where the lowermost occurrence (5400 m a.m.s.l.) of continuous perennial snowfield was observed in 2007. In October 2009 the area of the perennial snow was already imponderable.

Soils

In the Carhuasanta and Apacheta river basins, 10 soil profiles were identified, as shown in Fig. 6. These soils represent the main vegetation formation, parent material and relief, and may be divided into two main categories according to their spatial distribution:

The association of hydromorphic soils Soils are characterized by aquatic moisture regime, the presence of peaty horizons and formation of diagnostic horizons in oxidizing and reducing conditions of mineral-rich material. Hydromorphic mineral soils (fluvisols and gleysols) associated with histosols create various soil groups. Profiles are generally deep and slightly gravelly, with lithological stratification features, resulting from fluvial and wind accumulation processes. These processes are still active according to the existence of slightly decayed organic matter beneath the mineral horizons of various thicknesses. Rhythmic layering of fibric, mesic and humic organic horizons and mineral horizons in deep profiles of histosols indicate highly dynamic geomorphological processes, such as erosion, mudflows or landslides. Cryoturbation of horizons is rare because of the protective influence of champa vegetation. Only lower categories of soil classification reflect (in the form of diagnostic features) the influence of seasonal frost action. However, the ground is frozen only during the coldest months and soils developed in non-permafrost conditions recently. Resulting soil groups are localized to valley-floor and slope depressions. Histosols of champa type vegetation rank among valley bogs with predominance of *Dystichia muscoides*.

Soil properties were determined using laboratory analyses. These studies found that the gravel content in homogeneous organic layers ranged from 15 to 20%. Porosity ranged from 96 to 97% and very low bulk density (0.05 g cm^{-3}) resulted in high water-holding capacity of soils. The percentage of dry matter and maximal water-holding capacity therefore reached 60%. In the study area the soil associations of described physical properties were recorded up to the depth of 12 m, considering the fact that depth varies substantially as the result of irregular accumulation of aeolian and fluvial sediments. On the basis of depth measurements at 40 sites the mean depth of organic layer was calculated to be 1.5 m. Using this value, the total amount of organic matter in the area was calculated (24×10^6 m^3), along with carbon content ($15 \cdot 10^3$ kg) and maximum capacity of water retention ($21–23 \times 10^6$ m^3). According to radiocarbon data from the Apacheta River valley, the uppermost part of the hydromorphic soil (1.5 m deep) originated since 2200 years BP.

Histosols in champa formation are a very important landscape element for sequestration of organic carbon. Loss of living photosynthesizing plants caused by drying leads to progressive destruction of

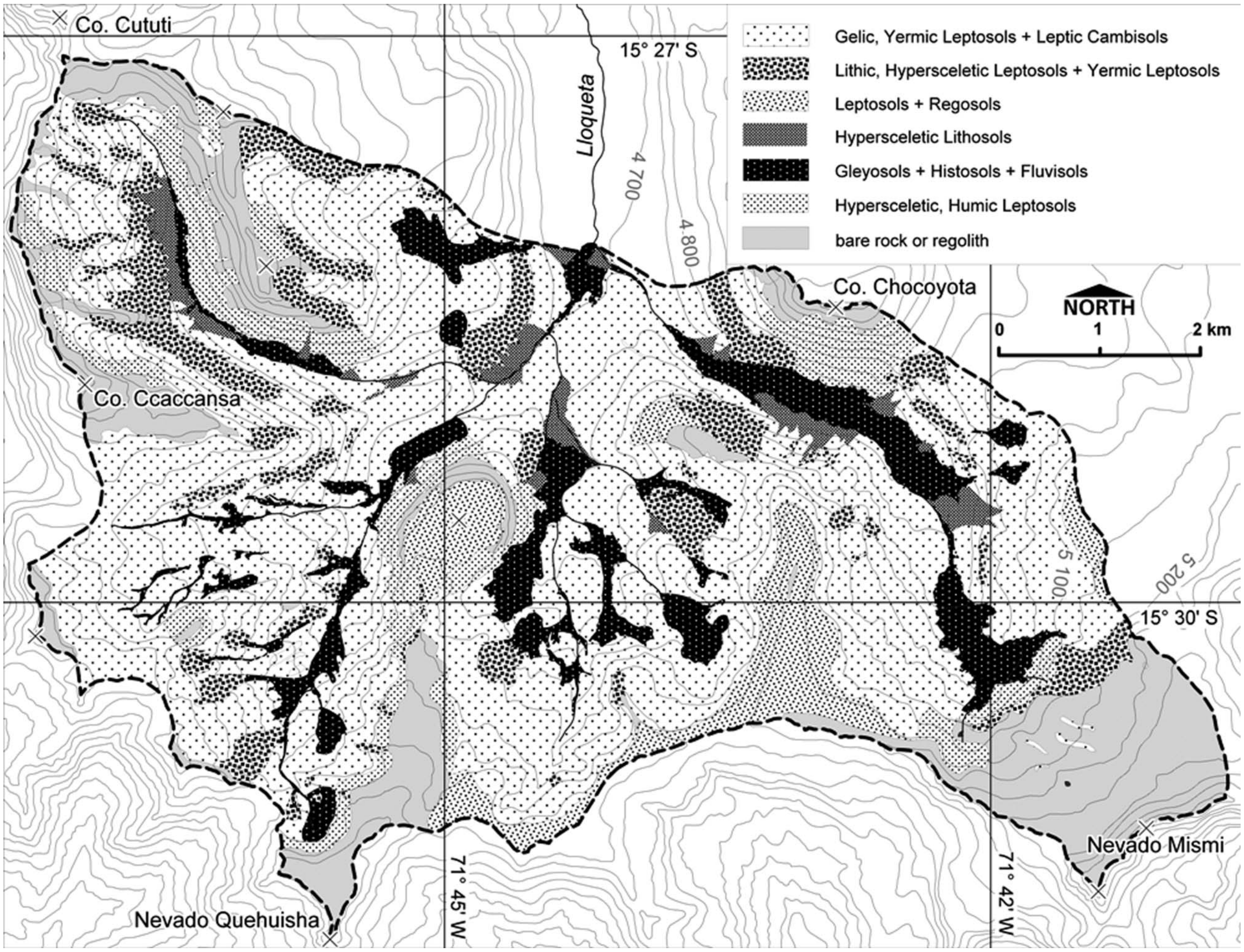

Fig. 6 Distribution of soils in the Amazon River headstream area.

histosols by water and wind erosion and to final mineralization. This leads to the return of organic carbon into the atmosphere in the form of CO_2. The recent deglaciation in the study area affected its water balance which could result in degradation of histosols and loss of its water reservoir. Changes in precipitation amount and distribution may play a significant role in this scenario. Possible loss of water would threaten pasturage that represents the main source of living for the aboriginal population.

Soils associated with higher elevated glacial and slope accumulations Gravelly and shallow cryic soils, lithosols and cryic rankers (frequently with signs of cambic horizons) dominate this group of soils. Soils are covered by discontinuous arid- to steppe-like vegetation with predominance of *Stipa*, *Festuca*, *Calamagrostis* and frequent pillows of *Azorella yarita* which each could cover an area up to 3 m^2. Soil profiles are characterized by lower development, low thickness and high content (more than 50%) of gravels and pebbles. Initial stages of red cambic horizons B_v could be identified in profiles. The sparsely vegetated surface horizons exposed to periglacial conditions are fragmented by frost action and subsequently disturbed by wind deflation (Fig. 7). Aeolian material captured selectively by tuft vegetation enriches A horizons and forms important allochthonous component of soil profiles. In lower elevations (up to 4800 m a.m.s.l.) grazing affects the soil cover, while in higher elevations, the surface of soils is generally free of vegetation. Uncovered soils are characterized by various cryic features, such as polygons or stripes. Despite the fact that vegetation is very rare, organic matter content indicates seasonal biologic activity. Compared to the hydromorphic soils, the soils associated with glacial and slope accumulations are characterized by a lower pH value and lower cation exchange capacity. Lithosols are characterized by pH values ($CaCl_2$) ranging from 4.4 to 5.0 and by cation exchange capacity of 7.6–9.4 mmol 100 g^{-1},

Fig. 7 Wind action-controlled cushions of vegetation. The existence of champa type vegetation affects the runoff regime in the study area significantly.

whereas the pH of hydromorphic soils ranges from 5.2 to 6.3 and cation exchange capacity from 16.7 to 38.0 mmol 100 g^{-1} (Šefrna, 2008).

DISCUSSION AND CONCLUSIONS

In this study, hydrographic criteria (in order of priority): length of the permanent river stream, river basin area and discharge, were used to determine the sources of the Amazon River. The data represent the primary results of field surveys carried out by Czech and Czech-Peruvian expeditions in 1999 and 2000. The longest permanent stream in the headwater area is the Ccaccansa River, which also represents the Apacheta River left tributary (its respective length is 6772.2 m). Its spring is situated 8926 m from the river basin outlet section. This stream also has the highest altitude of its spring (5177 m a.m.s.l.). The second longest stream is represented by the Carhuasanta River (8138.4 m), followed by the Apacheta River (8134.2 m). The shortest water course in the whole study area is the Sillanque River (4683.6 m). The furthest point of the study area from which the water runs to the Amazon River estuary is the ridge of Nevado Mismi, located 2130 m from the Carhuasanta left branch. Approximately the same distance lies between the Carhuasanta rock spring and the eastern edge of the watershed ridge. From all sources and headwaters, the Carhuasanta River also has the largest river basin area (16.9 km^2). According to flow rates, the Carhuasanta and Apacheta rivers are remarkably more water-rich than the remaining rivers. In 1999 and 2000, the Apacheta River instantaneous discharges significantly exceeded those of the Carhuasanta River. Considering the fact that the Carhuasanta River discharge has been artificially reduced by water transferred through the channel down to the Lloqueta River, both rivers featured comparable flow rates in above mentioned years. Within the 2008 and 2009 field surveys, different findings were made relating to the flow rates of these Lloqueta River sources. In the 1999–2009 period, the Carhuasanta River, in comparison to other water courses in this area, has gradually become the most significant stream with the highest rate of discharge. In 2009, instantaneous discharge showed higher values for the Carhuasanta River in comparison to the Apacheta River. Hydrometric characteristics (such as specific runoff) of water streams in the headstream area were calculated for the periods studied and showed that the Carhuasanta River has a balancing effect on the Lloqueta River runoff throughout the year. This fact was contradicted during the driest period of the year. Considering the fact that glacier and perennial snow cover no longer occur in the study area, the Carhuasanta River runoff permanency and flattening effect is very likely related to the considerable amount of humolites (fixed on champa formation) in the Carhuasanta River basin. This results in higher water retention and retardation despite the less favourable elongated shape of its catchment.

The results and outcomes of the recent field surveys show that the single and unique source of Amazon River cannot yet be unambiguously identified. Particular criteria support two of the four headstreams, namely the Carhuasanta and Ccaccansa rivers, as being the more likely sources. When compared, the Carhuasanta River has a prevailing role as it has the largest river basin area and flow rate. The furthest point from which the water flows down to the Atlantic Ocean, is also situated in its basin. On the other hand, the permanent stream of the Ccaccansa River is the longest. As the main source of the Amazon River cannot be unambiguously determined, we suggest that the northern hillside of the Cordillera Chila massif, with an area of 57.1 km^2, and the confluence of four courses (Carhuasanta, Apacheta, Ccaccansa and Sillanque rivers) feeding the Lloqueta River, should be regarded as the headwater territory of the Amazon River.

In order to assess the possible reaction of runoff conditions to recent deglaciation and snow line recession in this area, linear trend analysis of daily and monthly discharges was determined throughout the monitored period. Decreasing effect in a runoff hydrogram is probably caused by seasonal snow cover variations and precipitation character. This fact could also support the hypothesis that runoff conditions reflect the recent deglaciation (finished in 2007) and snow line recession in the area of the Nevado Mismi massif. Undoubtedly, the relatively short discharge time series has to be considered while stating final findings. The present network of automatic hydrological and meteorological gauges in this area represents very favourable conditions for the detailed analyses of the runoff ascending and descending phases and related partial goals.

Since 1955, the glaciers in the observed area have undergone rapid retreat: glaciers experienced a 60% decrease in surface area over the 20th century disappearing completely between 2000 and 2007. The deglaciation of the study area is consistent with observations of glacier retreat in other regions of the Peruvian Andes. The rate of glacier recession over the 20th century is similar to the retreat of glaciers in the Cordillera Blanca, where 60% decrease in glaciated area was observed between 1962 and 1999 (Mark, 2002). The progressive melting of glaciers in the study area at the beginning of the 21st century coincides with accelerated rates of glacier retreat that are well documented at high altitude throughout the tropics (Georges, 2004; Thompson *et al*., 2006).

Climatic and geomorphological conditions are the most decisive factors of the soil development. The variability in soil texture reflects aeolian and fluvial transport of the weathering products and easily decaying parent material (tuffs). Soils are predominantly sandy to loamy and pH decreases from watershed areas towards valley floors. Champa-type vegetation and more or less developed histosols contain significant amounts of organic matter and represent a vast water retention space. Soils could be ranked among two different associations: (a) cryic soils, organic soils, fluvisols and transitional groups of these soils tied to water saturated relief depressions; and (b) cryic soils, lithosols and cryic rankers on slopes and convex surfaces of landscape including lower elevated watershed plateaus.

Acknowledgements This research was funded by the Czech Science Foundation Project "Natural Hazards of the Amazon River Source Territory Caused by the Global Climatic Changes" (205/07/831) and by the Czech Ministry of Education Project "Geographical Systems and Risk Processes in the Context of Global Change and European Integration" (MSM 0021620831), Czech Republic.

REFERENCES

Ames, A. (ed.) (1989) *Glacier Inventory of Peru. Part II*. Huaraz: Hidrandina S.A.

Česák, J. & Janský, B. (2008) Laguna "Bohemia". In: *Los Orígenes del Amazonas* (B. Janský, ed.), 231–232. Praha: Ottovo Nakladatelství.

Davila, M. D. (1988) *Geología del Cuadrángulo de Cailloma (Hoja 31-s)*. Lima: INGEMET, Boletín no. 40, Serie A.

Engel, Z. (2002) Geomorphology of the Amazon source area in the Cordillera Chila. *Acta Montana Ser. A* **19**(123), 91–108.

Encyclopaedia Britannica (2001) Chicago: Macropaedia.

Georges, C. (2004) 20th-century glacier fluctuations in the tropical Cordillera Blanca, Peru. *Arctic, Antarctic, and Alpine Res.* **35**, 100–107.

Gicklhorn, J. & Gicklhorn, R. (1943) *In Kampf um den Amazonenstrom. (Das Forschungschicksal des P. Samuel Fritz)*. Praha: Noebe & Co.

Goicochea, Z. I. N. (1997) *El Origen del Río Amazonas*. Lima: Pontificia Universidad Católica del Perú.

Hardolph, A. W., Alan, H. C., Edward, F. & Robert, J. L. (1995) Grenvillian granulite-facies metamorphism in the Arequipa Massif, Peru: a Laurentia-Gondwana link. *Earth and Planet. Sci. Let.* **132**, 63–73.

Janský, B. (2001) Nuevo levantamiento geodésico—hidrográfico de los orígenes del Amazonas. *Rev. Geogr.* **128**, 151–164.

Janský, B., Castro, D. D., Česák, J., Engel, Z., Jakeš, P., Kastner, J., Kořínek, V., Kupčík, I., Penaherrera del Águila, C. & Šefrna, L. (2008) *Los Orígenes del Amazonas*. Praha: Ottovo Nakladatelství.

Johnson, A. M. (1976) The climate of Peru, Bolivia and Ecuador. In: *Climates of Central and South America* (W. Schwerdtfeger, ed.), 147–218. Amsterdam: Elsevier.

Kastner, J. (2008) Condiciónes climáticas. In: *Los Orígenes del Amazonas* (B. Janský, ed.), 208–213. Praha: Ottovo Nakladatelství.

Lettau, H. (1976) Dynamic and energetic factors which cause and limit aridity along South America's Pacific coast. In: *Climates of Central and South America*. (W. Schwerdtfeger, ed.), 188–192. Amsterdam: Elsevier.

Mark, B. (2002) Observations of modern deglaciation and hydrology in the Cordillera Blanca. *Acta Montana Ser. A* **19**(123), 23–36.

Palacios, M. O. (1991) *Geología del Cuadrángulo de Chivay*. Lima: INGEMET, Boletín no. 42, Serie A. Hoja 32-s.

Palkiewicz, J. (1997) *Towards the Origin—In Search of the Amazon, the Most Extraordinary Rriver on Earth*. Lima: El Dorado.

Peñaherrera, C. (1969) *Geografía General del Perú*. Tomo I,. *Aspectos Físicos*. Lima: Editorial Ausonia Talleres Graficos.

Šefrna, L. (2001) Pramen Amazonky (Amazon sources). *Vesmír* **80**(2), Prague, 95–101 (in Czech).

Šefrna, L. (2008) Los suelos y la biósfera en la región de las nacientes del Amazonas. In: *Los Orígenes del Amazonas* (B. Janský, ed.), 196–207. Praha: Ottovo Nakladatelství.

Thompson, L. G., Mosley-Thompson, E., Brecher, H., Davis, M. E., Léon, B., Les, D., Lin, P. N., Mashiotta, T. A. & Mountain, K. (2006) Abrupt tropical climate change: Past and present. *PNAS* **103**(28), 10536–10543.