

Correct placement of the most distant source of the Amazon River in the Mantaro River drainage

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The Amazon River ('Río de las Amazonas') has the highest discharge of any river in the world and is also the longest or second longest. Its source has therefore intrigued scholars and explorers for centuries. A river's source is often defined as the most distant upstream point in the drainage basin. For the past several decades, the longest upstream extension of the Amazon River has been held to be the Nevado Mismi area of the Río Apurímac drainage. We overturn this longstanding view by employing topographic maps, satellite imagery, digital hydrographic datasets and GPS tracking data to show that the Cordillera Rumi Cruz (10.7320°S, 76.6480°W; elevation ~5220 m) in the Río Mantaro drainage lies 75–92 km further upstream than Nevado Mismi. We compare various methods for measuring each of the Río Apurímac and Río Mantaro lengths, and show that high-resolution satellite imagery and GPS tracking most closely follow the path of the water. Our results reposition the 'most distant source' of the Amazon to a more tropical location, change the uppermost ~800 km of river to this point, and add 75–92 km to the river's maximal length.

Key words: Peru, hydrography, GIS, cartography, HYDROSHEDs, DEM

Introduction

At 6300–7000 km in maximal length, the Amazon River (also called 'Río de las Amazonas' or just 'Amazon') is the first or second longest river in the world and by far the largest, carrying an estimated 20% of the freshwater river flow on earth (Christ *et al.* 1990). There has been interest in defining the starting point of the river for centuries. Pinpointing the source is important for measuring the full length of the river, for properly indicating its origin point with a geographical monument, and for studying hydrological characteristics, the condition of glacial sources and other features associated with the headwaters of the river.

A river's source can be defined as either (a) the farthest upstream point along the main river, found by following the channels with the highest average discharge (the 'mainstem') or (b) the absolute farthest upstream point in the entire river basin, which may involve following a tributary upstream. These two source points are best termed the 'principal source' and 'most distant source',

respectively, and may or may not coincide. While the principal source stream usually commands the same name as the river at its mouth, the most distant source defines the river system's maximal length.

The most distant source of the Amazon was originally posited to lie at the uppermost Río¹ Vilcanota–Urubamba–Ucayali (Squier 1877; Kerbey 1905; Besley 1914). Once better maps became available, various geographers and adventurers proposed the uppermost Río Apurímac as the Amazon's source because Río Apurímac–Ene–Tambo extended more than 200 km further upstream compared with Río Vilcanota–Urubamba (Figures 1 and 2) (Dianderas 1955; Perrin 1955; Peñaherrera 1969; Schreider and Schreider 1970). Although initially Río Apurímac was believed to begin at Lago Vilafra, closer analyses indicated more distant sources at the nearby Cerro Huagra (Figure 3a) (Dianderas 1955; Perrin 1955; Schreider and Schreider 1970), Nevado Minaspata (Ridgway 1972) and Nevado Mismi (Peñaherrera 1969). McIntyre and his colleagues subsequently confirmed that Nevado Mismi was the source, a result published and



Figure 1 Amazon River basin, including dark traces for each posited source river: Napo, Marañón, Huallaga, Urubamba, Apurímac, and Mantaro. Yellow lines denote country borders.
Source: Texturized background derived from Google Maps and HydroSHEDS

popularised by *National Geographic* magazine (McIntyre 1972). The water coming off Nevado Mismi flows into Quebrada Carhuasanta and then Ríos Lloqueta–Challamayo–Hornillos–Apurímac, which became recognised as the upper Amazon (McIntyre 1991).

Over the past two decades, others interested in the source of the Amazon aimed to confirm Nevado Mismi and Quebrada Carhuasanta as the most distant extension of the river system (e.g. see Martini and Garcia 1996; Goicochea 1997; Palkiewicz 1997; Johnston *et al.* 1998; Johnston 2002; Jansky *et al.* 2011). Some disagreement arose primarily because in some seasons or years, the neighbouring Quebrada Apacheta (arising from Nevado Quehuisha) was found to have a more distant upstream extension of flowing surface water. The debate has centred on differing opinions about what should be considered a river's 'source': the most distant upstream point where (a) a drop of precipitation will make its way into the river, (b) a continuously flowing surface water emerges or (c) surface

water is found. Although all of these definitions are based on a most-distant point upstream, the uppermost points of surface water or flowing water can vary at different times of the year. In the case of Quebradas Apacheta vs Carhuasanta, the disagreement only affects the uppermost 8 km of river, but it does change the point considered the official 'most distant source' of the Amazon. The disagreements are reflected in various source-to-sea adventurer accounts. Most such expeditions have started at Quebrada Apacheta, but sometimes with members making short hikes up/down Quebrada Carhuasanta as well (e.g., see Chmielinski 1987; Kane 1989; Horn 1998; Angus 2002; Kalch 2010).

In the past several decades, all who have published opinions on the source of the Amazon have focused on the furthest upstream extension in the river basin as the most critical element for defining the source. Although recent studies have examined this issue in the upper Río Apurímac drainage, a larger analysis of the exact lengths



Figure 2 Ríos Mantaro and Apurímac. After the two join, the resulting stream is called Río Ene. Various bridges, dams and confluences are noted along each river at points separating measured segments in Tables 3 and 4. Boxed areas at the source area of each river are shown in more detail in Figure 3.

Note: R = Represa; P = Puente; Pen. = Península

Source: Texturized background derived from Google Maps

of other tributaries in the Amazon watershed has never been conducted. In the current study, we determined that the most distant source of the Amazon system was located in a previously unrecognised tributary, and then used a variety of methods to measure how much further upstream it was compared with Nevado Mismi.

Methods

Maps and datasets utilised in this study are listed in Table 1. Relevant datasets are available to download at www.SierraRios.org/Peru/AmazonSource.html and as Supporting Information to this article.

Topographic map measurements

To measure stream lengths with topographic maps, digitised 1:100 000 scale maps in the Transverse Mercator projection from Peru's Instituto Geográfico Nacional (IGN) were loaded into a Geographic Information System (GIS) software program Arcmap 10.1 from the Environmental Systems Research Institute (ESRI; Redlands, CA), georeferenced and projected into the appropriate Universal Transverse Mercator (UTM) zone (e.g. zone 18S for Ríos Mantaro and Apurímac), using the WGS 1984 datum. Gullies/streams were traced with vectors and the vector lengths measured with the 'measure geometry' function.

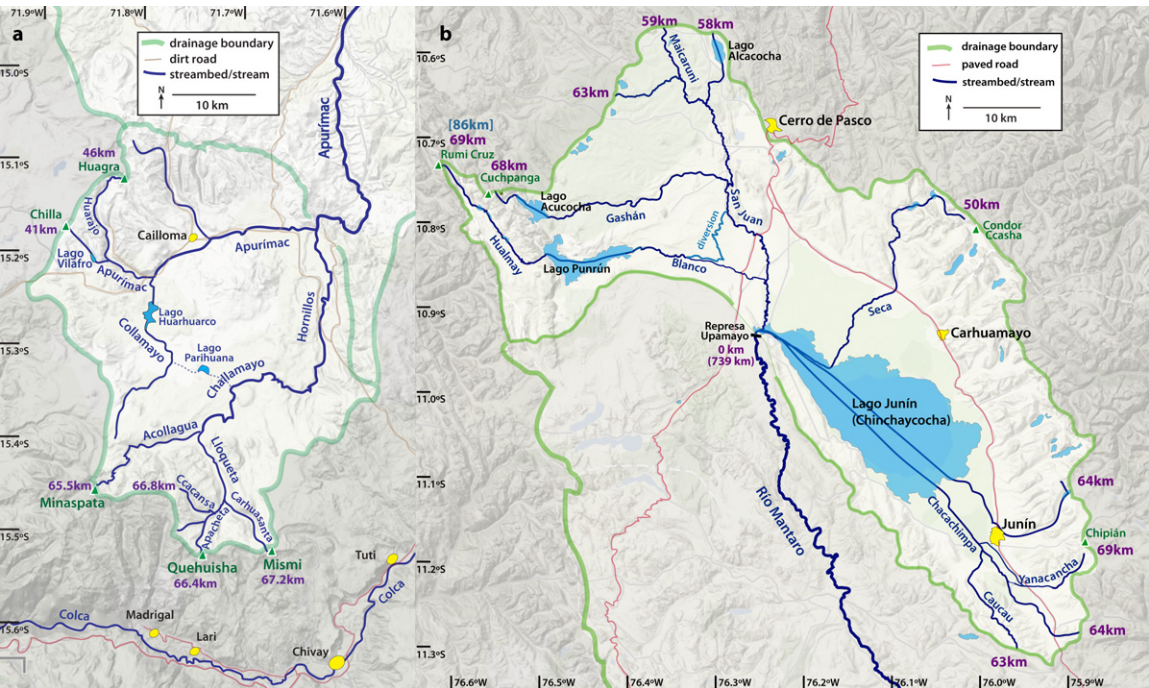


Figure 3 Most distant source areas of the Amazon River. (a) Headwaters area of Río Apurímac. Numbers by each potential source point are stream lengths from the mountain source to the Apurímac/Hornillos confluence. (b) Headwaters area of Río Mantaro, with Google Earth-measured distances from the mountain source to Represa Upamayo. Shortest straight-line paths were measured across lakes. The Cordillera Rumi Cruz and Cerro Chipián are the most distant upstream points in the Amazon River basin.
Source: Texturized background derived from Google Maps

Table 1 Sources of spatial data

Dataset	Source	Agency	Accuracy	Resolution
Contos GPS	Garmin GPS tracks	Global Navigation Satellite System	5–10 m horiz.	High
Google Imagery	Google Earth	Digital Globe/Google	1–15 m	Medium–high
Bing Imagery	ArcGIS WMS	Microsoft	1–15 m	Medium–high
Topographic Maps	survey/satellite/other	Instituto Geográfico Nacional	1:100 000	Med
VectorMAP1	JOG/Photogrammetry	NIMA/NGA	1:250 000	Med
Digital Peru 1.0	IGN 1:50,000/1:100,000	Instituto Geográfico Nacional	1:100 000	Med
HydroSHEDS	Radar (SRTM)	USGS	15 arc-sec	Low

Satellite imagery measurements

Stream paths were traced in the centre of the widest channel in a manual point-by-point method on the highest resolution satellite imagery available through Google Earth. The traces were then exported as .kml files, converted to shapefiles, imported into the ArcMap and then projected into UTM 18S. Where submetre resolution imagery was unavailable in Google Earth, we searched for higher-resolution satellite imagery elsewhere and

adjusted the traces to that imagery when possible. In some areas, we found such higher-resolution imagery in Microsoft Bing satellite imagery (a basemap layer available within Arcmap). Additionally, we imported and georeferenced a separate high-resolution Bing image (not available in Arcmap) covering most of Río Hualmay, and purchased two high-resolution satellite images from Digital Globe: a georeferenced 50 cm resolution WorldView-1 panchromatic image covering the first

~16 km of Río Blanco, and a 5 m resolution RapidEye image covering about a 5 km section of Quebrada Tunacancha.

Hydrographic vector data measurements

In this approach the metric distances of several hydrographic data sets were calculated. First, we used the HydroSHEDS 15-arc-second resolution dataset 'River Network' (Lehner *et al.* 2008) vectors that are derived from the USGS Shuttle Radar Topography Mission 3-arc-second Digital Elevation Model and available online (<http://hydrosheds.cr.usgs.gov>). Next, we measured stream lengths from the Vector MAP1 dataset (Joos 2012; National Imagery and Mapping Agency (NIMA) 1995) representing a digitised version of NIMA's 1:250 000 scale Joint Operations Graphics (JOG) aeronautical chart series. The limited distribution VMAP1 tile #191 covering southern Peru was obtained from NIMA via a Freedom of Information Act request. The Digital Peru 1998 vector data set was obtained from the Peruvian government. Its hydrographic layer 'hidro' is IGN map series hydrology at 1:100 000 scale. Stream paths from each data set were imported into ArcMap, projected into UTM 18 South using WGS1984 datum, and then polylines were selected manually and given a nominal value in the attribute table. Cumulative total length (in metres) for a river section was calculated by summing all line segments containing a nominal attribute. When segments were missing (<1% of overall data set), connecting paths were drawn in Arcmap using the Microsoft Bing satellite imagery basemap as a guide. The shortest straight-line paths across lakes/reservoirs were created for each of the data sets using the same projection. Other lines were added in for the uppermost segments of each stream from the most distant source point. When multiple paths were present for a stream, the middle path was preferably selected and if represented by polygons (i.e. sometimes in the VMAP1 dataset), polylines were traced by hand following the middle of the channel. Changes to the datasets were minimal (<2% of total river lengths) and can be viewed by comparing the modified traces with the original data sets.

GPS measurements

GPS tracks were obtained on the paddle/hike at the source area and also on river descents. We used three GPS devices: Garmin eTrex Vista Hcx (with barometric altimeter), Garmin eTrex10 and Garmin eTrex 20, each rated at 5–10 m horizontal accuracy (Londe 2005). The GPS devices were turned on at the beginning of each day of descent and turned off after arriving in camp. Generally, they remained in the kayaks to minimise deviations away from the main river channel. Tracks were periodically saved and new ones started, either at camps or various river section boundaries.

Field expeditions

The initial source area field expedition to the Cerros Cuchpanga and Río Hualmay was conducted 5–7 May 2012. The Río Mantaro kayak descent took 23 days of paddling between 1 May and 4 June 2012 starting at Lago Acucocha. Substantial water was flowing below Represa Upamayo (67 m³/s) and Represa Tablachaca (70–200 m³/s), but not below Represa Malpaso (~0.5 m³/s for ~2 km). The Río Apurímac kayak descent took 22 days total between 10 June and 8 October 2012 and started just upstream of the Apurímac/Hornillos confluence. A second source area reconnaissance expedition to the Cordillera Rumi Cruz–Río Blanco and Cerro Chipián–Río Chacachimpa occurred 29 May–7 June 2013. Uppermost parts were hiked. Kayak descents included Río Hualmay–Blanco starting at Lago Pistag and continuing on Río Blanco through the canal to Río San Juan, and Río Chacachimpa–Lago Junín starting near the obelisk. GPS units were carried for recording tracks on all field reconnaissance.

GPS track corrections

GPS tracks were imported into ArcMap and measured as polyline segments in a geodatabase feature class that was projected into Transverse Mercator using the UTM coordinate system. Obvious aberrations and deviations in the tracks were removed by eliminating the suspect vertices from the polylines. 'Aberrations and deviations' were defined as short looping circles, backtracks and abrupt deviations from an otherwise straight course. They generally were due to scouting, portaging, stopping (at ports, camps and other points of interest), and obscured satellite views (due to steep-walled gorge sections). The ends of GPS tracks were sometimes extended short distances to connect two consecutive tracks in the riverbed. This was generally a minimal distance (<0.3 km) except two ~6 km sections where tracks were missing due to battery failure (in these, the filled tracks followed the main river course according to satellite imagery). On Río Mantaro, tracks were adjusted to move directly over dam sites and into the subsequent riverbed to the point where paddling resumed. For the tracks above Represa Upamayo and above the Apurímac–Hornillos confluence, satellite imagery was used to trace stream paths where GPS tracks were missing or did not closely follow the course of water. The uppermost GPS tracks started near the base of the potential source summit and do not account for the additional estimated 120–200 m vertical rise to the summit. All adjustments to GPS tracks can be assessed by comparing the raw and adjusted tracks.

Results

In a recent analysis of rivers in Peru, topographic maps of major highland rivers were acquired and each river's

length and other features analysed. From this analysis, the most distant point in the Amazon drainage was found not to be in the Río Apurímac drainage as previously believed, but rather in the Río Mantaro drainage, the major river system that joins Río Apurímac to form Río Ene (Figures 1 and 2).

To accurately compare the maximal lengths of Ríos Mantaro and Apurímac, we had to define the most distant upstream point in each river basin. For the Apurímac basin, we used the previously established point of Nevado Mismi (Figure 3a) (McIntyre 1972; Goicochea 1997; Johnston 2002; Jansky *et al.* 2011). For the Mantaro basin, no such point had been determined previously. Although Río Mantaro nominally begins at about 4080 m elevation at Represa Upamayo (just downstream of the natural outlet of Lago Chinchaycocha/Junín), there are a number of river extensions upstream, of which the three longest are very close in length, extending between 68 and 70 km to their most distant points (Figure 3b). We undertook field expeditions to these three areas to assess the topography of

the most distant points, locations of flowing surface water and exact distances to Represa Upamayo (via GPS tracks obtained by kayaking/hiking). In total, five field expeditions were conducted between May 2012 and September 2013, with the following results (summarised in Plates 1 and 2 and Table 2; distances are the best measurements based on GPS and satellite imagery).

Cerros Cuchpanga (67.9 km)

The most distant point in the Río Gashán basin was located in the Cerros Cuchpanga at a horseshoe-shaped ridge with two peaks of approximately 5040 and 5154 m elevation on either side of a saddle at 4998 m (Plate 3a). We erected an apacheta (a pile of rocks) at the ridge saddle. The most distant part of the ridge was the 5154 m high west peak, 67.9 km from Represa Upamayo.

Below the ridge on 5 May 2012 (end of the rainy season), we found three small lakes with inflow and outflow of running water. This water disappeared into the rock after exiting the third lake and re-emerged about 500 m away at springs that flowed ~300 m down

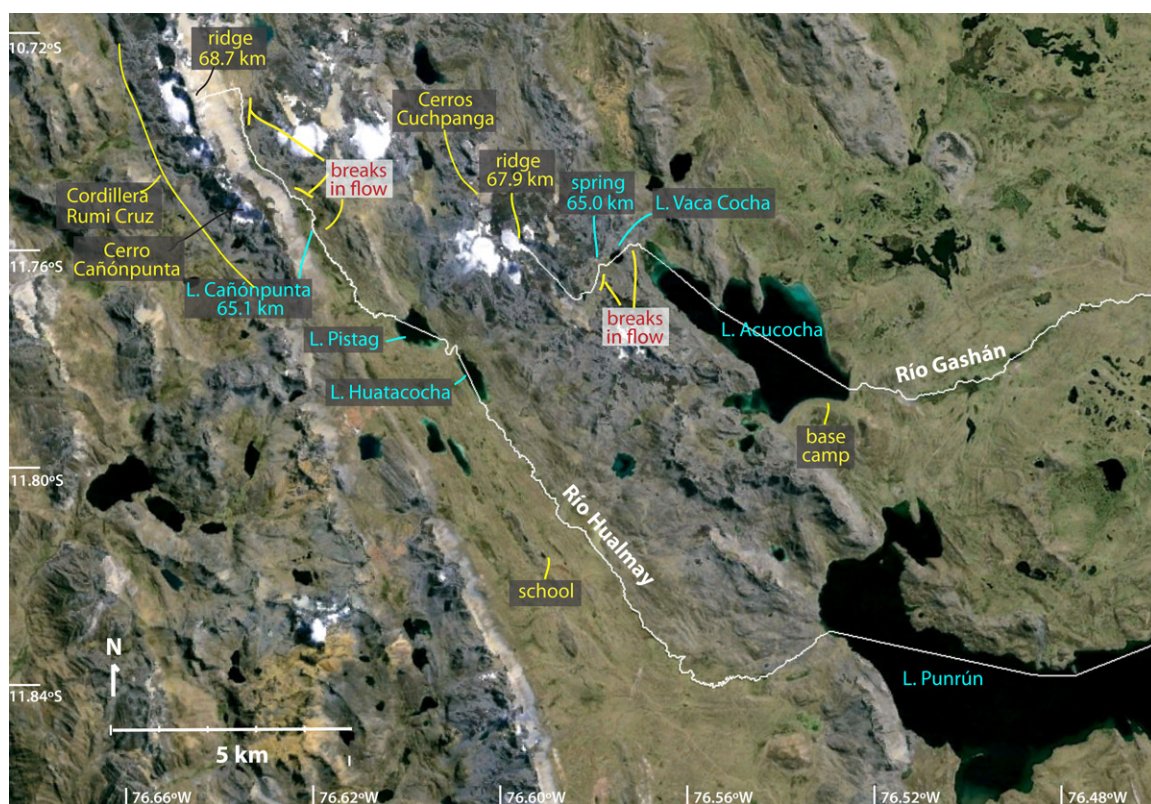


Plate 1 Cordillera Rumi Cruz and Cerros Cuchpanga headwaters of Río Mantaro. The white streambed traces show where paths were traced to measure the distances to Represa Upamayo.

Note: L = Lago; Q = Quebrada

Source: Satellite image taken 9 April 2013, used with permission from Google and Digital Globe

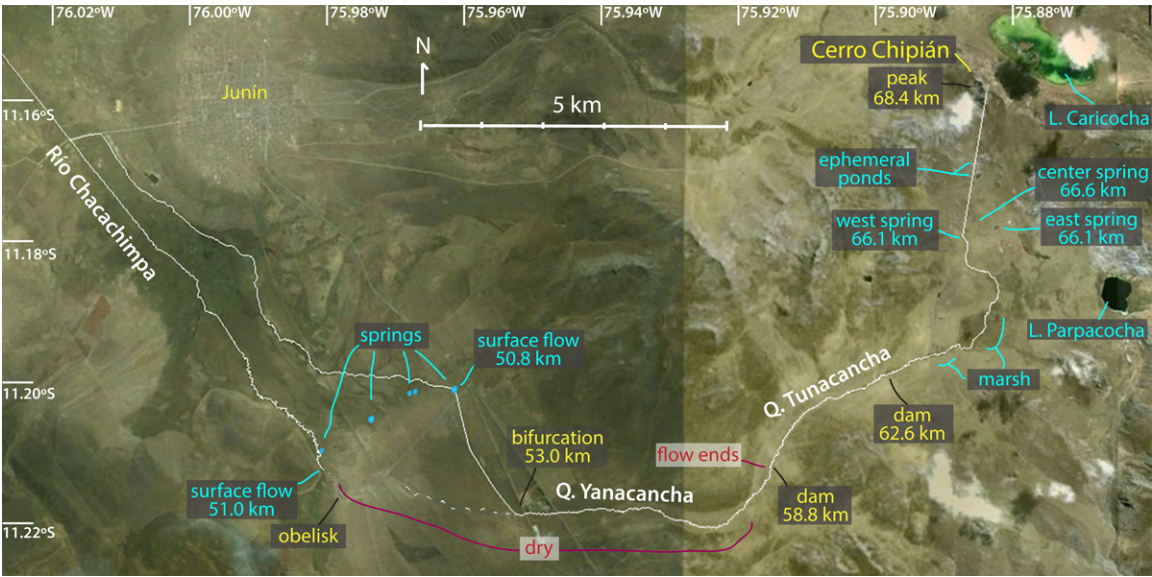


Plate 2 Cerro Chiapián headwaters area of Río Mantaro. The white streambed traces show where paths were traced to measure the distances to Represa Upamayo. Displayed distances follow the north branch of Quebrada Yanacancha downstream of the bifurcation point (where contiguous surface water sometimes flows). The east spring is the same distance to Cerro Chiapián as the west spring, while the (dry) centre spring is 0.25 km closer.

Note: L = Lago; Q = Quebrada

Source: Satellite images used with permission from Google and Digital Globe

Table 2 Comparison of most distant sources of Río Mantaro

Location	Kilometres	Elevation	Coordinates
<i>Most distant point (where a drop of rain flows into river)</i>			
Cerros Cuchpanga	67.9 km	5154 m	10.7608°S, 76.5888°W
Cordillera Rumi Cruz	68.7 km	5220 m	10.7320°S, 76.6480°W
Cerro Chiapián	68.4 km	4750 m	11.1575°S, 75.8844°W
<i>Most distant flowing surface water (with long breaks in surface flow)</i>			
Lake by Cerros Cuchpanga	67.1 km	4790 m	10.7623°S, 76.5829°W
Spring by Cordillera Rumi Cruz ridge	68.1 km	4760 m	10.7311°S, 76.6406°W
Spring by Cerro Chiapián	67.2 km	4430 m	11.1790°S, 75.8870°W
<i>Most distant contiguously flowing surface water</i>			
Spring by Lago Vacacocha	65.0 km	4587 m	10.7627°S, 76.5711°W
Spring by Lago Cañónpunta	65.1 km	4578 m	10.7498°S, 76.6294°W
Spring by Cerro Gloriapata	50.4 km	4140 m	11.2003°S, 75.9616°W

to Lago Vaca Cocha. Water exited Lago Vaca Cocha and flowed on the surface into Lago Acucocha, with the exception of one break in surface flow at 4536 m elevation where the water went under rocks for several metres. Water flowed out of Lago Acucocha into Río Gashán and was regulated by a small dam. On 20 August 2012 and 13 October 2012 (in the dry season), there was no flow of water from the springs above Lago Vaca Cocha or between Lago Vaca Cocha and Lago Acucocha, but water still flowed out of Lago Acucocha.

The spring above Lago Vaca Cocha was 65.0 km upstream of Represa Upamayo.

Cerro Chiapián (68.4 km)

The most distant point in the Lago Junín basin was located at Cerro Chiapián (Plates 2 and 3c). Most of the 2.1–2.3 km from the peak to the first springs had no signs that surface water ever flowed. White algae residue indicated that water aggregated in two ephemeral ponds during the rainy season, though these were

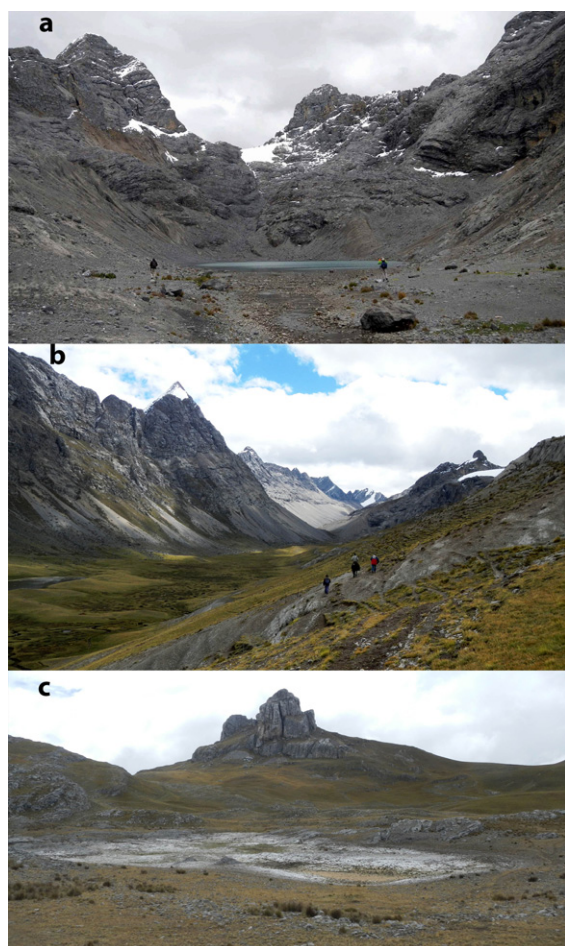


Plate 3 Most distant source areas. (a) Looking up past the final small lake in the Lago Acucocha drainage toward the horseshoe-shaped ridge and snow-covered 4998 m high saddle on 5 May 2012. Ridge is the most distant point in the Río Gashán basin. Note flowing water coming out of this small lake. (b) Looking upstream toward the Cordillera Rumi Cruz (left range) on 3 June 2013. The range is continuous with and located just past the visible pyramid-like peak, labelled 'Cerro Cañónpunta' on topographic maps (though residents call it 'Chacua Grande'). At the base of this peak is the lake referred to here as 'Lago Cañónpunta'. (c) Cerro Chipián on 2 June 2013 from a point ~1.5 km away showing one of the ephemeral ponds where water collects in the rainy season.

Source: James Contos

dry on 2 June 2013 and 23 September 2013. Cerro Chipián is at about 4750 m; 68.4 km from Represa Upamayo.

On 2 June 2013, we found several springs where water emerged and flowed into Quebrada Tunacancha–Yanacancha (i.e. Río Mantaro drainage) and/or Lago

Parpacocha (i.e. Río Perené drainage). The west spring (flowing almost entirely into the Río Mantaro drainage) was at 4430 m, 66.1 km upstream of Represa Upamayo (with water emerging ~0.1 km downstream on 23 September 2013). From this spring, water flowed 3.5 km through a marshy area to a small impoundment dam (same distance from east spring). A reduced surface outflow continued 3.8 km down to a second broken impoundment, after which we found no surface flow for 5.8 km to a bifurcation where the right channel continued 2.2 km in a canal to a spring, while the left (natural) channel became less and less apparent until all visual signs of former surface flow disappeared (2.3 km down; at a location 0.4 km east of an obelisk monument in the flat Pampa de Junín). The 68.4 km distance to Cerro Chipián is based on the right (north) branch after the bifurcation. Contiguously flowing surface water into Lago Junín emerged from a spring in this channel located 2.2 km downstream of the bifurcation at 4128 m elevation; 50.8 km from Represa Upamayo.

Cordillera Rumi Cruz (68.7 km or 85.8 km)

The most distant point in the Río Blanco basin was located on a ridge of the Cordillera Rumi Cruz (i.e. Rumi Cruz Mountain Range) at a point where water flows steeply down to a saddle area and then to the right (south), all in a surface gully (Plate 3b). The most distant point was at 5220 m elevation and 68.7 km from Represa Upamayo (85.8 km if the Río Blanco diversion canal is followed).

On 3 June 2013, we found a small trickle of flowing surface water near the base of the most distant point on the Rumi Cruz ridge. This water soon disappeared into the gully. Flowing surface water reappeared ~0.8 km downstream in a gently sloping valley and meandered for ~1.5 km to a steeper talus slope where it went underground again. Water reappeared ~0.3 km downstream just before a small lake (Lago Cañónpunta) with an outflow that went under rocks briefly (<20 m) and continued in surface flow to Lago Pistag (5.1 km downstream) and onward (assessed on 7 May 2012 as well). Lago Cañónpunta was at 4578 m; 65.1 km from Represa Upamayo (82.2 km via the Río Blanco diversion canal).

Outflow from Lago Punrún into Río Blanco was regulated by a small dam and flowed in the natural channel 6.5 km downstream to a point where all water was diverted into a canal (built ca. 1927). Water in the 18.7 km long canal passes through two powerhouses before joining Río San Juan at a point 13.6 km upstream of the natural Río Blanco confluence. Total lengths from the diversion point to the natural confluence were 32.3 km (canal) vs 15.2 km (natural channel).

With the most distant source point in the Río Mantaro basin defined at the Cordillera Rumi Cruz, various

Table 3 Measured distances on Río Apurímac

H.SHD	VMAP1	DigiPeru	Topo	GE	GPS	ID	River section
57.6 km	59.3	58.8	61.7	67.9	67.7	A1	FUENTE (Nevado Mismi to Hornillos/Apurímac)
68.7	68.3	68.1	70.8	73.1	73.3	A2	MACHU PUENTE (Hornillos/Apurímac to P. Santo Domingo)
115.2	115.5	116.0	120.3	123.1	124.1	A3	Q'ESWACHACA (P. Santo Domingo to P. Pillpinto)
130.6	137.5	140.1	140.6	143.2	146.5	A4	CAÑÓN PACPERO-NEGRO-GRANITA (P. Pillpinto to P. Cunyac)
84.1	90.4	94.8	95.7	98.1	98.0	A5	ABISMO (P. Cunyac to P. Pasaje)
78.1	86.5	93.1	92.2	94.7	94.8	A6	PASAJE (P. Pasaje to Lechemayo)
126.3	124.2	133.0	125.7	131.1	129.9	A7	SELVA (Lechemayo to Río Mantaro confluence)

660.6 681.7 704.0 707.0 731.2 734.3 Total length (from top of Nevado Mismi)

Note: The breakdown of distances between specific points is listed – measured by satellite imagery in DEM dataset HydroSHEDS (H.SHD), vector map datasets VMAP1 and Digital Peru (DigiPeru), topographic maps (Topo), Google Earth (GE), and GPS tracking (GPS). ID is the identifier for the river section in the online dataset. P: Puente

Table 4 Measured distances on Río Mantaro

H.SHD	VMAP1	DigiPeru	Topo	GE	GPS	ID	River section
60.9 km	62.6*	65.5*	66.5*	68.2	67.9	M1a	CUCHPANGA (Cerros Cuchpanga to R. Upamayo)
67.0*	N/A	63.1	62.6	68.5	68.4	M1f	CHIPIÁN (Cerro Chipián to R. Upamayo)
60.5	59.6	61.1	63.6	68.9*	68.7*	M1b	RUMI CRUZ (Cordillera Rumi Cruz to R. Upamayo)
68.0	78.0	77.1	81.1	83.4	83.0	M2	BOSQUE DE PIEDRAS (R. Upamayo to R. Malpaso)
98.1	98.6	101.2	103.3	107.4	107.1	M3	CAÑÓN LA OROYA (R. Malpaso to P. Stuart)
56.6	56.1	56.4	58.2	59.9	60.1	M4	VALLE MANTARO (P. Stuart to P. Chupuro)
88.4	87.9	86.7	89.8	90.8	91.1	M5	CAÑÓN IZCUCHACA (Chupuro to R. Tablachaca)
82.0	84.4	84.2	89.0	89.6	90.0	M6	CAÑÓN TABLACHACA (R. Tablachaca to Río Huarpa)
145.7	152.4	155.0	156.2	160.5	161.3	M7	ABISMO (Río Huarpa to P. Surcubamba)
131.3	132.7	145.3	143.5	146.1	147.7	M8	SELVA (P. Surcubamba to Río Apurímac confluence)

730.6 749.5 766.5 784.7 806.6 809.0 Total length (from Cordillera Rumi Cruz ridge)

Note: The breakdown of distances between specific points is listed – measured by satellite imagery in DEM dataset HydroSHEDS (H.SHD), vector map datasets VMAP1 and Digital Peru (DigiPeru), topographic maps (Topo), Google Earth (GE), and GPS tracking (GPS). ID is the identifier for the river section in the online dataset. Asterisks indicate the most distant source length and point determined with the given measurement method. P: Puente; R: Represa

methods were employed to measure the full stream lengths of both Ríos Mantaro and Apurímac down to their confluence from the uppermost drainage points. (In the following section, ‘Río Mantaro’ and ‘Río Apurímac’ refer to the courses from their uppermost sources to their confluence.)

First, using topographic maps, Río Mantaro was determined to be 784.7 km and Río Apurímac 707.0 km, a 77.7 km (11.0%) difference (Tables 3 and 4). An independent measurement method based entirely on Google Earth/Bing satellite imagery (nearly all high resolution) was then used, resulting in a measurement of Río Mantaro at 806.6 km and Río Apurímac at 731.1 km, a 75.5 km (10.3%) difference (Tables 3 and 4). These methods established Río Mantaro as clearly longer than Río Apurímac.

In a third method of measurement, a number of digital hydrography datasets were used to compare the lengths of Ríos Apurímac and Mantaro. The hydrography was

derived from a number of sources (Table 1), including satellite radar topography (HydroSHEDS from SRTM) and traditional photogrammetry (VMAP1 from NIMA JOG 1:250 000 series). The USGS HydroSHEDS dataset has the advantage of being consistent over large areas, but it was the lowest resolution dataset included in the study (i.e. 500 m horizontal resolution accuracy), and yielded 730.8 km and 660.6 km for Ríos Mantaro and Apurímac, respectively, a 70.0 km (10.6%) difference (Tables 3 and 4). The medium-resolution VMAP1 dataset yielded 749.5 km and 681.7 km for Ríos Mantaro and Apurímac, respectively, a 67.8 km (9.9%) difference (Tables 3 and 4). Another medium-resolution data set called Digital Peru yielded 766.5 km and 704.0 km for Ríos Mantaro and Apurímac, respectively, a 62.5 km (8.9%) difference (Tables 3 and 4).

As a most definitive measure of the lengths of Ríos Mantaro and Apurímac, we also undertook expeditions

down each river in kayaks carrying GPS units to measure stream lengths. In paddled sections, small corrections were made to the raw GPS data to make contiguous paths without the obvious deviations due to portages, stops and battery failure (e.g. see Plate 4d). Raw GPS tracks cover 98% of the Mantaro and 99% of the Apurímac navigable lengths. GPS tracks were corrected using visual assessment of topography. The final distance measurements using GPS for the Mantaro and Apurímac were 809.0 km and 734.3 km, respectively, a 74.7 km (10.2%) difference (Tables 3 and 4).

The various measurement methods are shown over a high-resolution satellite image of a short section of Río Mantaro (Plate 4a–c). This comparison illustrates the rela-

tive accuracy of each method for approximating the course of flowing water around curves, with relative order $\text{GPS} \approx \text{satellite imagery} > \text{topographic map} > \text{Digital Peru} \approx \text{VMAP1} > \text{HydroSHEDs}$. This is also the order of total river length measurements for each method (Tables 3 and 4).

Discussion

We have established that the most distant source of the Amazon River system is located in the Río Mantaro drainage rather than the Apurímac drainage. With the highest resolution measurement methods and following natural channels, the margin of this difference is

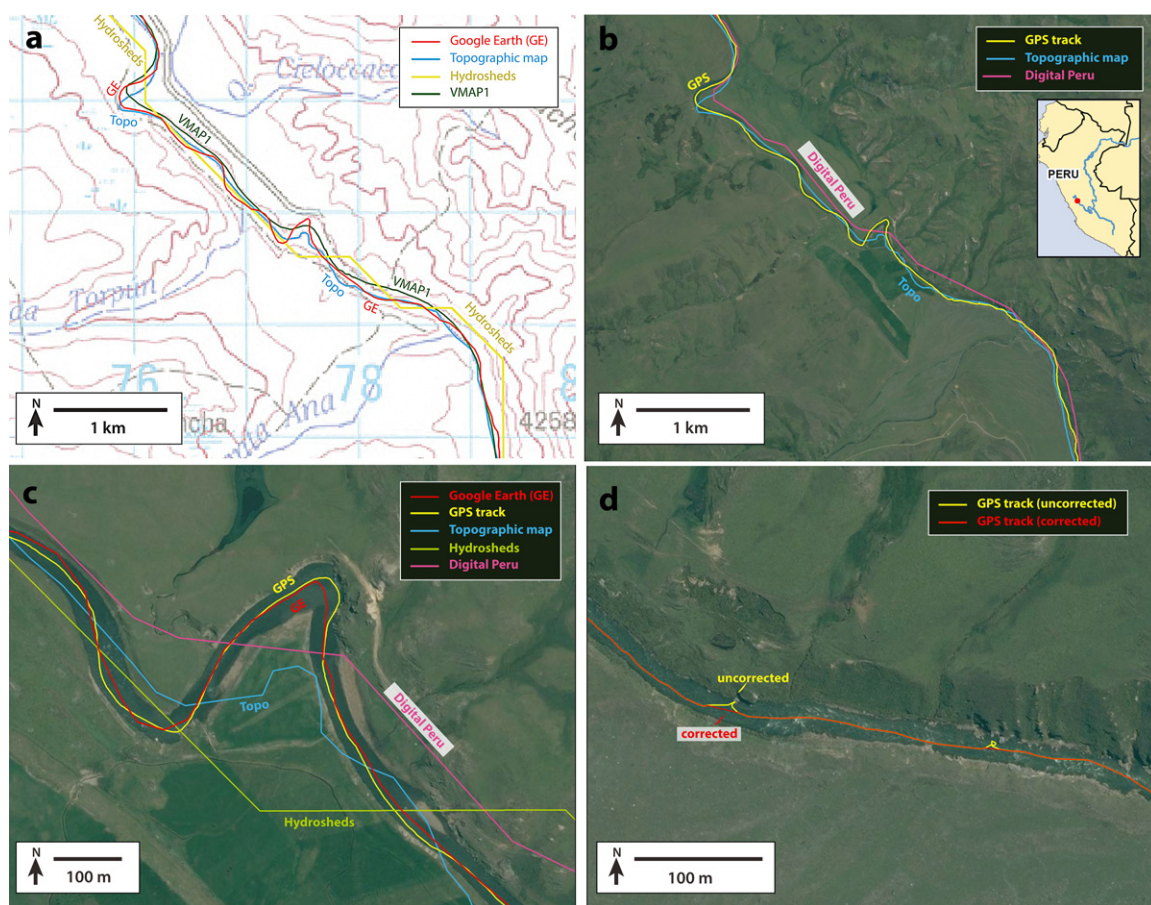


Plate 4 Comparison of the various river measurement methods for a section of Río Mantaro just upstream of Represa Malpaso. (a) Topographic map (from Instituto Geográfica Nacional) showing various measurement traces. (b) Bing Maps satellite imagery of the same section of river with three other measurement traces. (c) Close up of bend shown above with five different measurement traces. Note that the coarser HydroSHEDs, Digital Peru and VMAP1 cut short small curves in the river. Although topographic map traces account for more of these curves, they are not as accurate as satellite image tracing or GPS tracking on the river. (d) Uncorrected and corrected GPS tracks just upstream of Represa Malpaso demonstrate typical corrections for stops along the river.

Source: Bing Maps satellite imagery reprinted with permission from Microsoft Corporation

75–77 km or 10–11% of the length of Río Apurímac. Compared with the headwaters of the Apurímac at Nevado Mismi, the new most distant source position at the Cordillera Rumi Cruz is 754 km northwest (as a condor flies) and 4.36° – 4.75° further north (from 15.52°S to the more tropical 10.09° – 10.75°S). This is a substantial repositioning of a major geographical feature from the southern Peruvian puna to the central Peruvian puna.

An obvious question one might ask is why geographers overlooked Río Mantaro in the past. One possibility is that the Península de Tayacaja (a great twisting bend that Río Mantaro courses around in its lower half) has the effect of making the total river length appear shorter than the Apurímac on casual inspection (Figure 2). Other geographers may have noted Río Mantaro but not realised its significance. For example, the Instituto Nacional de Estadística e Informática lists Río Mantaro as 724 km compared with Río Apurímac at 690 km (García-Pérez *et al.* 2007), but these measurements apparently begin at the nominal start of each river (i.e. Represa Upamayo for Río Mantaro and Lago Vilafro for Río Apurímac). Also, McIntyre noted that the Mantaro was nearly as long as the Apurímac, but apparently did not measure it in detail (McIntyre 1991).

Each of the six methods of river length measurement that we used yielded the result that Río Mantaro was 8.9–10.6% longer than Río Apurímac (starting from the most distant upstream points). Of the six methods, GPS and satellite imagery were the most accurate in following the true course of a stream around curves (Plate 4), primarily because of the high-resolution data available for these measurement methods compared with the other four methods. Accounting for such curves leads to increased total river-length measurements. The relative order of method accuracy (i.e. Plate 4) is thus the same as the relative order for total measured length of each river (Tables 3 and 4). Lengths determined from the GPS and satellite imagery methods were particularly similar (differing by $<0.6\%$ overall), and agreed in placing the most distant source point at the Cordillera Rumi Cruz, whereas other methods generally placed it at the Cerros Cuchpanga (Tables 3 and 4). This can be explained by the fact that Río Hualmay (coming from the Cordillera Rumi Cruz) has extensive meanders that are only resolved with the higher resolution methods (GPS and high-resolution satellite imagery). While the generally higher resolution available for the satellite imagery and GPS measurement methods results in the highest accuracy, the other methods have utility in cases where satellite imagery is at low resolution, GPS measurements are difficult to acquire, only gross estimates are needed, or access to other features of a dataset are desired. We recommend that the satellite imagery-based metrics be cited in the

future, as these are highly accurate, easily verified and can be similarly applied to other rivers.

Still of interest is the maximal length of the Amazon River, especially with the recently realised distance added from Río Mantaro. Although a full navigational descent (with associated GPS track obtained) of Ríos Ene–Tambo–Ucayali–Amazon was completed on 7 November 2012 by the first author, the GPS and other measurement data will be the subject of a separate publication.

Of the three furthest sources above Represa Upamayo, the Cordillera Rumi Cruz is by far the most distant if manmade alterations are accounted for, because the Río Blanco diversion canal adds 17.1 km to the length. If natural watercourses are followed, the most distant point is either the Cordillera Rumi Cruz or Cerro Chipián. The ambiguity primarily surrounds the length of Río Chacachimpa, which flows through straight manmade channels in much of the Pampa de Junín, and for which the natural channels are no longer discernable. It is also unclear whether all precipitation falling between Cerro Chipián and the first springs emerges at those springs. The current situation, as best we can determine, indicates that the Cordillera Rumi Cruz is more distant by most definitions, so we advocate recognising the Cordillera Rumi Cruz as the most distant source of the Amazon.

One can argue for other ‘sources’ of the Amazon, depending on the criteria used to define ‘source’. Of prime importance is a ‘principal source’, which is found by following the mainstem river upstream at each bifurcation. Such a principal source for the Amazon has been posited as the uppermost Marañón River (Fritz 1707; La Condamine 1745; Raimondi 1874; Sievers 1910; Flornoy and Rouch 1954). In addition, other ‘most distant source’ locations for the Amazon can also be recognised, particularly if temporary manmade alterations in river length are accounted for and contiguously flowing surface water is critical to the definition. For example, for about 5 months in the dry season (June–October) when the entire Río Mantaro is diverted at Represa Tablachaca (a dam built in 1974) through a 20 km tunnel and bypasses the normal 197 km river course around the Península de Tayacaja, the length of the contiguously flowing river is shortened by 177 km. During these times, the Nevado Mismi area of Río Apurímac resumes its status as the most distant point in the Amazon drainage. It should also be noted that at all times of the year, the dams on Río Mantaro make Río Apurímac the longest uninterrupted contiguously flowing source of surface water in the Amazon basin.

In general, we propose avoiding shifting source locations for all rivers by endorsing definitions that are not

dependent on short-term changes in flow or manmade alterations to river courses. We suggest two primary definitions: (1) **PRINCIPAL SOURCE**: the most distant upstream point in the drainage giving rise to the stream from which all other joining streams have lower average annual discharge and (2) **MOST DISTANT SOURCE**: the most distant upstream point in the drainage along the natural course of the river or its tributaries from which a drop of rain will make its way to the river's mouth. A third potential definition is: (3) **MOST DISTANT SOURCE OF UNINTERRUPTED FLOW**: the most distant upstream point in the drainage along the natural course of the river or its tributaries with contiguously flowing surface water uninterrupted by dams or other blockages.

Applied to the Amazon River, the above definitions result in the following conclusions:

- 1 RÍO MARAÑÓN from Nevado Siula Grande or Cerro Caudalosa is the 'principal source' of the Amazon River.
- 2 RÍO MANTARO from the Cordillera Rumi Cruz is the 'most distant source' of water in the Amazon basin – and possibly the most distant source of any river in the world.
- 3 RÍO APURÍMAC from the Nevado Mismi/Nevado Quehuisha area is the 'most distant source of uninterrupted flow' in the Amazon basin.

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Note

- 1 Aside from using 'Amazon' and 'Amazon River', we use Spanish place names: *río* = river, *quebrada* = gully/creek, *represa* = dam, *puente* = bridge, *lago* = lake, *cerro* = hill or mountain, *cordillera* = mountain chain, and *nevado* = snowy mountain.

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- **GPS Tracks:** Consists of three Shapefiles including 'GPS_Raw' with GPS tracks directly from Contos fieldwork with Garmin GPS, 'GPS_Corrected' with geometry suitable for measuring stream lengths with updates based on high-resolution satellite imagery and 'GPS_Alt_Channels' that contains alternative stream paths and modifications that are relevant but not directly used in the stream length calculation. Accuracy is approximately 5–10 m, which is comparably high.
 - **GoogleEarth:** This Shapefile contains the relevant stream lengths traced on the screen based on GoogleEarth imagery and then imported as KML into Arcmap and reprojected into UTM 18 South for the horizontal distance calculation. Accuracy is 1–15 m depending on available imagery and inherent distortions. A comparably high accuracy dataset.
 - **DigitalPeru_h2:** These vectors are a subset of the level 2 streams layer data included in the DigitalPeru 1.0 GIS product from the Instituto Nacional de Geografía de Perú. The source data are generalised on 1:100 000 printed maps and may be considered medium accuracy.
 - **TopoMap:** These vectors are traced from scanned paper mapsheets of the 1:100 000 topographic map series from the Instituto Nacional de Geografía de Perú. Medium accuracy.
 - **VMAP1_wtr_crs:** These segments are derived from the VectorMap1 tile 191 (southern Peru) product from the US National Imagery and Mapping Agency (NIMA) based primary on 1:250 000 J.O.G. aviation maps. Medium to low accuracy.
 - **HydroSHEDS:** These hydrology layers are created from Shuttle Radar Topography Mission (SRTM) elevation data sampled at a 90-m (3-arc-second) cell resolution for evaluating entire watersheds. Low accuracy.

Supporting information

Additional Supporting Information may be found in the online version of this article:

Data are presented in Shapefile format in WGS1984 UTM 18 South coordinate system. An ESRI Arcmap 10.0 MXD project file is included that references the included Shapefiles, but Arcmap is not required to make use of these data as Shapefile is a widely used format.