Groundwater potential of pampa aquifers in two glacial watersheds, Cordillera Blanca, Peru

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Abstract

As climate change continues to drive glacier retreat in the Cordillera Blanca, Peru, the fraction of dry season runoff derived from groundwater baseflow is increasing. Therefore, it is necessary to improve our understanding of proglacial hydrogeology to forecast how groundwater can offset decreasing meltwater resources. Unfortunately, little is known about high-elevation groundwater, the physical hydrogeological properties of aquifers, or contributions to stream flows in the Cordillera Blanca, Peru. This thesis addresses these knowledge gaps and presents the results from a groundwater investigation of two glaciated watersheds in the Cordillera Blanca during the July 2012 dry season. Investigative techniques include drilling with a portable drill, slug tests to measure permeability, and hydrochemical mixing model analysis. In the Llanganuco Pampa, glaciofluvial outwash and glacial till aquifers were identified with hydraulic conductivities of 10^{-4} and 10^{-5} m/s and groundwater flow velocities of 0.62 and 0.09 m/day, respectively. In the Quilcayhuanca Pampa, a buried talus aquifer was identified with an average hydraulic conductivity of 10^{-5} m/s and an average groundwater flow velocity of 0.10 m/day. The buried talus aquifer extended across the valley and was hydraulically connected to recent talus slope deposits along the valley side. Talus slopes are ubiquitous features in the Cordillera Blanca and the results presented here show that they are a significant pathway for groundwater recharge of valley aquifers and springs. Tracers from surface water and groundwater samples were used in a binary mixing model to estimate tributary and groundwater contributions to stream flow. Groundwater contributions to stream flow were 18% in the Llanganuco Upper Pampa and 21% in the Quilcayhuanca Pampa. These results suggest that discharge from the studied valley aquifers are a crucial component of dry season stream flow in the Cordillera Blanca. Further research is still needed to identify and quantify the sources of groundwater recharge (i.e. precipitation, glacial meltwater, and/or bedrock fracture flow) to better understand the ability of groundwater to buffer dry season flows in the context of melting glaciers.

Résumé

Pendant que le retrait des glaciers de la Cordillera Blanca, Pérou, se poursuit à cause des changements climatiques, la part des eaux de ruissèlement provenant du débit de base des eaux souterraines augmente durant la saison sèche. Par conséquent, il est nécessaire d'améliorer nos connaissances en hydrogéologie périglaciaire afin de prévoir comment les eaux souterraines peuvent compenser la diminution des ressources en eaux de fontes. Malheureusement, les propriétés physico-hydrogéologiques des eaux souterraines de hautes altitudes, ainsi que leur contribution à l'écoulement des cours d'eau de la Cordillera Blanca, Pérou, sont très largement incomprises. Cette thèse présente les résultats de l'étude des eaux souterraines dans deux bassins versants de la Cordillera Blanca, menée en juillet 2012 durant la saison sèche. Pour se faire, les techniques d'investigation incluent des forages à la foreuse portative, des essais de perméabilité et des analyses de modèles hydrogéochimiques de mélange. Dans la Pampa Llanganuco, Il a été évalué que les aquifères d'épandages fluvio-glaciaires et de tills glaciaires atteignent respectivement des conductivités hydrauliques de 10^{-4} et 10^{-5} m/s et des vitesses d'écoulement d'eaux souterraines de 0.62 et 0.09 m/jour. Dans la Pampa Quilcayhuanca, le système aquifère de talus a été identifié avec, en moyenne, une conductivité hydraulique de 10^{-5} m\s et une vitesse d'écoulement d'eaux souterraines de 0.10 m/jour. Ce système s'étend à travers la vallée tout en étant hydrauliquement relié aux récents dépôts de débris rocheux le long des flancs. Les résultats présentés ici montrent l'omniprésence des dépôts de débris rocheux dans la Cordillera Blanca ainsi que leur importance dans la recharge des aquifères et des sources de la vallée. Les traceurs dans les échantillons d'eaux de surface et d'eaux souterraines ont été utilisés dans un modèle mixte à deux composantes pour estimer la contribution des affluents et des eaux souterraines dans l’écoulement du cours d’eau principal. La contribution des eaux souterraines à l’écoulement du cours d’eau était de 18% dans la Pampa Llanganuco et 21% dans la Pampa Quilcayhuanca. Ces résultats suggèrent que les eaux souterraines, provenant des aquifères des vallées, représentent une part importante de l’écoulement des cours d’eau durant la saison sèche dans la Cordillera Blanca. De plus amples recherches sont cependant nécessaires pour identifier et quantifier les sources de recharge en eaux souterraines (précipitations, eaux de fontes glaciaires et/ou écoulement dans les fractures du substrat rocheux) afin de mieux comprendre la capacité des eaux souterraines à entretenir l’écoulement des cours d’eau durant la saison sèche dans le contexte de la fonte des glaciers.

Preface

The following thesis presents original research by the author at the Department of Earth and Planetary Sciences, McGill University during the 2011-2013 academic years. It is submitted in a traditional thesis format, and is ultimately intended to form a manuscript to be submitted to a peer-reviewed journal.

Data acquisition, analysis and interpretation were advised by Professor Jeffrey M. McKenzie, who acted as principal research supervisor along with Professor Eric Galbraith, the additional committee member. The field work took place in the Cordillera Blanca, Peru during July 2012 with a research team supervised by Professor Bryan Mark from The Ohio State University. Water samples collected in the field were analyzed at The Ohio State University and Syracuse University for basic chemistry. Interpretation of the chemistry results was done by the author at McGill University. In addition, water sample collected by the 2008 field team, including Sara Fortner, were also included for analysis in this thesis.

Acknowledgements

Naturally I would like to thank my supervisor Jeffrey McKenzie for his unwavering support and advice during this entire MSc experience. In the field, Jeff and I labored through all the jammed drill bits, seized extension rods, and numerous obstacles that come with using a portable drill at 4,000 m.a.s.l. in rain, snow, and scorching sun. Thanks a lot Jeff, you'da man.

Next I would like to thank my office mates Rob Carver, Michel Baraer, and Elizabeth Walsh, for their companionship, advice, and wonderful personalities. Rob is probably the smartest man I will every meet, although he's too modest to admit it. His editorial skills were greatly appreciated. Michel is the local expert on glaciology and chalk full of wisdom that he was always willing to offer. Elizabeth has friendship eyes that can mean just about anything and she could probably survive anything after her experience with rabid dogs on a solo bike trip in the Andes.

Another big thanks goes out to the research team that came to Peru, especially our fearless leader, Bryan Mark. The hydrogeology group from Syracuse University, namely Laura Lautz, Ryan Gordon, and Anne-Marie Glose, was an invaluable group to have in the field. Not only were they experts in their field, but their dice skills were uncanny and they made the camping trips a fun and memorable experience. Additional gratitude goes to Ryan for analyzed the water samples from the Llanganuco Pampa and dealing with my endless stream of emails.

Lastly, I would like to thank the students and faculty of the Earth and Planetary Science Department at McGill University. They're a real lively bunch of people and made me feel like one of the family. Thank you for making my time in Montreal a wonderful experience.

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Chapter 1 - Introduction

Tropical glaciers in the Peruvian Andes release meltwater continuously throughout the year, which is a critical component of the stream flows in glaciated high elevation watersheds (Mark and Seltzer, 2003). In the outer tropics where the bulk of the annual precipitation is confined to the wet season, the ability of tropical glaciers to maintain stream flows during the dry season is essential for downstream users. The local inhabitants rely on this source of water for drinking water, agriculture, mining, and hydroelectricity (Vergara et al., 2007). As climate change continues to drive glacial retreat in the tropics, the future of meltwater resources is threatened as glacial watersheds undergo hydrologic transformations (Mark et al., 2010). Such is the case in Peru's Cordillera Blanca where several glacial watersheds have crossed a critical threshold and now exhibit declining annual and dry season runoff (Baraer et al., 2012). As downstream populations struggle to adapt to future water shortages (Carey et al., 2012), there is a growing necessity for research on the ability of groundwater to offset declining meltwater contributions during the dry season in the Cordillera Blanca.

The western drainage of the Cordillera Blanca is characterized by long 'U' shaped valleys with steep bedrock walls, talus slope deposits, and low relief wetlands in the valley bottoms, called pampas. In addition to the glacial fed streams that flow across the pampas, perennial streams have also been observed in non-glaciated sub-catchments, implying that stream discharge must have a groundwater baseflow component (Mark and McKenzie, 2007). The hydrochemistry and isotopic composition of groundwater fed streams have been previously used to quantify the groundwater component in watershed runoff studies. Mark et al. (2005) showed that dry season discharge from Cordillera Blanca valleys was comprised of 40% glacial meltwater, implying that groundwater provided the rest. Baraer et al. (2009) further refined this approach, and quantified dry season water origins in the glacier fed Querococha Watershed. They determined that groundwater contributed up to 70% of the total basin outflow during the dry season, and that the flux of groundwater was temporarily available as it was correlated to the antecedent precipitation regime.

Springs and seeps are also important groundwater components in the water budgets of high elevation lakes and streams (Roy and Hayashi, 2008; Clowe et al., 2003). In the Cordillera Blanca, springs are commonly found at the base of the talus and moraine slopes where they intersect the pampa, and flow from the pampa surface itself under artesian conditions. Talus and moraine deposits have been identified as key groundwater aquifers in other high elevation watersheds (Roy and Hayashi, 2009; Liu et al., 2004). In a recent study of the dry season water origins of four glacial fed watersheds in the Cordillera Blanca, springs from lateral deposits were identified as major hydrologic components in the dry season discharges of each watershed (Baraer et al., *In Revision*).

The pampas have previously been proposed as an important storage of groundwater (Mark and McKenzie, 2007). They were likely formed by the plaudification of moraine, avalanche, or basin dammed lakes. A shallow water table is commonly exposed at the surface in small pools and channels, or can be easily intercepted by shallow hand augured wells (<1 m). The shallow groundwater, however, appears to have little influence on the net flux of basin outflows (Baraer et al., *In Revision*). The disconnection of the shallow groundwater is likely caused by the presence of the wetlands, which usually indicate the accumulation of organic matter due to poor drainage and low permeability sediments. Underlying these low permeability sediments, however, are potential coarse grained deposits that may be an important zone of groundwater flow and storage. This is supported by a recent geophysical study in the Quilcayhuanca Watershed that identified buried talus deposits in the pampa (Maharaj, 2011). However, the physical hydrogeologic properties of the buried talus, such as hydraulic conductivity and grain size, remain to be studied.

Traditional groundwater investigations typically involve the installation of monitoring wells and/or piezometers by using truck mounted drill rigs. In the case of high elevation watersheds, this approach is not feasible due to the remoteness of the study area or the inability to obtain drilling permits in a park. As a result, the majority of studies in high elevation watersheds have used intrinsic chemical tracers in streams and springs to identify groundwater contributions to runoff. Fortunately, recent advances in portable drilling technology have made it possible to drill through bedrock and unconsolidated sediments in remote areas (e.g. Gabrielli and McDonnell, 2011).

In this thesis, I will present the results from drilling investigations in two glacier watersheds in the Cordillera Blanca where I used a portable drill to install monitoring wells in the pampas, and collected water samples from the main streams, their tributary inflows, and from the newly installed monitoring wells. The purpose of this research was to test the hypothesis that there are buried aquifers present in the pampas and determine what fraction of the pampa stream water can be explained by groundwater contribution from pampa aquifers. For the purpose of this thesis, a saturated geologic unit is considered an aquifer if it has a hydraulic conductivity greater than 10^{-6} m/s and is laterally continuous. The objectives of this study were to, (1) drill and install piezometers in the pampas, (2) conduct hydraulic conductivity tests to identify pampa aquifers, (3) estimate groundwater contributions to the stream flows using data from surface water and groundwater samples in a mixing model, and (4) generate conceptual models of the hydrogeology in each watershed. The results from this study are an important step in evaluating the role of groundwater in the high elevation watersheds of the Cordillera Blanca, and its ability to sustain stream flows in the context of melting glaciers.

Chapter 2 – Study Area

2.1 Cordillera Blanca

The Cordillera Blanca (Spanish for "White Mountain Range") is renowned for having the largest concentration of tropical glaciers in the world (Vuille et al., 2008). It is located approximately 175 km north of Lima in the north-central highlands of the Peruvian Andes (**Figure 1**). The range is approximately 180 km long by 21 km wide, orientated slightly NW-SE, and has several peaks over 6,000 meters above sea level (m.a.s.l.). The climate is typical of the outer tropics where more than 80% of the precipitation falls during the wet season (October to April), with very little occurring during the dry season (May to November). Temperatures are relatively warm as the average annual air temperature is less variable than daily temperatures; however, overnight temperatures commonly drop below zero in the high elevation watersheds (3,500 to 5,000 m.a.s.l).

Geologically, the range is approximately 10 Ma, located on top of a magmatic arc caused by the low angle subduction of the Nazca plate beneath the South American plate. Although the range is not volcanically active, it is seismically active along the Cordillera Blanca Detachment Fault; a normal fault running along the western flank of the range. The bedrock on the west side of the range consists of the Chicama Formation, an assortment of pyrite rich metasedimentary rocks (hornfels, shales, and quartzites), intruded by a massive grano-tonalite batholith, all overlain by recent glacial and landslide deposits (Wilson et al., 1967).

Tropical glaciers in the Cordillera Blanca and in other parts of Peru likely reached their maximum glacial extent between 1630 and 1680 (Jomelli et al., 2009). Glacial retreat began

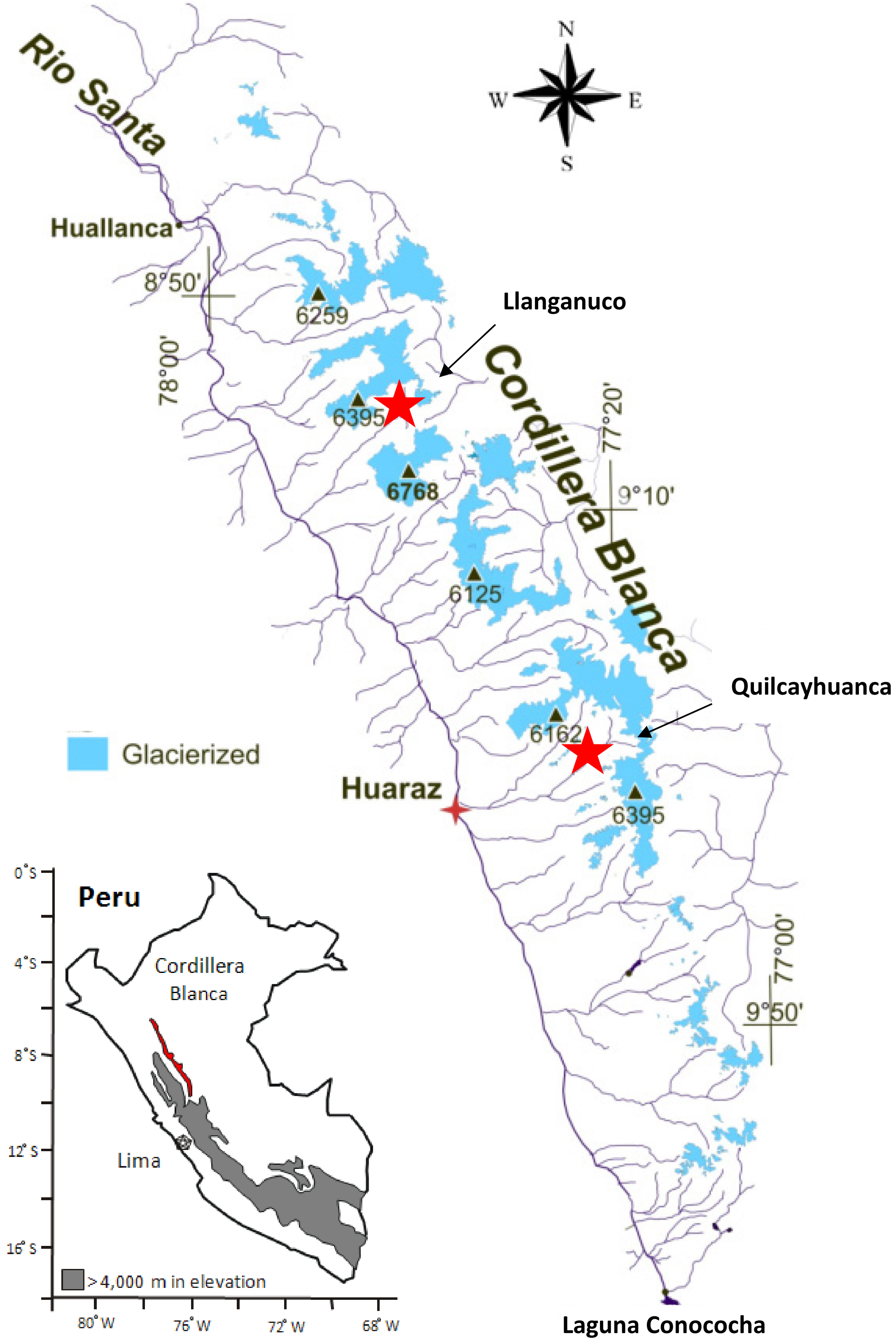

Figure 1. Llanganuco and Quilcayhuanca Pampa locations, Cordillera Blanca, Peru.

around 1860 AD (Ames and Francou, 1995) and has accelerated during the past few decades (Rabatel et al., 2013). As the glaciers retreated they left behind a trail of glacial deposits that include massive accumulations of unsorted fine and coarse grained sediments in form of moraines. Many of these deposits have been re-worked and sorted by glacial meltwater into fluvial and lacustrine deposits. Talus slope deposits from rock falls and landslides commonly overly and interfinger glacial deposits. Talus slope deposits are ubiquitous features in the glacial eroded valleys of the Cordillera Blanca.

2.2 Quilcayhuanca and Llanganuco Pampas

The two study areas, the Quilcayhuanca and Llanganuco Pampas, are located on the western side of the Cordillera Blanca (**Figure 1**). In high elevation watersheds of the Cordillera Blanca, the low relief valley bottoms are referred to as ‘pampas, and they are characterized by grassland and wetland plant communities that are locally known as *bofedales*. The pampas are managed by the local communities and used to pasture livestock. The pampas were likely formed by the plaudification of moraine, avalanche, or basin dammed lakes. Springs and glacial fed streams flow across the pampas and form the head waters of the Upper Rio Santa Watershed (~4,900 km^2) that drains the west side of the Cordillera Blanca and the east side of the Cordillera Negra. The Upper Rio Santa is approximately 120 km long and flows from Laguna Conococha at 4000 m.a.s.l. to the Cañon del Pato hydroelectric power plant at 1500 m.a.s.l.

The Quilcayhuanca Pampa study area (9.465° S, 77.379° W) is a 0.08 km^2 area within the greater Quilcayhuanca Watershed at approximately 3,900 m.a.s.l. The watershed is typical of other drainages in the western Cordillera Blanca that are characterized by a long valley with steep bedrock walls, talus slope deposits, and a narrow pampa. A glacial fed stream flows down the pampa and eventually becomes the Rio Quilcay, which flows through the provincial capital city of Huaraz and then joins the Rio Santa. Within the pampa valley, the stream is fed by the following four major tributaries: North Valley Tributary, South Valley Tributary, Tributary E, and Tributary F. The investigation site was on the south side of the main stream channel near Casa de Agua, a small water diversion station that also acts as a discharge monitoring station.

The Llanganuco Pampa study area (9.018° S, 77.603° W) is a 0.15 km^2 pampa located within the greater Llanganuco Watershed at approximately 4,400 m.a.s.l. Unlike the Quilcayhuanca Pampa, the Llanganuco Pampa is much wider because it is located in a cirque (bowl shape) basin. A glacial fed stream flows down the pampa until it plunges over a cliff at the south end of the pampa where the bedrock rises and funnels to a point. The stream is fed by three tributaries emanating from the base of an alluvial fan, and two tributaries emanating from the base of a moraine. Laguna 69 sits above the alluvial fan and Broggi Lake rests on top of the moraine; each proglacial lake belongs to a separate sub-catchment above the Llanganuco Pampa, and below the glaciated peak of Chacraraju. The investigation site was on the east side of the stream near the middle of the pampa.

Chapter 3 - Methods

3.1 Drilling and Well Installation

We used a portable core drill (**Figure 2**) from Shaw Tool Ltd to drill eight boreholes through clay, sand, gravel and crystalline rock. The drill was powered by a modified Tanaka stock 27 cc engine with 1.4 hp and a 4:1 gear ratio. The engine weighed 6.4 kg and was fueled by a 30:1 ratio of gasoline to two-stroke engine oil.

At the base of the engine, a water swivel introduced water down the inside of the drill pipe to lubricate the drill bit and circulate fine-grained sediment to the surface along the outside of the drill pipe. The water was supplied by a 7.4 L compression tank that was attached to the water swivel assembly. Continuous water circulation was essential during the drilling to prevent the drill bit from clogging up and jamming. This was facilitated by a quick release ball valve on the water swivel assembly and the use of a second compression tank.

The drill string was made of 41 mm OD stainless steel extensions that were 61 cm long, with three Teflon O-rings on the male end, and two J-slots on the female end. Extension rods were attached to one another by a simple push and turn motion. To prevent fine grained sediment from locking up the extension joints, silicone lubricant was applied to the extension ends prior to attaching them together.

Two types of drill bits were used during drilling – one for loose sediments and one for coring through rock. The loose material bit, essentially an oversized twist bit, was 42 mm OD stainless steel (25.4 cm long) with a helical flute and a water injection hole below a silicon carbide tip.

Figure 2. Portable drill.

The bit drove easily through muskeg, clay, silt and poorly sorted sand, but took much longer through hard packed, high plasticity clay. It was not very effective in drilling through gravel, which tended to deflect the drill bit and widened the borehole.

To drill through crystalline rock and talus, we used a 42.5 mm OD diamond core bit. The bit was 6.57 cm long and attached to a 41 mm OD stainless steel lead pipe (54 cm long) that usually captured cored rock fragments. To retrieve cores from the host rock, we used a core breaker (cylindrical wedge) and a core catcher attached to a length of drill stem with a T-bar handle. Often a knock out rod was used to push the core out of the core catcher. In some cases, the core catcher was also used to retrieve soft sediment cores.

Groundwater monitoring wells were installed using 31.8 mm OD polyvinyl chloride (PVC) pipe. The pipe segments were friction fitted together and sealed using silicone and duct tape. Well screens were made using hacksaw to cut slots every 5 cm on opposite sides of the PVC. The well screen was enclosed by a PVC slip on cap at the base and a nylon mesh along the outside to prevent sediment from entering the well. Above the well screen, duct tape was wound several times around the pipe to make a donut-shaped packer that prevented cement from reaching the well screen. After the well was inserted into the borehole, cement was poured down to the duct tape packer to seal off the well screen. The well was cut slightly below the ground surface and a large rock was placed on top to conceal it and prevent livestock from tampering with it.

Instead of installing a traditional sand-based filter pack, the borehole sediments were allowed to collapse around the well screen to create a natural filter pack. This was facilitated by developing the wells using a surging motion. High density tubing and a foot valve were lowered to the base of the well and shaken up and down repeatedly causing water to surge across the well screen. The surging water also breaks up any mud cake along the inside of the borehole and establishes a hydraulic connection between the well and the aquifer. Lastly, the tubing and foot valve were used to pump the wells dry removing any turbidity produced by the drilling process.

In order to measure hydraulic gradients, the well tops and selected stream banks were surveyed to a local datum. This was done using a self-leveling rotating laser (Leika Rugby 100) with a range of 300 m and an accuracy of ± 1.5 mm. The laser was setup roughly equidistant from each well and a receiver was lowered up and down a survey rod to intercept the laser and measure the elevation. At the Quilcayhuanca Pampa, the laser was setup in two locations because a small hill prevented the line of sight to all the well locations.

3.2 Hydraulic Conductivity

Hydraulic conductivity is an important hydrogeologic property that describes the rate at which water flows through a saturated geologic unit under a hydraulic gradient of unity. The hydraulic conductivity was measured at each well by conducting at least two slug tests (also called falling/rising head tests). The general method is to measure the static water level, rapidly displace a volume of water in the well, and measure the responding water levels until at least 80% recovery. In this thesis, the Hvorslev (1951) method was used to analyze the water level data and calculate the hydraulic conductivities.

In the Llanganuco Pampa, slug tests were performed on GW1s, GW1d, and GW3 by adding ~ 1 L of water to the well to displace the static water level. For GW2, water was removed from the well instead of added because the static water level was just below the top of casing. This was done using the same tubing and foot valve that was used to develop the wells.

In the Quilcayhuanca Pampa, slug tests were performed by using a peristaltic pump (GeoTech GeoPump^{TM}) to remove water from each well. This method was used because time constraints required that water samples be collected on the same day of the slug tests. Although the highest flow rate on the pump was used, the removal of water was not instantaneous, and took ~ 30 seconds to complete. As such, the hydraulic conductivities for the Quilcayhuanca Pampa are considered conservative estimates.

The water levels during the slug tests were measured electronically using non-vented, pressure transducers (Schlumberger Mini-diver, DI 501). The divers were installed ~ 15 to 30 cm above the base of each well and secured in place using a metal cable and carabineer attached to the top of the well. The water levels were corrected for atmospheric pressure by using a second pressure transducer (Schlumberger Baro-diver, DI 500) installed above the water column. These divers have a pressure range of 10 mH_2O, an accuracy of ±0.5 cm, and resolutions of 0.2 cm (Mini-diver) and 0.1 cm (Baro-diver). Both divers also record temperature within a range of -20 to +80 °C to an accuracy of ±0.1 °C and a resolution of 0.01 °C. These divers are ideal for long-term monitoring as they can record 24,000 data points of time, pressure and temperature. As such, the divers were re-installed after the slug tests to record water levels as part of a long-term groundwater monitoring program.

3.3 Water Samples and Analysis

Water samples were collected from the wells using a peristaltic pump and from surface water bodies by hand-sampling. At each sample location, one non-filtered and two filtered water samples were collected into 30 ml polyethylene bottles with minimal head space. The sample bottles were rinsed twice before samples were collected. Filtered water samples were filtered using a plastic syringe and a 45 µm filter. Water samples were stored in a cool dark location before they were submitted for analysis. Water quality parameters including pH, temperature and electrical conductivity (EC) were measured at each location.

Water samples were analyzed for major dissolved ions (Ca, Mg, Na, K, Cl, and SO_4) by researchers at two universities. The Quilcayhuanca Pampa water samples were analyzed at The Ohio State University using a Dionex DX500 Ion Chromotograph. The Llanganuco Pampa samples were analyzed at Syracuse University, New York, using a Dionex ICS-2000 Ion Chromatograph. Stable isotopes, δ18O and δ2H, were also scheduled to be analyzed at each university, but due to long turn around times the samples were not analyzed in time to be included in this thesis. HCO_3 was not directly measured, but calculated based on pH and the charge balance of the major dissolved ions (e.g. Mark et al., 2005). Similarly, total dissolved solids (TDS) were not directly measured, but calculated by summing the major dissolved ion concentrations.

3.5 Mixing Model

A binary mixing model was used to calculate tributary and groundwater contributions to stream flow by using the ion-tracer concentrations from representative samples of each water body. In this thesis, Na and K were selected as conservative tracers to use in the mixing model based on the piper plot analyses and following the criteria set by Baraer et al. (2009) for selecting suitable hydrochemical tracers. The model assumes that the tracer concentration in the stream is composed entirely of the two end members (i.e. groundwater and tributary fractions add to 1). The mixing model equation is as follows:

$$C_{STREAM} = f_{TRIB}\, C_{TRIB} + f_{GW}\, C_{GW} \tag{1}$$

where C_{STREAM} is the tracer concentration in the outlet stream, C_{TRIB} is the average tracer concentration of the tributaries, C_{GW} is the average tracer concentration of the groundwater, f_{STREAM} is the fraction of tributary water in the stream, and f_{GW} is the fraction of groundwater in the stream. The mixing model is calculated separately for each tracer and the fraction of each end member is presented as a percentage of stream flow.

Chapter 4 – Llanganuco Results

4.1 Drilling & Monitoring Wells

Four boreholes were drilled, with depths 1.86 to 6.10 m below the ground surface, in the Llanganuco Pamapa from July 8 to July 11, 2012 (**Figure 3**). Descriptions of the drill cuttings and schematics of the monitoring wells are provided in the borehole logs in **Appendix A**. Monitoring wells were installed in four of the boreholes and a table of the borehole depths, well construction details, and survey elevations are provided in **Table 1**.

Monitoring wells were installed in a sand lens (GW1s) within a glaciolacustrine clay, in the glaciolacustrine clay itself (GW1d), in glacial till (GW2), and in glaciofluvial outwash (GW3). The saturated conditions and coarse gravel in GW3 made it impossible to keep the drill bit centered and make significant penetration of the glacial outwash. In each borehole, slough was a common problem where borehole sediments either caved in or, in the case of tight clay, expanded when the drill stem was removed. Despite every effort made to install the wells as deep as possible, the well depths do not match the borehole depths, and range from 1.49 to 4.84 m. Water levels in the wells ranged from 0.05 to 0.68 m, excluding the water level from GW1d because the well screen was not effectively sealed from the overlying sand lens.

4.2 Hydraulic Conductivities

Hydraulic conductivity tests were conducted on each of the four monitoring wells on July 25, 2012 (**Table 2**) producing one value for each well, with the exception of GW1d for reasons outlined above. Overall, the hydraulic conductivities had a geometric mean of 5.6×10^{-5} m/s.

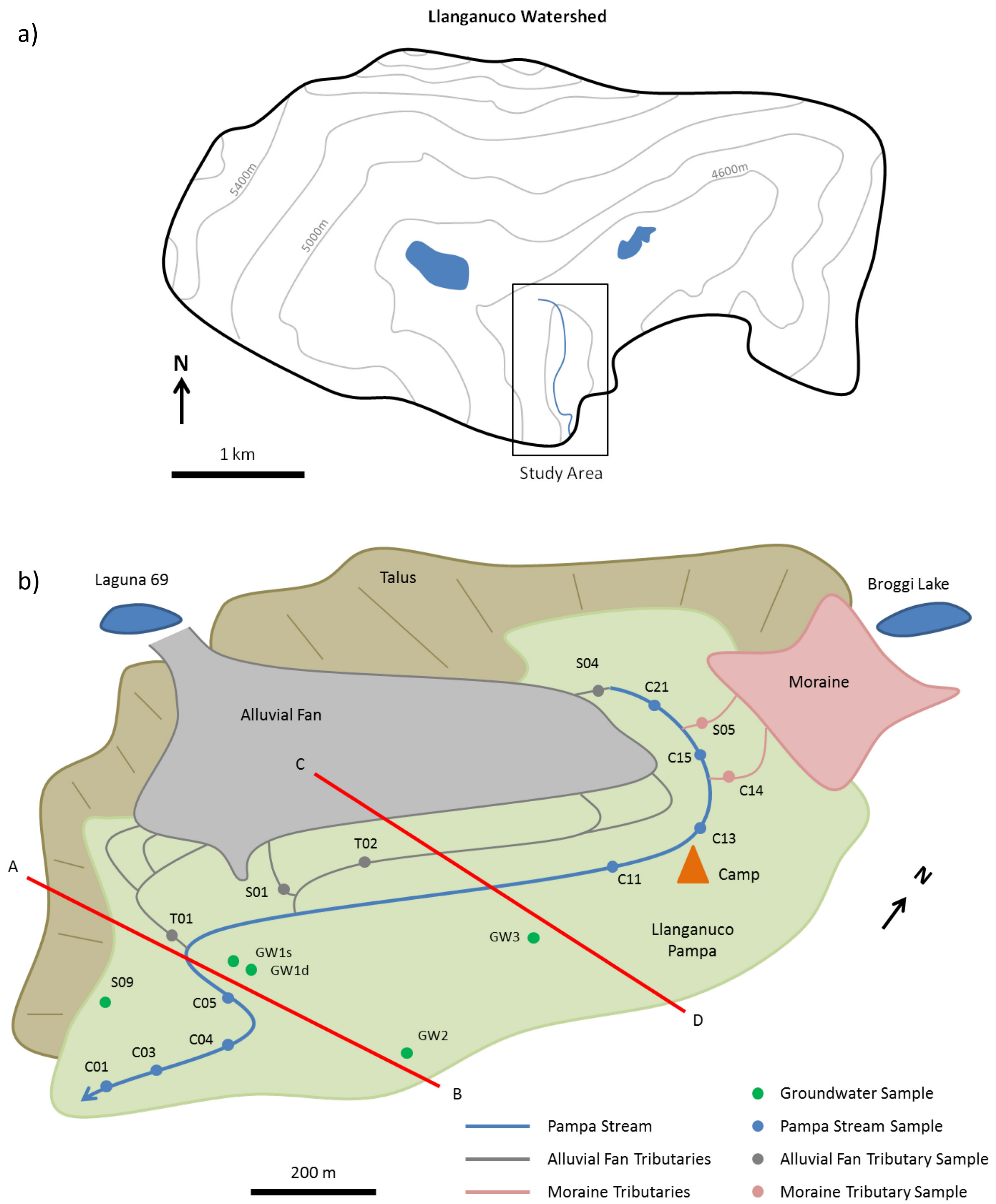

Figure 3. Llanganuco Watershed (a) and site map of the drilling and sample locations in the Llanganuco Pampa (b) where GW = groundwater well, C = channel, T = tributary, S = spring. Note: size of landforms in (b) are approximate.

Table 1. Borehole depths, well construction details, and survey elevations for the Llanganuco Pampa.

Well	Latitude	Longitude	TOC Elevation	Borehole Depth	Well Depth	Water Level	Screen Length	Screened Geology	Depth to Geology
	deg	deg	mAD	mBGS	mBGS	mBTOC	m		mBTOC
GW1s	-9.0187	-77.0604	98.554	3.35	2.51	0.68	0.61	Sand Lens	2.44
GW1d	-9.0187	-77.6039	98.434	6.10	4.84	-	0.61	Glaciolacustrine Clay	0.15
GW2	-9.0188	-77.6030	98.664	3.24	2.90	0.05	0.61	Glacial Till	2.74
GW3	-9.0181	-77.6037	100.176	1.83	1.49	0.30	0.31	Glaciofluvial Outwash	1.22

Note:

mAD - metres above datum

mBGS - metres below ground surface

mBTOC - metres below top of casing

Table 2. Hydraulic conductivities, hydraulic gradients, and groundwater flow velocities for the Llanganuco Pampa.

Well	**Geology**	**Hydraulic Conductivity** m/s	**Hydraulic Gradient to Stream** unitless	**Horizontal Groundwater Flow Velocity to Stream** m/day
GW1s	Glaciolacustrine - sand lens	3.8×10^{-5}	-	-
GW1d	Glaciolacustrine	-	-	-
GW2	Glacial Till	3.0×10^{-5}	0.007	0.09
GW3	Glaciofluvial Outwash	1.6×10^{-4}	0.009	0.62
Average		**5.6×10^{-5} ***		**0.35**

Notes:

* - geometric mean

Although GW1d could not be properly tested, the hydraulic conductivity can be estimated based on grain size. The large clay fraction inferred from the high plasticity of the drill cuttings suggests that the hydraulic conductivity of this glaciolacustrine clay is likely 10^{-9} m/s or less, which corresponds with published hydraulic conductivity values for other glaciolacustrine clays (Gordon and Huebner, 1983; Grisak and Cherry, 1975).

4.3 Chemistry

The field parameters (pH and EC) and chemistry results (Ca, Mg, Na, K, Cl, SO_4, HCO_3, and TDS) for the water samples collected from the Llanganuco Pampa in July 2012 are presented in **Table 3**. Average values are provided for the water samples grouped into the five following water groups: Pampa Groundwater, Proglacial Lakes, Alluvial Fan Tributaries, Moraine Tributaries, and Stream. Unusually high concentrations of Ca in the samples from GW1d and GW3 suggest that the concrete used to seal off the well screens had not set properly and contaminated the samples. Consequently, the field parameters and chemical results from GW1d and GW3 are considered unreliable and are excluded from analysis.

The pH of the water samples ranged from 6.8 to 7.9 and is consistent with circumneutral water (pH 6-8). The average EC of 75 uS/cm is low and typical of fresh water in head water catchments.

The relative abundance of each ion was calculated as the percentage of each ion to the total sum of the cations or anions. The average ion abundance for all of the samples in **Table 3** are as follows: Ca (84%), Mg (6%), Na (7%), K (2%), Cl (<1%), SO_4 (46%), and HCO_3 (54%). Calcium is

Table 3. Hydrochemistry results for the Llanganuco Pampa.

Location	**Sample**	**pH**	**EC**	**Temp**	**Ca**	**Mg**	**Na**	**K**	**Cl**	**SO_4**	**HCO_3**	**TDS**	**Water Type**
			uS/cm	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
GW1s	GW1s	7.8	75	10.3	9.23	0.57	2.10	1.32	0.11	3.73	32.61	17.55	Ca-HCO3
GW2	GW2	7.5	104	11.5	14.97	0.82	3.16	1.27	0.08	11.98	42.96	33.12	Ca-HCO3
Spring	S09	7.7	-	5.4	7.66	0.15	1.56	0.29	0.06	4.39	21.14	14.82	Ca-HCO3
Pampa Groundwater		**7.6**	**90**	**9.1**	**10.62**	**0.51**	**2.27**	**0.96**	**0.08**	**6.70**	**32.24**	**21.83**	**Ca-HCO3**
Laguna 69	L02	7.2	-	8.0	9.98	0.40	0.37	0.22	0.04	13.47	15.67	25.05	Ca-SO4
Broggi Lake	L01	7.2	-	9.9	12.31	1.16	0.72	0.37	0.04	28.20	9.46	43.00	Ca-SO4
Proglacial Lakes		**7.2**	**-**	**9.0**	**11.14**	**0.78**	**0.54**	**0.29**	**0.04**	**20.84**	**12.56**	**34.03**	**Ca-SO4**
Tributary 1	S04	7.7	-	5.4	11.74	0.29	1.23	0.37	0.05	12.13	22.60	27.06	Ca-HCO3
Tributary 2A	S01	7.1	72	6.7	11.55	0.44	1.18	0.59	0.04	14.55	21.52	29.20	Ca-HCO3
Tributary 2B	T02	7.4	70	8.9	11.73	0.32	1.15	0.62	0.05	12.32	23.31	27.44	Ca-HCO3
Tributary 3	T01	7.2	62	13.3	10.58	0.33	0.72	0.37	0.04	11.01	20.54	23.84	Ca-HCO3
Alluvial Fan Tributaries		**7.4**	**68**	**8.6**	**11.40**	**0.35**	**1.07**	**0.49**	**0.04**	**12.50**	**21.99**	**26.89**	**Ca-HCO3**
Tributary 1	S05	7.4	-	7.0	12.36	0.95	0.73	0.63	0.01	23.52	14.81	38.40	Ca-SO4
Tributary 2	C14	7.0	82	6.8	13.22	0.87	0.77	0.84	0.00	19.63	22.36	35.53	Ca-SO4
Moraine Tributaries		**7.2**	**-**	**6.9**	**12.79**	**0.91**	**0.75**	**0.73**	**0.01**	**21.57**	**18.58**	**36.97**	**Ca-SO4**
Stream	C21	7.7	-	5.8	11.81	0.28	1.25	0.37	0.05	12.14	22.89	27.08	Ca-HCO3
Stream	C15	7.1	75	7.2	12.08	0.55	1.05	0.48	0.03	16.02	20.64	31.04	Ca-SO4/HCO3
Stream	C13	7.9	76	5.6	12.43	0.64	1.05	0.57	0.03	16.59	21.84	32.05	Ca-SO4/HCO3
Stream	C11	7.5	76	10.6	12.14	0.56	1.02	0.56	0.03	16.46	20.59	31.46	Ca-SO4
Stream	C05	7.1	71	7.4	11.54	0.42	1.17	0.56	0.04	14.64	20.56	29.29	Ca-HCO3
Stream	C04	6.8	72	7.3	11.56	0.44	1.21	0.57	0.05	14.61	20.86	29.35	Ca-HCO3
Stream	C03	7.3	71	6.9	11.60	0.44	1.17	0.57	0.04	14.59	20.94	29.31	Ca-HCO3
Stream Out	C01	7.6	71	6.3	11.49	0.43	1.18	0.55	0.04	14.48	21.13	29.08	Ca-HCO3
Stream		**7.4**	**73**	**7.1**	**11.83**	**0.47**	**1.14**	**0.53**	**0.04**	**14.94**	**21.18**	**29.83**	**Ca-HCO3**

the dominant cation in the study area with SO_4 and HCO_3 alternating between the main anion as Cl is so low.

In terms of pampa chemistry (i.e. excluding the proglacial lakes), the average major ion and TDS concentrations were 11.6 mg Ca/L, 14.1 mg SO_4/L, 22.4 mg HCO_3/L, and 28.9 mg TDS/L. The Moraine Tributaries group had the largest averaged concentrations of Ca, SO_4, and TDS, while HCO_3 was greatest in the Pampa Groundwater group. Extreme values of the major ions were not observed in the Alluvial Fan Tributaries or Stream groups, which had the most similar chemistry concentrations. In terms of minor ion chemistry, the most notable observation was that Na concentrations were usually 2-3 times greater in the Pampa Groundwater group than any other group.

Chapter 5 – Llanganuco Discussion

5.1 Geology

The majority of the Llanganuco Pampa was covered with ~0.15 m of organic rich soil, which was thickest in the southern half of the pampa where there was poor surface drainage indicated by pooling water, water tracks, and a wetland vegetation. In the north half of the pampa, thin soil (~5 cm) and a rocky ground surface indicated very good drainage conditions.

Drilling in the south half of the Pampa identified a clay layer that was determined to be glaciolacustrine in origin due to the depositional setting and the large fraction of fine grained sediments. The clay layer thins to the north where it becomes sandier in what appears to be a near shore facie. It has a maximum thickness greater than 5.85 m based on the bottom of the clay layer not being encountered in the deepest borehole (GW1d). The presence of peat at the base of the clay layer in GW2 supports the theory that these pampas formed by the paludification of proglacial lakes (Mark and McKenzie, 2007), which likely had seasonal shifting shorelines. Additional features in this clay layer included two sand lenses ranging in thickness from 0.20 to 0.75 m in GW2 and GW1s, respectively, and tightly packed, high plasticity clay identified at varying depths within the unit. The sand lenses were not considered continuous layers due to insufficient borehole density to establish lateral continuity.

Glacial till was identified in GW2 underlying the clay layer at 3.2 m depth. It was considered glacial till based on lithology, location and stratigraphic position. The lithology of a cored rock fragment in the glacial till did not match the granite bedrock, but that of an argillite, which belongs to the Chicama Formation that is exposed further up the valley in the Broggi Lake sub-catchment. Therefore, it must have been glacially transported. The close proximity of the drill site to the valley wall is consistent with the depositional setting of a lateral moraine; a glacial landform consisting of glacial till. In terms of stratigraphy, the presence of the overlying glaciolacustrine layer suggests that this bottom unit was deposited as the glacier retreated. As glaciers retreat they leave behind a trail of glacial till that is formed by the release of fine and coarse grained sediment from stagnant ice. As in the Llanganuco Pampa, the abundant release of melt water in a cirque (bowl shaped) basin typically results in the formation of a proglacial lake.

Sand and coarse gravel were discovered in two locations, the test hole drilled in the camp site and in GW-3 at 1.70 m. Based on grain size, close proximity to the glaciers, the distribution of good soil drainage and rocky ground surface, this deposit was classified as glaciofluvial outwash and likely covers the north half of the pampa. It is uncertain what the thickness of the glaciofluvial outwash is as the bottom of the unit was not encountered.

5.2 Groundwater

The glacial till unit is considered to be an aquifer because it has a hydraulic conductivity of 3.0×10^{-5} m/s and is laterally continuous. Although the glacial till was only encountered in one borehole, the shallow water level (0.05 m) indicates that the aquifer is under artesian conditions. This requires a confining unit (the glaciolacustrine clay) and a hydraulic connection to a recharge area at a higher elevation, implying lateral continuity. The glaciolacustrine deposit behaves as an aquitard due to its low estimated hydraulic conductivity of $<10^{-9}$ m/s. The occurrence of artesian conditions further defines the glacial till as a confined aquifer. It is possible that the glacial till aquifer is hydraulically connected with glaciofluvial outwash, but this has yet to be confirmed.

The glaciofluvial outwash deposit was defined as an aquifer because it has a hydraulic conductivity of 1.6 x 10^{-4} m/s and is laterally continuous. It is mostly unconfined in the north half of the pampa, as indicated by the rocky ground surface. However, in an east-west belt across the middle of the pampa, the aquifer is semi-confined as it overlain by a near shore (sandier) glaciolacustrine deposit. This stretch of pampa also coincides with an abundance of pampa springs and water tracks that were observed in the field.

Stream and groundwater elevations were used to calculate hydraulic gradients (**Table 2**) between two wells (GW2 and GW3) and the stream. Combining these gradients with the measured hydraulic conductivities and an assumed porosity of 0.3 for the glacial till and glaciofluvial outwash deposits (Freeze and Cherry, 1979) the average linear horizontal groundwater flow velocities were calculated to be 0.06 and 0.41 m/day (**Table 2**). These values are considered average to fast in terms of general groundwater flow velocities. The assumed porosity for the glacial till may seem high, but glacial till from mountain glaciers tends to be coarse grained and poorly sorted (Fetter, 2001).

The same values from **Table 2** were used to calculate the specific discharge of groundwater to the stream, which was 8.2 x 10^{-7} m/s. This could be taken one step further to estimate the volumetric groundwater discharge to the stream using Darcy's Law, but there is a considerable amount of uncertainty associated with estimating the cross-sectional area of groundwater discharging to the stream. Hence, the majority of groundwater discharge estimates to stream bodies are completed using hydrograph recession or separation, stream flow analysis, physical or chemical tracers, computer models, or chemical mixing models (Section 5.5).

Additionally, flux estimates are complicated by the scale dependency of the hydraulic conductivity. The slug tests measure hydraulic conductivity of the aquifer immediately surrounding the well (~1m^3), and the groundwater flow velocities were calculated over horizontal distances of ~75 to 150 m. In general, the hydraulic conductivity of a heterogeneous aquifer increases with scale (Schulze-Markuch et al., 1999), up to a volume threshold beyond which hydraulic conductivity is constant (i.e. the aquifer behaves as a homogeneous media). Therefore, the hydraulic conductivities and groundwater flow velocities presented in **Table 2** are conservative estimates for the Llanganuco Pampa, and are potentially an order of magnitude greater at the pampa scale.

5.3 **Conceptual Models**

Conceptual models of the stratigraphy and groundwater flow were drawn along two cross-sections to illustrate the hydrogeology in the south (**Figure 4**) and north (**Figure 5**) halves of the pampa. In the absence of boreholes west of the main stream channel, field observations were used to complete the geology.

The bedrock is drawn in a wide 'U' shape that is consistent with the bedrock topography of glacier eroded valleys. Glacial till is draped over the bedrock as it would appear if the glacier melted evenly across the valley. In the southern half of the pampa (**Figure 4**), the glaciolacustrine clay lies on top of the glacial till and represents the formation of a proglacial lake as the glacier retreated. The lake was likely dammed by the bedrock which rises and

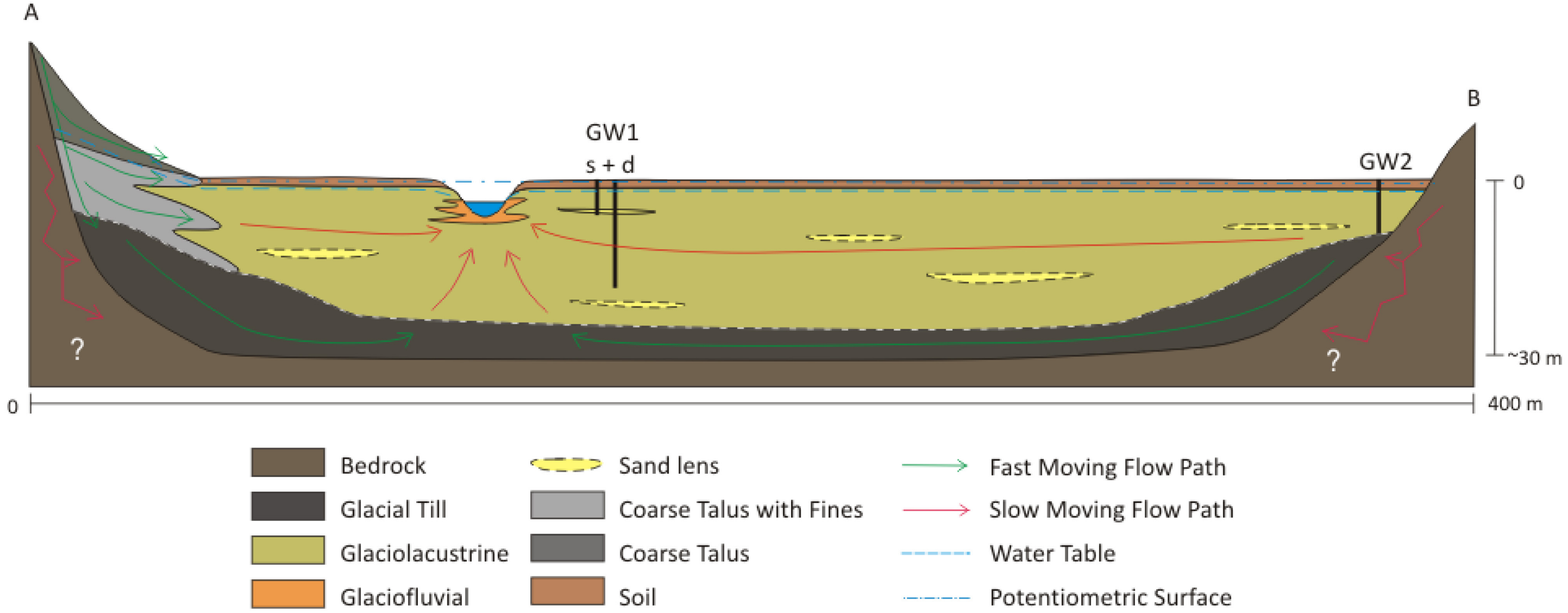

Figure 4. South hydrogeologic conceptual model of the Llanganuco Pampa.

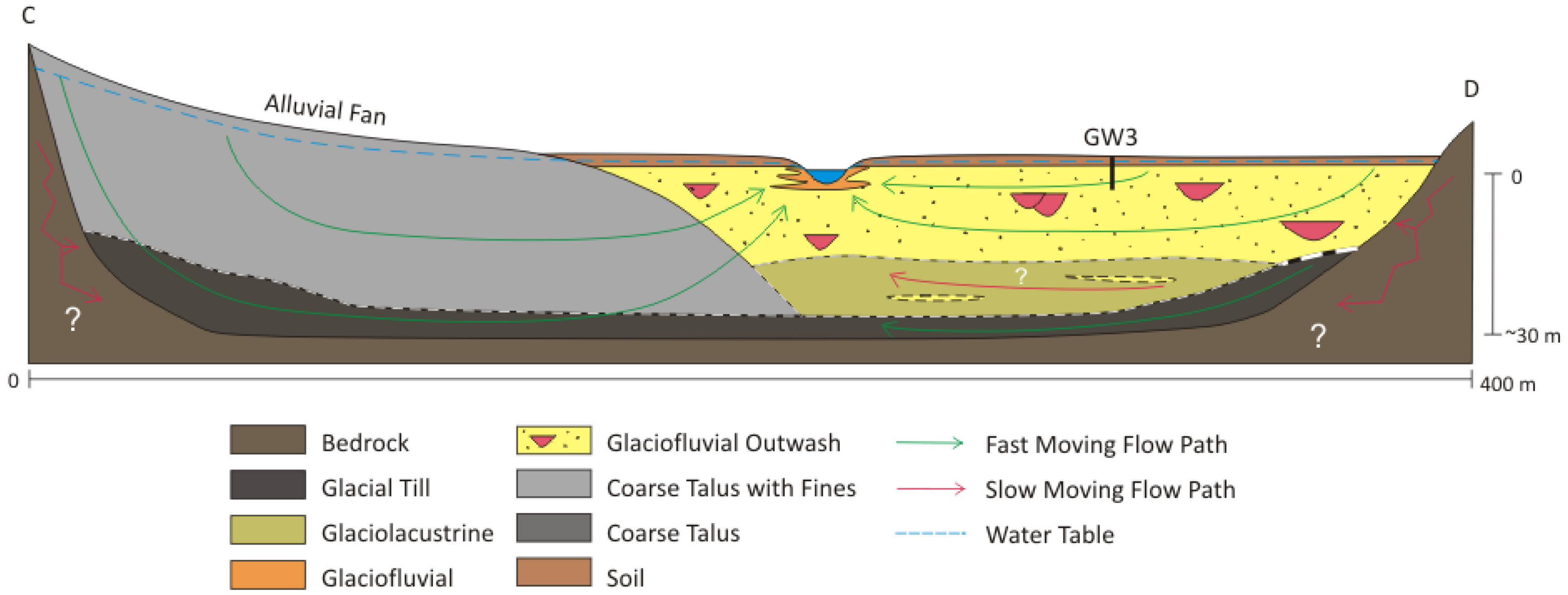

Figure 5. North hydrogeologic conceptual model of the Llanganuco Pampa.

funnels to a point at the south end of the pampa where the main stream plunges over a cliff. On the west side of the pampa, talus deposits are visible at the base of the valley wall and visibly feed a number of springs in the wetland that occupies the southwest corner of the pampa. The course grained nature of the talus and hydraulic conductivity of the glacial till suggests that these units are the main pathways for groundwater flow. In contrast, the fine grained nature of the glaciolacustrine clay makes it a large barrier to groundwater flow. It is possible that talus and the glacial till are hydraulically connected, but it is uncertain what the lateral continuity and thickness is of the two units. Fracture flow in the granite bedrock is also a possibility, but groundwater springs directly from exposed bedrock on the valley walls has yet to be observed in the study area and no boreholes were drilled into the bedrock.

In the north half of the pampa (**Figure 5**), the bedrock and glacial till are assumed to be present in the same form as in the south half of the pampa. Due to the high sediment loads at the glacier snout, it is possible that glaciofluvial outwash overlays or is interbedded with the glaciolacustrine clay. However, the drilling did not penetrate the base of the glaciofluvial outwash so it’s uncertain if a lower glaciolacustrine deposit exists. As the main focus of the study was on the pampa aquifers, drilling was not carried out on the alluvial fan. In the field, however, it was clear that the alluvial fan was a coarse grained deposit with an audible groundwater component, as one could easily hear subsurface water flow in a number of locations. These observations and the high hydraulically conductivity of the glacial outwash suggest that these deposits are main pathways of groundwater flow that can easily be recharged by precipitation. As the stream cuts through the glaciofluvial outwash, a large degree of surface water-groundwater interaction is expected in the north half of the pampa.

5.4 Chemistry

Samples from the Broggi Lake sub-catchment, including Broggi Lake and the Moraine Tributaries group, had the greatest concentrations of Ca, Mg, SO4, and TDS. This is likely explained by the elevated weathering rates associated with glacial debris rich environments (Tranter, 2005). The Broggi Lake sub-catchment is full of relatively fresh glacial debris from the Broggi Glacier that disappeared in 2005, and with fresh debris continually added from the existing glacier hugging the summit of Chacraraju. The exposure of the sulfide rich Chicama Formation in this catchment can also help explain the elevated concentrations as it has been associated with enhancing sulfide weathering and higher cation loads in other valleys, such as the Quilcayhuanca Watershed (Fortner et al., 2011).

The Pampa Groundwater group had the greatest concentrations for Na, K, Cl, and HCO_3. These elevated concentrations can also be explained by enhanced weathering rates that commonly occur in groundwater due to the increased water-rock interaction time. Longer groundwater residence times, and hence weathering rates, generally increase with depth, which explains why the concentrations from the monitoring wells are greater than that of the spring sample. Based on the pH and high HCO_3, carbonate weathering is likely occurring in the groundwater.

Representative samples from each of the five water groups were plotted on a Piper Plot diagram (Piper, 1944) in **Figure 6**. This diagram is a useful tool to illustrate the abundance of the major ions, determine water types (or hydrochemical facies) of water bodies, and identify mixing relationships between these water bodies. Llanganuco water samples have a Ca-HCO_3 or Ca-SO_4 water type (**Table 3**), with the first type being the most common as it describes the

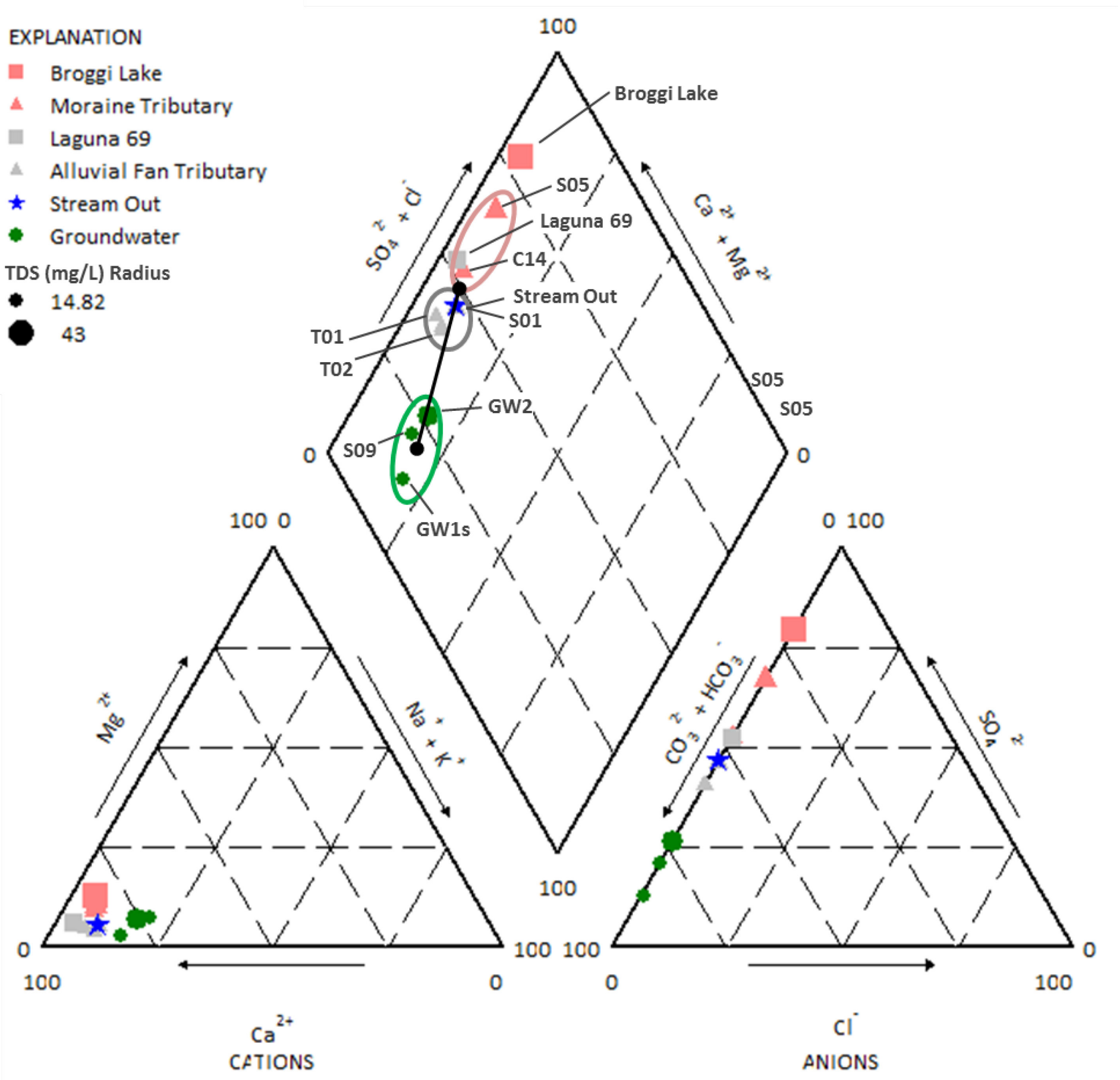

Figure 6. Piper plot of surface water and groundwater samples from the Llanganuco Pampa.

Alluvial Fan Tributaries, Stream, and Pampa Groundwater water groups. A Ca-HCO_3 water type is typical of shallow fresh water systems in carbonate and granite bedrock watersheds. Two water groups, Proglacial Lakes and Moraine Tributaries, have Ca-SO_4 water types, which is similar to glacial fed water bodies in other watersheds in the Cordillera Blanca, such as the Querococha watershed (Mark et al., 2005) and Quilcayhuanca (Fortner et al., 2011).

On the Piper Plot (**Figure 6**), a mixing line is drawn between the two end members (tributaries and pampa groundwater) that can reasonably explain stream flow. The stream out sample (C01) plots along the mixing line, but very close to the tributary end member. In fact, the stream out sample plots within the Alluvial Fan Tributary group, directly on top of the S01 sample. This suggests that the stream flow is mainly derived from the Alluvial Fan tributaries, which is also supported by the similarity between their chemical compositions. The Pampa Groundwater group plots much lower than the rest of the samples as it has a much lower SO_4 and greater Na. The greater Na in the Pampa Groundwater is unique to this water body and is used in the mixing model to isolate the groundwater component from the stream. There also appears to be a slight increase in Na from Laguna 69 to the Alluvial Fan tributaries. This would suggest that a similar weather reaction(s) that is producing Na in the pampa groundwater is also occurring in the Alluvial Fan.

5.5 Mixing Model

The binary mixing model outlined in Equation (1) is used to determine what fraction of the stream-out component (C01) of the Llanganuco Pampa is from the tributary and groundwater components. Na was selected as a conservative tracer for the mixing model based on the piper plot analysis in the previous section and following the criteria set forth by Baraer et al (2009) for selecting hydrochemical tracers. Groundwater accounted for approximately 18 % of the stream flow, and tributary inputs for the remaining 82 %. In comparison, dry season groundwater contributions from the Querococha Watershed in the Cordillera Blanca ranged from 18 to 74 % over 5 years (Baraer et al., 2009). However, it should be noted that the published values are based on the chemical signature from a stream emanating from a non-glacial catchment, and not collected from pampa aquifers. Understandably, groundwater contributions to stream flow vary across watersheds due to disparities in glacial coverage, groundwater reservoir sizes, recharge rates, and exchange fluxes between surface water and groundwater bodies.

The mixing model results also agree with the position of the stream out component on the Piper Plot (**Figure 6**), which lies closer to the tributary components on the mixing line, implying that tributary flows are the largest contributor to stream flow. However, the stream component on the mixing line is not 18 % of the graphical distance from the groundwater end member. This could be explained by the fact that concentrations and not mass fluxes (i.e. mass per volume) of ions were used in the mixing model, which would account for the differences in discharge between groundwater and the tributaries. This should be addressed in future work where surface water and groundwater discharges need to be measured.

Chapter 6 – Quilcayhuanca Results

6.1 Drilling & Monitoring Wells

Four boreholes were drilled, with depths from 1.83 to 6.33 m below the ground surface, in the Quilcayhuanca Pampa from July 15 to July 17, 2012 (**Figure 7**). Descriptions of the drill cuttings and schematics of the monitoring wells are provided in the borehole logs in **Appendix A**. Monitoring wells were installed in each of the four boreholes and a table of the borehole depths, well construction details, and survey elevations are provided in **Table 4**.

Each monitoring well was installed in the buried talus deposit that was exposed above ground on the south side of the valley. Due to flowing artesian conditions observed in GW2, water samples were collected before the well casing was removed and the borehole plugged using concrete. As in Llanganuco, slough in each borehole prevented the installation of wells to the bottom of each hole. As a result, well depths do not match the borehole depths, and range from 1.51 to 6.17 m. Water levels in the wells ranged from 0.39 to 0.63 m. Unfortunately, the water level could not be measured in GW2 due to the artesian conditions.

6.2 Hydraulic Conductivities

Hydraulic conductivity tests were conducted on GW1, GW3 and GW4 (all installed in the buried talus deposit) on July 26, 2012 (**Table 5**). The geometric mean of the hydraulic conductivities was 2.1 x 10^{-5} m/s. Due to the flowing artesian conditions in GW2, it was not possible to measure the hydraulic conductivity; however, it likely has a similar value to the other three wells installed in the same talus unit. Although no wells were installed in the clay layer

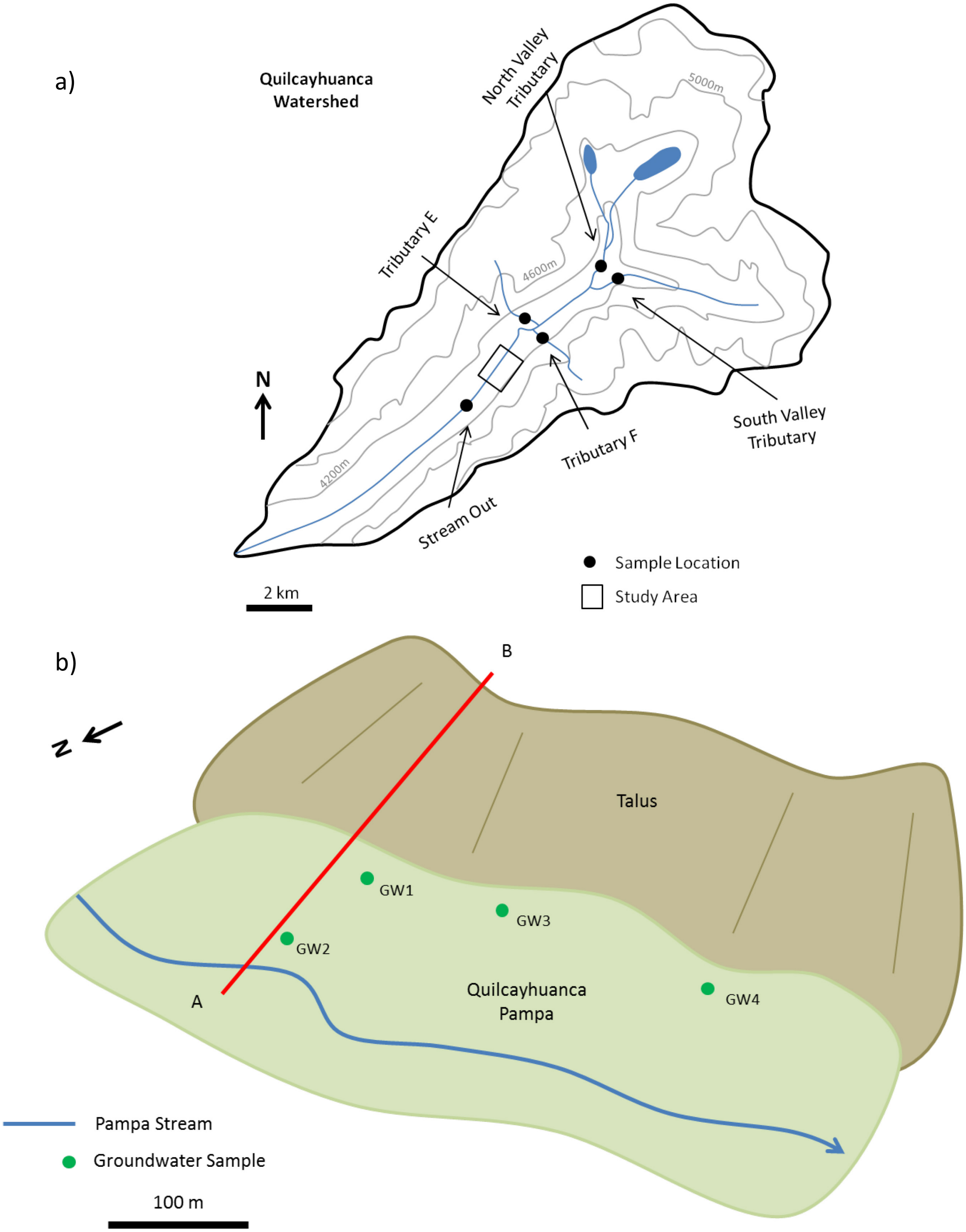

Figure 7. Quilcayhuanca Watershed (a) and site map of the drilling locations in the Quilcayhuanc Pampa (b) where GW = groundwater well. Note: size of landforms in (b) are approximate.

Table 4. Borehole depths, well construction details, and survey elevations for the Quilcayhuanca Pampa.

Well	**Latitude**	**Longitude**	**TOC Elevation**	**Borehole Depth**	**Well Depth**	**Water Level**	**Screen Length**	**Screened Geology**	**Depth to Geology**
	deg	deg	mAD	mBGS	mBGS	mBTOC	m		mBTOC
GW1	-9.4661	-77.3782	101.508	3.79	3.70	0.39	0.914	Talus	2.439
GW2	-9.4657	-77.3789	98.635	6.33	6.17	Artesian	0.610	Talus	5.183
GW3	-9.4668	-77.3790	100.845	1.83	1.51	0.40	1.110	Talus	0.610
GW4	-9.4678	-77.3801	97.700	2.44	2.27	0.63	1.635	Talus	1.448

Notes:

mAD - metres above datum

mBGS - metres below ground surface

mBTOC - metres below top of casing

Table 5. Hydraulic conductivities, hydraulic gradients, and groundwater flow velocities for the Quilcayhuanca Pampa.

Well	**Geology**	**Hydraulic Conductivity** m/s	**Hydraulic Gradient to Stream** unitless	**Horizontal Groundwater Flow Velocity to Stream** m/day
GW1	Talus	7.3×10^{-5}	0.021	0.43
GW2	Talus	-	-	-
GW3	Talus	2.0×10^{-5}	0.022	0.13
GW4	Talus	6.5×10^{-6}	0.015	0.03
Average		$\mathbf{2.1 \times 10^{-5}}$ *****	**0.019**	**0.20**

Notes:

* - geometric mean

overlying the talus deposit, the hydraulic conductivity was estimated to be less than 10^{-8} m/s based on the typical values associated with clay (Fetter, 2001).

6.3 Chemistry

The field parameters (pH and EC) and chemistry results (Ca, Mg, Na, K, Cl, SO_4, HCO_3, TDS) for the groundwater samples collected from the Quilcayhuanca Pampa in July 2012 are presented in **Table 6**. Although, surface water samples were collected in July 2012, longer than expected lab turnaround time prevents their inclusion in this thesis. Therefore, results for surface water samples collected in July 2008 from the pampa stream and each of its four main tributaries are presented in **Table 6**. Average hydrochemical values are provided for the water samples, divided into the three following water groups: Pampa Groundwater, Tributaries, and Stream. Unusually high concentrations of Ca in the samples from GW1 and GW3 suggest that the concrete used to seal off the well screens had not set properly and contaminated the samples. Consequently, the field parameters and chemical results from GW1 and GW3 are considered unreliable and are excluded from analysis.

The majority of the surface water samples had an average pH of 3.5 and are consistent with acidic conditions that are usually associated with acid mine drainage. The pH of GW4 and Tributary E were 8.7 and 6.9, which indicate basic and circumneutral waters. Although the field parameters were not measured in GW2 before it was abandoned, it likely has similar pH to GW4 because they were installed in the buried talus and had similar major ion chemistry. The average EC of 231 uS/cm is greater than most head water catchments, but is still typical of fresh water.

Table 6. Hydrochemistry results for the Quilcayhuanca Pampa.

Location	**Sample**	**pH**	**EC** uS/cm	**Ca** mg/L	**Mg** mg/L	**Na** mg/L	**K** mg/L	**Cl** mg/L	**SO_4** mg/L	**HCO_3** mg/L	**TDS** mg/L	**Water Type**
GW2	GW2	-	-	15.24	1.66	9.64	1.66	1.00	24.92	49.24	54.21	Ca-HCO3
GW4	GW4	8.7	180	19.12	1.60	5.14	3.14	0.87	27.40	48.29	57.31	Ca-HCO3
Pampa Groundwater				**17.18**	**1.63**	**7.39**	**2.40**	**0.94**	**26.16**	**48.76**	**55.76**	**Ca-HCO3**
North Valley	9	3.8	276	22.70	7.60	1.90	1.00	0.62	125.0	0	161.4	Ca-SO4
South Valley	15	3.3	358	27.80	3.80	0.10	0.05	0.49	154.0	0	194.0	Ca-SO4
Tributary E	Trib E	6.9	57	8.65	0.07	0.82	0.73	0.58	7.80	17.54	19.13	Ca-HCO3
Trbutary F	Trib F	3.6	90	12.83	3.11	1.47	0.26	0.59	58.54	0	78.45	Ca-SO4
Tributaries		**4.4**	**195**	**17.99**	**3.65**	**1.07**	**0.51**	**0.57**	**86.34**	**4.38**	**113.3**	**Ca-SO4**
Stream	18	3.4	338	24.34	8.41	1.50	0.60	-	148.0	0	189.6	Ca-SO4
Stream	20	3.4	316	22.20	7.50	1.60	0.60	-	134.0	0	170.5	Ca-SO4
Stream	21	3.5	-	22.10	7.20	1.60	0.70	-	133.0	0	168.7	Ca-SO4
Stream Out	23	3.7	-	19.40	6.20	2.40	0.90		116.0	0	149.0	Ca-SO4
Stream		**3.5**	**327**	**22.01**	**7.33**	**1.78**	**0.70**	**-**	**132.75**	**0.00**	**169.5**	**Ca-SO4**

Notes:

Dashes = data not measured

Surface water data from July 2008

The relative abundance of each ion was calculated as the percentage of each ion to the total sum of the cations or anions. The average ion abundance for all of the samples in **Table 6** are as follows: Ca (67%), Mg (23%), Na (9%), K (2%), Cl (1%), SO_4 (81%), and HCO_3 (18%). Similar to the Llanganuco Pampa, calcium is the dominant cation in the Quilcayhuanca Pampa with SO_4 and HCO_3 alternating as the main anion. Magnesium and SO_4 are much larger components in the Quilcayhuanca Pampa than the Llanganuco Pampa, with Na, K, and Cl being similar between the study areas.

In terms of major ion (e.g. Ca, SO_4, Mg, and TDS) concentrations, the North and South Valley tributaries most closely match the main stream channel, and are much greater than the other water bodies. This is most pronounced in the SO_4 and TDS concentrations (~135 mg SO_4/L and ~172 mg TDS/L), which were four and three times greater, respectively, than the other tributary and groundwater samples (~30 mg SO_4/L and ~52 mg TDS/L). In terms of other ion concentrations, Na and K are more elevated in the groundwater samples than the other water bodies.

Chapter 7 – Quilcayhuanca Discussion

7.1 Geology

The surface of the pampa is covered by clay, organic rich soil that was thinnest (~0.05 m) in the middle of the pampa and thickest (~1.40 m) near the valley edge. Underlying the organic soil was another clay layer, believed to be glaciolacustrine in origin, and is also thickest in the middle of the valley and pinches out towards the valley edge. The clay layer overlays a buried talus deposit that was encountered in each of the four boreholes. Depth to the talus deposit ranged from 5.35 m in the middle of the pampa to zero where it was exposed at the surface along the south valley edge. Although the drill was advanced 1.35 m into the buried talus, the bottom of the layer was not encountered. Cored rock fragments from the buried talus were 0.05 to 0.30 m in size and included granites, a quartz vein, argillites and hornfels (the latter two coming from the Chicama Formation). Gravel was also encountered at the base of GW2 (6.33 m) although none was recovered in the core catcher.

The likelihood of recovering fine grained sediment during the coring is very low as water was circulated through the drill pipe to lubricate the drill bit, and would have flushed away any fine grained sediment. However, based on the talus hydraulic conductivities (**Table 5**) and the strong relationship between grain size and hydraulic conductivity (Fetter, 2001), there is likely a fine grained component of silty sand in the talus. With only one deep well drilled in the middle of the pampa, it is uncertain how continuous the buried talus is up and down the valley (ie. to the east and west). However, the abundance of talus deposits on both sides of the valley walls suggests that buried talus is ubiquitous throughout the Quilcayhuanca Watershed.

7.2 Groundwater

The buried talus in the pampa is considered an aquifer based on the lateral continuity established by the drilling and the high hydraulic conductivity of 2.1×10^{-5} m/s (geometric mean). This is not surprising based on the coarse-grained nature and abundance of talus deposits in the study area. In the middle of the pampa, the talus aquifer is confined by the glaciolacustrine layer and under flowing artesian conditions, as indicated by GW2. As the clay layer decreases in thickness towards the edge of the valley wall, the talus aquifer shifts from a confined aquifer to an unconfined aquifer.

In comparison to other talus deposits, the range of hydraulic conductivities in **Table 5** is three to four orders of magnitude smaller. For example, in the Canadian Rockies the hydraulic conductivity of a talus deposit ranged from 0.01 to 0.03 m/s based on the hydrograph analysis of a talus spring (Muir et al., 2011). And in the Colorado Rockies, the hydraulic conductivities of talus deposits ranged from 0.007 to 0.009 m/s based on the grain size of talus soil samples from various depths (Clowe et al., 2003). In the latter study, the lower hydraulic conductivities are associated with the larger proportion of fine grained material in the deeper talus samples. The vertical profile of talus deposits has been well documented (White, 1981; Lautridou, 1988; Davinroy, 2000) and is generally characterized by a surface layer of large rocks in an open-work structure and a lower clast supported matrix with voids either completely or partially filled with fine grained sediment. As the hydraulic conductivities in **Table 5** were measured in buried talus, it is not surprising that the values are lower than the values for other talus deposits based on the larger portion of fine grained sediments that are present lower down in a talus profile.

At this time, there does not appear to be any published data of hydraulic conductivity values for buried talus deposits for comparison.

Previous studies have also identified multiple flow paths within talus or talus-moraine deposits (Caballeo et al., 2002; Roy and Hayashi, 2009; Muir et al., 2011). In general, the flow paths have been characterized as quick and shallow, or slow and deep. These different flow paths are likely channeled by the internal structure of the deposits and the change in permeability associated with underlying units, such as bedrock (Muir et al., 2011) or buried moraine (Caballero et al., 2002). This suggests that the hydraulic conductivity is not consistent throughout talus and moraine deposits. Therefore, the hydraulic conductivities in **Table 5** are only representative of the top of the buried talus aquifer and are likely larger than the hydraulic conductivity at the bottom of the deposit.

Stream and groundwater elevations were used to calculate the hydraulic gradients (**Table 5**) between three wells (GW1, GW2, and GW3) and the stream. Combining these gradients with the hydraulic conductivities (**Table 5**) and an assumed porosity of 0.3 for the sandy gravel (Fetter, 2001), the average linear horizontal groundwater flow velocities were calculated (**Table 5**) to be 0.03, 0.13, and 0.43 m/day, with an average of 0.20 m/day. These values are considered fast in terms of general groundwater flow velocities. The values in **Table 5** were also used to estimate the groundwater specific discharge to the stream for the Quilcayhuanca Pampa, which was 6.9×10^{-7} m/s.

As explained in Section 5.2, hydraulic conductivity is scale dependent and typically increases over the scale of measurement (Schulze-Makuch et al., 1999). Therefore, the hydraulic conductivity and groundwater flow velocities presented in **Table 5** are considered conservative, and are potentially an order of magnitude greater at the pampa scale.

7.3 Conceptual Model

A conceptual model of the stratigraphy and groundwater flow in the Quilcayhuanca Pampa is illustrated along a cross-section that is perpendicular to the long axis of the valley, from the south valley wall to the stream in the middle of the pampa (**Figure 8**). The bedrock is drawn in a wide ‘U’ shape that is consistent with the bedrock topography of glacier eroded valleys. Based on the glacial history of the Cordillera Blanca there is likely a lower glacial till unit resting on top of the bedrock. It is uncertain what the stratigraphy is between the glacial till and the buried talus in the middle of the valley, if any, but it likely contains glaciolacustrine or glaciofluvial deposits with possible fingers or layers of buried talus from multiple landslide events. Another uncertainty is the thickness of the buried talus as the drilling only penetrated 1.35 m into this unit. Overlying the buried talus and believed to be covering most of the pampa is the clay layer that was likely deposited in a glacial lake environment. The lake was likely dammed by a moraine or avalanche deposit that has since been eroded away. The estimated low hydraulic conductivity ($<10^{-8}$ m/s) of the clay layer makes it a barrier to groundwater flow, but its large capacity to retain water results in a shallow water table that has been measured between 0.35 and 0.57 m depth below the land surface perennially (Maharaj, 2011).

The buried talus behaves as an aquifer and constitutes the main pathway for groundwater flow in the Quilcayhuanca Pampa. It is very likely recharged from precipitation and glacial meltwater (where present) running down the valley walls and flowing into the talus above the pampa.

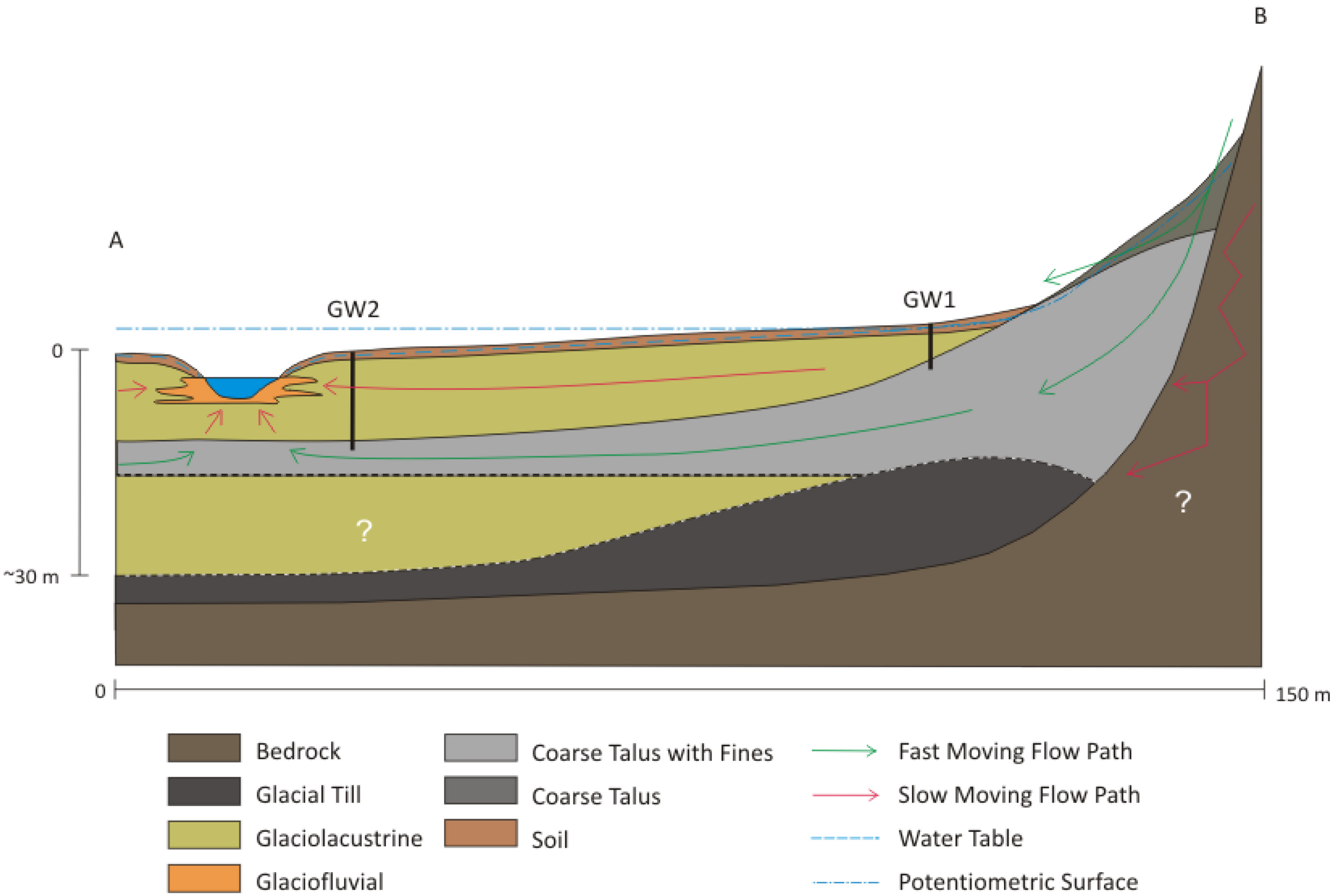

Figure 8. Hydrogeologic conceptual model of the Quilcayhuanca Pampa.

The occurrence of buried talus and artesian conditions in GW2 is an important discovery as it confirms the suspicion that these deposits are hydraulically connected and extends continuously under the pampa. Although drilling was confined to the south side of the stream in the pampa, the symmetrical 'U' shape of the valley and presence of talus deposits on the north side of the valley suggests that the buried talus extends completely across the valley. Future drilling on the west side of the stream can clarify this. Near the edge of the pampa where the clay layer is the thinnest, the upward hydraulic gradient in the buried talus is likely the source of the springs that were observed flowing from the pampa surface.

7.4 Chemistry

The low pH and elevated Ca, Mg, SO_4, and TDS concentrations in the North and South Valley tributaries, and the main stream, can be explained by enhanced sulfide weathering of the pyrite rich Chicama Formation. This explanation was proposed by Fortner et al. (2011) during a previous trace-metal study in the Quilcayhuanca Watershed where the enhanced sulfide weathering was also responsible for naturally occurring acid rock drainage conditions. However, these conditions were not pervasive throughout the whole watershed. Tributary E had circumneutral pH and very low TDS that suggests there is little to no exposure of the Chicama Formation along its drainage. And as there are no glaciers mapped near the head water of Tributary E, it is likely sourced from snow melt.

The groundwater samples were also not acidic and were less concentrated, in terms of Ca, Mg, SO_4, and TDS; however, they did have higher Na and K concentrations. The elevated Na and K in the groundwater were likely produced by water-rock reactions in the subsurface, which based on the pH and HCO_3 concentrations was preferentially carbonate weathering. Although the sulphate concentrations in the groundwater were lower than most of the surface water samples, they were similar in magnitude (~25 mg /L) to the sulphate concentrations from the Broggi Lake sub-catchment in the Llanganuco study area where the Chicama Formation is exposed. This suggests that sulfide weather is also taking place in the groundwater, which is further supported by the cored rock fragments of the Chicama Formation in the buried talus.

Representative samples of the three water groups from **Table 6** were plotted in a Piper plot diagram (Piper 1944) in **Figure 9** to illustrate the different water types (i.e. hydrochemical facies) and identify any mixing relationships between water bodies. With the exception of Tributary E, the surface water samples have a $Ca\text{-}SO_4$ water type and plot near the apex of the ternary diagram. The similarity between the stream-out sample and the majority of the surface water samples suggests that stream flow is largely driven by the glacier fed tributaries. However, the stream out sample plots more towards the right diamond point indicating a larger fraction of Na and K that is likely from groundwater contributions.

The groundwater and Tributary E samples have a $Ca\text{-}HCO_3$ water type and plot relatively close together and well away from the other samples. The similarity between these samples suggests that they share the same head water source, in this case precipitation. As the elevated Na and K in the groundwater samples is particularly unique to this water body, these ions are used in the mixing model to explain what fraction of the stream out component can be explained by groundwater from buried talus.

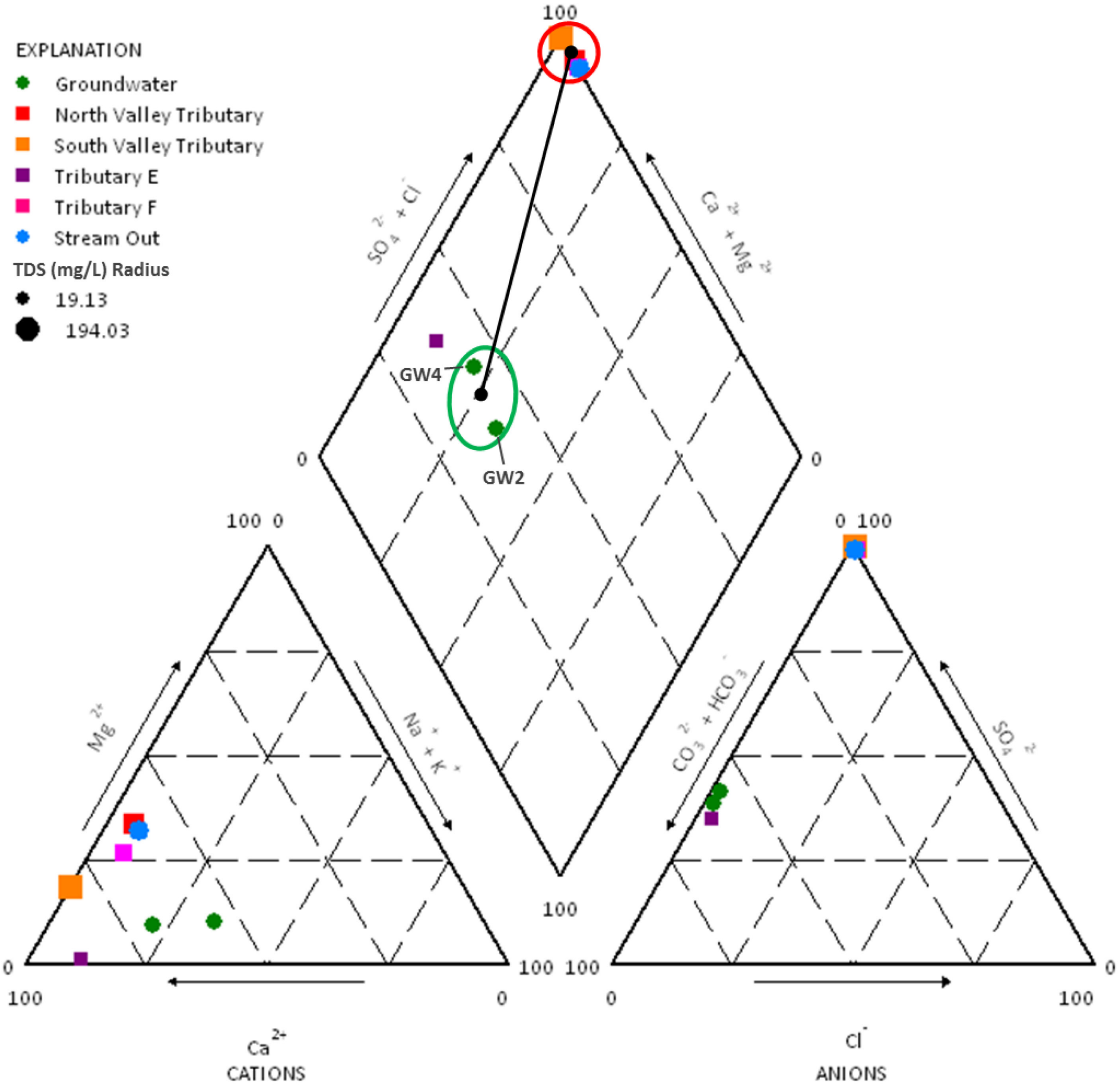

Figure 9. Piper plot of surface water and groundwater samples from the Quilcayhuanca Pampa.

7.5 Mixing Model

The binary mixing model (Equation 1) was used to determine what portions of the stream out component (Sample 23) of the Quilcayhuanca Pampa are from tributary and groundwater components. Na and K were selected as a conservative tracer for the mixing model based on the piper plot analysis in the previous section and following the criteria set forth by Baraer et al. (2009) for selecting hydrochemical tracers. Interestingly, the mixing model calculations for both Na and K produced the same estimates of 21 % and 79 % for the groundwater and tributary components, respectively. Therefore, the groundwater from the buried talus aquifer can account for 21 % of the stream flow.

For comparison, Burns et al. (2011) estimated that dry season groundwater contributions to stream flow were 24 % and 34 % across the Quilcayhuanca Watershed. Although the estimates are comparable with this study, Burns et al. (2011) collected groundwater from talus and moraine springs, not from a buried talus aquifer. This suggests that springs and buried talus aquifer share the same recharge source – precipitation running down the valley walls and flowing into the upper talus above the pampa, as illustrated in the conceptual model **Figure 8**.

The mixing model results also agree with the position of the stream out component on the Piper Plot (**Figure 9**), which lies closer to the tributary components on the mixing line, implying that tributary flows are the largest contributor to stream flow. However, the stream component on the mixing line does not lay 21 % of the graphical distance from the groundwater end member. This suggests that the binary mixing model could be improved.

One way would be to use mass fluxes instead of concentrations of the tracer in the model. This would require measuring the discharges of the groundwater, tributaries and stream.

Chapter 8 - Conclusions

Using a portable drill to investigate groundwater in high elevation watersheds is a relatively new approach that has yielded fresh insights about the pampa hydrogeology in Cordillera Blanca, Peru. In the Llanganuco Pampa, the glacial till and glaciofluvial deposits have been identified as aquifers based on their high hydraulic conductivities and lateral extent. And for similar reasons, buried talus was identified as an aquifer in the Quilcayhuanca Pampa. These aquifers are important groundwater reservoirs that are likely contributing baseflow to pampa streams during the dry season.

The artesian conditions in the buried talus aquifer suggest that it is hydraulically connected with the exposed valley wall talus deposits. As talus slopes are ubiquitous feature in the high elevation watersheds of the Cordillera Blanca, the results presented herein show that they are a main pathway for aquifer recharge. Another aspect about the artesian conditions is the upward, vertical hydraulic gradient that may also be driving groundwater baseflow to pampa streams, and also responsible for the springs emanating from the pampa floor.

Dissolved ions were typically lower in the pampa groundwater than the surface waters of the tributaries and the main streams, which tended to be more hydrochemically related in terms of dissolved ion concentrations and relative ion abundances. Enhanced sulfide weathering of the pyrite rich Chicama Formation resulted in high SO_4, Ca, Mg, and TDS in most of the surface water samples. In contrast, low SO_4 and high HCO_3 in the pampa groundwaters suggest that carbonate weathering exceeds sulfide weathering in the groundwater.

Elevated Na and K were unique to the pampa groundwaters and were used as tracers in a binary mixing model to estimate tributary and groundwater contributions to stream flow. Groundwater accounted for 18 % and 21 % of the stream flows in the Llanganuco and Quilcayhuanca Pampas, respectively. Although, these estimates are comparable with the results from similar studies in the Cordillera Blanca (Baraer et al., 2009; Burns et al., 2011), they could be further refined by measuring groundwater and surface water discharges to use Na and K mass fluxes in the mixing model. In addition, stable isotopes and other dissolved species may also provide unique markers of groundwater in these environments. Regardless, the mixing model results suggest that groundwater is a significant component in the dry season stream flow in these watersheds.

Dry season stream flows in the Cordillera Blanca are mostly driven by glacial meltwater, but as climate change continues to drive glacier retreat in the Andes, long-term meltwater contributions will diminish and groundwater will become a larger component of dry season stream flows (e.g. Baraer et al., 2012). In order to adapt to this climate change related water shortage, we need a better understanding the ability of groundwater to buffer stream flows in head water catchments. This thesis is an important step forward in our understanding of pampa hydrogeology as it is the first known study to use a portable drill to directly explore pampa aquifers in the Cordillera Blanca. However, significant questions remain unanswered. For example, are glaciers a significant source of recharge for pampa aquifers? If so, to what extent will pampa aquifers be affected by declining meltwater contributions? Also, how will pampa aquifers be affected by the projected increase in precipitation during the wet season, and decrease during the dry season (Vera et al., 2006)? Future work on pampa hydrogeology is still needed to address these questions.

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Appendix A

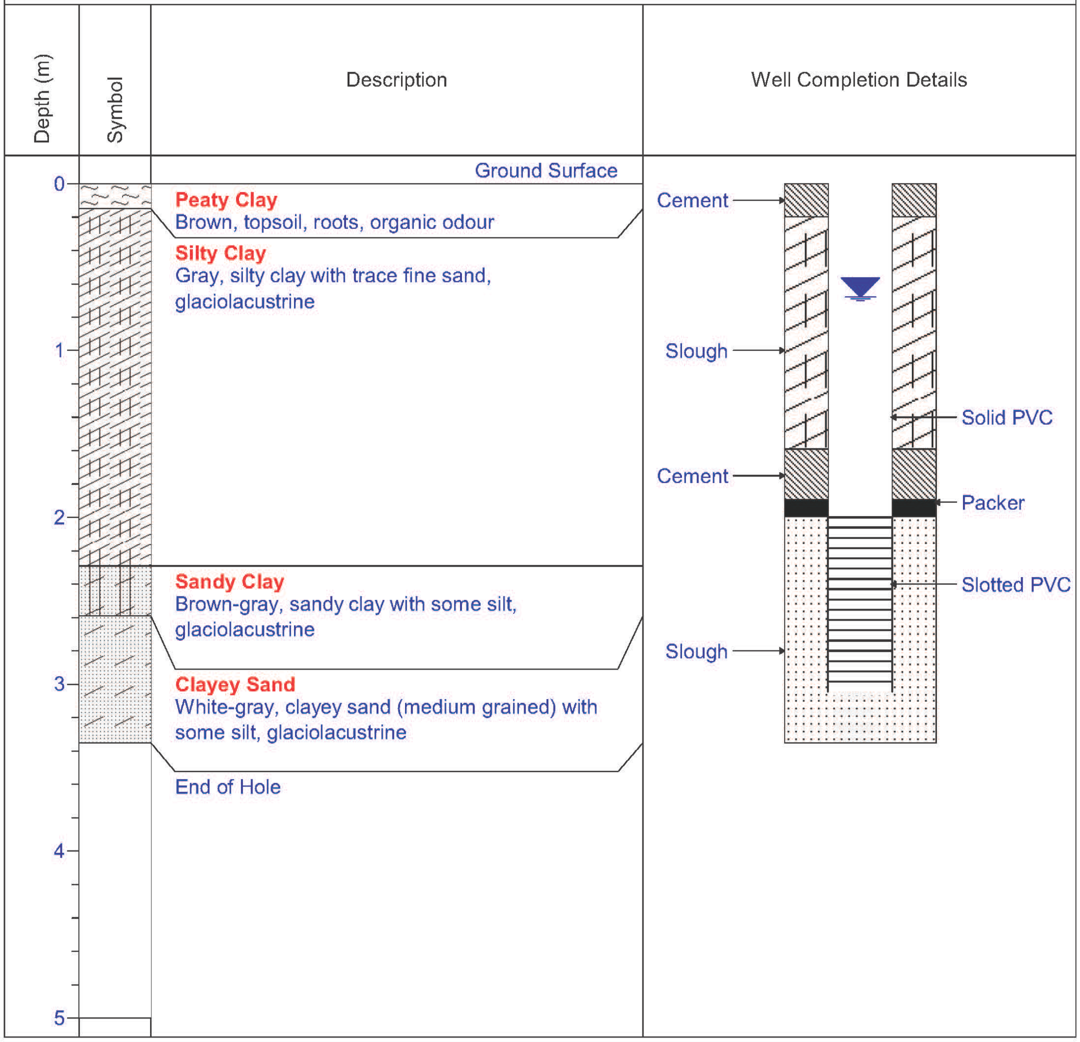
Borehole Logs

Earth & Planetary Science
3450 University Drive
Montreal, Quebec
H3A 2A7

Monitoring Well: GW-1s

Location: Llanganuco
Drill Date: July 9, 2012
Total Depth: 3.353 m
TOC Elevation: 98.554 mAD
Latitude: -9.01842096
Longitude: -77.60381791

SUBSURFACE PROFILE



Ground Surface

Peaty Clay
Brown, topsoil, roots, organic odour

Silty Clay
Gray, silty clay with trace fine sand, glaciolacustrine

Sandy Clay
Brown-gray, sandy clay with some silt, glaciolacustrine

Clayey Sand
White-gray, clayey sand (medium grained) with some silt, glaciolacustrine

End of Hole

Drilled By: DC & JM
Drill Method: Portable Core Drill
Mud Type: Water
Borehole Diameter: 0.051 m (2")
Casing Diameter: 0.032 m (1 1/4")
Screen Length: 0.610 m (2')

Earth & Planetary Science
3450 University Drive
Montreal, Quebec
H3A 2A7

Monitoring Well: GW-1d

Location: Llanganuco

Drill Date: July 8, 2012

Total Depth: 6 m

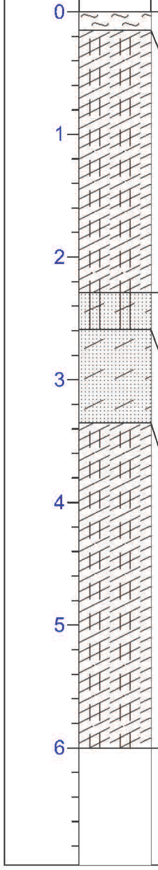
TOC Elevation: 98.434 mAD

Latitude: -9.01842096

Longitude: -77.60381791

SUBSURFACE PROFILE

Depth (m)	Symbol	Description	Well Completion Details



Ground Surface

Peaty Clay
Brown, topsoil, roots, organic odour

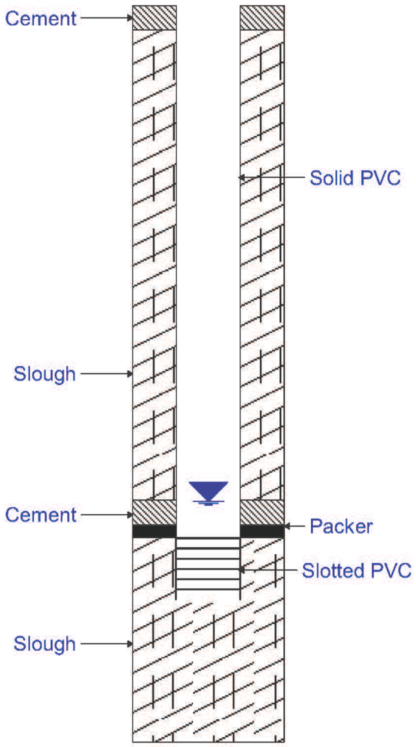
Silty Clay
Gray, silty clay with trace fine sand, glaciolacustrine

Sandy Clay
Brown-gray, sandy clay with some silt, glaciolacustrine

Clayey Sand
White-gray, clayey sand (medium grained) with some silt, glaciolacustrine

Silty Clay
Gray, silty clay with some fine sand, glaciolacustrine

End of Hole



Drilled By: DC & JM

Drill Method: Portable Core Drill

Mud Type: Water

Borehole Diameter: 0.051 m (2")

Casing Diameter: 0.032 m (1 1/4")

Screen Length: 0.610 m (2')

McGill

Earth & Planetary Science
3450 University Drive
Montreal, Quebec
H3A 2A7

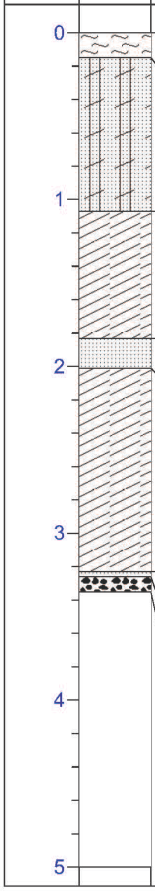
Monitoring Well: GW-2

Location: Llanganuco
Drill Date: July 10, 2012
Total Depth: 2.9 m

TOC Elevation: 98.664 m
Latitude: -9.018777
Longitude: -77.603020

SUBSURFACE PROFILE

Depth (m) | Symbol | Description | Well Completion Details



Ground Surface

Peaty Clay
Brown, topsoil, roots, organic odour

Sandy Clay
Gray, clay with some fine sand, glaciolacustrine

Clay
Gray, very plastic clay with trace fine sand, glaciolacustrine

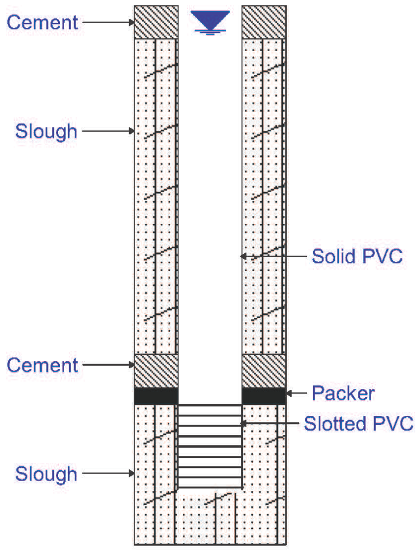
Sand Lens
Brown, medium grained sand lense, loose

Clay
Gray, clay with trace sand

Sand
White, medium to coarse grained sand, very loose, angular

Talus
Black to gray, diorite

End of Hole



Drilled By: DC & JM
Drill Method: Portable Core Drill
Mud Type: Water

Borehole Diameter: 0.051 m (2")
Casing Diameter: 0.032 m (1 1/4")
Screen Length: 0.610 m (2')

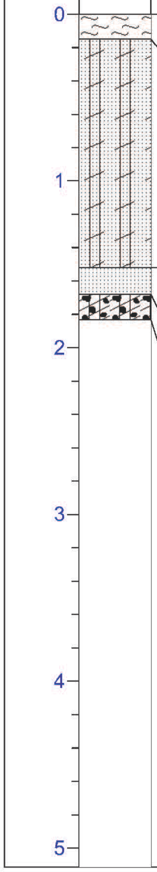
Earth & Planetary Science
3450 University Drive
Montreal, Quebec
H3A 2A7

Monitoring Well: GW-3

Location: Llanganuco	**TOC Elevation:** 100.176 mAD
Drill Date: July 10, 2012	**Latitude:** -9.018777
Total Depth: 1.829 m	**Longitude:** -77.603653

SUBSURFACE PROFILE

Depth (m) | Symbol | Description | Well Completion Details



Ground Surface

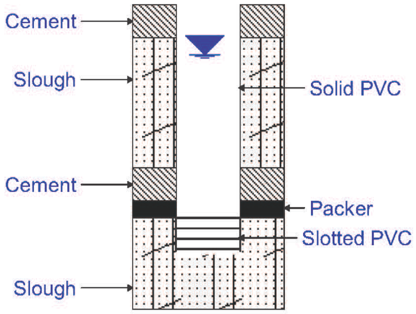
Peaty Clay
Brown, topsoil, roots, organic odour

Sandy Clay
Gray, clay with some medium grained sand, glaciofluvial

Sand
Black, medium grained sand, sub-angular to rounded, well sorted, glaciofluvial

Gravel
Gray to black, gravel with some sand and silt

End of Hole



Drilled By: DC & JM	**Borehole Diameter:** 0.051 m (2")
Drill Method: Portable Core Drill	**Casing Diameter:** 0.032 (1 1/4")
Mud Type: Water	**Screen Length:** 0.305 m (1')

McGill

Earth & Planetary Science
3450 University Drive
Montreal, Quebec
H3A 2A7

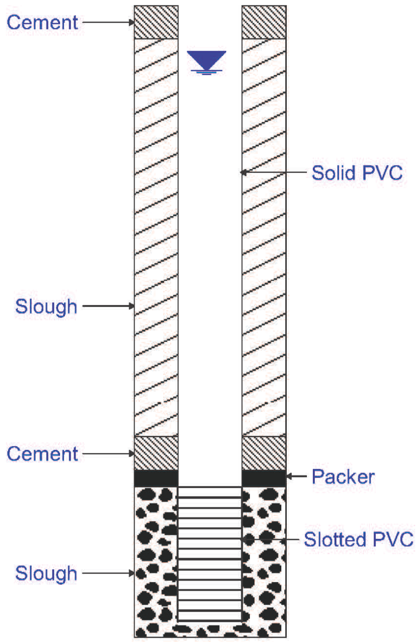
Monitoring Well: GW-1

Location: Quilcahuanca	**TOC Elevation:** 101.508 mAD
Drill Date: July 15, 2012	**Latitude:** -9.466079
Total Depth: 3.785 m	**Longitude:** -77.378177

SUBSURFACE PROFILE

Depth (m)	Description
	Ground Surface
0	**Peaty Clay** Orange-brown, topsoil, roots, organic odour
	Dark Brown-gray Clay Dark brown, clay with 0% coarse fragments
1	**Orange-brown Clay** Orange-brown, clay with 0% coarse fragments
2	**Dark Brown-gray Clay** Dark brown, clay with 0% coarse fragments
3	**Talus** Cored through five boulders ranging from 0.1 to 0.4 m in diameter, mostly from the Chicama Formation
4	End of Hole
5	

Well Completion Details



Drilled By: DC & JM	**Borehole Diameter:** 0.051 m (2")
Drill Method: Portable Core Drill	**Casing Diameter:** 0.032 m (1 1/4")
Mud Type: Water	**Screen Length:** 0.914 m (3')

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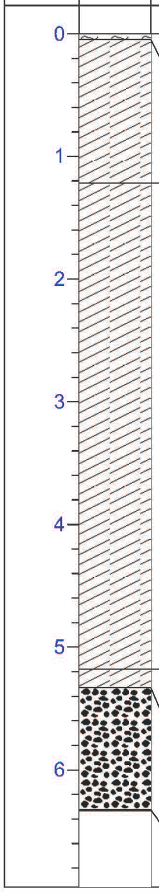
Monitoring Well: GW-2

Location: Quilcahuanca
Drill Date: July 16, 2012
Total Depth: 6.325 m
TOC Elevation: 98.635 mAD
Latitude: -9.465677
Longitude: -77.378915

SUBSURFACE PROFILE



Description

Ground Surface

Topsoil
Orange-brown, clay topsoil, roots, organic odour

Dark Brown-gray Clay
Dark brown-gray, clay with 0% coarse fragments, glaciolacustrine

Orange-brown Clay
Organge-brown, clay with 0% coarse fragment, glaciolacustrine

Dark Brown-gray Clay
Dark brown-gray, clay with 0% coarse fragments, glaciolacustrine

Talus
Dark gray boulder (~0.9 m) from the Chicama Formation with sand and gravel at its base (not recovered)

End of Hole

Well Completion Details

Encountered flowing artesian conditions. After water samples were collected the hole was backfilled with clay, gravel and cement to seal it.

Drilled By: DC & JM
Drill Method: Portable Core Drill
Mud Type: Water
Borehole Diameter: 0.051 m (2')
Casing Diameter: 0.032 m (1 1/4")
Screen Length: 0.610 m (2')

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Monitoring Well: GW-3

Location: Quilcahuanca

Drill Date: July 17, 2012

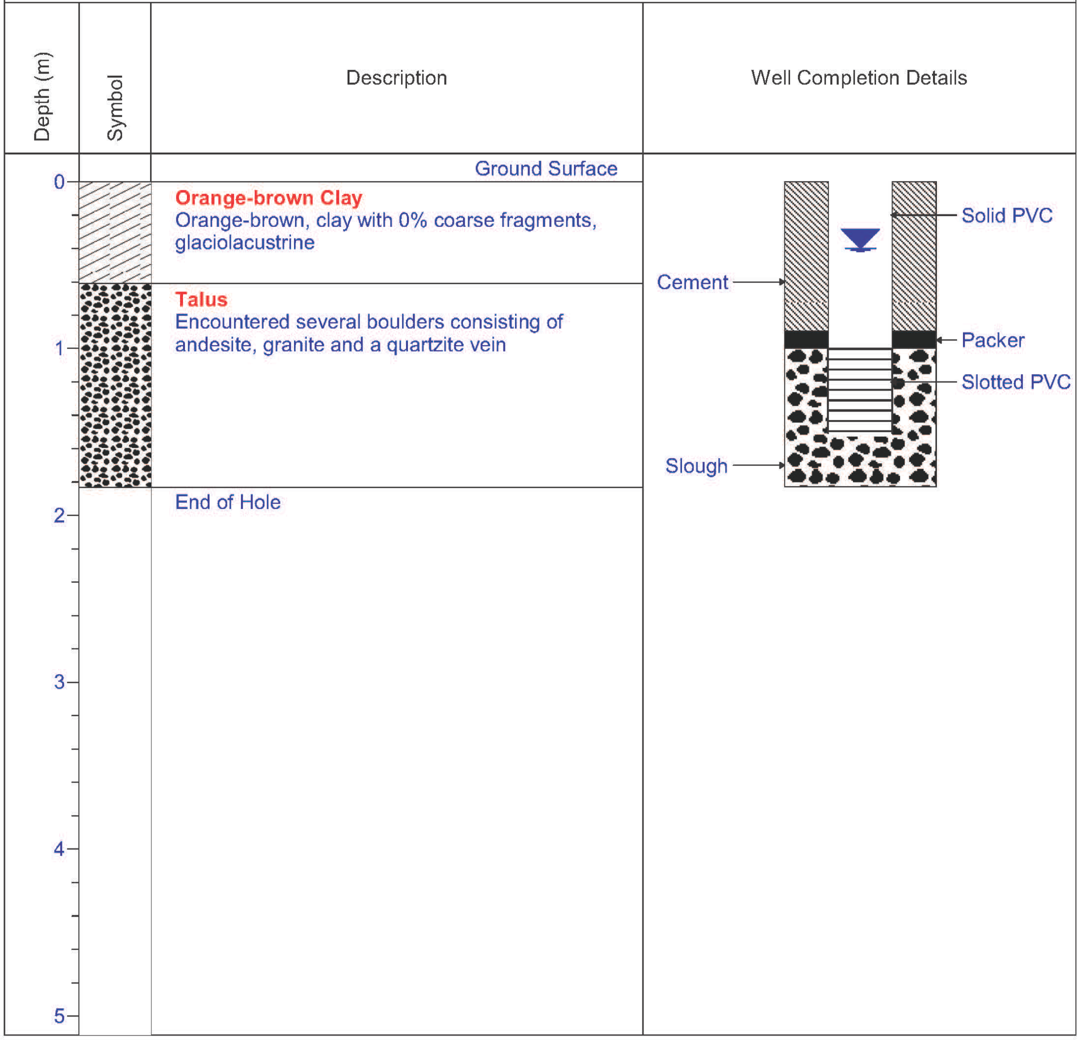
Total Depth: 1.829 m

TOC Elevation: 100.847 mAD

Latitude: -9.466793

Longitude: -77.378965

SUBSURFACE PROFILE



Orange-brown Clay
Orange-brown, clay with 0% coarse fragments, glaciolacustrine

Talus
Encountered several boulders consisting of andesite, granite and a quartzite vein

End of Hole

Drilled By: DC & JM

Drill Method: Portable Core Drill

Mud Type: Water

Borehole Diameter: 0.051 m (2")

Casing Diameter: 0.032 m (1 1/4")

Screen Length: 0.610 m (2')

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Monitoring Well: GW-4

Location: Quilcahuanca

Drill Date: July 17, 2012

Total Depth: 2.438 m

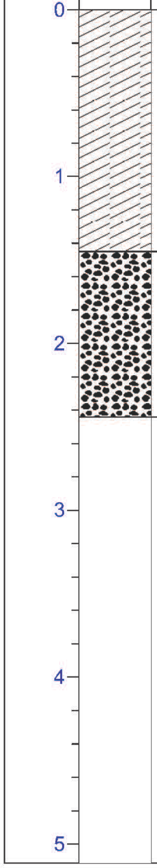
TOC Elevation: 97.702 mAD

Latitude: -9.467814

Longitude: -77.380070

SUBSURFACE PROFILE

Depth (m)	Symbol	Description	Well Completion Details

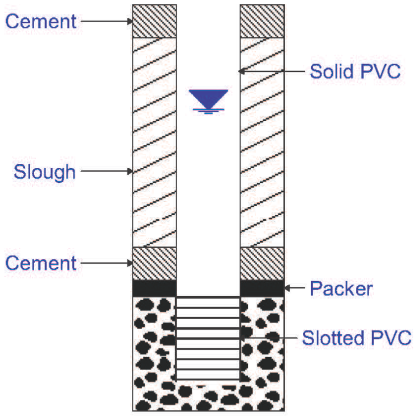


Ground Surface

Orange-brown clay
Orange-brown, clay with 0% coarse fragments, glaciolacustrine

Talus
Encountered several boulders of granite, andisite, and diorite ranging from 0.05 to 0.30 m

End of Hole



Drilled By: DC & JM

Drill Method: Portable Core Drill

Mud Type: Water

Borehole Diameter: 0.051 m (2")

Casing Diameter: 0.032 m (1 1/4")

Screen Length: 0.610 m (2')