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Abstract
This paper reports new data on qocha ponds from the Rio Pucara–Azángaro interfluvial zone, northern Lake Titicaca Basin, Peru. Qocha are a little known form of Andean agriculture that developed around 800–500 B.C. and remain in use today. Prior estimates suggested that in the study area, there were more than 25,000 qocha. While most Andean sunken beds are excavated to reach groundwater, qocha are rain-fed ponds. How these rain-fed ponds functioned has been an open question, but one that is answered in part by research presented in this paper. We suggest that a thick impermeable stratum of clay that was possibly deposited by paleolake “Minchin” created a perched water table that makes rain-fed qocha reservoir agriculture possible. Field geology shows that within the study area, this stratum only exists under Terrace E. Based on this model, we hypothesized that persistently used qocha should only be found on Terrace E. To test this hypothesis we used remotely sensed data to inventory qocha and to determine their distribution by each terrace present. We identified 11,737 qocha. By area 93.77% and by count 94.33% of the qocha are located on Terrace E. These results strongly supported our hypothesis. This case study illustrates that the long term viability of this form of agriculture is made possible by a physical context that is beyond human control.

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1. Introduction

This paper reports new data from the northern Lake Titicaca Basin regarding a type of poorly understood precolumbian agricultural infrastructure that remains in use today—the rain-fed qocha reservoir. Cultural processes such as the development and long term use of agricultural infrastructure must be considered in light of how they are permitted and constrained by spatio-temporally variable physical contexts that are beyond human control. We provide an example of this relationship through a case study from the Pucara–Azángaro interfluvial area of the northern Lake Titicaca Basin. We hypothesize that in this area, lacustrine clays formed by paleolake “Minchin” create a perched water table, and this geologic phenomenon makes rain-fed qocha pond agriculture hydrologically possible. Given this model, we hypothesize that persistently used qocha are restricted to those areas where the paleolake clays are extant. We test this hypothesis by using remote sensing to inventory qocha and evaluate their distribution in relation to the extent of the paleolake clays. First we introduce relevant background information that highlights the anthropological importance of the region under study and summarize the relevant prior knowledge regarding qocha. We then continue by presenting our geologic model and specifying the hypothesis that derives from it. Following this we present our methods and results. These data are then brought to bear on the hypothesis that derives from our model.

2. Background

With respect to geography, high resolution climate reconstructions, the origins of agriculture, and the development of socio-political complexity, the Lake Titicaca Basin—and the northern basin in particular—is an extremely important region. By volume of water, Lake Titicaca is the largest lake in South America (WWDR 2003). Laminated sediments from the main basin of Lake Titicaca provide a high resolution, long term, multi-proxy climate record...
Five major rivers drain into Lake Titicaca. Located in the northern basin, and formed at the confluence of the Ríos Pucara and Azángro, the Río Ramis has the greatest discharge of any of these five drainages (Fig. 1).

Recent studies indicate that the northern basin is a probable location for the domestication of potatoes and chenopods (Bruno, 2006, 2008; Rumold, 2010; Spooner et al., 2005). Considered as a whole, the Lake Titicaca Basin is a largely autonomous area of ancient state formation (Stanish, 2001, 2003). Within this region, the earliest evidence for sustained socio-political complexity comes from the archaeological site of Pukara (Klarich, 2005, 2009), located in the northern basin to the west of the Río Pucara. Immediately to the south of the site of Pukara, in the area between the Ríos Pucara and Azángaro, lies the system of intensified agriculture that consists of reservoirs or ponds that are known as qochas. Qochas from this area were initially described as occurring in the “mesopotamia” or chapwimuyu of the Ríos Pucara and Azángaro (Flores Ochoa and Paz Flores, 1983a: 69, 72, 1984: 68, 88, 93). In Quechua, chapw means middle, center, or between and mayu means river. This chapwimuyu is host to the single largest concentration of qochas known anywhere in the Andes (Erickson, 2000: 341), and this concentration of qochas has been linked to the rise of the Pukara polity. This interfluvial zone, from the confluence of the Ríos Pucara and Azángaro northward past the town of Pucara, forms our study area (Fig. 2).

Many physical and social facets of qocha agriculture are documented in the pioneering work of Flores Ochoa and Paz Flores. Yet, in 1999, qocha were still described as “poorly studied infrastructure” “infraestructura muy poco estudiada” (Valdivia et al., 1999: 147; authors’ translation), and it was argued that qochas were without doubt the least understood agricultural infrastructure of the Titicaca altiplano “es sin duda la infraestructura agraria menos estudiada en el altiplano del Titicaca” (Valdivia et al., 1999: 149; authors’ translation). To the best of our knowledge, since 1999, no new empirical studies of qocha agriculture in the northern Lake Titicaca Basin have been conducted or published. As of the year 2000, the origin and history of qochas remained largely unknown, and a comprehensive inventory of qochas in the Pucara–Azángaro interfluvial did not yet exist (Erickson, 2000: 341). In this paper, we report an inventory of qochas that considers their distribution in relation to landscape evolution. In doing so, we provide a refined understanding of how natural and cultural processes interact with respect to this agricultural technology. First we briefly review relevant prior research on qocha. This review both highlights earlier results that our study refines and identifies the fact that how qocha ponds are capable of holding water remains, up until now, an unanswered question. This question is answered by our new geologically oriented model for qocha distribution.

2.1. Temporal context

It has been suggested that within the Lake Titicaca Basin, associated, temporally diagnostic artifacts indicate that all of the major
agricultural techniques, including qocha, appear to have developed by as early as 800 B.C., and probably before (Stanish, 2007: 130, 2006: 390). Qocha agriculture was first formally reported in the early 1980s by Flores Ochoa and Paz Flores (1983a,b). In the area where they examined qochas, they found few pieces of pottery but those recovered were generally diagnostic Pukara type fragments. Near Llallahua, where there is a major concentration of qochas (Fig. 2), researchers have reported the presence of a Pukara style carved monolith located on top of Mount Kojra (Flores Ochoa and Paz Flores, 1986: 103; Rowe, 1942: 72). Flores Ochoa and Paz Flores suggested that all the qocha in the Pucara–Azángaro interfluvial are located within a day to a day and a half walk from the site of Pukara (Flores Ochoa, 1987: 286; Flores Ochoa and Paz Flores, 1983a: 75, 1983b: 139, 1984: 95, 1986: 103–104, 1987: 95–96, 1992: 264; Flores Ochoa et al., 1996: 256; Washington and Alvarez, 1991: 171).

Recent pedestrian survey in the Pucara–Azángaro interfluvial sheds new light on associations between temporally diagnostic archaeological materials and qocha reservoirs. Aldenderfer and Flores Blanco (2008) identified a carved stone monolith that is located in the middle of a large qocha that is named María Huanca Qocha that is located adjacent to the Quechua community of Chiqchipani. The carvings on the monolith depict a stylized goggle eyed feline catfish “water cat” creature that is typical of Qaluyu–Pukara transitional (ca. 750–200 B.C.) early Middle Formative motifs. Additionally, pedestrian survey of the Pucara–Azángaro interfluvial zone (Aldenderfer and Flores Blanco, 2008) revealed that Qaluyu (ca. 800–500 B.C.; Browman, 1980; Chávez, 1977), Qaluyu–Pukara transitional (ca. 750–200 B.C.; Chávez, 1977),
Limited sub-surface testing was undertaken at two sites that are directly associated with *qochas* (Alenderfer and Flores Blanco, 2008): Tulani (RM621–622) and Laroqocha (RM1190, 1192, 1194–1195). Tulani is a 1 ha dense surface scatter that contains pottery, chipped stone debitage, obsidian, and stone hoe fragments. Following the typology of Chávez Justo (2008a,b), the surface pottery assemblage from the site consists of Formative (ca. 800 B.C.–A.D. 400), Early Huaña (A.D. 100–600), Altiplano (A.D. 1100–1475), and Inca (A.D. 1475–1532) styles. Three 1 × 1 m sub-surface test pits were excavated into Tulani. These excavations revealed the presence of stone hoe fragments, burned camelid bone, obsidian projectile points, temporally diagnostic pottery, and numerous small ash filled pits. Following the typology of Klink and Aldenderfer (2005), the projectile points are Type 5B and 5D forms. Excavations recovered a single Qaluyu sherd; Qaluyu–Pukara transitional and Pukara were the dominant pottery styles (Table 1). Early Huaña and Altiplano style fragments were present, but in much lower abundance than either Qaluyu–Pukara or Pukara materials.

Laroqocha is a 3.2 ha scatter of artifacts that is composed of pottery, chipped stone debris, and stone hoe fragments (Fig. 3). Surface pottery consists of Middle–Upper Formative (ca. 800 B.C.–A.D. 200), Early Huaña, Altiplano, and Inca styles. Three 1 × 1 m sub-surface test units were excavated into Laroqocha. This sub-surface testing revealed the presence of fragments of burned camelid bone, concentrations of burned clay, chipped stonedebitage, hoe fragments, and pieces of temporally diagnostic pottery. Excavations recovered eight Qaluyu sherds but the pottery assemblage is again dominated by Qaluyu–Pukara and Pukara sherds; Huaña and Altiplano style materials were much less abundant (Table 1). Excavations also exposed an earth oven in association with Pukara pottery. Together, Tulani and Laroqocha reveal that significant amounts of Middle Formative pottery and agricultural implements are found in direct association with *qocha* ponds (Fig. 3). Both Tulani and Laroqocha are located on river Terrace E (see below).

While stylistically diagnostic pottery reveals associations between Qaluyu–Pukara transitional (ca. 800–500 B.C.) and the *qochas* of the Pucara–Azángaro interfluvial, somewhat later Pukara (ca. 800 B.C.–A.D. 200) style pottery is far more abundant. The presence of Qaluyu and Qaluyu–Pukara pottery, both earlier Middle Formative styles, in association with these *qochas* indicates that in the Pucara–Azángaro interfluvial this agricultural technology likely predates the apogee of the Pukara polity. However, the greater abundance of Pukara pottery in association with these *qochas* indicates that the ponds were probably used more intensively during the height of the Middle Formative Period (ca. 500 B.C.). Material from later traditions including Huaña, Altiplano, and Inca are also found in direct association with the Pucara–Azángaro *qochas*. These associations with later temporally diagnostic styles indicates that *qocha* infrastructure remained in use well after the decline of the Pukara tradition. However, the lower abundance of post-Pukara forms suggests that after the decline of Pukara the intensity of *qocha* use probably declined.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Diagnostic pottery types recovered from excavations at Tulani and Laroqocha.</th>
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<td>Site</td>
<td>Qaluyu</td>
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<tr>
<td>Tulani</td>
<td>1</td>
</tr>
<tr>
<td>Laroqocha</td>
<td>8</td>
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</tbody>
</table>

Immediately to the east of the present study area, in the Huancané–Putina river valley, and to the south in the Juli–Pomata region, pedestrian survey indicates that *qochas* in these other areas were also in use by the Middle Formative (Stanish and Stedman, 1994; Stanish et al., 1997; Stanish, 1994, 2006: 384). *Qochas* located on the Huatta Pampa to the north (Erickson, 2000: 341) and in the Tiwanaku Valley to the south (Albarracín-Jordan, 1996) are reportedly associated with multicomponent occupations that span from the Middle Formative to the present.

These multiple associations with temporally diagnostic artifact types indicate that prior to Spanish contact, *qochas* were used for a long period of time. Unlike other prehispanic agricultural technologies that were abandoned after contact (i.e. raised fields), the modern indigenous inhabitants of the region continue to use *qocha*. This continued use of the technology is further indication that in some contexts *qocha* infrastructure can be used over the long term. However, we recognize that over time the nature and intensity of *qocha* use may have shifted.

### 2.2. Qocha water Sources

It has been suggested that in the Pucara–Azángaro interfluvial region, the groundwater is too deep for *qocha* to function as wells (Flores Ochoa and Paz Flores, 1983a: 57; 1983b: 130, 1984: 79; 1986: 93; 1987: 82; Kendall and Rodríguez, 2002: 242; Valdivia et al., 1999: 152; Washington and Alvarez, 1991: 166). Flores Ochoa and Paz Flores (1987): 277 states that, “[t]he substantial depth at which the subterranean water table is encountered eliminates the possibility of utilizing water from the water table for agriculture” (authors’ translation). For those few wells that have been excavated in the region, the groundwater is found at a depth of 4–15 m. The fact that *qochas* do not function as wells stands in contrast to the majority of archaeological and contemporary sunken bed agricultural fields from Peru (Soldi 1982: 17; Denevan, 1980: 631–632). These sunken beds are located along the coast of Peru, and nearly all known examples of these are excavated to groundwater or the phreatic zone. Examples of Peruvian groundwater wells include: *hoyas*, *mahames*, *sachaques*, *totorales*, *bolsares*, *melgas*, *canchones*, and occasionally *puquios*, which are actually subterranean irrigation systems (Denevan, 1980, 2001; Moseley, 1969; Parsons and Psuty, 1974, 1975; Rowe, 1969; Schreiber and Rojas, 1988, 2003; Soldi 1982).

Rather than basins designed to tap into groundwater, the use of *qochas* is based on rainwater which is stored in and transferred between the reservoirs or ponds through open channels (Flores Ochoa, 1987: 277; Flores Ochoa and Paz Flores, 1983a: 57–58; 1983b: 130; 1984: 79; 1986: 93; 1987: 82; 1992: 255; Flores Ochoa et al., 1996: 247; Rozas 1987: 110; Valdivia et al., 1999: 152; Washington and Alvarez, 1991: 166; Denevan, 2001: 163). Water can be stored in a *qocha* for months after a rain. How it is possible to store water in these ponds for extended periods of time without loss of water through percolation remains unspecified by previous descriptions of *qochas*. Our geology-based model provides an explanation as to why water can be contained in the *qocha* ponds for extended periods of time. This model is based on the premise that the distribution of rain-fed *qochas* is controlled by the presence of a stratum of a buried, impermeable sediment. Before turning to our model we discuss the results of prior attempts to count the total number of *qochas* and to estimate their density within the study area.

### 2.3. Estimates of the count and density of Qocha

Flores Ochoa and Paz Flores attempted to count *qochas* using a combined approach of field visits, aerial photographs taken in 1961 by Servicio Aereofotográfico Nacional (SAN), and 1:100,000...
They estimate that the study region has a total area of 528 km$^2$, and that about 384 km$^2$ of this is suitable for cultivation and pasture. According to their classification scheme: larger qocha are $>200$ m dia and $>31,400$ m$^2$ in area; the smaller and more numerous qocha have a mean area of 6500 m$^2$.

Based on a 0.5 km$^2$ sample, Flores Ochoa and Paz Flores estimated the total number of qochas present in the chapwimayu of the Ríos Pucara and Azángaro (Flores Ochoa, 1987: 283–284; Flores Ochoa and Paz Flores, 1983a: 69; 1983b: 134; 1984: 88–89; 1986: 97; 1987: 87; Flores Ochoa et al., 1996: 254). They counted close to twenty qochas in 0.5 km$^2$, and from this count they estimated that there are 80 qochas in 1 km$^2$. They assumed that qochas are circular, and modeled qocha size as 60 m dia. This gave each qocha an area of approximately 2863 m$^2$ (We note that the correct solution is 2827 m$^2$. However, we also observe that given a rounding operation that these authors later applied to the estimated total number of qocha, the difference in area is insignificant). Based on this estimate, there are 0.226 km$^2$ of qocha area per km$^2$. They assumed that the study area was 256 km$^2$, and from their 0.5 km$^2$ sample they calculated a regional total of 57.88 km$^2$ of qocha area. Dividing this by the estimated area of a single qocha (2863 m$^2$) produced an estimated 20,215 qochas. The authors rounded this figure up to 25,000, and suggested it served as a conservative estimate of the total number of qochas in the study area (Flores Ochoa, 1987: 284; Flores Ochoa and Paz Flores, 1983a: 71; 1983b: 135; 1984: 91; 1986: 98; 1987: 89; 1992: 263; Flores Ochoa et al., 1996).

Based on estimates of the density of qochas per km$^2$, Flores Ochoa and Paz Flores defined three different zones (Fig. 2; Flores Ochoa, 1987: 283; Flores Ochoa and Paz Flores, 1983a: 69–70, Map 3; 1983b: 134, 151, Fig. 14, 1984: 89 Map 3; 1986: 97; 1987: 89–90; 1992: 262; Flores Ochoa et al., 1996: 254, Fig. 122; Valdivia et al., 1999: 147, 148, Fig. 1):

1) Disused or Damaged
2) Spaced
3) Numerous.

The Disused or Damaged zone is located to the west of the study area, and they suggest that this area has an extent of about 128 km$^2$. Interpretation of aerial photographs led them to suggest that in this zone, salinization may have led to the deterioration of the qochas. They also note that several haciendas are present in this area including Qoa (Ccoa), Pichacani, and Cojempati. This led Flores Ochoa and Paz Flores to offer the alternative hypothesis that agricultural intensification on the part of the haciendas and the use of mechanized agriculture may have contributed to the deterioration of qochas in this zone. By flattening and leveling the ground surface,
mechanized agriculture can physically damage qochas. The Spaced zone is defined by areas where there are < 100 qochas per km². They estimate that the Spaced zone has an extent of approximately 96 km². It is located on the eastern side of the Río Azángaro in the areas known as Tuturco, Juyacache, Huayrapata, and the ex-hacienda Corpa in front of the town of Achaya and in the general area of Calapuja. The Numerous zone has a density of > 100 qochas per km², and this zone covers an estimated 160 km². The Numerous Zone is found around the communities of Iquilo, Mataro Grande, Llallahua, the former hacienda of Sullata, and in the Laro and Charamicaya pampas. Having reviewed prior attempts to count and estimate the distribution of qocha we now turn to relevant aspects of the geologic setting of the region.

3. Geologic setting and expectations for Qocha location

Fluvial geomorphological research in the interfluvial or chapwimayu of the Ríos Pucara and Azángaro indicated the presence of five river terraces and three major facies associations (Farabaugh and Rigsby, 2005). Termed A–E, A is the lowest terrace above the active floodplain and E is the highest (Fig. 4). The entire modern surface of the area between these two rivers is covered by a combination of braided and meandering fluvial sediments that form two of the region’s three major facies associations. The deposition and erosion of these two fluvial deposits is strongly correlated with periods of high and low precipitation respectively (Baker et al., 2001a). The third facies association is only found underlying Terrace E, and it is always found directly below the aforementioned fluvial deposits. This third facies association is composed of a meter-thick accumulation of thinly laminated gray to blue–gray clays that bear gastropods, ostracods, and abundant organic material (Fig. 5; Farabaugh and Rigsby, 2005: 19). These clays were deposited by the settling of fine particles suspended in a lacustrine environment (Farabaugh and Rigsby, 2005: 20). Carbon from this clay stratum dates to 40,170 ± 430 cal B.P. Although near the limit of finite radiocarbon dating, we trust that this single radiocarbon date corresponds to a wetter period from 46,000–36,000 cal yr B.P (Clapperton, 1993; Clapperton et al., 1997; Fritz et al., 2004) during which palaeolake “Minchin” extended across vast areas of the Andean altiplano (Baker et al., 2001a; Fritz et al., 2004). The blue–gray lacustrine clay stratum underlying Terrace E is today found 40 m above the current level of the Río Ramis and about 150 m above the modern level of Lake Titicaca (Farabaugh and Rigsby, 2005: 25). This implies that the water level of palaeolake “Minchin” was at least 150 m above the modern level of Lake Titicaca (Fig. 1). We believe that subsequent tectonism, tilting due to folding and faulting, differentially elevated the northern shores of the Lake Titicaca basin since the original deposition of the lacustrine clay.

We hypothesize that the extant lacustrine clays deposited in palaeolake “Minchin” are responsible for creating a perched water table, and it is this geologic phenomenon that makes rain-fed qocha pond agriculture hydrologically possible. If our model is correct, then the large majority of qochas should be located on Terrace E where the palaeolake “Minchin” clay is present. Experimentation and attempts to expand this agricultural infrastructure may have resulted in the presence of a few qochas on lower terraces.

4. Methods for inventorying Qocha and evaluating geologic expectations for their location

To determine 1) the total number and density of qochas and 2) whether or not they are restricted spatially to Terrace E, the entire lower interfluvial zone of the Ríos Pucara and Azangaro was examined by inspecting satellite and aerial remote sensing imagery. In any remote sensing survey, the ability to detect features is a function of the size of the targets of interest and the spatial resolution of the imagery (Craig and Chagnon, 2006; Jensen, 1996; McGwire et al., 1996: 102–105, Fig. 6.2; Sabins, 1987). In addition to prior publications, field survey and GPS data that we collected from the interfluvial region indicated that qochas were generally larger than 30 m. We had access to 0.5 m spatial resolution aerial photographs that covered the entire study area. Thus, the size of the features and the resolution of the imagery rendered qocha reservoirs well suited for mapping with satellite and aerial remote sensing imagery. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) level 3 orthorectified imagery covering the study area was obtained from the Land Process Distributed Active Archive Center (LP DAAC). An image captured on 15 August 2007 covered the entire study area in a single cloud-free scene. From this multispectral dataset, a VNR 1,2,3N band false color composite image was created and inspected. Declassified CORONA imagery was obtained from the USGS as a film positive. The CORONA image

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![Fig. 4. Schematic diagram illustrating the terrace sequence of the Rio Ramis valley. Figure adapted from Farabaugh and Rigsby (2005): Figs. 6 and 12.](image-url)
was captured 30 June 1979 (mission number 1215-5, Ops designation 00473). The image was taken with the KH-9 film camera, which has a reported spatial resolution of 20–30 ft (6–9 m). The film was scanned at 3000 dpi and georeferenced to the orthorectified ASTER false color composite. We purchased 1 m spatial resolution IKONOS-2 satellite image that was captured on 20 June 2001 (Fig. 3). Printed paper aerial photographs covering the study area from August of 1979 that are available through Programa Especial de Titulación Tierras (PETT) were scanned at 3000 dpi and georeferenced to the ASTER and CORONA images. Examination of the scanned PETT imagery indicated that the aerial photographs had a spatial resolution of 0.5 m. This resolution is more than sufficient to detect qochas (e.g. McGwire et al., 1996: 104). Field checking showed that anomalies interpreted in these air photos were in fact qochas. The georeferenced IKONOS-2 scene and the PETT images were visually inspected and all detectable qochas were digitized into a geographic information system (GIS) as polygon features. In the imagery, qochas were identified based on two primary criteria: 1) the anomaly appeared to be a basin and 2) canals were visible either entering or exiting the basin-like anomaly. In most cases, the basin-like anomaly bore evidence of recent cultivation. In some cases, the basin-like anomalies appeared to be no longer under cultivation. These anomalies were interpreted as qocha which are

Fig. 5. Photograph showing the thick stratum of laminated gray to blue–gray lacustrine clays. This photograph is from the Rio Iquilo B measured section reported by Farabaugh and Rigsby (2005): Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
no longer in use. Some of these basin-like anomalies were extremely faint, and a conclusive identification could not be made. Field checking confirmed that these features likely represent abandoned and badly eroded qocha. These extremely faint basin-like anomalies were not inventoried.

River terrace breaks were identified and defined through field geology (Farabaugh and Rigsby, 2005). These terraces are large features that are easily observed in the satellite and aerial imagery. The terraces were digitized from inspection of the ASTER, CORONA, IKONOS-2, and PETT images.

From the GIS polygon coverages we determined: qocha count, qocha area, terrace extent, and terrace area. This allowed us to calculate: qocha count by terrace, qocha area by terrace, and mean qocha area. These calculations provide a test of the hypothesis that persistently used qochas should only be located on Terrace E where the paleolake “Minchin” clay is present. We also provide revised density calculations that are based on both qocha count and qocha area.

5. Results of the inventory

Within the survey area, a total of 11,737 qochas were remotely identified and digitized as polygons (Fig. 6 and Tables 1 and 2). In terms of the area of these polygons, 99.5% of the qochas fall within two standard deviations of the mean. 57 or 0.49% of the qochas have areas that are larger than two standard deviations of the mean. We characterize these as exceptionally large qocha (area >2s). In terms of either counts or proportions of the total survey area, it is useful to retain the exceptionally large qochas in the sample. Outlier removal helps to reduce skew, and this operation is important for equations that assume a normal distribution. We present both transformed and untransformed data since they provide distinct insights into qocha size.

Removing outliers, the mean declines by 178.43 m and it shifts towards the median (Table 2). Outlier removal decreases the standard deviation by 4903.92 m; the untransformed value is 3.45 times this figure. Outlier removal reduces the skewness from 81.99
to 2.41. Even with outlier removal, the distribution remains positively or right-skewed.

All of the qochas are located on Terraces C–E (Table 3). Together these terraces constitute half (50.6%) of the total survey area. Terrace E is a little more than a third (34.7%) of the total survey area, but the limits of this terrace contain 94.33% of the total qocha count and 93.76% of the total qocha area. Thus, 35% of the study area contains 94% of the qochas.

Considering qocha counts by terrace area, densities ranged from 0.6–62 qochas/km². Qocha density is highest on Terrace E (Table 4). With respect to their area, qocha constitute 6% of the study area. In terms of their area, qocha comprise >1% of Terrace C, 8% of Terrace D, and 17% of Terrace E. Exceptionally large qocha (area >25) are found on each of these three terraces.

### Table 2

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### Table 4

<table>
<thead>
<tr>
<th>Feature</th>
<th>Area (km²)</th>
<th>Number</th>
<th>% Total area</th>
<th>% Total count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey zone</td>
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<td>100</td>
<td>0.862</td>
<td>100</td>
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<tr>
<td>Terrace A</td>
<td>4.478</td>
<td>0.004</td>
<td>1.309</td>
<td>0.004</td>
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<tr>
<td>Terrace B</td>
<td>10.207</td>
<td>0.195</td>
<td>0.195</td>
<td>0.195</td>
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<tr>
<td>Terrace C</td>
<td>61.357</td>
<td>1.181</td>
<td>11.811</td>
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<tr>
<td>Terrace D</td>
<td>21.159</td>
<td>0.403</td>
<td>4.037</td>
<td>4.037</td>
</tr>
<tr>
<td>Terrace E</td>
<td>180.405</td>
<td>34.728</td>
<td>34.728</td>
<td>34.728</td>
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<tr>
<td>Qocha by C</td>
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<td>0.017</td>
<td>0.332</td>
<td>0.332</td>
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<tr>
<td>Qocha by D</td>
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<tr>
<td>Qocha by E</td>
<td>31.369</td>
<td>9.762</td>
<td>93.762</td>
<td>93.762</td>
</tr>
</tbody>
</table>

6. Discussion of the results

The scanned PETT imagery that we used to detect the qochas has a spatial resolution of 0.5 m, thus each pixel covers an area of 0.25 m². Once the exceptionally large outliers are removed, qochas have a mean area of 2672 m². This indicates that typically a qocha is represented by about 10,000 pixels. Given that the distribution is still positive or right-skewed even after removing outliers, most qochas are probably represented by more than 10,000 pixels. At 0.5 m spatial resolution, qochas are easy to spot and define. While, we do not claim to have defined the absolute total number of qochas, we believe that our count is an extremely close approximation of the actual number of qochas present in the study area.

Prior estimates suggested that there were over 25,000 qochas in the Pucara–Azángaro interfluvial zone. Our remote sensing survey of this area produced 11,737 qochas, or roughly half the prior estimate. Previously, it was estimated that >100 qocha/km² were present in the Numerous Zone. The highest density of qochas (62 qocha/km²) is located on Terrace E. Our inventory indicates that qocha density by count is considerably lower than prior estimates. Even on Terrace E, the area of greatest qocha density, the ponds comprise less than 15% of the space. In light of this revised inventory, let us now return to our geologic model and the expectation regarding qocha distribution that derives from it.

In the remote past, palaeolake “Minchin” apparently extended across a large portion of the Altiplano including the interfluvial of the Ríos Pucara and Azángaro (Baker et al., 2001a; Fritz et al., 2004). Within the Pucara–Azángaro interfluvial, palaeolake “Minchin” left a thick deposit of laminar blue–gray lacustrine clays (Farabaugh and Rigsby, 2005). This deposit now underlies the highest Terrace E (Farabaugh and Rigsby, 2005: 24–26, Fig. 12). Elsewhere in the interfluvial region, within the mapped boundaries of the surfaces of Terraces D–A, river downcutting and erosion has removed this lacustrine unit.

With respect to our present study area, we believe that the impermeable nature of the lacustrine clay deposit is responsible for creating a perched water table that makes qocha agriculture possible. If this hypothesis is correct, then qochas should be located on Terrace E. Experimentation by early agropastoralists may have led to the expansion of qochas into the lower Terraces D–A, but our hypothesis dictates that the large majority of the qochas should be located on Terrace E.

The distribution of qochas conforms well to our hypothesis. Whether considered by count or by area, more than 90% of the qochas are located on Terrace E. The existence of 553 qocha on Terrace D and 39 qocha on Terrace C might appear to stand in contrast to our expectation that qochas should be located on Terrace E. However, field observations and remote imagery indicate that the qochas on Terraces E and D are largely abandoned. The extremely faint un-definable basin-like anomalies described earlier were located within the limits of Terraces D and C. Notably, these two terraces are within the Disused or Damaged Zone that was defined by Flores Ochoa and Paz Flores (compare Figs. 2 and 6). In light of this, we suspect that qochas were created on Terraces D and C during a period of agricultural expansion. Following this period, qochas within this zone were abandoned. Periodically, people may re-attempt use of qochas on these terraces. Yet compared to Terrace E, use of qochas on Terraces D and C was limited in both scope and duration. Further investigation of this zone is required to more fully understand what we believe represents a fluctuating use of Terraces D and C for qocha cultivation.

7. Conclusions

Qaluyu (ca. 800–500 B.C.; Browman, 1980; Chávez, 1977), Qaluyu–Pukara transitional (ca. 750–200 B.C.; Chávez Justo, 2008a: Fig. 14), and Pukara (ca. 800 B.C.–A.D. 200; Stanish, 2006: 85–89; Klarich, 2005: 242) are the earliest pottery styles found in association with qocha ponds that are located on Terrace E. Near Llallahua, a Pukara style caved monolith was found in association with qochas (Flores Ochoa and Paz Flores, 1986: 103; Rowe, 1942: 72). Recent pedestrian surface survey located a Qaluyu–Pukara
style stone monolith that was placed inside a large qocha named María Huancaq Qocha which is located near the community of Chiqchípiani. Excavations at Tulani (RM621–622) and Larqocha (RM1190, 1192, 1194–1195) produced an abundance of Middle Formative ceramics and stone hoes. Both of these sites are situated on Terrace E and are found in very close association with a dense concentration of qochas. Together, these associations suggest that on Terrace E, use of qochas began by at least 500 B.C. and probably earlier. Within this same area, pottery diagnostic to all major time periods is found in association with qochas (Aldenderfer and Blanco, 2008). Based on pottery styles, Pukara appears to represent the most intense use of qochas. Pottery styles that post-date the Middle Formative are much less abundant. This suggests that qochas were used less intensively after the decline of Pukara. Yet, the qocha on Terrace E are still used today by modern Quechua agropastoralists. On Terrace E, the multiple associations with ancient and modern material culture indicate that qochas have been used, perhaps in different ways and probably with varying degrees of intensity, over a period of 2500 years. Yet the capacity for the ancient lake that left a relatively impermeable strata of clay, and use is due in part to the presence of an ancient lake that left a relatively impermeable strata of clay, and this strata creates a perched water table that makes qocha agriculture possible.

Qochas are known for other parts of the Andes (Fig. 1). Many of these qocha groupings are located in relatively flat areas near modern lakes. The techniques presented in this paper provide a method for inventorizing qochas in other parts of the Andes. If our guiding perched water table hypothesis is correct, then other persistently used qocha may be found in areas that are underlain by ancient lake clays or other relatively impermeable deposits.

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