Nurturing Water: Ancestral Ground Water Recharging in the Americas

Type: Long paper

**Author:** Kashyapa A. S Yapa, Ph.D. (UC Berkeley), Independent consultant, Ecuador, kyapa@yahoo.com, 593-3-2394809/ 593-986267632

**Abstract:** For a groundwater supply to be sustainable, its rate of recharging needs to match the demand. If natural replenishing rate falls short of the demand, water users have to take steps to enhance it. That requires a good understanding of the groundwater flow mechanism in the locality, a quite difficult task even for today's water experts. Evidence shows that our ancestors used their observational skills and trial and error techniques to overcome this difficulty. When the leaders had to mobilize the villagers for construction and maintenance, they incorporated religious rituals with every activity, thus transferring to the collective faith the responsibility for proper functioning of the recharging mechanism. We use some cases from the Americas to elucidate different techniques our ancestors employed in recharging groundwater. These technologies have a great potential for today's water-stressed watersheds, but only after adapting them to local conditions.

**Introduction**

The first raindrops percolating through the ground surface may adhere to solid particles or fill the tiny spaces around them, and thus, stay near the surface. A part of that water may return to the surface through capillary action and evaporate, while nearby plant roots may absorb another part. If rainfall continues, some drops will travel deeper to feed the groundwater. This natural groundwater recharging process works better if the surface soil is more porous and if runoff velocity is smaller. Therefore, any vegetation covering the surface soil helps increase the rate of infiltration.

Since ancient times, large human settlements prospered in dry zones because of greater agricultural productivity there. Rainstorms in dry zones are generally very intense and cause flash floods, which do not allow much infiltration and groundwater recharge. On the other hand, in these climates, people have to rely more on groundwater because surface water evaporates fast. Thus, they have to find ways to augment the natural recharging process in order to guarantee their long-term survival. Precisely understanding the movement of groundwater is a challenge, even with today's sophisticated geological and geophysical knowledge and equipment. Then, how did our ancestors manage to procure groundwater in quantities sufficient to support large towns and agricultural lands in desert areas?

**Context and aims**

In this paper, we intend to explore the knowledge and practices related to groundwater management of precolonial States and communities that successfully populated drier areas in the American continent. Our inability to correctly interpret and comprehend precolonial administrative records greatly hinders our understanding of such technologies. From the early days of European invasion of the American continent, the newcomers expressed their surprise at large public infrastructure works, like roads, irrigation systems, terraces and ceremonial buildings, built and maintained by a population whom they had considered technologically inferior.
Unfortunately, no serious investigations were carried out to find how those structures were built. The European colonial administrations focused primarily on extracting and exporting as many local resources as possible for the benefit of their empires. The independent, republican administrations that followed neither spent sufficient effort to understand and promote native technologies because a colonial mentality prevails until today among many a political leadership. Over the last few decades, some archaeological investigations on precolonial water supply systems have been done, partly to boost tourism and partly out of academic interest. However, the limited scope of those investigations and their funding do not permit us to have a thorough understanding on how precolonial users managed their groundwater resources.

Despite a limited amount of data, we aim to shed light on the existence of ancient groundwater management systems in the American continent and share this knowledge with a wider audience. We hope that, in this way, more practitioners, policy makers, technicians and other professionals can become aware of and be vigilant to discover possible locations where local populations can benefit from such resources.

We will describe our case studies from the point of view of a community leader with limited technical knowledge searching for a reliable water source in a dry zone. She has access to only the observational information about the quality and quantity of water from that particular source. She will match that information with the community demand for water. If the historical data are sufficiently precise, she can establish reliability and sufficiency of that water supply over the long run. If periodical deficits in quality and quantity were to occur, the community leader will face a complex situation. Generally, augmenting the flow of a natural groundwater supply could improve the quality as well. Yet, lacking access to technical knowledge on how to recharge groundwater with the least effort, she has to tap into ancestral experiences, or to take the risk and practice trial and error methods. The risk lies in mobilizing community labor to conduct large-scale groundwater recharging operations without knowing whether the result would favor the community. If it would not, she would lose credibility.

We suggest that, based on our observations and archeological investigations, our ancestors solved this problem by insisting that public works begin and end with rituals, offerings and appeals to the deities, embedding them into groundwater management practices. The ceremonies help shift the burden of uncertainty from the leader’s judgment to the participants’ faith on supernatural forces. Moreover, such rituals strengthen the sense of unity and belonging, thus increasing community resilience. Many rural communities continue to maintain their groundwater supplies by applying such knowledge systems and practices, since technical expertise is hard to come by.

Case studies

<table>
<thead>
<tr>
<th>#</th>
<th>Community</th>
<th>Country</th>
<th>Description of the technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highlands of Ayacucho</td>
<td>Peru</td>
<td>shallow water holes dug by shepherds to trap runoff contribute through infiltration</td>
</tr>
<tr>
<td>2</td>
<td>Huamantanga, Lima</td>
<td>Peru</td>
<td>unpaved artificial ponds fed with canals to sustain dry season flow of small springs</td>
</tr>
<tr>
<td>3</td>
<td>Santa Elena &amp; Manabi</td>
<td>Ecuador</td>
<td>unpaved artificial lagoons capture runoff &amp; sustain dry season flow of streams</td>
</tr>
<tr>
<td>4</td>
<td>Chan Chan, Trujillo</td>
<td>Peru</td>
<td>irrigating upslope agricultural lots to feed downstream city pools and sunken fields</td>
</tr>
<tr>
<td>5</td>
<td>Huamantanga, Lima</td>
<td>Peru</td>
<td>dumping stream runoff on rocky slopes to sustain dry season flow of springs</td>
</tr>
<tr>
<td>6</td>
<td>Tupicocha, Lima</td>
<td>Peru</td>
<td>dumping stream runoff on rocky slopes to sustain dry season flow of springs</td>
</tr>
<tr>
<td>7</td>
<td>Pampachiri, Apurimac</td>
<td>Peru</td>
<td>maintaining a volcanic crater mouth that feeds a large perennial spring</td>
</tr>
<tr>
<td>8</td>
<td>Andamarca, Ayacucho</td>
<td>Peru</td>
<td>identifying the distant source of a large perennial spring</td>
</tr>
<tr>
<td>9</td>
<td>Characato, Arequipa</td>
<td>Peru</td>
<td>hosting religious ceremonies to restore a large perennial spring</td>
</tr>
<tr>
<td>10</td>
<td>San Andres, Chimborazo</td>
<td>Ecuador</td>
<td>long-dormant snow-capped volcano feeding huge perennial springs far away</td>
</tr>
</tbody>
</table>
1. Shepherds' water holes (cuchacuchas) in Ayacucho, Peru

Central and Southern Peruvian highlands (above 4000m), when not covered by ice or snow, are generally dry, compared to extensive spongy wetlands (páramos) in Northern Andes. Thus, Peruvian pastoralists have a hard time finding sufficient green pasture and water for their animals. Generations of shepherds have tried to overcome this difficulty by artificially creating small ponds, 2 to 12m in diameter and 0.3 to 0.6m deep (Jayo, 2015), wherever they roam with animals year after year. Known in Quechua as cuchacucha, these ponds trap runoff from rain or snowmelt, regenerating a patch of grass for the next trip of the herd. While keeping an eye on the animals, the herdsmen dig new ponds or clean sediments of old ones using the hand tools they carry.

![Cuchacuchas at 4300m in Licapa, Paras, Cangallo, Ayacucho (Courtesy of Adripino Jayo)](image)

*Cuchacuchas* served another important purpose: water infiltrating from these ponds fed the springs below high plains. No research has enumerated these, but in certain areas, a hectare may contain hundreds of water holes. Individually, groundwater recharge from a pond may not amount to much, but collectively their contribution is significant. Recent changes to shepherds' lifestyles and to land tenure have reduced the probability of the same person returning yearly to the same location, and thus, these ponds are slowly vanishing from the landscape due to lack of maintenance.

2. Ancestors' ponds in Huamantanga, Lima, Peru

Huamantanga, a district capital in the department of Lima, appears in colonial documents since 1543 (Avila, 2012). The Spanish established the town in the current location, a small plateau (at 3380m elevation) perched in the middle of an otherwise steep slope. The plateau was a prime agricultural land before that. However, this mountainous area has no glacier peaks, nor perennial streams.

Many small ponds (size varying from 20 to 200 m$^3$), excavated (2 to 3m deep) in part behind stone masonry walls, dot the slope above Huamantanga. Who built these ponds has not been established archaeologically, but the locals respectfully call them ancestors' ponds (*lagunas de los abuelos*). Canals leading from an intermittent
stream fed them long ago, but now all lay abandoned. No canals lead from the ponds, but the elders say small springs at the foot of the slope made feasible agricultural activity in the plateau, before the growing town gobbled up that land.

A hydrogeological study mentions that volcanic rock base of the slope above the plateau has some geological fault lines, but estimates that their capacity to store and conduct groundwater is limited (Cotinet, 2014). The study showed that small springs near the plateau have their flow originating from rainfall runoff, not from deeper aquifers. Thus, we propose the hypothesis that water infiltrating from ancestors' ponds travelled down through subsurface soil layers or along the fractures in weathered rock. That also may explain the limited nature of spring outputs, none having a flow greater than 1 liter per second (l/s). Ancestors of Huamantanga must have had to clean pond bottoms frequently to prevent the sediments from blocking infiltration.

It is highly unlikely that the ponds were built under some imperial precocious patronage. The closest large imperial centers, Pachacamac and Caral, are over 100km away, in the coast, with little influence this high up in the Andes. Being a small village (even now it has only about 300 families), how did Huamantanga mobilize resources to build over a dozen of these ponds?

Irrigation for agriculture has always been a necessity, as rainfall on this western Andean slope is sparse and irregular (average 300+ mm/year). Even if it rains, it does not last more than three months (Cotinet, 2014). Local streams run dry after the rains, making canal irrigation futile. The steep mountain slope does not permit any large storage tank either. Letting the rainwater infiltrate and capturing it at the bottom of the slope is a good, common sense approach. However, the village chief could not simply order his people to build the ponds. If the spring water would not materialize in sufficient quantities after all that hard labor, the chief would lose credibility.

A sacred feature called 'huanca' - a roughly worked stone pillar erected in the middle of many a pond, apparently modelled after Caral ceremonial complex (Avila, 2012), may give us a clue as to how local authorities would have acted.
Once you adorn a community activity with ritualistic ceremonies, making people associate their religion with it, even if the activity would not produce the expected result, the chief will not face any blame. The burden will rest upon the strength of collective faith. The next time, people can be convinced to perform the ceremonies bigger, displaying stronger belief in what they do. Such situations would rather strengthen the community social organization.

3. Infiltration lagoons (*albarradas*) in coastal Ecuador

Thousands of structures similar to Huamantanga ponds appear in Ecuadorean coastal provinces of Santa Elena and Manabi. These U-shaped lagoons (called *albarradas*), at places occupying a few hectares of surface area, retain water behind small earth dams. They date from 2000 BC (Marcos, 2006) and needed only locally available resources to build. The dams are just a few meters tall, so the villagers excavated surface soil within the lagoon, piled it up along the downstream perimeter and compacted it manually. They did not build *albarradas* across fast flowing streams, but set them up in gentle slopes where the streams are beginning to form. The open arms of the U-shaped earthen embankment collect the rainwater runoff without the need for feeder canals.

This semi-arid region receives rain for only about 4 months a year. The dry air would rapidly evaporate surface water from these shallow lagoons. Therefore, *albarrada* builders usually focused on infiltrating the collected water and capturing the subsurface flow through wells or springs downstream. An extensive study revealed that most old *albarradas* were located above Tablazo geologic formation, a porous marine terrace, raised later by tectonic activity (Marcos, 2006).

Similar to Huamantanga, this region too did not enjoy any State sponsorship to build the lagoons. The village chief would have had to summon the population to build them, convincing each of the benefit of letting the precious liquid infiltrate. However, in these mildly sloping landscapes, the argument that infiltrated water will come out from a spring a short distance downstream and will benefit the same village may not have been that convincing. Probably the chief had better success in telling them that the more lagoons they build, more rain would fall around the village (Pizarro et al, 2013).
Three large *mollus* shells (*Spondylus princeps*), found ritually buried in the dike of *albarrada* Achallan in Santa Elena (Stothert, 1995) signified a practice common in the Andes: people used them to plead divine agents for more rain (Paulsen, 1974). Again, using rituals during communal activities, the village chief could avoid the blame if the project were to fail.

4. Irrigating the desert in Chan Chan, Trujillo, Peru

From about 850 AD, the Chimu civilization spread along a 1000km stretch of northern coastal Peru. They located the imperial capital at Chan Chan, near the modern city of Trujillo, in the middle of a desert plain slightly sloping towards the sea. Each successive ruler built his own adobe-walled city of about 14ha, with elite residencies containing large fresh water pools, in addition to walk-in water wells for the public. Total urban area, at the arrival of Spanish, had spread over 20km², which included 16 walled cities, pyramids, service and residential areas, as well as huge sunken agricultural fields extending behind the city walls towards the beach. The closest fresh water source, Moche River, flows some 7km away from Chan Chan, but there was no visible water supply route to the city. How did the Chimu serve its huge urban population in this extremely arid climate?

![Fig. 4 - Large pool within Tschudi walled city of Chan Chan](image)

The Chimu people were masters of irrigation agriculture (Rodriguez, 1970; Ortloff, 1985). In Chan Chan area, they diverted water from Moche River using Vichansao canal (C2 in Fig. 6) and irrigated the vast sandy plains upslope of the city walls. Since Moche flow decreases drastically during some months of the year, they attempted to tap into the more stable flow of Chicama River with the 80km long Intervalle canal (CIV in Fig. 6). A small portion of these plains above Chan Chan is still cultivated, though Trujillo urban area continues to encroach it with buildings.
Fig. 6 - Irrigation canals CIV and C2 feeding plains above Chan Chan  
(Courtesy of Museo de Chan Chan, Trujillo)

Irrigation water the crops cannot absorb percolates through sandy soil and flows under the city of Chan Chan. By irrigating in excess, they could maintain the groundwater level below the city sufficiently high to feed internal wells, pools and pleasure gardens (Topic and Topic, 1980). Near the coast, fresh groundwater floats above heavier salty water. The Chimu, in order to practice intensive agriculture between the City and the sea, had to lower the planting surface artificially, at places to a depth of 8m (Schjellerup, 2009; Moseley and Feldman, 1984). These sunken gardens, called huachaquies, are still in use, though the use of chemicals and pumps by today's farmers cause difficulties.

Unfortunately, archaeological investigations to date have failed to explain how those large pools inside Chan Chan captured groundwater in quantities sufficient to keep their storage fresh and clean. Farmers in huachaquies recall seeing, before the archaeological site was cordoned-off, neatly constructed underground drainage conduits coming out of Chan Chan (Gómez, 2015). Further south along the coast, in Nasca, a couple of millennia ago, people had built kilometers-long filtration galleries to capture groundwater for irrigation (Schreiber and Lancho Rojas, 2003). Chan Chan engineers may have used the same technology to feed and drain the city lagoons. In any case, not having a visible water supply route to the city kept their water safe from any enemy attack.

5. Dumping water on rocky slopes in Huamantanga and Tupicocha, Peru

In the same steep Andean slopes above Huamantanga where ancestors' ponds (case #2) are located, a series of earthen canals are visible. They do not lead to the ponds, nor to agricultural fields. Two of these canals, recently rehabilitated, divert water from the main intermittent stream Pachipugro towards weathered granitic rock outcrops, a kilometer or so away. The upper canal begins near point #29 in the image below and one branch ends at #35. The second canal runs parallel to the first, starting from point #28.
Several hundred meters below, at the bottom of a rock escarpment, a couple of springs feed a canal that irrigates farm lots below the town. During the rainy season, when the stream runs full, the irrigators organize themselves to repair and clean the two diversion canals. Saturating the area around the rock outcrop, they attempt to increase the flow of the springs below. They call this process 'mamanteo', referring to the similarity with breast-feeding.

These two canals, apparently precolonial (according to the villagers), laid abandoned like ancestors' ponds until their rehabilitation in 2013 with the help of two NGOs. The irrigation canal starting from the springs below pertains to a better-organized sector (albyu) of the town, capable of mobilizing hard manual labor required for cleaning the diversion canals. Decades-long wave of migration to Lima probably debilitated the community organization in Huamantanga, causing the abandonment of those canals. Recent, drastic dry spells combined with uncontrolled pasturing in the upper catchment have severely reduced the irrigation water supply, forcing the farmers to revert to the ancient practice of recharging spring flows.

Even though the volcanic base rock is said to have low permeability (Cotinet, 2014) large weathered boulders in recharging area may provide decent seepage paths. One of the NGOs, CONDESAN, indicates that first 'mamanteo' water flows appeared in the springs 3 to 4 weeks after recharging started. Pachipugro stream dries out soon after the rains end. Thus, the longer the delay between recharging and its emergence in springs, the better for the farmers, as they can irrigate deeper into the dry season. CONDESAN (2015) expects the irrigation canal to capture up to 40% of recharged water. It has launched an experiment in parallel, to check whether conserving the upstream vegetation cover would prolong the stream runoff.

San Andrés de Tupicocha (Province of Huarochiri, Department of Lima), an Andean community located 64km SE of Huamantanga at about the same altitude, has been continuing a precolonial groundwater recharging technique. Until the 1990s, together with a few neighboring communities, it maintained many rainfall runoff diversion canals that benefitted all of them with decent increases in spring flows. The hard labor involved in the annual cleaning of these long canals and the heavy migration of inhabitants to Lima forced the other communities to withdraw.

Since Inca days, Tupicocha maintains its communal land-holding tradition and a social organization based on family ties (parcialidades or albyu) (Salomon, 2006). Each of its ten parcialidades provides, proportionately to the rights each holds, the manual labor required for the community work. These traditions run so deep that, till
early twentieth century, the community work completed and the labor expended were all registered in the khipu (Inca node-based system of accounting) pertaining to each partialidad (Salomon, 2006). Therefore, Tupicocha has not faced difficulties in continuing its canal-maintenance festival, embedded with rituals, accompanied by ceremonial music and dancing.

A basic hydrogeological investigation (Apaza et al, 2006) indicated that the fractures in the base rock of the sloping area are not open enough to facilitate rapid and large subsurface water flows. The biggest spring in the area has a flow rate around 5 l/s and the rest, flows much smaller. After the initial water infiltration, the flow in a spring some 1000m below would begin to increase in about a couple of months (Apaza et al, 2006). Therefore, it is likely that the subsurface flow occurs mainly through the thin soil layer and the fractured and decomposed rocks immediately below. This recharge mechanism is quite similar to 'mamanteo' of Huamantanga, even though it is known as 'amuna' in Tupicocha.

6. Perennial water spring in a terraced-agriculture and ceremonial site in Tipon, Peru

Tipon, a 240-hectare archaeological site 27km east of Cuzco, is best known for its Inca ceremonial complex. It includes elite residences, temples and an elaborately built terraced water garden centered on a perennial spring, all circumscribed by a huge rock wall. This large site also contains 100 ha of roughly built agricultural terraces, some of which date prior to Inca period (Wright et al, 2001).
This area receives, on average, 800 mm of rain annually. During the Inca period, canals diverted water from Rio Pukara, at the top edge of the land (3690 m elevation), to irrigate about half of the agricultural terraces, in addition to supplying water for ritual and domestic purposes. The main irrigation canal has the capacity to deliver a flow close to 100 l/s, but Rio Pukara in dry season carried only 22 l/s (Wright et al, 2001). During the last few decades, this canal has stayed dry, as agricultural activities are no longer permitted within the site. Currently, the Inca water garden, located near the bottom edge of the site, is fed only from its water spring (at 3448 m elevation) on the third garden-terrace from the top, whose output was measured at 18 l/s during the dry season (Wright et al, 2001).

Since Tipon spring's drainage basin is only 64 ha and the average rainfall is also low, how does it produce such a high water flow? In contrast, Rio Pukara drains 340 ha and its flow isn't any bigger. The mountain range, on whose slope sits the site of Tipon, rises to 4000 m elevation, but has no permanent snowcap. Nor are there any lagoons on top of the range that could feed the spring perennially.

For intensive cultivation in Inca times, 50+ ha of terraces fed by the irrigation canal required much more water than Pukara river's dry season flow (Wright et al, 2001). Thus, the Inca had to divert rainy season river flow, using a large-sized canal, and store the excess moisture in terraced fields for later use. This excess water storage in well-draining terrace soils would have generated a lot of seepage towards the spring directly below, increasing its flow substantially. The large carrying capacities of water distribution canals below the spring support this hypothesis. Excavations at the spring also revealed a very elaborate effort by the Inca to collect groundwater from every possible direction, using seven different underground conduits (Wright et al, 2001).
In addition, Wright and others (2001) propose that long fissures in volcanic rock base above the spring may increase its drainage basin. The Cruzmoco peak, lying some 2km behind the spring at the top of the range, forms a part of a long dormant volcano (Hostnig and Carreño, 2007). Andean volcanoes, uplifted through subduction tectonic movements, when active, tend to accumulate inside huge quantities of water at high pressure and temperature (Shiina et al, 2013). These high pore pressures and temperatures break internal rock walls of the volcanic cone, creating large open spaces inside (Day, 1996; Farquharson et al, 2015; Farquharson et al, 2016). In Japan, springs located around this type of dormant volcanoes continuously emit substantial water flows, and the scientists posit that long rock fractures may connect those springs with large internal water storage (Asai et al, 2009). This situation may explain, at least partially, the high flows of Tipon spring, even during times of low rainfall, no snow cover and no irrigation above it.

7. Large spring flows in volcanic mountain flanks

Apart from many small springs that quench rural populations, Andean mountains have dotted the South American landscape with a few privileged locations where some springs emit flows over hundreds of liters per second. Pumapuquio spring, located in the district capital Pampachiri (Department of Apurimac, Peru) is one of those.
The local population has identified a large, earth-filled, ancient volcanic crater lake, some 4km away from the spring and 300+m above, as the origin of this water. During several months of the year, a small depression in the middle of the crater swallows rain and snowmelt runoff through a rocky opening. The spring flow varies through the year, and may drop to 50 l/s in drier months (Jayo, 2015). The local farmers annually make the trip up the hill to direct the runoff towards the depression in the crater and clean its 'mouth' to prevent the sediments from blocking it.

A similar spring, albeit with a lower flow rate, is located within the agricultural terraces of the community of Andamarca (District of Carmen Salcedo, Department of Ayacucho, Peru). The closest mountain range, at a 6km distance, has small lagoons and its volcanic peaks are occasionally snow-capped. The villagers often recite a legend (UNDP, 2013) which explains how they identified the origin of their spring, emptying tiny quinua seeds into a lagoon.
A few km off the Peruvian desert city of Arequipa, in Cerillo (District of Characato), a spring provides 200+ l/s of irrigation water for the farmers in the area. The only possible sources of this water, the volcanic peaks Mismi and Pichu-Pichu, are located some 20km away from the spring.

According to the farmers, not many years ago, the spring dried out almost completely. After a series of ritualistic ceremonies and many pleas to their deities, the groundwater flow was restored, which gave rise to its name 'Ojo del Milagro' (eye of the miracle).

Some 15 to 20km away from the snowy peak of 6300m high Chimborazo volcano in Ecuador, three large springs (manantiales) are found. Two of them emit close to 100 l/s of irrigation water and the other, at Llillo, supplies the provincial capital Riobamba with 300+ l/s. A 30km long, ancient lava flow from the volcano outcrops as a small ridge containing large blocks of basalt, and the springs appear either side of this ridge.
Since no lakes or perennial streams appear along this flank of Chimborazo, glaciers may be the only visible source for this spring water. With the ever-diminishing snowcap, some water users say that spring flows also have diminished by 10-20% over the last 20 years. Indigenous communities in Chimborazo region were famous for their rituals celebrating this white giant and its gift of water (Moya, 1981) but the current beneficiaries of these springs have no memory of such ceremonies.

No detailed hydrogeological studies exist for any of these Andean large springs. The precipitation levels may range from 50mm to 400mm per year in these locations, though slightly higher values can be expected at mountain peaks. The rain and snowmelt runoff alone cannot explain the high flow values at these springs. In Andamarca, some lagoons are present at higher altitudes, but their small storage cannot feed such flows continuously. Since these spring waters are generally cooler than even the ambient temperature, we have to discard any geothermal emissions contributing to them. Therefore, the only plausible explanation for these large spring flows reside in the phenomena we described in the case of Tipon spring. That is, the springs must be connected through wide-open, long rock fractures to large storages of water inside the dormant Andean volcanoes nearby.

The communities of Pampachiri and Andamarca identify their springs as amunas or millpu. As we discussed before, the small springs in San Andrés de Tupicocha, fed through near-surface groundwater movements, are also known as amunas. To avoid any misunderstandings, and to differentiate between these two very distinct groundwater movements, we suggest using the name 'millpu' to refer to all volcano-associated springs with high flow rates.

Discussion, Conclusions and Recommendations:

The examples cited above demonstrate various ancestral practices employed by governing regimes and communities in the Americas to ensure sufficient groundwater supplies for their inhabitants. In some cases, they have ingeniously employed technologies intended for improving agricultural production to augment groundwater recharge indirectly. In other situations, the communities have organized themselves, mostly without any State help, to build specific structures to increase the groundwater flow.

To design such recharge systems, ancient community leaders had to have a good understanding of the local hydrogeology. As some case studies showed, they succeeded in providing solutions for the population even in situations where modern scientists had expressed doubts. That proves the value of detailed, long-term observations coupled with trial and error methods because geological conditions could vary in a scale of meters at tectonically altered locations.

By promoting this type of ancestral technologies, many rural communities today will be able to augment their groundwater resources without depending on external help. Unfortunately, little systematic work has been done to unearth such ancestral knowledge. Even in archaeologically important sites, ancestral use of groundwater sources has not received the attention it deserves.

After constructing groundwater recharge systems, the communities expect direct benefits to their water supply sources. However, even to this day, estimating when and what percentage of naturally or artificially infiltrated water will find its way to a particular spring or a well is a tough task, riddled with many uncertainties.

In extremely arid, Amargosa River near Death Valley, California, USA, natural recharging process of its mid valley alluvial deposits was studied using borehole data and flow gauges (Stonestrom et al, 2004). They
estimated that 12 to 15% of the amount infiltrated from the riverbed continued towards the water table. In comparison, agricultural sites in the valley, irrigated using sprinklers, allowed 8 to 16% of that water to percolate deep. They further found that flat shrub-covered lands, away from stream channels, contributed hardly any water as recharge. The time to recharge, for infiltrated water to reach 100m deep water table under the riverbed, estimated by Stonestrom et al (2004) as 225 to 475 years, is strongly contested. Flint et al (2004) suggested that, in arid environments, time for deep percolation might vary from years to days, depending on climatic conditions.

In humid climates, where evapotranspiration is less than precipitation, deep percolation is continuous as gravity can easily overcome suction forces created by evapotranspiration activity. However, under arid conditions, where evapotranspiration is much greater and infiltrating flows are minimal, suction and capillary forces dominate the unsaturated soil zone. Nevertheless, in any locality, humid and arid subterranean conditions swap, depending on the climate prevailing at a given time. Furthermore, those conditions differ with the location too, depending on the source of infiltration. Beneath a saturated agricultural terrace or a temporary lake, we should consider that conditions akin to a humid climate would prevail and calculate percolation rates accordingly. Many other hydrogeological situations may complicate these calculations as well.

Crerar et al (1988) reported that instrumented Swakop River middle valley in western Namibia showed flash floods recharging its shallow alluvial deposits in just a few hours. However, when the flood velocity became slow enough to deposit a silt layer on the riverbed, recharge decreased to almost zero. When water percolating through permeable deposits encounter preferred pathways, such as open fractures in otherwise impermeable rock layers, recharge time calculations become very complex (Balek, 1988). Van der Sommen and Geirnaert (1988) studied the aquifer system in West African Shield, extending south from Niger to Ghana, which consists of two components: hard rock with fractures and the weathered mantle above it. Initially this aquifer was considered as a series of discontinuous blocks of water, but further drilling revealed a large regional recharge-discharge system.

Since rural communities have no access to sophisticated equipment to disentangle all these complications in groundwater recharge, it is worthwhile analyzing the strategy used by ancestral village leaders to mobilize community labor to do hydraulic works, without sacrificing their credibility in case of a failure. The employment of ceremonies and appeals to the deities during such community works moves that risk away from the political leadership. The foremost blame for the failure of a project, if it happens, would fall upon the lack of collective faith. The most logical next step would be to conduct the next project with stronger religious fervor so that the deities would hear the pleas.

Many of the techniques and the concepts described above are valid for today. Once the basics are understood, the techniques need to be modified and adapted to the local conditions, before employing them in a community under serious water stress. However, instead of seeking piecemeal repairs to specific issues, community leaders need to look at the problem from a holistic point of view to find a solution socially, technically, economically and environmentally compatible with locally available resources.

Acknowledgements:

This work is the result of our 30+ years of immersion in the Americas. We are deeply indebted to thousands of friends who helped us with travelling, volunteer work and research that enriched our knowledge. We apologize for the lack of space to acknowledge every one and send a big thank you to all.
References:


Avila C., Jorge (2012) "El sistema de infiltración hídrica para el mamanteo de Huamantanga", ONG Alternativa y Municipalidad Distrital de Huamantanga, Julio.


Cotinet, Rémy (2014) "Estudio hidrogeológico preliminar de un sistema acondicionado: Los Mamanteos de Huamantanga, Perú", tesis de maestría, Université d'Avignon, Francia.


Moya, Ruth (1981) "Simbolismo y ritual en el Ecuador andino y el quichua en el español de Quito", Pendoneros #40, Instituto Otavaleño de Antropología, Otavalo, Ecuador.


**Contact Details:**

Name of Lead Author: Kashyapa A. S. Yapa

Email: kyapa@yahoo.com