# MACHU PICCHU: ITS ENGINEERING INFRASTRUCTURE

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"Did you say samples from Machu Picchu?" asked the inspector. Our luggage at the Lima airport had just failed the x-ray test as we were checking in for the flight to Miami in January 1996. "Yes," Ken said, "the dark spots on the screen are the Machu Picchu samples." While Ken answered the inspector's question, Ruth extracted a special governmental resolution from her handbag and put it into the inspector's hands who, upon reading a few lines said, "Excuse me for any inconvenience, sir!"

We were at the airport with seventy pounds of moist agricultural soil samples from the ancient Machu Picchu terraces. We were heading to Colorado to test the samples for agronomic characteristics. The bags of soil absorbed the x-rays like lead weights. There was no mistaking the mass in the luggage. The governmental resolution was from the Instituto Nacional de Cultura, signed and dated by the director himself, just the day before. The formal resolution identified us and the Machu Picchu samples and, with proper Peruvian flourish, described the need for scientific testing in the states.

"Why soil samples from Machu Picchu?" you might ask. Well, obtaining the soil analyses was an important step in defining the ancient agricultural potential at this mountain-top royal estate of the Inca ruler Pachacuti. The rich topsoil had been carried to the terraces some 500 years ago to create 4.5 hectares of primary agricultural land on the steep site to help demonstrate the Inca power over the land. In a similar way, the flow of water through the sixteen fountains of Machu Picchu demonstrated the Inca power over the water.

In April of 1994 the Peruvian Embassy in Washington had telephoned us in Denver to say that the long-awaited and much sought-after archaeology permit had been issued for paleohydrological studies at Machu Picchu. What a surprise it was to hear the word "issued," because it had been ten years of waiting, filing applications and justifications, telephoning, and writing proposals for a permit to conduct hydraulic engineering studies at Machu Picchu. Ken hadn't at all given up on the permit, but somehow, when it arrived, he was a little surprised. "What do I do first?" he asked himself. Seeking the permit had been so time consuming that now that it was time for action, Ken realized that his plans needed formulation and the skeleton outline of the engineering research proposal needed substantial flesh.

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In October of 1994, Ken and Ruth Wright arrived in Cusco on a 7:00 a.m. flight from. Our first job was to retain a local registered archaeologist recommended by Dr. Gordon McEwan of the Denver Art Museum. Our permit requires that we employ a local registered archaeologist. Fortunately, Professor Alfredo Valencia Zegarra of the Universidad de Cusco answered our hurried telephone call and met us at the Royal Inca II for coffee; before the day was over, our basic core research team was functioning and formulating detailed plans!

Professor Valencia was tailor-made for our hydrological and engineering research at Machu Picchu. He had served as resident archaeologist at Machu Picchu years earlier; he seemed to know every stone and structure as if each was a friend; he was already studying the water canal which served the Wari administrative center of nearby Pikillacta a thousand years ago; and he understood what we wanted to do. Professor Valencia's wife, Señora Arminda Gibaja Oviedo, serves as director of the Cusco Regional Museum of the Instituto Nacional de Cultura, and the two of them had recently completed the best archaeological summary publication on Machu Picchu entitled, *Machu Picchu: La Investigatión y Conservación del Monumento Arqueológico Después de Hiram Bingham* (Valencia and Gibaja 1992) (Fig. 1).

Fig. 1. Arminda Gibaja Oviedo and Alfredo Valencia Zegarra of Cusco, Peru. Professor Alfredo Valencia is the registered archaeologist for the Machu Picchu Paleohydrological Survey Project. Señora Arminda Gibaja is Director of the Cusco Regional Museum and the spouse of Professor Valencia.

After our third cup of coffee and several hours of discussion which led to a signed agreement between Professor Valencia and the Wrights, Ruth leaned back and said, "Things tend to work out if one has faith!"

## THE PROJECT

The permitted paleohydrological and engineering research at Machu Picchu is about sixty percent completed, with good progress being made on our objectives. Our five objectives are:

1. Evaluation of the ancient Inca spring on the north slope of Machu Picchu Mountain and its relationship to the Machu Picchu geologic fault;
2. Hydraulic analysis of the 749-meter-long Inca domestic water supply canal which traverses the steep mountainside, crosses the Lower Agricultural Sector, and terminates at Fountain 1 adjacent to the Temple of the Sun;
3. Study of the hydraulic system of the sixteen fountains in the Urban Sector;
4. Determination the paleo-agronomic character of the agricultural terraces in terms of rainfall adequacy and food production capability; and
5. Study of the urban drainage infrastructure of Machu Picchu to determine how the Inca kept the royal estate from flooding with nearly 2,000 millimeters of rainfall each year.
6. Exploration of new hydraulic components and of miscellaneous general interest features. A gold bracelet was discovered in one of the excavations for our agricultural soil samples (Fig. 2).

## THE RESEARCH SITE

Machu Picchu, the royal estate of the Inca ruler Pachacuti (Rowe 1990) is the most well-known of all Inca archaeological sites. It is situated on a high mountain ridge at 2,438 meters above sea level between the two prominent peaks of Machu Picchu and Huayna Picchu. The ridge plunges downward precipitously on both sides some 450 meters to the Urubamba River. It supported a permanent population of about 300 people with a peak of 1000 for nearly a century, from 1450 to 1540 AD (Hemming and Ranney 1982).

Fig. 2. The Machu Picchu gold bracelet found buried adjacent to an early stone wall which itself was buried west of the Temple of the Condor. The bracelet now resides in the Cusco Regional Museum.

Machu Picchu lies about 1,400 kilometers south of the Equator on the eastern slope of the Andes of Peru (Fig. 3). The site lies near the headwaters of the Urubamba River, a tributary to the Amazon River at longitude 72°32' and latitude 13°9'. There are two Inca trails; one to Cusco and the other to the lowlands of the Amazon.

Geologic faults cross the Machu Picchu ridge setting (Fig. 4). The Machu Picchu fault set the stage for the Inca water supply source by helping create the ancient primary spring water supply at elevation 2,458 meters and east of the ancient perimeter wall. A second spring emerges 40 meters higher up on the mountain slope and drains into the domestic water supply canal.

During the time since the Instituto Nacional de Cultura granted the 1994 permit, we have conducted six field trips to collect data, perform instrument surveys of the plans and profile of the canal, measure and test the spring water flow, do mapping, inspect the agricultural terraces, and search for drainage outlets and undocumented structures on the thickly-forested lower slopes of the site. Each time we arrive at Machu Picchu for the continuing research effort, my feeling of admiration for the ancient workmen and planners grows.

Professor Valencia makes it clear that the miracle of Machu Picchu is largely unseen. His many archaeological excavations at Machu Picchu have shown him what lies beneath the ground surface. The miracle is in the underground foundations, the subsurface preparation of the drainage, and the thoughtful underground work which created the structural basis for the walls, terraces, stairs and buildings of Machu Picchu. Their lasting through the centuries is a result of the ancient foundation preparation.

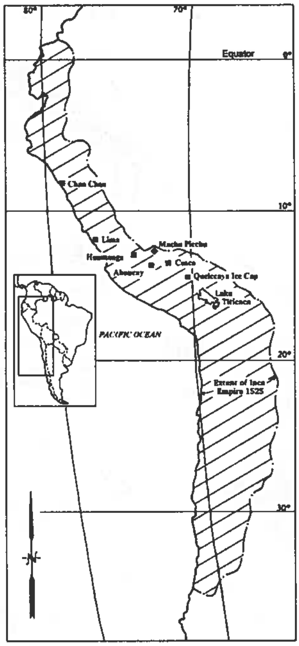


Fig. 3. Map of the Inca Empire in 1525 showing the capital of Cusco and Machu Picchu. The colonial city of Lima is shown for reference purposes.

Similarly, we are now seeing that another miracle of Machu Picchu is the engineering infrastructure consisting of the water supply, canal, fountains, agricultural terraces, and urban drainage network that made the royal estate a habitable, civilized environment with then-appropriate urban amenities. As we study and document these infrastructure facilities, tangential surprises turn up such as the potential ancient figurative wall art "hummingbird" which is judged by Inca period experts to likely be merely "random stone placement". Then there are the utilitarian baths far down on the mountainside incorporated into the little-explored or mapped agricultural terraces seemingly hanging out over the Urubamba River and visible from the peak of Huayna Picchu.

## THE MACHU PICCHU WATER SYSTEM

Hiram Bingham was on track in April 1913 when he told *National Geographic Magazine* readers that "the Incas were good engineers". Over eighty years later, we have reaffirmed Bingham's opinion about the Inca workers after intensive field research on the hydraulic and agricultural infrastructure of Machu Picchu (Wright, McGregor, Kelly & Valencia) (Figure 5).

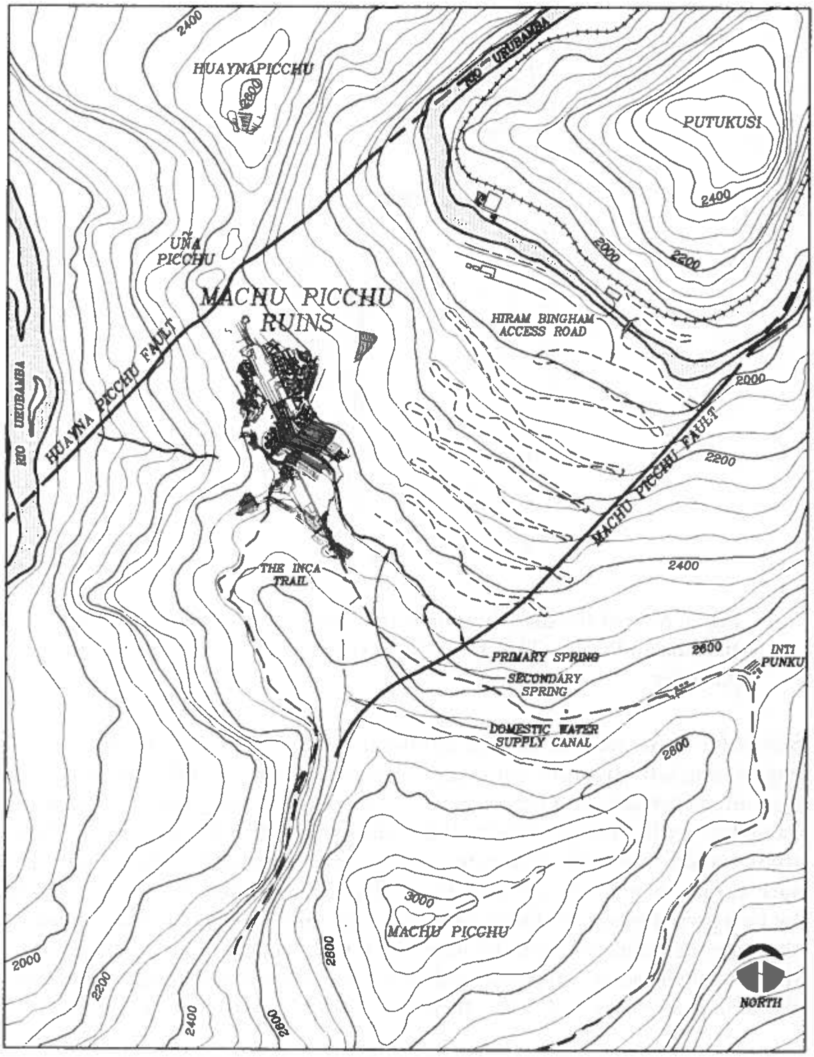


Fig. 4. Machu Picchu and environs showing the two main geologic faults associated with Machu Picchu.

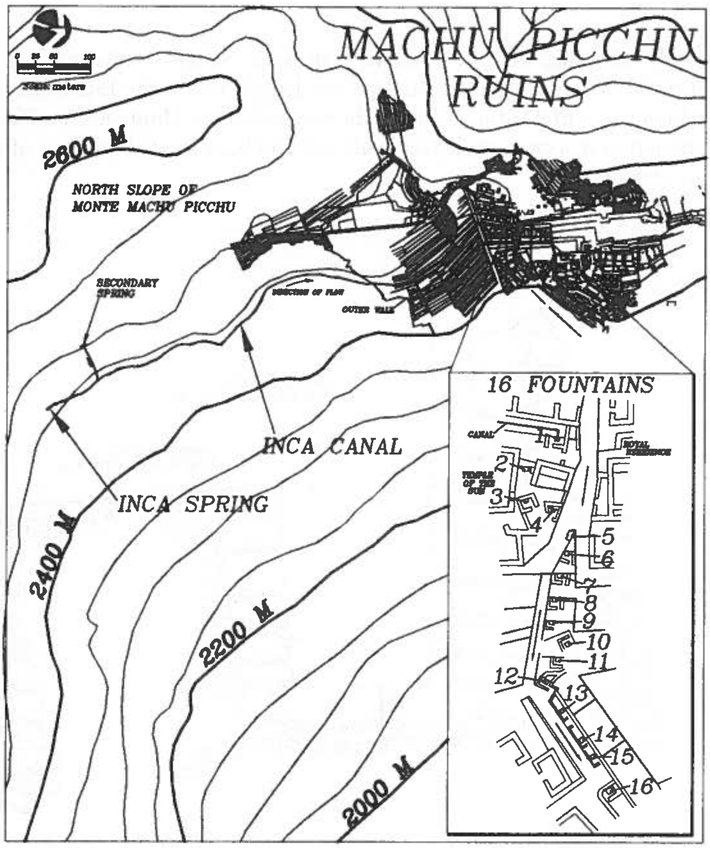


Fig. 5. Site map showing Machu Picchu, the Inca canal and spring, and the sixteen domestic water supply fountains.

The Spring

When the Inca engineers surveyed the high ridge 450 meters above the Urubamba River after cutting through the dense forest in the 15th century, they found a natural spring. It is on the north slope of Monte Machu Picchu—a manifestation of a giant geological fault that had been created millions of years before (Fig. 6).

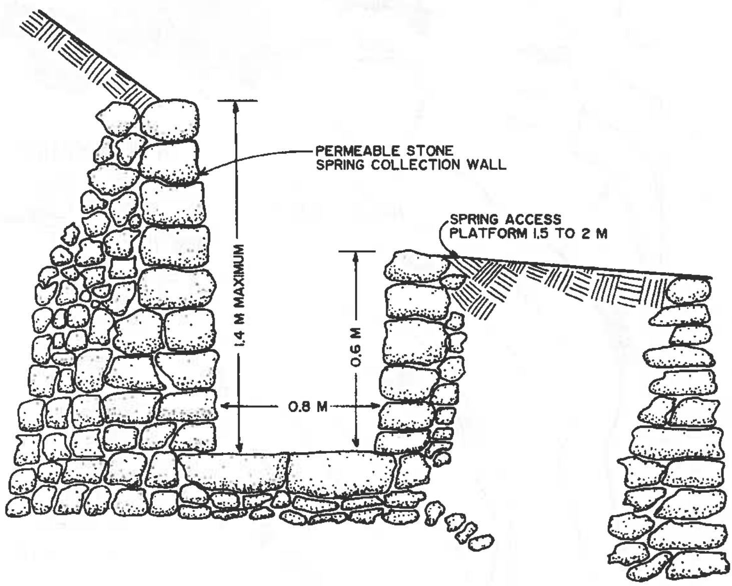


Fig. 6. Spring Cross-Section. Ancient Inca spring collection works at Machu Picchu showing the permeable stone wall inserted into the mountainside to collect groundwater from the steep slope.

Developing the spring with a steep earth cut and then building a sturdy permeable stone wall was the next step for the Inca workmen. When it was completed, water running through the permeable stone wall was pure and clear (Table 1). The basic water supply for the new royal retreat was assured!

Table 1. Machu Picchu Domestic Spring Water Quality Sampling Results

| | Units | October 1994 | February 1995 | January 1996 |
|---|---|---|---|---|
| **Inorganics** | | | | |
| Total Dissolved Solids | mg/L | 40.00[1] | 30.00 | 35.00[2] |
| Total Alkalinity | mg/L | 11.10[1] | 11.40 | 14.00 |
| Total Kjeldahl Nitrogen | mg/L | <0.20[1] | <0.20 | <0.20[3] |
| Ammonia-N | mg/L | <0.80[1] | – | <0.80[3] |
| Chloride | mg/L | <0.25[1] | – | 0.87 |
| Sulfur | mg/L | 0.233[1] | – | 4.42 |
| **Dissolved Metals** | | | | |
| Manganese | mg/L | <0.004 | <0.004 | <0.004 (0.0055)[4] |
| Copper | mg/L | <0.012 | <0.003 | <0.003 |
| Zinc | mg/L | 0.03 (0.04)[4] | <0.10 | <0.10 |
| Iron | mg/L | 0.035 | <0.04 | <0.04 |
| Aluminum | mg/L | <0.09 | <0.09 | <0.12 |
| Sodium | mg/L | 1.80 | 4.30 (2.10)[4] | 1.80 (0.23)[4] |
| Potassium | mg/L | <0.41 | <0.41 | 0.58 |
| Calcium | mg/L | 2.60 | 3.00 | 3.60 (0.26)[4] |
| Magnesium | mg/L | 0.53 | 0.48 | 0.58 |
| **Total Metals** | | | | |
| Manganese | mg/L | 0.009 | <0.004 | 0.01 (0.0055)[4] |
| Copper | mg/L | <0.012 | <0.003 | <0.003 |
| Zinc | mg/L | 0.03 (0.04)[4] | <0.10 | <0.10 |
| Iron | mg/L | 0.20 | 0.05 | 0.24 |
| Aluminum | mg/L | 0.33 | <0.09 | 0.20 |
| Sodium | mg/L | 1.60 | 3.20 (2.10)[4] | 3.00 (0.23)[4] |
| Potassium | mg/L | <0.41 | <0.41 | 0.65 |
| Calcium | mg/L | 2.70 | 3.00 | 4.10 (0.26)[4] |
| Magnesium | mg/L | 0.65 | 0.51 | 0.74 |
| **Radioactivity** | | | | |
| Gross Alpha | pCi/L | 0.8 (+/- 1.2) | 0.0 (+/- 1.1) | – |
| Gross Beta | pCi/L | 3.2 (+/- 3.2) | 0.0 (+/- 2.4) | – |
| **Field Measurements** | | | | **July 1995** |
| Water Temperature | °C | 14 | 14 | 16 |
| Conductivity | µs/cm | 30 | 25 | 35 |
| pH | | 7.2 | 7.3 | 6.45 |

[1] Sample was filtered in lab with 0.45 micron filter to remove suspended material believed to be organic matter.

[2] Sample received and analyzed outside holding time.

[3] Analyses performed on an unpreserved sample.

[4] This element was detected in the reagent blank. The blank value was not subtracted from the sample result. Blank value shown in parentheses.

The Canal

Carrying the water to the new community site was another matter. Walking back and forth to the spring to fill the aryballo water containers would be time consuming and there would not be the sight and sound of rushing water. It was not practical to require inhabitants of the mountain top retreat to hike to the spring to get water. A survey of the spring location showed that it was too low in elevation to deliver water by gravity flow to the actual ridge top; but on the other hand, a canal could deliver running water by gravity to a point about 15 meters lower on the steep sideslope which plunged precipitously to the Urubamba River below.

Getting the water to the city would not be easy as the canal would need to traverse the steep north slope of Monte Machu Picchu which would be exposed to earth slides because of its steepness and the mantle of rich, highly organic soil. The slope of the mountain face was nearly thirty-eight degrees. A canal would need to be built on flat ground supported by stone terrace walls ranging from about 2 to 6 meters in height. This would be no ordinary terrace; it would need to be well-founded and permanent for all time!

The route of the canal was laid out. The terrace wall was built and a canal was constructed on flat ground to carry the spring flow by gravity. To prevent sediment accumulation in the bottom the slope of the canal could not be too flat, and to avoid dangerously high flow velocities which might cause water to jump the canal sides it could not be too steep. The Inca engineer settled on a slope ranging from 4.8 percent near the spring to 1.0 percent reach across the Agricultural Sector within the outer walls (Table 2).

Table 2. Hydraulic Characteristics of Inca Water Supply Canal At Nominal Flow Of 300 L/Min

| Reach | Typical Cross-Section | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Length (m) | Bottom Width (cm) | Top Width (cm) | Depth (cm) | Canal Slope (%) | Flow Depth (%) | Flow Area ($cm^2$) | Velocity (M/sec) | Froude Number |
| Urban Sector | 48 | 10 | 11 | 16 | 2.7 | 41 | 67 | 0.76 | 0.95 |
| Agricultural Sector | 153 | 12 | 12 | 12 | 2.9 | 68 [1] | 98 [1] | 0.52 [1] | 0.58 [1] |
| Lower Mountain | 461 | 12 | 13 | 10 | 2.5 | 54 | 67 | 0.74 | 1.0 |
| Upper Mountain | 87 | 12 | 14 | 10 | 4.8 | 44 | 53 | 0.96 | 1.5 |
| Total | 749 | | | | | | | | |

[1] Based on a limiting 31 meter reach at a slope of 1.0 percent.

The slope and cross-sectional size of the canal were chosen to be a practical balance between three constraints: the elevation loss needed for good gravity flow, the location of the first and the highest fountain in the center of the new community, and the need to efficiently transport the typically small dry season spring yield of about 25 liters per minute and maybe as little as 10 liters per minute in drought years. The Inca engineers settled on a small canal to be lined with cut stone which would then be sealed with clay if needed. The total length of the canal would be 749 meters.

If too much water entered the canal from either the primary spring or the nearby secondary spring, or even from surface runoff during a heavy rainstorm, the water could create an erosion problem. For this reason, the Inca engineers built a relatively flat reach into the canal some 31 meters long in the Agricultural Sector (Fig. 7). Excess water would overflow from the canal, upstream of the Urban Sector, onto the agricultural terraces below. Excess water could also be controlled at the dry moat just upstream of the Urban Wall. Here, the canal was supported on a stone aqueduct over the moat which served as a main drainageway. Excess amounts of water could spill over and into the drainageway.

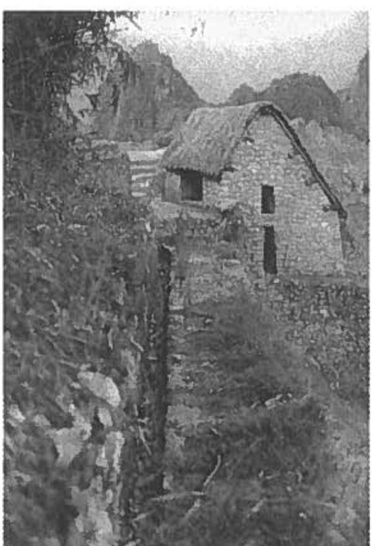

Fig. 7. Inca domestic water canal entering the Agricultural Sector. Cut granite stones forming the right bank contribute to hydraulic efficiency. The two-story building was for grain storage.

The new canal was carried through the Outer Wall and Urban Wall in small holes just big enough for the canal. When the canal reached the Urban Sector where the priests and high officials would see and have regular access to the canal, it was built straight as an arrow and at a uniform grade. Capacity was provided so that rainfall runoff from a few buildings uphill could be discharged into the canal, but only after the water flowed across a short grassed area (Fig. 8).

Finally, the canal reached a point where the first and highest fountain would be located. It was here that the Inca workmen built the royal residence so that the Inca ruler Pachacuti would have first use of the new water supply. In fact, Fountain 1 was situated nearly at the front door of the residence and just above the Temple of the Sun, which Hiram Bingham described as having a wall containing the most beautiful stonework in all of South America.

The new canal was built in an efficient manner. It would reasonably carry as much as 300 liters per minute, a lot more than needed and more than the mountainside springs would flow, even in the rainy season. The Inca engineers did not want to cut corners on the important water supply canal, so to help guard against canal problems, an access foot path was provided for canal inspection and maintenance for its full length.

## Inca Power Over the Water

In planning the new water supply for Machu Picchu the Inca workmen realized that it had to do more than just satisfy the thirst of the inhabitants. The water supply works should be able to create a show of power! This meant that the sight and sound of jetting water plunging into water-filled basins along the "Longest Stairway" was needed. The sight and sound of water in a long line of fountains should be evident for a wide range of flow, from 10 liters per minute to 100 liters per minute, a range of ten times from minimum to maximum flow. For this multiple use of the domestic water supply the Inca builders would call upon their fountain specialists.

## Fountains

The elevation of Fountain 1 was controlled by the skill of the Inca canal engineers who were able to define a reasonable grade for the gravity flow canal from the spring water source across the steep mountainside, through the Agricultural Sector and then into the Urban Sector. The "Longest Stairway" in the heart of the community would then define the exact location of Fountain 1 once the fountain elevation was established by the canal grade.

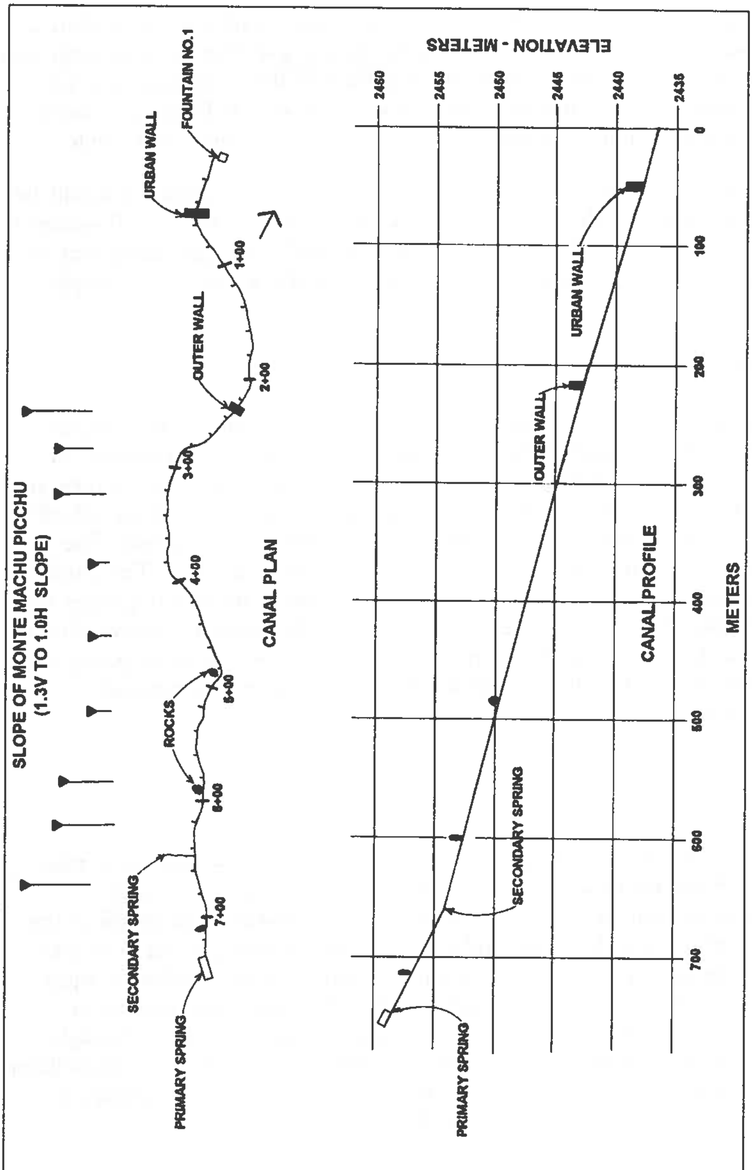


Fig. 8. Plan and profile of Machu Picchu domestic water supply works from the Primary Spring to Fountain 1.

Fountain 1 would have a walk-in enclosure complete with a niche for idols, a rectangular stone basin 45 x 60 centimeters in area and 20 centimeters deep with a circular outlet. To demonstrate the stonecutter's skill, a polished, curved, open channel would carry away water from Fountain 1 to Fountain 2 under and across an important north - south, level walkway about 1 meter wide.

While Fountain 1 would serve the Inca ruler's residence, Fountain 2 would be in the area between the open Wayrona and the Temple of the Sun. Fountain 2 was tucked in between the two buildings at the end of an open passageway to provide a semblance of privacy for the users as well as a ready water supply.

The Sacred Fountain

A special fountain was needed below the Enigmatic Window (a.k.a. Serpent Window) in the Temple of the Sun. This would be the Sacred Fountain, or Fountain 3. This fountain was polished and contained four niches. However, a potential unique feature of Fountain 3 was that it could be turned on and off using a bypass channel, that is, if the bypass channel is of Inca origin. The water could be diverted directly to Fountain 4 from Fountain 2. This would have meant that the priests could have the sight and sound of jetting water into a water filled basin, or relative peace and quiet at the adjacent ceremonial rock platform just to the east of the Enigmatic Window. I will be investigating the origin of the "bypass channel" further with the Machu Picchu resident archaeologist.

Fountains 4-6

To round out the fountain placement and design at the focal point of Machu Picchu, Fountain 4 collected water from either Fountains 2 or 3, or in combination from both. Fountains 5 and 6 were situated in the middle of the bifurcated "Longest Stairway" and provided a roar of falling water to all who might pass by (Fig. 9). These fountains were almost directly below the open wall of the Wayrona which provides a view of the magnificent mountains across the Urubamba River as well as of the ceremonial platform. The sight and sound of the fountains, when coupled with the roar of the Urubamba River below, must have complemented the view of the mountains in a manner to impress even the most indifferent of visitors.

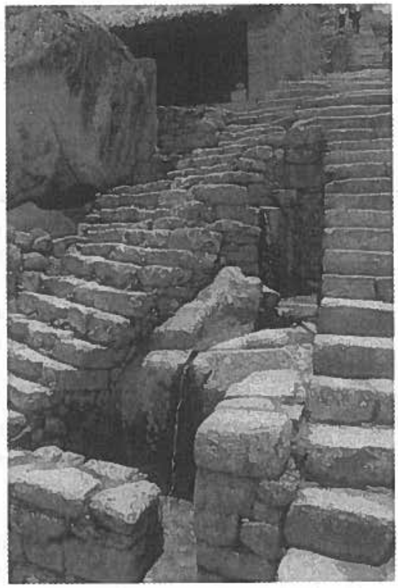

Fig. 9. Fountain Nos. 5 and 6 with the "Longest Stairway" (To the left and out of the picture is the Temple of the Sun).

The stonecutters challenged themselves between Fountains 5 and 6; they cut a bifurcated channel for beauty and hydraulic interest. Downstream of Fountain 6 a special channel was cut in the granite rocks with a plunging entrance to an underground channel leading to the next fountain.

It was planned that there would be a total of sixteen fountains in all. That meant that there would be ten more fountains constructed along Machu Picchu's "Longest Stairway", also known as the "Stairway of the Fountains".

## The Private Fountain

Nine of the next ten fountains were for public use with the sixteenth being a private fountain accessible only from the Temple of the Condor area.

Fountain 16 was special with high walls for added privacy, and a 1.6-meter-high water drop into the stone basin at the bottom. Due to the fact that this was the last fountain and the need to protect the purity of the water no longer existed, the engineers routed an important drainage path into the Fountain 16 enclosure, directly to the stone basin at the bottom. During low flow periods, the users of Fountain 16 would not normally dip water from the stone basin as they could have in the other fountains. This would be particularly true if it was raining and there was surface runoff entering the stone basin.

Fountains 7-15

Fountains 7 through 15 would be similar to the rest, with no special hydraulic specialties incorporated into them, except between Fountains 9 and 10 and at No. 12. Here the designers used their ingenuity and engineering skills to reverse the flow direction of Fountain 10 by carrying the water through a channel built within the wall (Fig. 10). Then they proceeded to cut a surface channel with two right angles so the water would flow into the fountain enclosure from the east, rather than from the west as with all the other fountains. A unique feature exists at Fountain 12 where the stonecutters shaped a smooth polished lip for the approach channel terminus to help create a good jet of water which would spring free from the back wall of the fountain enclosure.

What to do with the flow in the fountains following Fountain 16? The water from Fountain 16 was routed underground to discharge into a narrow, steep channel on the west side of a long staircase which conveniently went all the way to the "Dry Moat", a large, steep drainage and flood control channel which separated the Agricultural Sector from the Urban Sector.

The sixteen fountains stretch from west to east a distance of 51 meters with a fall of 26 meters. This allows for adequate slope between fountains to efficiently carry the water flow from one to another and still provide for a typical 1.2-meter drop within the fountain.

The flow through the fountains was limited hydraulically to 100 liters per minute through the use of a smaller circular outlet with a diameter of only 3.8 cm from the basin of Fountain 4. Here, if the flow exceeded 100 liters per minute, the stone basin would fill and overflow relatively harmlessly onto the granite stone staircase until adjustments could be made upstream. To limit fountain overflows, the canal flow could be regulated in the Agricultural Sector where the 31 meters of 1 percent slope canal existed and where the excess water would be easily spilled to the agricultural terraces where an elaborate and well-designed drainage system existed, or the excess flow could be directly spilled into the dry moat where the canal-bridged aqueduct had been constructed over the moat. In either place the canal flow could be easily regulated to limit the flow into the Urban Sector to the desired amount without erosional damage.

Fig. 10. Fountain No. 10 with water jetting from east to west. All other fountains jet from west to east.

Were They Good Engineers?

Hiram Bingham was correct when he said the "Inca were good engineers"(Bingham 1913). Bingham fortunately was a good photographer and documentor of evidence. His classical photo (Bingham 1930) showing the Agricultural Sector and the complete route of the canal across it demonstrates that the canal had not failed even after more than three centuries of abandonment. His photo shows the 1 percent grade reach of 31 meters in length. His 3-D drawing of the community (Bingham 1930) clearly shows the canal aqueduct over the "Dry Moat", the aqueduct which has been lost and the span filled in.

Had Bingham more time and less to do during his 1912 work at Machu Picchu, he might have further mapped the water supply system from its source to its ultimate disposal. Bingham would have likely concluded that the Inca were extraordinarily good at hydraulic engineering planning and design. Their public works infrastructure capabilities were a tribute to their accumulated empirical knowledge and ability to blend what nature provided with man's needs!

Additional Fountains

The clearing of the tropical forest and debris from several lower and less accessible agricultural terraces on the lower flanks of Machu Picchu by the paleohydrology team during 1995 and 1996 resulted in the documentation of additional fountains and baths. The first two structures found in July 1995 were simple baths, but well suited for the workers to wash up in before climbing back up to Machu Picchu with their agricultural bounty (Fig. 11). The water supply for these two baths came from the uphill subsurface drainage system of the adjacent agricultural terraces. This represents an example of water reuse at Machu Picchu.

Fig. 11. Exploration was conducted on the Lower Agricultural Terraces. The author is shown at an agricultural worker's bath area which utilized drainage seepage water.

Then in the winter of 1996 the fountain exploration really paid off. Further north, down at the base of Huayna Picchu and with a spectacular view of the Urubamba River and the granite mountain peaks to the northeast, our team found two ceremonial fountains at the intersection of two grand granite staircases.

Ken had requested that Alfredo Valencia start cutting a trail into the area prior to the August 1996 research trip, and the trail clearing started a few weeks before my arrival (Fig. 12). Already on August 6 people in Cusco were discussing the "new fountain discovery".

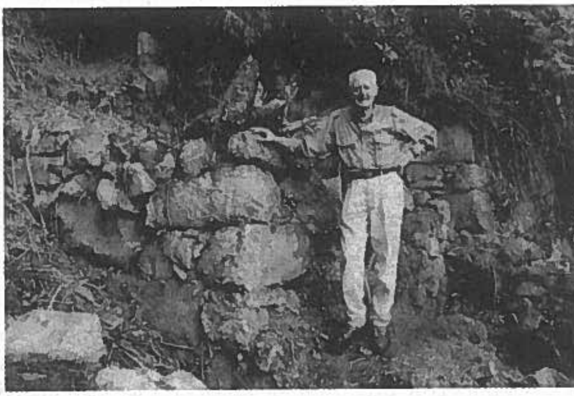

Fig. 12. The author beside one of the new ceremonial fountains recently rediscovered. An additional fountain lies to the author's left which still needs to be excavated under the authority of the Instituto Nacional de Cultura.

Actually, the new ceremonial fountains complete with Inca pottery pieces were not discovered, but "rediscovered". Back in 1969 Alfredo Valencia had spotted the fountains after a forest fire had burned the mountain slopes of their vegetative cover! The locations of the fountains were not documented, but Alfredo, like most top-notch field archaeologists, had a feel for the approximate site. Again this proved that fortune smiled on our project team when we engaged Valencia as our local registered archaeologist.

The lower terrace baths and fountains are a matter for continued study and documentation by the paleohydrologic team; however, the two baths and the two ceremonial fountains have already been cleaned and partially field measured, and show the careful planning and construction performed by the Inca builders of Machu Picchu. One of the two ceremonial fountains will require excavation by the INC prior to final study and measurements. Dr. José Altamirano Vallenas, Director of the Instituto Nacional de Cultural Departamental Cusco, plans to have the area furthered cleared and make the new ceremonial fountains a new tourist area at Machu Picchu.

## AGRICULTURE

Our scientific research interests extended to the agricultural production potential of ancient Machu Picchu (Wright, Wright, Jensen & Valencia). We conducted complete agronomic soil tests at the Colorado State University Soils, Water and Plant Testing Laboratory in 1996 on samples excavated by Señorita Elva Torres Pino of the INC. In obtaining a soil sample in one of the plazas, an ancient Inca wall was uncovered. At the foot of this long buried wall a gold bracelet was discovered—the only gold object ever found at Machu Picchu.

It was Dr. José Altamirano Vallenas who turned the soil samples over to me in his corner office of the grand colonial building which serves as the INC Cusco Departmental headquarters. Dr. Altamirano and Ken discussed the scientific need for the soil analyses, but we also talked about the beautiful gold bracelet found by Señorita Torres.

The size of the main agricultural areas was determined from our detailed maps (Fig. 13). It totals 4.5 hectares (11.1 acres). We needed to know what the likely precipitation was in ancient times, so we correlated the modern weather records for 1964-1977 with ice core data from the Quelccaya Ice Cap shared with us by Dr. Lonnie Thompson of the University of Ohio. The ice cap is situated halfway between Machu Picchu and Lake Titicaca. We found that the period of occupation (1450-1540 AD) likely experienced rainfall of 98 percent of the long term average, or 1940 millimeters per year (Table 3). We used the modern record for temperature and wind in our computations.

Fig. 13. Visually dominating agricultural terraces at Machu Picchu.

Table 3. Annual Precipitation[1] at Machu Picchu By Decade Relative to Normal Long-Term (540-1984 AD) Precipitation

| Decade | Percent of Long-Term Normal | Equivalent Annual Precipitation (mm/yr) |
|---|---|---|
| 1450-59 | 89 | 1770 |
| 1460-69 | 96 | 1900 |
| 1470-79 | 92 | 1830 |
| 1480-89 | 89 | 1770 |
| 1490-99 | 94 | 1860 |
| 1500-09 | 102 | 2020 |
| 1510-19 | 108 | 2150 |
| 1520-29 | 99 | 1980 |
| 1530-39 | 112 | 2220 |
| Average | 98 | 1940 |
| 1964-1977 | 99 | 1960 |

[1] Ancient precipitation estimates based on correlations with ice core analyses results from the Quelccaya Ice Cap.

Then the real work began. What was the solar radiation at Machu Picchu, what crops should be chosen for the calculations, what was the nutrient content of the crops, and how many calories per day would have been needed by the Inca people? To help with the answers we called in Dr. Marvin Jensen as a consultant to help with the analysis and check our estimates and assumptions. Jensen is a long-time colleague of ours who has spent a lifetime studying food production potential all over the world. Jensen helped us through a complex set of computations.

Because we wanted to know what the likely maximum nutrient production potential could have been, we chose a hypothetical 2.25 hectares of maize and a double-cropping of 2.25 hectares of potatoes. We knew that the length of the growing season and the rainfall would likely have supported two potato crops during most years.

Water requirements for crop growth were computed based on two reference crops, short grass and alfalfa. Evapotranspiration for short grass and alfalfa averaged 4.02 mm/day and 4.82 mm/day, respectively, and was calculated using the Penman-Monteith equation. This data was then translated to maize and potatoes using standard irrigation engineering curves.

The agricultural research found that the 4.5 hectares could potentially have produced 3500 kilograms of maize and 141,000 kilograms of potatoes each year, if the Inca had chosen such crops rather than, say, cocoa, all maize, or herbs. With maize and potatoes, the 4.5 hectares of terraced agricultural land would have supported only fifty adults. To feed the estimated 300 permanent residents of Machu Picchu would have required 27 hectares of land. Our studies also showed that the terraced agricultural land was not irrigated, but relied on the ample precipitation of nearly 2000 mm/year. As a result, it could be concluded that food was brought into Machu Picchu because the agriculture land within the perimeter walls was too small in area to make Machu Picchu self sufficient in nutrient production. The 4.5 hectares was more likely used for growing maize for producing ceremonial beer.

## URBAN DRAINAGE

Our research to date has left the urban drainage system to be documented last. One reason for this is the need to develop a strong background before tracing out all the many drainage routes and their contributing basins. It seems as though each time we begin to verify and document the known drainage system, more outlets are found in the various nooks and crannies of the Urban Sector. Nevertheless, we have documented some 127 drainage outlets to date. We are not sure when the drainage surprises will finally cease. A typical drainage outlet is illustrated in Fig. 14.

Our graphic specialists plan to portray the urban drainage system on a computer-generated map which is presently under development. Perhaps more than any other aspect of the engineering infrastructure of Machu Picchu, the urban drainage system represents a high level of planning. For here, the drainage system was incorporated into the walls of the buildings as each wall was built. Even with modern urban development in the USA, one does not usually see the drainage infrastructure so well incorporated into the community. By studying the elevation and location of the drainage outlets, it is obvious that a master plan had to be adhered to in the community construction. That is, the floor elevations of interior rooms and walkways were established even while major conjunto (sector) exterior walls were under construction. Drainage was neither left to chance nor worked out later as is so often the case with modern city planning.

Fig. 14. An example of an Urban Drainage outlet (upper center ) with a vertical drop channel cut into the stone wall rocks below the outlet.

## THE NEXT STEP

Engineering research at an archaeological site provides rich opportunities to learn more about ancient people because the work deals with numbers, physics and engineering relationships which these people mastered using trial and error. As our research work at Machu Picchu begins to draw to an end, it would seem that our paleohydrological team would plan to just pack up and declare the work completed. It isn't working that way, though!

As we learn more about the engineering infrastructure, the little details tend to take on more significance. For instance, the routes of the storm runoff drainage to the stone basin of the very last fountain, but to no upstream basin, makes it clear that the Inca were aware of the importance of clean water for drinking purposes. The stone lip of Fountain 12 demonstrates their knowledge of forming a free-falling water jet. One carefully planned stone drainage outlet near the Royal Residence illustrated the concern of the builders to ward against ponding at the front door of the royal residence much in the same way that present day builders of department stores are concerned about having good drainage at their front doors.

Following our completion of the study of the urban drainage system we will go into the final mapping stage and the verification of findings and technical facts so that archaeologists and anthropologists can use the engineering evaluations with a degree of confidence to help piece together what the ancient Inca workers did to make their cities work and how the community infrastructure functioned.

Fig. 15. Ruth Wright, the driving force behind the Machu Picchu Paleohydrological Survey work is looking forward to more field expeditions at Machu Picchu

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