**The perennial spring of Tipon was formalized with Inca hydraulic enhancements to optimize its yield.**

WRIGHT WATER ENGINEERS

# A True Test of Sustainability

## The triumph of Incan civil engineering over scarce water resources survives today

*Kenneth R. Wright*

Inca water planning, management, and construction of water facilities were as varied as the Peruvian landscape. Decadelong field studies at the pre-Columbian archaeological sites of Machu Picchu, Moray, and Tipon have revealed that the Incas possessed an uncanny ability to develop water resources on a site-specific basis. This remarkable knowledge of water resources development principles occurred without a written language, use of the wheel, or the availability of iron or steel.

The author has had the privilege of studying ancient water use and handling, or paleohydrology, in Peru since 1994. What began as a modern-day engineer's curiosity about prehistoric water resources management quickly became a fixation. The author collaborated with archaeologists and other experts, obtained access to ancient sites, and learned about the skills of the Inca engineers.

Throughout their empire, the Incas used consistent building design standards that were adapted to the diverse environments of their many sites. The water resources infrastructure at Machu Picchu was planned for domestic use because the annual rainfall was adequate for agriculture without irrigation. At the drier Moray and Tipon locales, however, water resources were developed for both domestic and irrigation use by a unique means of collection and conveyance systems and canals. These civil engineering features were designed for both sustainability and beauty.

### Machu Picchu: Fountains for a King

Machu Picchu was the royal estate of the Inca Ruler Pachacuti, established in A.D. 1450. It is situated 450 m above the valley bottom on a mountain ridge between two prominent mountain peaks — Machu Picchu and Huayna Picchu. The site is a remarkable union of Inca ingenuity in the face of challenging natural topography and environment.

With 2000-mm annual rainfall averages, wa-

**Sixteen fountains at Machu Picchu adjacent to a long stairway provided an easily accessible domestic water source.**

WRIGHT WATER ENGINEERS

**The hydraulic engineering of the Tipon fountain represents a high standard of care to create an aesthetic amenity.**
WRIGHT WATER ENGINEERS

ter resources development at Machu Picchu was focused on domestic use. The three main components were the spring-water source, the fountains, and the canal. The well-preserved remains of Machu Picchu show that the Incas had an advanced understanding of such principles as hydrology and hydraulics.

***Importance of Spring-Water Source***

Machu Picchu never would have existed if it weren't for the perennial spring that the Inca engineers found and developed on the steep north slope of Machu Picchu Mountain. Although the spring is a natural phenomenon, its reliable yield is enhanced by an innovative and well-engineered stone collection system that allowed the water to percolate through its wall and flow into the receiving channel. It is still functioning today. This ancient spring works is set into the steep hillside. Based on field measurements, the linear stone wall is approximately 14.6 m long and up to 1.4 m high. A rectangular collection trench approximately 0.8 m wide and about 0.6 m high resides at the foot of the wall.

Measurements of the primary spring yield at various times showed noteworthy seasonal flow variation. The spring yield ranged from a measured low of 23 L/min to a high of 125 L/min. This variability suggests that the spring flow is derived from a relatively local hydrogeologic source influenced by seasonal variation in precipitation.

***Water Supply Canal Hydraulics***

Spring water was carried 749 m to the city center in a small domestic water canal formed with cut stones. The ancient Machu Picchu water supply canal illustrates the Incas' ability to carry an appropriate grade over a long distance, as well as their ability to build sustainably, even on steep, unstable slopes.

Canal construction constraints would have included steep terrain, variable spring yield throughout the year, and siltation and plugging of the canal with forest litter. The typical slope of the canal varies from 2.5% to 4.8%, which seems reasonable, based on site conditions. The nominal design capacity of the canal — approximately 300 L/min — is more than twice the maximum measured flow rate of the primary spring during the period of measurement and three times the capacity of the fountain system.

The canal's well-fitted cut-stone lining promoted hydraulic and operational efficiency and control of seepage loss. Seepage losses were likely less than about 10% because of the stone lining and the fact that the joints were sealed with

**While each fountain at Machu Picchu is unique, all sixteen have common hydraulic features.**

WRIGHT WATER ENGINEERS

**A stone-lined canal carries the water from the Machu Picchu spring to the center of the royal estate.**

WRIGHT WATER ENGINEERS

WRIGHT WATER ENGINEERS

clay. The stone lining also would have minimized maintenance requirements. The canal is supported by terraces built on the steep slopes of Machu Picchu to resist sliding and settlement.

***Beauty of Fountains***

Machu Picchu's canal leads to one of its urban focal points, a religious center with a succession of 16 fountains. The functionality and beauty of the fountains make them a notable example of pre-Colombian water resources development. The fountains were laid out to provide domestic water for the population, to enhance the urban environment, and as a manifestation of the power of the Inca ruler Pachacuti.

There is a 26-m vertical drop between Fountain No. 1 and Fountain No. 16.

Fountain No. 1 was installed adjacent to the doorway of the Inca ruler, providing him with the first opportunity to utilize the imported water supply. Fountain No. 3 is known as the Sacred Fountain because it is adjacent to a stone of adoration, a *huaca*, and the enigmatic window of the Temple of the Sun. The water flows in sequence, from Fountain No. 4 through 12 more fountains to Fountain No. 16.

Detailed field instrument surveys were conducted, such as hydraulic flow tests, measurements of the fountain structures, and measurements of channel and outlet sizes. A small orifice outlet 3.8 cm in diameter measured in the basin of Fountain No. 4 would have limited the maximum fountain system flow capacity to 100 L/min. However, the individual fountains, based on flow tests, were designed to operate optimally with a flow of about 25 L/min to fill the common Inca water jug, known as the *aryballo*. Field testing of the fountain hydraulic characteristics showed that the fountains would operate satisfactorily at flows as low as 10 L/min.

A common form, function, and layout are shared by all 16 fountains. Each has a carefully cut stone channel or conduit that delivers water at or near the top of the fountain enclosure that provided a degree of privacy and a sharp-edged or lipped rectangular fountain spout that created a falling jet into a cut-stone basin at the bottom of the enclosure. Except for Fountain No. 16, each fountain can be reached via common stairways and walkways. The water in each fountain is channeled to the next fountain through a 3.8 to 5.0-cm-diameter circular cut-stone drain outlet.

**Delivery of water from upper Tipon terraces to lower terraces was accomplished using vertical drop structures inset into the terrace stonework.**


WRIGHT WATER ENGINEERS

Four natural depressions were used at Moray to create concentric circles for irrigated crops.

## Moray: Mystery Circles

The Moray archaeological site lies on a large plain above and south of the Vilcanota River, about halfway between Machu Picchu and the Inca capital of Cusco. The site is most famous for its three large natural depressions, or *muyus*, that have been shaped and terraced to form concentric circles. A fourth terraced depression is shallower and smaller in diameter. The entire archaeological complex covers 37 ha.

Moray has been known to the world only since 1931, and its original purpose and function are still an enigma. The site is Imperial Inca in construction, but pre-Inca people were active in the area much earlier. A series of handsome linear terraces complement the concentric circles and vertical channels that dropped water from terrace to terrace. The carefully placed hydraulic drop structures (vertical channels) in each *muyu*, coupled with geometrically situated “flying stairs” (stones protruding from the walls), add order and detail to each set of circles.

The genius of the Incas was their ability to grow a surplus of food, making large portions of their population available to construct temples and roads and develop textiles, art, and crafts while building the military and empire. While Moray was an Inca ceremonial site, the physical focus seems to have been agriculture, with crops grown on all of the site’s terraces.

With Moray’s relatively dry annual average precipitation of about 500 mm, irrigation was necessary for success. Unlike Machu Picchu, where agriculture was secondary to the main purpose of the site and performed independently of irrigation, irrigation was very important at Moray. The key water resource components of Moray, therefore, are its springs, canals and reservoirs, and irrigation features.

### *Still-Adequate Moray Springs Yield*

The springs of Moray and nearby Misminay were historically — and are currently — the water source for the area. Six springs were identified in the field in Misminay and three were identified at Moray, providing evidence of a reasonable water supply. Yields of the springs vary considerably during the year due to seasonal precipitation, annual variations in total precipitation, and lag time between rainfall and spring flow. During October 2005 fieldwork, various spring flow measurements were made ranging from 0.1 to 150 L/min.

Inca reservoirs on the upper slopes of Moray and modern reservoirs in Misminay provide evidence that careful water management was practiced by the Incas and is still practiced by the Quechua Indians of Misminay. Two reservoirs at Moray provided storage for modest flows from the springs, so that releases could be made periodically with a good head of water to carry the flow at cost-effective rates through outlet canals and to the point of use. The reservoirs also would have provided convenient drinking water supplies.

The reservoirs are semicircular 10- and 19-m structures. The larger of the two is mostly destroyed. The reservoirs contain some good Inca stonework with tight-fitting joints.

Remains of Inca canals tend to be sparse at Moray, likely because of continued agricultural activity and grazing in the area, along with erosion and sedimentation on the steep slopes. Nevertheless, several surface remains of Inca canals were identified.

### *Irrigation Practices*

In October 2005, a time of modest spring-water yields, Quechua farmers irrigated maize fields east of and adjacent to Moray. They were able to use a flow in the field of about 1000 L/min and route the water efficiently to the ridge- and furrow-planted maize fields using shovels and hoes. Inca irrigation of Moray may have been similar.

The hydraulic drop structures on each of the terraces show that the Incas intended to be able to irrigate each circular terrace, even though it is not entirely clear how water was adequately conveyed along the circumference of each terrace. If adverse slopes on any of the circular terraces existed in Inca times as they do today, subirrigation could have occurred on lower terraces. On the other hand, excavations by archaeologist Rosa Quirita showed an underground canal conduit that provides evidence that the Incas installed components for water distribution on the circular terraces. More study is required to understand fully how the Incas irrigated at Moray.

## Tipon: Hydraulic Poetry

The Tipon archaeological site is a 200-ha, self-contained, walled settlement that, like Machu Picchu, served as an estate for Inca nobility. Tipon could be called an Inca water garden because of its canal hydraulics and related features of terraces, fountains, and drop structures. Like Moray, Tipon was an agricultural center requiring irrigation. At Tipon, the Incas drew upon the technology of past empires and refined the techniques. Water resource development at Tipon harmoniously fit the site's topography, hydrology, and water needs. Water was an important part of the whole.

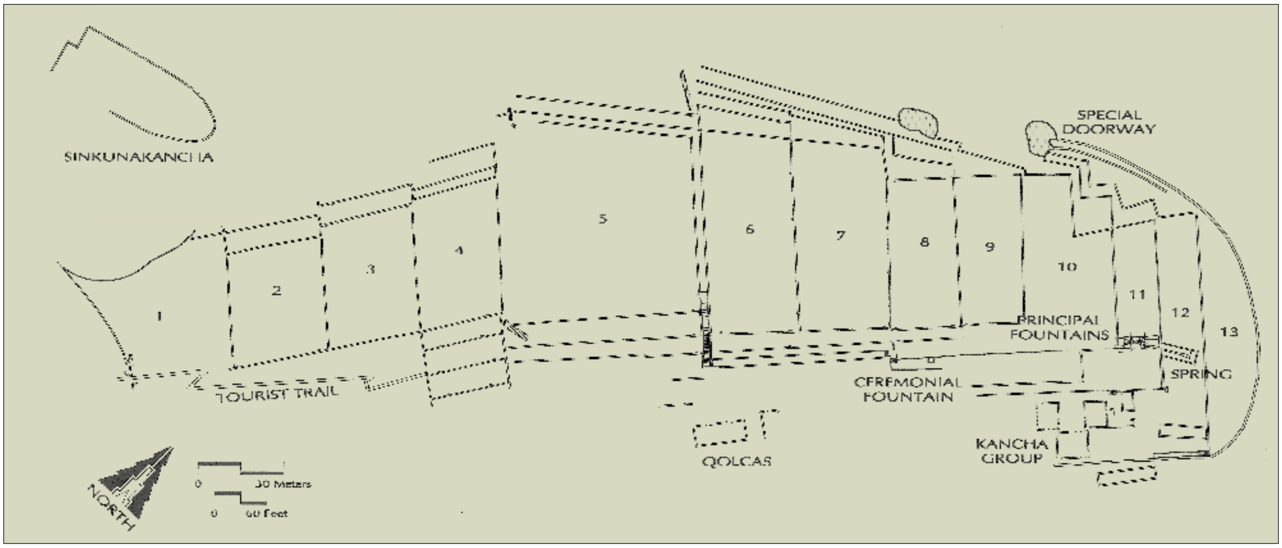
The main canal diverted water at a 3700-m elevation directly from the bed of the Rio Pukara to the Tipon central terraces. The canal also served extensive areas of agricultural land extending near the religious complex, or *Intiwatana*, and a ceremonial plaza. Beyond the *Intiwatana*, the main canal follows a relatively gentle and uniform slope to the valley north of the central terraces.

### *Efficiency of Tipon Spring*

The Incas knew about the conjunctive use of water, a strategy water engineers use today. In ad-

**Machu Picchu Fountains 5 and 6 are situated at a stairway bifurcation. The Inca civil engineers carved special channels in the granite rock to create hydraulic variety and the sight and sound of rushing water.**

WRIGHT WATER ENGINEERS




WRIGHT WATER ENGINEERS

**The central terraces of Tipon are inspiring examples of engineering layout and conjunctive use of surface and groundwater.**

dition to the main canal (surface water supply), Tipon's civil engineers utilized a high-yielding spring (groundwater supply) with a pure, reliable base flow of nearly 1100 L/min. The perennial Tipon spring issues from the base of a volcanic-rock deposit enhanced by elegant Inca headworks. It is clear that the Inca engineers knew about the fundamentals of groundwater flow, because the headworks were effective and efficient in concentrating the discharge of the subsurface flow while being aesthetically pleasing.

The Tipon spring's topographic tributary drainage basin covers only 62 ha, although the geologic drainage basin is likely greater by a factor of perhaps 5 due to fracturing and jointing of the volcanic bedrock and solution cavities in the underlying limestone.

September 2000 hydrological surveys found that Inca-formed stone conduits of the Tipon spring extended back into the hillside. Eight separate conduits were noted that served to collect the subsurface flow so that it could be concentrated in one location for ease of handling and distribution.

### *Flexibility of Central Terrace Canals*

Several longitudinal canals were built on the central terraces, some of which were designed for supercritical high-velocity flow. The Tipon spring flows 8 m to a point of bifurcation. The right canal then bifurcates again to create two separate canals. If modern water engineers were laying out the water distribution system, they might have used this same layout. The three-canal layout of the water distribution system enabled prehistoric water managers to route water to the entire central terrace system lying below the spring, as well as directly to Patallaqta and Sinkunakancha. The three canals could be operated independently or jointly, depending on the desires of the Inca canal operator.

When irrigation engineers need total flexibility in routing water evenly to three branches or all the water in just one, the hydraulics must be well balanced, and the individual channels must be sized for a variety of discharges. To this challenge can be added both subcritical and supercritical flow, with provisions made for hydraulic jumps that otherwise could cause channel sides to be overtopped. Inca engineers mastered such complexities.

### *Design of Tipon's Hydraulic Features*

The hydraulic three-canal system includes numerous hydraulic structures that serve important functions while being designed and built for beauty, interest, and enhancement of an aesthetic environment. The hydraulic perfection of the central terrace water handling is one of the primary factors in making Tipon an estate suitable for Inca nobility. It would have been impressive to important visitors invited into the compound and to the workmen viewing the works from a distance.

Tipon's dramatic focal point is a set of 13 large, irrigated water-garden-type central terraces that stair-step down a former ravine, the terraces being formed by handsome, carefully designed stone walls judged to be among the finest in all of Peru. Near the middle of the terrace complex, a series of elaborate drop structures provide the invigorating sight and sound of cascading water.

A ceremonial fountain lies opposite Terrace No. 8 and would have been a suitable place for holding ceremonies. Inca engineers constructed another remarkable fountain, now restored, with four jet streams, on Terrace No. 11.

Tipon engineers worked successfully with day-to-day technical difficulties. For instance, where an *aryballo* had to be filled, the fountain's jet size and trajectory had to be suitable to enter the small opening at the top of a large-diameter ceramic vessel. The jet could not fall too close to the wall or spill out too far horizontally. While this may seem like a simple matter to a layman, it is not so easy when the rate of flow varies and when one uses building stones.

The central terraces stepped down from north to south a total of about 50 m from Terrace No. 13 to Terrace No. 1, with elevation differences as much as 5 m. Here, the Inca engineers were faced with challenges in hydraulic energy dissipation, because the drops had to meet design standards of controlled splash, pleasant appearance, and complete integration into the high-status stonework of the walls. Their solution was to use unique near-vertical channels inset into the walls. The resulting design is a visual highlight of the terraces and an extraordinary engineering achievement.

The flow of water into and through the drop structures conveys a feeling of order and harmony; the smooth stream lines throughout the entire vertical drop were contrasted with the controlled point of impact at the bottom, where splash was limited laterally because of the inset channel. The controlled rush of flowing and falling water would have helped demonstrate the power of the Incas over land and water, as well as their capabilities in creating hydraulic poetry.

## Sustainability of Incan Water Systems

Incan water development was not only site-specific but also sustainable, as evidenced by the fact that so much of the Inca water resource infrastructure remains for study. One reason we know about Inca water resources is because of the great care they took in incorporating adequate foundation drainage so that after four centuries, the infrastructure still exists. Trouble also was taken by the Incas to maintain the purity of the domestic water supply by directing agricultural and urban stormwater discharges away from the open domestic water supply canals. They also designed excellent foundations that enabled many features to last indefinitely.

One example of sustainability was found in 1998, when the archaeological team discovered an Inca ceremonial fountain in Machu Picchu under lush vegetation and covered with thick earth. When the fountain was excavated and its channels were cleared out, water appeared as if by magic and flowed into the fountain, creating an arcing jet of water. It was inspiring to see the fountain operating after five centuries of lying dormant. It was a tribute to the talented engineers who designed the hydraulic system 450 years before.

At the completion of the fountain excavations and after the site had been cleaned up, one of the Quechua Indians in the excavation crew called the team together for a traditional Incan thanksgiving prayer. The prayer was made to the gods in Quechua, the ancient language of the Incas, translated here into English:

> *Today, having finished our excavations at Machu Picchu next to this water fountain, I call to the spirits of the gods of Machu Picchu, Putucusi, Intipunka, and Mandor. Here, Pachamama–Pacha earth, beautiful mother, do not let the fountains go dry; every year, water must flow forth so that we can drink.*


WRIGHT WATER ENGINEERS

**Hydraulic drop structures at Moray carried water from the upper circular terraces to the very bottom of the depressions. The author is shown checking terrace levels.**

***Kenneth R. Wright*** *is founder and chief engineer of Wright Water Engineers Inc. (Denver) and president of Wright Paleohydrological Institute (Boulder, Colo.).*