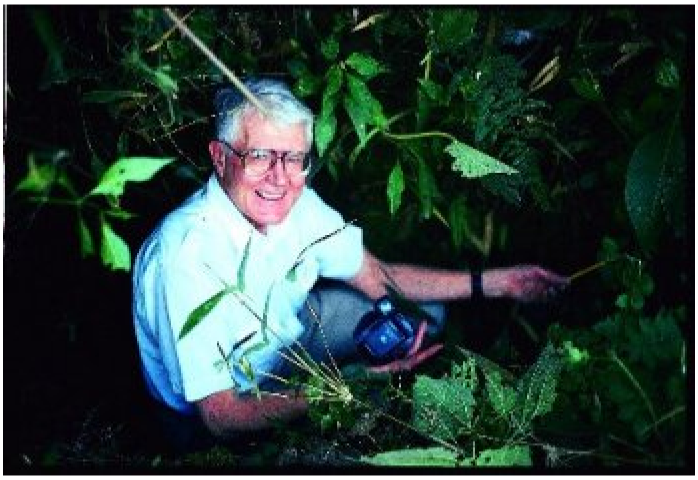
Machu Picchu's unique geography presented Inca engineers with a number of challenges related to water supply, drainage, and foundations.

REDISCOVERING

THE LOST CITY

Ninety years have passed since the discovery of Machu Picchu, the celebrated "lost city" of the Inca hidden in the mountains of Peru. But only recently an American water engineer uncovered some of its most fascinating secrets.

Jeff L. Brown



Kenneth R. Wright

With bright eyes, Ruth Wright recalls her second visit to Machu Picchu. She had traveled there with her husband, Kenneth R. Wright, to search for the spring that supplied water to the Inca people who lived there some 450 years ago. A local Quechua Indian led them through the dense forest to the spot where the water emerged from the ground. The Wrights knew they had found what they were looking for when the man showed them a carved stone foundation, tapping it with the handle of his machete. "Inca," he told them. "Inca."

The city of Machu Picchu, once the royal estate of a powerful Inca emperor, lay hidden in the mountains of Peru until 1911, when Hiram Bingham, a professor of history at Yale, discovered its ruins. Since then, it has become perhaps the most important archaeological site in the Americas. Most people know Machu Picchu not for its history, but for its breathtaking beauty. For years, few even within the scientific community recognized that it also represents a remarkable achievement of civil engineering.

Then came Ken Wright.

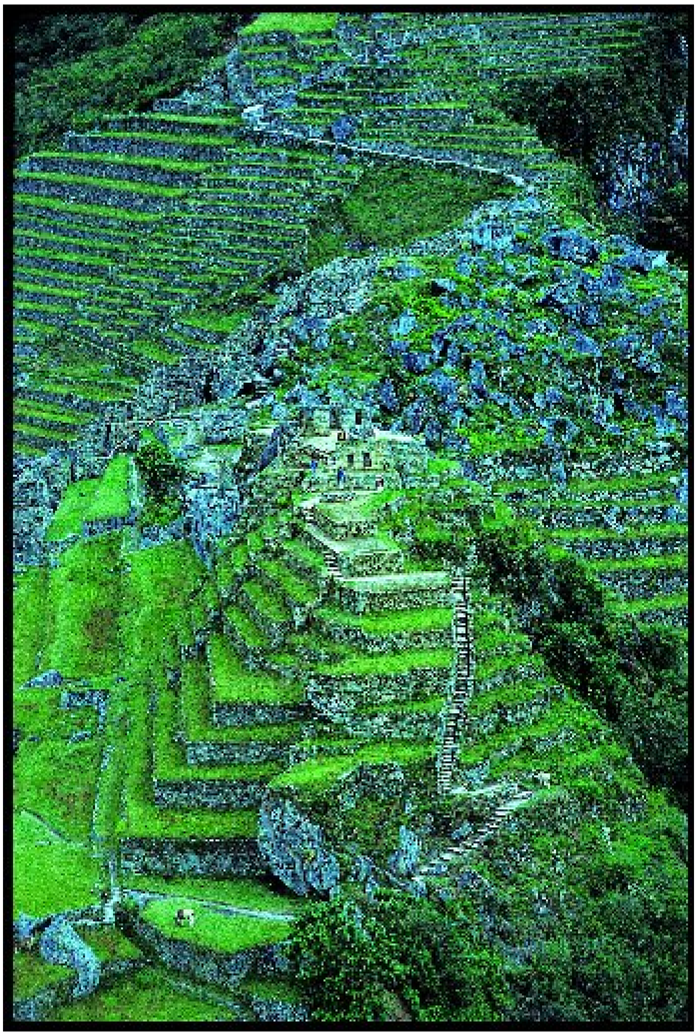
Were it not for his wife's curiosity, Wright-the president of Wright Water Engineers, of Denver-might never have visited Machu Picchu. Ruth visited Machu Picchu in 1974 and of course showed Ken the photographs from her trip-and told him about the fountains and other structures the Inca had built to handle water. But Machu Picchu sits on the top of a mountain ridge, and Ruth asked, Where did the Inca get their water?

Ken Wright decided to find out. After all, who better to study the Inca water supply than a water engineer?

But one problem stood in his way: Not just anyone can go to Peru and start digging things up-especially an American engineer with no archaeological experience. Wright spent the next 20 years seeking permission from the Peruvian government to study water engineering at Machu Picchu. Finally, he enlisted the help of Timothy Wirth, a

U.S. senator from Colorado who later became the undersecretary of state for global affairs under President Clinton. At last the Peruvian government took notice, and in April 1994 the cultural authorities in Peru gave Wright a permit to work there. Soon afterward, Wright began his research at Machu Picchu. For the next six years, he would go there one to three times a year-while still working full-time for his own company.

Of course, the real feat of engineering at Machu Picchu is the work not of Wright but of the Inca themselves. The names of the Inca engineers will never be known because the Inca had no written language. Yet by the time they built Machu Picchu, Wright discovered, they had accumulated a practical knowledge of hydrology, hydraulics, drainage, and foundation engineering.



Machu Picchu's agricultural terraces play a key role in stabilizing slopes and controlling erosion. A quarry, upper right, provided granite for construction.

In 1450 the Inca came to this site-a 2,440 m high mountain ridge in the Andes-with one goal in mind: to build an estate for their emperor, Pachacuti. "They had a perfect site," notes Wright, but its suitability would have been apparent only to a trained engineer. The slopes were steep; how would buildings be prevented from sliding downhill in a heavy rain? How would drinking water be made accessible? And from what source would the water come?

Wright's research revealed that the Inca must have planned the city carefully before building it. First, the Inca engineers had to determine the exact location of the spring and whether it would meet the needs of the anticipated population. The Wright team found that the spring, on a steep mountain slope to the north of Machu Picchu, is fed by a 16.3 ha tributary drainage basin. After conducting an inflow-outflow evaluation, the team also concluded that the spring draws on drainage from a much larger hydrogeologic catchment basin.

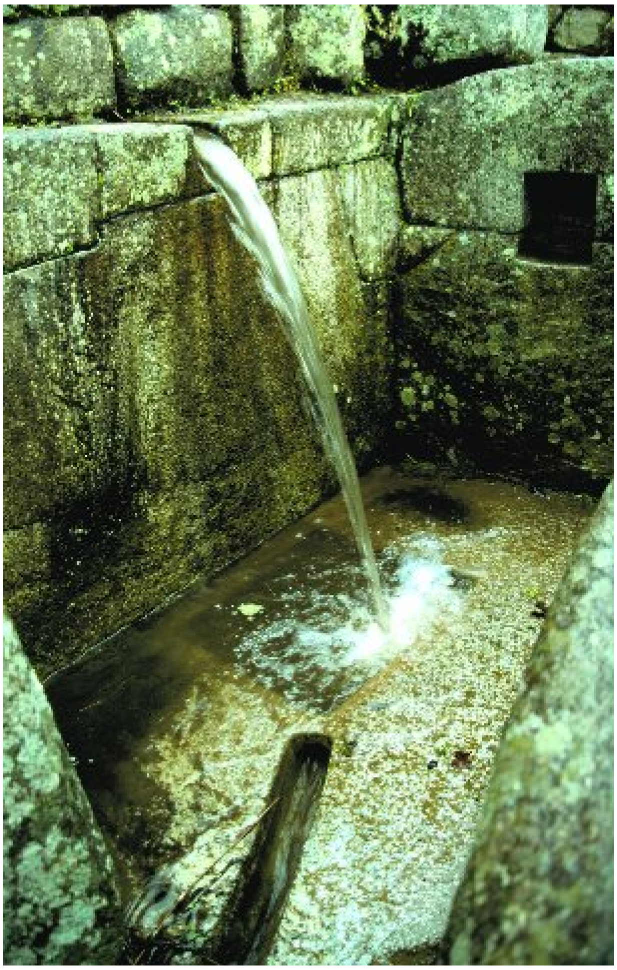
The Inca enhanced the yield of the spring by building a spring collection system set into the hillside. The system consists of a stone wall about 14.6 m long and up to 1.4 m high. Water from the spring seeps through the wall into a rectangular stone trench about 0.8 m wide. Water from a secondary spring enters the canal about 80 m west of the primary spring. The Inca also built a 1.5 to 2 m wide terrace to allow easy access for operating and maintaining the spring works. The condition of the spring works surprised Wright. "The spring works was still intact and still working," he says. "It was still yielding a water supply after all these centuries of abandonment."

Before the city could be built, however, the Inca engineers had to plan how to convey the water from the spring-at an elevation of 2,458 m-to the proposed site on the ridge below. They decided to build a canal 749 m long with a slope of about 3 percent. Within the city walls, the water would be made accessible through a series of 16 fountains, the first of which would be reserved for the emperor. Thus the canal design, says Wright, determined the location of the emperor's residence and the layout of the entire city of Machu Picchu.

The Inca built the water supply canal on a relatively steady grade, depending on gravity flow to carry the water from the spring to the city center. They used cut stones to construct a channel that typically ranged from 10 to 16 cm deep and 10 to 12 cm wide at the bottom. Wright's team concluded that the nominal design capacity of the channel was about 300 L/min, or more than twice the typical 25 to 150 L/min yield of the primary and secondary springs.

The canal descends the mountain slope, enters the city walls, passes through the agricultural sector, then crosses an inner wall into the urban sector, where it feeds a series of 16 fountains known as the stairway of fountains. The fountains are publicly accessible and partially enclosed by walls that are typically about 1.2 m high, except for the lowest fountain, which is a private fountain for the Temple of the Condor and has higher walls. At the head of each fountain, a cut stone conduit carries the water to a rectangular spout, which is shaped to create a jet of water suitable for filling an aryballo-a typical Inca clay water jug. The water collects in a cut stone basin in the floor of the fountain, then enters a circular drain that delivers it to the approach channel for the next fountain.

Wright and his team studied the fountains in detail, conducting hydraulic flow tests and measuring the channels and outlets. They concluded that the Inca designed the fountains to operate optimally with a flow of about 25 L/min, but the fountains would operate with flows as low as 10 L/min and could handle a maximum flow of 100 L/min. The team found water control points at two places along the canal where excess water would have spilled onto the agricultural terraces or into Machu Picchu's main drain before reaching the fountains.



The water supply canal ends in a series of 16 semiprivate fountains, the first of which was for the use of the Inca emperor Pachacuti.

Wright's study of Machu Picchu's hydrology and hydraulic engineering led him to conclude that the Inca understood the importance of pure drinking water. The surface drainage system generally directed agricultural and urban storm water runoff away from the water supply canal. Wright also notes that the Inca apparently did not use the fountains for bathing. The emperor, for example, had a bathing room with a separate drain, so that bathing water did not reenter the water supply.

In 1998 Wright's team discovered another, previously unknown series of fountains on the eastern side of the ridge, downhill from Machu Picchu. These fountains received their water not from the canal but from intercepted groundwater drainage. While elaborate spring works were not necessary here, Wright says, the Inca would have had to identify the dry-weather groundwater flow locations to concentrate the flow for use in the fountains. Adjacent to some of the fountains, an important trail, which Wright's team also discovered, connected Machu Picchu to the Urubamba River in the valley below. After clearing away the dense forest undergrowth, the team restored the water flow to this second series of fountains for probably the first time in 450 years.

How successful were the Inca in planning their water supply? Observers have advanced several theories to explain why the Inca abandoned Machu Picchu; some suggested that a water shortage forced the Inca to leave. Wright says his research puts that theory to rest.

A hydrological analysis showed that the yield of the primary spring was related to rainfall. To determine rainfall levels during the time the Inca occupied Machu Picchu-from 1450 to about 1540-Wright analyzed ice core data from a glacier that lies 250 km to the southeast. The analysis suggested that Machu Picchu received nearly 2,000 mm of rainfall annually and that in the final decade of occupancy rainfall actually increased.

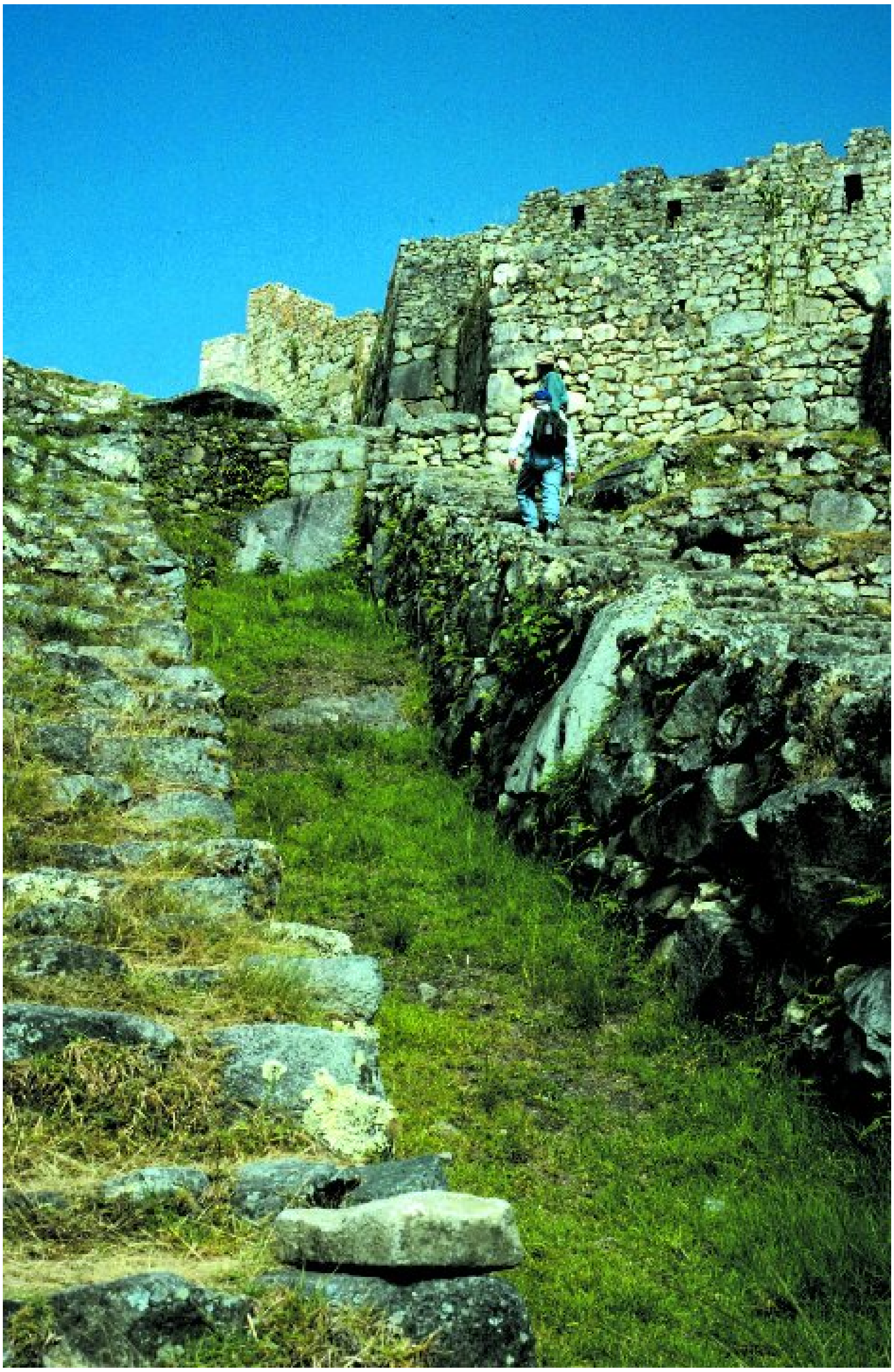
Wright determined that a flow of 10 L/min to the fountains during the dry months would have been enough to meet the needs of the population-estimated to have varied from 300 to 1,000 when the emperor was in residence. In the winter of a dry year, Wright says, the Inca may have experienced a temporary water shortage. But his discovery of the trail leading down to the Urubamba River seemed to confirm that the Inca would have used the river as a secondary water source. Therefore, Wright concluded, a water shortage does not explain the abandonment of Machu Picchu.

Wright originally planned to spend three years studying Machu Picchu's hydrology and water supply. In only one and a half years, he and his team had completed that project. But the more he learned, the more questions arose. Archaeologists had studied Machu Picchu for 90 years, but Wright began to realize that one important area had been overlooked: civil engineering.

"No one has looked at the engineering. Nobody," Wright says. Yet all around him, he saw canals, foundations, drainage systems-evidence that the Inca planned their cities carefully and had learned from experience how to build for the long term. He knew then that he had found a new area of exploration.

A clear gap existed in the knowledge about Machu Picchu. Wright was able to step in and fill the gap-first of all, because of persistence: he had sought an excavation permit for 20 years before his application was finally accepted. "Once we got the permit, everything just opened up," says Wright. But his success was also due to his ability to forge good working relationships with officials and archaeologists in Peru. For the six years he has been working in Peru, Wright has collaborated closely with Alfredo Valencia Zegarra, a Peruvian archaeologist who has studied Machu Picchu for much of his professional life. They work well together, says Valencia Zegarra, who speaks highly of Wright's contribution.

Wright frequently expresses his appreciation for Valencia Zegarra's work, crediting him with providing much-needed cultural and historical context. "We are able to speak with certainty about these things because of him," he says. The two recently collaborated on a book, Machu Picchu: A Civil Engineering Marvel, which summarizes Wright's research. ASCE Press published the book in October.



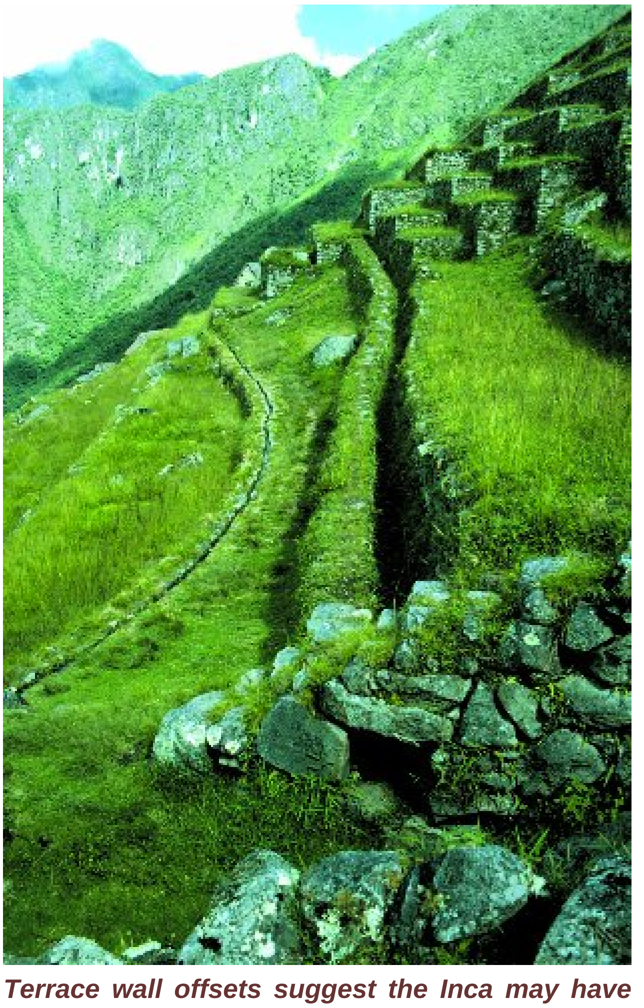
The primary component of Machu Picchu's drainage system is the main drain, which divides the agricultural and urban sectors of the city.

"One of the reasons I have been successful at Machu Picchu is that I haven't ventured into becoming an amateur archaeologist or anthropologist," says Wright. "I tell people, 'Look, I'm here as an engineer. I'm leaving the archaeology up to the archaeologists.' I don't step into their field." In another culture, he says, stepping on someone else's professional turf would be a serious mistake: "You'd be destroyed."

For a water engineer, the next logical subject to investigate was drainage. Machu Picchu contains numerous signs of drainage engineering, yet the subject had gone almost entirely unnoticed in the technical literature, says Wright. For example, previous architectural analyses had not even mentioned drainage outlets, he says, even though the Inca integrated about 130 of them into walls and other structures throughout the city.

At Machu Picchu, drainage was a serious problem. The site rested on top of a ridge with a roughly 50 percent slope and received almost 2,000 mm of rainfall. For their city to endure, the Inca had to find a way to keep it from sliding down the mountain.

Perhaps the most visually striking features of the drainage system are the agricultural terraces. Machu Picchu includes 4.9 ha of agricultural terraces, which are held in place by stone retaining walls. In addition to maximizing the land available for farming, the terraces also protected the agricultural sector from erosion. Wright conducted soil analyses that showed that the Inca constructed the terraces with subsurface drainage in mind. They layered each terrace for efficient drainage, with a layer of stones at the bottom, followed by gravel, sandy material, and topsoil.



Terrace wall offsets suggest the Inca may have experienced a landslide during construction. Later they built a channel to carry surface runoff to the main drain. Just below the channel, the water supply canal crosses the terraces as it enters the city.

The terrace structures also promote good surface drainage, Wright found. The slope of the terraces generally directs water toward a system of drainage channels that are integrated with stairways and other structures. These channels direct the drainage water to a large, east-west main drain that runs through the center of Machu Picchu, separating the agricultural and urban sectors. Gravity flow carries runoff into the main drain from both sectors, taking it safely away from the city.

In one instance, the Inca apparently experienced a landslide while a part of the terrace area was under construction. Wright notes that in this area, close to the main drain, the terraces are offset by 1 to 2 m. Wright speculates that after the landslide, the Inca stabilized the terraces and continued to build the walls but did not attempt to correct the offset. The Inca engineers realized, however, the importance of controlling surface runoff in this area. Just uphill from the place where the water supply canal crosses the terraces, they built a north-south interceptor drain. This 42 m long channel carries runoff from the land above into the main drain.

In the urban sector, the Inca took equal care to address drainage. Wright's excavations found that the Inca constructed their plazas in the same way as their terraces, with a deep subsurface layer of rock chips. The plazas received runoff from other areas of Machu Picchu, and the subsurface layer of rocks helped the water to penetrate the ground quickly.

To understand the problem of urban surface drainage at Machu Picchu, it is important to remember that the city appeared much different in the 15th century than it does today. The buildings in the urban sector would have been covered with thick thatched roofs. Because of the density of these buildings with impermeable roofs, Wright estimated that about 60 percent of the water yield from the urban area would have occurred as surface flow.

To deal with the runoff problem, the Inca incorporated about 130 drainage holes into the walls and other structures at Machu Picchu. They also integrated numerous drainage channels into stairways, walkways, and building interiors to carry runoff to the main drain. One especially carefully constructed channel drains water away from the entrance to the emperor's residence. To direct water away from building foundations, the Inca carved channels that would collect the water that dripped from the roofs.

Based on their measurements of the urban drainage outlets, Wright's team calculated rough Inca drainage criteria. They determined that the Inca placed one outlet for a tributary area of about 200 m2, and the design flow per outlet was about 500 L/min. The typical outlet size was 10 by 13 cm. The Inca departed from this scheme, however, when other means were available to remove runoff. At the Temple of the Condor, for instance, they built only one drainage outlet for an area of 0.045 ha, apparently because they understood that a system of subterranean caves beneath the temple was sufficient to handle the runoff.

Machu Picchu's well-designed drainage infrastructure is one of its most remarkable secrets. It is also one of the keys to its longevity, says Wright: "They built for permanency. They didn't do anything halfway." Perhaps the greatest testimony to their success is that the city still exists in such good condition.

Wright hopes his staff at Wright Water Engineers are learning from that success. Much of the manpower for his research at Machu Picchu comes from his own employees, who volunteer their time and expertise. To Wright, it is a valuable opportunity for employee development. "They learn a lot from the archaeologists," he says. "Discipline, focus, documentation." Perhaps they also learn from the Inca-the value of engineering for long-term sustainability and of exercising a high standard of care.

Wright's company is the sole source of funding for the research. He sees the pro bono research expeditions as a natural outgrowth of the company mission. "The reason it works is that it's the same kind of work we do for clients," he says. Every week, the staff used to have public relations planning meetings. "We don't do that anymore," Wright says. The company's paleohydrological work at Machu Picchu, he says, generates so much interest from clients that it renders additional public relations work unnecessary.

Like all good research, Wright's analysis of Machu Picchu continued to raise more questions than it answered. He found himself returning again and again, to study other aspects of Inca engineering, such as agricultural planning and construction methods.

Ruth Wright, who has accompanied her husband on too many trips to count, tells of some of the obstacles to studying a site so close to the hearts of the Peruvian people. On one return trip to the United States, the Wrights had to bring home some unusual luggage: 70 small bags of soil for analysis. Upon seeing the material in the X-ray machine, one Lima airport official was suspicious.

"What is that?"
"It's soil."
"From where?"
"Machu Picchu."

Imagine a foreign visitor in a US airport trying to take home 70 pieces of copper chipped from the Statue of Liberty, and you may begin to have an idea of the official's reaction. Fortunately, the Wrights had with them their letter of permission from the Instituto Nacional de Cultura, in Cuzco, Peru.

The soil samples were part of an agricultural study that attempted to answer several questions that have often been asked about Machu Picchu: Were the crops irrigated or was rainfall sufficient to support the agriculture? Did the terraces produce enough food for the population?

Wright's analysis of the annual rainfall and crop requirements determined that the rainfall was sufficient to supply the crops. This finding corroborated his study of the water supply and drainage infrastructure, which showed no evidence that the Inca irrigated their crops. The water supply canal crosses the agricultural sector but includes no turnouts to irrigate the terraces. In addition, Wright found no evidence that surface runoff was used for irrigation; it was simply directed into the drainage system.

The study did show, however, that the crops grown on the agricultural terraces-probably mostly corn and potatoes-would not have been enough to feed the resident population. Therefore, he concluded, the Inca must have imported food to Machu Picchu.

Not limited to water and agriculture, Inca engineering also extended to the buildings themselves. Even a casual observer may notice numerous stones the Inca carved to serve special functions, such as large lintel beams and stone rings over doorways. The Inca had no iron or steel, so they shaped each stone with only bronze tools and hammer stones. Wright has distinguished at least 18 types of stone wall construction at Machu Picchu. Yet he estimates that about 60 percent of the Inca construction effort was actually underground.

Machu Picchu lies on a ridge between two peaks in the Andes Mountains, with access to the Urubamba River in the valley below.

The Inca had "at least a rudimentary knowledge of slope stability technology," says Wright. In addition to planning a complex drainage infrastructure, they took great care in site preparation and foundation building. Wright's excavations showed that the Inca typically prepared to build a wall foundation by placing small rocks at the bottom, then placing larger and larger rocks as the foundation reached the ground surface. But their building methods also reflect a remarkable variety depending on site conditions and on the intended function of the structure. In some places-perhaps most dramatically at the Temple of the Sun and the Temple of the Condor-they incorporated large in situ rock formations into their building foundations. In this way they achieved a rare harmony between the buildings and the natural environment. "They built with aesthetics in mind," observes Wright.

When the Inca left Machu Picchu, they abandoned some construction work that was in progress. At one temple site, a large stone still sits at an angle, apparently waiting to be finished and moved into position. Wright was especially intrigued by an unfinished canal-a 40 m stretch over which are scattered partially carved stones in various stages of completion. The workers, he speculates, had planned a branch canal that would perhaps have extended the main water supply canal to a new series of fountains.

Wright is already planning his next trip-probably later this year-when he will study more closely the unfinished construction at Machu Picchu, as well as geotechnical aspects of the landslide that occurred on the agricultural terraces. In the meantime, he has expanded his paleohydrological research to other sites. Last fall he began a hydraulic study at a second Inca site in Peru called Tipon, which contains what he describes as a water garden-an intricate system of channels and fountains. He and his staff have also completed two projects, and are now working on a third, for the National Park Service at Mesa Verde National Park, all dealing with Native American structures that Wright has determined to be reservoirs.

As his ever-expanding interests draw him to new sites, this paleohydrological pioneer is forced to admit that it may be time to move on from Machu Picchu. Still, mysteries remain-especially with regard to several areas adjacent to the site that have never been excavated-and Wright will return. "We're finished, really, with our work at Machu Picchu, with everything that we intended to do. It's just hard to let go, because it's a magical place."

Copies of *Machu Picchu: A Civil Engineering Marvel* may be ordered by calling (800) 548-ASCE or by visiting (www.pubs.asce.org). The list price is $49; the price for ASCE members is $36.75. Please inquire about international prices.

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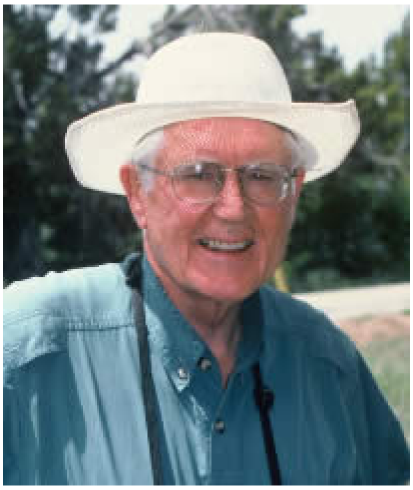

Kenneth R. Wright, president and chief engineer of Wright Water Engineers in Denver, CO USA, has studied and investigated the paleohydrology of Machu Picchu (Peru) and two ancient sites at Mesa Verde National Park (CO). Wright is a civil engineer and business school graduate of the University of Wisconsin. When the mapmakers at *National Geographic* created an image of how Machu Picchu must have looked during its peak, they turned to Kenneth and his wife Ruth for assistance. The pair gladly accommodated. The following paragraphs about Kenneth and Ruth appeared on *National Geographic's* (2002) website.

". . . Kenneth Wright has written *Machu Picchu: A Civil Engineering Marvel* (ASCE Press, 2000) and many other published reports on the infrastructure of the prehistoric city. Ruth, a lawyer with a special interest in city planning, recently wrote The *Machu Picchu Guidebook* (Johnson Books, 2001), which contains a highly detailed site map of the ruins.

The couple's interest in Machu Picchu began in 1974, when Ruth first visited the Inca landmark with their two daughters. She was puzzled by how the Inca were able to obtain water for daily needs on such a high mountain ridge.

She posed the question to Kenneth after returning home, and 'we vowed to go back and explore,' Ruth said in a telephone interview. They tried for 20 years to get a government permit to study the prehistoric water supply of Machu Picchu, but were unsuccessful. Finally, in 1994, they obtained permission.

Since they they've returned to the site a dozen times to do in-depth research on paleohydrology, the drainage system, agricultural production, building foundations, and other aspects of infrastructure. . . . The Wrights work closely with local archeologists and government personnel. 'They do the archeology and we do the technical work,' Kenneth said."

According to *Civil Engineering* (2001) Magazine, "Much of the manpower for the research at Machu Picchu has come from his (Kenneth's) own employees, who volunteer their time and expertise. To Wright, it is a valuable opportunity for employee development. 'They learn a lot from the archeologists,' he says, ‘Discipline, focus, documentation.' Perhaps they also learn from the Inca–the value of engineering for long-term sustainability and of exercising a high standard of care.

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Source:

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- Brown, Jeff, 2001. "Discovering the Lost City," *Civil Engineering*, April, p. 39.