Two Thousand Years of Engineering Genius on the Angkor Plain

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Com­mand­ing a strategic location on the upper­most tip of Cambodia’s great Tonle Sap lake, the ruins of the Khmer Empire expand north, east and west from the shores of the lake up to the sacred Kulen mountain plateau. This entire 5,000-square-kilometer site, once the location of one of the world’s largest metropolitan areas, is a relic cultural landscape—an environment which was intensively engineered by human activity over time to suit the Empire’s changing temporal needs. During this process the land was continually reshaped into an ever more perfect image of the celestial city of which Angkor was the earthly reflection, ruled over by human incarnations of the very gods themselves.

The area we call Angkor today was, in fact, the site of at least seven capital cities built by a succession of Khmer rulers between the 9th and 13th centuries A.D. (Fig. 1). Before it became the capital of an empire, the region was already peppered with a mosaic of mound and moated villages inhabited by subsistence farmers and fishermen (Fig. 2; see box). As the wealth of the Khmer kingdoms grew, a succession of “kings of the kings” chose to live in and around Angkor and to build the metropolitan center of an empire. Even after the final breakup of the empire in the 15th century and the move of the capital elsewhere, the Angkor area continued to be relatively densely populated. As we shall see, it was the very prosperity of the Khmer Empire which put eventual limits to its growth. This prosperity was based on the finely tuned and sustainable exploitation of the land and its resources—most importantly its water resources.

THE CHALLENGE OF ANGKOR’S ENVIRONMENT

The climate of the heartland of the ancient Khmer Empire is controlled by the tropical monsoon system. Seasonal rainfall averages 1500 mm/year and temperatures are constantly warm. During the rainy season, violent storms release large volumes of water within relatively short periods of time. The storms occur in a predictable cyclical pattern of frequency and intensity.

Each year, during the rains, the Tonle Sap River reverses its flow and quadruples the capacity of the Tonle Sap lake, flooding the forests and bringing a bounty of fish (Fig. 3). During the Angkor period, hundreds of thousands of people from the farthest reaches of the Empire swarmed to the lake shores to harvest one of the world’s richest aquatic resources. This harvest supplied the Empire’s protein needs and assured the economic prosperity of Angkor as the central marketplace of the entire region (Fig. 4).

Large areas of the Angkor plain are also flooded by the Tonle Sap. The floods recede rapidly, however, and the subsequent dry season is characterized by drought and severe ecological stress. Intensive management of water resources is necessary if the growing season is to be extended beyond the end of the rains.

To the north and east of Angkor, the Kulen plateau rises high above the ruined city on the plain, trapping monsoon water coming from the southwest. The basic drainage pattern of the area consists of a series of radiating streams which rise in the hills and flow across alluvial fans to the Tonle Sap. The importance of preserving this watershed as a source of water for the rice paddies and to fill the city’s transportation canals and municipal water system was clearly understood by the earliest inhabitants of the area. Phnom Kulen was perceived as a sacred site from which flowed...
the very origin of Khmer civilization. Home of gods and retreat of kings, the mountain was for the ancient Khmer Mount Meru on Earth, and its revered primeval forests were left untouched over the centuries. The coronation rites for all of the kings of Angkor took place atop Phnom Kulen, vividly reinforcing the king’s paramount role as protector of sacred ancestral lands as “king of the mountain.”

The Preak River is the only permanent stream draining the Angkor plain. It has a catchment area of 670 square kilometers. Rising in the hills at an altitude of 420 meters, the river cuts deeply into the plateau to discharge through a gorge onto the plains below. The main river is joined by a number of tributaries until it is diverted into an ancient artificial canal built to join the original Siem Reap River at Phnum Khleu. The ancient bed of the Preak River continues southwest to the town of Preak, where it becomes lost in the marshes of the Tonle Sap.

During the reign of Rajendravarman I in the 10th century A.D., the Preak River was diverted eastward to join with the Siem Reap River which, for most of Angkor’s long history, was the capital’s principal water course. The diverted river, which has a total length of 80 kilometers, was canalized to supply the water needs of the Empire’s capital city, including the moats of Angkor Wat, Angkor Thom, as well as the Eastern, Western, and Northern barays (reservoirs). This half-natural, half-manmade river was the Ganges of the Khmer Empire, as important symbolically as it was economically and ecologically.

The second most important river system of the Angkor plain is the Roluos which rises from springs at the foot of the Kulen (Fig. 5) and eventually flows into the marshes of the Tonle Sap. This river was also canalized in ancient times to supply the lake Baray (the Indratataka), the moats of the city of Hariharalaya, and the various temples of the Angkor plain, such as Angkor Wat, Angkor Thom, and Preah Khan.

Fig. 3. Khmer fisherman near the mouth of the Siem Reap River where it enters the Tonle Sap lake. Notice the similarity of his boat, net and costume to those depicted in the 12th century bas-reliefs on the Bayon Temple (Fig. 6). Photo by author, 1993.

Fig. 4. Bas-relief from the Bayon Temple of ancient Khmer fishermen on the Tonle Sap lake. The “Great Lake” supplied the water for irrigated rice cultivation and the fish protein to sustain the Khmer Empire’s population of more than 1 million. Late 12th century A.D.

Photo by author.

Fig. 5. The Roluos River, along which the first capital city of Angkor, Hariharalaya, was founded in the 9th century A.D. Note how the river bed was widened and straightened in ancient times to increase capacity and facilitate transport.

Photo by author.

Fig. 6. Traditional bamboo waterwheel used, probably since the time of the Khmer Empire, along the canals and rivers of the Angkor plain to lift water into the rice paddies fields.

Photo by author, 1993.

Fig. 7. Aerial view of the field system of the Angkor plain with the small, square-shaped fields of the Angkor period still in use today.

Photo by author, 1993.
the monuments of the Preah Ko, Bakong, Trapeang Phong, and others.

Since Angkorian times, dry-season flow in the rivers has been insufficient to meet potential demand for water, particularly for irrigation. Modification and channelization of the rivers ensured the urban settlements of the Khmer Empire with a year-round supply of water and enabled the control of water for irrigation of agricultural land. Retention and storage of surplus water during the rainy and flood seasons for use during the rest of the year was, along with the building of religious monuments, the major preoccupation of Khmer engineers throughout the long history of the empire.

All the rivers and streams draining the Angkor plain show entrenched meanders, indicating a slow lowering of the base of the drainage system. As the channels continued to cut down, the water level was lowered significantly. Waterwheels or other mechanisms to lift the water from the streams up into the city's moats and canals were needed, and major maintenance of the water works would have been required to maintain water in the barays throughout the dry season (Fig. 6). The ever-increasing cost in terms of both labor and equipment needed to counteract the lowering of the base water system may have contributed to the eventual abandonment of the Angkor site as the metropolitan capital.

ANCIENT FIELD SYSTEMS: NEW EVIDENCE FROM REMOTE SENSING

The stability of the food supply of the Khmer Empire depended on the modification and management of the hydrology of the area to ensure adequate rice production. A broad belt of land suitable for the cultivation of rice was established across the Angkor plain at an early date. Old field patterns are still visible under some of the new land divisions: the old fields tend to be much smaller and run in a different angle to the present land holdings (Fig. 7).

In recent years, satellite and aerial photography have proven to be powerful tools in helping to identify and interpret many types of archaeological sites and, in particular, ancient field patterns (Fig. 8). Present-day botanical patterns remain extremely sensitive to past disturbance of the ground, especially if that disturbance depleted soil resources. In the upper reaches of the old Siem Reap-Poek river system, the early pattern is still visible in aerial photographs, although on the ground it is totally invisible and the area is both uncultivated and depopulated. One important implication of these discoveries is that the Khmer field pattern—and perhaps much else in Khmer culture—may have origins far earlier than the classic Angkor period. Khmer engineers since well before the height of the imperial period seem to have been preoccupied with the problem of extending the growing season. To do so meant dealing with a surplus of water during the flood season and a shortage during the dry season (Groslier 1979). However, in the end, they did not succeed. Observations from the separate disciplines of geology, hydrology, and botany all provide support for the same archaeological hypothesis: Angkor was abandoned because of a collapse in agricultural productivity; the system could no longer sustain a large urban population. The cause was an overcultivated ecosystem which was, in any case, deteriorating because of incremental changes in the natural hydrology of the region. To overcome these changes required a technological investment which became increasingly less cost-effective to maintain.
THE BARAY: KEY TO CONTROLLING FLOOD WATER

In order to maximize the potential of their ecological setting, the ancient Khmer developed extensive hydrological systems. These retained and managed flood water for irrigation and ensured a continuous year-round supply of water for the urban centers and religious complexes. Rivers were dredged and straightened into canals and vast water storage reservoirs called barays were created behind dams with embankments (Fig. 9). Dikes were built across the flood plain to deflect and store flood waters to irrigate crops during the dry season. The annual rise and fall of Tonle Sap was exploited to grow first, floating rice on the rising flood and then, receding rice as the waters subsided.

To fill the barays, monsoon flood waters were trapped behind a system of dikes hundreds of kilometers long. In this way, the entire flood plain between the Kulen and the Tonle Sap was turned into a landscape of gradually sloping rice terraces. With triple-cropping, these terraces could supply the food needs of the population of between 200,000 and 1 million inhabitants.

Before the system collapsed, the farmers and engineers of Angkor had a remarkable record of success lasting over a thousand years. They gradually and progressively prolonged the growing season with a simple but effective system of dikes. These trapped the early rain water as it flowed down toward the lake and then, at the end of the wet season, retained the flood water retreating toward the lake. This system of diking appears to be one of the most productive technology as the building of a rice paddle and, when further elaborated, the same as the technology that went into building the great baray water-storage reservoirs (Garrett and Kertai 1993:297). The more than any other single feature, is the diagnostic "technological marker" of the ancient Khmer Empire.

The Khmer word baray comes from a Sanskrit word meaning "to transverse" or "to cross," suggesting a local evolution from transverse dike to baray in the Angkor plain. Initially and in its simplest form, a baray consisted of a southeast angle built to trap the retreating water and to change the natural contour of the land. Later, structures were built to the north and west of earlier structures, forming a square reservoir. This enabled an additional amount of water to be trapped, and the large volume of water was then raised above the surrounding plain. This water could then be fed into the city's water and irrigation system. After the capital moved to Yasodharapura (site now today as Angkor), the old capital of Harshatraya (Rohan) was apparently still linked into the greater metropolitan area's water system through a long dike which channelled water down to the old city from the new.

Study of aerial photographs also shows that parts of the earlier system were incorporated into new town planning designs as the city of Angkor was reorganized and remodeled by successive rulers. One example is the reuse of the old most of the first city of Angkor (Yashodharapura) around the Phnom Bakheng as a spillway. This spillway channelled excess water out of the Western Baray into the Siem Reap River/Canal north of the new city of Angkor Thom, thus preventing the possibility of a disastrous flood during periods of excess water.

POST-ANGKORIAN SETTLEMENT AND LAND USE

Little is known about the land-use patterns in Siem Reap in the post-Angkor period. After the collapse of the waterworks, people apparently became more dependent on the natural cycles of the Tonle Sap for agricultural production. There is also evidence that the population decreased over the northern plains and used fire to clear land. This practice resulted in the degradation of much of the forests and precipitated a further drop in productivity.

After the abandonment of Angkor as the capital and the dispersal of a major portion of its population, extensive areas which had been occupied or farmed were re-colonized by evergreen forest species. These extended southwards to the core monumental area at Angkor even in quite recent times. The presence of tall and moderately dense forest in the immediate vicinity of Angkor Thom indicates the extent of the woodland that developed after Angkor was abandoned. This forest remained relatively untouched into the 19th century.

Time, war, and illegal logging have all taken their toll on this, one of the most productive man-made landscapes of all time. Water continues to be a problem. A gradual, almost imperceptible geologic uplift tilting has occurred along a northwest-southeast axis following the orientation of the Kulen plateau. As a result, the rivers have cut 6 meters into the ground, putting them well below the level of the 10th-11th century reservoirs, canals, and moats (Fig. 10), and driving the upper reaches of the streams underground (Thang 1994). Various attempts to correct this problem have taken place over the past 1,200 years. Larger and ever more labor- and capital-intensive corrections have been tried, but in the long run the result has been an unprofitably expensive system which only functioned satisfactorily at the center. And as the system siphoned water from outlining farmland, agricultural productivity declined.

The monuments themselves have been affected by the disruptions in the hydrology, both natural and man-made. Isolated from the water system at large, many of the moats surrounding each monument have silted in and the water table underneath these monuments is no longer stable. The result is suble seasonal shifting of the ground under the heavy stone monuments which lead to their breakage and potential collapse (Fig. 11). The situation is exacerbated by the breakdown of the drainage system, causing perennial waterlogging of foundations and periodic flooding of the buildings themselves.

WATER AND THE KHMER

It was probably the potential of the permanent rivers and seasonal floods between the Kulen plateau and the Tonle Sap that attracted settlers to the Angkor area long before it became the metropolitan capital. Early hydrological structures were extended and enlarged during the development of the sequence of city states. By the height of the Angkor period, these structures were elaborated to create the complex water management regime necessary to supply the barays, moats, and canals that lead water into the heart of the city and to the temple compounds. While the demand for water increased immensely over time, water resources remained constant. This put pressure on Khmer hydrological engineers to innovate and to continually adapt and modify the city's public water works.

Each water-based feature fulfilled several functions. Barays provide agricultural and domestic water, and fish and plant foods. Canals channelled water for public sanitation, and were transport arteries. Embankments and dikes were usually oriented east-west following the contours and acted both as levers to control floods and elevated causeways for roads. Moats surrounding temples, monuments, and inhabited areas also fulfilled several functions: they served as sacred boundaries, they were a source of domestic water and food, and they provided fill for foundations to raise the level of the terrain for drainage and protection. Access to domestic water was provided by tanks or basins dug into the water table.

The unique character of Angkor's water features indicates a highly sophisticated identification of spatial and temporal water which prompted and sustained the repeated construction of water-related structures. Religion and daily life were inseparable. Given the dependence of people living in the Angkor region on their environment, it is not surprising that a strong
attachment to the land of the ancestors continues to this
day. This is symbolized by an almost universal allene-
giance to guardian spirits of the land and place which
are called neak tha (Fig. 12). Over the years, these local
ancestral spirits have been incorporated and subsumed
into the structure of the elite gods of Hinduism and
Buddhism who also guard the ancient lands of Angkor.
Deriving ways to control the flow and supply of
water was at the heart of the genius of the ancient
Angkorans. The hydrological system of Angkor was
principles of rice paddy construction began in prehis-
toric times. Recent archaeological survey and research
have confirmed the long history and indigenous ingeni-
ity of this work. As the Empire grew so did the water
system, until engineering feats of truly awesome dimen-
sions were accomplished. The result was a unique man-
made environment which assured the productivity of
the Empire and at the same time transposed onto the
landscape the mental picture the people had of the
perfect universe of their gods.  

In spite of more than a century of research
and scholarship, our knowledge of the economy
and sociology of the ancient Khmer Empire
remains sketchy. This is because attention has been
focused primarily on the restoration of the reli-
gious monuments and the interpretation of associ-
ated inscriptions. However, the very term
"Angkor" connotes not only "temple" but also
"town." We know that every temple was the center
of a community. Therefore, future research has the
potential to yield much important information about
the sociology of the ancient Khmer Empire,
its evolution, and eventual collapse.

Most of our current understanding of
Angkorian culture comes from research on the
period between the 9th and 11th centuries A.D.
However, we know that the formation of the cul-
ture began much earlier, as evidenced by finds of
stone tools and bronze castings from the prehis-
toric period. Evidence of prehistoric and pre-
Angkorian period habitation has been found under
structures of the Angkor era, many of which were
built on top of ancient ritual or habitation mounds.
The date of the earliest habitation on the Angkor
plain is unknown, although investigations of
prehistoric settlement have been carried out in
other regions of Cambodia. For example, sites
along the middle Mekong River have yielded pre-
historic pottery and bronze. Laang Spean Cave in
Battambang has been radiocarbon dated to AD 920
B.C. - A.D. 810, and has yielded a stratigraphic
sequence of prehistoric pottery and stone tools
(Mourer 1977:29-56). Bernard-Philipp Groslier,
a long-time conservator of Angkor, reported clues
to prehistoric occupation in the central Angkor
area. These included pottery finds and a large
dwelling site of the Bronze Age that may date back
to the 1st millennium B.C. However, no systematic
excavations took place, and his preliminary find-
ings have not yet been fully published (Groslier
1985/86:34).

From 1991 to 1994, I was the Head of the
newly established UNESCO Office in Cambodia.
Angkor had just been put on UNESCO's World
Heritage List, and I was in charge of helping the
Cambodian authorities develop a zoning and envi-
ronmental management plan for the site. In order
to determine the true extent of the site, archaeo-
logical surveys were carried out by a team of
UNESCO consultants working on the project. The
team consisted of Dr. Elizabeth Moore, Dr. Heng
Thuang, Prof. Claude Jacques, Mr. Seung Kong,
Mr. Christophe Pottier, and Ms. Pamela Rumball
Rogers, as well as myself.

During the surveys nearly 1000 archaeo-
logical sites were identified, of these, approxi-
mately half were previously unrecorded. Many of
the newly discovered sites have been tentatively
identified as habitation mounds. Suddenly, a new
picture of old Angkor has emerged. Rather than existing in glorious isolation on the Angkor plain, the Khmer Empire's capital city was situated in a heavily populated area, surrounded by settlements dating back before the founding of the Empire itself (Fig. 15, page 30). Analysis of aerial photographs and satellite remote-sensing imagery revealed at least 69 elevated circular mounds scattered over the plain, some with associated earthworks and/or moats (Moore 1995). These mounds appear to be naturally occurring elevations which have been formed over time by downcutting and diversion of rivers, as well as by aeolian action and the accumulation of debris from human habitation. Today their shape is defined by vegetation encouraged by the mounds' slightly elevated position above the flood plain. Generally the mounds appear circular, but there is no standard form; each has a unique shape.

The density of the prehistoric inhabitation of the area is indicated by the fact that all mounds investigated to date have yielded stone tools, pottery, and other evidence of human occupation. The presence of stone tools in the Angkor Khmer links these mound sites to the few other "proto-historic" Cambodian sites that are known, such as Somrong Sen (Mansuy 1923) and Muo Pri (Levy 1945) which also have polished stone tools.

THE PUOK RIVER BASIN

Thirty-four of the 69 newly identified prehistoric sites are located in the area of the old Siem Reap-Puok rivers drainage basin. This area was also the site of the earliest known urban settlement in the area—a 7th century pre-Angkorian town called Anaditapura. The town or village was one of the spots to which Jayavarman II brought his nomadic capital during the Empire's early days. The remains of the site are now mostly under the Western Bassac which was built in the 11th century (Jacques 1990).

At least 8 pre-Angkorian settlement sites have been identified near Anaditapura. The remaining 26 sites are distributed continuously up the Puok valley. There is also evidence of a canal, with a concentration of ancient rice paddies nearby. In addition to diversing river water toward Angkor, the canal may have been part of an Angkorian period attempt to reanimate the rice fields of the upper Puok drainage basin.

THE SIEM REAP RIVER BASIN

In the Siem Reap river system, 14 habitation mounds were surveyed in the valley north of the main Angkor complex by Dr. Moore and the UNESCO team. An eastern tributary of the Siem Reap River flows into this valley from the principal Kulen plateau springs. All the sites are located along or near a water course north of the Angkor-period dam where the artificial canalization of the Siem Reap River begins. As the diversion of the Siem Reap River dates from the 10th century reign of Rajendravarman I (Jacques 1990:165) while the present course of the river dates from the 16th century (Garani and Kerris 1993:27), and no habitation mounds have been found south of the diversion, it seems a likely hypothesis that the sites north of the diversion are earlier in date and represent a pre-Angkorian settlement pattern (Moore 1993).

THE ROLLOUS RIVER BASIN

Sites in the valley of the Roluos River were surveyed by the initial UNESCO team. Subsequently, several additional sites have been identified near the ancient shoreline of the Tonle Sap. Like those in the Puok and Siem Reap river valleys, some of these sites have vestiges of moats.

When plotted, the distribution of sites appears relatively dense throughout the Angkor plain. However, when the sites are placed in a scatter diagram no "nearest-neighbor" statistical tests applied, the heaviest concentration of sites is evident in the three river valleys, with the intervening areas evenly but not so heavily settled.

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FIG. 15. Computer-generated map of archaeological sites on the Angkor plain. Note the widespread distribution of sites, with heaviest concentrations along present and former watercourses.

Photo courtesy UNESCO.