REDEFINING ANGKOR:
STRUCTURE AND ENVIRONMENT IN THE LARGEST LOW DENSITY URBAN COMPLEX OF THE PRE-INDUSTRIAL WORLD

Greater Angkor Project[1]

Introduction

Angkor, the capital of the Khmer state from the 9th century AD to some time in the 15th or the 16th century AD is best known for its immense and beautiful temples. The monuments have been studied with great care and interest for over a century yet the most basic information about the vast urban complex that contains them is still a matter of dispute. Around the conspicuous, massive stone monuments lay a vast, ephemeral city of timber houses, mud and sand embankments and long channels of water extending across more than 1000 sq km between the lake and the hills to the north (figure 1). Today, this ephemeral city is still visible to aerial photography and radar imaging. The paradox of Cambodia's history in the last quarter of the 20th century is that the tragedy of its people shielded one of the greatest and most fragile, pre-industrial urban archaeological sites from intensive development for twenty-five years. In the past decade this preservation has allowed the application of new research technologies to the plan of the city to enhance our understanding of the layout of Angkor and the way in which it functioned.

AIRSAR survey results

In September 2000 NASA/JPL (JPL 2002) carried out a comprehensive AIRSAR aerial radar survey of about 7000 sq km of territory extending from the Kulen and Khnor hills in the north to just south of the southern shore of the Tonle Sap and from the longitude of Beng Mealea westwards towards Battambang in order to study the extent and demise of Angkor (Dayton 2001; Fletcher 2001; Fletcher and Pottier 2002). The 3000 sq km of this survey that specifically covers Angkor has been analysed over the past two years (Evans 2002; Fletcher, Evans and Tapley 2002). A new map of Angkor has been prepared at the University of Sydney by Damian Evans, combining the radar data with the survey work of Christophe Pottier in a GIS database (figure 1).

The mapping focused on the locations of prasat (small shrines), trapeang (water tanks), channels

[1] The Greater Angkor Project is a collaborative research project of Australian, Cambodian and French researchers. Contributors to the present report, written by Roland Fletcher, include: Roland Fletcher and Damian Evans (Department of Archaeology – University of Sydney), Mike Barbetti (N. W. G. Macintosh Center for Quaternary Dating – University of Sydney), Dan Penny (Department of Archaeology – University of Sydney), Heng Than, Im Sokrithy, Khieu Chan and Tous Somaneath (Department of Culture and Research – APSARA Authority); and Christophe Pottier (École Française d'Extrême-Orient, Siem Reap).

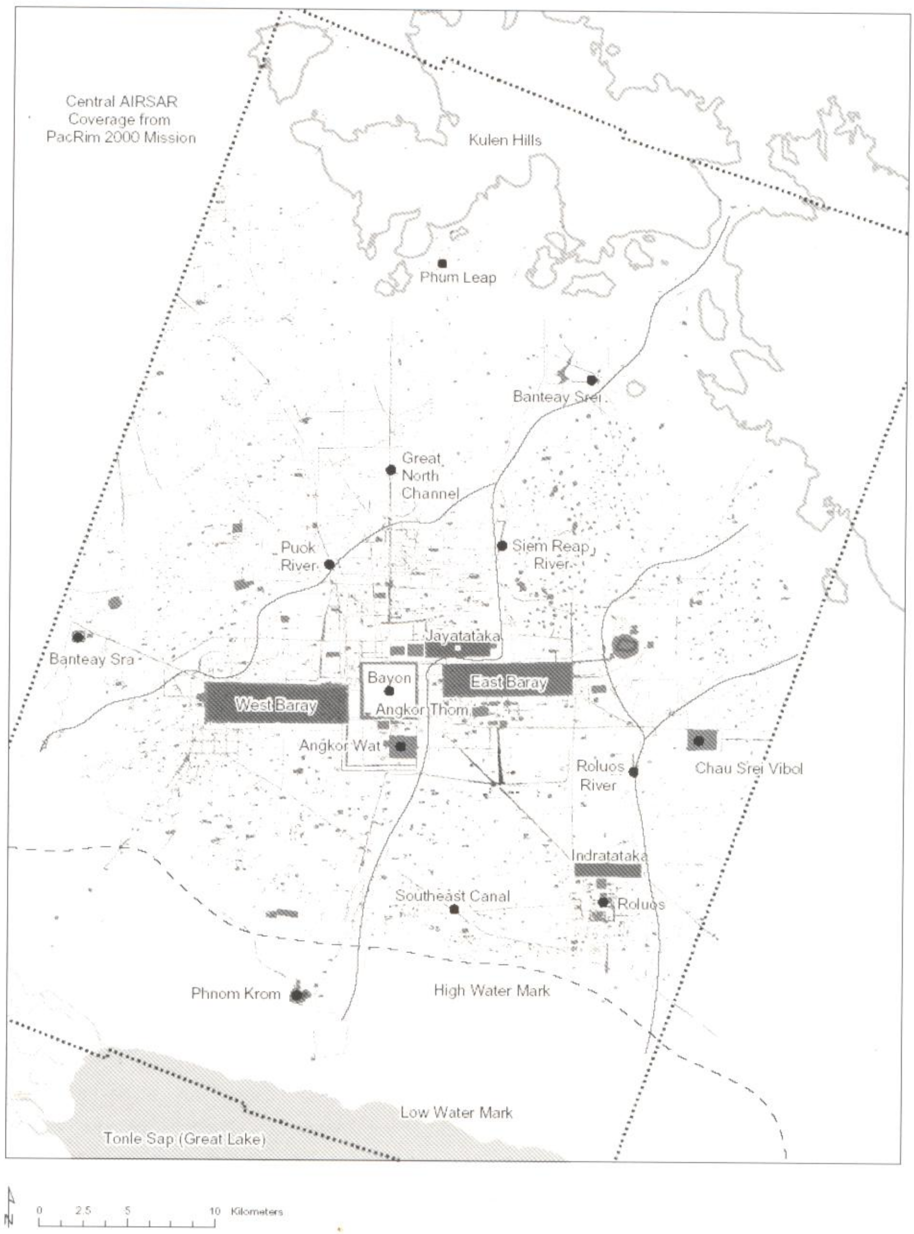

Figure 1: Map of Greater Angkor based on surveys by Christophe Pottier (EFEO) and on the analysis of the AIRSAR data acquired by JPL/NASA. Map prepared by Damian Evans.

and embankments in the northern half of Angkor extending from the line of Preah Khan temple northwards to the Kulen hills. The aim was to complement the survey of southern Angkor carried out by Christophe Pottier between 1992 and 1998 (1999) which had identified an extensive, dispersed low density scatter of occupation features, including house-mounds from Chau Srei Vibol in the east to Banteay Sra in the west and from Preah Khan southwards towards Phnom Krom. The same kinds of features were found in the northern half of Angkor. However, house-mounds were not mapped in the north because their small size makes it difficult to systematically recognize them at the scale of the image resolution and because some areas are obscured by dense vegetation.

The analysis has shown that Angkor was a vast, dispersed, low density urban complex consisting of a network of linear features such as embankments and channels superimposed on the extensive scatter of prasat, trapeang and house-mounds which lie in an apparently random distribution across the landscape. Angkor therefore consists of a communications network of vast linear embankments centered on Angkor Thom and arranged around the zone of the major barays. The network covers about 1000 sq km and extends northward as far as Banteay Srei in the NE and to the north of the large trapeang of Nokor Pheas in the NW. The configuration of the embankments appears to be different in the north and the south while the individual structures, by contrast, are consistently dispersed throughout the region.

The Structure of the Urban Complex

Location of occupation: The initial assumption about the places where people lived in Angkor was that housing lay within the walled enclosures of Angkor Thom and within the temple enclosures (Jacques 1978). Substantial survey work and excavations by Jacques Gaucher's team has revealed the complexity of the residential pattern within Angkor Thom (1997, 2002) and Chan Chamroeun's innovative field research within the Preah Khan enclosure has indeed shown that houses, trapeang and small channels were present. The vast new addition to the repertoire of housing sites has been provided by Christophe Pottier's work which has shown the extent of the distribution of house-mound clusters near trapeang and prasat across the entire region. In addition excavations at Prei Khmeng by the EFEO team and at other sites have identified deep, stratified deposits of occupation debris in the house-mounds (Pottier 2002; Zoppi et al 2002).

What now needs to be added to those residential locations is the use of the embankments. The large linear features of the channels and road embankments are as much part of the residential structure of Angkor as the house-mounds and trapeang. Just as ceramics and occupation debris are found on the latter so likewise they have been found in field surveys along the banks of channels as far south as Phnom Krom, along the Angkor Wat canal, on the banks of the canal which runs westward to the NE corner of the West baray, along the east-west embankment (Tumnup Barang site) that lies just south of Preah Khan and along the banks of the Great North canal for several kilometres north of Angkor Thom. Occupation deposits and ceramics have also been found in excavations in the latter three features, in the sections through the Angkor Wat canal and in the old canal on the line of the Siem Reap river, south of Siem Reap town. This pattern of occupation is consistent with the present day Khmer residential pattern of linear settlements along roads, canals and river channels. Deep stratified occupation deposits dating from the 12th to 14th centuries have been found both in the channel of the Tumnup Barang site and in its embankment (figure 2).

Relationship between embankments and other residential locations: The most surprising result of the spatial analysis is that the distribution of the discrete features such as house-mounds, prasat and trapeang does not correlate with, or cluster around, the lines of the great linear embankments and channels. Angkor operated as if there were two different systems of residence and production, with the distribution of the

Figure 2: Cross section and view of Tumnup Barang site. Site management, Heng Than, Tous Somaneath, Wayne Johnson, Shaun Mackey and Sam Bolton. Section courtesy of Wayne Johnson and photograph courtesy of Catherine Wu.

discrete features apparently based on crop production independent of the linear features (figure 3). The discrete features display no obvious pattern other than an apparently random distribution across the landscape and do not show any tendency towards concentration around the centre of Angkor. The density of structures does not markedly decline away from Angkor Thom, though there is a decline at the periphery towards the Kulen hills. The house-mounds and water tanks are both evenly scattered and form denser patches but these patches also do not show any particular correlation with distance from the centre. In the south there are patches of house-mounds and trapeang near Pre Rup, Angkor Wat and Phnom Bakheng, near the Indratataka and around the Bakong and also along the channel that runs SW from the SW corner of the West baray (Pottier 1999 Maps). A similar patchiness occurs in the north as well for the distribution of trapeang.

The non-correspondence between the linear features and the discrete structures suggests that we are looking at two distinct, though inter-related, systems of land use and management. The dispersed residence pattern allows that a significant proportion of the population of Angkor lived off rice production in fields around their houses and at more remote plots of land, in a dispersed arrangement of landholdings. That families and institutions in the medieval period had landholdings dispersed into different ecological zones across the region is apparent in the inscriptions (Coedès 1951, 1952; Ricklefs 1967), just as they do today (see Delvert 1961). The non-correspondence is then interesting and surprising since, as I will argue below, the linear features were also apparently part of a huge water management system that could supply water for irrigation and could therefore have serviced the production of rice by the local residents. How the water management system worked is therefore of some significance since that may resolve why the house mounds did not cluster along the water supply channels.

The linear features appear to be a network superimposed on a landscape of traditional landownership (Evans 2002). These features would have had several crucial functions which deserve further investigation. First, whatever the other functions of the embankments – whether they were actual roads or the embankments of barays or the banks of canals, would have served as routeways across the landscape of bunded rice

Figure 3: Greater Angkor. Linear features (left) and prasat and trapeang features (right). Prepared by Damian Evans.

fields. As such they gave clear access over very long distances of up to 25 km (e.g. the Great North canal) and even 40 km (e.g. the SE canal from the West baray to Damdek) across the various sectors of Angkor. Such distances exceed the pre-industrial daily travel range which is about 6-7 km out and back between dawn and dusk ((Koder 1995: 52-53). These routes tied together the urban complex by facilitating relatively rapid interconnections compared to those available over equivalent distances across the paddy fields. Even today many of these embankments still serve as long distance links across the region.

Secondly, the embankments may have served a crucial residential role much like that of the banks of the Siem Reap river near Wat Bo Lanka where landless and economically marginal people have set up houses and a community over the past decade. From the 9th to 12th centuries AD the urban complex of Angkor was expanding over the top of an existing population of rice farmers whose land ownership would have been decisively specified by tradition and by attachment to their ancestors. Such land would not have been readily alienable by the state nor are the occupants likely to have welcomed newcomers. But the essential demographic characteristic of a burgeoning capital is that it draws in people from the rest of the state. Many would have been landless and the embankments would have provided a place for their homes. As Angkor expanded the growth of housing along the embankments would therefore have transformed the visual landscape (Polkinghorne and Fletcher 2002). We should also find that the occupancy of the embankments initially differed from that of the house-mounds. Through time, however, that difference ought to have diminished as marriage created connections between the traditional land holders who held rice land and the residents of the embankment who held favorable access to trading locations.

Thirdly, all embankments that run across the lie of the land (i.e. approximately E-W or NW to SE) would have acted as barriers to the movement of water in the monsoon season. The great E-W embankments would have created huge ponded sheets of water on their northern side. Where the N-S and E-W banks meet water would be trapped on the eastern side. Furthermore, any embankment running NW to SE, such as the "road" from the old core of Yasodharapura to the NW corner of the Indratataka (figure 1), would have shunted water across the lie of the landscape by blocking the flow down slope to the SW. It is notable that the SE canal, among others, only has a substantial bank on its southern side. The distinction between road embankment and canal bank and water distributor channel may have had little meaning in Angkor as most embankments would have functioned to re-direct water across the landscape.

The Function of Water Management in Angkor

The debate: The map derived from the AIRSAR survey not only redefines the extent of Angkor, it also impacts on the frustrating debate about the function of the barays and the great moats of the temples. The topic became a matter of dispute following the insightful paper by Van Liere in the 1970s in which he argued that the massive water management structures of Angkor were either not necessary for irrigation or did not have the characteristics required for them to act as an irrigation system (see Fukui 1999 and Stott 1992). The issue has polarized into an English-speaking non-utilitarian "ritual" posture contra a supposedly "French" utilitarian, hydraulic civilization viewpoint. Acker (1998) neatly summarized the operational part of the "English" perspective and elaborated on the claim that the network of tanks and channels would not have produced enough rice to be worthwhile as an irrigation system because too small a proportion of the total population of Angkor could have been fed. The irony of the debate, as pointed out by Pottier (2000) and also by Lustig in a IVth year Honours thesis (2001) is that the dispute involves a misapprehension of the data and is built on a set of false premises.

The technical and social premises of the "non-utilitarian" viewpoint need to be reappraised. Key technical and evidential assumptions of the Acker-van Liere perspective, specifically about the absence of inlets and outlets for the great barays and the absence of distributor channels, are empirically invalid. The Jayatataka has a feeder canal running to its NE corner and both the major barays also have inlets and outlets in their eastern walls (Pottier 2000: 103). Pottier's comprehensive surveys have also shown that immense channels derive from the West baray and from the Angkor Wat moat and may also derive from the initial layout of the East Baray. Furthermore, the social premises are problematic. Groslier, who is the epitome of the French viewpoint, never advocated a sharply defined utilitarian view (Pottier 2000: 101). Nor is it easy to see how anyone who worked at Angkor for many years could possible deny the ritual component. The immense E-W, N-S orientation of the Angkorean landscape would, in itself, suffice to require the recognition of a cosmological component. Groslier just wrote about the ritual and operational interpretations on different occasions in his numerous books and papers from the 1950s to the 1980s. Furthermore the non-centrality thesis simply repeats, in the inverse, the logic of the hydraulic civilization model because both presume a correlation between social form (i.e. degree of state power) and material form whether it is to the presence or absence of large scale irrigation. Groslier argued that irrigation was the foundation of central state power in the standard old Wittfogel model (1979). Higham presents the inverse that because of the instability of the Khmer state and the power of the other grandee families (1989: 322-35, 345, 353-4;

2001: 156-161, 165) there would not have been a large scale, engineered irrigation system. But there is an alternative, outlined below, that a water management system was needed for irrigation precisely because the rulers did not securely control absolute power among the great lords of the state and that the need for large irrigation works to provide food for a relatively small number of people is a corollary of that situation. What needs to be envisaged is a non-correspondent relationship between the scale of social power and the scale of a hydraulic system.

The nature of the water management system: The large perspective made possible by the comprehensive AIRSAR coverage is crucial for beginning to grasp the nature and overall operation of the water system in Angkor. Focusing on the central part of Angkor (e.g. Egawa 1999; Nakamura 2000) prevents a recognition of the crucial role of the northern half of Angkor and the function of the Great North canal and its subsidiaries. These are clearly visible on the 1994 radar image from the space shuttle Endeavor that was commissioned by the World Monuments Fund and are, in part, mapped on the ZEMP GIS database (Engelhardt 1996). They are also partially represented on Claude Jacques' map of Angkor in 1978.

Once the entire system from the lake to the hills is on a single map and has been systematically extracted from one consistent information source it is apparent that the great barays are the middle zone of a huge water management system (figure 4). The northern zone between the hills and the major barays is a collector and flow management system for spreading water across the landscape and also directing it southwards down major canals from which it was shunted to the east or the west into lateral channels and large holding basins. Such basins occur just to the north of the NE corner of the West baray. They have two parallel N-S banks and are 200-300m wide and as much as 2 to 4 km long. Rather than just being canals to take water somewhere, they are probably better understood as basins to bring large amounts of water to a halt and then bleed the water off into other channels as and when required. In effect the system uses the only available bulk material – sand with a small admixture of clay – to reduce the flow rate of the incoming water, to disperse it and to then concentrate huge masses of still water for redirection across the

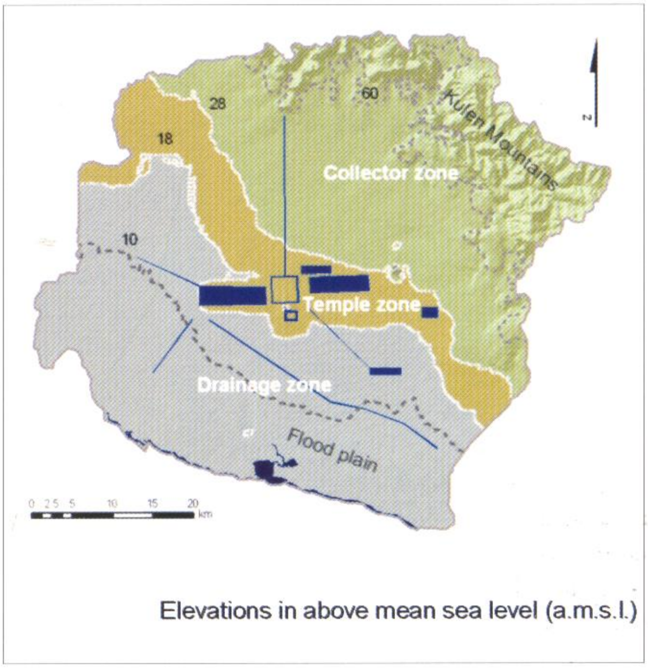

Figure 4: Water management zones of Greater Angkor. Linear features after Damian Evans, zones after Matti Kummu.

landscape.

The central zone of the system is the band of major barays and temple moats that were built from the 10th to the 12th century AD across the width of Angkor from Banteay Sra to Chau Srei Vibol. These now appear as a set of massive water storage units fed by the northern collector system. What has become apparent from excavations in the banks of the West baray is that these great structures were built very systematically and were not merely heaps of sand and clay to hold water for ritual display. While the East and West Mebon and the Neak Pean leave no doubt that the barays had a ritual meaning the West baray, for example, was also meticulously built to assist the transmission of water to the land to the south. An E-W section through the southern end of the western embankment has revealed the tip lines of successive layers of paddy field, sand and brick rubble stripped from the adjacent area within the baray (figure 5). Though the barays in Angkor were not excavated basins the section shows that part at least of the western end of the baray, close to the banks, was stripped of the paddy fields and their clay-pan that would have prevent-

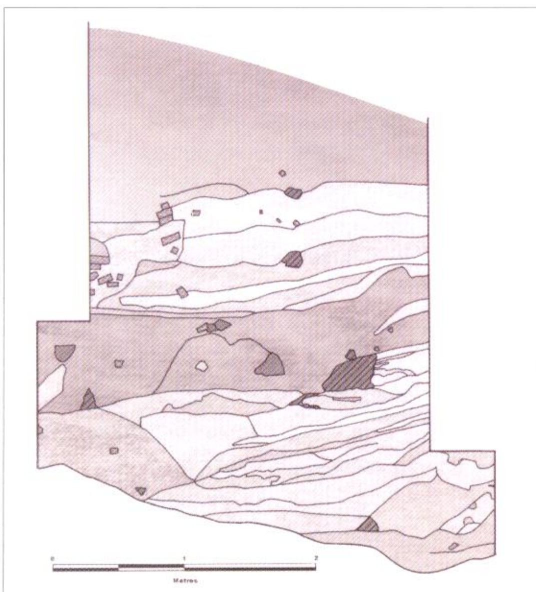

Figure 5: East-West cross section on the eastern side of the west bank of the West baray. Excavation managed by Heng Than. Field team – University of Sydney volunteers and APSARA staff. Illustration prepared by Andrew Wilson.

ed water percolating through the floor of the baray. In addition, the lower layers of the banks are meticulously constructed (figure 6). Just above the level of the water these layers have surfaces which are absolutely horizontal. The precise function is not clear but the deliberate effort to build a specific structure with some exact purpose in mind is very evident. Further evidence of a precise function or function is provided by the grid of channels south of the SW corner of the West baray, identified by Pottier (2000) and previously mis-identified as the boundary of a pre-Angkorean "city". There are some indications that east-west channels may run along the southern side of the south bank of the baray (Pers comm. Terry Lustig) in association with the problematic "bastions" found by Pottier (1999).

The southern zone of the system is a suite of dispersor and distributor channels. The most obvious set is associated with the West baray and consists of a channel running to the SW which is the shortest, steepest and therefore quickest dispersal route to move water away from the baray area and down to the lake; and a channel to the SE which runs across the slope of the land and goes all the way to the south of Roluos and then on to the Damdek "canal". The latter is the slowest route the water could take and still flow, suggesting that this was a distributor canal to spread water across all of the land south of the canal down to the dry season edge of the lake. Coring of the canal indicates that it was of variable depth and profile along its length (figure 7).

Other dispersor canals run from the Angkor Wat moat down to Phnom Krom and also from the direction of the East Baray to the same terminus by the lake. The Siem Reap river now follows part of the course of the latter canal. South of Siem Reap town, where the river diverges to the east the line of the abandoned channel is still visible as a row of house-mounds aligned on Vat Adhvea and also by a buried

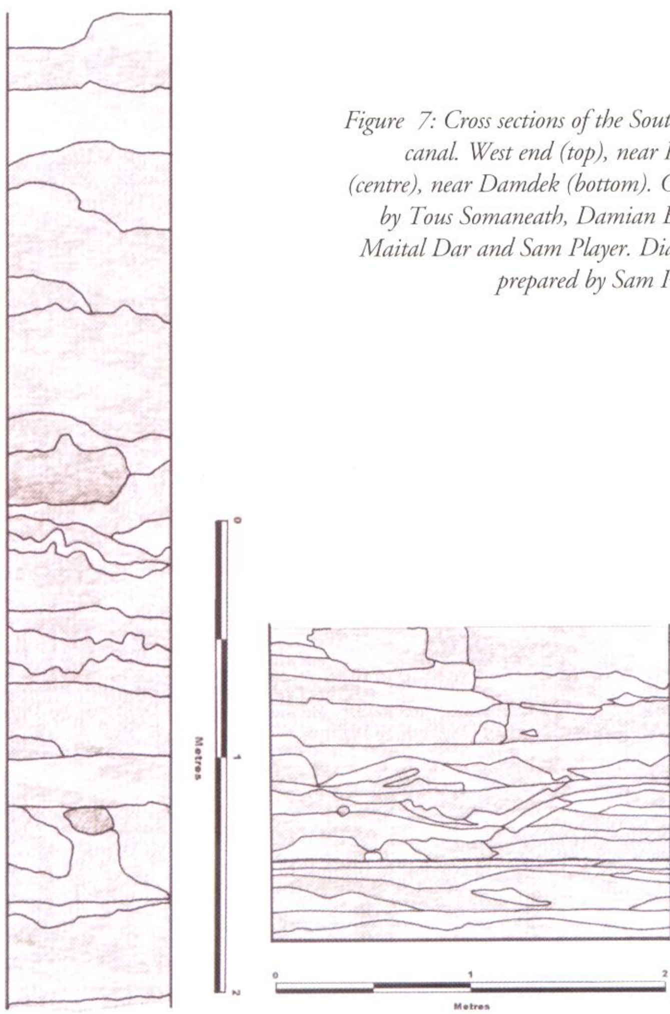

Figure 6: Two sections along the inner face of the banks of the West baray. West bank (left), south bank near modern sluice (right). Excavation managed by Heng Than. Field team - University of Sydney volunteers and APSARA staff. Illustration prepared by Andrew Wilson.

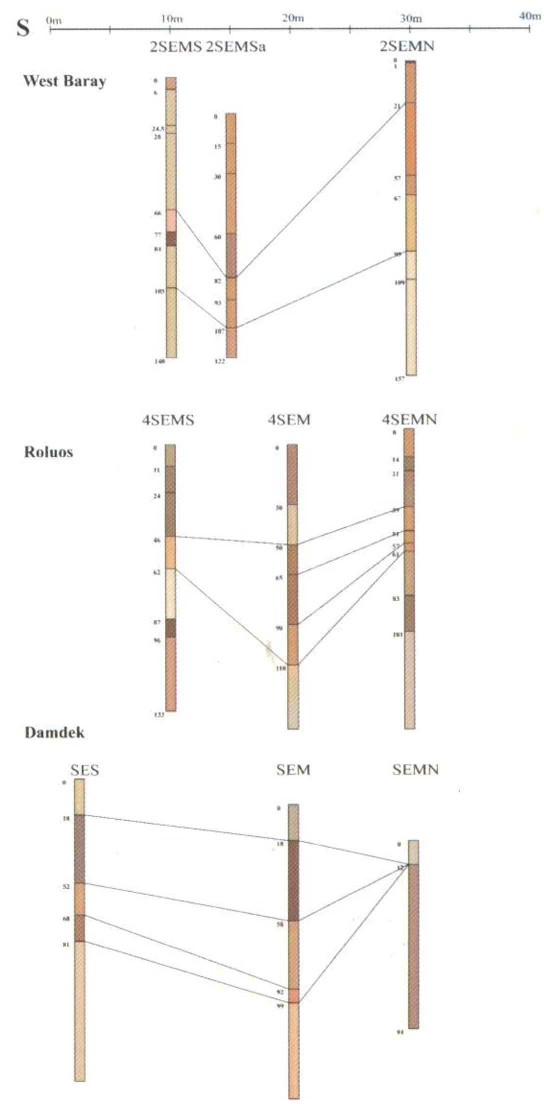

Figure 7: Cross sections of the South-east canal. West end (top), near Rolous (centre), near Damdek (bottom). Coring by Tous Somaneath, Damian Evans, Maital Dar and Sam Player. Diagram prepared by Sam Player.

channel which is exposed in cross-section in the ditch of the new ring road. The channel was about 40 m wide and only 1-2 m deep (figure 8). Further east the SE road leading SE from the centre of Angkor to the Indratataka and the Angkorean road running SE from the SE corner of that baray may need to be reappraised as a water distributor system as well as a roadway. The Rolous group then deserves further attention as it has a baray (the Indratataka) and also a major channel running due south to the lake which would have acted as a dispersor channel. The village of Kompong Plok is located at the southern end of this channel. As mentioned earlier, the line of what is now National Route 6, east of the Indratataka, would have served as a distributor channel. In addition a channel also runs westwards towards Vat Adhvea. The implication is that we should find a 9^{th} century collector system north of the Roluos, the antecedent of the vast system that now lies north of the East and West barays.

The function of the water management system and the population of Angkor: What then was the relationship of the water management system to the residence pattern and the population? As Acker (1998) has correctly noted, these utilities, if used for irrigation, would not have fed a large number of people. Estimates range from 100,000 to about 200,000 people. This seems far too small a support role given the availability of huge quantities of rice each year from the 7000 sq km of flooded land around the lake and estimates of over 1 million people in Angkor (Groslier 1979 and critique by Acker 1998). The function of the water management system of Angkor is, however, readily understandable in the context of the insecure status of the ruler's power between the 9^{th} and the 12^{th} century AD. A recent reappraisal of the supply of rice from the 1000-1500 sq km around Angkor suggests provisionally that the region could have fed up to about 750,000 people (figure 9) on rain-fed and lake-flooded rice alone in a good year (Lustig 2001). However, in a bad monsoon year, there would have been a shortfall of rice for approximately 100-200,000 of those people.

While the figures are provisional the essential point is that a general scenario for food supply within the area of Angkor would include a shortfall for a not insignificant percentage of the population in a bad year. Though the yields from engineered irrigation need never have been large they would, however, have been decisive because that supplemented supply would have ensured that the staple crop was always available for the whole population of Angkor. The irrigation system was not therefore maximizing yields to enhance the economic power of the ruler but may have been a risk management strategy to shield the ruler of Angkor from dependency on other provinces and great lords for rice in a bad monsoon year. The political value of that autonomy would have been immense and the Angkor network would have been a profoundly valuable strategic asset. The system was on such a large scale that it would have been ordered into being by the ruler of Angkor, but its components could then have been run at the local level and would have been exploited by the state through civil and temple taxation (see Sahai 1970 for taxation).

Implications of the Structure of the Angkor Urban Complex

Distribution of population: If the water management network which defines the extent of Angkor was a risk minimization system then it had no role in defining where the bulk of the populace was located. In the main they would be distributed across the landscape in whatever residence pattern would have aided their own production of rice. The dispersed layout of the discrete residential structure is an even distribution of the population across what is almost an ideal von Thunen surface, precisely what one would expect in a region with poor crop yields for which intensification of yield is not feasible. Analyses of rice production

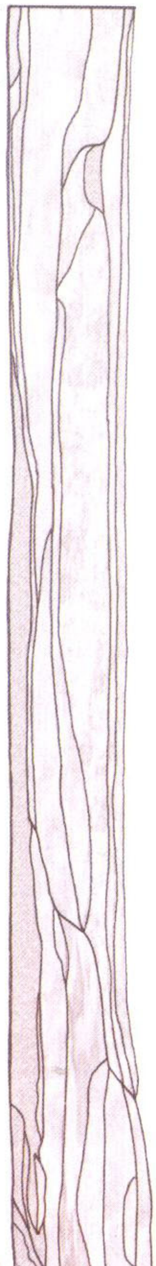

Figure 8: Channel of canal in cross section at the Kar Kranh site on the ring road south of Siem Reap. Excavation and cleaning of section managed by Tous Somaneath and Khieu Chan, assisted by Sam Player. Illustration prepared by Andrew Wilson.

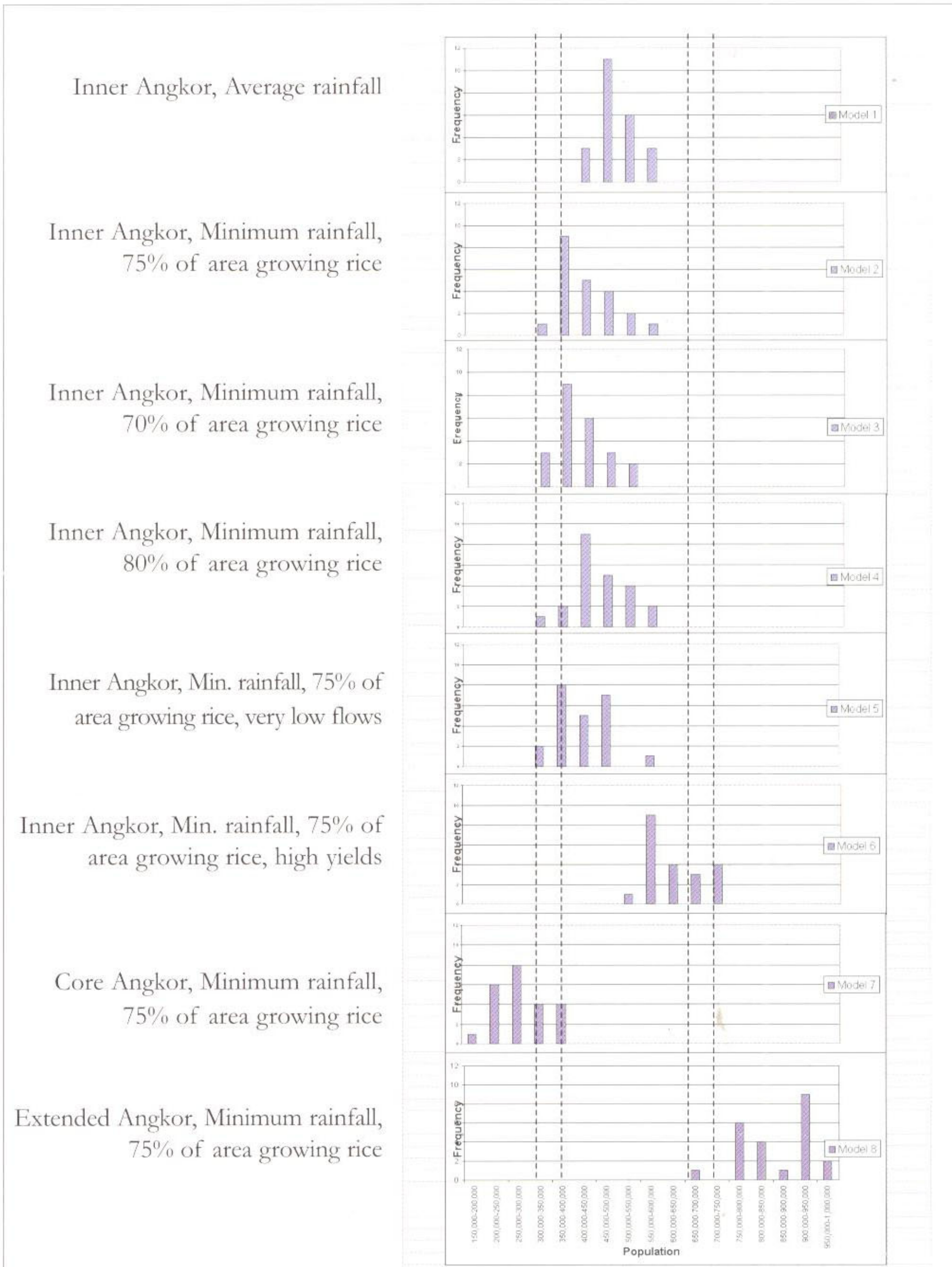

Figure 9: Greater Angkor Provisional Populations from alternative yield estimates for various models of land-use. From Eileen Lustig 2001.

in Cambodia emphasize that returns from rice production are poor (Bray 1986; Helmers 1997; Nesbitt 1997 e.g. p. 177), particularly in the Angkor region. If more rice is needed as population increases then the only way to obtain it is to clear more forest for rice fields. The selective factor that was affecting the rate and scale of the expansion of Angkor was the extensification of rice production. After a very few years the yield from newly cleared land would fall and thereafter, presumably remain relatively stable. Interestingly the stable, low yield condition means that in the parts of the Angkor area with low gradients, continual farming would not further deteriorate the soil because rice production was operating on basal yields and water flow rates would be controlled by the bunds and the numerous small, local distributor channels. This has implications for the demise of Angkor because its expansion into its hinterland to acquire more land for rice eventually led to the occupation of the lower slopes of the hill ranges north of Angkor.

The radar survey indicated that there was Angkorean occupation on those lower slopes. A field survey in 2002 showed that in the Phnom Liep area there were shrines, occupation sites and quarries (figure 10). Initial assessment of the ceramics from the Phloe Ampil occupation site suggests a date range in the 12th to 14th century though this may be modified by the results of the field season planned for January 2004.

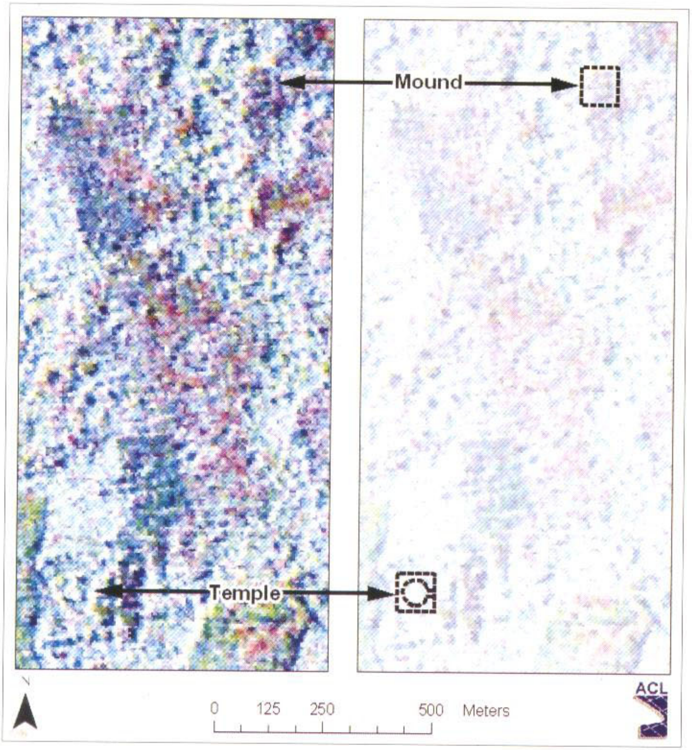

Figure 10: AIRSAR image and plan of Phnum Liep area and location of Phloe Ampil site. Prepared by Damian Evans.

What is striking is that the sites below Phnum Liep appear to be an outlier of the Angkor urban complex, suggesting that this is how the expansion occurred with new concentrations of settlement being pushed into areas of forest, whether partially cleared or near pristine. By extension, this is what Banteay Srei represented in the 10th century.

Ecology and demise: The disturbing environmental feature of the Phnum Liep area is that it was re-cleared in the 1960s and now suffers from severe channel erosion with steep-sided gullies 1 to 2m deep dissecting the landscape. The implication is that clearing even shallow slopes has potentially very damaging consequences. This is consistent with the evidence from other regions where tropical or monsoon forest is being cleared (Bruijnzwel 1990; Heng Thung 2002; Turkelboom et al 1997; Ung Phyrun 1990s). Clearing slopes leads to increased run-off and erosion with larger quantities of water carrying increased sediment loads flowing down into the major rivers and canals and damaging embankments (Devine and Van Rouen 2001). The significance of this in Angkor is that during heavy seasonal rainfall pulses of water and sediment would have been sent into the water management network. The network is elaborate and delicate – elaborate because it contains many duplicate channels and also displayed repeated re-organization of the network which produced redundant channels (figure 11); delicate because the gradients within Angkor are shallow (a mean slope of just 0.1 percent over the 40 km from the lake to the hills; see Acker 1998:7 and Fletcher 2001:17) and for the system to work water had to flow down very precisely from one channel and basin to the next. Each component of the network would have been fundamentally dependent on the correct operation of the adjacent component further up slope - it was therefore highly susceptible to systemic failures that could easily 'cascade' through the entire network. If the depth of the channels was increased by sudden

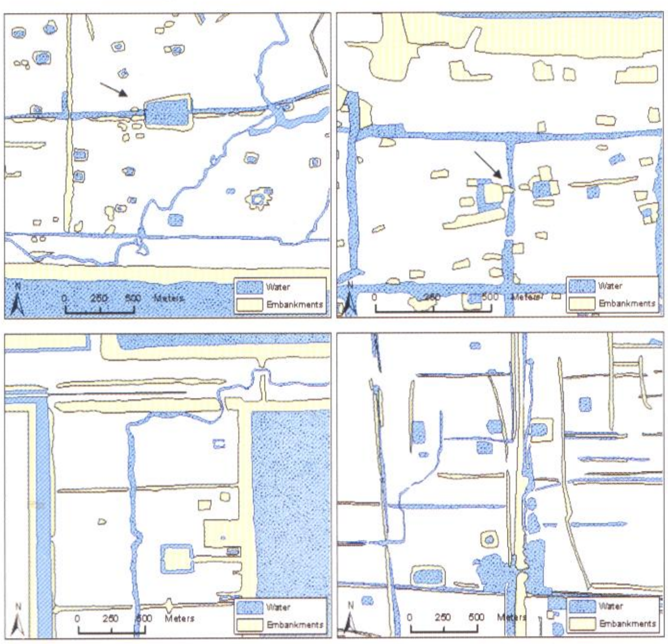

Figure 11: Multiple and re-configured channels in the Greater Angkor water management network. From Pottier and from Evans. Prepared by Damian Evans.

erosion or blocked by deposits of sediment the connections in the network would be disrupted. This therefore offers a process whereby the normal procedure of clearing forest for rice fields would gradually create a situation that was damaging to the operations of the water management network.

There are some indications that substantial deposition and erosion was in progress in Angkor from the 12th century AD. In the Tumnup Barang site the old channel is filled with nearly 4m of sediment and the embankment was repeatedly and deliberately built up by dumps of deposit so that eventually, its top was 1-2m above the former land surface (figure 2). Just to the south, at some time between the 13th and the 16th century, the Siem Reap river was diverted through the huge E-W barrier between Angkor Thom and the East Baray. It now runs about 5m below the level of its Angkorean period channel. To the south of modern Siem Reap town the section through the old canal on a line from the present Siem Reap river to Vat Adhvea shows that its channel was filled with cross-bedded sands. These are indicative of relatively rapid, episodic water flow. After the channel was filled with sediment a rejuvenated river, whose natural meanders are clearly visible on aerial photographs and on the AIRSAR images, incised a new steep-sided channel that winds back and forth across the line of the former canal. In the North moat of Angkor Thom, a layer of laterite debris, small rolled lumps of sandstone and ceramic fragments lies just below the level of the paddy fields which form the top of the stratigraphy, suggesting a phase of rapid water flow dumping old occupation debris into the moat. That the impact of whatever processes were operating across Angkor were irregular is clearly demonstrated just to the north of the moat of Angkor Thom in the channel of the Great North canal. Near Prasat Tonle Snguot, one of Jayavarman VII's hospital chapels, a section in the canal showed that it was less than a metre deep and had only about 35 cm of fine grey silt in its bed. There is no trace of any disruption or change in the entire history of deposition in the canal. Quite why this was so is unclear, as is the function of the south end of the canal. But it is apparent that water flow and deposition were extremely varied throughout the central and southern portions of the network in the later history of the Angkor urban complex.

The Issue of Demise

Extensification suggests a parsimonious explanation of the overall context of the demise of the Angkor urban complex. Clearance of hill slopes should lead to higher and more variable water flow in the channel network. Gradually, parts of the system would fail to deliver water while others would be overloaded with water and sediment. Portions that no longer worked and were flooding adjacent rice land would be juxtaposed with sectors which were still functioning. Some people along the embankments would be adversely affected by flooding and breaches to the embankments while adjacent communities would still have functioning, undisturbed, local rice production. The implications for social relationships between adjacent communities are ominous.

The model leads to an interesting analytic conundrum. While some people might have left the region because the resource supply conditions had become too problematic and the infrastructure disruption intolerable, others would have been able to carry on living in the area of the urban complex. There are indications, for example, from pollen data and radiocarbon dates from sediment cores in Srah Srang obtained by Dan Penny that, between the 12th and the 16th century the surrounding environment was, in some key respects, much like that of today. There is no indication of a return of dense forest cover, as the claim for an early 15th century demise would lead us to expect. Furthermore, as Evans notes (2002), if the populace generally did not need the massive water management infrastructure to obtain adequate rice yields under normal rainfall conditions then the mere failure of the system should not have affected them very much. They might fare badly in a poor monsoon year but they only had to stay put in order to survive. Their prospects should not have been directly affected by the demise of the network or collateral damage to the regional political authority. The risk management role of the network was only really relevant to the maintenance of the authority of the ruler. The new map of Angkor suggests that an explanation for the demise of the Angkor urban complex network can be proposed and, also, that the issue of whether or not, or to what degree, the population which was dispersed across the landscape abandoned the region remains a conundrum. A possibility is that the breakdown of such a huge water management network had so many disruptive consequences that until the system had entirely collapsed and the natural rivers had re-established a new equilibrium the environment of the region was largely unusable. If this were the case, both the geomorphology of the hydraulic collapse and the locations where continuity of occupation could feasibly occur should be very visible in the archaeological record.

Conclusions

The vast extent of Angkor and the structure of its network of roads and canals were closely related to the ecology of the region and may have played a significant role in the demise of the urban complex. Interaction between the extensification of rice production and the combined complexity and scale of the water management system could have created the conditions that would have disrupted the network of canals and basins leading to a cascade of failure. However, the structure of the settlement pattern of Angkor also suggests that a significant proportion of the population was not directly dependent on the network and should, in principle, have been able to endure despite its collapse. The vast extent of Angkor and the non-correspondence between the dispersed residential pattern and the network of linear channels and embankments is clearly central to the issues involved in understanding the demise of the urban complex.

Acknowledgements

There are many people to acknowledge who have made the work at Angkor possible. Without Ian Brookes, who managed the initial logistics and gave the university team its introduction to Cambodia, the University component of the project would never have got off the ground. Ashley Thompson has given judicious and valuable advice over many years. Koy Sin Chenda and Vân Sary of the staff of EFEO have given much valuable assistance in the field and with administration. Thanks to Dominique Raymakers and to Mrs Ouk Chamroen for the assistance with vehicles, sustenance and a place to stay. The fieldwork volunteers over the past four years have been a great asset and a pleasure to work with. Specific thanks to Terry Lustig and Matti Kummu for good sense about water management and hydrology, to Eileen Lustig for the work on inscriptions and rice, and to Catherine Wu for her photographic work. Thanks to Juha Zarkkula for introducing Matti to the project. Aedeen Cremin, Wayne Johnson, Andrew Wilson, Bess Moylan and Terry Lustig have directed crews on the project. Their help has been much appreciated. Many thanks to Sam Player for his work on the Kar Kranh site in June 2003. Donald Cooney, Alexandra Rosen and Eddie Smith have graciously given their time and expertise to running the ultralight plane survey in Angkor for the project. Their participation is much appreciated. To Ian Brookes and to Seng Lo of ALLTRANS many thanks for getting the ultralight plane into Cambodia. The project is indebted to Scott Hensley, Ian Tapley and Tony Milne for the acquisition and the processing of the AIRSAR data. The staff and facilities of the Archaeological Computing Laboratory and the Spatial Science Innovation Unit and VISLAB in the University of Sydney have been of great assistance especially with the preparation of the radar data and with the illustrations for this and other papers and reports.

References Cited

Acker, R., 1998, "New geographical tests of the hydraulic thesis at Angkor," *South East Asia Research* 6 (1): 5-47.

Bray, F., 1986, *The Rice Economies. Technology and Development in Asian Societies*, Basil Blackwell Ltd., Oxford.

Bruijnzwel, L.A., 1990, *Hydrology of Moist Tropical Forests and Effects of Conversion: a state of knowledge review,* Free University, Amsterdam.

Coedès, G., 1951, "Stèle de Trapan Don On" *Inscriptions du Cambodge,* Vol. III, École Française d'Extrême-Orient, Collection de Textes et Documents sur Indochine, E. de Boccard, Paris.

Coedès, G., 1952, "Inscriptions de Vat Prah Einkosei," 108-39, *Inscriptions du Cambodge,* Vol. IV, École Française d'Extrême-Orient, Collection de Textes et Documents sur Indochine, E. de Boccard, Paris.

Dayton, L., 2001, "The Lost City," *New Scientist* 169 (No. 2273): 30-33.

Delvert, J., 1961, *Le Paysan Cambodgien*, Mouton, Paris.

Devine, A. and Van Rouen, 2001, "Hunger gap," *The Cambodian Daily Weekend* 152 (Jan 6-7): 6-7.

Egawa, Y., 1999, "Newly acquired topographical maps for the Angkor Archaeological Area and an interpretation of the ancient infrastructure," *Renaissance Culturelle du Cambodge* 16: 293-319.

Engelhardt, R.A., 1996, "New directions for archaeological research on the Angkor Plain: the use of remote sensing technology for research into ancient Khmer environmental engineering," I*ndo-Pacific Prehistory: The Chiang Mai Papers. Vol 1. Bulletin of the Indo-Pacific Prehistory Association* 14: 151-60.

Evans, D., 2002, *Pixels, Ponds and People: Urban Form at Angkor from Radar Imaging*, Unpublished BA (Hons) Thesis, Department of Archaeology, University of Sydney.

Fletcher, R.J., 2001, "Seeing Angkor- new views on an old city," A R Davis Memorial lecture, *Journal of the Oriental Society of Australia* 320-321: 1-27.

Fletcher, R. and C. Pottier, 2002, "The Gossamer City: a new inquiry," *Museum International* 54 (1): 23-27.

Fletcher R., D.H. Evans and I.J. Tapley, 2002, "AIRSAR's contribution to understanding the Angkor World Heritage Site, Cambodia - Objectives and preliminary findings from an examination of PACRIM2 datasets," *Proceedings of the 11th Australasian Remote Sensing and Photogrammetry Conference,* Brisbane, Australia September 2-6 2002.

Fukui, H., 1999, "Groslier's hydraulic society theory of Angkor in the eyes of an agroecologist," *Southeast Asian Studies* 36(4): 546-54.

Gaucher, J., 1997, *Etudes Archéologiques à Angkor: de Yashodharapura à Angkor Thom, Rapport Campagne 1996-7* (typescript), Ministère des Affaires Etrangères, Paris.

Gaucher, J., 2002, "The City of Angkor. What is it?," *Museum International* 54 (1): 28-36.

Groslier, B.P., 1974, "Agriculture and religion in the Angkorean empire," *Etudes-rurales* 53-56, Jan-Dec.: 95-117.

Groslier, B.P., 1979, "*La cité hydraulique angkorienne: exploitation ou surexploration du sol?,*" *BEFEO* 66(1): 161-206.

Helmers, K., 1997, "Rice in the Cambodian Economy: Past and Present," Nesbitt H.J., ed., *Rice Production in Cambodia,* International Rice Research Institute, Manila.

Heng, L. Thung, 2002, "Angkor revisited: lessons to learn," *SPAFA journal* 121 (2): 5-17.

Higham, C., 1989, *The Archaeology of Mainland Southeast Asia,* Cambridge University Press, Cambridge.

Higham, C., 2001, *The Civilization of Angkor,* Weidenfeld and Nicholson, London.

Jacques, C., 1978, "Etudes d'épigraphie cambodgienne – 10. Autours de quelques toponymes de l'inscription de Prasat Trapan Run K.598. La capitale angkorienne de Yasovarman Ier à Suryavarman Ier," *BEFEO* 65(1): 281-321.

Jacques, C. and M. Freeman, 1997, *Angkor. Cities and Temples*, Thames and Hudson, London.

JPL 2002, *AIRSAR: Airborne Synthetic Aperture Radar.* URL: http://airsar.jpl.nasa.gov/.

Koder, J., 1995, "Fresh vegetables for the capital," 49-58, C. Mango and G. Dagron G., eds., *Constantinople and its Hinterland,* Variorum, Brookfield.

Lustig, E., 2001, *Water and the Transformation of Power at Angkor, 10th to 13th Centuries A.D.*, Unpublished BA (Hons) Thesis, Department of Archaeology, University of Sydney.

Nakamura, H., 2000, "Baray as a storage for buffer water in the Angkor period," *Journal of THE University of Sophia Asian Studies* 18: 91-97.

Nesbitt, H.J., ed., *Rice Production in Cambodia*, International Rice Research Institute, Manila.

Polkinghorne, M. and R.J. Fletcher, 2003, "Bounded Space: The Enclosed Galleries at Angkor" TAASA Review, *The Journal of the Asian Art Society of Australia* 12(2): 6-7.

Pottier, C., 1999, *Carte Archéologique de la Région d'Angkor. Zone Sud,* unpublished Ph.D thesis, 3 vols. Université de Paris III – Sorbonne Nouvelle (UFR Orient et Monde Arabe).

Pottier, C., 2000, "Some evidence of an inter-relationship between hydraulic features and rice field patterns at Angkor during ancient times," *Journal of Sophia University Asian Studies* 18: 99-119.

Pottier,C., 2002, "Résultats préliminaires des fouilles dans trois sites pré-angkoriens de la région d'Angkor," *Udaya 2*: 117-32.

Ricklefs, M.C., 1967, "Land and Law in the Epigraphy of Tenth-Century Cambodia," *Journal of the Asiatic Society* 26 (3): 411-420.

Sahai, S., 1970, *Les Institutions Politiques et L'Organisation Administrative du Cambodge Ancien (VIe-XIIIe Siècles)*, PEFEO LXXV, Paris.

Stott, P., 1992, "Angkor: shifting the hydraulic paradigm," 47-58, J. Rigg, ed., *The Gift of Water, School of Oriental and African Studies*, London.

Ung Phyrun, 1990s, "The Environmental Situation in Cambodia," <business.hol.gr/~bio/ allfile/HTML /PUBS/VOL5/html/pjy-cam.htm>.

Turkelboom, F., J. Poesen, I. Ohler, K. van Keer, S. Ongsprasert. and K. Vlassak, 1997, "*Assessment of tillage erosion rates on steep slopes in northern Thailand,*" *Catena* 29: 29-44.

Van Liere, W.J., 1980, "Traditional water management in the lower Mekong basin," *World Archaeology* 11(3): 265-80.

Wittfogel, K., 1981, *Oriental Despotism*, Random House, New York.

Zoppi, U., M. Barbetti, R.K. Chhem, R. Fletcher, Q. Hua, C. Pottier and M. Watanasak, 2002, "The con tribution of ^{14}C AMS dating to the Greater Angkor archaeological project," Paper presented at the International Conference on Accelerator Mass Spectrometry, Nagoya, Japan, Sept 2002.