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Meticulous survey of the banks, channels and reservoirs at Angkor shows them to have been part of a large scale water management network instigated in the ninth century AD. Water collected from the hills was stored and could have been distributed for a wide variety of purposes including flood control, agriculture and ritual while a system of overflows and bypasses carried surplus water away to the lake, the Tonle Sap, to the south. The network had a history of numerous additions and modifications. Earlier channels both distributed and disposed of water. From the twelfth century onwards the large new channels primarily disposed of water to the lake. The authors here present and document the latest definitive map of the water network of Angkor.

Keywords: Cambodia, Angkor, Khmer, baray, water management, water ritual

Introduction

From the 1950s onwards, Bernard-Philippe Groslier of the Ecole française d'Extrême-Orient (EFEO) articulated his idea of Angkor (Figure 1) as a 'hydraulic city'. From the 1980s that description and its economic and social implications have been much debated. However, contention has been at cross-purposes and has lacked empirical traction (Pottier 2000a; 2001). In particular, the extent, the structure and the components of the water management network of Angkor were only partially known. Over the past decade or so, the EFEO and the Greater Angkor Project (GAP) – a collaboration between the University of Sydney, APSARA, the Cambodian government agency that manages Angkor, and the EFEO in Siem Reap – have been surveying Angkor (Figure 2). The mapping has shown that between the ninth and the thirteenth centuries AD Angkor developed a vast network of reservoirs, channels

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Figure 1. Location of Angkor.

and embankments, covering over 1000km². Inlets and outlets are visible. Elaborate masonry structures that were integral components of the network have been revealed by excavation. In the first half of the second millennium the inhabitants of Angkor were clearly able to engineer the distribution of water, meticulously and systematically across the landscape, on an enormous scale. The terms of the debate have now been redefined.

Research

Discovery and debate

In 1860 Henri Mouhot produced the first known map of Angkor by a European, showing very clearly the moats of Angkor Wat and Angkor Thom, the Siem Reap river and the major central temples (Dagens

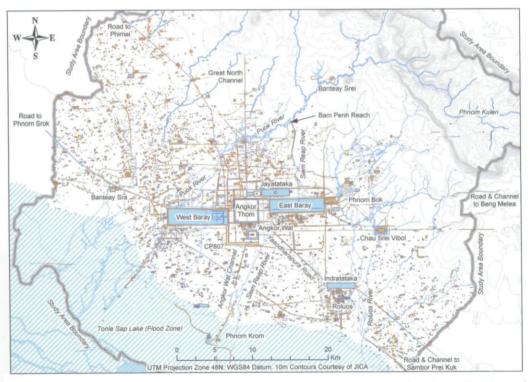


Figure 2. Greater Angkor archaeological map (Damian Evans and Christophe Pottier). Note channels to south and west of Roluos. Note channel-embankment connection from Beng Melea in the east to Chau Sri Vibol and westwards towards the centre of Angkor.

1989: 38). Following Ducret's topographic work for the mission of Lunet de Lajonquière (1902-11), the great reservoirs or *baray* and the temples of the central part of the Angkorian landscape were mapped. From the mid-1920s, the EFEO commenced a highly productive period of remote sensing and aerial exploration with the colonial armed forces (Goloubew 1936; Claeys 1951: 92-6), combined with field surveys and new mapping. As a result much greater detail on the hydraulic network of Angkor began to appear on the archaeological maps of the 1930s (e.g. Dumarçay & Pottier 1993: Plate 1), showing a complex network of canals and embankments stretching between and beyond the great monuments of the central zone.

Trouvé, in 1933, published the first serious analysis of the mechanics of water distribution throughout the central area. Soon after, however, Goloubew (1941) began to explore the social and economic dimensions of the system, arguing convincingly that the hydraulic features had a 'double aspect'. While undeniably part of a ritual tradition, they also clearly served a utilitarian purpose, which he assumed was to ameliorate, through irrigation, the impact of the sharp seasonality of rainfall on rice farming (Goloubew 1941: 11-4). In the post-war period, virtually all of Goloubew's methods and ideas were developed and much extended by Bernard-Philippe Groslier (1952a; 1956b) - perhaps rather uncritically in the case of the rice irrigation hypotheses, which still require further examination. To his credit, however, Groslier began to implement a comprehensive and systematic programme of aerial survey and mapping to establish the nature of the settlement pattern and the hydraulic network around the monuments (Groslier 1960; 1962). Even before this project was properly underway, he also began to develop the model of Angkor as a 'hydraulic city', a vast and populous urban complex defined and sustained by a complex irrigation system under state control (1952a; 1952b; 1956a; 1956b; 1960), and ultimately overwhelmed by its failure. His interpretation was summarised in his famous 1979 paper. Regrettably, the process of data collection that Groslier initiated was never completed. War and unrest in Cambodia disrupted field research from the early 1970s to the early 1990s.

The 'hydraulic city' hypothesis was challenged, in 1980, by W.J. van Liere, in a highly influential article (cited in overviews, e.g. Mabbett & Chandler 1995; Vickery 2002). He argued against the idea on a number of technical grounds, notably that the baray had neither outlets nor any means of water distribution, and that the area the system could have irrigated, and hence its productive impact, would have been insignificant. Acker (1998) further developed the latter argument and accepted van Liere's outlet/distributor argument at face value. They both, perhaps inevitably, judged Angkorian technology to be inadequate by modern engineering and agricultural standards. Subsequent research has refuted some of their core propositions while offering qualified support for Groslier's theory (Pottier 2000a; 2001; and see below). Other critics have preferred a variety of ritualsymbolic interpretations (van Liere 1980: 274, 279; Stott 1992; Moore 1995: 38; Acker 1998: 35; Higham 2001) focussing on varied issues of social organisation and intrinsic cultural meanings, while Stott also sought to dismiss Groslier's theory on the grounds that it was 'colonial' and 'orientalist' and damned it by association with Wittfogel (1957). These various claims and theoretical positions are convoluted, in some cases problematic, and, especially in relation to Wittfogel, are rather partial (see overview by Scarborough 2003).

Research

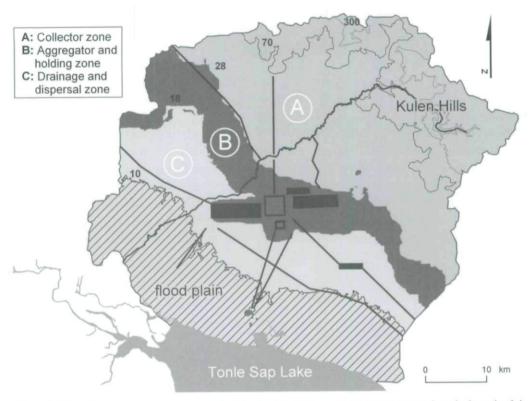


Figure 3. Tripartite water management network of Angkor (Matti Kummu). Note: the west and south channels of the Indratataka are not included as their relationship to the rest of the system is obscure. Also the Beng Melea-Chau Srei Vibol road-channel link is not included (see Figure 2) as it is fed from the catchment to the east. Note also the two western embankments that connect to the West Baray and to the Puok west of the Great North Channel.

Identifying the network

The mapping of Angkor by EFEO and GAP has shown that the main temple cluster lies at the centre of a dispersed, low-density urban complex (Pottier 1999: 185-6; Fletcher 2001; Fletcher & Pottier 2002; Fletcher *et al.* 2003: 109-10; Evans *et al.* 2007), spread across the plain between the Tonle Sap lake to the south and the Kulen hills to the north (Figure 3). People lived both along linear embankments and on occupation mounds around small shrines and water tanks. The linear network of channels and embankments is superimposed on an apparently random distribution of local shrines (*prasat*), water tanks (*trapeang*) and occupation-mounds across the landscape. While the configuration of the linear features is distinctly different in the north and the south, the shrine-water tank-occupation mound pattern is, by contrast, generally similar everywhere (Evans 2002).

From 1994 to 1999 Christophe Pottier of the EFEO mapped the southern half of Angkor using the EFEO archives, FINNMAP 1:250 000 scale aerial photographs and field surveys (1999). In 1994 a space-borne radar image of Angkor covering 4500km² was recorded from the shuttle *Endeavour* at the request of the World Monuments Fund. It clearly showed the complexity of the landscape north of the central temple area including

the Great North Channel, a linear feature running southwards for 25km from the northern hills to the north gate of Angkor Thom. In September 2000, at the request of the University of Sydney, the Jet Propulsion Laboratory (JPL) at the National Aeronautics and Space Administration (NASA) undertook an airborne synthetic aperture radar (AIRSAR) survey of about 8000km² of territory covering the western end of the Tonle Sap lake (JPL 2002; Fletcher *et al.* 2004). Of this area, the 2300km² that specifically encompasses Angkor was integrated into an initial map at the University of Sydney, combining Pottier's survey and an additional 1300km² to the north (Evans 2002; Fletcher *et al.* 2004; and see Coe 2003: 193; Jessup 2004:144). From 2003 to 2007 a new, more comprehensive map of Greater Angkor has been prepared at the University of Sydney by Damian Evans. The map, which covers about 3000km² within a boundary defined by the water catchment of the rivers of Angkor (Figure 2), integrates in a geographic information systems (GIS) database all the diverse site inventories, every archaeological map of the past century, Pottier's surveys, the topographic datasets, information from the AIRSAR radar survey, as well as data from various remote sensing sources (Evans 2007; Evans *et al.* 2007).

Characteristics of the network

The water management network depended on elaborate configurations of channels and embankments built from huge quantities of clayey sand, the available bulk material on the Angkor plain. The structures would have reduced the flow rate of the incoming water, dispersed it, allowed the concentration of masses of still water and enabled its redirection across the landscape. As such they would have served to manage the vast quantities of water delivered by the monsoon from May to November and either dispose of it or potentially retain it for the dry months of the year. The network consists of cumulative modifications and additions over a period of about 500 years between the ninth and the thirteenth centuries AD. It is immense, as are several of its well-known features. The largest component, and probably the largest single artefact created before the mid-nineteenth century is the West Baray, a reservoir about 8km long and 2km across, containing approximately 50 million m³ of water. The embankments were about 120m wide and 10m high, with a volume of approximately 12 million m³. The built channels of the network are also substantial. A linear embankment that forms the south side of shallow channel commencing near the south-west corner of the West Baray, runs east south-eastwards for at least 40km to the south of Roluos.

In the main, a distinction between road embankments or embanked water distributor channels may have had little meaning in Angkor. The banks of channels serve as roads raised above the water level for at least part of the year and most embankments, whether solitary or in pairs, would have functioned to re-direct water across the landscape. Those that run across the lie of the land (i.e. approximately east-west or north-west to south-east) act as barriers to the movement of water in the monsoon season, whatever other function they may have had. The same phenomenon can be seen today on the upslope side of the modern main road, the Route Nationale 6.

This point about multiple functions needs to be extended to the operations of the components of the network. Arguing for oppositions between single functions, e.g. that baray are for assisting agriculture through percolation or are storage for distribution along

canals, is unlikely to be productive. That each part of the network may have had varied functions at any one time, depending on circumstances, and also changed function over several hundred years has to be seriously considered.

The tripartite structure of the network

An integrated perspective, made possible by the comprehensive AIRSAR coverage, is required to understand the nature and overall operation of the network. Once the entire network from the lake to the hills is presented on a single map it is apparent that the East and the West Baray and the Jayatataka Baray are in the middle of a tripartite water management system (Figure 3) (Kummu 2003). The northern zone (A) between the hills and the major baray is a collector and flow management system whose channels and embankments could spread water across the landscape and direct it southwards. The central zone (B) contains the major baray and temple moats, built between the ninth and the thirteenth centuries. These structures were massive water retention units fed by the northern collector system, whatever other function they had. The southern zone of the network (C) is a suite of dispersal and distribution channels taking water southwards and eastwards out of the central zone. The most obvious examples are the channels associated with the West Baray, one of which runs from the vicinity of the south-west corner of the baray southwards to the lake, and the other, mentioned above, that runs 40km to the south-east. The gradients across the entire plain are extremely shallow -0.1 per cent (Kummu pers. comm.) - and the whole network was delicately balanced, depending upon the maintenance of stable water levels and flow rates.

The details of the northern zone (A on Figure 3) derive from the remote sensing mapping of GAP. The zone consists of a complex grid of long linear embankments and channels aligned north-south and east-west, with numerous right-angle turns and cross channels (Figure 2). The network would have affected water flow and sedimentation. The eastwest banks, some of which run for about 40km across the landscape, would have created extensive ponding on their northern side. In the northern zone, water flowed to the south towards the baray, down channels with numerous right angle turns. These channels offered many options for redirecting water and would have served to slow the water's velocity, reducing the risk of erosion. Water was first fed into the East Baray from the north-east from the upper Roluos river (Pottier 1999: 101-3) and then, probably in the tenth century (Groslier 1979: 173, 179-80), by a diversion off the Puok river, which is now the Siem Reap river. This diversion at Bam Penh Reach, identified by Groslier, ran south through a linear zig-zag channel, turning off eastwards into three west-east channels and then south to the north-east corner inlet of the baray (Pottier 1999: 103-4). Near the junction of the old Puok river and the Siem Reap offtake, a large masonry structure spillway has been discovered at Bam Penh Reach and is currently being excavated by GAP (Figure 4a). The spillway would allow excess water in the offtake channel to flow to the west during the monsoon. It is about 50m wide with an estimated length of about 80-90m and slopes westward at a gradient of about 2.5 per cent. The spillway was built of interlocking, ashlar, laterite masonry - a distinct construction technique of the period. At the western end is a substantial, sloping face, five courses deep. Though investigations continue, the structure demonstrates that the population of Angkor could engineer precise, durable and

The water management network of Angkor, Cambodia

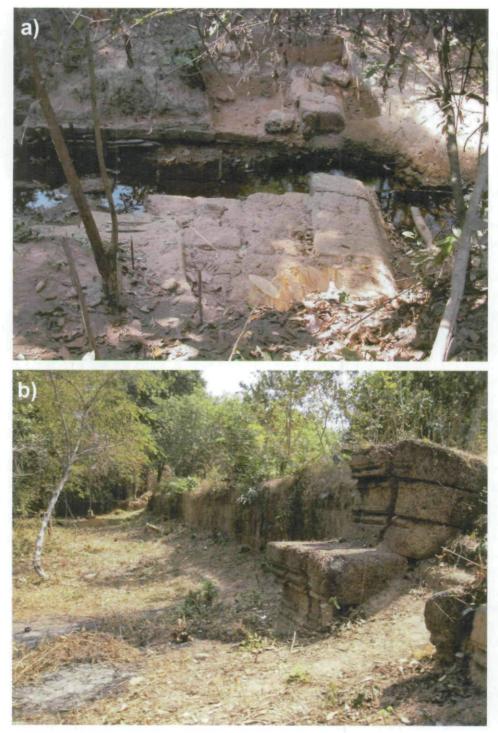


Figure 4. For legend see facing page.

monumental masonry for the management of water. It also indicates that we have far more to learn about a technology that has been strongly denied since van Liere. Without a Khmer Rouge-era channel that cut through its western end, 2.5m below ground level, we would not know of the spillway's existence. In addition, analyses of the strata indicate that the spillway was systematically buried, as if it was either no longer appropriate, or was unable to carry out its designated function and/or was overwhelmed by unknown circumstances.

Further west the junction of the Great North Channel and the Puok river clearly illustrates the complex options available in the network for moving water (Figure 5a). There is no direct connection between the northern and the southern parts of the Great North Channel. On the north side of the Puok river, water was either diverted to the south-east or south-west with only the water in the south-east diversion flowing back into the southern part of the Great North Channel. This part of the network deserves much attention, particularly to test whether the two parts of the Great North Channel were indeed successive constructions – the southern part contemporaneous with the West Baray in the eleventh century and the northern part perhaps contemporaneous with the new ritual constructions at Phnom Dei in the late twelfth century and the construction of the Jayatataka to which the Great North Channel delivered part of its water.

The *central zone* (B on Figure 3) is characterised by the baray, by the moats of Angkor Thom and numerous temples and the outlets to the south. Some of the inlets and outlets are clearly visible (Pottier 1999: 96-111). In the north-east corner of the West Baray is an intake channel about 25m wide. A channel of uncertain function cuts through the southern portion of the east bank of the baray. Another channel cuts through the outer part of the south-east corner of the embankment to enter feature CP807 to the south. CP807 would have allowed water to be transferred back to the east of Angkor Wat (see Pottier 2000b and also on previous misinterpretations of CP807 as a late ninth-century city moat). That the baray were clearly associated with elaborate systems for redirecting water is shown by the grid of large channels visible just to the south-west of the West Baray, identified by Pottier (1999: 120-3; 2000a), and previously mis-identified as the boundary of a pre-Angkorian 'city' (Figure 2). This grid would allow water to be transferred around the west and south sides of the baray, and redirected down to the south-west and back to the south-east.

The late ninth-century East Baray possesses a clearly visible, massive eastern exit, Krol Romeas, which regulated water passing through its east bank and off to the east and southeast (see map by Trouvé 1933; Dumarcay & Pottier 1993: Plate 1; Pottier 1999: 109-11) (Figure 5b). Ongoing excavation by GAP is clarifying the details of the two parallel, 100mlong walls of ashlar, laterite masonry, over 30m apart, that are 3.50m high and more than 1.2m thick (Figure 4b). Further to the east the line of the masonry channel is continued by

Figure 4. Masonry water management structures at Angkor. a) Bam Pen Reach (Andrew Wilson). View south showing the sloping surface of the western end of the spillway with the very steep, bevelled western face to the right. The central channel cut through the structure is modern. The visible part of the spillway is about 6m wide. The view is from the top of the bank of the channel dug in the Khmer Rouge period. b) Krol Romeas, the East Baray outlet (Dan Penny). View eastwards along the south wall across the stairway, as first cleared of vegetation in January-February 2007. The wall is c. 3.5m high.

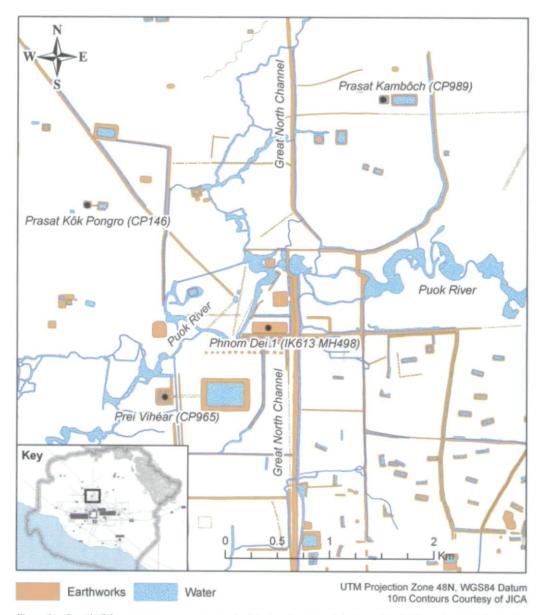


Figure 5a. Detail of the water management network of Angkor. Junction of the Great North Channel and the Puok river. Note the embankment that carries the road to Phimai commencing just north and west of Phnom Dei 1.

two embankments 1.5km long which directed water further east to allow it to go southward towards the earlier, ninth-century centre at Roluos.

The network of the *southern zone* (C on Figure 3) is simple compared to the other two. It was documented by Groslier (1979) and comprehensively mapped and analysed in the 1990s by Pottier (1999). To the south-west of the West Baray the basic components are well preserved. One clearly defined channel commences at the grid and drains to the south-west on the shortest route to the lake, i.e. it is able to dispose rapidly of water into the lake.

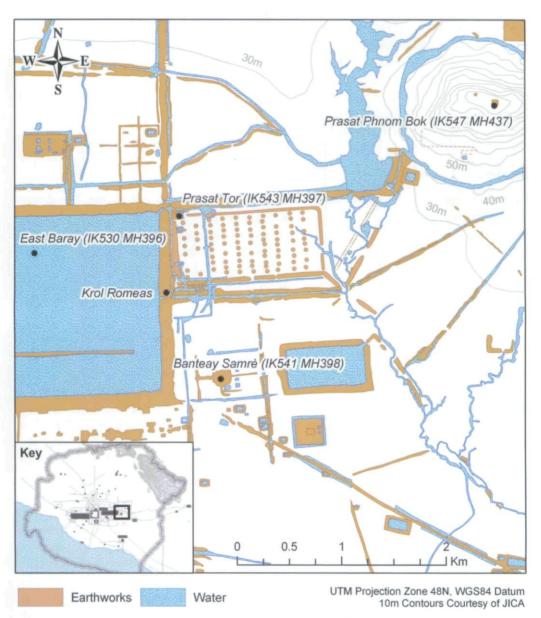


Figure 5b. Detail of the water management network of Angkor. Inlets and outlets of the East Baray. Note the north-east corner entry to the baray and an outlet from the centre of the east bank of the East Baray south of the enclosure with many parallel lines of mounds.

The other, wide channel is the linear feature noted earlier running to the east-south-east. It consists of a single embankment with water trapped in a wide, shallow channel on its northern, upslope side. This format of channels going southward to the lake and linear features running across the slope of the plain to the east is repeated all across southern Angkor. A major disposal channel runs south from the Angkor Wat moat and converges with another such channel, just to the east, about 2km north of Phnom Krom (Figure 2).

The modern Siem Reap river flows in part of this former channel. To the east of Siem Reap town a linear embankment, which also traps water on its northern side, runs from the late ninth-century core of Angkor south-east to the north-west corner of the ninth-century baray at Roluos and continues to the south-east from the south-east corner of the baray (Figure 2). This embankment and the great embankment extending south-eastward from the West Baray, runs across the landscape on a similar, shallow gradient, potentially facilitating the dispersal of water across the entire floodplain to their south.

Review

Understanding how the network functioned requires much excavation, as there was drastic remodelling of the landscape throughout the Angkorian period that may have removed or concealed earlier features. For example, in the area to the south of the East Baray, a twelfth-century temple, the Ta Prohm, was located south of the south-west corner of the baray and would have largely destroyed any equivalent of the grid of channels at the south-west corner of the West Baray. Likewise, if there had originally been an enormous eastern exit from the West Baray, equivalent to Krol Romeas on the East Baray, it would have been taken out of commission when Angkor Thom was built in the late twelfth century.

The network had a long developmental history indicating a tradition of inter-related, competent practice and practical knowledge. The precise construction of the masonry spillway of Bam Penh Reach and the exit channel of Krol Romeas shows that the tradition was already well established in the tenth century. Since the gradient of the landscape is shallow and channels 20-40km long were constructed down-slope and across the slope, the creation of the network was necessarily systematic. That it may also have been flawed or unable to cope with changing circumstances does not alter that premise. The network was subject to much remodelling and at various stages in its history may have been affected by channel down-cutting in the northern and central parts of Angkor with severe sedimentation in the south late in its history. Ominously, the old former channel of the lower Siem Reap river contains 1-2m of cross-bedded sand (Fletcher et al. 2003: 117, 120). The history of how the network was remodelled is also critical to understanding the stresses that it confronted. It is striking that the two disposal channels south of Angkor Thom were the last major network additions, suggesting that from the twelfth century onwards the emphasis in the southern zone was on channels that could promptly dispose of excess water. Elaborate and versatile though it may have been, the network eventually could not be sustained. Developing from Groslier's remarks, the massive inertia, convoluted layout and inter-dependent components of the network should be considered as potentially critical factors in the demise of Angkor.

Conclusions

The new comprehensive regional surveys of Angkor illustrate how extensive and consistent data collection procedure can redefine a major issue. A massive water management network with three, distinct, interconnected operational zones for versatile control, storage and redirection of water has been identified, possessing the components required for systematic

flood control and the distribution of water to support agriculture. The immense water tanks and moats of Angkor were nodes in a profoundly ritualised, elaborate system of hydraulic engineering. When the West Baray was built in the eleventh century, an exquisite and unique water-court temple, the West Mebon, which contained a 6m-long, reclining bronze statue of Vishnu, was added at its centre. Separating ritual and mundane functions in Angkor is not meaningful. The old debates about water management should now be replaced by a more productive discussion about the role of the network, how it was developed, the way it was managed, the degree to which the state managed its day-today functions, and the relationship between the operation of the network and the demise of Angkor.

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