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Water management in Angkor: Human impacts on hydrology and sediment transportation

Matti Kummu*

Helsinki University of Technology, Water resources laboratory, Tietotie 1E, 02150 ESPOO, Finland

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ABSTRACT

The city of Angkor, capital of the Khmer empire from the 9th to 15th century CE, is well known for its impressive temples, but recent research has uncovered an extensive channel network stretching across over 1000 km^2. The channel network with large reservoirs (termed *baray*) formed the structure of the city and was the basis for its water management. The annual long dry season associated with the monsoon climate has challenged water management for centuries, and the extensive water management system must have played an important role in the mitigation of such marked seasonality. However, by changing the natural water courses with off-take channels the original catchments were also reshaped. Moreover, severe problems of erosion and sedimentation in human built channels evolved and impacted on the whole water management system. This paper describes the present hydrology of the area and discusses the impacts of water management on hydrology during the Angkor era. The paper, moreover, attempts to summarise lessons that could be learnt from Angkorian water management that might apply to present challenges within the field.

1. Introduction

Water is crucial for every civilisation and human settlement. Safe and reliable access to clean water throughout the year is fundamental for sustainable population growth and development. The monsoon climate has for a long time challenged human kind to store water for the dry season (e.g. Barker and Molle, 2004) and/or to find reliable sources of water that are available year-round, such as easily accessible groundwater. The city of Angkor, the capital of the Khmer empire from the 9th to 15th century CE, developed an extensive water management system over hundreds of years in order to meet these challenges.

Angkor was, at its peak, the most extensive pre-industrial low-density urban complex in the world (Fletcher, 2001; Evans et al., 2007). It is located in the vicinity of Tonle Sap Lake in present-day Cambodia (Fig. 1) and by the 12th century, the Khmer empire ruled most of the mainland of Southeast Asia. Angkor is famous for its monumental religious constructions, such as Angkor Wat and Bayon. The temples are, however, just a part of the whole city structure. The French archaeologist Bernard-Philippe Groslier (1967, 1974, 1979) was among the first to recognise that Angkor had an extensive hydraulic system based on channels and reservoirs. He proposed an integrated programme of archaeological research that took into account both the 'vertical' dimension (e.g. traditional excavation techniques) and the 'horizontal' dimension, exemplified by his (1979) time-sequence series of maps derived from aerial survey. He was, however, unable to complete the programme due to unstable conditions in Cambodia from the early 1970s to the beginning of 1990s.

Recent research has uncovered an even more extensive hydraulic network stretching across 1000 km^2 (Pottier, 1999; Fletcher, 2001; Evans, 2002; Evans et al., 2007) by using more sophisticated remote sensing techniques than those available to Groslier. Although Angkor's hydrology and hydraulic system are probably not as well understood as its religious architecture, it has been argued already by Groslier (1974), and again with further evidence by Evans et al. (2007), that they may have played an important role in the operation of the city. The large water management features, such as channels and *baray* (large water reservoirs), seem to represent the boundary of the city during the Angkor era. Groslier's hydraulic thesis, however, has attracted criticism and contradictory theories have been proposed (e.g. van Liere, 1980, 1982; Acker, 1998).

This article aims first to present the key characteristics of the present hydrology of the Angkor area to form a basis for understanding the water management opportunities and challenges during the Angkor era. Water management in Angkor was based mainly on four sources of water: (1) natural rivers, (2) groundwater,

* Corresponding author. Tel.: +358 9 451 3833; fax: +358 9 451 3856.
E-mail address: matti.kummu@iki.fi

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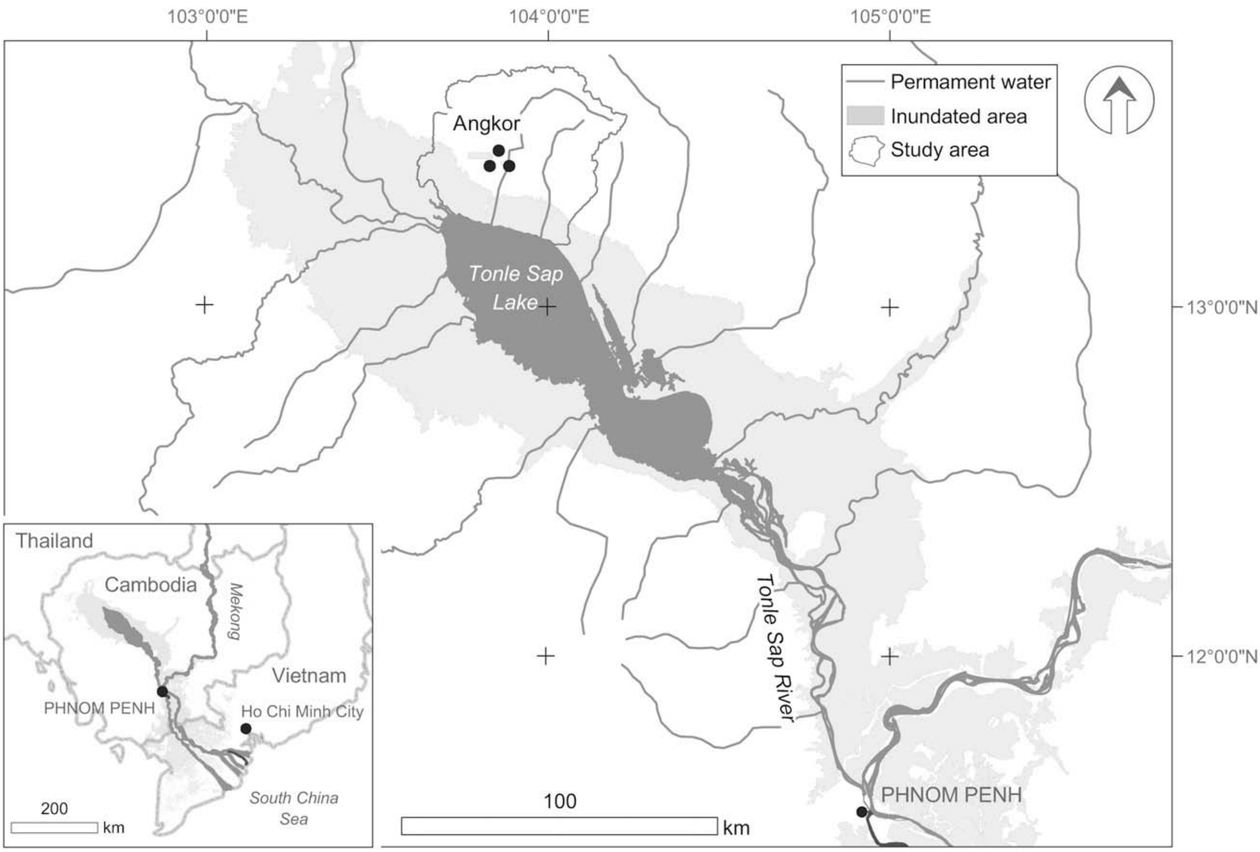

Fig. 1. Location of Angkor and study area (see detail map in Fig. 2) in relation to the Tonle Sap Lake (modified from Kummu et al., 2008).

(3) precipitation, and (4) Tonle Sap Lake. The monsoon climate dominates the hydrology of the region, dividing the year into a wet (May–October) and dry season (November–April). The three catchments on which Angkor was established, belonging to the Roluos, Siem Reap and Puok Rivers, form the study area of this research (Fig. 2).

To better understand the human modifications of the natural waterways, the study area has been divided into three water management zones derived from the presumed uses of water during the latter part of the Angkorian period, based on the latest archaeological mapping (Evans et al., 2007) and the present topography of the area. The zoning has been supplemented with three water management levels derived from the water management structures. The impacts of human actions, such as channelling the water from natural rivers to the reservoirs, on the hydrology have been significant. The paper aims to analyse the changes to natural catchment boundaries and subsequent erosion and sedimentation of the channels as a result of their unnatural slopes.

The water management sector is developing fast in Cambodia and other Mekong region countries. In the conclusions, the paper attempts to summarise lessons that could be learnt from Angkorian-period water management that might apply to present challenges within the water resources development discipline in Cambodia and elsewhere.

The paper is concerned with the impacts of human actions on the hydrology and sediment transportation in the Angkor area. Governance issues related to water management however, are not within its domain and are therefore not discussed in the article.

2. Present-day environment and hydrology

Angkor is located north of Tonle Sap Lake in the northwest of Cambodia, Southeast Asia (Fig. 1). The Kulen Hills region sets a boundary to the study area in the north while Tonle Sap Lake, with its 8–12 km wide floodplain, represents the southern boundary (Fig. 2). The study area covers a total area of 2885 km^2. The terrain between Tonle Sap Lake and the Kulen Hills is very flat, with an average slope of 0.1%, trending NE–SW, while the elevation varies from 2 to 60 m above mean sea level (AMSL). The Kulen Hills rise to between 300 and 400 m AMSL, with a maximum elevation of 490 m. The study area is situated between latitudes 13°04 and 13°44 and between longitudes 103°36 and 104°13.

2.1. Hydrometeorology

The climate in the study area is tropical and dominated by the monsoons. The wet southwest monsoon arrives around May with heavy clouds and thunderstorms. It usually continues until the end of October, with rain occurring almost on a daily basis. The dry northeast monsoon, therefore, normally starts in November and continues until April. The wet season brings on average 88% of the annual rainfall that varies between 1180 mm year^{-1} over the Tonle Sap floodplain at Phnom Krom to 1850 mm year^{-1} in the Kulen Hills (Kummu, 2003). The town of Siem Reap has an average precipitation of 1425 mm year^{-1} (35 year data-set, 1922–2002: Mekong River Commission, 2005). The annual average open water evaporation rate in the region is 1690 mm, being highest in March–April and lowest in August–September while the average temperature for the region is 28.2 °C being lowest in December (25.3 °C) and highest in April (30.6 °C) (Kummu, 2003).

2.2. Hydrology

At the present time, the Angkor hydrological area, as it is defined here, consists of three river catchments: Puok, Siem Reap and Roluos (see Fig. 5B), forming natural boundaries for the study area with Tonle

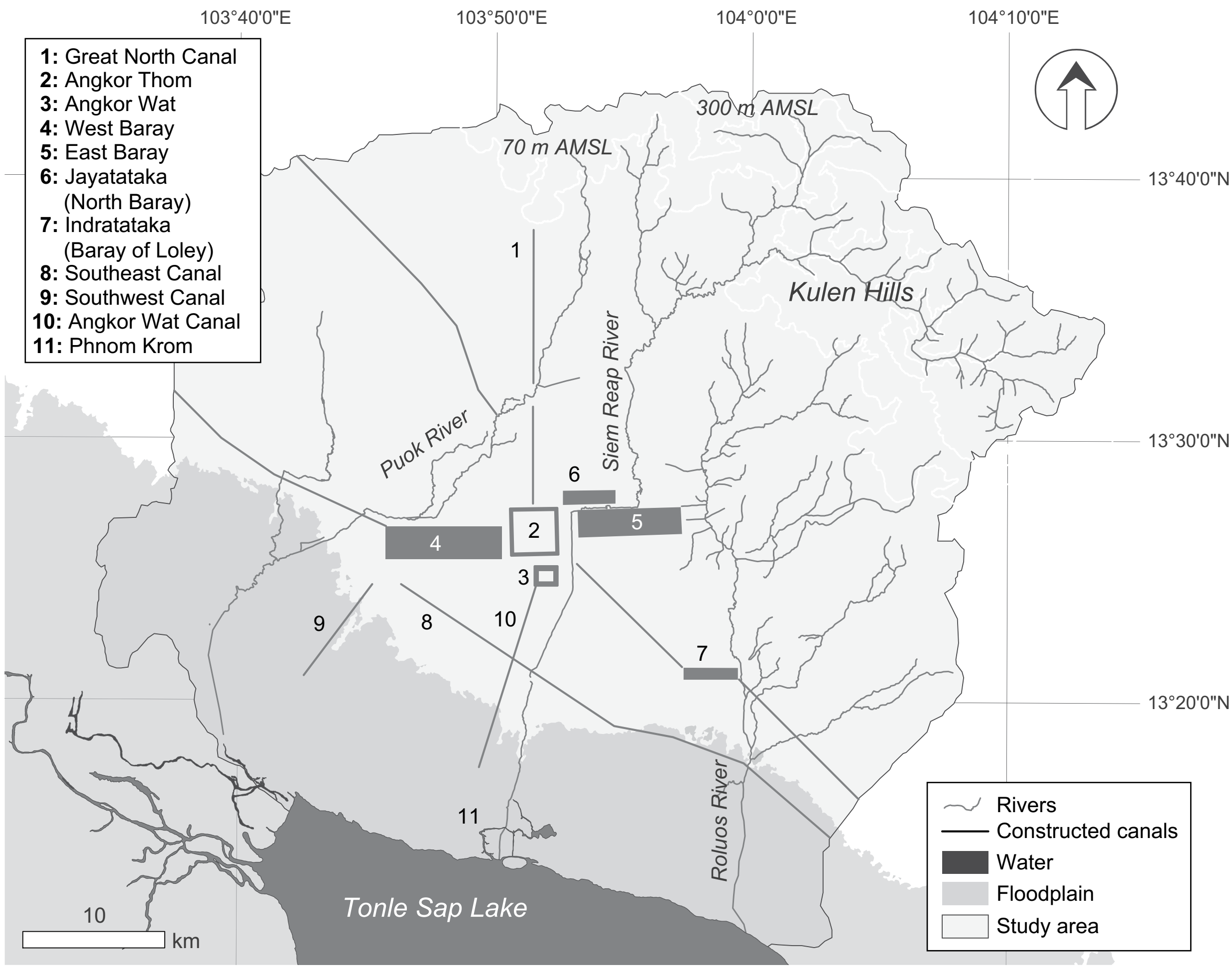

Fig. 2. Map of the study area and location of the major hydraulic features and main temples. Source of the GIS data: natural rivers, lake, contours, and flood plain from the Mekong River Commission (2005); linear and storage features from Evans et al. (2007).

Sap Lake (Fig. 2). The natural rivers originate in the Kulen Hills and drain down to Tonle Sap Lake. The average annual runoff for the three catchments is around 500 mm. The characteristics of the Roluos, Siem Reap and Puok Rivers are reviewed in more detail in Kummu (2003).

Groundwater is another important source of water for the Angkor region. It is easily accessible, as the water table lies between depths of 0 and 5 m below ground level during the wet and dry seasons, respectively (JICA, 2000; JSA, 2002). This offers relatively easy and reliable access to clean water during the dry season, which is crucial for sustainable community development. Seasonal variation in the groundwater level clearly follows the precipitation pattern (see Kummu, 2003). The groundwater aquifer seems to be rather homogenous, i.e. having the water table close to the ground surface, over a large part of the terrain between the Tonle Sap floodplain and Kulen Hills (JSA, 2002; Friedli, 2003).

Although the groundwater is rather easily accessible in the Angkor area, the depth to the groundwater table varies greatly around the Tonle Sap area. It depends on the depth of the bedrock and the characteristics of the soil. In Kralanh District, west of Siem Reap, the surface of the aquifer is located at depths greater than 40 m, while in Sotr Nikum, east of Siem Reap, the groundwater table lies between 11 and 12 m deep (Garami and Kertai, 1993). Therefore, Angkor is clearly located on an easily accessible aquifer compared to its surrounding areas.

2.3. Tonle Sap Lake

Tonle Sap Lake is the largest permanent freshwater body in Southeast Asia. At the present time, the area of the lake varies between the dry and wet seasons, from an area of 2300 km^2 up to between 10,000 km^2 and 15,000 km^2, while the water level of the lake increases from around 1.44 to 6.8–10.3 m AMSL in Hatien Datum (Kummu et al., 2008; Kummu and Sarkkula, 2008). That is, while the water level recedes to similar levels each year, the flood peak varies greatly (Kummu and Sarkkula, 2008). Since the bottom of the lake has an elevation of around 0.7 m AMSL, the water is very shallow (depths of less than 1 m) at the end of the dry season.

The Tonle Sap is believed to be among the most productive freshwater ecosystems in the world (Rainboth, 1996; Bonheur, 2001). Its high productivity is driven mainly by flooding from the Mekong River, which transfers primary products of terrestrial origin into the aquatic system (Lamberts, 2001, 2006; MRCS/WUP-FIN, 2003; Sarkkula et al., 2005; Kummu et al., 2006). The floodplain of the lake, and particularly the gallery forest and scrublands at its margin, offers favourable conditions for breeding and growth for migratory fish from the Mekong River (Poulsen et al., 2002).

The lake supports the majority of the present-day commercial and household fisheries of Cambodia and provides a significant part of the animal protein intake for the whole country. More than one million people are directly dependent on the natural resources (mainly fish + farming) of the lake at the present time (Keskinen, 2006). It is very probable that the Tonle Sap was a major and essential food supply, particularly of fish, for communities during the Angkor era.

Besides fish and other natural resources, the lake was also an important part of the transportation network for Angkor. Goods and people were easily moved between regional centres and the capital by boats, particularly during the wet season (Hendrickson, 2007, p. 259). In relation to Tonle Sap Lake, the location of Angkor is close to ideal. It is safe from the flood but at the same time very close to the lake even during the dry season. The floodplain is relatively narrow in the Angkor region (on average some 12–14 km in width) compared to the other parts of the lake where it can be four times as large (see Fig. 1). This made Angkor relatively accessible by boat even during the dry season.

3. Water management: levels and zones

The water management system is discussed here from two different perspectives: levels and zones. The three water management levels, listed and briefly discussed in Section 3.1, are based on the water management structures while the zones are derived from the ways the water was managed through the landscape at a larger scale. The levels highlight the diversion of water management at different scales, and also within each of the zones.

3.1. Water management levels

During the Angkorian era, each of the management levels had its typical water management structures (Fig. 3). In this paper the three principal management levels are defined as: (a) household level; (b) village level; and (c) city level. This hierarchy is based on the type and size of the structures. The possible governance issues related to these structures and water management levels, however, are not within the domain of the paper.

Many of the houses were built on small mounds (Fig. 3a) that raised the house above the flood. Due to the long dry season, the collection and storage of water was very important. At the household level, this was accomplished by building/excavating small ponds which were dug into the water table. For village use, bigger ponds (*trapeang*) were built (Fig. 3b). Typically, *trapeang* were closely connected with the temples. The vast majority of *trapeang* had a length–width ratio of 2:1 and were generally aligned E–W (Pottier, 1999; Evans, 2002). Almost every temple had also its own moat which was also dug into the water table. The moats were square or rectangular and generally oriented E–W and N–S (Pottier, 1999). Water was normally collected in the moats, house ponds and *trapeang* from rain and groundwater sources.

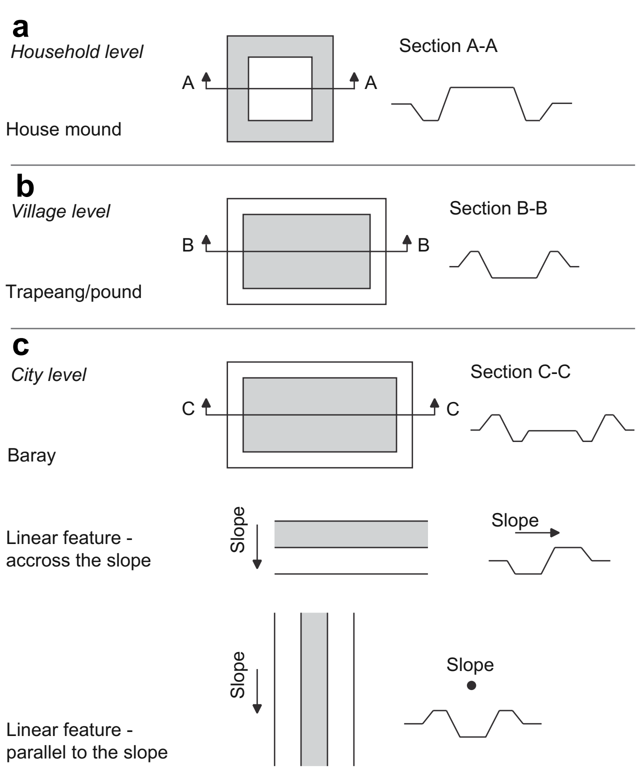

Fig. 3. Schematic illustration of the water management levels and typical associated structures. The different levels include: (a) household, (b) village, and (c) city levels (adapted from Pottier, 1999).

At the city level, two principal water management features can be identified: *baray* (large reservoirs) and linear features (channels, roads and embankments). It can be argued that these large-scale hydraulic features formed the city's intercommunication network (Fig. 4). In the urban area (aggregator and holding zone; see Section 3.2) the water was collected in *baray*, which were fed by channels originating from the natural rivers (in the collector zone). Angkor has four major *baray*: Indratataka (Baray of Lolei), Yasodharatataka (East Baray), West Baray, and Jayatataka (North Baray). *Baray* were fed directly by the channel network and rainfall. They were largely built by creating earthen embankments around a large enclosed area with limited excavation (Fig. 3c) (e.g. Fletcher, 2001). Channels criss-crossed the whole landscape (see Fig. 4). They were generally very shallow (1–2 m below ground level) and rather wide (30–40 m). The shallow channels kept the water as high as possible in order to supply the baray, the bottom of which were at ground level. Embankment(s) of the channels were approximately 1–2 m above the natural land surface and were often used as a road at the same time, and therefore serving multiple purposes.

3.2. Water management zones

The catchments of the Tonle Sap floodplain were fundamentally altered during the Angkorian period by diverting the water from natural rivers through channels to large reservoirs, creating a new system for dividing the landscape according to the use and management of water (Kummu, 2003). Thus, it appears to be desirable to divide the study area into water management zones according to elevation, spatial location of the major hydraulic features (Fig. 2), and the presumed historical use of water during the Angkorian era, to assess the range of causes and effects. The study area can be divided into three principal zones (Fig. 4): (A) collector zone; (B) aggregator and holding zone (temple zone); and (C) drainage and dispersal zone.

The extent of the water management system can be roughly based on the linear water features illustrated in Fig. 4, covering approximately 1200 km^2 of the study area (2885 km^2). The zoning, however, has been done for the whole study area to include the natural rivers and the whole floodplain in the analysis. The water system has been mapped for the two lower zones by Pottier (1999) using aerial photographs with extensive and systematic ground truthing. The collector zone has been mapped using radar images (Evans, 2002) and aerial photographs using GIS (Evans et al., 2007), supported by extensive field work.

The zoning was first presented by Kummu (2003) and it is elaborated further here by using the latest archaeological mapping (Evans et al., 2007) together with the elevation of the terrain. The borders of each zone are based here purely on elevation to keep the definition of the zones simple and transparent. However, one could argue whether different hydraulic features and structures should be combined with the elevation data to define the boundaries of the three zones and better reflect their water management functions. Moreover, the zoning is, at this stage, synchronic although a diachronic description of the water management zoning would be more valuable and reflect the development of the complex system over several centuries more accurately. The issue is discussed in more detail in Section 5.

Each zone has its typical water management characteristics irrespective of the natural catchment boundaries. In the

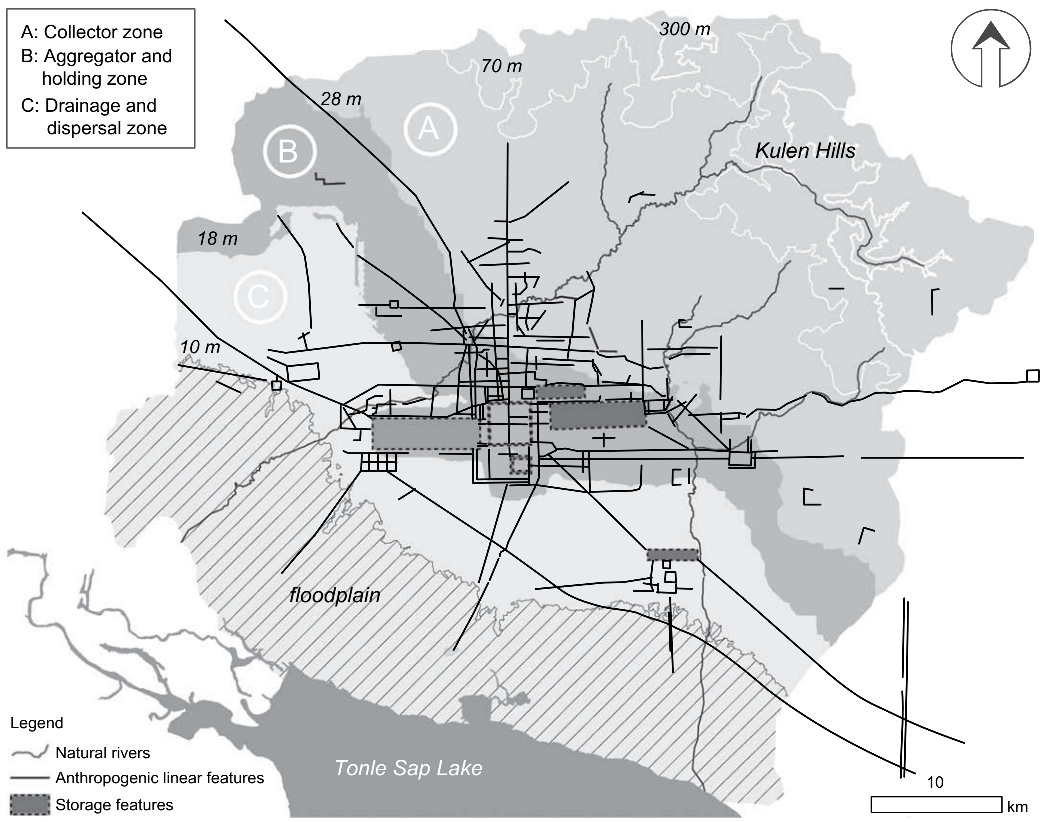

Fig. 4. Anthropogenic water management zones in Angkor based on elevation (in AMSL) and historical human use and management of water. Source of the GIS data: natural rivers, lake, DEM, and flood plain from the Mekong River Commission (2005); linear and storage features from Evans et al. (2007).

collector zone, the water was taken from natural rivers originating in the Kulen Hills primarily by north–south aligned channels. In the aggregator and collector zones the water was collected mainly in the large *baray*. The drainage and dispersal zone is the area that operated to disperse the water down into Tonle Sap Lake.

The collector zone includes the Kulen Hills and the upper floodplain between 28 and 490 m AMSL having a total area of 1218 km^2. The zone is divided into two sub-zones: (a) upper plain (elevation between 28 and 70 m AMSL), and (b) Kulen Hills (elevation above 70 m AMSL). One of the principal sources of water for the Angkor area is the Kulen Hills region, from which all three rivers originate. The precipitation in the upland areas is almost double that of the upper plain (Kummu, 2003). From the 10th or 11th century CE the water was diverted from the natural rivers to the aggregator and holding zone by N–S aligned channels, such as the Great North Channel and the Siem Reap Channel (the present-day Siem Reap River, locations in Fig. 2) (Lustig et al., 2008). East–west aligned zones behind the embankments were probably used to spread or collect the water from/to the main channel.

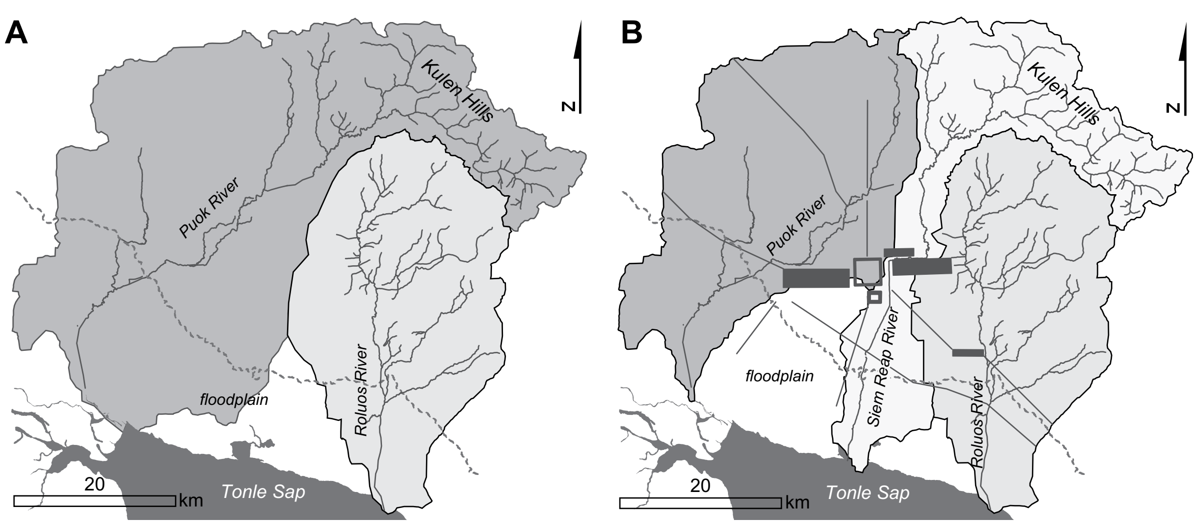

Fig. 5. Evolution of the watersheds: (A) natural watersheds; and (B) present watersheds. Source of the GIS data: natural rivers, lake, DEM, and floodplain from the Mekong River Commission (2005); linear and storage features from Evans et al. (2007).

The aggregator and holding zone includes the main temple area, excluding the Roluos group. It is situated between elevations of 18 and 28 m AMSL covering an area of 465 km^2. All the major constructions of channels and *baray* were done using earthen embankments. The *baray* were the main means of storage, but large amounts of water also accumulated in the temple moats and small reservoirs (*trapeang*), mainly from rain and groundwater sources.

The drainage and dispersal zone includes the area below the 18 m AMSL having a total area of 1202 km^2. The zone can be divided into two sub-zones, namely (a) Tonle Sap floodplain (1–10 m AMSL) and (b) upper drainage area (10–18 m AMSL). The Southeast Channel and Southwest Channel spread out from the West Baray towards the SE and SW, respectively. The former Siem Reap Channel and Angkor Wat Channel, together with the Southwest Channel, are the main means of transporting water from the aggregator and holding zone towards the lake. Those channels, orientated NE–SW, were relatively fast flowing with greater slope, whereas those orientated NW–SE, perpendicular to the slope of the land, were relatively slow-flowing channels as they were following the contours with very mild slope.

4. Impacts of human action on hydrology and sediment transportation

Human activities during the Angkor era, such as diverting water from natural rivers to storages through artificial channels, altered the natural hydrology of the Angkor area significantly. Building the channels across the natural slope of the terrain also created problems with erosion and sedimentation.

4.1. Impact of natural hydrology and watersheds

Today, the Angkor hydrological area consists of three catchments – Puok, Siem Reap and Roluos (Fig. 5B). However, before the Angkor kingdom emerged in the 9th century, the region probably had only two main catchments – the Puok (including most of the present Siem Reap catchment) and the Roluos (Fig. 5A) (Kummu, 2003). During the Angkorian epoch, the natural water system changed due to human activities breaking the original Puok watershed into two: the Siem Reap and the new Puok watersheds. This evolution of the watersheds is illustrated in Fig. 5. The analysis is based on the digital elevation model over the area (Kummu, 2003).

Parts of the main water-related constructions were off-take channels diverting water south from the Puok River. Lustig et al. (2008), supported by Groslier (1979), suggest that this happened as early as the 10th century. This estimate is based on the type of masonry work at Bam Penh Reach (Fletcher et al., 2003; Lustig et al., 2008), and the location of the off-take channel (Fletcher et al., 2003). One of the off-takes was the present upper section of the Siem Reap River. The assumed reason for the construction of this channel was to take more water down towards the East Baray. The off-take and evolution of the Siem Reap River is presented and discussed in more detail in Lustig et al. (2008).

4.2. Impact of erosion/sedimentation

The off-take channels from natural rivers, such as the present Siem Reap River, were built across the natural slope. Also, the artificial channels were straight, in contrast to natural rivers, which are strongly sinuous (Lustig et al., 2008). Straight channels have higher flow velocities and thus higher potential to erode. When the channel is built across the natural slope the channel tries to find equilibrium by eroding its bed and banks (e.g. Song and Yang, 1980).

The sedimentation and erosion processes in the Siem Reap channel have been modelled to simulate the erosion rates in the channel. Based on the model simulations, described in more detail in Lustig et al. (2008), the channel of the Siem Reap has had rather high erosion just downstream from its junction with the Puok River, to some 6 m below its original level (Fig. 6). The ground level is based on the 50 m resolution digital elevation model (Mekong River Commission, 2005) and TOPSAR elevation model (Fletcher et al., 2002). The original level of the channel bed is estimated to be around 2 m below that, derived from the typical dimensions of the channels in the area (see Section 3.1). About 15 km downstream from this junction the channel has been eroded around 5 m below the estimated original channel bed, based on the simulation, while there is little or no erosion at Siem Reap town, 25–30 km downstream from the junction (Fig. 6). The results of the modelling correspond to these measured bed levels rather well (Fig. 6), although a denser set of measurements would enable a more reliable comparison.

Model results (Fig. 6) therefore, suggest that the artificial channel has eroded along its upper part and accreted in its lower part downstream of Siem Reap town, so that its stream power is similar to that of other watercourses on the alluvial fan. If the stream power has now dropped to that of the other watercourses most of the down-cutting should have ceased (Lustig et al., 2008). Thus, the extensive modifications of the natural watercourses would have led to severe problems with erosion and sedimentation in the artificial channels. Down-cutting of the channels may also have led to difficulties in diverting water to the *baray*, the bottom of which were at ground level (see Section 3.1).

Moreover, the possible extensive forest clearance over the entire Angkor plain, that stands in a vast expanse of rice fields (Evans et al., 2007), may have had an impact on the sediments transported into channels and also the hydrology of the area. With the limited information available, however, no comprehensive conclusions of the issue can be drawn.

5. Discussion

Hydrological data for the Angkor region is limited due to the recent turbulent history of Cambodia, and therefore the analysis of the area's present-day hydrology is not comprehensive. However, the available information is enough to begin to understand the dynamics of the present-day natural hydrology. MRCS/WUP-FIN (2006), for example, provides a detailed water balance analysis on a larger scale based on the available data of Tonle Sap Lake and its catchments. However, the rainfall or other hydrometeorological conditions during the Angkorian era, and how these varied during that period, are not known. The present hydrological conditions must therefore be regarded as only an approximation of the conditions occurring during the medieval period.

The division of the Angkor area into water management zones, based on elevation, simplifies the complex system and allows an interpretation of its functional logic. It may, however, provide an overly simplistic picture of a system that was created over many hundreds of years, possibly to perform various functions. Furthermore, the zoning presented here may force the system into categories that have meaning for us as modern observers but may not reflect the intentions of those who created it. Zoning based exclusively on elevation may also lead to the misclassification of infrastructure. For example the channel/road leading NW from the West Baray, located in the aggregator zone, was presumably created to 'collect' rather than store water, and move it to the SE (i.e. across the slope). Probably a combined classification, based on the elevation and presumed function of infrastructure, would be a more accurate way to define the zones. The zoning is based on the principal, large-scale, water management function(s) of each area, and there has

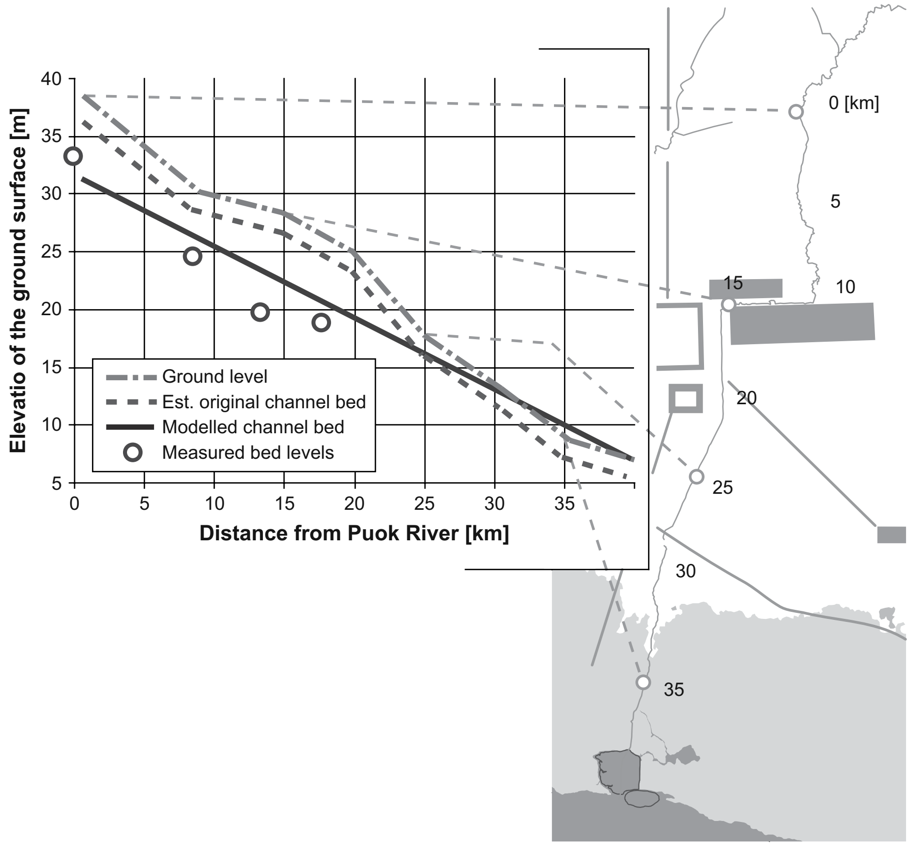

Fig. 6. The result of mathematical modelling of the down-cutting of the Siem Reap Channel. The dotted line is the original long section inferred for the bottom of the channel, while the solid one is the bottom of the channel after it stabilises (updated and modified from Lustig et al., 2008).

most likely been significant variation in water management function(s) at a smaller scale within the zones, as the study of water management levels already suggests.

The classification is synchronic and reflects the palimpsest that we are able to see today, based on the recent archaeological mapping and elevation, being a transparent and explicit method to classify the zones. It fails, however, to show how the system evolved with time. Possibly an evolving, diachronic classification of the water management zones would be more nuanced and would better reflect the complexity of the system, following e.g. Groslier's (1979) diachronic view of its evolution. Detailed chronological information on the water-related features is not yet complete, however. Despite the shortcomings in the zoning discussed above, it does help to understand the large-scale water management functions in the area. To summarise, the preliminary zoning presented here should be seen as a first step that should be developed and enhanced with more detailed information of the system's development over time.

The mathematical model used to estimate the erosion rate along the present Siem Reap River is based on many assumptions; for example, that the original channel bed was around 2 m below the ground surface. This is based on the typical dimensions of the human-made channels in Angkor but it is not certain whether the original channel conformed to this. Moreover, the Siem Reap channel was most probably built in two or more phases and thus, to conduct more reliable modelling, these different phases should be modelled separately. This remains a part of the proposed future work.

The human impact on natural watershed boundaries and erosion rates in human built channels are presented in the paper. The chronology for those alterations is, unfortunately, still uncertain. To increase understanding of the time sequence of those changes, multidisciplinary research is needed where, for example, hydraulic, hydrological, sedimentological, geomorphological, archaeological, historical, palaeontological, and geoinformatic research are combined. Examples of this approach can be found in the recent literature (e.g. Fletcher et al., 2003, 2006; Penny et al., 2006, 2007a,b).

6. Conclusions

The monsoons dominate the climate conditions in the Angkor area. This led to the development of a systematic and extensive water management network in the city of Angkor over hundreds of years, and which probably served multiple functions (e.g. a store for water for the dry seasons, or the mitigation of wet-season floods). This paper describes the present-day hydrology and main water sources in the Angkor area, specifically, natural rivers, groundwater and the Tonle Sap Lake. The article aims to describe how water management impacted on these natural sources of water during the Angkorian era.

The location of Angkor was, from a water management point of view, very convenient for many reasons. Firstly, groundwater was close to the surface throughout the year. Secondly, Tonle Sap Lake offered an excellent transport link to the riparian provinces and the Mekong River and, at the same time, secured part of the food supply and maintained a fertile floodplain to cultivate rice. Thirdly, natural rivers originating in the Kulen Hills meandered across the plain. A drawback was the long dry season for which water needed to be stored. Therefore the Angkorian engineers built an extensive water management network of channels and *baray* around and within the main temple area covering an area of approximately 1200 km^2.

The study area is formed by the natural boundaries derived from the three present watersheds of the area covering 2885 km^2. Due to the intensive human impact on natural waterways during the Angkorian era, it also proved to be necessary to divide the area into water management levels and zones. The three levels include: (a) household level, (b) village level and (c) city level, based on the typical water management structures in the Angkor area. The zoning is based on elevation and the latest archaeological mapping, and is intended to simplify the cultural water management of the area and assist in understanding the large-scale water management functions of Angkor. The zones can be divided into three principal types: (A) collector zone, (B) aggregator and holding zone (temple zone), and (C) drainage and dispersal zone. Each zone has the characteristics typical of each water management function. It has also been discussed within the paper whether this simplification, presenting a synchronic view of the water management system, has real value in understanding the functional hydraulics and management of the area. An evolving, diachronic classification of the water management zones would possibly be more nuanced and better reflect the complexity of the system. The classification presented in the paper is, therefore, the first iteration for these water management zones. Future research on more detailed chronological information on the water management features, such as channels and water reservoirs, is needed for diachronic zoning.

The extensive water diversion from the natural rivers to the channels in the collector zone has had a major impact on the catchments, breaking the original Puok catchment into two: the Siem Reap and the new Puok catchments. This changed the natural hydrology significantly and led to problems with erosion and sedimentation in the channels. Over time, these problems may have challenged the functionality of the hydraulic network and caused possible problems in the overall water management scheme in Angkor.

The results suggest that modern water management concerns, and particularly impacts of different types of human actions such as water diversions and reservoir constructions, on hydrology and sediment transportation – and further on ecosystems and people's livelihoods – should be examined with a much longer-term perspective than is presently employed. At Angkor, for example, human modification of the natural waterways from the 10th–11th centuries changed the natural hydrology of the area permanently and the decisions made then are still clearly visible in the landscape. The results of the paper also show that even small changes and disturbances in the natural equilibrium might start a chain reaction that over time may alter the whole natural system, as happened in Angkor when one off-take channel gradually evolved into a new river.

Present-day Cambodia, together with other countries in the Mekong region, is currently facing rapid economic development, and the speed and scale of water management projects, such as hydropower dams and irrigation schemes, are increasing. The assessment of environmental impacts is, however, often overlooked or viewed from a short-term perspective. This example from Angkor reminds us of the importance of comprehensive impact assessment, preferably with multi- and cross-disciplinary approaches, and that impacts of water management may be unforeseen or occur over hundreds of years.

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