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Top-down and bottom-up water management: A diachronic model of changing water management strategies at Angkor, Cambodia

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ABSTRACT

The Greater Angkor region, in northwestern Cambodia, was home to several successive capitals of the Khmer Empire (9th to 15th centuries CE). During this time, the Khmer developed an extensive agricultural and water management system characterized by top-down state-sponsored hydraulic infrastructure. Archaeological evidence now shows that the well-documented state temples and water management features formed the core of an extended settlement complex consisting of many thousands of ponds, habitation mounds, and community temples. These community temples are difficult to date, and so far, the lack of chronological resolution in surface archaeological data has been the most significant challenge to understanding the trajectory of Angkor's growth and decline. In this paper, we combine heterogeneous archaeological datasets and create diachronic models of the landscape as it was developed for agricultural production. We trace the foundation of new temple communities as they emerge on the landscape in relation to the construction of extensive state-sponsored hydraulic infrastructure. Together, these two forms of water management transformed over 1000 km^2 of the Greater Angkor Region into an elaborate engineered landscape. Our results indicate that, over time, autonomous temple communities are replaced by large, state-sponsored agricultural units in an attempt by the state to centralize production.

1. Introduction

Most societies with water management systems have an institutional locus that acts authoritatively to regulate and ensure proper operation (Hunt, 1988; Hunt et al., 1976, p. 391; O'Connor, 1995, p. 971). These social and political institutions are often categorized as top-down or bottom-up. Top-down systems tend to be sponsored by and serve the aspirations of the state, whereas bottom-up systems are sponsored by and prioritize the service of local communities (Morehart and Eisenberg, 2010). Some have argued that state-level societies often have top-down organization and are associated with larger and more complex water management systems (Bushnell, 1957, p. 56; Forbes, 1955, p. 8; Harris, 1979, p. 104; Linton, 1939, p. 286; Wittfogel, 1957). However, archaeological and ethnographic studies show that many large irrigation systems are managed through self-organized co-operatives with bottom-up administration (Hauser-Schäublin, 2005; Hunt, 1988; Hunt et al., 2005, 1976; Lansing, 2007; Lansing and Kremer, 1993; Leach, 1959; Ostrom, 1990; Scarborough and Burnside, 2010) or a combination of the two (Chase, 2019). For example, in Sri Lanka, a bottom-up feudal system of administration managed large water storage facilities and a sophisticated hydraulic system (Leach, 1959). Similarly, on the island of Bali, Indonesia, water is managed through a self-organized, bottom-up system of cooperatives associated with a network of water temples (Hauser-Schäublin, 2005; Lansing, 2007; Scarborough and Burnside, 2010).

In this paper, we investigate the relationship between top-down and bottom-up water management strategies for rice irrigation at Angkor, in Cambodia, where a massive and complex state-sponsored hydraulic system was developed over many centuries (Fletcher, Pottier et al., 2008). The infrastructure re-routed river systems and substantially transformed the natural hydrology of the region. The scale of the hydraulic system is perhaps unparalleled in the pre-industrial world, and includes channels 20 km in length and 40–60 m wide, reservoirs with surface areas of up to 16.8 km^2, and a vast network of walled fields used for flooded rice agriculture (Acker, 1998; Evans, 2007; Fletcher and Evans, 2012a; Hawken, 2012). Most prior accounts of agriculture at Angkor have focused on major infrastructure associated with top-down management because of theoretical preconceptions, scholarly preoccupation with Angkorian elites, and the prominence of the huge reservoirs and channels (Van Liere, 1980). However, in addition to the

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state-sponsored infrastructure, temple communities with residential hamlets and a primary temple with associated reservoirs regulated water management and rice production at a local level (Hawken, 2012, 2013). At Angkor, therefore, we see two distinct and parallel systems of state-sponsored/top-down and localized/bottom-up water management.

Archaeological work has now been underway in post-conflict Cambodia for more than two decades, producing archaeological maps and chronological models of development that finally allow us to ask more nuanced questions about the relationship between top-down and bottom-up water management strategies at Angkor (Evans et al., 2013; Klassen et al., 2018). Our knowledge of the archaeological landscape at Angkor is sufficiently developed to assess how the top-down and bottom-up strategies at Angkor interact with and complement each other, and also to evaluate whether, and how, this changes over time. If the two systems do not interact, we would expect small-scale temple communities to be scattered across the landscape without spatial association or functional linkages to state-sponsored hydraulic infrastructure; we would also expect large-scale, royal temple foundations to be directly associated with hydraulic infrastructure, indicating a clear separation of the two water management systems. If, on the other hand, the two systems were tightly coupled, we would expect to see clear evidence of spatial and functional relationships between top-down and bottom-up water management systems.

In this paper, we trace the emergence of temple communities and infrastructural networks on the landscape at multiple scales of time and space. With these diachronic models, we use geospatial statistical methods to determine whether bottom-up temple communities had access and functional linkages to the top-down, state-sponsored hydraulic infrastructure. Our results indicate that temple communities tend to cluster around emerging epicenters and state-sponsored hydraulic features, indicating the presence of tightly coupled top-down and bottom-up water management systems, in particular in earlier periods. However, our results also reveal a gradual shift over time, from an agricultural system that initially revolved around local temple communities taking advantage of state-sponsored hydraulic infrastructure, towards the increased accumulation of land by the state and the eventual predominance of the top-down approach.

2. Sources

2.1. Extended settlement network

The Greater Angkor region was the site of successive capitals of the Khmer and, by the beginning of the second millennium CE, had emerged as one of the largest aggregated urban complexes in the pre-industrial world (Fletcher and Evans, 2012b; Stark, 2004). The site has been the focus of intensive archaeological mapping projects since the early 1990s, and by 2007 most of the archaeological landscape across all of the watersheds of the Angkor region had been mapped by remote sensing and ground survey, with the exception of areas that were obscured by dense forest (Evans et al., 2007). In 2012, the Khmer Archaeology Lidar Consortium (KALC) organized a campaign of airborne laser scanning (or lidar) across 370 km^2 of Cambodia, including the forested areas at the center of Angkor (Evans et al., 2013). The lidar imagery revealed the underlying ground surface of Angkor through dense vegetation, and researchers were subsequently able to map the formally-planned urban core at the center of the Angkor complex, completing our archaeological maps of the site (Chevance et al., 2019; Evans, 2016; Evans et al., 2013). The maps reveal that there are two types of settlement patterns: epicenters, which are areas of dense occupation, typically orthogonal in structure, cardinally-oriented, and formally-planned; and beyond the epicenters, lower-density settlement patterns comprised of less-ordered scatters of community temples and associated reservoirs and occupation mounds (Fig. 1).

2.2. Epicenters

Epicenters have often been referred to as "cities" or "temple cities" (Briggs, 1999 [1951], pp. 220,221; Jacques and Lafond, 2007), but recent work by Carter et al. (2018) suggests that these areas were not discrete cities, but rather "civic-ceremonial zones" or royal-ritual districts (and/or neighborhoods) within the larger settlement complex. Carter et al. base this argument on the absence of evidence of specific urban components within the temple precincts, like markets and craft production areas (Carter et al., 2018). The epicenters are associated with large state-sponsored temples with foundation inscriptions that can be used to date both the temples and their associated occupation areas.

Epicenters were constructed successively across the landscape with evolving and distinct urban forms, which have been extensively mapped and surveyed (Evans et al., 2007; Pottier, 1999). Evans et al. (2013) present a general chronological model of urbanization and evolving urban forms, relying on decades of work on inscriptions, architecture, and art historical styles from the major temples at Angkor (Coe, 2003; Coedès, 1928; Stern, 1927). Following Pottier's model of urban development at Angkor (Pottier, 2000a), Evans et al. suggest that early urban centers at Angkor in the 9th to 10th centuries CE were "open cities", consisting of central state temples that were often moated, but lacked well-structured urban spaces either inside or outside the moats (Evans et al., 2013). Orthogonal and cardinally orientated grids followed in the 11th and 12th centuries CE at Angkor Wat and Angkor Thom. The rigidly-structured, grid-like partition of space in Angkor Wat is typical of urbanism in the early to mid-12th century CE (Fletcher, Penny, et al., 2008, p. 63). While there is an orthogonal, cardinally oriented city grid inside Angkor Thom, the city blocks are heterogeneous and not as formalized as those at Angkor Wat. The construction of the walls of Angkor Thom, at three kilometres on each side, marks a clear shift from *temple* enclosure to *city* enclosure. The lidar data also show that urban grids extend beyond the enclosures of both Angkor Wat and Angkor Thom. By the 12th century CE, the formally-planned and densely-inhabited urban area had developed into more or less its final form, concentrated in the area around Angkor Thom (Evans et al., 2013). Angkor reached its largest extent during this period, with the urban core expanding beyond the enclosure of Angkor Thom and covering over 35 km^2 and the low-density network of temples and rice fields extending throughout at least 1500 km^2 of the Greater Angkor Project's (GAP) 3000 km^2 study region.

This model of the development of the epicenters of Angkor was developed primarily from remote sensing and surface survey, but it has now been substantiated by other archaeological investigations including excavation. Overall, this work suggests a long and complicated history of occupation that existed in some form from at least the 6th century CE, was formalized during the 11th to 12th centuries CE and continues in some form to the present day (Stark et al., 2015). Excavations in the epicenters have focused on "house-mounds" associated with shrines and water management features, embankments with artifact accumulations, and walled enclosures at two Angkorian period temples: Ta Prohm and Angkor Wat. At Ta Prohm, the excavations focused on linear mounds and mound-pond features to determine the nature of occupation and obtain dates from cultural assemblages and ^{14}C dating. The results from the excavation indicate four occupational phases between the 10th and 13th centuries CE. At Angkor Wat, the excavations confirmed the city grid inside the enclosure and suggested that the epicenter represents one construction phase (Carter et al., 2018, 2019).

2.3. Hydraulic and agricultural systems

In addition to the epicenters, there are low-density zones extending in a huge swath along the northern edge of Cambodia's great lake, the Tonle Sap, spanning several thousand square kilometers and consisting

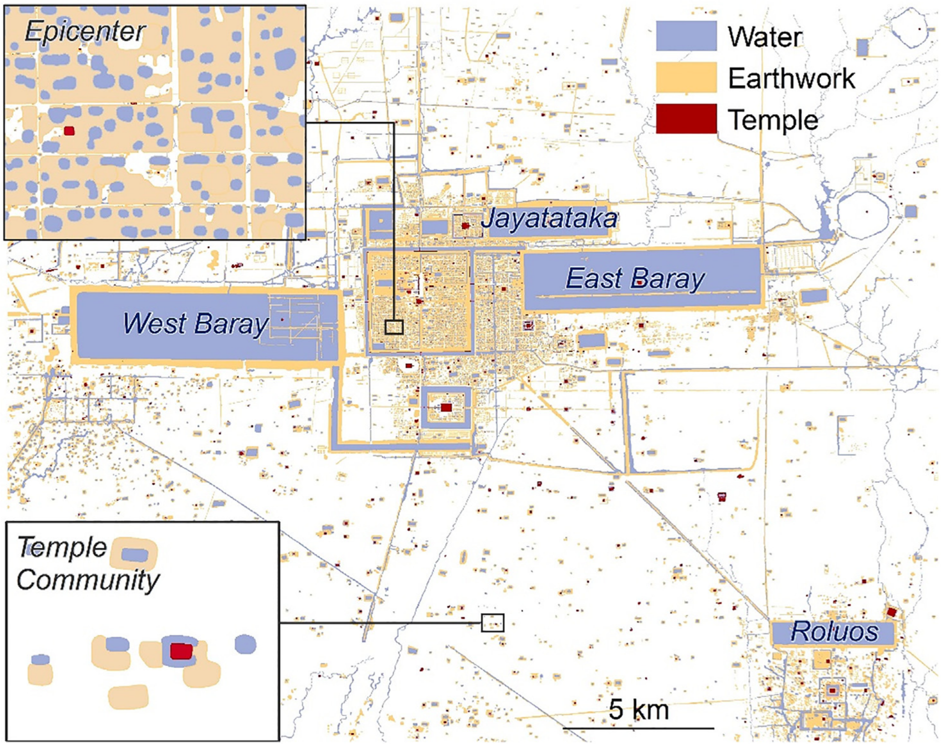

Fig. 1. Map of Angkor. The insets depict the regular grid of the epicenter and a temple community at the same scale.

of *trapeang-prasat* (reservoir-temple) configurations of moated temples and reservoirs with associated occupation mounds and ricefields (Evans et al., 2007; Hawken, 2012, 2013). We refer to individual temples and their associated reservoirs (trapeang-prasat configurations) and occupation mounds as temple communities. Inscriptional evidence suggests that temple communities were important administrative and economic centers, regulating many aspects of Khmer life (Vickery, 1998, p. 278). Similar notions of temple communities as economic centers have been documented in Bali (Lansing, 2007; Lansing, Cox, Downey, Janssen, and Schoenfelder, 2009; Lansing and Kremer, 1993) and in South India (Stein, 1960).

The inscriptional record indicates that temple communities were often organized at the local level (Hall, 1985; see also Lustig, 2009, pp. 52-53). Building on the work of Sedov, Hall proposes the *Temple Hierarchy Model* and suggests that a hierarchical network of temple communities integrated Angkor both economically and ideologically (Hall, 1985, 2011; Sedov, 1967). According to Hall's widely accepted model, temples served as collection and redistribution centers where resources were collected and passed from local temple communities to elite and royal temples (Hall, 2011). The inscriptional record documents the elite or royal status of approximately 100 temples at Angkor (for an example, see: K. 254: B:9-12 (1126 CE) (Coedès, 1951) Translation Philip Jenner). Royal and elite temples are often built of durable materials like sandstone and laterite and built on a massive scale. The famed Angkor Wat is one example of a royal temple. In addition to the temples with inscriptions, there are hundreds of community temples scattered across the Angkorian landscape without inscriptions. Today, these temples may consist of little more than a scatter of bricks or stones, or in some cases even just a faint topographic impression of a moated mound.

Over centuries, state-sponsored hydraulic infrastructure aggregated to form one of the largest hydraulic systems in the pre-industrial world. The construction dates for many of the large features are described in Fletcher et al. (2008). Given the size and complexity of the hydraulic infrastructure, much research to date has focused on the centralized elements of the system, and in particular the question of whether they were ritual or functional (Acker, 1998; Bourdonneau, 2003; Fukui, 1999; Stott, 1992). However, it is now widely accepted that these large centralized features had both functional and ritual purposes (Pottier, 2000b).

In addition to the state-sponsored monumental building projects (e.g., the East and West Barays), there were many local adaptations made to the landscape in association with temple communities. As with Bali, temple communities at Angkor were involved in the management and distribution of water. This management included orchestrating and designing local water infrastructure for individual temple lands (e.g., moats and reservoirs) (K. 254: B:9–12 (1126 CE) (Coedès, 1951, pp. 180–192 Translation Philip Jenner). An inscription from the North Kleang depicts a map of a temple-ricefield landscape with temples indicated and boundary markers demarcating the extents of agricultural systems (Coedès, 1951 K. 542). Studies of remote sensing data and inscriptions have identified spatial associations among temples, hydraulic features, and rice fields and have substantiated the relationship between temples and rice production (Groslier, 1974, 1979; Hawken, 2012, 2013; Lustig and Hendrickson, 2012). Similarly, archaeological excavations have revealed associations between temples and water management features, such as laterite (stone-lined) channels, leading from the temple moats to nearby ricefields (Bâty, 2005; Pottier, 2000b).

Evaluating common alignments between nearby features on the terrain has played a key role in establishing functional and chronological relationships between elements of the surface archaeological record. Hawken, for example, has analyzed the relationship between rice field walls and temples (Hawken, 2011; Pottier, 2000b) He identified three consecutive spatial signatures (radial, coaxial, and cardinal) that he argues indicate an increase in the scale of operation and complexity of reuse across the Angkorian landscape over time (Hawken 2011: 236). Radial systems originate from temples into the surrounding landscape. Temples with similar orientations are interwoven with coaxial systems that form large topographically sensitive matrixes that change along a single axis. Cardinal systems, in contrast, are characterized by orthogonal and cardinally orientated grids that seem to extend from individual temples. All three systems are strongly associated with local temples (Hawken, 2013, p. 364). Based on associations with the dates of specific hydraulic infrastructure and superimposition of features, Hawken argues that radial systems date to the pre-Angkorian period. Coaxial systems were utilized from the pre-Angkorian period throughout the Angkorian period, and cardinal system emerged in the 10th century CE, often in association with state-sponsored hydraulic infrastructure and covering larger areas. The timing of the emergence of radial and coaxial phases is unknown. However, they appear to have emerged before the Angkorian period. In contrast, the origin of the cardinal systems is linked to the Angkorian period (Hawken, 2012). This work shows how chronological information from well-dated features such as temples can be used as a basis for inferring the dates of features on the landscape, such as agricultural systems and hydraulic features, that are otherwise difficult to date. In this way, we can build a web of relative spatial, functional and chronological information that is anchored in places to calendar dates by temples and inscriptions.

2.4. Inscriptions

Inscriptional records suggest a transfer of land ownership from autonomous village communities to elites during the 10th and 11th centuries CE. In an analysis of inscription land sales, Lustig and Lustig (2019) found that approximately half of the records of land sales in the 10th and 11th centuries CE were nominally by individuals while many of the others were by communal groups — families, villages or corporations or associations known as *varṇa* and *varga*. The buyers were always of the same or higher status than the vendors, indicating that land was passing to more elite ownership. Nearly two-thirds of named vendors were titled *vāp*, free males of middle-ranking status. Another significant group, titled *loñ*, were of somewhat higher rank and arguably linked more closely to the elite (Mabbett, 1977). By the mid-11th century CE *vāp* disappear from the inscriptions, and from the start of the next century *loñ* are seen in roles as temple personnel. Soon after, records of land sales all but cease. Lustig and Lustig suggest these changes are due to both the relative shortage of land for new foundations and to the curtailment of privileges previously enjoyed by elites in control of large temple land holdings (Lustig and Lustig, 2019).

3. Methodology

3.1. Dating temple communities

The chronological information for the hydraulic system was drawn from Fletcher et al. (2008). The dates for the temples communities were drawn from Klassen et al. (2018), who use a combination of semi-supervised machine learning and multiple linear regression to predict dates for temples without dates (from either inscriptions or art historical elements). We include 936 temple communities in our analysis (see Fig. 2), with 3351 associated reservoirs/ponds and 915 associated moats. In total, we were able to assign dates to over 5000 features (Fig. 3).

3.2. Assessing spatial clustering of temples

To assess whether peripheral temple communities are clustered on the landscape or are randomly distributed on the landscape, we conducted an average nearest neighbor analysis. Average nearest neighbor calculates the average distance between the centroid of each temple and the nearest temple. This value is then compared with the predicted hypothetical average distance between temples if the same number of temples were randomly distributed within the same defined space. The average nearest neighbor ratio is defined as the observed average distance between temples divided by the hypothetical average distance between randomly distributed temple (Ebdon, 1991). If the index is greater than one, there is a trend towards dispersion. If the index is less than one, there is clustering. This calculation requires a fixed study area, which we defined as 3000 km^2 (the approximate area of the Rolous and Siem Reap/Puok River catchments).

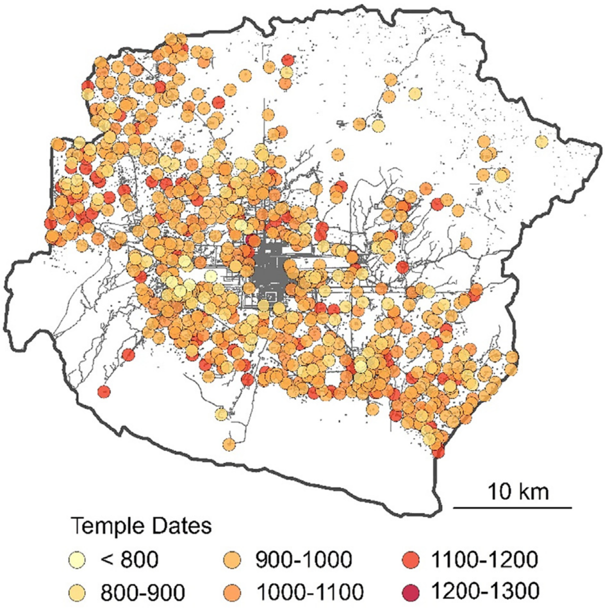

Fig. 2. Dated features in the greater Angkor region.

To determine where the temple communities nucleate on the landscape and if they cluster around pre-existing and contemporaneously emerging epicenters, we evaluated the point density of temples (using the centroid of each temple). Point density calculates a magnitude-per-unit area based on the number of features that are within a defined neighborhood of a given point. We first converted all dated temples to points based on the location of their centroids. We then converted the points from a projected coordinate system (WGS 1984 UTM zone 48 N) to a geographic coordinate system (WGS 1984). Using the point density tool available in ArcMap 10.5.1, we calculated the density of point features in the neighborhood of each output raster cell. The value for each output raster cell is calculated as the number of points that are within the neighborhood of the cell divided by the area of the neighbourhood.

To test whether the nucleation occurred around hydraulic infrastructure, we measured the average distance between the temples and large-scale hydraulic features for each period using the “Spatial Join” tool in ArcMap 10.5.1. We then created random points on the landscape for each period using the “Create Random Points” tool in ArcMap 10.5.1. For each period, we created as many points as there are temples. We used a shape file of the study area to define the boundary. The results indicate that the temples do cluster around hydraulic infrastructure in comparison to the random points.

Using the results from the point density of temple communities (using the centroid of each temple) and all features (using the centroid of each temple, reservoir, and moat), we identified areas of nucleation on the landscape for each period. To identify instances of polynucleation and primary and secondary areas of nucleation, we consider areas in the top 20% of relative density as primary nucleation areas and areas in the top 20–60% of relative density as secondary nucleation areas (Fig. 3).

4. Results

4.1. Nearest neighbor analysis

The results from the nearest neighbor analysis indicate that cumulative temple community distributions trend towards clustering with ratios around 0.64 at a significant level ($p = 0$) for all centuries. When

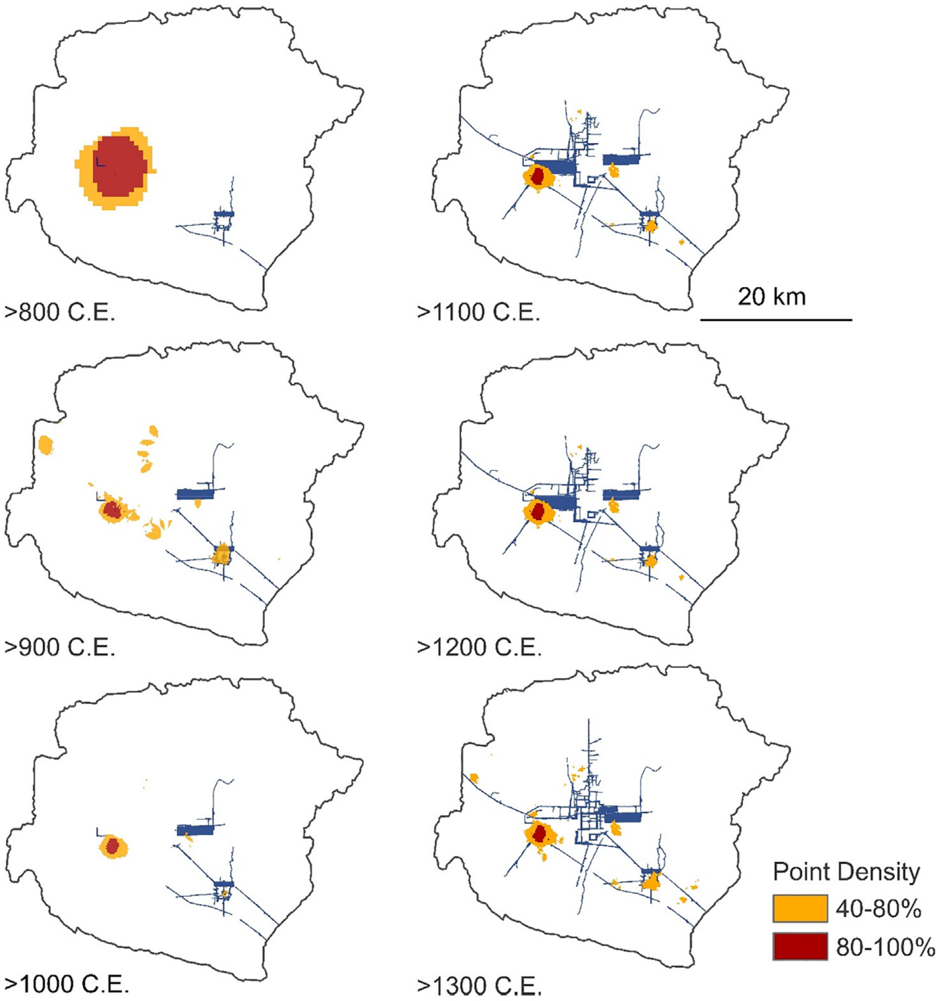

Fig. 3. Point density analysis of temple communities only (using the centroid of each temple) showing areas of primary and secondary clustering during each century.

Table 1
Results from the average nearest neighbor analysis by century for new temple constructions and cumulative temples on the landscape. If the nearest neighbor ratio is less than 1, there is clustering. Similarly, a negative z-score also indicates clustering.

Century (CE)	Observed mean distance (m)	Hypothetical mean distance (m)	Nearest neighbor	z score	p-value
800–899	1121	1790	0.6264	−10.9330	0
900–999	657	1004	0.6545	−18.0170	0
1000–1099	1364	2165	0.6302	−8.9492	0
1100–1199	1520	2243	0.6778	−7.5252	0
1200–1299	2006	6454	0.3109	−5.5932	0
1300–1327	4888	12,247	0.3991	−2.5703	0.0102
> 900	1062	1735	0.6120	−11.7141	0
> 1000	557	869	0.6419	−21.5854	0
> 1100	512	806	0.6352	–23.6944	0
> 1200	497	758	0.6555	–23.7926	0
> 1300	488	753	0.6486	−24.4238	0
> 1327	487	752	0.6482	−24.496	0

only the new constructions for each period are considered, there is clustering with ratios around 0.65 ($p = 0$) for the 9th – 12th centuries CE and heightened clustering in the 13th and 14th centuries CE with ratios of 0.31 ($p = 0$) and 0.40 ($p = 0.01$), respectively (Table 1). Temples are expected to cluster around areas that are more agriculturally suitable for rice production. While we did expect to see clustering in these areas, what is notable is that the level of clustering changes among time periods.

4.2. *Point density analysis*

The results from the point density analysis indicate that temples cluster closest to the hydraulic infrastructure during the 8th, 12th, and 13th centuries CE (Table 2). The temples during the 9th, 10th, and 11th centuries CE have an average distance of almost three times further away. In the 8th century CE, there is a primary area of nucleation around the future location of the West Baray where there was likely a hydraulic structure that preceeded the West Baray. There is some development around the Roluos area but this is overshadowed by the activity at the near the West Baray. In the 9th century CE, the areas of nucleation remain in the Rolous area and south of the West baray and there is a new area of nucleation south of the East Baray and south of the future location of Angkor Wat. This may indicate that there was a

Table 2
Distance (m) between temples and random points to hydraulic features.

Year (CE)	Normal	Random
< 800	2561	14,112
800–900	6000	11,051
900–1000	6863	12,618
1000–1100	5992	13,094
1100–1200	2584	8414
1200–1300	1891	9367

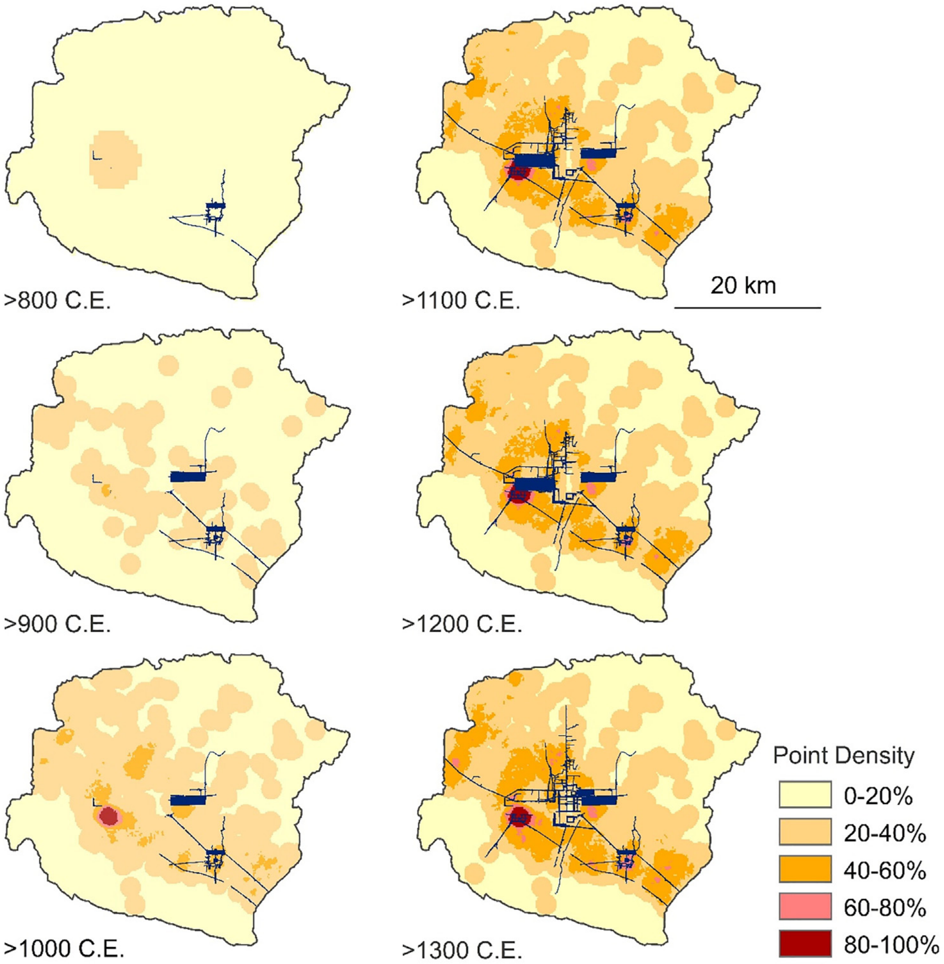

Fig. 4. Relative point density of temples on the landscape (based on the centroid of temples).

water feature in this area that was later destroyed during the construction of Angkor Wat, which we know was built in one phase. The areas of nucleation remain south of the East and West Barays and the Roluos area through the remainder of the periods.

We also compared the relative density of all features on the landscape over time (Fig. 4). There are sharp increases in density on the landscape from the 9th to 11th centuries CE. After the 11th century CE, the density does not increase significantly (Fig. 4).

5. Discussion

The results indicate that temple production units cluster around contemporary epicenters and hydraulic features, which suggest that top-down and bottom-up water management strategies operated in unison at Angkor. The nucleation of temples around the West Baray and Roluos in the 9th century CE coincided with the construction of the massive reservoir there with its associated network of channels (Fletcher, Pottier, et al., 2008). This nucleation of temple communities seems confined to these two areas and does not yet extend to the greater Angkor region. During the 10th and 11th centuries CE, the areas of nucleation gravitated towards the East Baray, with secondary areas of nucleation around the southwest corner of the West Baray and the Roluos, mirroring the location of state-sponsored hydraulic infrastructure building projects for each century. By the 12th and 13th century CE, the entire space was subsumed into a massive low-density urban network of local temples encompassing the epicenters (Fig. 4). Because temple communities tend to cluster around newly-constructed hydraulic features, we argue that they were likely utilizing the infrastructure built by the state while retaining some autonomy over land ownership and agricultural practices.

As previously noted, inscriptions from as early as the 10th century CE become increasingly concerned with the rights of land-owners, land grants, and land disputes (Ricklefs, 1967), which scholars have argued indicates increased competition for access to land (Vickery, 1985). However, by the mid-11th century CE, specific titles of free males of middle rank (the *vāp*) are no longer referenced in the context of land transactions or the foundation of new temples. By the 12th century CE, the title for the free males of higher rank (*loñ*) is referenced as temple personnel rather than as landowners. Lustig and Lustig argue that this inscriptional data reflects more competition for land during this period, leading to the concentration of the ownership of land to the elites (Lustig and Lustig, 2019).

The landscape data support the inferences from the inscriptions as fewer temples are founded during the 11th century CE (Klassen et al., 2018). The decrease in the foundation of temple communities in the second half of the 11th century CE coincides with a period of intensified urbanization of the epicenters, whose populations were likely relying on agricultural surplus from the temple communities (Evans et al., 2013). We do not expect that the Greater Angkor region supplied all the resources and rice required by the urban population (Hendrickson, 2007, p. 258). For example, during the 10th and 11th centuries CE other large temple foundations, such as Banteay Srei, were founded in open areas north of Angkor that are less well-suited to rice agriculture because of poor access to water and marginal soils. It seems logical that local production would increase with the foundations of epicenters that peaked during the 12th and 13th centuries CE (Evans et al., 2013);

however, the landscape and inscription evidence suggests the foundation of fewer temple communities. It is possible that this indicates an intensification of agricultural production in response to increased population in the epicenters; however, this hypothesis requires further testing.

6. Conclusion

Social institutions that regulate access to water are key components of water management systems (Anderies, 2006; Hunt, 1988; Hunt et al., 2005; Hunt et al., 1976; O'Connor, 1995; Ostrom, 1990). In the literature, we find a prevailing categorical distinction between top-down systems, which imply hierarchy, centralization, and state control. In contrast, bottom-up systems imply heterarchy, localization, and community control.

In this analysis, we have traced top-down and bottom-up water management systems at Angkor over time. In contrast to the dichotomy presented in the literature, our analysis indicates that the system at Angkor was a hybrid one, combining elements of top-down and bottom-up water management. These results suggest that combining top-down and bottom-up water management strategies may have allowed Angkor to thrive and expand through the 11th century CE. After the 11th century CE, we identify a shift from the construction of temple communities on previously-undeveloped land towards the development of large, state-sponsored temples on land previously owned and developed by temple communities. We argue that increased competition for land and increased demand for surplus led to the gradual accumulation of land by elites as part of a state-sanctioned effort to extract more resources from peripheral areas of the Greater Angkor region. This concentration of land ownership would have undermined the autonomy and decentralization of community-organized agricultural production as fewer local temple communities were founded, and as land rights associated with the pre-existing temples were transferred to elites.

This hypothesized change in the administration of agriculture has significant implications for our understanding of the Khmer empire, including a change in the structure of the ownership and management of land. Further testing is required to understand the implications in the change of land ownership for the resilience of the system. However, we note that this period of rapid change and urbanization in the 12th and 13th centuries, which coincides with the emergence of very large populations in epicentres, represents the apogee of Angkor's political power and foreshadows an extended period of political and economic decline in the following centuries (Penny, Hall, Evans, and Polkinghorne, 2019). Our analysis adds to a body of recent research (Evans et al., 2013; Penny et al., 2018) which suggest that processes of urbanisation, concentration of land ownership and management, the development of inertial hydraulic infrastructure, and rapid growth in the population of non-rice producing citizens in the urban core all conspired to introduced systemic vulnerability into the network of Greater Angkor, creating challenges to its longer-term viability as a regional political centre.

Credit Authorship Contribution Statement

Sarah Klassen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Damian Evans:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaa.2020.101166.

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