Adaptive Capacity of the Water Management Systems of Two Medieval Khmer Cities, Angkor and Koh Ker

by

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ABSTRACT

Understanding the resilience of water management systems is critical for the continued existence and growth of communities today, in urban and rural contexts alike. In recent years, many studies have evaluated long-term human-environmental interactions related to water management across the world, highlighting both resilient systems and those that eventually succumb to their vulnerabilities. To understand the multitude of factors impacting resilience, scholars often use the concept of adaptive capacity. Adaptive capacity is the ability of actors in a system to make adaptations in anticipation of and in response to change to minimize potential negative impacts.

In this three-paper dissertation, I evaluate the adaptive capacity of the water management systems of two medieval Khmer cities, located in present-day Cambodia, over the course of centuries. Angkor was the capital of the Khmer Empire for over 600 years (9 th -15 th centuries CE), except for one brief period when the capital was relocated to Koh Ker (921 – 944 CE). These cities both have massive water management systems that provide a comparative context for studying resilience; while Angkor thrived for hundreds of years, Koh Ker was occupied as the capital of the empire for a relatively short period. In the first paper, I trace the chronological and spatial development of two types of settlement patterns (epicenters and lower-density temple-reservoir settlement units) at Angkor in relation to state-sponsored hydraulic infrastructure. In the second and third papers, I conduct a diachronic analysis using empirical data for the adaptive capacity of the water management systems at both cities. The results suggest that adaptive capacity is useful for identifying causal factors in the resilience and failures of systems over the long term. The case studies also demonstrate the importance and warn of the danger of large centralized water management features.

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CHAPTER 1:

INTRODUCTION

In recent years, many studies have evaluated long-term human-environmental interactions related to water management across the world, highlighting both resilient systems and those that eventually succumb to their vulnerabilities (Diamond, 2009; Dunning et al., 2011; Gill et al., 2007; Haug et al., 2003; Hegmon et al., 2008; Hodell et al., 1995; Kennett et al., 2012; Lucero et al., 2015; McGovern et al., 1988; Medina-Elizalde & Rohling, 2012; M. C. Nelson et al., 2010; Redman & Kinzig, 2003; Turner & Sabloff, 2012). Understanding the ability of systems to successfully change while maintaining essentially the same functions is crucial to the success of present and future urban landscapes. To understand the multitude of factors impacting resilience, scholars often use the concept of adaptive capacity. Adaptive capacity is the ability of actors in a system to make adaptations in anticipation of and in response to change to minimize potential negative impacts. Relief and development organizations often examine elements of adaptive capacity of water management systems and the social institutions that regulate them to assess the ability of contemporary countries to respond to and prepare for climate change. The impact of elements of adaptive capacity on the overall resilience of water management systems is most visible in the long term where one can observe changes that communities experience as the population grows, political and religious regimes change, and the climate varies around them over centuries.

In my dissertation, I evaluate the adaptive capacity of the water management systems of two medieval Khmer cities, located in present-day Cambodia, over the course of centuries. Angkor was the capital of the Khmer Empire for over 600 years (9th-15th centuries CE), except for one brief period when the capital was relocated to Koh Ker (921 – 944 CE). These cities are ideal for studying water management systems because the Khmer developed some of the largest and most complex water management systems in the pre-industrial world. They also provide a comparative context for studying resilience; while Angkor thrived for hundreds of years, Koh Ker was occupied as the capital of the empire for a relatively short period.

This dissertation is comprised of three stand-alone papers and an appendix. In the following sections, I first introduce the concepts of resilience and adaptive capacity. I then report the introductions from the appendix, each of the stand-alone articles, and a description of how each chapter contributes to the central database and thesis. This dissertation is a product of my collaborative relationships with the Cambodian Archaeological LiDAR Initiative, the University of Sydney, the Greater Angkor Project, the Khmer Archaeology LiDAR Consortium, the École Française d'Extrême-Orient, and the Authority for the Protection and Management of Angkor and the Region of Siem Reap. Through these collaborative relationships, I was granted access to the archaeological site and data. As a result of partnerships, several of the chapters are co-authored with my collaborators. Appendix I and Chapter 2 are co-authored with Jonathan Weed. Jonathan helped devise mathematically robust methods for dating temples and grouping temple communities. Chapter 4 is co-authored with Terry Lustig and Damian

Evans. Terry and Damian have been working at Koh Ker for several years. This chapter would not have been possible without their collaboration and their contributions to our understandings of Koh Ker and its water management system (Evans et al., 2013; Lustig et al., 2017).

Adaptive Capacity

Scholars recognize that complex social-ecological systems are dynamic and are interested in understanding the implications of change for the ability of systems to function (Eakin & Luers, 2006; Srinivasan et al., 2013; Turner, Kasperson, et al., 2003). Social scientists have identified several crucial attributes (resilience, vulnerability, robustness, and adaptive capacity) that can be used to better understand how well systems respond to hazards and change (Burby, 1998; Cumming et al., 2005; Gallopin, 2006; Miller et al., 2010; Turner, Kasperson, et al., 2003; Turner, Matson, et al., 2003). These theoretical concepts have been used by scholars in many disciplinary fields as heuristic with considerable variation in their uses and definitions (Gallopin, 2006, p. 293; Redman, 2014, p. 37). For example, resilience, vulnerability, and robustness have been used both as system-level concepts and as measures to evaluate the performance of specific elements of systems.

For this dissertation, I seek to operationalize these concepts to better conceptualize and assess my archaeological research questions. I propose that adaptive capacity can be used as a unifying heuristic to build a framework, incorporating notions of vulnerability and robustness, for evaluating social systems in the past and present. Furthermore, I argue that adaptive capacity lends itself particularly well to archaeological case studies and can be used by archaeologists to engage in interdisciplinary discourses of system-level resilience. In this section, I will first outline the fundamental attributes of resilience, vulnerability, robustness, and adaptive capacity. I will then discuss implications for identifying, measuring, and assessing them in the archaeological record.

Resilience

Resilience theory has been applied by natural and social scientists to understand how interlinked, complex systems respond to exogenous and endogenous hazards (Anderies et al., 2013; Carpenter et al., 2001, p. 765; Hegmon et al., 2008). Turner et al. 2003 define hazards as stressors (continuous or slowly increasing pressure) and perturbations (spikes in pressure) that threaten the ability of systems to function (Turner, Kasperson, et al., 2003, p. 8074) (See also: Gallopin, 2006, p. 295). The concept of resilience was first introduced in the early 20th century in materials engineering. Since its introduction in engineering, the concept has been adopted in many fields to study ecological, social, and social-ecological systems.

Ecological Systems. In 1973, C.S. Holling introduced ecological resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling, 1973, p. 14). In contrast to engineering resilience, which measured a system's ability to return to its original state after a systemic stress or shock, Holling's definition of ecological resilience asserts that change is a normal condition and that ecosystems can move between multiple equilibrium, stable states (also called stability domains) (Holling, 1973, 1996) (See also: Folke et al., 2010; Miller et al., 2010, p. 13). Because systems move through multiple stable states, the very nature of systems may change over time (Scheffer, 2009); however, resilient systems are able to gracefully adapt to change and move through stable states with minimal loss to their controls, identity, and ability to function (Redman 2014).

Social Systems. The theoretical concept of social resilience has been utilized by social scientists to better understand how social institutional systems respond to external and internal hazards like political, social, and environmental change (Adger, 2000, p. 347; Gallopin, 2006, p. 297).

Social-Ecological Systems. Social-ecological system investigations combine elements from social and ecological studies. They characterize resilience as the ability of systems to undergo change and disturbances while maintaining essentially the same system functions, controls, and identity, but recognize human capabilities for learning and adaptation (Carpenter et al., 2001, p. 766; Chapin et al., 2009, p. 24; Cumming et al., 2005, pp. 975, 976; Fiksel et al., 2014; Folke et al., 2010; M. C. Nelson et al., 2010, p. 32; Park et al., 2013, p. 357; Redman, 2014; Walker et al., 2006, p. 14; Walker et al., 2004; Walker & Salt, 2006, pp. 1,37).

Across these different applications, resilience is often conceptualized as a system-level concept (general resilience) or as a quality of specific elements of systems (specific resilience). Generalized resilience measures resilience to all, unspecified, and novel hazards (Folke et al., 2010; Miller et al., 2010, p. 13; Walker et al., 2009, p. 14). It can be used heuristically to assesses system-level qualities, like the amount of stress systems can take, the ability of systems to self-organize, and the capacity of systems to learn and adapt to unforeseen disturbances (Anderies et al., 2013, p. 7; Folke et al., 2010; Walker et al., 2009, p. 14; Walker & Salt, 2006, p. 121), that are beneficial to the functioning of systems. Unfortunately, this can be difficult to apply in practice (Cumming et al. 2005: 976). Specified resilience, in contrast, addresses the question of "resilience of what to what." This allows resilience thinkers to assess specific variables and their responses to specific disturbances (Carpenter et al., 2001) (See also: Anderies et al., 2013, p. 7; Folke et al., 2010; Miller et al., 2010, p. 13; M. C. Nelson et al., 2010, p. 33; Walker & Salt, 2006, pp. 120-121).

Vulnerability

Vulnerability has been widely used in the social and natural sciences (Gallopin, 2006, p. 294). Most frequently, vulnerability is used to refer to the level of risk of exposure to hazards and the susceptibility of a system to damage or harm when it is exposed, (Adger, 2000) (See also: Chapin et al., 2009, p. 22; Gallopin, 2006, p. 294; Miller et al., 2010, p. 14). This can be applied at the general system-level, to assess how the system as a whole responds to exposure and hazards (O'Brien & Leichenko, 2001), and as a quality of specific elements of systems. When conceptualized as a quality of specific elements of systems, elements can be assessed based on their "vulnerability of what to what." For example, in the southern Yucatán, hurricanes tend to arrive during the main harvest period, which can drastically reduce crop yields. In response to this specific stress, farmers take an early dry-season crop to reduce their vulnerability to hurricanes (Turner, Matson, et al., 2003).

Robustness

The concept of robustness is most typically associated with computation methods and algorithms (Huber, 1972) to understand how well the outputs of the method or algorithm work despite variations, incomplete, or imperfect inputs (Anderies et al., 2013; Csete & Doyle, 2002). Similarly, in engineering, robust control refers to the ability of a system to maintain performance when it is exposed to perturbation (Anderies, 2006). In social-ecological systems, robustness, as a system-level concept, can be understood as the sensitivity of a system's outputs (the system's ability to function and maintain its identity) to variation in inputs (shocks, stresses, and perturbations).

Robustness can also be understood as a quality of specific elements of systems (Anderies, 2006; Anderies et al., 2013). In order to assess robustness, the analysis must be able to measure performance, identify the boundaries of the system, and identify trade-offs between performance, shocks, and robustness (Anderies et al., 2013). As such, robustness can be used to design attributes that will prevent systems from failing given a defined range of uncertainty (defined shocks, stresses, and perturbations) (Anderies et al., 2013). Robustness and vulnerability are often used as complementary terms in resilience theory. Much research surrounds robustness-vulnerability trade-offs, where systems become more vulnerable to some hazards when they are made more robust to others (Anderies, 2006, p. 134).

Adaptive Capacity

Adaptive capacity refers to the ability of actors in a system to make adaptations in anticipation of and in response to change in order to improve the system's condition. It is defined in the glossary of the Intergovernmental Panel on Climate Change (IPCC) as "the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (*Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 2001). The concept emphasizes the behaviors and capacity of people and social institutions to learn and respond to external change and internal processes (Brown & Westaway, 2011; Carpenter & Brock, 2008; Folke et al., 2010; D. R. Nelson et al., 2007; Smit & Wandel, 2006; Walker et al., 2004, p. 7).

Adaptive capacity is often conceptualized as a system-level concept that is manifested and expressed through adaptations to specific elements of systems. Adaptations are the decision-making processes and actions of actors and institutions. They are intended to maintain the established order of the system and increase the robustness of specific elements of the system to minimize potential near-term, specific vulnerabilities. As such, adaptations are often modest, incremental, and conservative (Redman, 2014; Smit & Wandel, 2006, pp. 282,286; Walker & Salt, 2006, p. 119). In general, there are two types of adaptations: incremental adaptations and transformational adaptations. Incremental adaptations are extensions of pre-existing system behaviors that act to minimize the damage or enhance the benefits of change and do not alter the underlying dynamics of systems (Kates 2012: 7156). Transformational adaptations are adopted for larger scales and intensities, are new introductions to the system, or transform places (Kates et al., 2012, p. 7156). Transformational adaptations may be necessary when systems have large vulnerabilities or when they face severe change that threaten even robust elements of the system (Kates 2012: 7158). In some cases, transformational adaptations in the social domain result in entirely alternative governance systems and agencies (Olsson et al., 2006). While transformational adaptations have the ability to make entire systems more resilient, uncertainties about change and the benefits of adaptation, cost, path dependencies, and institutional and behavioral barriers can make them difficult to implement (Kates 2012: 7158; Schoon, Fabricius, Anderies, & Nelson, 2011).

Linking Resilience, Vulnerability, Robustness, and Adaptive Capacity: Implications for Archaeology

While adaptive capacity is very similar to resiliency, I argue that adaptive capacity is a better unifying system-level conceptual tool for archaeologists. Practically speaking, it is easier to operationalize and less nebulous than resiliency (Cumming et al., 2005, p. 976). Adaptive capacity is often tied to adaptations made to technical and infrastructural aspects of systems. Technology influences how infrastructure is built and together they form engineered systems with physical infrastructure (canals, embankments, reservoirs, etc.) that are artifacts of anthropogenic intention and intervention (Park et al., 2013, p. 357). Successful adaptations made to infrastructure, which increase robustness and introduce few or minor vulnerabilities, can enhance adaptive capacity. Alternatively, a failure to implement necessary adaptations can reduce adaptive capacity. Both scenarios have implications for system-level resiliency.

I also argue that adaptive capacity is more successful at linking ecological and social domains than resilience. While much work has been done linking these principles in social-ecological systems, ecology remains the dominant field from which most resilience theory arises. Adaptive capacity acknowledges both ecological (ex. climate change) and social (ex. changing social and political values) hazards that are often ignored in ecological resilience theory. It also emphasizes the role of humans in making systems more resilient (Walker et al., 2004, p. 9). It understands that human designed responses are often both reactive and proactive; in contrast to biological systems, where adaptations to hazards are purely reactive (Gallopin, 2006, p. 300; Walker et al., 2006, p. 15)

Finally, adaptive capacity allows for value-based assessments of system elements. The human agency afforded by adaptive capacity recognizes that resilience is not always a good thing for humans (Carpenter et al., 2001, p. 766; Cumming et al., 2005, p. 976). For example, poverty is very resilient in the sense that it persists; however, poverty is not good for all people (Sachs et al., 2004). Because adaptive capacity considers adaptations designed by humans, an anthropogenic-centered value judgement can be made on the outcome of the direction of the state of the system. As such, adaptive capacity allows the human decision-making processes behind qualities, like inequality, to be better understood in the context of social-ecological systems.

Evaluating Adaptive Capacity

Adaptive capacity is often assessed on the basis of several elements of the system that allow for adaptation. These elements include the economic, biological, and cultural diversity, the capacity of actors to learn, experimentation and innovation, and the capacity to govern effectively (Chapin et al., 2009). The economic, biological, and cultural diversity refer to a variety of capitals (natural, human, social, built) that contribute the raw materials that allow for adaptations (Elmqvist et al., 2003; Norberg et al., 2008) and in many cases, determine what types of adaptations are possible. While the capitals are the building blocks, innovation and experimentation can be used to increase the ability of options available for the system.

It is not possible to directly assess adaptive capacity; instead traditional frameworks typically focus on measuring its indicators based on the elements (capitals and assets) that influence it (Dulal et al., 2010), while some frameworks also consider processes and functions (Jones et al., 2010). There is not a comprehensive and agreed upon list of elements that influence adaptive capacity. This is because adaptive capacity can be applied to an array of types of human-environmental systems, which have unique types of challenges. However, many programs have adopted the five capitals (human, economic, social, physical, and natural) from the UK Department of Foreign and International Development (DFID)'s Sustainability Livelihoods framework (Elasha et al., 2005; Vincent, 2007). Some frameworks also try to incorporate intangible elements, like redundancy, institutions and entitlements, knowledge and information, innovation, and flexible forward-looking decision-making and governance (Jones et al., 2010).

In this analysis, I evaluate the elements of adaptive capacity that are relevant to water management systems and are possible to measure given the limitations of the archaeological record. The capitals and assets are easiest to measure in archaeological case studies, as they often leave material traces on the landscape. However, I was also able to identify some intangible processes. I chose to assess adaptive capacity at Angkor and Koh Ker based on three elements of the asset base: human capital (population), natural capital (the amount of water stored in the system), physical capital (infrastructure) as well as an intangible element: redundancy (multiple functionally analogous elements in the system). I also quantified institutions and entitlements (percent of temple communities that have access to state hydraulic infrastructure) at Angkor, but the calculations were not possible at Koh Ker. I argue that these chosen elements represent the diversity of elements often referred to in the adaptive capacity literature. I am holding all of the other elements constant because I cannot measure them due to the limits of the archaeological record. The elements will be defined in Chapter 3.

Semi-supervised machine learning approaches for predicting the chronology of archaeological sites: A case study of temples in medieval Angkor, Cambodia

I begin by introducing Appendix I because it is a key antecedent to the work presented in Chapters 2 and 3. Due to the long history of occupation and the complex palimpsest at Angkor, I first needed to develop a chronologically sequenced urban morphology of the region. There are over 25,000 mapped features in the greater Angkor region that are included as part of this study. These features were both too numerous and too difficult to date using traditional archaeological methods, which presented a serious impediment to diachronic analyses of the water management system. In Appendix I, I focus on one key component of the landscape, local temples. There are 1437 local temples that have been mapped and/or surveyed in the greater Angkor region. These temples were primary production units, with associated hydraulic features and residential hamlets (discussed further in Chapter 2). By dating these temples, it is then possible to date their associated hydraulic features and populations (Chapter 2), which was necessary to calculate the elements of adaptive capacity of the water management system over time (Chapter 3). Statistical methods for dating the temples are limited due to incomplete datasets. To date the temples, I used multiple-linear regression combined with a semi-supervised machine learning algorithm, which uses known date information for some units along with a similarity measure between plan units to infer dates for the remainder of the temples. Our results suggest that temples from 821 – 1150 CE with a 50-year average absolute error and temples before and after this period with approximately 100-year absolute average error. This article will be submitted to the *Journal of Archaeological Sciences*.

Appendix Introduction

Archaeologists often need to date and group artifact types to discern typologies, chronologies, and classifications. For over a century, statisticians have been using classification and clustering techniques to infer patterns in data that can be defined by algorithms. In this scenario, algorithms refer to the equation, rules, or set of steps and pattern recognition necessary to transform the data (input) into the categories (output) (Alpaydin, 2014, p. 1). Pattern recognition is the process of finding structure in data that can be used to divide the data into discrete categories (Salazar, 2012, p. 2). In the case of archaeology, linear regression algorithms are often used to chronologically date features and sites, and pattern recognition is used to develop typologies and classifications. However, archaeological data is often expensive to collect, and analyses are often limited by poor sample sizes and datasets.

Recent advances in computation have allowed the machine learning community to use much of the same statistical theory to address more complex problems using increased computing power and larger datasets (Rasmussen & Williams, 2005, p. xiv). Machine learning mimics human pattern recognition and learning processes through a series of complex mathematical computations to find structure in large datasets (Salazar, 2012, p. 1).

These types of identification and classification problems are prevalent in archaeology. Our case study, Angkor, was the political center of the Khmer Empire (9th – 15th centuries CE) in present-day Cambodia. There are over 1400 temples in the greater Angkor region that were economic and religious centers of residential hamlets. Several mapping projects have shown the relationship between temples and other urban features, like occupation mounds and reservoirs (Evans, 2016; Evans et al., 2013; Evans et al., 2007). I argue that by dating the temples, I can also date associated urban features to create historical models of urban morphology. Ideally, I would like to create historical models for each one-hundred-year period for future studies evaluating changes in the landscape, water management system, and agricultural system over time.

In this paper, I first introduce statistical learning paradigms and our archaeological case study and dataset. I then explore four classical mathematical approaches to find statistically significant predictors for temple construction dates. I find that k-means clustering, discriminant function analysis, and principle component analysis cannot accurately predict temple dates to within 100-year time periods. Multiple linear regression can predict temples with a low absolute average error. However, it only works on well-specified data-points and cannot predict dates for approximately half of the temples. I then introduce semi-supervised machine learning as a potential method to address some of the inadequacies of supervised and unsupervised statistical paradigms. Our results indicate that graph-based semi-supervised machine learning, unlike multiple linear regression, can predict dates for all the temples in the dataset. When combined with the results of the multiple linear regression for more-specified data, I can create a historical model of urban development in terms of temple construction at Angkor for temples constructed between 821 – 1149 CE with an absolute average error (AAE) of 49-66 years.

Emerging epicenters and complementary centralized and decentralized water management systems at medieval Angkor, Cambodia

This chapter integrates over 20 years of archaeological mapping with the diachronic analysis of temple foundations from Appendix I. As part of this project, I mapped 19,000 previously unknown archaeological features (e.g., occupation mounds, channels, and reservoirs) revealed by remotely sensed data, which was combined with three other mapping projects to form a comprehensive map of over 25,000 archaeological features. In this paper, I define and date instances of two types of settlement patterns in the greater Angkor region, formally planned dense urban zones and lower-density agricultural units, and group and date reservoirs based on their associations with local temples. Using these data, I create models of the urban development of Angkor. I then analyze the spatial distribution of new temple communities over time. The results indicate that new temple communities are built near state-sponsored hydraulic features that were preexisting or built around the same time. The results also support inferences from inscriptions that there may have been more competition for land in the mid-11th century CE, which was followed by a centralization of land ownership by the state in the 12th and 13th centuries CE. The diachronic mapping work produced in this chapter lays the foundation for quantifying the five elements of adaptive capacity in Chapter 3. This article will be submitted to the *Journal of Anthropological Archaeology*.

Adaptive capacity at Angkor, Cambodia

In Chapter 3, I use geographic information system (GIS) analysis to quantitatively and qualitatively assess five elements of adaptive capacity over five centuries and three droughts at Angkor. Angkor was able to successfully navigate the first two periods of drought, but the third drought coincides with the collapse of populations living in the epicenters. The elements remain largely consistent between the three droughts with the exception of natural capital in the third drought. This suggests that natural capital may have been a causal element in the lowered resilience of the system in the third drought. This article will be submitted to *Ecology and Society*.

Chapter 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, defined as administration from the state or local level. Top-down systems often tend to serve the aspirations of the state, whereas bottom-up systems prioritize the service of local communities (Morehart & Eisenberg, 2010). Some have argued that state-level societies often tend to 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 cooperatives with bottom-up administration (Hauser-Schäublin, 2005; Hunt, 1988; Hunt et al., 2005; Hunt et al., 1976; Lansing, 2007; Lansing & Kremer, 1993; Leach, 1959; Ostrom, 1990; Scarborough & Burnside, 2010). For example, in Sri Lanka, a bottom-up feudal system of administration managed large water storage facilities and a sophisticated hydraulic system (Leach, 1959). Bali, Indonesia also manages water through a self-organized, bottom-up system of cooperatives associated with a network of water temples (Hauser-Schäublin, 2005; Lansing, 2007; Scarborough & Burnside, 2010). Blanton and Fargher suggest that the level of state involvement in the construction of water management infrastructure is dependent on the collective vs. autocratic political nature of the state. For example, highly centralized collective regimes are often involved in the construction of water management systems while highly centralized autocratic regimes are not (Blanton & Fargher, 2008).

In this paper, I consider new lines of evidence that shed light on the urban development and agricultural system of Angkor, Cambodia. Recent LiDAR data and archaeological investigations combined with over 20 years of mapping have been used to develop chronological models of the emergence of dense occupation areas at Angkor (Evans et al., 2013), referred to as epicenters (Carter et al., In Press). The state likely constructed the epicenters, which would have contained non-producers dependent on agricultural surplus (Evans et al., 2013). Prior accounts of agriculture at Angkor have focused on centralized infrastructure and production, because of both theoretical preconceptions and the documentation of huge reservoirs and channels (Van Liere, 1980). However, in addition to these large hydraulic works, there were approximately one thousand temple communities, lower-density settlements with residential hamlets and associated reservoirs, that would have been highly involved in the management of water for agricultural purposes. In a recent study, Lustig and Lustig use land sales records from inscriptions to argue that there was increased competition for land and a gradual shift of the state accumulating land from autonomous communities over time. I argue that these temple communities, in combination with extensive state-sponsored hydraulic infrastructure, were important components of the agricultural production system at Angkor in response to the increased demand for agricultural surplus for the epicenters from the 9th to 14th centuries CE and find landscape evidence to support Lustig and

Lustig's findings that there were fewer temples founded by local communities after the 11th century.

In the following sections, I trace the chronology and spatial development of temple communities in relation to emerging epicenters and the construction of state-sponsored hydraulic infrastructure. I first provide a historical and archaeological basis for defining temple communities at Angkor. I then use computational methods to group temples and reservoirs into temple communities and date the communities based on the temple chronology in Appendix I. I then perform a series of spatial statistical analyses that trace the foundation of new temple communities across five centuries. These analyses indicate that temple communities cluster around contemporaneous epicenters and state-sponsored hydraulic infrastructure and that there was a decrease in the construction of new temple communities in the 11th century CE. These results fit well with expectations drawn from inscriptions suggesting that there was more competition for land and fewer foundations of smaller, autonomous local temples during this period.

Chapter Introduction

In 2012, the Intergovernmental Panel on Climate Change stated that "water and its availability and quality will be the main pressures on, and issues for, societies and the environment under climate change" (UN, 2012), especially in increasingly urbanized environments (Boa & Fang, 2007; R. R. Brown & Farrelly, 2009; Collins & Bolin, 2007; Cosgrove & Rijsberman, 2000; Gober & Kirkwood, 2010; McDonald et al., 2011; Meinzen-Dick & Appasamy, 2002; Srinivasan et al., 2013). As populations increasingly move from rural to urban areas, water security and understanding how cities can best deal with issues of water supply and guard against water-related disasters will continue to rise in importance (UN, 2012, 2013). Water security is particularly crucial in developing urban areas in tropical environments characterized by monsoon systems, like Southeast Asia. Southeast Asia is currently undergoing rapid urbanization in flood-prone areas, and extensive agricultural development is quickly outpacing the availability of freshwater resources (UN, 2012, p. 24). These issues are exacerbated by the encroachment of urbanism to highly productive and fertile agricultural lands and by an increase in the frequency and magnitude of floods and droughts because of climate change. The consequences of these stresses manifest themselves through poverty, reduced production, and human causalities resulting from flooding disasters, like the 2011 monsoon season in Southeast Asia that claimed nearly 3000 lives. Additionally, there are about 600 million people in Asia who are undernourished, and this number is only expected to rise with increased demands on water availability and increased population pressure (UN, 2011).

Such rapid urbanization and water-related issues in Asia today were foreshadowed by historic cases like Angkor, Cambodia. Archaeologists can make a significant contribution to interdisciplinary discourses on adaptive capacity and human-environmental relationships by examining trade-offs social and ecological imperatives (Hegmon, 2017). Such trade-offs are most visible in the long term where one can observe changes that communities experience as populations grow, political and religious regimes change, and the climate varies over centuries.

In this paper, I evaluate the changing elements of adaptive capacity of the water management system at Angkor, which was the center of the Khmer Empire for over 600 years (9th-15th centuries CE). During this time, the Khmer developed one of the most extensive and complex water management systems in the pre-industrial world, which lasted centuries. In 1974, B.P. Groslier suggested the failure of the water management system precipitated the collapse of the urban center (Groslier, 1974, 1979). Recent research has demonstrated that the water management system was highly resilient for centuries. However, it may have ultimately succumbed to vulnerabilities related to path dependency and an over-extension of infrastructure that left the system vulnerable to an array of environmental factors like erosion and climate change (Buckley et al., 2010; Evans, 2007; Fletcher, 2007; Fletcher et al., 2003; Fletcher & Evans, 2012; Lieberman & Buckley, 2012). I now have sufficient data to test these propositions over the long term. Mapping from over two decades of survey has allowed us to identify and map over 25,000 archaeological features (temples, reservoirs, channels) in the greater Angkor landscape. I have also associated these features with a chronologically robust urban morphology that allows me to evaluate the system diachronically. Finally, high-resolution topographical data (a 50 cm digital terrain model derived from airborne laser scanning, or LiDAR) can be used for geographic information system calculations to quantify changes in the landscape over time.

With these data, I assess the adaptive capacity of the water management system diachronically with particular attention paid to three periods of drought, 1040-1090 CE, 1155-1170 CE, and 1200-1250 CE (Buckley et al., 2010). As discussed in Chapter 2, the first drought occurred near the end of a period of rapid expansion, while the final drought ushered in Angkor's period of decline. In this chapter, I compare the adaptive capacities of these phases in relative terms to gain insight into the resilience of water management systems of the past and present and the usefulness of the metrics of adaptive capacity for improving system-level resilience.

Systemic failure in the water management of an Angkor-era capital city: Adaptive capacity at Koh Ker, Cambodia

In contrast to Angkor, Koh Ker was occupied as the capital for a short period of time and the urban morphology and diachronic construction of hydraulic infrastructure can be discerned with relative clarity. During its time as capital, a 7 km long dike was constructed to the north of the city. In this chapter, I use GIS analysis to quantitatively and qualitatively assess five elements of the adaptive capacity and observed how the decision to build an unprecedentedly large water structure influenced the dynamics of adaptive capacity. This chapter builds off a recent publication (Lustig, Klassen, et al. 2017), which establishes the archaeological evidence for failure of the dike and provides estimates for the time frame of failure based on hydraulic and hydrological modeling. Lustig et al. (2017) was a necessary precursor to this one as it establishes the failure of the dike. This paper differs from Lustig et al. (2017) in that it views the water management system as a whole and through the lense of adaptive capacity, which allows me to draw comparisons with Angkor in the conclusion. This article is in submission with *Plos One*.

Chapter Introduction

Since its introduction in engineering, natural and social scientists have adopted the concept of resilience to understand better how complex social-environmental systems respond to shock and stress (Gallopin, 2006; Miller et al., 2010). Holling proposes that change is a normal condition and that ecosystems can move between multiple equilibriums and stable states (Holling, 1973, 1996) (See also: Folke et al., 2010; Miller et al., 2010, p. 13). Accordingly, the very nature of systems may change over time (Scheffer, 2009). Resilient systems can adapt to change and move through stable states with minimal loss to their controls, identity, and ability to function (Redman, 2014).

Resilience is most visible in the *longue durée* where one can observe changes that communities experience, as populations grow, political and religious regimes change, and the climate varies around them over centuries. In recent years, many studies conducted on long-term interactions related to water management have highlighted both resilient systems and those that succumb to their vulnerabilities. For example, studies in Mesoamerica have produced some examples of resilient water management systems, like that of Tikal (Lentz et al., 2015; Scarborough et al., 2012), in the process also providing a framework for studying collapse (Turner & Sabloff, 2012). Similarly, research from the United States Southwest indicates that while irrigation systems ameliorate vulnerability to variability in precipitation, they may create other environmental and societal vulnerabilities that require further transformations of the landscape (Nelson et al., 2010). In contrast, Bali, Indonesia represents a resilient system where water is managed through a self-organized, decentralized system of cooperatives associated with a network of water temples (Hauser-Schäublin, 2005; Lansing, 2007; Scarborough & Burnside, 2010, p. 350).

Scholars often use a variety of conceptual tools to operationalize broader themes of resilience. In this paper, I employ the argument that scholars can use adaptive capacity to build a framework of observable dynamics to understand the multitude of factors impacting the resilience of social-environmental systems. The Intergovernmental Panel on Climate Change defines adaptive capacity as “the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences” (*Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 2001). It is often evaluated by how effective a system is at responding to shocks. As such, systems with high adaptive capacity build and plan for shocks and stresses before they are realized. Adaptive capacity frameworks are often used by Non-Governmental Organizations for assessing the ability of developing countries to respond to climate change. Such organizations include the Intergovernmental Panel on Climate Change (IPCC), Care, Save the Children, World Vision, Africa Climate Change Resilience Alliance, and Oxfam (Dulal et al., 2010; 2007; Jones et al., 2010; Pettengell, 2010; World Resources Institute, 2009). Frameworks for assessing adaptive capacity often consider a combination of interrelated and interdependent elements that encompass the assets of systems, such as harnessed natural capital, physical infrastructure, and human capital, (Dulal et al., 2010; Elasha et al., 2005) as well as emergent properties, such as redundancy. Successful adaptations made to the physical infrastructure of systems are those that meet the social and environmental needs of the system while introducing few risks.

Using this framework, I evaluate the water management choices that were made at Koh Ker in response to increased water needs during its period as the center of the Khmer Empire in the 10th century CE. Before the 10th century CE, the water management system at Koh Ker consisted of small dikes blocking tributaries and hundreds of small reservoirs scattered across the landscape (Evans, 2013, pp. 101-102). Whether the population surged during the 10th century CE or if it had been steadily rising, it is reasonable to expect that Koh Ker needed more water to meet the economic and social needs of the city as the center of an empire. In response to these increased needs, a large embankment, which transformed and restructured the water management system, was built to the North of Koh Ker. I argue that in addition to providing a greater supply of water, the construction likely served as a key element of the king's statecraft. Water control features elaborated beyond functional necessity are a key component of the Khmer sacred geography and are seen elsewhere in association with temples. The results of this study highlight how centralizing resources within a system can increase risk and help explain the rapid decline of Koh Ker as the political center of the Khmer Empire.

Conclusion

In the final chapter, I provide concluding remarks about the work presented in this document and outline the methodological and theoretical contributions of this study. This project used a variety of methods, including GIS mapping with remote sensing (LiDAR), excavation, survey, ground-penetrating radar, and semi-supervised machine learning statistical analyses to construct an urban morphology of Greater Angkor and quantify elements of adaptive capacity of both systems over time. I review an intriguing set of large and complex water management systems in medieval Cambodia, with very different outcomes. While Angkor persisted for centuries, our models indicate that the large hydraulic features at Koh Ker failed within a matter of decades, which had catastrophic consequences for the city. Finally, this study demonstrates the utility of adaptive capacity for archaeologists studying human-environmental relationships over the long term. I find that the elements of adaptive capacity may not be useful as a composite concept, but rather to identify elements that may have caused the failure of the systems. In both cases, I identify the importance of large centralized features to increase the natural capital of the systems. However, both cases also warn of the danger of large, centralized water management features. At both Angkor and Koh Ker, the failure and disuse of the largest features, the West Baray and the dike, coincide with the collapse of the epicenters.

CHAPTER 2:

EMERGING EPICENTERS AND COMPLEMENTARY CENTRALIZED AND DECENTRALIZED WATER MANAGEMENT STRATEGIES AT MEDIEVAL ANGKOR, CAMBODIA

Sarah Klassen and Jonathan Weed

Abstract

Recent research at Angkor has aggregated over 20 years of archaeological map data, which is providing important new perspectives on the agricultural production system of the polycentric low-density urban complex. Much scholarly attention has been directed towards the functional vs. ritual nature of the huge reservoirs and channels (Van Liere, 1980). However, smaller, community-based agricultural units were likely important components of the agricultural system. In this paper, I trace the chronological and spatial development of two types of settlement patterns: 1) formally-planned dense urban zones that I call epicenters and 2) lower-density settlement units comprised of temples and associated reservoirs and occupation mounds that I call temple communities. Building from the work of Evans et al. 2013, I argue that groups of non-producers that lived in the epicenters would have been highly dependent on agricultural surplus produced by temple communities utilizing local and state hydraulic features. To

determine if new temple communities are built near state-sponsored hydraulic infrastructure, I conduct a nearest neighbor analysis and point density analysis, which suggest that temple communities cluster around state-sponsored hydraulic features. This analysis also indicates that there is a decline in the establishment of new temple communities in the 11th century CE, around the same time that inscriptions indicate increased competition for land. This suggests that there was a restructuring in the agricultural system and a transition from food being primarily produced by small, autonomous temples to large temples, often associated with the state, with large landholdings accumulated from smaller temples.

Chapter 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, defined as administration from the state or local level. Top-down systems often tend to serve the aspirations of the state, whereas bottom-up systems prioritize the service of local communities (Morehart & Eisenberg, 2010). Some have argued that state-level societies often tend to 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 cooperatives with bottom-up administration (Hauser-Schäublin, 2005; Hunt, 1988; Hunt et al., 2005; Hunt et al., 1976; Lansing, 2007;

Lansing & Kremer, 1993; Leach, 1959; Ostrom, 1990; Scarborough & Burnside, 2010). For example, in Sri Lanka, a bottom-up feudal system of administration managed large water storage facilities and a sophisticated hydraulic system (Leach, 1959). Bali, Indonesia also manages water through a self-organized, bottom-up system of cooperatives associated with a network of water temples (Hauser-Schäublin, 2005; Lansing, 2007; Scarborough & Burnside, 2010). Blanton and Fargher suggest that the level of state involvement in the construction of water management infrastructure is dependent on the collective vs. autocratic political nature of the state. For example, highly centralized collective regimes are often involved in the construction of water management systems while highly centralized autocratic regimes are not (Blanton & Fargher, 2008).

In this paper, I consider new lines of evidence that shed light on the urban development and agricultural system of Angkor, Cambodia. Recent LiDAR data and archaeological investigations combined with over 20 years of mapping have been used to develop chronological models of the emergence of dense occupation areas at Angkor (Evans et al., 2013), referred to as epicenters (Carter et al., In Press). The state likely constructed the epicenters, which would have contained non-producers dependent on agricultural surplus (Evans et al., 2013). Prior accounts of agriculture at Angkor have focused on centralized infrastructure and production, because of both theoretical preconceptions and the documentation of huge reservoirs and channels (Van Liere, 1980). However, in addition to these large hydraulic works, there were approximately one thousand temple communities, lower-density settlements with residential hamlets and associated reservoirs, that would have been highly involved in the management of water for agricultural purposes. In a recent study, Lustig and Lustig use land sales records from inscriptions to argue that there was increased competition for land and a gradual shift of the state accumulating land from autonomous communities over time. I argue that these temple communities, in combination with extensive state-sponsored hydraulic infrastructure, were important components of the agricultural production system at Angkor in response to the increased demand for agricultural surplus for the epicenters from the 9th to 14th centuries CE and find landscape evidence to support Lustig and Lustig's findings that there were fewer temples founded by local communities after the 11th century.

In the following sections, I trace the chronology and spatial development of temple communities in relation to emerging epicenters and the construction of state-sponsored hydraulic infrastructure. I first provide a historical and archaeological basis for defining temple communities at Angkor. I then use computational methods to group temples and reservoirs into temple communities and date the communities based on the temple chronology in Appendix I. I then perform a series of spatial statistical analyses that trace the foundation of new temple communities across five centuries. These analyses indicate that temple communities cluster around contemporaneous epicenters and state-sponsored hydraulic infrastructure and that there was a decrease in the construction of new temple communities in the 11th century CE. These results fit well with expectations drawn from inscriptions suggesting that there was more competition for land and fewer foundations of smaller, autonomous local temples during this period.

Historical Background

Urban Development of Angkor Cambodia

The greater Angkor region was the site of successive capitals of the Khmer and emerged as one of the largest aggregated urban complexes in the preindustrial world after a thousand years of gradual urbanization across Southeast Asia (Fletcher, 2012; Stark, 2004). Khmer inscriptions suggest that Jayavarman II founded the kingdom in 802 CE after uniting Khmer kingdoms. At this time, Jayavarman II became *cakravartin* (sovereign of the world) and established the cult of the *devarāja* and the royal liṅga, which established a divine-kingship (Briggs, 1999 [1951], pp. 89-90). After unification, urbanization was rapid and expansive. By the 12th century CE, the empire ruled most of mainland Southeast Asia and continued to flourish until the 13th century CE before entering a period of decline (Evans, 2007, p. 18; Kummu, 2009; Stark, 2004, p. 103).

Settlement Patterns

In 2012, researchers from the Greater Angkor Project (GAP), an international team of researchers, partnered with five other teams to form the Khmer Archaeology LiDAR Consortium that organized a mission of airborne laser scanning (light detection and ranging, or LiDAR) across 370 km^2 of this world heritage site (Evans et al., 2013). This technology revealed the underlying ground surface of Angkor through dense vegetation. With the LiDAR imagery, the team uncovered a formally-planned urban grid that helped define a more comprehensive nature of urbanism at Angkor (Evans et al., 2013). With this imagery, I identify two types of settlement patterns: epicenters (areas of dense occupation) and temple communities (lower-density settlement units comprised of a temple and associated reservoirs and occupation mounds) (Figure 1).

Epicenters I argue that the densely-inhabited areas are analogous to Maya epicenters. These areas have often been referred to as cities or temple cities (Briggs, 1999 [1951], pp. 220,221; Jacques & Lafond, 2007), but recent work by Carter et al. (In press) 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. (In press) 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., In Press). The epicenters are often associated with large state-sponsored temples associated with specific kings.

The epicenters were constructed contemporaneously and successively across the landscape with evolving and distinct urban forms, which have been extensively mapped and surveyed (Figure 1) (Evans et al., 2007; Pottier, 1999b). 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 articles by Pottier on open cities (Pottier, 2000a), Evans et al. suggest that early urban centers were characterized by central state temples in the 9th and 10th centuries CE at Rolous and south of what would become the West Baray and Angkor Thom. These temples were often moated, but the urban landscape within the moated area was largely unstructured (Evans et al., 2013). Orthogonal and cardinally orientated grids followed in the 11th and 12th centuries at Angkor Wat and Angkor Thom. The highly-structured space in Angkor Wat characterize urbanism in the early to mid 12th century (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. In contrast to the grids from the 9th and 10th centuries that were restricted to temple precincts, the construction of the walls of Angkor Thom marks a 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, nucleated around Angkor Thom (Evans et al., 2013). Angkor reaches 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 the Greater Angkor Project's (GAP) 3000 km^2 study region.

Recent archaeological investigations conducted by GAP have substantiated this model of the development of the epicenters of Angkor. These investigations suggest a long and complicated history of occupation that existed in some form in the 6th century CE, was formalized during the eleventh to twelfth centuries and continues in some form to the present day (Stark et al., 2015). The excavations 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 C14 dating. The results from the excavation indicate four occupational phases between the 10th and 13th centuries CE (Heng et al., 2015). At Angkor Wat, the excavations confirmed the city grid inside the enclosure and suggested that the epicenter represents one construction phase (APSARA et al., 2015).

Temple Communities In addition to the epicenters, there are low-density zones extending along the Tonle Sap characterized by trapeang-prasat (reservoir-temple) configurations of moated temples and reservoirs with associated occupation mounds and ricefields (Evans et al., 2007; Hawken, 2011, 2013). I refer to individual temples (trapeang-prasat configurations) and their associated reservoirs and occupation mounds as temple communities. Inscriptional evidence suggests that temple communities were important administrative and economic centers for communities, 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 et al., 2009; Lansing & Kremer, 1993) and in South India (Stein, 1960).

The inscriptional record indicates that temple communities were often organized at the community level (Hall, 1985; see also Lustig, 2009, pp. 52-53). Building on the work of Sedov (Sedov, 1967), Hall (1985) proposes the *Temple Hierarchy Model* and suggests that a hierarchical network of temple communities integrated Angkor both economically and ideologically (Hall, 1985, 2011). 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). Hawken similarly proposes that the state economically integrated peripheral

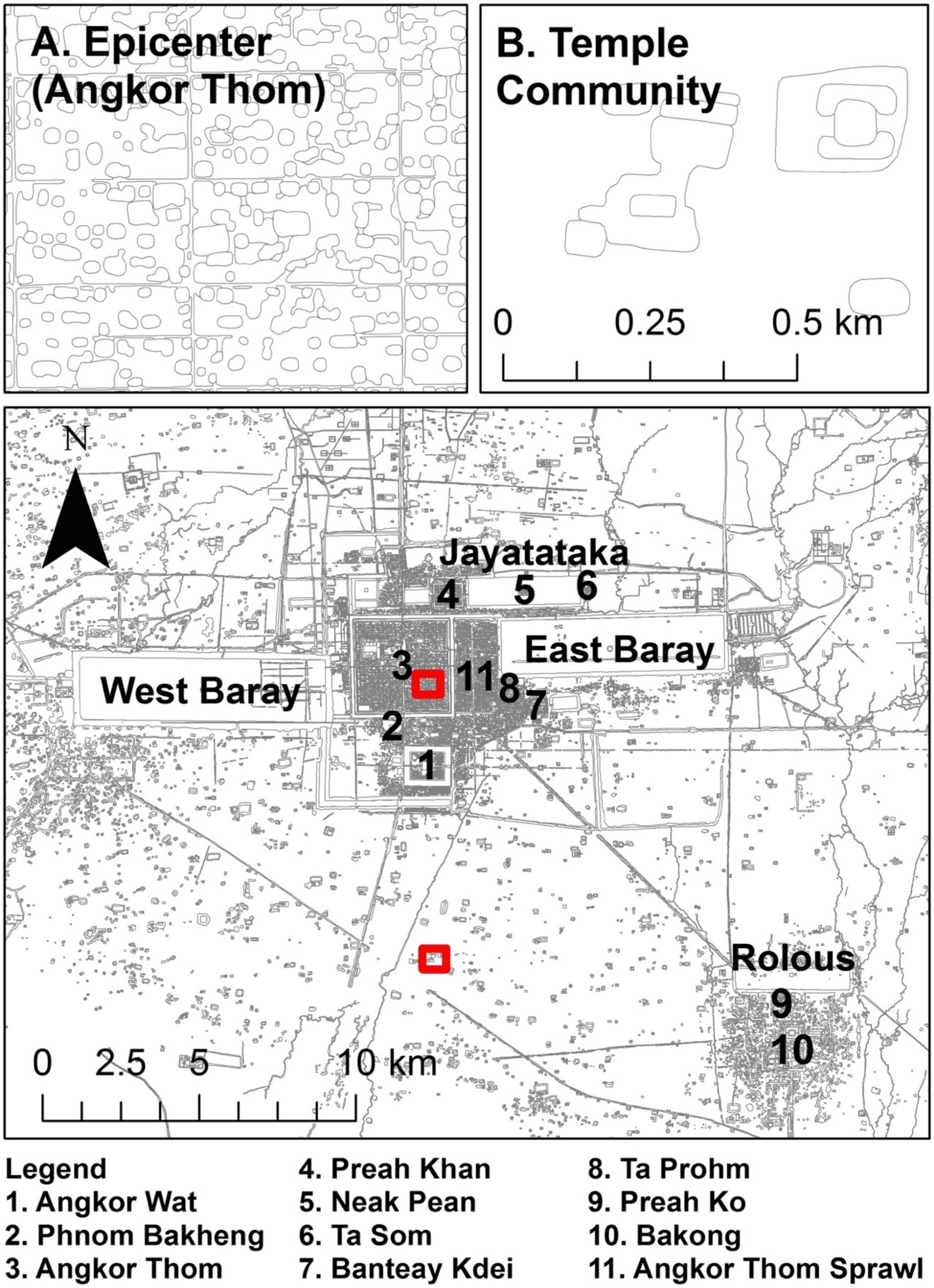

Figure 1: Map of Angkor, Cambodia showing notable features and epicenters. A. and B. depict the regular grid of the epicenter and a temple community at the same scale.

temples through rent collection and sharecropping (Hawken, 2013, p. 365). The inscription 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. Angkor Wat, the largest religious monument in the world, is one example of a royal temple. In addition to the temples with inscriptions, there are approximately 1000 temples scattered across the Angkorian landscape without inscriptions. Today, these temples consist of anything from a footing to a few bricks or stones or are little more than the faint impression of a moated mound. These temples were most likely associated with small, local communities having less political power and wealth.

Water Management at Angkor

Rice was the primary component of the Angkorian economy and a complex state-sponsored hydraulic system developed over the course of centuries (Fletcher, Pottier, et al., 2008). This hydraulic infrastructure was massive. It re-routed rivers and transformed the hydrology of the region over time. The scale of the hydraulic system is likely unparalleled in the pre-industrial world with channels having lengths of over 20 km and 40-60 m wide, reservoirs with surface areas of up to 16.8 km^2, and thousands of agricultural fields (Acker, 1998; Evans, 2007; Fletcher & Evans, 2012; Hawken, 2011). The construction dates for many of the large features are described in Fletcher 2008 and reconstructed here (Figure 2). Given the size and complexity of the hydraulic infrastructure, much research to date has focused on the centralized elements of the system and the ritual-functional dichotomy (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).

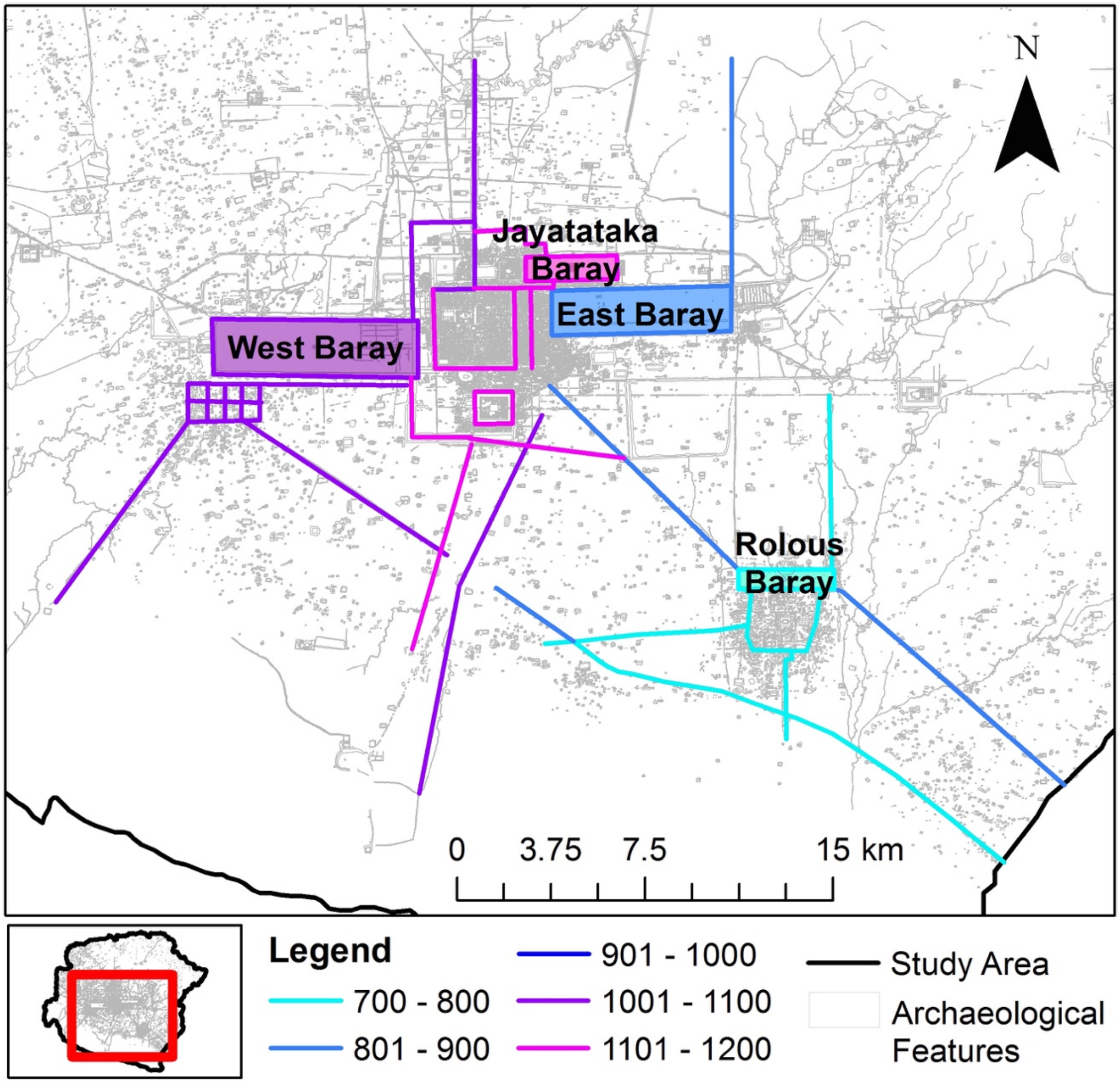

Figure 2: Development of the state constructed hydraulic infrastructure over time based on Fletcher et al. 2008.

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. Like 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 each agricultural system's extents (Coedès, 1951 K. 542). Remote sensing projects have identified spatial associations among temples, hydraulic features, and rice fields that have substantiated the relationship between temples and rice production (Groslier, 1974, 1979; Hawken, 2011, 2013; Lustig & 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).

In 2011, Hawken systematically evaluated the relationship between large-scale settlement patterns, temples, and ricefield morphology (Hawken 2011). 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 (Figure 3). 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 (Figure 4). 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 (Figure 5). Figure 5, from Hawken 2011 (Figure 13.1), depicts the duration of signature ricefield systems on the landscape. The emergence of radial and coaxial phases is unknown. However, they appear to have emerged before the Angkorian period. In contrast, the original of cardinal systems is linked the Angkorian period (Hawken, 2011).

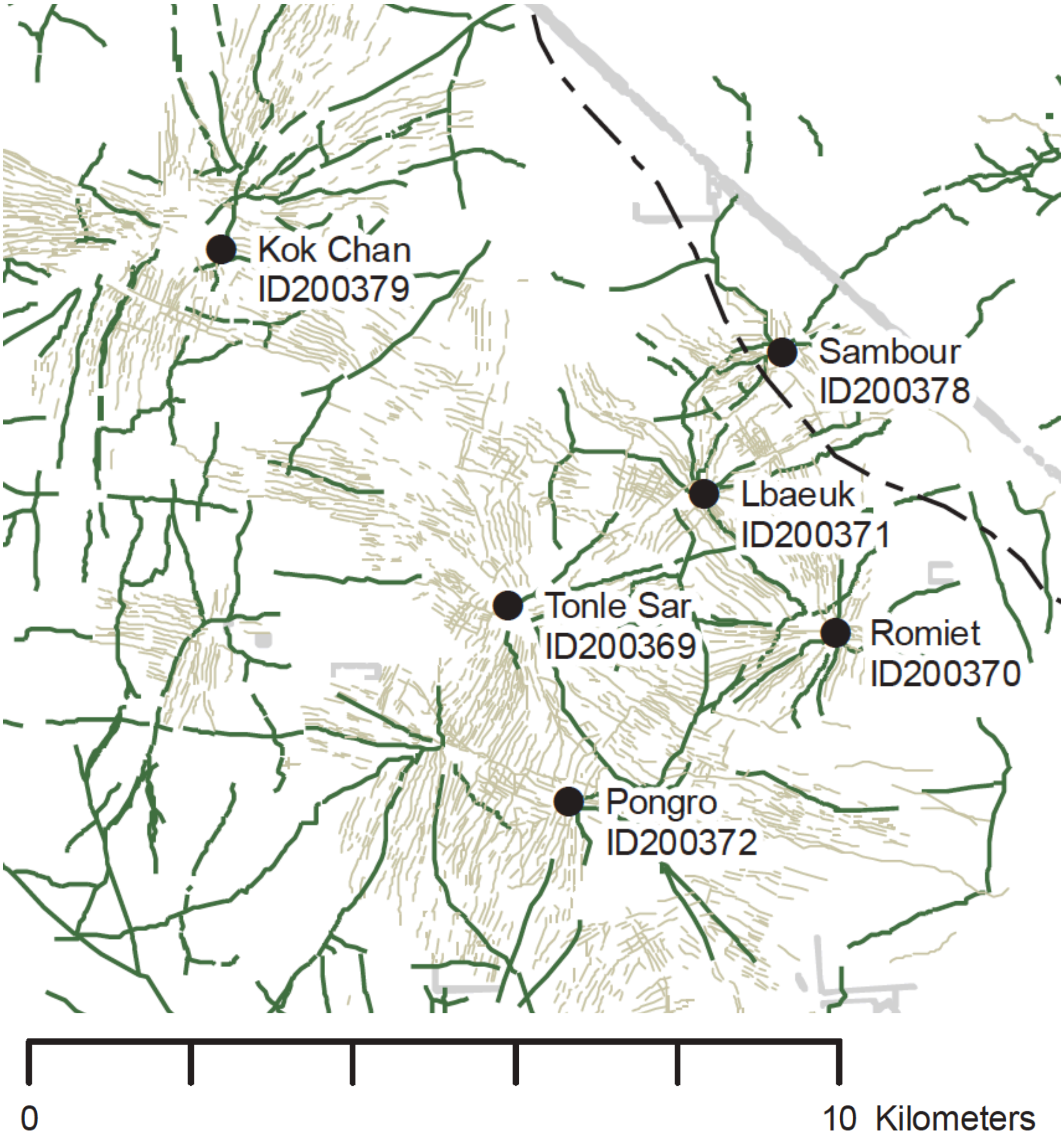

Figure 3: Radial field systems identified by Hawken (adapted from Hawken, 2011, p. Figure 7.4).

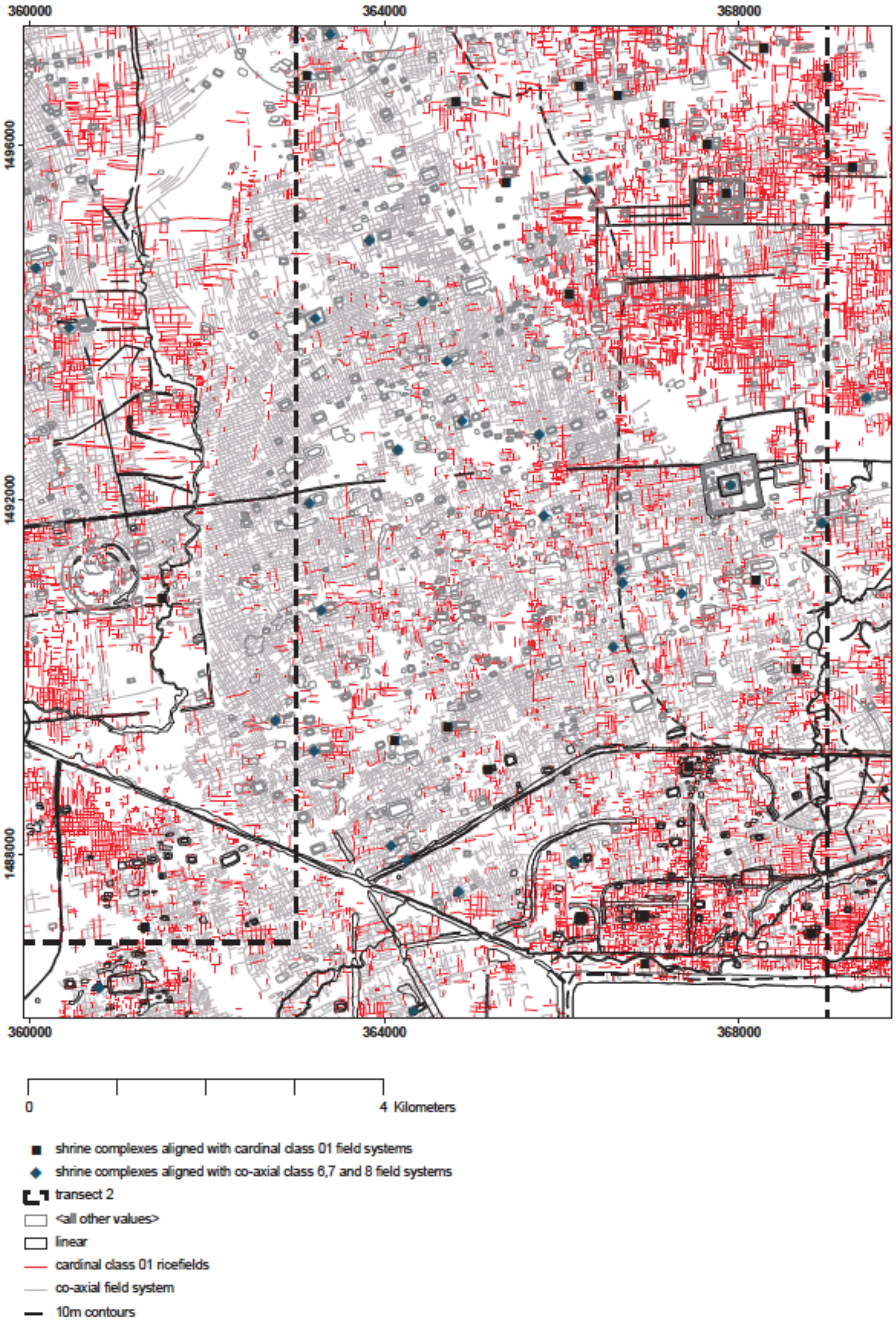

Figure 4: Coaxial and cardinal rice field systems (Hawken, 2011, p. Figure 8.6).

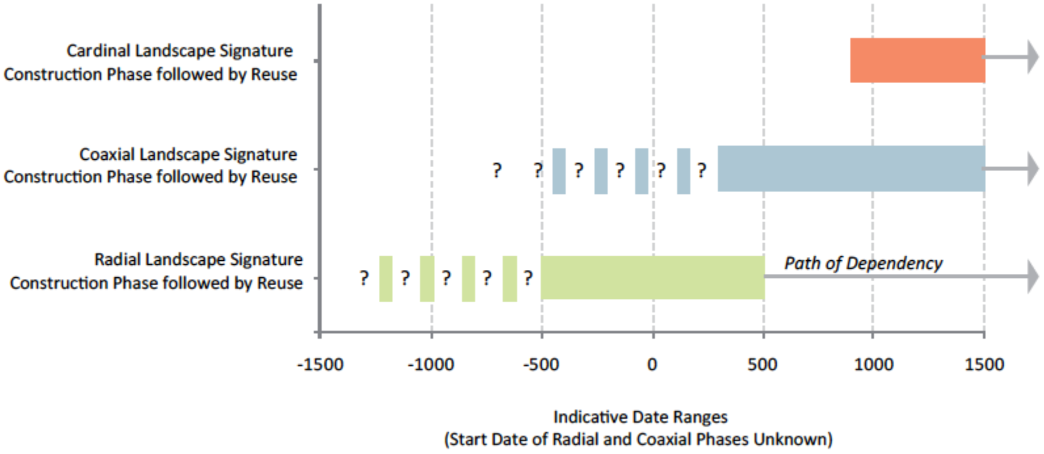

Figure 5: Duration of ricefield landscape phases.

Increasing competition for land

One key component of resilient water management systems are the social institutions that regulate them (Anderies, 2006; Hunt, 1988; Hunt et al., 2005; Hunt et al., 1976; O'Connor, 1995; Ostrom, 1990). At Angkor, temple communities regulated water management and rice production at a local level. However, inscriptional records suggest a transfer of land ownership from autonomous village communities to elites during the 10th and 11th centuries. In an analysis of inscription land sales, Lustig and Lustig found that approximately half of the records of land sales in the 10th and 11th centuries 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. By the mid 11th century *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 & Lustig, 01/05/2018).

In the following sections, I outline the methodology for identifying temple communities on the landscape and assigning dates to mapped features. I then conduct a series of statistical analyses that indicate that temples cluster around emerging urban centers and state-sponsored hydraulic features. I also determine if there is a nonlinear relationship in the number of temples constructed over time, to substantiate inferences from inscriptions that there were fewer temple foundations by the mid-11th century CE

Methodology

Identifying Temple Communities

The existence of historically recorded relationships between temple communities and water management features establishes the framework for grouping reservoirs and temples into spatial zones that represent plan units at Angkor (Bâty, 2005; Groslier, 1974, 1979; Hawken, 2011; Pottier, 2000b). I draw the basis for the community identification from a collaboration of archaeological mapping and survey work conducted over decades in the greater Angkor region. The mapped polygons of archaeological features are the product of four mapping projects conducted by Pottier, Evans, Klassen, and Wijker (Evans, 2007; Pottier, 1999a). The final product includes over 25,000 mapped archaeological features in the greater Angkor region. I then grouped temples with reservoirs based on proximity and orientation. Azimuth was calculated by drawing lines along the long axis of reservoirs and temples, calculating the values, and associating the value of the azimuth with the corresponding feature in ArcMap 10.5.1. The distance between features was calculated using the geographic coordinates of the centroid of features.

To assign reservoirs to temples, I used a Gaussian mixture classifier. This classifier is a standard procedure used to cluster data in a variety of fields, such as biology (Ouyang et al., 2004), linguistics (Reynolds & Rose, 1995), and engineering (Huang et al., 2005). Calculation of this classifier requires that there is a consistent way to measure the similarity between two data points. I computed a measure of similarity for each possible temple and reservoir pair using a weighted L2 distance, which turned two measurements (the distance in km and relative rotation in degrees) into a single number. The modeling assumption that the latitudes, longitudes, and azimuths of reservoirs associated with a given temple are all independent Gaussian random variables justifies the choice of the L2 metric. The dissimilarity between two sites x and y is given by

$$\text{dissimilarity} = 9 \text{ dist } (x, y)^2 + (1/25) \text{ rot } (x, y)^2$$

where *dist* is the distance between the sites in kilometers and *rot* is the relative rotation in degrees. These parameters (9 and 1/25) assume that the average distance between a reservoir and its associated temple is 1 km and that the average relative rotation is 15 degrees.

The parameters are loosely based on ethnographic studies that suggest farmers will walk up to 1-2 km from their villages to their fields on a daily basis (Mudar, 1995, p. 180) and assumptions that buildings within a community are likely to be oriented within approximately 15 degrees of each other.

To test these assumptions, I compared the results from 9 algorithms with the parameter defined by combinations of average distance (1, 2, and 3 km) and average relative rotation (5, 10, and 15 degrees) to eight temple communities identified by Evans and Klassen. Through a training dataset that was assembled based on a subjective analysis of multiple lines of evidence, Klassen and Evans selected the eight temple communities that they felt could most clearly be grouped based on orientation and proximity. The results indicate that the algorithm with parameters 1 km and 15 degrees was the only algorithm to correctly group all the reservoirs that Evans and Klassen grouped with all eight temples (Table 1). The "% of temples identified by the archaeologists that were also identified by the algorithm" column represents the total percentage of reservoirs that each algorithm correctly identified, given the archaeologists' groupings. The algorithm with parameters 1 km and 15° was the only algorithm that correctly identified all of the reservoirs that the archaeologists identified. The "% of temples identified by the algorithm that were also identified by the archaeologists" column represents the total percentage of reservoirs that archaeologists identified in comparison to each algorithm. Lower percentages in this column suggest the algorithm grouped more reservoirs with each temple than did the archaeologists.

Parameter permutations 2 km, 15° and 3 km, 15° included the reservoirs grouped by Evans and Klassen with 96% accuracy; however, they were much more inclusive than the 1 km, 15° parameter, meaning that they were more likely to group reservoirs with a given temple than Evans and Klassen. More inclusive similarity formulas may be preferred if the goal of computer clustering is to identify potential connections between reservoirs and temples that can then be verified using other archaeological data. As such, it seems reasonable to favor a similarity formula that is more generous rather than less with the groupings. However, I argue that this should be done within reason: one to three additional reservoirs will not skew the results of future analyses as much as seven to ten additional reservoirs can. For example, the 1 km, 15° algorithm grouped, at most, three additional reservoirs to any temple group identified by Evans and Klassen (average = 1.5 additional reservoirs per temple group). In contrast, the algorithm with parameters 2 km, 15° grouped as many as seven additional reservoirs to a single temple group (average = 2.7 additional reservoirs per temple group) and 3 km, 15° grouped as many as ten additional reservoirs to a single temple group (average = 3.6 additional reservoirs per temple group). As a result, the 15°, 1 km algorithm corresponded between Evans and Klassen's groupings at 70%, while 15°, 2 km and 15°, 3 km were 43% and 50% respectively. As such, I determined that 1 km and 15 degrees yield the most consistent and accurate results.

Once I calculated the dissimilarity between reservoirs and temples, I treated each temple as the center of a Gaussian distribution and assigned each reservoir one-by-one to temples to which it could plausibly belong. With this choice of weighting, I ensure that the variance of the latitude, longitude, and azimuth are approximately the same. Smaller dissimilarity values represent temple and reservoir groupings that are more similar. When under the Gaussian assumption with a uniform prior probability on each temple, the Bayes optimal classifier for each reservoir assigns it to the temple to which it is most similar. This procedure is unlikely to be robust when a reservoir is not especially like any temple. Therefore, if the dissimilarity value for a reservoir and its most similar temple is greater than 5, the reservoir was not assigned to any temple group. If the dissimilarity between the reservoir and its most similar temple is less than or equal to 5, I assigned the reservoir to its most similar temple. Almost all reservoirs had best matches with a dissimilarity score less than 5.

To assign reservoirs to more than one temple, I set a threshold: reservoirs are also assigned to any temple whose dissimilarity score was no more than 50% higher than the dissimilarity score of the most similar temple. So, if the most similar temple to a given reservoir had a dissimilarity score of 1, I also assigned the reservoir to any temple whose dissimilarity from the reservoir is at most 1.5 (Figure 6).

Table 1: Results from the permutations of distance and azimuth for eight temple communities.

Algorithm permutation	**% of temples identified by the archaeologists that were also identified by the algorithm**	**% of temples identified by the algorithm that were also identified by the archaeologists**
15°, 1 km	100%	70%
15°, 2 km	96%	50%
15°, 3 km	96%	43%
10°, 2 km	92%	44%
10°, 1 km	85%	76%
10°, 3 km	81%	34%
5°, 2 km	73%	40%
5°, 1 km	69%	82%
5°, 3 km	58%	34%

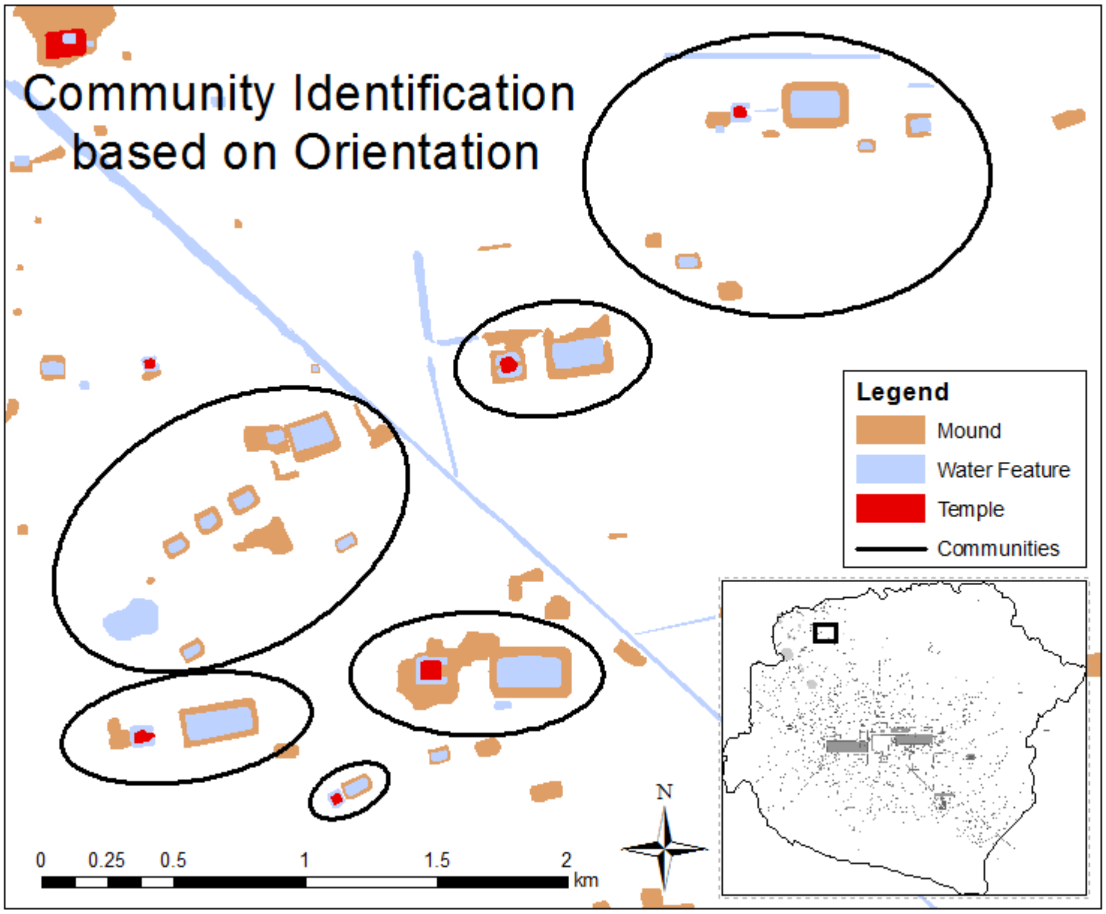

Figure 6: Temple groupings based on orientation and distance.

I then incorporated the chronological information into the mapping work. The chronological information for the hydraulic system was drawn from Fletcher 2008 and the dates for the temples were drawn from the analysis in Appendix I. In Appendix I, I used 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). For features associated with the dated temples, reservoirs, and hydraulic infrastructure (i.e., moats, reservoir mounds, linear embankments flanking hydraulic infrastructure), dates were determined based on their association with dated features. I used the "Spatial Join" feature in ArcMap 10.5.1 to join reservoirs with their embankments, temples with their moats, and water channels with their embankments. For moats and reservoir banks, I used the “Join One-to-Many” join operation to associate moats with the closest temple and reservoir embankments with the closest reservoirs. For the hydraulic infrastructure, I used the “Join One-to-Many” join operation in ArcMap 10.5.1 but limited the search radius to 10 m from the identified hydraulic features to limit the joins to embankments and components of dated hydraulic features. After I completed the joins, I visually inspected the results, especially the hydraulic infrastructure and linear embankments. In many instances, the joins between linear embankments and hydraulic features were incorrect and needed to be manually corrected. At this time, I did not assign dates to the occupation mounds. I reasoned that they were not essential components in this analysis and that future work should be done to determine how to associate them with temples as most are irregularly shaped and don’t fit the orientation component of our analysis. In total, I include 936 temples communities in our analysis with 3351 associated reservoirs/ponds and 915 associated moats. In total, I was able to assign dates to over 5000 features (Figure 7).

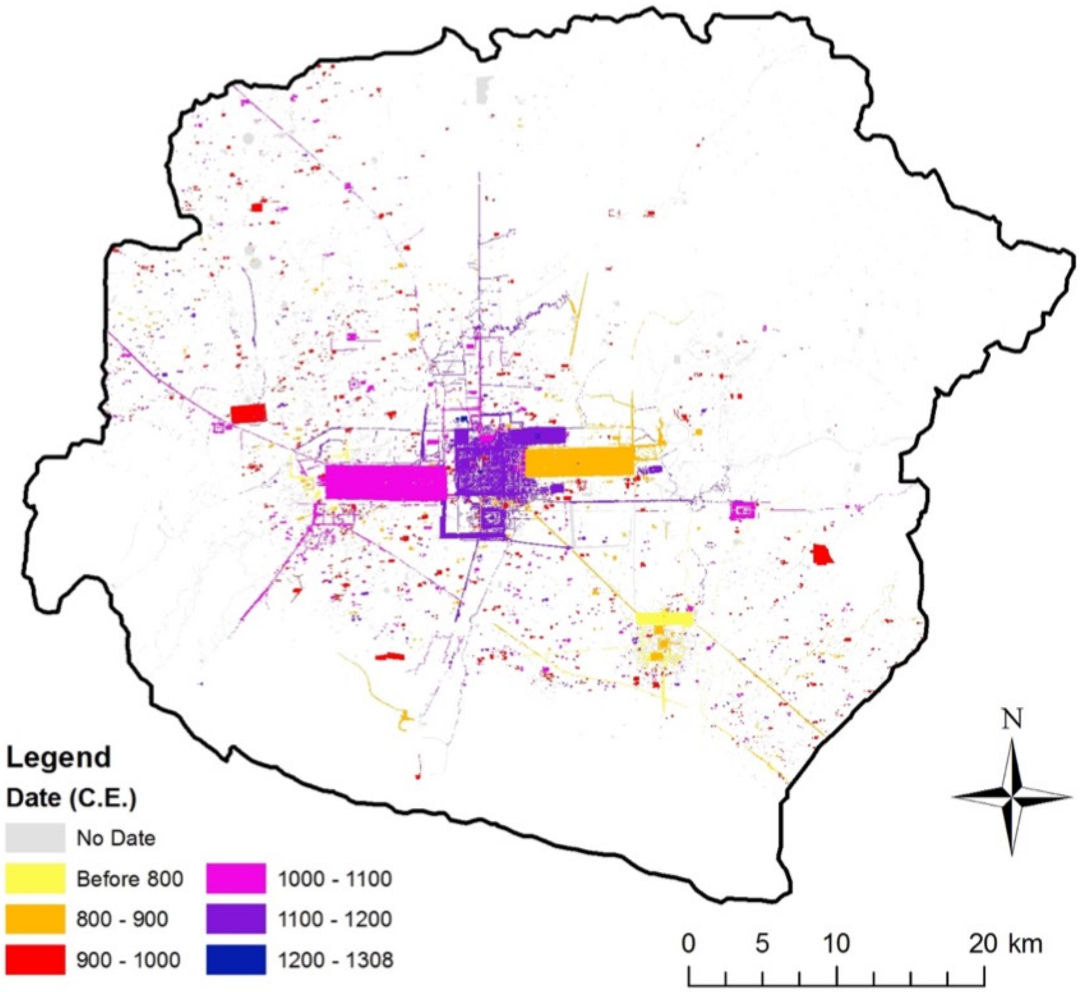

Figure 7: Dated features in the greater Angkor region.

Spatial clustering of temples

To assess whether peripheral temple communities cluster are clustered on the landscape or are randomly distributed on the landscape, I 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 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 I defined as 3000 km^2 (the approximate area of the Rolous and Siem Reap/Puok River catchments). The results indicate that cumulative temple community distributions trend towards clustering with ratios around .64 at a significant level (p = 0) for all centuries. When only the new constructions for each period are considered, there is clustering with ratios around .65 (p = 0) for the 9th – 12th centuries and heightened clustering in the 13th and 14th centuries with ratios of .31 (p = 0) and .4 (p = 0.01), respectively (Table 2).

Table 2: 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 (C.E)	**observed mean distance (m)**	**expected mean distance (m)**	**Nearest Neighbor ratio**	**z score**	**p-value**
800-899	1121	1790	0.626405	-10.9330	0
900-999	657	1004	0.654491	-18.0170	0
1000-1099	1364	2165	0.630177	-8.9492	0
1100-1199	1520	2243	0.677749	-7.5252	0
1200-1299	2006	6454	0.310879	-5.5932	0
1300-1327	4888	12247	0.399145	-2.5703	0.0102
>900	1062	1735	0.611957	-11.7141	0
>1000	557	869	0.64194	-21.5854	0
>1100	512	806	0.635244	-23.6944	0
>1200	497	758	0.65546	-23.7926	0
>1300	488	753	0.648605	-24.4238	0
>1327	487	752	0.648238	-24.4956	0

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

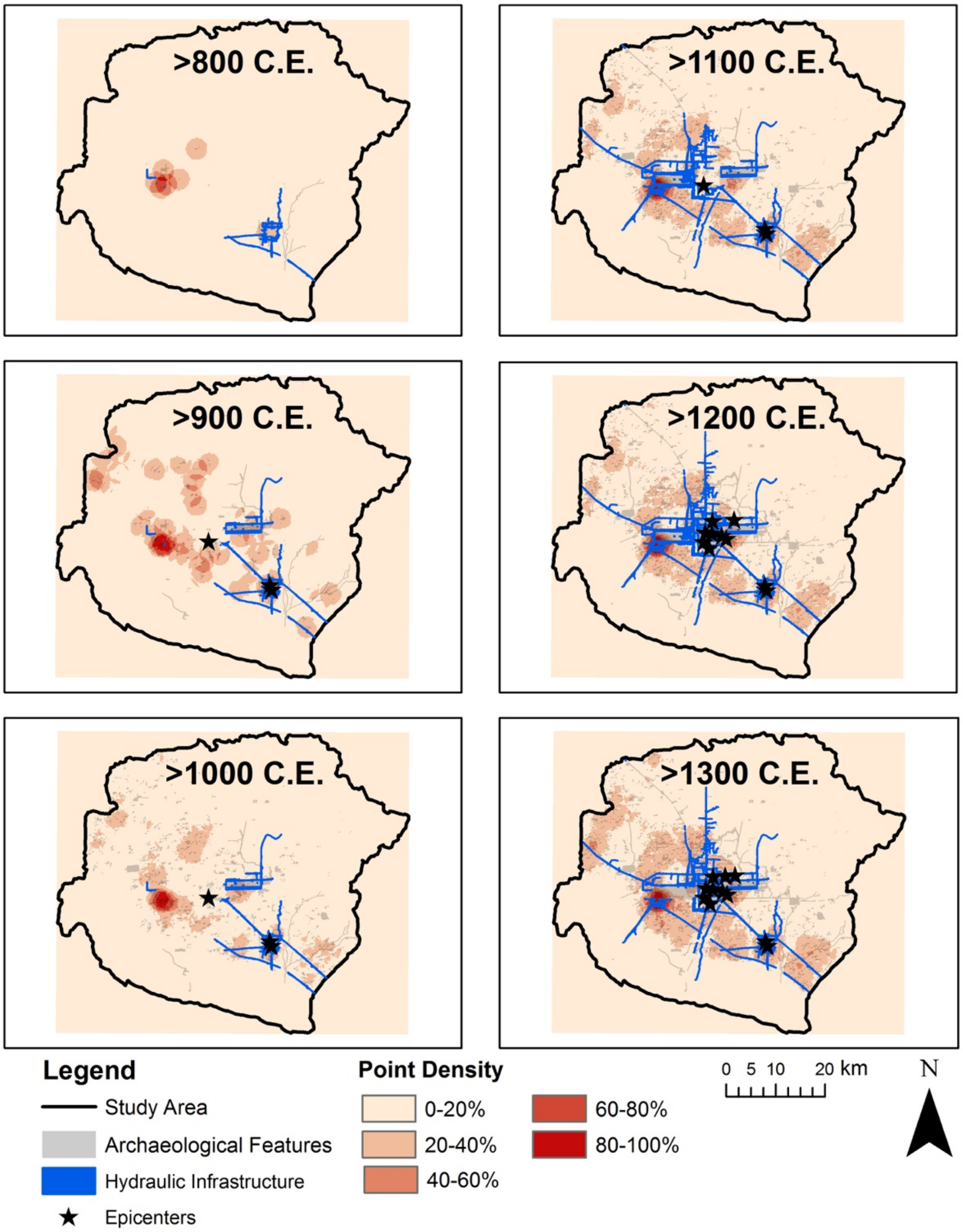

Figure 8).

To test whether the nucleation occurred around hydraulic infrastructure, I measured the average distance between the temples and hydraulic feature for each period using the "Spatial Join" tool in ArcMap 10.5.1. I then created random points on the landscape for each period using the "Create Random Points" tool in ArcMap 10.5.1. For each period, I created as many points as there are temples. I 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 (Table 3). The temples cluster closest to the hydraulic infrastructure during the 8th, 12th, and 13th centuries CE. The temples during the 9th, 10th, and 11th centuries CE have an average distance of almost three times further away.

Table 3: Distance (m) between temples and random points to hydraulic features.

Year	**Normal**	**Random**
Less than 800	2561	14112
800-900	6000	11051
900-1000	6863	12618
1000-1100	5992	13094
1100-1200	2584	8414
1200-1300	1891	9367

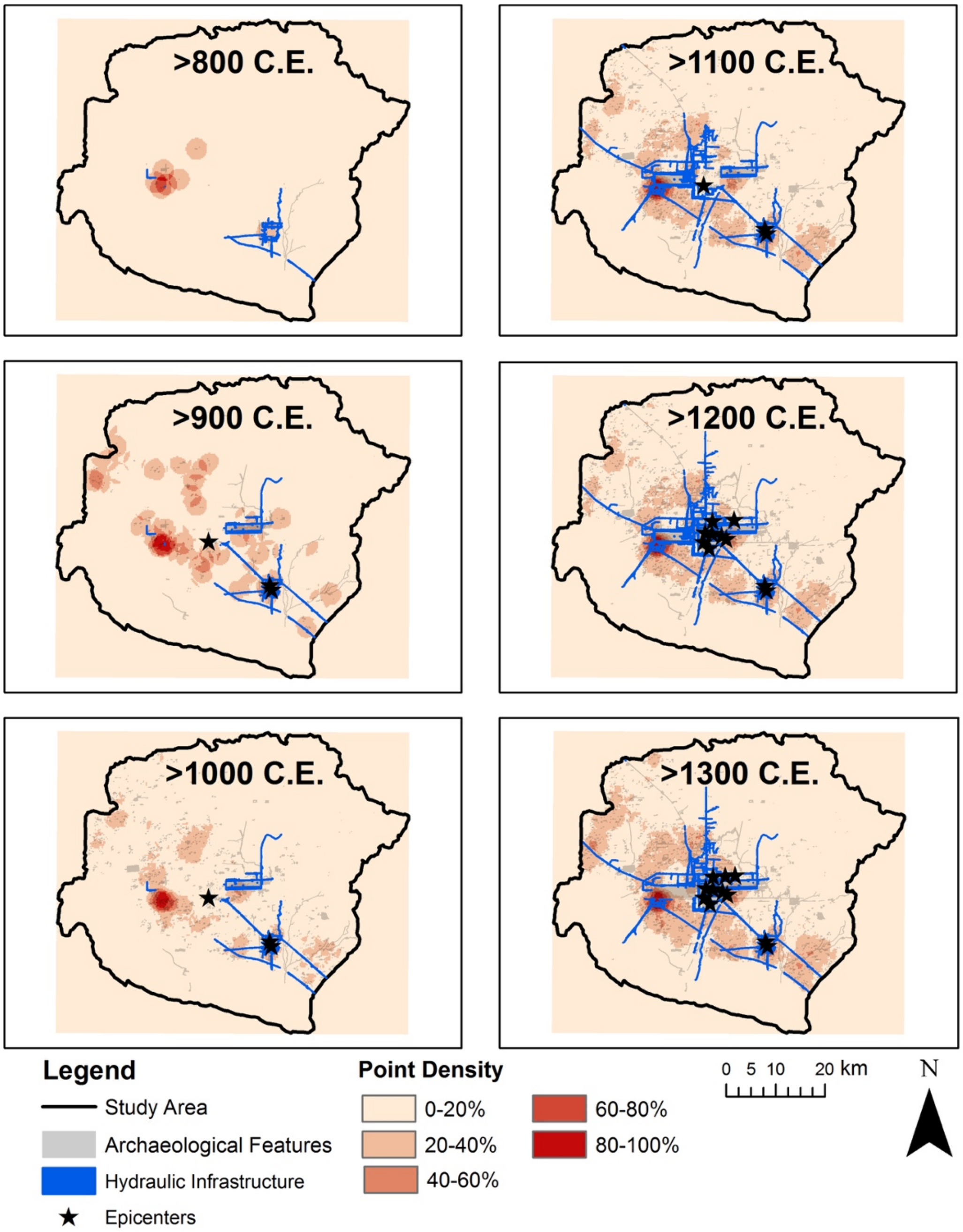

Figure 8: Point density analysis of temple communities only (using the centroid of each temple) showing areas of primary and secondary clustering during each century.

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), I identified areas of nucleation on the landscape for each period. To identify instances of polynucleation and primary and secondary areas of nucleation, I consider areas in the top 20% of relative density as primary nucleation areas and areas in the top 20-40% of relative density as secondary nucleation areas. The results indicate that in the 8th century, there is a primary area of nucleation around the Rolous and a secondary area of nucleation south of the future location of the West Baray where there was likely a hydraulic structure that was a precurser to 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. The areas of nucleation remain south of the East and West Barays through the remainder of the periods. I also compared the relative density of all features on the landscape over time (Figure 9). 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.

Does the landscape data support inference from inscriptional data that there is more competition for land over time?

To determine if the number of temple constructions increases linearly over time, I plotted the temple construction dates predicted in Appendix I (Figure 10). I note that methodology utilized in Appendix I tends to underestimate the number of temples at the

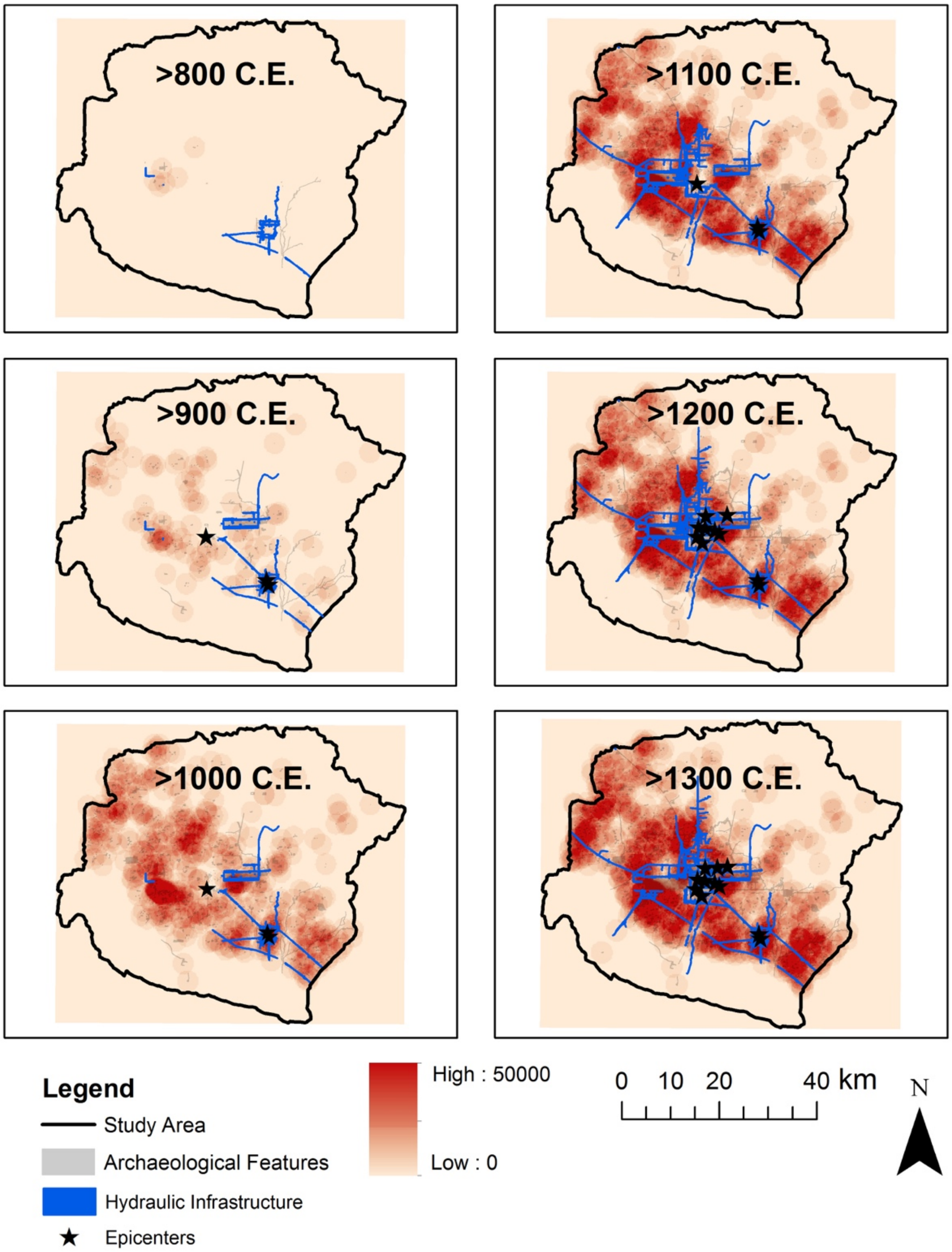

Figure 9: Relative point density of temples on the landscape (based on the centroid of temples).

beginning and end of the study period. The methodology also tends to replicate the distribution that exists in the originally labeled dataset, which the authors argue is likely to be representative of the entire dataset with fewer temple constructions at the beginning and end of the study period. Based on the limitations of the methodology, I provide heuristics of the expected error for each temple. Since this error also conforms to a Sigmoid curve, I argue that I can trust the distribution of the dates with the above caveats noted. I identify the end of the exponential growth phase of the Sigmoid curve during the first half of the 11th century CE.

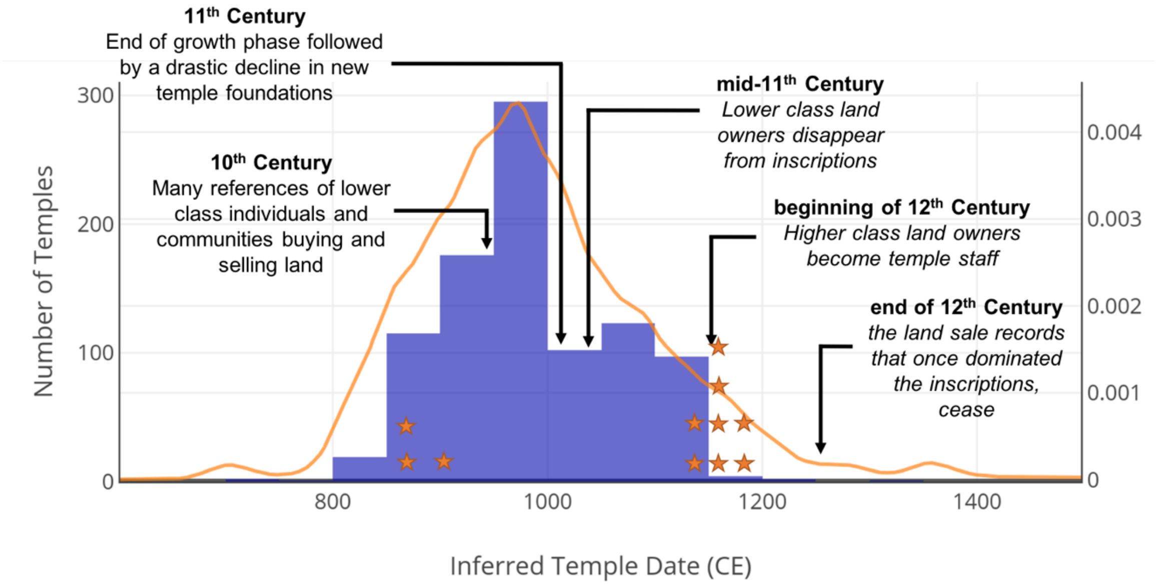

Figure 10: Plot of temple construction dates with epicenters indicated as stars based on Appendix I.

Chapter Discussion and Conclusion

The results indicate that there is clustering of the temple production units around contemporary epicenters and hydraulic features. The nucleation of temples around the West Baray and the change throughout the Rolous in the 9th century CE coincided with the construction of the Rolous Baray and the network of channels flowing in and out of the Rolous region that were also constructed during this period (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 Rolous, 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 (Figure 9).

The population in the epicenters were likely relying on agricultural surplus from the temple communities (Evans et al., 2013). 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, indicating increased competition for access to land (Ricklefs, 1967). 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 centralization of the ownership of land to the elites (Lustig & Lustig, 01/05/2018). The landscape data seems to support the inferences from the inscriptions as fewer temple foundations during the 11th century CE.

The decrease in the foundation of temple communities in the second half of the 11th century CE, as noted by both inscriptional and landscape data, during a period of intensified urbanization of the epicenters, has interesting implications for the agricultural system and the structure of the Angkorian economy. I 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 other large temple foundations, such as Banteay Srei, were founded in open areas north of Angkor that is marginal and less well suited to rice agricultural. It seems logical that local production would increase with the intensification of urbanism in the epicenter at Angkor Thom that peaked during the 12th and 13th centuries CE (Evans et al., 2013). The construction of significant hydraulic infrastructure, like the West Baray suggests a movement to increase agricultural production. These results indicate that the end of the exponential growth phase of new temple foundations is around the mid-11th century CE. These temple communities tend to cluster around newly constructed hydraulic feature, which suggests that they were likely utilizing the infrastructure built by the state while retaining some autonomy over land ownership.

I argue that increased competition for land led to the gradual accumulation of land by elites as part of a state-sanctioned effort to extract more resources from the peripheries. This centralization of land ownership would have undermined the autonomy and decentralization of community-organized agricultural production as fewer local temple communities were founded and land rights associated with the pre-existing temples were sold to elites. The 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.

CHAPTER 3:

ADAPTIVE CAPACITY AT MEDIEVAL ANGKOR, CAMBODIA

Sarah Klassen

Abstract

In this paper, I use geographic information systems analysis to quantitatively and qualitatively assess elements of the adaptive capacity of the water management systems of Angkor among three droughts. The first (1040 – 1090 CE) and last (1200 – 1250 CE) were more severe than the second (1155 – 1170 CE) measured by the Palmer Drought Severity Index (PDSI). The system during the first drought was resilient and continued to survive and thrive for several centuries. In contrast, the system during the third drought coincides with the decline of the city. This case study presents an opportunity to test whether all elements of adaptive capacity considered in this study needed to be high for the system to be resilient. The results indicate that four of the elements (human capital, physical infrastructure, redundancy, and institutions and entitlements) remain largely consistent and/or increase between the three periods of drought. However, natural capital decreases significantly before the third period of drought when the West Baray stopped functioning as a water-retaining feature. The decrease in natural capital suggests that the

abandonment of the West Baray likely played a major causative role in the observed changes in the resilience of the system.

Chapter Introduction

In 2012, the Intergovernmental Panel on Climate Change stated that “water and its availability and quality will be the main pressures on, and issues for, societies and the environment under climate change” (UN, 2012), especially in increasingly urbanized environments (Boa & Fang, 2007; R. R. Brown & Farrelly, 2009; Collins & Bolin, 2007; Cosgrove & Rijsberman, 2000; Gober & Kirkwood, 2010; McDonald et al., 2011; Meinzen-Dick & Appasamy, 2002; Srinivasan et al., 2013). As populations increasingly move from rural to urban areas, water security and understanding how cities can best deal with issues of water supply and guard against water-related disasters will continue to rise in importance (UN, 2012, 2013). Water security is particularly crucial in developing urban areas in tropical environments characterized by monsoon systems, like Southeast Asia. Southeast Asia is currently undergoing rapid urbanization in flood-prone areas, and extensive agricultural development is quickly outpacing the availability of freshwater resources (UN, 2012, p. 24). These issues are exacerbated by the encroachment of urbanism to highly productive and fertile agricultural lands and by an increase in the frequency and magnitude of floods and droughts because of climate change. The consequences of these stresses manifest themselves through poverty, reduced production, and human causalities resulting from flooding disasters, like the 2011 monsoon season in Southeast Asia that claimed nearly 3000 lives. Additionally, there are about 600 million people in Asia who are undernourished, and this number is only expected to rise with increased demands on water availability and increased population pressure (UN, 2011).

Such rapid urbanization and water-related issues in Asia today were foreshadowed by historic cases like Angkor, Cambodia. Archaeologists can make a significant contribution to interdisciplinary discourses on adaptive capacity and human-environmental relationships by examining trade-offs social and ecological imperatives (Hegmon, 2017). Such trade-offs are most visible in the long term where one can observe changes that communities experience as populations grow, political and religious regimes change, and the climate varies over centuries.

In this paper, I evaluate the changing elements of adaptive capacity of the water management system at Angkor, which was the center of the Khmer Empire for over 600 years (9th-15th centuries CE). During this time, the Khmer developed one of the most extensive and complex water management systems in the pre-industrial world, which lasted centuries. In 1974, B.P. Groslier suggested the failure of the water management system precipitated the collapse of the urban center (Groslier, 1974, 1979). Recent research has demonstrated that the water management system was highly resilient for centuries. However, it may have ultimately succumbed to vulnerabilities related to path dependency and an over-extension of infrastructure that left the system vulnerable to an array of environmental factors like erosion and climate change (Buckley et al., 2010; Evans, 2007; Fletcher, 2007; Fletcher et al., 2003; Fletcher & Evans, 2012; Lieberman & Buckley, 2012). I now have sufficient data to test these propositions over the long term. Mapping from over two decades of survey has allowed us to identify and map over

25,000 archaeological features (temples, reservoirs, channels) in the greater Angkor landscape. I have also associated these features with a chronologically robust urban morphology that allows me to evaluate the system diachronically. Finally, high-resolution topographical data (a 50 cm digital terrain model derived from airborne laser scanning, or LiDAR) can be used for geographic information system calculations to quantify changes in the landscape over time.

With these data, I assess the adaptive capacity of the water management system diachronically with particular attention paid to three periods of drought, 1040-1090 CE, 1155-1170 CE, and 1200-1250 CE (Buckley et al., 2010). As discussed in Chapter 2, the first drought occurred near the end of a period of rapid expansion, while the final drought ushered in Angkor's period of decline. In this chapter, I compare the adaptive capacities of these phases in relative terms to gain insight into the resilience of water management systems of the past and present and the usefulness of the metrics of adaptive capacity for improving system-level resilience.

Adaptive Capacity

Water management infrastructure is often built to ameliorate spatial and temporal variability in water availability. The resulting landscapes are capital-intensive anthropogenic environments that require the construction and maintenance of channels, allocation of water, conflict resolution, and organization of ritual (Håkansson & Widgern, 2007). In this paper, I am concerned with human and environmental systems that manage and distribute water for irrigation. Irrigation water is defined here as the water managed by anthropogenic infrastructure that is harnessed, stored, and transported to agricultural soils (Hunt, 1988, p. 339; Kelly, 1983, p. 881; O'Connor, 1995, p. 970; van der Mere, 1968, p. 720).

Archaeology has a rich history of investigating human interactions with the environment because it can identify long-term trade-offs and characteristics of resilient systems (Diamond, 2009; Dunning et al., 2011; Gill et al., 2007; Haug et al., 2003; Hegmon, 2017; Hegmon et al., 2008; Hodell et al., 1995; Kennett et al., 2012; Lucero et al., 2015; McGovern et al., 1988; Medina-Elizalde & Rohling, 2012; M. C. Nelson et al., 2010; Redman & Kinzig, 2003; Turner & Sabloff, 2012). Resilience refers to the ability of systems to experience change while maintaining the same system functions, identity, structure, and feedbacks through reorganization or recovery (Chapin et al., 2009, p. 24; Holling, 1973). Scholars often break down the conceptual domain into features that stimulate diverse models and empirical analyses. One feature that can be used by archaeologists to engage in interdisciplinary discourses on resilience is adaptive capacity (Carpenter & Brock, 2008, p. 41). Adaptive capacity is defined by the Intergovernmental Panel on Climate Change (IPCC) as “the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with consequences” (*Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 2001).

Adaptive capacity is a particularly useful framework for social scientists for four reasons. First, it successfully links ecological and social domains by acknowledging environmental hazards (e.g., climate change) as well as social change (e.g., changing social and political values). While much work has linked these domains in socio-ecological systems, ecology, which focuses primarily on environmental hazards, remains the dominant field from which most resilience theory arises (Holling, 1973). Second, adaptive capacity frameworks recognize that systems are constantly changing and encompass the behaviors and capacities of people and social institutions to learn, cope, innovate, adapt, and respond to these changes (K. Brown & Westaway, 2011; Carpenter & Brock, 2008; Folke et al., 2010; D. R. Nelson et al., 2007; Smit & Wandel, 2006; Walker et al., 2004, p. 7). Third, adaptive capacity frameworks highlight the role of human agency to actively navigate transformation into new desired states when necessary (Adger et al., 2005; Chapin et al., 2009, p. 23; Gallopin, 2006, p. 300; Walker et al., 2006, p. 15; Walker et al., 2004, p. 9). Finally, adaptive capacity can be broken down into elements that can be empirically measured.

Frameworks for assessing adaptive capacity often consider a combination of distinct yet interrelated and interdependent elements that encompass the assets of systems (Dulal et al., 2010; Elasha et al., 2005) as well as organizational properties that highlight how actors alter systems to enable adaptation (Jones et al., 2010, p. 1; World Resources Institute, 2009). The asset base of a system includes all the resources a system has at its disposal to respond to change (e.g., natural capital, physical capital, human capital) (Chapin et al., 2009, p. 23). Access to resources, more than any other factor, defines what types of adaptations are possible (Pettengell, 2010, p. 9). Organizational properties define how actors decide to build features on the landscape based on the asset base, objectives, and cultural understanding of the system (e.g., redundancy and institutions and entitlements). I can use the relationships and trade-offs among elements to evaluate the overall adaptive capacity, and resilience, of systems over time.

Elements of Adaptive Capacity

Adaptive capacity cannot be calculated directly, instead elements of adaptive capacity are often measured as a proxy for the ability of the system to adapt to change. For the present research, I consider five elements of adaptive capacity that can be measured archaeologically and are pertinent to the type of system at Angkor: human capital, natural capital, physical capital, institutions and entitlements, and redundancy.

Human capital refers to the labor of people within the system (Chapin et al., 2009, p. 23; Dulal et al., 2010, p. 7) and includes the skills, competencies, and attributes of these individuals (Dulal et al., 2010, p. 7; Smith & Skinner, 1982). In this paper, I calculate human capital based on the population. It is difficult to evaluate the skills, competencies, and attributes of individuals archaeologically; however, I can distinguish between populations that are likely to be engaged in agricultural production and non-producers. Irrigated wet-rice agriculture is a specialized agricultural technique that is very labor-intensive, and production is often limited by population size (Morrison et al., 1996, p. 587). While increased labor may allow for more agricultural production, some studies suggest that too much population growth can lead to degradation of the natural landscape (Dunning et al., 2002; Haug et al., 2003). In contrast, other studies suggest that populations can avoid degrading their landscapes through proper resource management (Fisher et al., 2003; Scarborough, 2003). Similarly, high amounts of non-producers can add stress to the system because of the need to supply additional surplus.

Natural capital refers to the natural resources (e.g., water) to which a society has access (Dulal et al., 2010, p. 7; Elasha et al., 2005). For this analysis, I calculate natural capacity based on the amount of water stored in the infrastructure of the system. In general, higher amounts of stored water can increase productive capacity and surplus, thereby accommodating increases in population (Kennett et al., 2012; M. C. Nelson et al., 2010). Increased amounts of harnessed water may also increase system-level resilience. For example, the water managed by the system of reservoirs and water diversion features at Tikal allowed the center to survive the Terminal Pre-classic drying trend while many other Maya centers were abandoned (Scarborough et al., 2012).

Physical capital refers to labor that is banked in the landscape through the construction of infrastructure (Håkansson & Widgern, 2007). Water management systems can develop water supplies by harnessing new sources of water and storing water for later use through the construction of large and small dams, reservoirs, and channels (Cosgrove & Rijsberman, 2000). This infrastructure is often substantial and immobile, and once built, tethers the social system in place, even when the local resources are depleted (Fletcher, 2010). These sunk costs can lead to path dependency. Once introduced, path dependencies create trajectories that are difficult and expensive to change or reverse (Page, 2006; Pierson, 2000). As such, while the infrastructure associated with irrigation can mitigate against variability in water availability and initially promote adaptive capacity, an over-accumulation of infrastructure can create attachment to place that may ultimately reduce the capacity of the system for change (Hegmon et al., 2008, p. 322; Janssen et al., 2003; Lucero et al., 2015; M. C. Nelson et al., 2010, pp. 32,34).

Institutions and entitlements refer to the "existence of an appropriate and evolving institutional environment that allows fair access and entitlement to key assets and capitals" (Jones et al., 2010, p. 4). Fair access has been linked in theoretical literature with systems with well-developed social institutions that have a greater ability to respond to change (Pettengell, 2010, p. 15); however, there is little empirical evidence to support this (Jones et al., 2010, p. 5). In this study, I quantify institutional evidence as the percentage of temple communities that have access to the state-sponsored hydraulic infrastructure.

Redundancy refers to the diversity of functionally analogous components that allow for multiple means of accomplishing similar ends within a system. For this study, I will identify redundancies in the infrastructure of the systems used to store water between state hydraulic infrastructure and local reservoirs. Redundancy reduces the vulnerability of the system during periods of rapid change and can help prevent disasters by having other aspects of the system compensate for specific failures (Chapin et al., 2009, p. 68).

Historical Background: Water Management System at Angkor, Cambodia

The evolution of Angkor's water management system illustrates how changes in the adaptive capacity of the water management system allowed it to respond to external climate challenges successfully or less successfully. Angkor was the capital of the Khmer Empire (9th-15th centuries CE) and is one of the largest low-density urban complexes in the preindustrial world (Fletcher, 2012; Stark, 2004). Khmer inscriptions suggest that Jayavarman II founded the imperial kingdom in 802 CE when he pacified and united the Cambodian countryside. After unification, urbanisation was rapid and expansive. By the

12th century CE the empire ruled most of mainland Southeast Asia and continued to flourish until the 13th century CE before entering a period of decline (Evans, 2007, p. 18; Kummu, 2009, p. 1413; Stark, 2004, p. 103).

The Angkor region is characterized by lowland forest, dense forest, and floodplains of the Tonle Sap Lake. It is characterized by a seasonal monsoon climate, with ninety percent of rainfall occurring between May and December. The Khmer developed a complex hydraulic system over the course of centuries. The scale of this system is likely unparalleled in the pre-industrial world, with channels at lengths of over 20 km and 40-60 m wide, reservoirs with surface areas of up to 16.8 km^2, and 1000 km^2 of mapped agricultural fields (Acker, 1998; Evans, 2007; Fletcher & Evans, 2012). The water management system was designed to protect the urban space against flooding during the monsoons, while simultaneously harnessing the water for agriculture (Evans, 2007). The system contained elements of state-sponsored infrastructure, like the long channels and vast reservoirs of the East and West Baray, in addition to thousands of smaller reservoirs and channels built by local temple communities (Chapter 2).

Angkor is a unique case study for understanding the resilience of water management systems because it has a large and complex water management system that persisted for centuries through several severe droughts and high-magnitude monsoon seasons. The importance of water management in the rise and decline of the urban center has been the subject of much debate; however, most scholars now agree that the water management system was essential to the city’s longevity (Buckley et al., 2010; Evans, 2007; Hawken, 2011; Kummu, 2003). Buckley et al. (2010) document regional climate variation from 1030 – 2008 CE with tree rings from southern Vietnam (Buckley et al., 2010), later validated with speleothem records (Hua et al., 2017). There is no agreed upon methodology to define the beginning and end of periods of drought and monsoon, although methods for identifying extreme climate intervals are being developed (Kintigh & Ingram, 2018). In this paper, I use the Palmer Drought Severity Index (PDSI) used by Buckley et al. (2010), which indicates periods of decades long drought oscillating with periods of high-magnitude monsoons (Figure 11). Based on this data, there are three periods where the PDSI drops below zero for sustained periods of time (greater than one decade). The first is from 1040-1090 CE, the second from 1155-1170 CE is much less severe, and the third one in 1200-1250 CE is similar in severity to the first. The systems during the first and second periods of drought continued to function for centuries and were more resilient than the system in the third drought that ushered in Angkor's period of decline. I expect that the water management system of the first and second periods of drought had more redundancy, higher distribution of resources through institutions and entitlements, and greater natural capital than that of the third period. I also expect that that first and second periods of drought had lower human capital and fewer path dependencies as a result of less physical infrastructure than the third period of drought.

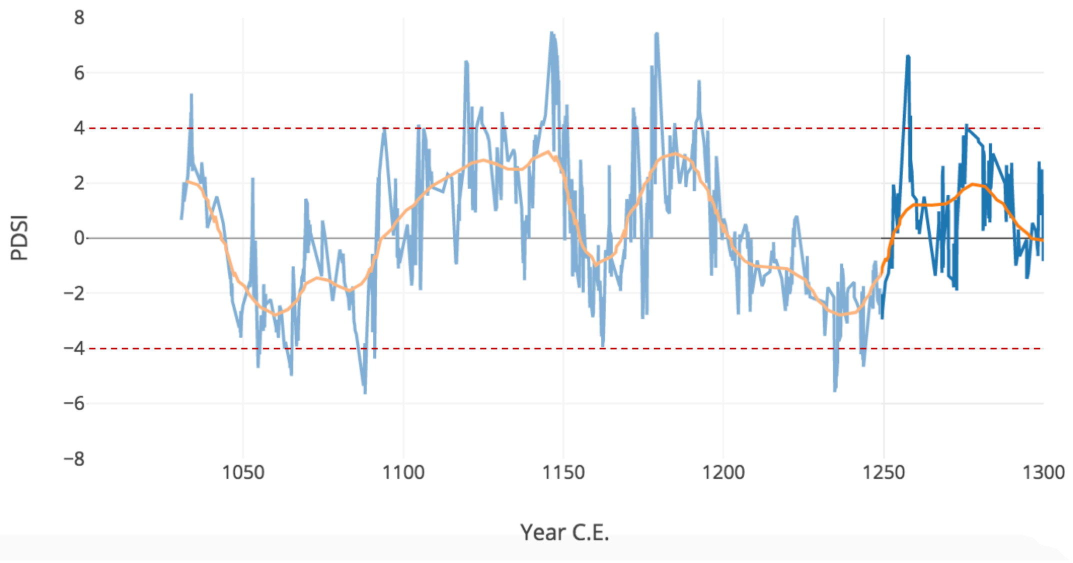

Figure 11: Precipitation calculations from southern Vietnam from 950 CE to the present day. The faded areas indicate the portion of the record before 1250 CE that is considered less reliable because of reduced sample sizes (Buckley et al., 2010).

Methodology

In 2012, the Greater Angkor Project (GAP), an international team of researchers, and the Khmer Archaeology LiDAR Consortium organized a mission of airborne laser scanning (light detection and ranging, or LiDAR) across 370 km^2 of this site (Evans et al., 2013). Using this technology, researchers algorithmically filtered vegetation cover to reveal the underlying ground surface, which aided our mapping efforts and was used to construct a high-resolution digital elevation model used for the calculations described here. The bare-earth elevation models derived from the lidar point cloud have 0.5 m spatial resolution: with elevations given as “above sea level” (ASL).

In 2016, Pelle Wijker combined several sets of mapping work into a unified and consistent spatial database with polygons of mapped features including temples, reservoirs, channels, occupation mounds, and embankments. The dates of temple features are based on a combination of known temple dates from inscriptions and art historical reference and a semi-supervised machine learning algorithm with an average absolute error of approximately 49-66 years from 821 – 1149 CE, as described in Appendix I. The dating of non-temple archaeological features is based on the community identification analysis in Chapter 2. In that analysis, I assigned dates to reservoirs based on the date of their associated temple. Large hydraulic features were incorporated in the database based on the analysis by Fletcher et al. 2008 (Fletcher et al., 2008).

Assessing the Adaptive Capacity of Water Management Systems

Human Capital

Archaeological estimates of population are exceptionally difficult to achieve with any degree of accuracy in cases, like Angkor, where settlements were mainly built with non-durable materials. However, many studies, like Rice and Culbert (1990) in Mesoamerica, have used the remains of occupation mounds and residential platforms to estimate population size, recognizing that not all of the structures were occupied at the same time (Rice & Culbert, 1990). In this paper, I do not have clear indications of the number of occupation mounds in the temple communities. Instead, I take a similar approach and calculate the amount of human capital based on the number of active temples on the landscape. Contemporary Khmer communities are also organized in village-level units called *phum.* These contemporary local temples in Cambodia service approximately 100 families (Delvert, 1961). We follow earlier studies at Angkor suggesting that each family consists of approximately five members (Hanus & Evans, 2015). Like most archaeological sites, Angkor is a complex palimpsest; however, with the temple chronology in Appendix I, I can estimate the population over time by calculating the accumulation of temples on the landscape *terminus post quem*. As in Appendix I and Chapter 2, I argue that once temple communities were founded, their associated populations were continuously replaced through subsequent generations.

In addition to the temple communities in the peripheries, Angkor also had densely occupied areas, which I call epicenters in Chapter 2. The LiDAR imagery uncovered a formally planned urban grid and helped fill lacunae in the previously documented nature of urbanism at Angkor (Evans et al., 2013). Among the features revealed by the imagery are thousands of patterns that are recognizable as archaeological features, such as house platforms, ponds, reservoirs, channels, and roads. As previously described by Gaucher, the urban space within the moated and walled enclosure of Angkor Thom conforms to orthogonal, cardinally oriented "city blocks" (Gaucher, 2004). City streets delineate the a grid system of roads that likely doubled as a system of channels during the wet season. This geometric rendering of the landscape extends well beyond the enclosures of both Angkor Wat and Angkor Thom (Evans et al., 2013).

To include the population of these dense urban cores, or epicenters, in our analysis, I relied on pre-existing estimates for major temple complexes and the densely occupied area around Angkor Thom. Evans and Fletcher created population estimates based on the number of ponds visible in the LiDAR imagery and historical records from Zhou Daguan's observation that there were one to three "families" per pond in Angkor Thom (Zhou, 2007). Since the entire landscape of each temple complex is not preserved, Evans and Fletcher had to estimate the number of ponds that likely existed in antiquity.

Based on the estimated number of ponds, Evans and Fletcher estimated a maximum population of 4500 for Angkor Wat and 1800-2000 for Ta Prohm (Evans & Fletcher, 2015, p. 1410). Hanus and Evans (2015) conducted a similar analysis at Angkor Thom and estimated the population inside the walls of Angkor Thom to be approximately 16,000 people, based on the number of occupation mounds and ponds (Hanus & Evans, 2015). In addition to Angkor Thom, Angkor Wat, and Ta Prohm, there are several other major temple complexes in the Greater Angkor region (including Preah Khan, Phnom Bakheng, Neak Pean, Ta Som, Banteay Kdei, Preah Ko, and Bakong) and urban sprawl extending from Angkor Thom. Unfortunately, even with the LiDAR data the other large temple complexes are not as clearly defined as they are at Angkor Thom and Angkor Wat and the pond counts are even less reliable. Instead, I estimated the population for the remaining temples based on population densities from the published population estimates of Angkor Wat and Angkor Thom. I based my population estimates on two families per pond, as it was the average of Zhou's observations; however, it creates estimates that are notably lower than the maximum range by Evans and Fletcher (2015) and Hanus and Evans (2015). The estimated densities for Angkor Wat, Ta Prohm, and Angkor Thom are between 25.7 and 32.73 people per hectare (Table 4). I used the average density, 30.06, to estimate population for the remaining temple complexes and urban sprawl extending from Angkor Thom (Table 5).

These numbers remain provisional. However, current work on household archaeology will help to improve the population estimates of the epicenters. For example, recent excavations at Ta Prohm and Angkor Wat indicate complex occupation sequences

Table 4: Table with population estimates based on number of ponds

Temple Name	**Year (CE)**	**Ha.**	**Number of ponds mapped**	**Estimate of ponds***	**Population estimate****	**Density**
Angkor Wat	1150	84	151	250 - 300	2750	32.74
Ta Prohm	1193	68.1	156	125-130	1750	25.70
Angkor Thom	1175	818.6	2133	1600	26000	31.76

*Based on Evans and Fletcher 2015 and Hanus and Evans 2015
**Based on three families per pond and the average of the estimate number of ponds.

Table 5: Epicenter population estimates

Temple Name	**Year (CE)**	**Ha.**	**Population estimate**	**Density**
Angkor Wat	1150	84	2750	32.74
Ta Prohm	1193	68.1	1750	25.70
Angkor Thom	1175	818.6	26000	31.76
Phnom Bakheng	900	27.9	838.674	30.06
Preah Khan	1151	56	1683.36	30.06
Neak Pean	1250	9.6	288.576	30.06
Ta Som	1175	5.2	156.312	30.06
Banteay Kdei	1175	34.6	1040.076	30.06
Preah Ko	879	48.7	1463.922	30.06
Bakong	881	51.5	1548.09	30.06
Angkor Thom Sprawl	1175	1545.1	46445.706	30.06

beginning with sparse occupations in the 10th centuries CE (Carter et al., In Press; Stark et al., 2015). Due to the current limitations in data, I do not yet know the extent or intensities of occupation before the foundation of the epicenters or their associated populations. Similarly, more work can be done in the hinterlands to increase the confidence in those population estimates. Our analysis suggests a total population that rose to approximately 600,000 people, having increased steadily from the 9th to mid-12th century CE (Figure 12).

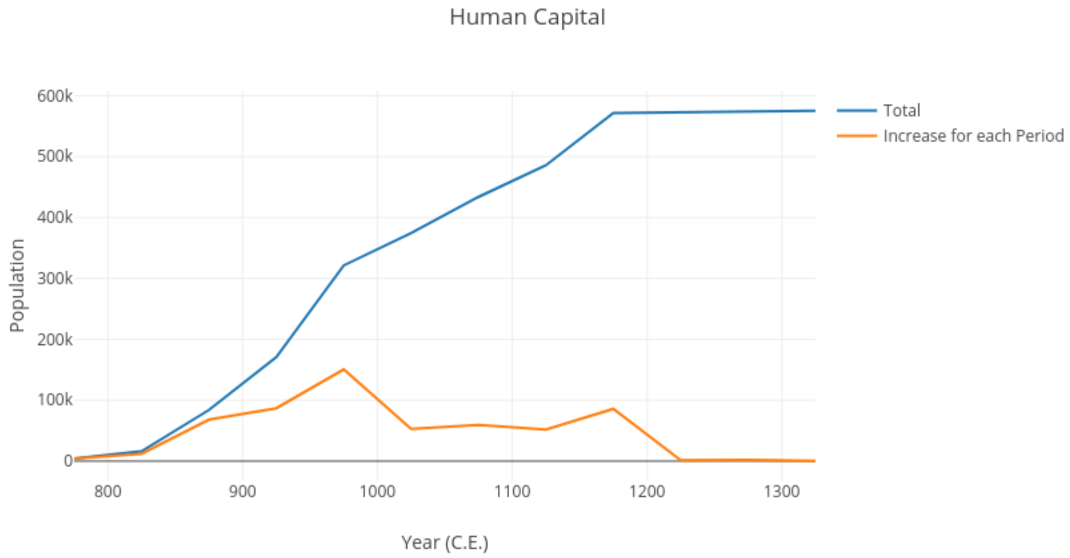

Figure 12: Human capital calculations for pre-800 to 1300 CE. The orange line represents the population increase for each period and the blue is the total population on the landscape. The data was continuous and split into periods of 50 years. The data points for each 50-year period was plotted in the middle of that period. For example, the total accumulation for 800-850 CE was plotted at 825 CE. This graph assumes that once a temple community is established, the associated populations are continuously replaced by subsequent generations, allowing for the accumulation of population on the landscape to culminate in the final period.

Natural Capital

Reservoirs of variable size are scattered across the landscape were built to harness rainwater and store water rerouted from the Puok and Rolous rivers. To determine the capacity of the system to store water, I calculated the total capacity of each reservoir when full. I calculated the maximum capacity for features to allow for consistency; however, I acknowledge that features cannot be expected to have had been at full capacity for the duration of their use.

I calculated the capacity of the reservoirs based on their surface area and depth. Many of the reservoirs in the study area are outside of the LiDAR coverage. As such, I estimated reservoir depths based on a subset of 50 reservoirs that were within the zone of the LiDAR-derived digital elevation model and ranged in size from .12 ha to 1514 ha. I created profile graphs in ArcMap 10.5.1 and calculated the depth to the nearest 10 cm based on the highest and lowest points, to account for erosion that has occurred over the last 500 – 1000 years (Figure 13). LiDAR lasers red lasers do not penetrate water; however, most of the features no longer retain water, and the LiDAR data were collected during the dry season when the features that are still functional were less likely to have water in them. The lowest and highest embankment elevations for the sample of 50 reservoirs were 0.7 m and 14.8 m, respectively. I plotted the size of the reservoirs against the height of their embankments (Figure 14) and again for reservoirs less than 4 ha in size (Figure 15). Based on the distribution of the reservoir depths, I used an average of 2.0 m depths for reservoirs less than 1 ha and 4 m embankments for reservoirs between 1 and 100 ha. For the seven reservoirs greater than 100 ha, I used depths calculated using the LiDAR data, for the three that were not in the LiDAR range (ObjectID 8708, 162426, and 1502), I used 5 m.

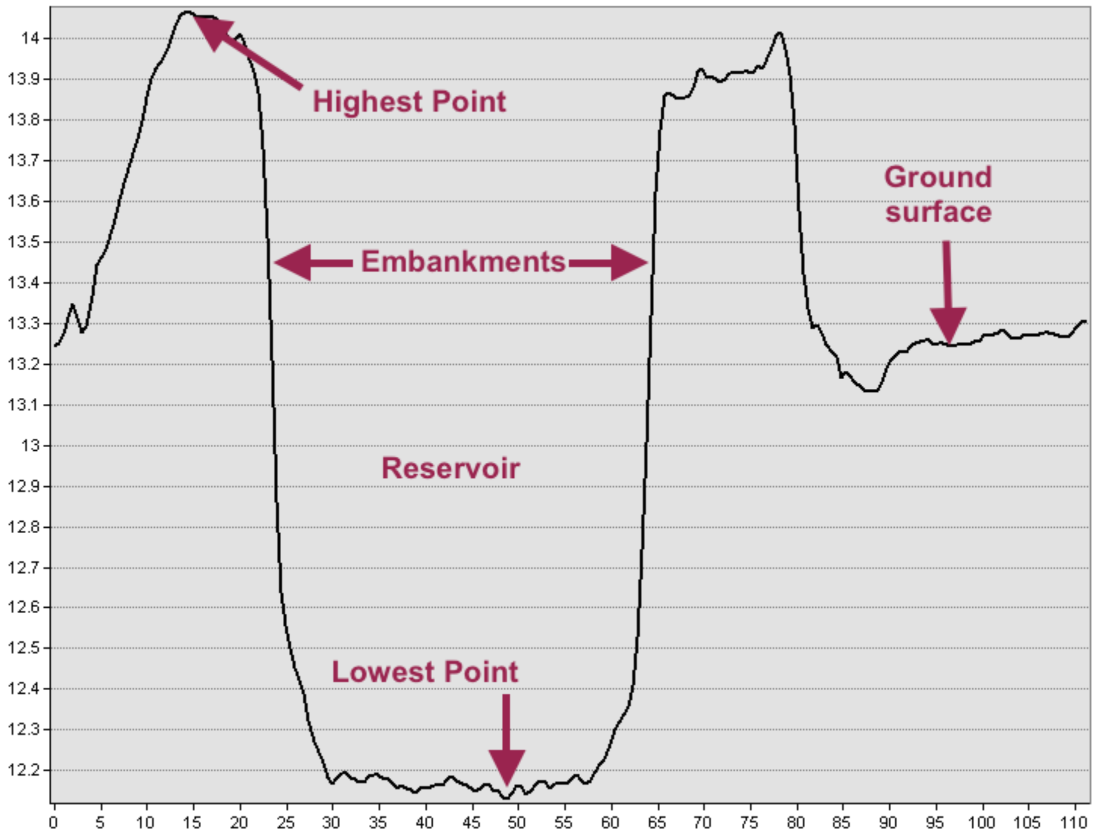

Figure 13: Elevation profile graph of reservoir ObjectID 21679 depicting the base of the reservoir, embankments, and ground surface.

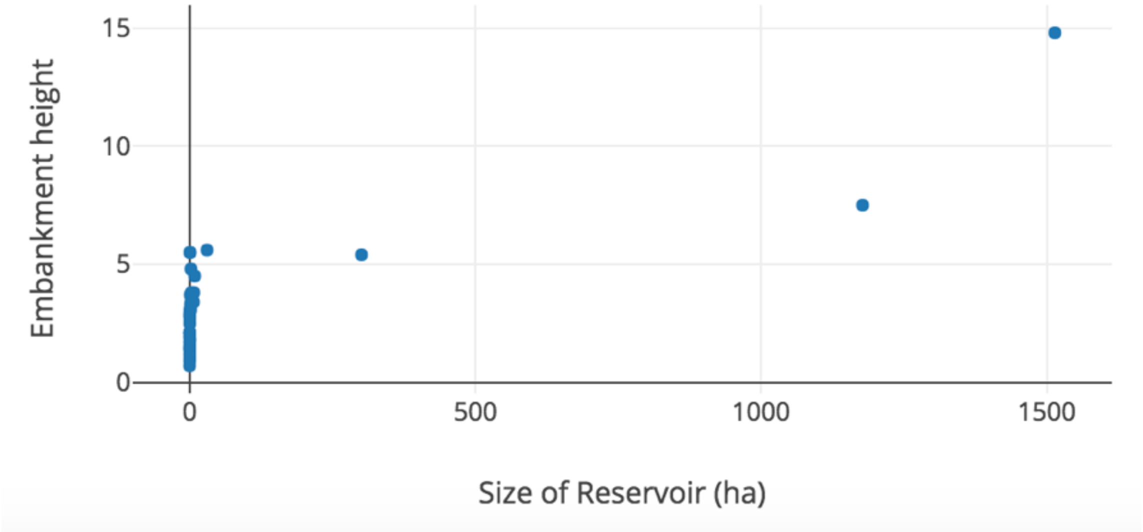

Figure 14: Plot of the height of the embankments (m) and the size of the reservoir (ha).

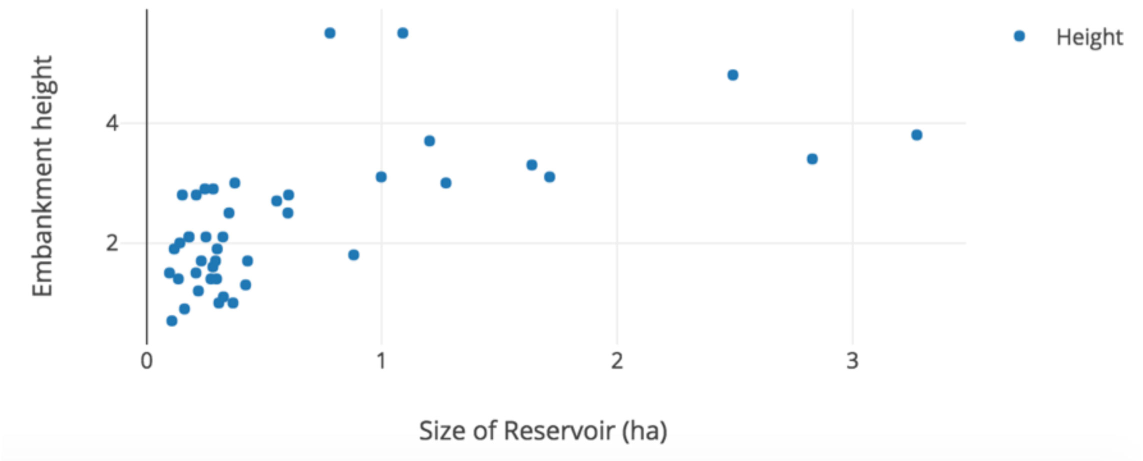

Figure 15: Plot of the reservoir depth (m) and the size of the reservoirs (ha) for reservoirs less than 4 ha in size. A second major source of water storage is temple moats. Similar to reservoirs, I calculated the depths of 20 moats. The depth of the moat from the top of the embankment to the base of the moat ranged from 0.7 m to 4.9 m (Figure 16 and Figure 17). Based on the distribution of moat depths and surface areas, I used an average of 2 m depth for temples less than 1 ha and 4 m depth for moats larger than 1 ha.

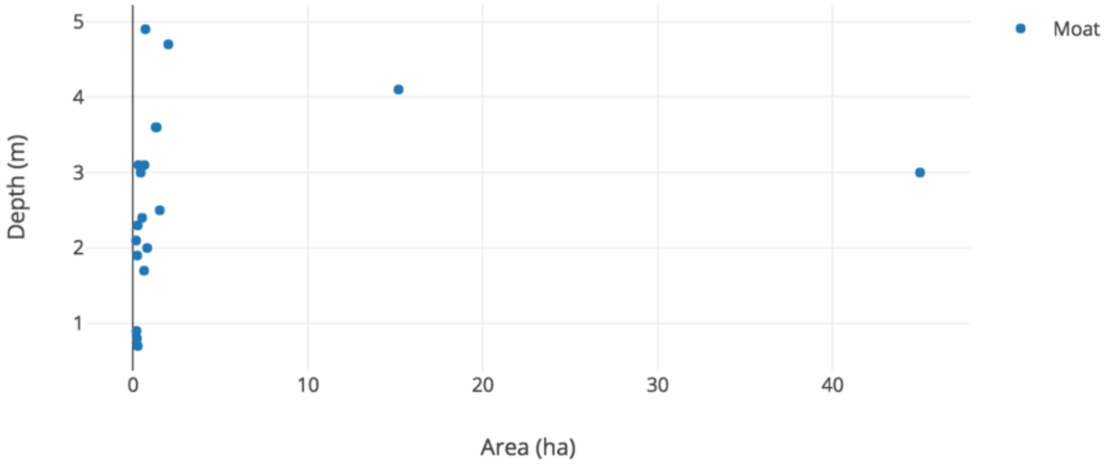

Figure 16: Plot of moat depth (m) and area (ha).

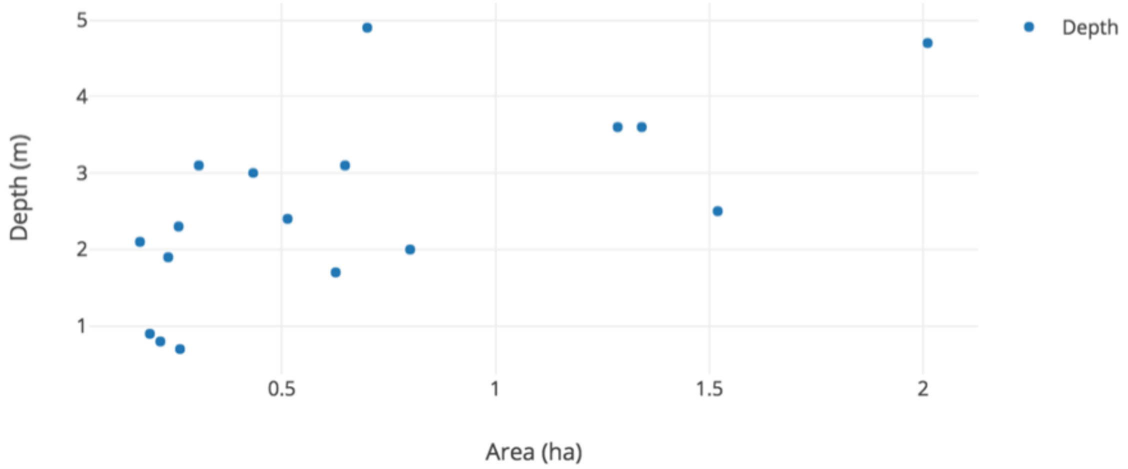

Figure 17: Plot of moat depth (m) and area (ha), for moats less than 2.5 ha.

I then calculated the volume using the area of the mapped features and the estimated depths. All features are considered to be in use after they were constructed, except for the West Baray, where pale-botanical analysis indicates it was no longer holding water by the late 12th century CE (Dan Penny et al., 2005). As such, it was not included in the total figures after the 12th century CE (Figure 18).

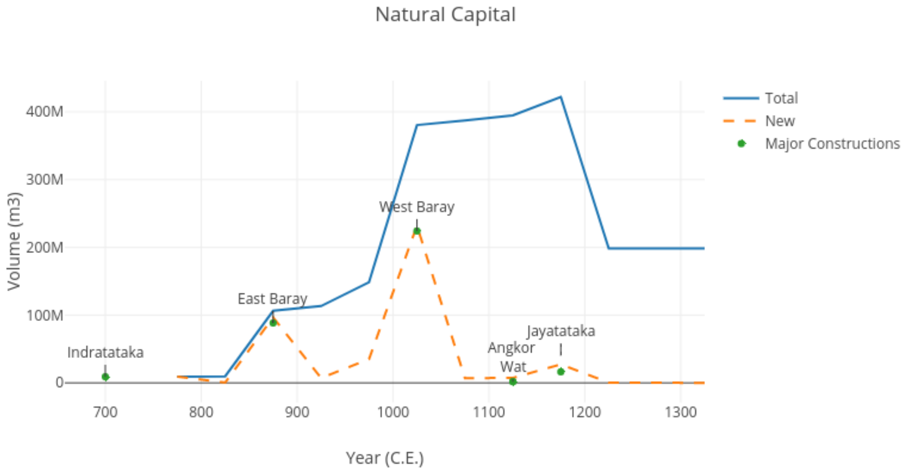

Figure 18: Amount of water harnessed on the landscape (natural capital) during each period, including major hydraulic constructions.

Physical Capital

I quantified the physical capital at Angkor by calculating the expenditure of human energy required to build the water management infrastructure in terms of the amount of soil moved (Abrams & Bolland, 1999; Fisher & Feinman, 2005). There are two types of infrastructure at Angkor, state constructions and local constructions. To measure the state constructions, I reconstructed polygon shape files of the major constructed features on the landscape based on Fletcher et al. (2008). There are five major constructions (Indrataka Baray, East Baray, Angkor Wat moat, West Baray, and Jayatataka Baray) and over 185 km of channels. These major features are deemed state constructions because they are often referenced in inscriptions and credited to specific kings. The major constructions are all within the LiDAR data, and I calculated the height and widths of the embankments based on the areas where they were best preserved. I used these calculations, along with the length of the embankments, to calculate the amount of fill that was necessary to construct the features. All the features were built with above ground embankments except the Angkor Wat moat that was excavated to a depth of 4 m. For the Angkor Wat moat, I calculated the amount of fill that was excavated. Channels were also built above ground and contained by two linear embankments. Very few of the channels are located within the LiDAR data; however, based on the mapping polygons and elevation profiles for those that are within the LiDAR coverage, I determined that the average height is 1 m with an average width of 40 m. As such, the amount of soil for each channel was calculated based on 80 m (40 m for each linear embankment) x 1 m x length.

In addition to the large state hydraulic infrastructure, each temple community has a series of reservoirs. To calculate the amount of soil moved to create these, I calculated the volume of fill moved based on surface area and height. Most of the reservoirs are outside of the LiDAR coverage. To generalize, I measured the height of 25 reservoir and moat embankments and used their average, 1.3 m, as the height. As a result of ca. 1000 years of erosion, these calculations likely underrepresent the true amount of fill used (Figure 19).

As is to be expected, the amount of state-sponsored physical infrastructure coincides with major constructions (Indratataka, East Baray, West Baray, Angkor Wat, and Jayatataka). There are other state-sponsored physical infrastructure associated with water management included in this analysis, like channels, but they have little impact on to the final numbers. For local infrastructure, the most infrastructure is constructed in the period 950-1000 CE. This is to be expected as that is the period with the most temple constructions (Chapter 2).

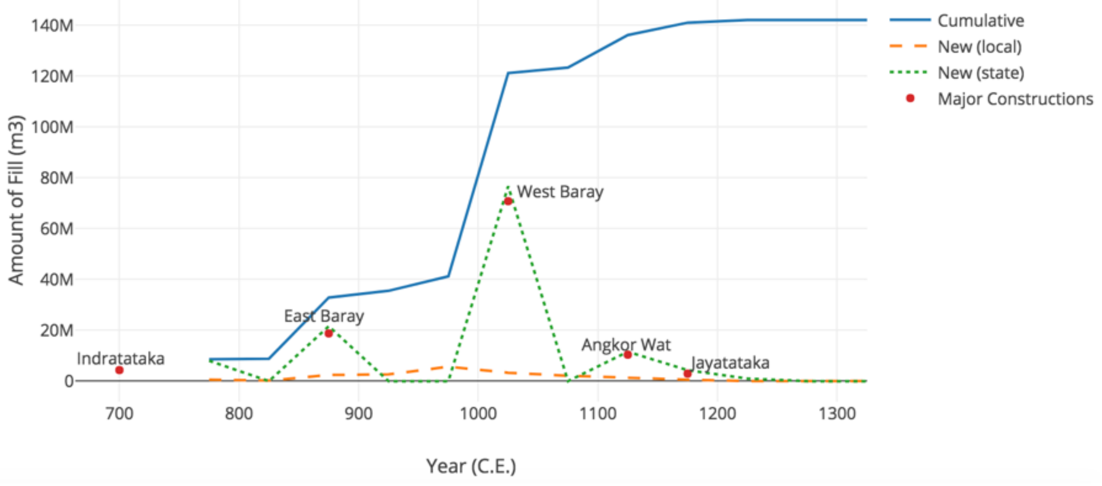

Figure 19: The amount of state-sponsored and local physical infrastructure built during each 50-year period.

Institutions and Entitlements

It is likely that the Khmer incorporated innovations in wet-rice irrigation technology with pre-existing rice production strategies (Nesbitt, 1997, pp. 1, 15). As a result, some temple communities are expected to have maintained pre-existing rice production strategies and may not have had, or needed, access to the hydraulic infrastructure for intensive irrigated wet-rice production (Fletcher, 2012, p. 307).

To better understand how water resources were distributed at Angkor, I consider temples that are within 1 km from hydraulic infrastructure and/or downstream from the infrastructure as having access. This determination is based on hypothetical access and does not account for social institutions that may have restricted access to features. Water can move relatively easily through networks of rice fields that share bunds because ad-hoc divots can be made in the bunds to allow water to flow into adjacent fields as necessary (Figure 20). Almost the entire landscape at Angkor is covered with ricefields, so I consider that any field downstream may have had access to hydraulic infrastructure through its adjacent ricefields. I acknowledge that not all the ricefields were constructed at the same time and more work must be done to associate ricefields with temples and associate temples that may have functioned as part of the same network of ricefields (Figure 21). Temples upslope but within 1 km of the hydraulic infrastructure were also included in the analysis as the engineered systems and channels could have moved the water the relatively short distance.

Figure 20: Contemporary ricefield with divots on bunds allowing water to flow between fields.

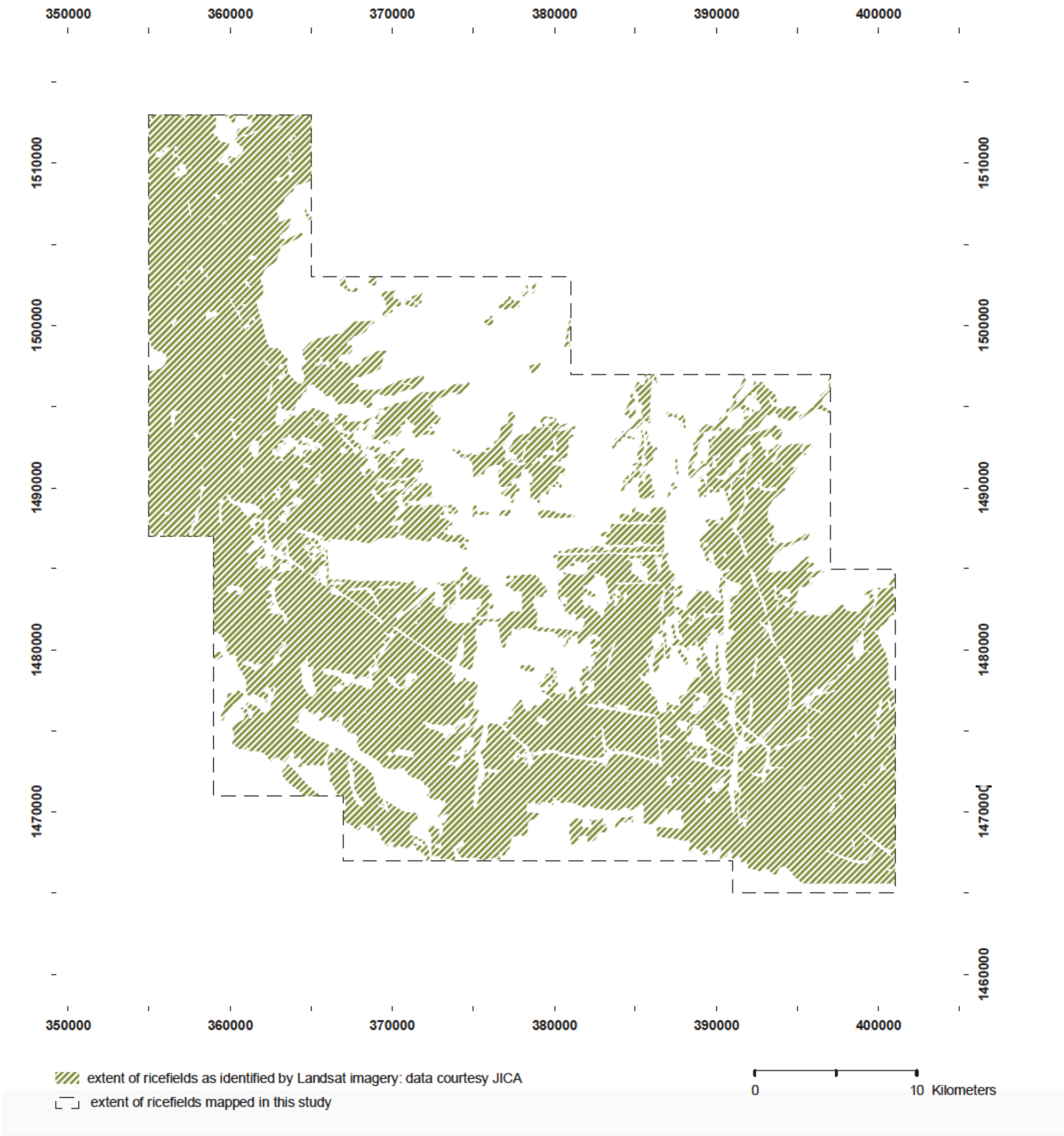

Figure 21: Extent of ricefields mapped by Hawken at Angkor (Hawken 2011, Figure 6.10).

To determine proximity to hydraulic infrastructure, I calculated the distance from the coordinates of the temple to the nearest piece of state-sponsored hydraulic infrastructure. To do this, I created maps of the hydraulic infrastructure as described by Fletcher et al. 2008. To account for the error in the generation of the dates of the state hydraulic feature construction and the 50-year average absolute error of the temples, I calculated the distance from each temple to each hydraulic feature that was constructed either before or up to 50 years after the construction of the temple. I then used the Near tool in ArcMap 10.5.1 to calculate the flat earth (planar) distance between temples and active existing hydraulic features for each period. To determine if the temples were downstream, I calculated the angle between the temple and the nearest piece of state-sponsored infrastructure using the Near tool in ArcMap 10.5.1, which calculates the angle to the nearest feature where East = 0°, North = 90°, West = 180°/-180°, and South = -90°. The terrain in the greater Angkor region is very flat; however, it does have an average slope of 0.1% NE-SW. As such, I consider any temple that is -45° to -180° or 135° to 180° as being downstream of the nearest element of hydraulic infrastructure. I then calculated the percentage of temples that had access to hydraulic infrastructure during each period (Figure 22).

The results indicate that over 70% of the temples constructed before 850 CE had access to the hydraulic infrastructure, this declined to less than 55% by 950 CE. This suggests that over half of the temples in the landscape had access to the hydraulic infrastructure, which suggests high levels of access. The percentage of total temples on the landscape with access to hydraulic infrastructure rises above 60% in 1000 CE and remains fairly consistent throughout the rest of the study period. There are also high levels of access for temples built from 1000-1150 CE and 1250-1350 CE. However, because so few temples were built after 1150 CE, the high levels of access in new temple constructions around 1300 CE do not significantly increase the percentage of total temples on the landscape with access to hydraulic infrastructure.

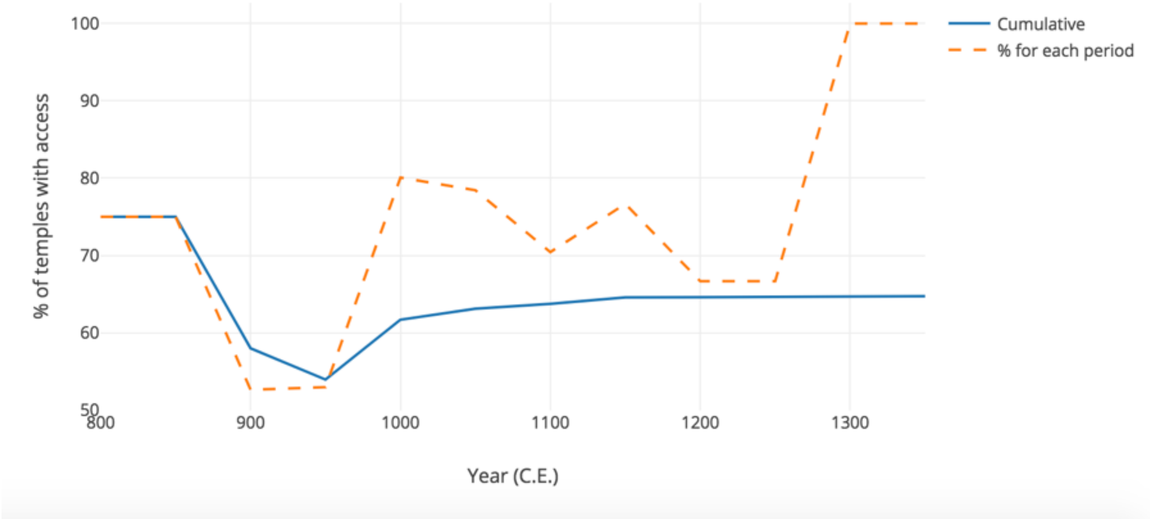

Figure 22: Percentage of temples within 1km from hydraulic infrastructure and/or downstream from the hydraulic infrastructure for each period (blue) and cumulatively (orange).

Redundancy

To calculate redundancy at Angkor, I used the harnessed water calculations from the natural capital section of this paper to determine the distribution of water between features. I calculated redundancy between state hydraulic infrastructure and local reservoirs. For each period, the majority of the water in the system (no less than 96% for any given period) is centralized in the four large reservoirs (East Baray, West Baray, Jayatataka, and Indratataka) (Figure 11). Based on this definition of redundancy, the periods with the lowest percentage of water stored in state infrastructure are the most redundant (800 – 850 CE, 950 – 1000 CE, 1200-1300 CE). However, there is very little variation among periods, and it seems as though the system during each period was not very redundant.

Figure 23: Redundancy. The dark blue line indicates the percent of water in the system stored in state infrastructure.

Results and Discussion

In this analysis, I have quantified elements of adaptive capacity of the water management system of Angkor, Cambodia over the course of 600 years and compared them to three periods of drought. The city of Angkor survived the first two droughts (1040-1090 CE and 1155-1170 CE); however, the third drought (1200-1250 CE) coincides with the decline of the city and has often been noted as a contributing factor to Angkor's demise. As such, investigating changes in the adaptive capacity of the water management system in each period of drought can lend insight into the usefulness of the concept of adaptive capacity for increasing system-level resilience of water management systems.

After quantifying the elements, I compared the elements among the three droughts, using the cumulative values at the end of each period. To understand how the elements compare among periods, I indexed the values. I made the highest of the three values 100 and divided the other values for the other two periods by the value of the highest period and multiplied the result by 100. The results indicate that all the values increase and/or remain largely constant from the first drought to the second and third with the exception of natural capital. Natural capital decreases at the end of the 12th century CE when the West Baray is no longer holding water (Dan Penny et al., 2005).

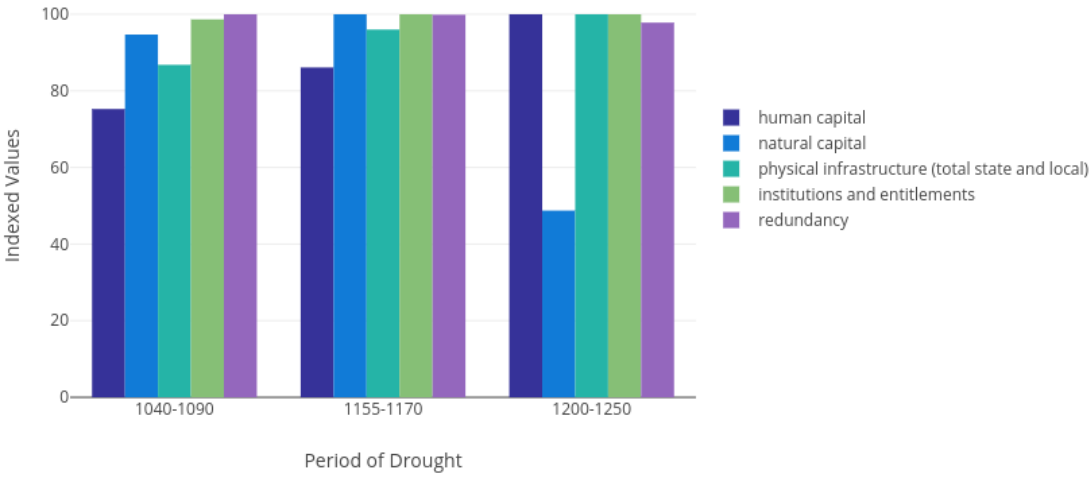

Figure 24: Indexed values for elements of adaptive capacity for each period of drought.

This analysis indicates that human capital increased throughout the study period, plateauing in the late 12th century CE. As expected, the population was lowest during the first period of drought and increased through the second and third periods of droughts (Figure 25). I calculated population by tracking the new foundations of two identified settlement types, local temple communities and epicenters (see Chapter 2). Because the population data is continuous, I was able to calculate the exact population at the end of each period of drought. However, since I've used bins of 50 years to simplify the graphics, I've included a 50-year moving average to graphically depict fluctuations within the 50 years. This is particularly important for the first and second periods of drought. There are four major epicenters that are constructed in 1175 CE, five years after the cut off for the second drought. As a result, the data binned by 50 years suggests a much higher population during the drought than the continuous data or the 50-year moving average.

There is much evidence (see Chapter 2) indicating that local temple communities and their associated populations were engaged with agricultural production. In contrast, the populations living in epicenters are not expected to be significant contributors agriculturally. Instead, they were likely engaged in activities related to worship and learning (Carter et al., In Press). As such, I consider populations associated with local temple communities as producers, and populations associated with epicenters as non-producers.

Wet-rice agriculture is labor-intensive, and production is often limited by population size; higher amounts of producers could cultivate more land and increase the surplus. In contrast, higher amounts of non-producers may have increased the burden on producers in the agricultural system. To look at the ratio of producers to non-producers, I calculated the percentages of individuals associated with local temple communities and epicenters at the end of each drought. There were high percentages of producers in the first (99%) and second (98%) droughts. In contrast, there is a lower percentage of producers (85%) in the third period of drought. This is largely related to the foundation of seven epicenters from 1150 – 1193 CE (Angkor Wat in 1150 CE; Preah Khan in 1151; Angkor Thom in 1175 CE; Angkor Thom Sprawl in 1175; Ta Som in 1175 CE; Banteay

Kdei in 1175 CE; and Ta Prohm in 1193 CE). The increase in the number of non-producers in epicenters during and leading up to the third drought may have increased the burden on the system for additional surplus; however, further research is needed with additional case studies to substantiate this proposition.

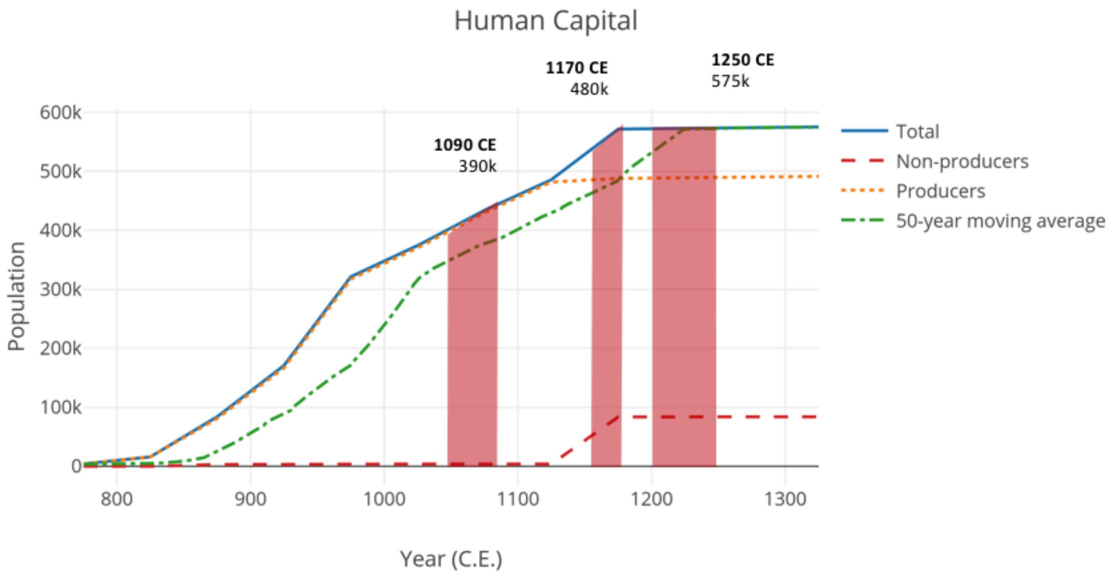

Figure 25: Total human capital during three periods of drought (red), indicating the relative population increases of people who are likely producers engaged in agricultural production (population associated with local temple communities) and non-producers living in the epicenters.

The water management system could store larger amounts of water during the first two periods of drought than the third drought (Figure 26). This is mostly due to the construction of major hydraulic features like the West Baray, which was built shortly before the first period of drought and continued to function into the second period of drought. Additionally, the Angkor Wat complex was built before the second drought and the Jayatataka, the last major hydraulic feature, was constructed at the end of the second period of drought in approximately 1175 CE. Paleo-botanical evidence suggests that the West Baray no longer retained water by the end of the 12th century CE, which coincides with the beginning of the third drought, and had minimal levels of water until the late 16th century CE (Daniel Penny et al., 2007). Penny et al. 2007 suggest that the drying of the West Baray is unlikely to be related to reduced rainfall. Instead, the authors suggest that the water may have been redirected into features associated with Angkor Wat or, following Dumarçay (1994, 2003), this period may mark a shift in the hydraulic system from storing water to a greater reliance on channels. These interpretations are consistent with Buckley et al. 2010's hydroclimatic reconstructions that the end of the 12th century CE is characterized by a period of high-magnitude monsoon. It is possible that the West Baray was drained in an attempt to remove excess water from the system or to help mediate the damage caused by high flows during the high-magnitude monsoons. Regardless of the cause, the timing of the drying of the West Baray meant the water management system in the third drought could store only half as much water as the first two droughts. This supports our expectations that large amounts of stored water allowed the system to function successfully during the first and second droughts, but that it was more vulnerable in the third.

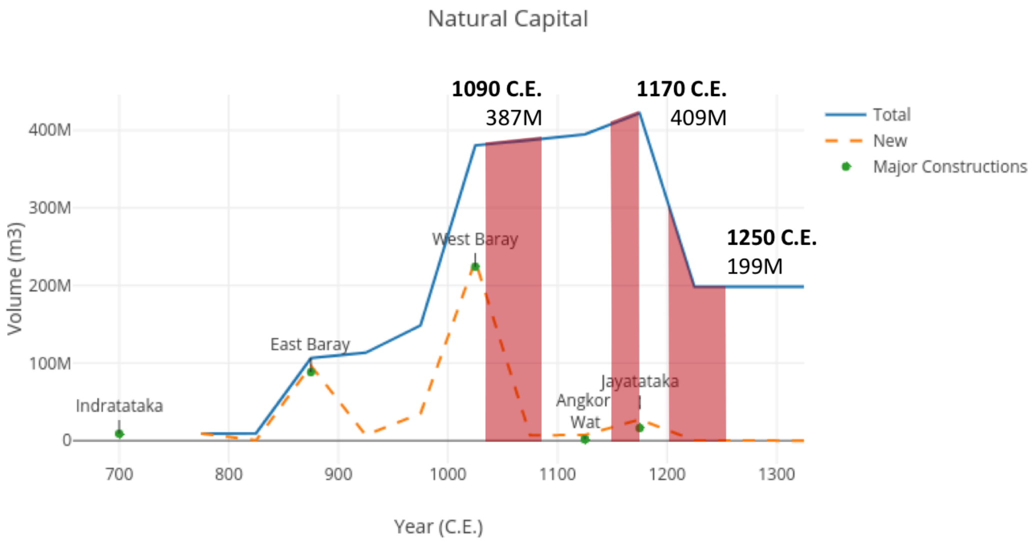

Figure 26: Natural capital for three periods of drought (red).

The Khmer invested huge amounts of human energy over the course of 600 years in the built environment in the greater Angkor region. In total, over 140,000,000 m^3 of soil was moved. This includes the state-sponsored construction of massive hydraulic features, which transformed the landscape and hydrology of the region by rerouting rivers into large holding basins, and smaller locally managed reservoirs, ponds, and channels. The amount of physical capital accumulating on the landscape increases from the first to third droughts, although the increases are not very substantial (Figure 27). These increases in physical capital would have made the system more susceptible to path dependency with time. This was especially problematic when the features began to fail. For example, the water management features left a huge footprint on the landscape of the 13th century CE greater Angkor region and increased the cost of constructing new features. For example, it would have been possible to re-purpose the land inside the West

Baray once it failed; however, repurposing the land with massive preexisting infrastructure would have been more labor intensive than developing new land without large earthen embankments and features.

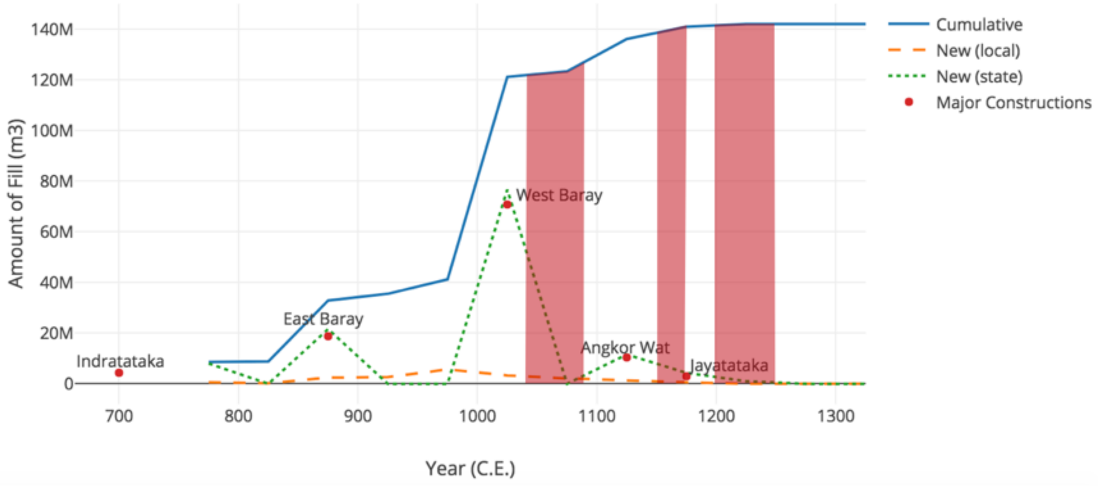

Figure 27: Physical infrastructure for three periods of drought (red).

While the access to the hydraulic features by individual temple communities, used to quantify institutions and entitlements, increases among all three droughts, the cumulative increases are not notable (Figure 28). As such, it seems that high levels of access did not play a large role in how the water management system functioned among the three periods of drought.

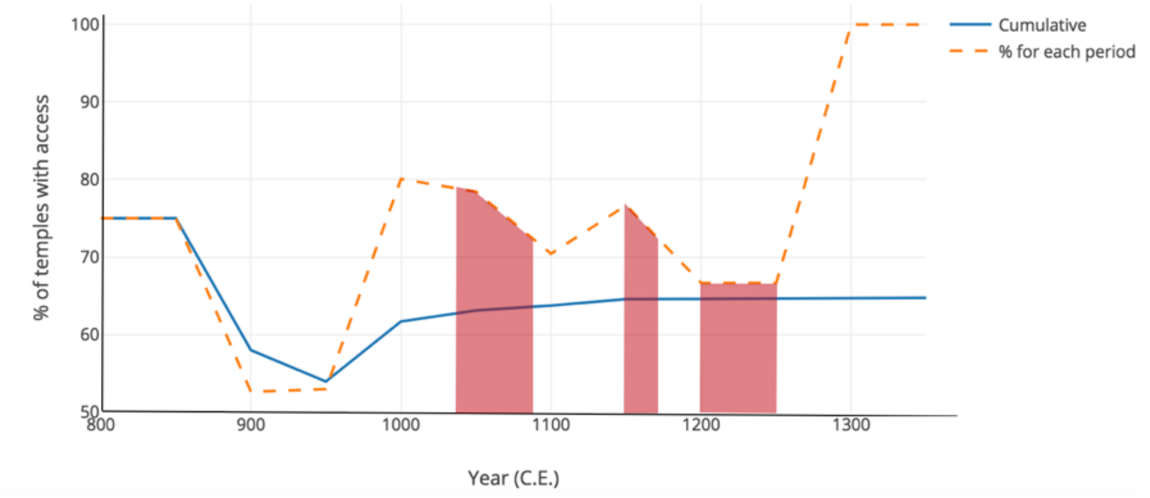

Figure 28: Access for three periods of drought (red).

The third period of drought had less redundancy than the first two periods of drought. This is due in large part to the absence of the holding capacity of the West Baray. Three of these features (the Indratataka, East Baray, and West Baray) had been built before the first period of drought. All five features were in existence leading into the second period of drought and, the West Baray was no longer functioning by the third drought. Despite only having three massive hydraulic features in the first period of drought, there were fewer features on the landscape which meant that these three features made up 99% of the system's water storage capacity. 99% of the system's storage capacity was centralized in the massive hydraulic features in the second period of drought; however, this storage was split between five features, instead of three, adding more redundancy to the centralized aspects of the system. With the accumulation of other smaller water storage facilities on the landscape and the disuse of the West Baray, the four remaining massive hydraulic features only account for 98% of the system's storage capacity by the third period of drought, even if the total capacity of the system is much lower than the systems of the first two droughts.

This analysis, however, only shows one dimension of a two-pronged problem. The system has five very large features that overshadow all of the other features of the landscape. If the five features are excluded from the analysis, there are very high levels of redundancy on the landscape with hundreds of small ponds and reservoirs. These types of systems have been noted elsewhere as being very resilient (Isendahl & Smith, 2013). The large features at Angkor increase the catchment area, by rerouting rivers into large holding basis, which increases the total amount of water available for the system than would otherwise be available with smaller, local features. It is possible that a commensurately large number of smaller water storage features – equivalent in volume to the small number of huge reservoirs that were built at Angkor – may support a similarly large population, and in a more resilient way.

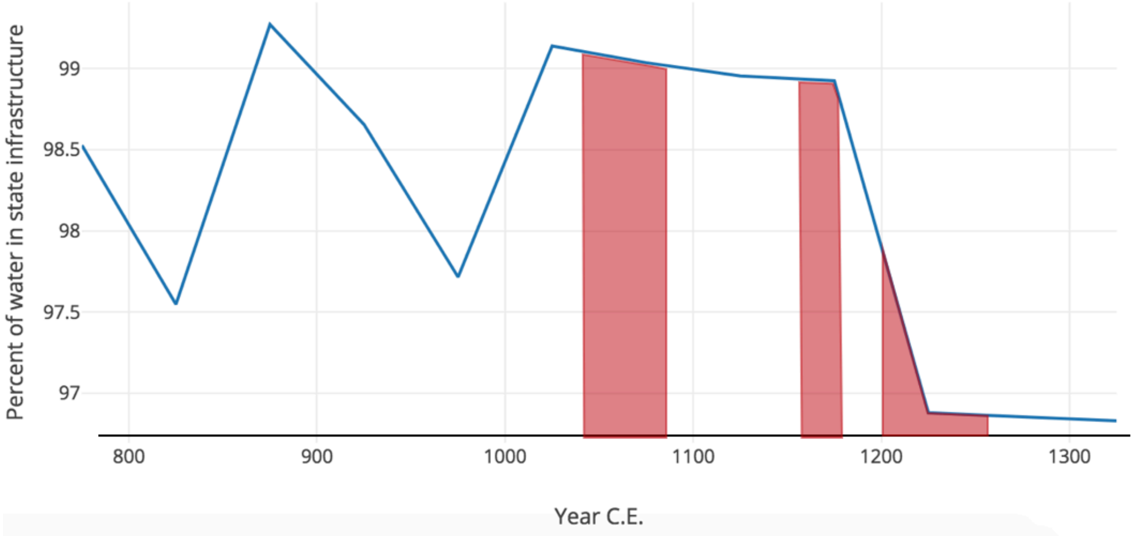

Figure 29: Redundancy for three periods of drought.

Chapter Conclusion

Understanding how humans interact with the environment and the ability of systems to change while maintaining essentially the same functions, i.e., their resilience, is critical for the continued existence and growth of communities today in urban and rural contexts alike. Archaeologists can make a significant contribution to interdisciplinary discourse on human-environmental relationships by examining the performance of water management systems of the past that were faced with social and climatic challenges and using these case studies to test contemporary metrics for assessing the ability of countries to respond to and prepare for climate change. Angkor presents a perfect case study for exploring the usefulness of adaptive capacity as a way of thinking about the resilience of water-management histories, specifically the usefulness of adaptive capacity, because the system persisted for centuries despite hydro-climatic challenges.

In this analysis, I have quantified five elements of adaptive capacity of the water management system of the medieval city of Angkor, Cambodia over the course of 600 years. During this period, the system encountered two severe droughts (1040 - 1090 CE and 1200 - 1250 CE) and one less-severe drought (1155 – 1170 CE). Four of the elements either increased into the final period of drought or show little difference between the three periods. The most notable change in the elements was natural capital. The disuse of the West Baray after the 12th century CE meant that the system had less than half of the natural capital of the system during the first and second periods of drought. As natural capital was the only element that changed significantly leading into the third period of drought, I argue that of all the measured elements of adaptive capacity, it is a suspected causal factor in the reduced resilience of the system during the third period of drought.

This analysis further suggests that the characteristics that comprise adaptive capacity and are widely considered in the current literature to contribute to system resilience may not be as impactful as suggested. This study indicates that of the five elements analyzed, only one of them, natural capital, decreased significantly during the third period of drought. In doing so, this study highlights the importance of involving the insights and long-term perspective from archaeological data in contemporary initiatives to increase socio-ecological resilience to climate challenges.

CHAPTER 4:

SYSTEMIC FAILURE IN THE WATER MANAGEMENT OF ANGKOR-ERA CAPITAL CITY: ADAPTIVE CAPACITY AT KOH KER, CAMBODIA

Sarah Klassen, Terry Lustig, and Damian Evans

Abstract

The time depth available in archaeology provides a basis for interdisciplinary discourse assessing system-level resilience and adaptive capacity over the long term. I present the results of an archaeological assessment of the adaptive capacity of the medieval water management of Koh Ker, Cambodia. Koh Ker had a long history of occupation, but it is best known for the seventeen years between 928-944 CE when it served as the political center of the Khmer Empire (~9th to 15th centuries CE). The most notable adaptation made to the water management infrastructure during Koh Ker's brief period of florescence was the construction of a seven-kilometer-long water-retention structure to the North of the city. How this altered the adaptive capacity and resilience of the existing system is evaluated. The structure increased the capacity to harness and store water six-fold, by centralizing over 85% of the water in one feature. At the same time, it introduced risk because the system was extremely vulnerable to a failure of that one feature. It is suggested that the engineering of this critical piece of water management

infrastructure was subordinated to the social experience created by aligning the embankment to permit one to view the ruler's other monumental features while entering the city. Additionally, the embankment could not accommodate substantial variations in water flow and overtopping led to a major breach in the decade after it was constructed. This changed the landscape dramatically and had significant implications for Koh Ker as the political center of the Khmer Empire.

Chapter Introduction

Since its introduction in engineering, natural and social scientists have adopted the concept of resilience to understand better how complex social-environmental systems respond to shock and stress (Gallopin, 2006; Miller et al., 2010). Holling proposes that change is a normal condition and that ecosystems can move between multiple equilibriums and stable states (Holling, 1973, 1996) (See also: Folke et al., 2010; Miller et al., 2010, p. 13). Accordingly, the very nature of systems may change over time (Scheffer, 2009). Resilient systems can adapt to change and move through stable states with minimal loss to their controls, identity, and ability to function (Redman, 2014).

Resilience is most visible in the *longue durée* where one can observe changes that communities experience, as populations grow, political and religious regimes change, and the climate varies around them over centuries. In recent years, many studies conducted on long-term interactions related to water management have highlighted both resilient systems and those that succumb to their vulnerabilities. For example, studies in Mesoamerica have produced some examples of resilient water management systems, like that of Tikal (Lentz et al., 2015; Scarborough et al., 2012), in the process also providing a framework for studying collapse (Turner & Sabloff, 2012). Similarly, research from the United States Southwest indicates that while irrigation systems ameliorate vulnerability to variability in precipitation, they may create other environmental and societal vulnerabilities that require further transformations of the landscape (Nelson et al., 2010). In contrast, Bali, Indonesia represents a resilient system where water is managed through a self-organized, decentralized system of cooperatives associated with a network of water temples (Hauser-Schäublin, 2005; Lansing, 2007; Scarborough & Burnside, 2010, p. 350).

Scholars often use a variety of conceptual tools to operationalize broader themes of resilience. In this paper, I employ the argument that scholars can use adaptive capacity to build a framework of observable dynamics to understand the multitude of factors impacting the resilience of social-environmental systems. The Intergovernmental Panel on Climate Change defines adaptive capacity as "the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (*Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 2001). It is often evaluated by how effective a system is at responding to shocks. As such, systems with high adaptive capacity build and plan for shocks and stresses before they are realized. Adaptive capacity frameworks are often used by Non-Governmental Organizations for assessing the ability of developing countries to respond to climate change. Such organizations include the Intergovernmental Panel on Climate Change (IPCC), Care, Save the Children, World Vision, Africa Climate Change Resilience Alliance, and Oxfam (Dulal et al., 2010; 2007; Jones et al., 2010; Pettengell, 2010; World Resources Institute, 2009). Frameworks for assessing adaptive capacity often consider a combination of interrelated and interdependent elements that encompass the assets of systems, such as harnessed natural capital, physical infrastructure, and human capital, (Dulal et al., 2010; Elasha et al., 2005) as well as emergent properties, such as redundancy. Successful adaptations made to the physical infrastructure of systems are those that meet the social and environmental needs of the system while introducing few risks.

Using this framework, I evaluate the water management choices that were made at Koh Ker in response to increased water needs during its period as the center of the Khmer Empire in the 10th century CE. Before the 10th century CE, the water management system at Koh Ker consisted of small dikes blocking tributaries and hundreds of small reservoirs scattered across the landscape (Evans, 2013, pp. 101-102). Whether the population surged during the 10th century CE or if it had been steadily rising, it is reasonable to expect that Koh Ker needed more water to meet the economic and social needs of the city as the center of an empire. In response to these increased needs, a large embankment, which transformed and restructured the water management system, was built to the North of Koh Ker. I argue that in addition to providing a greater supply of water, the construction likely served as a key element of the king's statecraft. Water control features elaborated beyond functional necessity are a key component of the Khmer sacred geography and are seen elsewhere in association with temples. The results of this study highlight how centralizing resources within a system can increase risk and help explain the rapid decline of Koh Ker as the political center of the Khmer Empire.

Adaptive Capacity

For the proposed research, I considered a variety of elements of adaptive capacity and have narrowed the focus of this study to four (harnessed natural capital, physical capital, human capital, and redundancy). I chose these elements because they can be effectively measured archaeologically and are pertinent to the type of water management system at Koh Ker.

As defined in Chapter 3, **human capital** refers "the labor of people within the system (Chapin et al., 2009, p. 23; Dulal et al., 2010, p. 7) and includes the skills, competencies, and attributes of these individuals (Dulal et al., 2010, p. 7; Smith & Skinner, 1982)." In this analysis, I measure human capital based on the population at Koh Ker before and after it became the capital of the Khmer empire.

In this study, **natural capital** is the "natural resources (eg., water) to which a society has access" (Dulal et al., 2010, p. 7; Elasha et al., 2005). For this analysis, I have calculated the amount of water that could be stored in the system at Koh Ker before and after the construction of the dike.

Societies can increase the quantity of harnessed natural capital by redirecting sources of water and storing water for later use in **physical capital** (i.e., dams, channels, and reservoirs) (Cosgrove & Rijsberman, 2000). As defined in Chapter 3, "physical capital refers to labor that is banked in the landscape through the construction of infrastructure (Håkansson & Widgern, 2007)." For this analysis, I calculate the amount of soil that was used to construct all of the water management features, including the dike, at Koh Ker.

Investments in infrastructure can increase the system's harnessed natural capital; however, it can also introduce trade-offs. For example, water management systems often have massive and highly durable infrastructural elements that, once built, may result in trajectories with long-term inertia in material culture (Fletcher, 2010). These trajectories can limit future sets of decisions because they are difficult or expensive to change or reverse (Levi, 1997, p. 28; Pierson, 2000). As such, while the infrastructure associated with water management can help to mitigate extremes in hydroclimatic variability and initially promote adaptive capacity, if it is too expensive to maintain or is relied on excessively it may reduce the capacity of the system to change in the face of a new stress or shock (Hegmon et al., 2008, p. 322; Janssen et al., 2003; Lucero et al., 2015; Nelson et al., 2010, pp. 32,34).

In this study, **redundancy** refers to how water is distributed and stored throughout the system between large state hydraulic infrastructure and local infrastructure.

Using this framework, I argue that researchers can evaluate the dynamics between elements of adaptive capacity over time periods using case studies, to contribute to the broader contemporary discourses of system-level resilience.

Historical Background

The Khmer Empire (9-15th centuries CE) controlled much of mainland Southeast Asia by the 12th century CE and continued to flourish until the 13th century CE before entering a period of decline. For most of this time, the political center was based at Angkor, near present-day Siem Reap, Cambodia. Today, Angkor is famous for the temple complex of Angkor Wat but is also known for its large and extensive water management system. Despite Angkor’s longevity, some scholars argue that the collapse of an unsustainable hydraulic network was a major factor in the abandonment of medieval Angkor as the center of the Khmer state (Groslier, 1979). These studies often cite changing precipitation patterns, extensification of the urban space, and intensification of the water management infrastructure as causal factors (Buckley et al., 2010; Buckley et al., 2014; Diamond, 2009).

In addition to its functional and environmental importance, water management was also an essential component of the statecraft and kingship of Khmer rulers. Much like the social landscapes and monumental architecture seen in Mesoamerica and the United States were intended to construct a sense of community and legitimize governance (Clark, 1997, 2004a, 2004b). Large Khmer water management infrastructure, like the East and West Baray at Angkor, are described by Van Liere as “theocratic superstructures” (Van Liere, 1980). These centralized features helped to construct sacred geography that reinforced and legitimized the authority of the divine kingship. Much debate has circulated about the functional and/or theocratic nature of massive water management features at cities throughout the Khmer Empire (Acker, 1998; Moore, 1995; Stott, 1992; Van Liere, 1980). I suggest this is a false dichotomy, as the sacred and profane are not mutually exclusive in Khmer landscapes (Engelhardt, 1995). For a Khmer water management system to be successful, it had to be able to absorb environmental stresses while simultaneously serving to legitimize the kingship and reinforce sacred geography, an important component of the Khmer social system.

The spatial and temporal complexity of the archaeological remains mean that many of the factors that influenced the development of Angkor's water management system are still not understood. The Khmer city of Koh Ker, in contrast, provides the opportunity to study a medieval water management system whose structure and functioning can be discerned with relative ease. Jayavarman IV moved the center of the Khmer Empire to Koh Ker in the mid-10th century CE (Figure 30). Inscriptions from the principal temple of Prasat Thom (K. 184, K. 682, 921 CE) indicate that Jayavarman IV claimed kingship from 921 CE (Coedès, 1931, p. 16), but it is not until 928 CE that inscriptions (K. 35, K. 183) suggest that he had command of the whole Khmer territory. During this period, there were several monumental building projects and modifications made to existing adjacent temples and the water management system. These would have enhanced Jayavarman IV's prestige and helped legitimize his claim to kingship as well as his use of Koh Ker as the political center (Stern, 1954). Inscriptions indicate that there was continued development during the sixty years after the transfer of the center of the Empire away from Koh Ker (Evans, 2013, p. 92); however, many of the building initiatives remained incomplete.

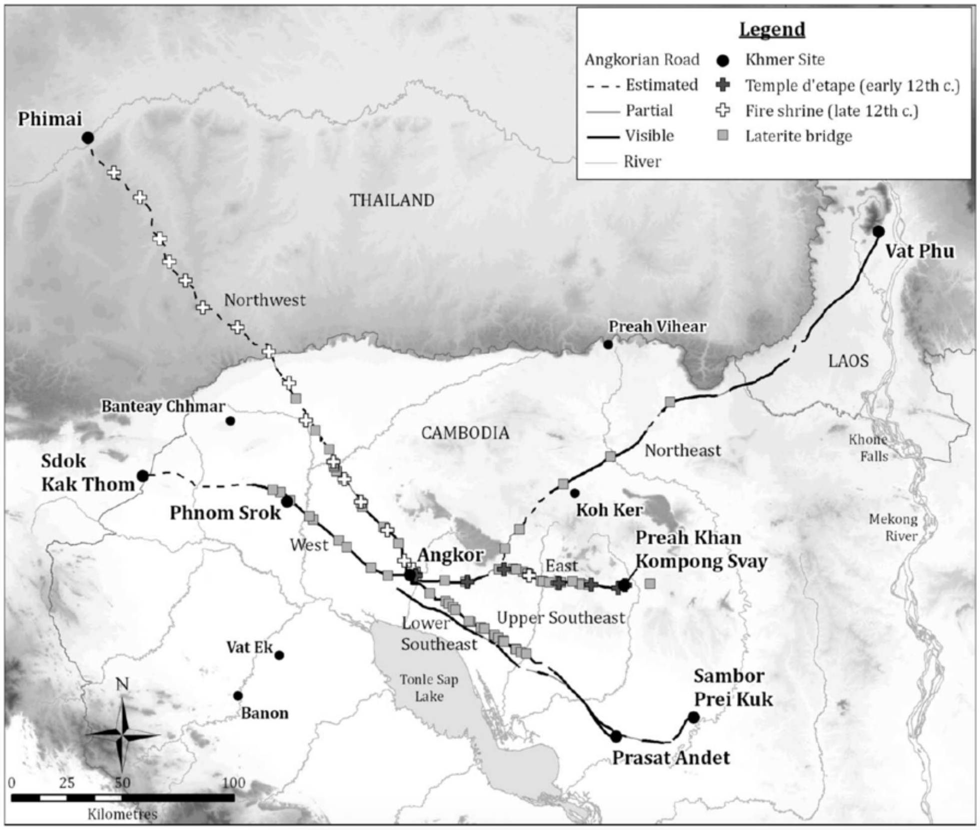

Figure 30: Khmer road system, showing the route from Angkor to Wat Ph'u (Vat Phu). The route bypasses Koh Ker, and the dike connects the road to the city (Hendrickson 2011: 447).

To what extent Koh Ker was occupied before 920 CE is unknown. Recent surveys and ceramic analyses suggest that the mid-10th century CE represents a brief demographic, architectural, and political florescence that punctuated a complex history that extended over centuries. APSARA National Authority conducted excavations in the central temple precinct in 2006 and 2007. These investigations recovered a 1.5 m deep ceramic sequence, with pre-Angkorian earthenware at the lowest levels. The report concluded that the central area of Koh Ker could have been inhabited as early as the proto-historic period (~ 500 CE) (Evans 2013: 94, 100). Recent surface surveys have also revealed a rich and uninterrupted ceramic sequence from prehistory up to the present (Thon, Tho, Personal Communication, July 2015).

Regardless of whether Jayavarman IV relocated the royal court from Angkor or had been steadily gaining power from a seat at Koh Ker, one can assume that the water management needs of Koh Ker dramatically increased when it became the political center. Inscriptional and archaeological evidence from Angkor indicates that royal courts and their associated temples had supporting workforces numbering in the tens of thousands of people (Evans & Fletcher, 2015). This included a specialized workforce of non-rural and non-rice-producing people that would have been highly dependent on surplus rice yield and a stable water supply. The landscape at Koh Ker is characterized by low rolling hills that are not particularly well-suited to the floodplain-based wet-rice cultivation that had been the foundation of the Khmer civilization (Moore, 1989). However, there are small floodplains that are seasonally inundated and allow for bunded field systems, fields separated by berms, which help retain surface runoff water. To capitalize on the natural environment, a hybrid water management system was used at Koh Ker. The system combined elements of a 'highland system' of impounding river valleys with elements of the classical 'lowland system' of reservoirs, channels and bunded fields. It was fundamentally different from the system used at Angkor and, despite colonial scholarship that presents the landscape as dry and the soil as impoverished (Aymonier, 1900, pp. 397-411; Briggs, 1999 [1951], p. 117; Jacques & Lafond, 2007, p. 107), it actually gets 20-25% more rainfall than Angkor (Mekong River Commission, 2005, p. 17). In contrast to the Tonle Sap at Angkor, there are no large permanent bodies of water at Koh Ker. However, there are bodies of standing water along the tributaries of the major river in the region, the Stung Rongea, which flows throughout the dry season.

The water management features at Koh Ker have been extensively mapped and recorded (Figure 31) (Evans et al., 2013). Using LiDAR data collected in 2012, I identified over 480 reservoirs and ponds. Field survey indicates that at least some of these reservoirs can be expected to retain water through the end of the dry season (Evans, 2013, p. 101). The largest reservoir (or *baray*) at Koh Ker, known locally as the "Rahal," is located to the southeast of the main temple, Prasat Thom. The Rahal sits in a natural river valley and has large dikes on the north and west that capture seasonal flows. Excavations by the APSARA National Authority in 2006 and 2007 at the north exit of the Rahal found evidence for multiple stages of construction (Evans, 2013, p. 94). This suggests that it existed in some modest form, probably just as a simple dike across the valley, before being expanded and formalized during the time of major construction in the 920s – 940s.

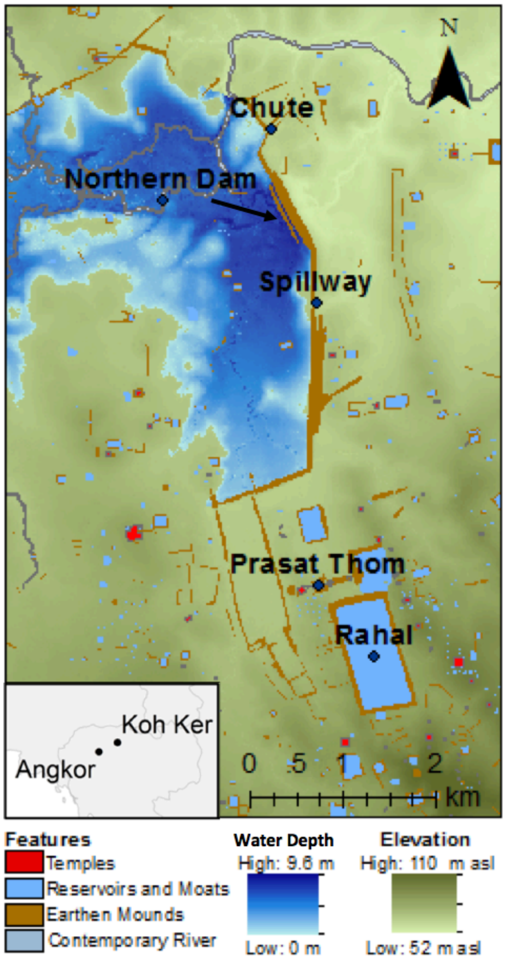

Figure 31: Map of Koh Ker indicating the Northern dike, chute, outlet, Prasat Thom, and the Rahal.

The focus of this paper is a multi-functional structure, which doubled as a dike and roadway that was built to the north of Koh Ker. Evans identified the water feature in 2013, and its functional capacity was confirmed through recent surveys (2014 and 2015) and excavation (2015). The dike consists of an artificial earthen embankment 15-150 m wide and 7 km long that formed a reservoir by capturing the flow of the Stung Rongea to the west. The embankment ranges in height from 0 – 10 m, such that the entire length of the embankment is between 69-72 m ASL. LiDAR data and ground survey have confirmed the existence of a chute and spillway (Figure 32). Spillways and chutes are both outlets that are designed to allow excess water out of the dike. Chutes are designed to be used on a regular basis while spillways are engineered to be used only during periods of high flow. At Koh Ker, the chute was intended to be used during average-level period of flows and the spillway was designed to be used during periods of excess-flow. Both the spillway and chute have engineered elements that have been seen only once previously in late 9th or early 10th century CE baray outlets at Angkor (T. Lustig, 2012, p. Figure 16.12). It would have ensured a stable water supply for Koh Ker, would have guaranteed an abundant and easily-exploited source of protein in the form of fish, and may have provided opportunities for irrigated rice agriculture. The dike curves west at its northern end to meet the Angkorian road that stretches from Angkor to Wat Ph'u in what is now Laos (Figure 30). This road connected Koh Ker to Angkor, the former and subsequent center of the Khmer Empire (Hendrickson, 2010). Wat Ph'u is considered by some to have been the spiritual heartland of the Khmer Empire and an important place of pilgrimage (Jacques & Lafond, 2007). Visitors to Koh Ker arriving from the Wat Ph'u road would have had a direct line of sight to the central temple, Prasat Thom, with an extensive body of water to their right as they entered the city. For this study, I evaluate the decision to construct the embankment based on how it affected adaptive capacity and system-level resilience of the water management system.

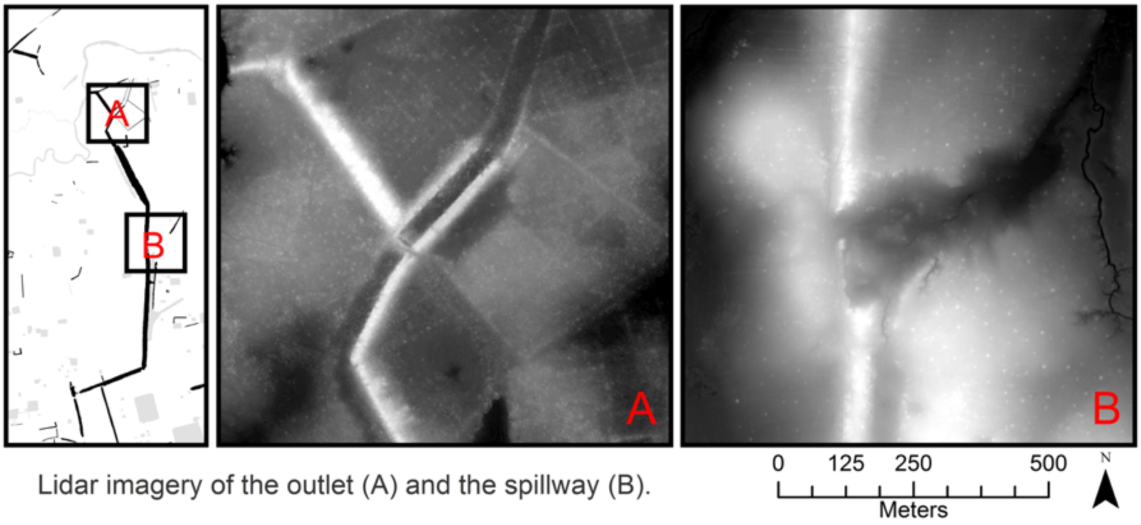

Figure 32: Layout of the embankment (A), LiDAR imagery of the chute outlet (B) and the spillway of the Northern dike at Koh Ker.

Methods

I measured **harnessed natural capital** based on the relative ability to manage and store water before and after the construction of the dike. I calculate natural capital as the water that is harnessed and stored in the physical infrastructure of the system. Potential sources of water at Koh Ker include the Stung Rongea, groundwater, and precipitation. While important for the hydrology of the region, groundwater was not considered in this analysis because it does not appear to have been impacted by the construction of infrastructure. Further, given unknown historical seasonal precipitation and flow in the region, I have assumed that water entering the geographic constraints of the water infrastructure remains relatively consistent between periods.

To determine the holding capacity of the reservoirs, I calculated the surface area of mapped reservoirs in ArcMap 10.5.1. Due to 1,000 years of erosion and vegetation growth, it was difficult to determine the exact height of the embankments other than the Rahal; however, I did note that the smaller embankments range from 1-2m in height. Using this range, I determined the total holding capacity of all reservoirs at Koh Ker (not including the Rahal) to be 1½ – 3 gigaliters (GL) and the Rahal to have a capacity of 2½ GL. I used the higher range in our calculations for a total pre-dike holding capacity of 5 GL.

Through remotely sensed data and surveys conducted in 2014 and 2015 I determined that erosion along the embankment indicates that the water has reached at least 68.8-69.7m asl. However, the operating top water level is the level of the crest of the spillway in the chute at approximately 68.5 m asl. Using the digital elevation model (DEM) derived from 50cm resolution LiDAR data and functions available in GRASS GIS (r.lake, r.surf.area, and r.volume), I determined that the holding capacity of the dike to be close to 35 GL of water if the water was at 69m asl (GRASS Development Team, 2015).

Contemporary water management systems often evaluate the cost of **physical infrastructure** in terms of the amount of money invested in them. Such estimates are irrelevant to the Khmer Empire because it did not have a cash economy. Instead, I calculated the architectural energetics for earthen features to determine the cost of physical infrastructure constructed during each period. This is often referred to as landesque capital, labor that is invested in the landscape through the construction of infrastructure (Fisher & Feinman, 2005; Håkansson & Widgern, 2007; Sheehan et al., 2018). In a study conducted in Mesoamerica, Erasmus (1965) found that one person could excavate 2.6 m^3 of earthen fill and transport it 50 m in one day (Erasmus, 1965). Erasmus's calculations likely underestimate the amount of labor required, and in a study of the earthworks Mississippian and prehistoric Maya, Gomez-Pompa et al. (1982) and Muller (1997) propose that a worker can excavate and place 1.1 m^3 and 1.2 m^3 of earthen fill, respectively, in one day (Gomez-Pompa et al., 1982; Muller, 1997, p. 273). For this study, I used the most and least conservative estimates of 1.1 m^3 and 2.6 m^3 per day for earthen features to calculate the maximum and minimum range of architectural energetics for earthen features. Similar to studies that have been conducted at Poverty Point (Ortmann & Kidder, 2013).

Cubic meters of fill used at Koh Ker were calculated based on the elevation and surface area of digitized features in GRASS (GRASS Development Team, 2015). I first created a smoothed DEM devoid of infrastructure. To do this, I removed areas with infrastructure from a 50m DEM of the region. I then created 5000 random points and interpolated them across the landscape and smoothed the surface to create a continuous elevation raster of the entire study region. I then reset the resolution of the raster to 50cm, masked the areas of infrastructure and subtracted the original DEM from the smoothed elevation raster. The resulting raster represents the volume of fill used to construct features.

Human capital estimates based on the amount of available water to support a population, or the carrying capacity, were drawn from Evans' (2013) methodology and rough calculations of the population by others at Angkor (Acker, 1998; Groslier, 1979; E. Lustig, 2001; Pottier, 2000). The carrying capacity estimates at Angkor and by Evans at

Koh Ker assume a relationship between $1m^3$ of irrigation water and $1m^2$ of irrigated land. Each hectare of bunded field systems is assumed to produce approximately 1.46 tonnes/ha of rice if water if properly managed, with each tonne supporting 5 people/year (Evans, 2013, p. 100). The estimates at Koh Ker were based on the amount of water supplied by the dike and are likely overestimates as it is unlikely that 3500 hectares of land were systematically irrigated because of the additional irrigation water. As such, I have based our estimates of the increase in human capital on inscriptional references to the size of royal courts and landscape comparisons between Ta Prohm and Angkor.

To understand changing levels of **redundancy** in the water management system at Koh Ker, I used the calculated capacity of features to understand how much water was contained in each reservoir and how the storage of this water was dispersed across the landscape of Koh Ker between the dike and other features. The results suggest that over 85% of the water was stored in the dike's reservoir and that together, the dike and the Rahal, accounted for over 93% of the water stored in the system.

Results

Apart from this reservoir, over 480 large and small reservoirs scattered across the landscape were built to store rainwater. The largest of these other features, the Rahal, has 5 m embankments and covers 60 ha with a holding capacity of approximately 2.4 gigaliters (GL) of water. The total holding capacity of all these reservoirs at Koh Ker, including the Rahal, is about 5 GL. In comparison, the large reservoir formed by the embankment may have resulted in a capacity of approximately 35 GL, about seven times the **harnessed natural capital** of all the other features combined.

To estimate **physical infrastructure** for the earthen features, I calculated the architectural energetics (in person days). This was then used to determine the cost of physical infrastructure built during each period. Our calculations suggest that approximately 1½ -3½ million person days were required to build all water infrastructure at Koh Ker. The large dike alone would have taken approximately 1 – 2½ million person days to construct. In addition to moving large amounts of fill, construction of the dike also included the spillway and chute, which were constructed of laterite and would have required additional labor input. This suggests that the architectural energetics necessary to construct the dike are almost as high as those that went into the construction of every other water management feature across the landscape of Koh Ker.

Human capital is difficult to estimate at Koh Ker; however, it can be inferred that the population was substantially greater when the city was the center of the empire than it was before or after this period. Evans (2013) has conducted some preliminary calculations on the population-carrying capacity within the study area and found that, without large hydraulic works, the landscape could likely support a population of more than 30,000 people (Evans, 2013, p. 101). Evans' estimates of the carrying capacity of Koh Ker, including the Rahal, suggest the landscape could support a population of over 32,000 people. When the same metrics as Evans' are used, it is found that the northern dike would have contained enough water to increase the carrying capacity of the landscape by 26,000 people. However, this estimate assumes that the agricultural production of the additional water was systematically realized.

More accurate estimates about the sizes of royal courts can be gleaned from inscriptional references. For example, inscriptions from Ta Prohm suggest that the temple had a workforce of 13,000 people (Coèdes, 1906). Based on the landscape comparisons, Evans and Fletcher estimate that the workforce of Angkor Wat, a primary state temple, was double that of Ta Prohm with a total workforce of around 25,000 people (Evans & Fletcher, 2015). Both lines of evidence seem to suggest that the population of Koh Ker increased in the range of no less than 10,000 – 20,000 people with the relocation of the royal court.

I argue that the construction of the large dike decreased the **redundancy** of the water storage features. Before its construction, the Rahal stored 50% of the water in the system at Koh Ker, and the other 50% was distributed across the landscape in small reservoirs with proximity to fields and occupation mounds. This suggests that the system was much more redundant with as much water stored in the large features as across the rest of the landscape. It is likely that the small reservoirs would have provided enough redundancy and risk mitigation to support the pre-capital population. The construction of the dike greatly reduced redundancy by centralizing over 85% of the water in the system in one feature. Additionally, the dike seems to be the only significant water management feature constructed during this time to facilitate the consolidation of Koh Ker as the capital of an empire. It is therefore proposed, that this was a key feature relied on to support the increased population.

Evidence of the Dike's Failure and Alternate Road Alignments

The LiDAR shows a major breach in the dike that rerouted the course of the river to run 2km further north of the city and rendered the structure unable to impound water. Lustig et al. 2017 conducted extensive surveys (2014 to 2015), excavation (2015), and hydraulic, hydrological, and wave modeling to determine the nature and timing of the breach. These models indicate that the embankment overtopped twice within less than a decade, the second time resulting in the dike break. The authors also conclude that the breach event took no more than a few hours.

The results from Lustig et al. 2017 indicate that the embankment along with its two main features, the spillway and chute, were not optimally engineered or constructed, given the natural topography or regional flows. Hydraulic and hydrological modeling indicates that the maximum level of the water in the reservoir was 70 m above sea level (ASL) and this level could be expected to be reached on average every six years and 69.8m ASL every two years. The current route of the river is 10 m below the crest of the embankment and 8 m below the nearby natural ground. The spillway must have been made of laterite, as all such water features are, but no laterite was found in the area. This suggests that the breach must have been forceful enough to transport the laterite blocks downstream. There are additional erosion marks to the west of the final breach (Figure 33). This suggests that the flow through the final breach was substantial and did not prevent other areas of the embankment from overtopping.

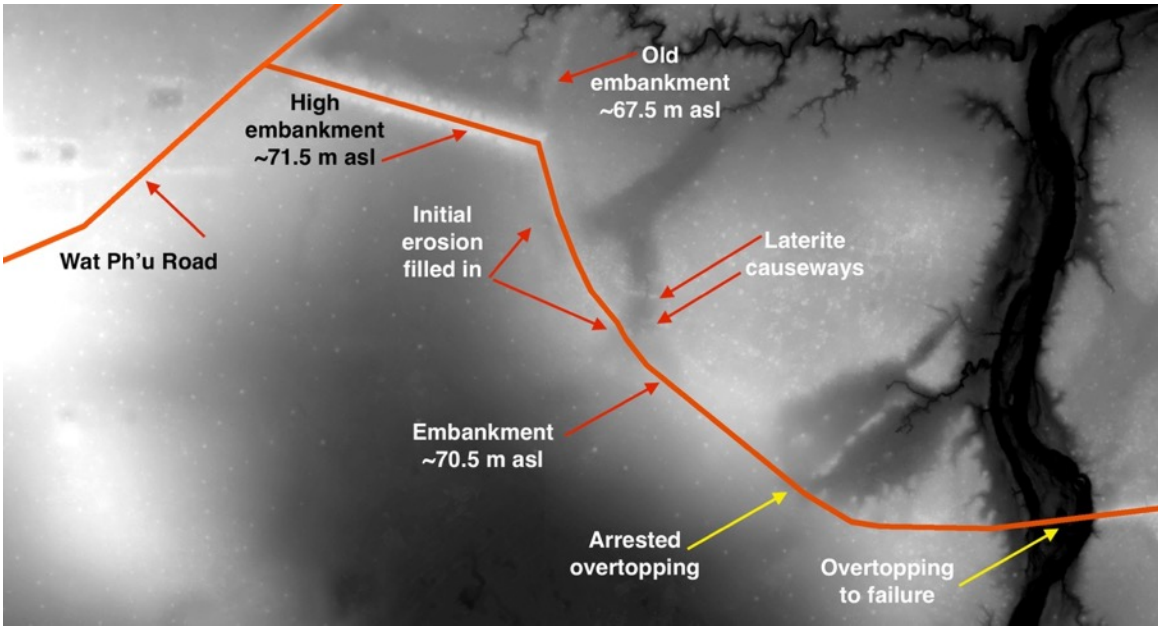

Figure 33: Northwestern section of embankment. Figure from T. Lustig et al (2017).

The engineering and construction of the spillway and chute were also flawed. To start, the capacities of the two outlets were too small for the flows coming from the catchment, so that the risk of the reservoir becoming too full and leading to overtopping was high. The original crest of the spillway was at 69.6 m ASL; however, there is a natural ridge of sandstone with a 68.9 m to 69.7 m ASL crest upstream. This higher natural crest upstream would have impeded the flow of water from the reservoir and reduced the spillway's discharge capacity (Figure 34). Additionally, the masonry construction of the spillway was not designed to handle high velocities of water. Much of the spillway has washed 10-20 m downstream in layers. This indicates that the laterite blocks used to build it were too light to resist the high-water velocities of the overflowing water; the blocks were not keyed in; the toe of the spillway was not protected from erosion; and the foundation of some sections was sandy clay rather than rock. The damage at the spillway may have occurred over several wet seasons and could have been easily repaired in the dry season. However, there is no evidence of repairs, which fits with our estimates that the dike was breached within a decade. There is no point in repairing a feature of a dike that is no longer functioning (T. Lustig et al., 2017).

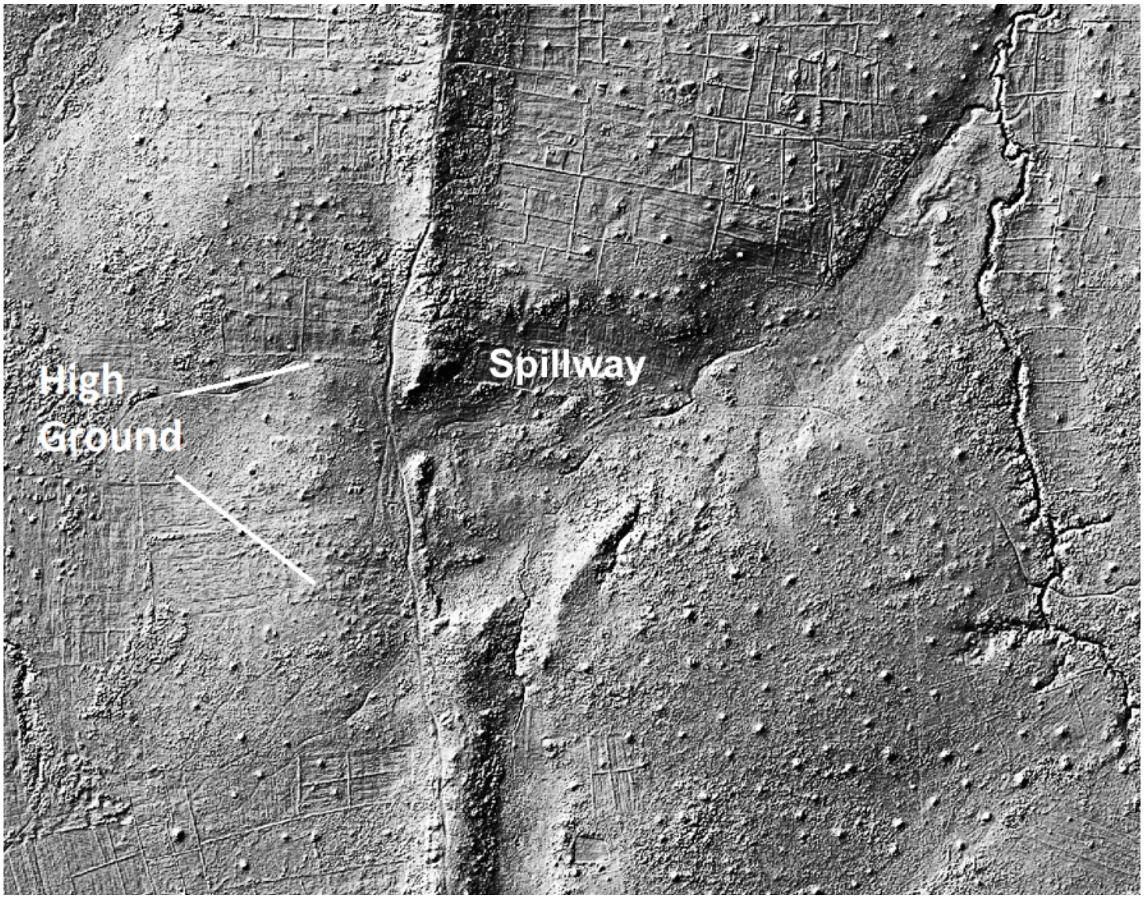

Figure 34: High ground east of spillway. Figure from T. Lustig et al. (2017).

The chute appears to have failed to a lesser degree; however, like the spillway, there is no evidence of repair. The original laterite blocks in the spillway were repurposed to create a linear pavement-like structure blocking the opening of the chute. This must have been done after the course of the river was rerouted, when the dike was no longer functioning, and the chute was no longer discharging water. The linear structure could have been built to help restore access from the Wat Phu'u Road to Koh Ker. Lustig et al. argue that this structure would have entailed much effort and was likely done under the authority of the king (T. Lustig et al., 2017). This evidence aligns with the hydraulic, hydrological, and wave modeling and places the failure of the dike to within the reign of Jayavarman IV.

Given the natural topography of the region, the better structural alternative would have been a road 100 m to the east, along a higher natural ridge (Figure 35). This more cost-effective option would have reduced the work to build the section of the embankment substantially. About a kilometer to the east of the constructed dike, there is a long ridge that is mostly higher than 70 m ASL. Additionally, it only crosses 150 m of the floodplain and building a water-retention structure with a spillway here would have entailed even less effort than the constructed dike. Indeed, a linear feature running along the crest of the ridge is visible on the LiDAR, which suggests that they may have started construction on a second dike after the first dike failed. Such a reservoir could have been designed to provide the same volume of water and a more secure all-weather access to the Wat Ph'u Road. An alternative approach would have been to invest the same amount of labor in physical infrastructure that was more evenly distributed across the landscape while also creating more local reservoirs. However, neither alternatives would have provided the aesthetic impact of an extremely large artificial lake abutting the road used by visitors approaching Koh Ker from Wat Ph'u road (Figure 36 and Figure 37).

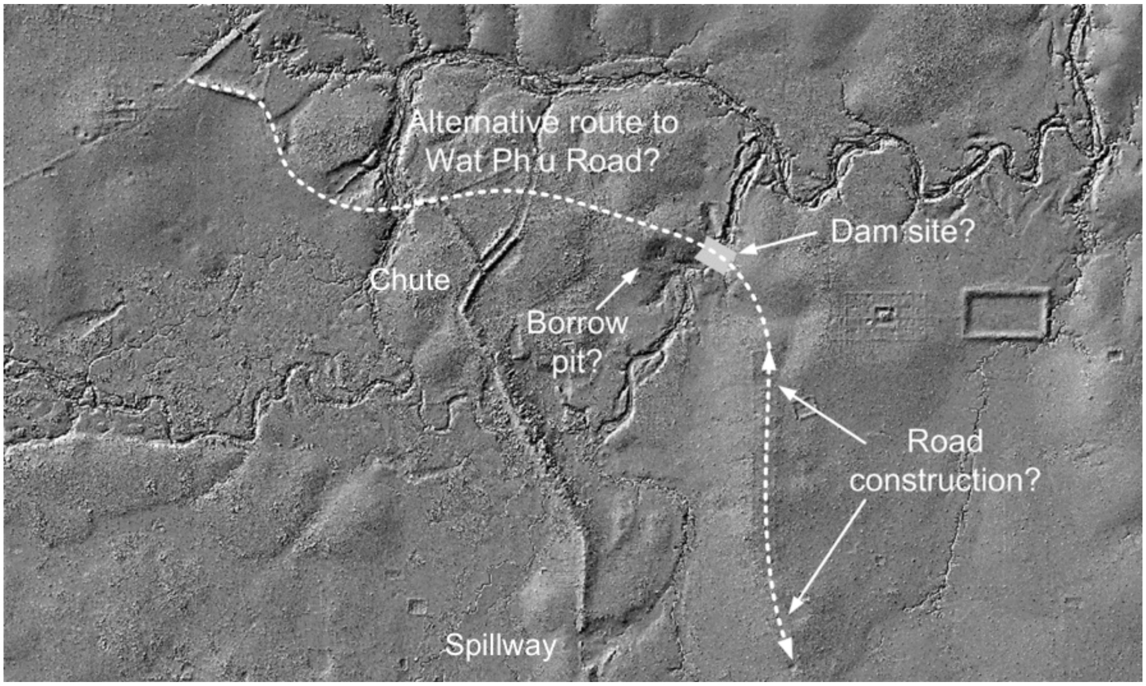

Figure 35: Possible unfinished road and embankment.

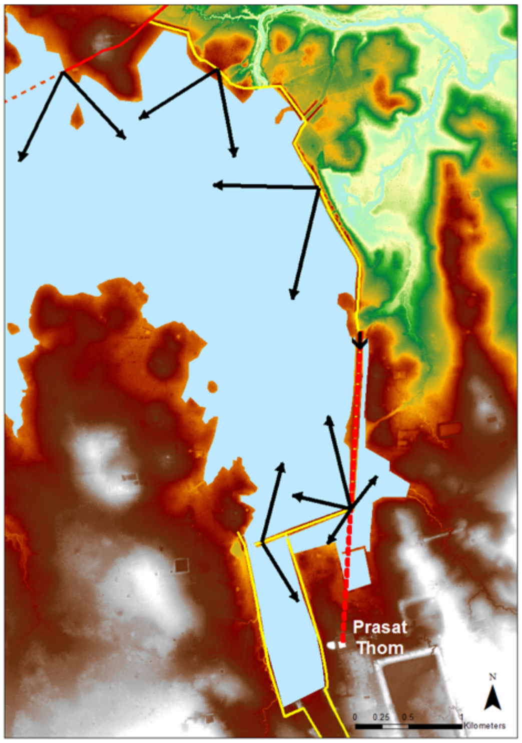

Figure 36: Expansive water views with constructed embankment. Figure from T. Lustig (2017).

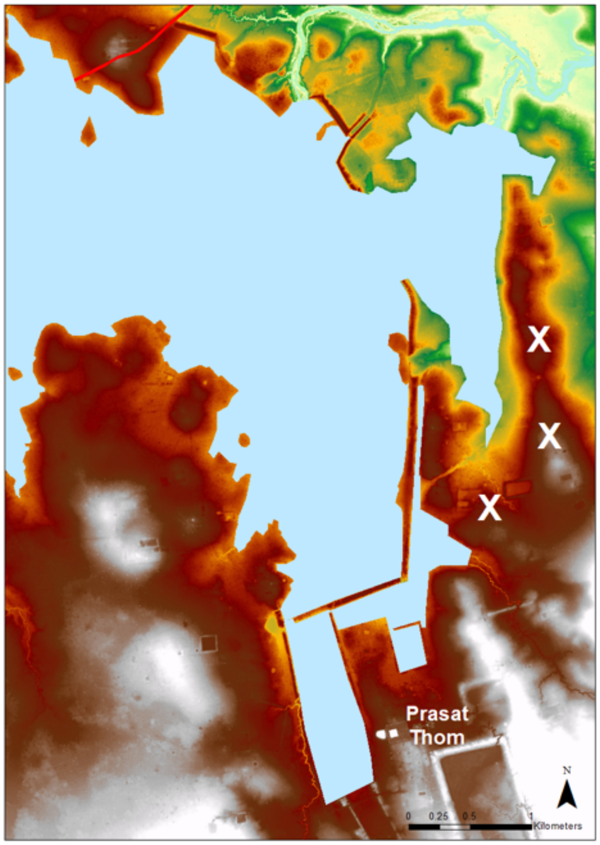

Figure 37: Zone of less extensive water views, marked with Xs (T. Lustig et al., 2017).

The flaws in the design of the dike at Koh Ker, together with its unprecedented size, suggest that the royal engineers were not given the time to develop their designs using the standard engineering technique of trail-and-error. I suggest that the political effects of a serious of failure of the dike would have been profound, and could have strengthened support for the idea of returning the political center to Angkor.

Discussion

When Koh Ker became the center of the Khmer Empire, the demand for water likely increased to meet the needs of the growing population and to enhance the prestige of the new political center. In response to or in preparation for this change, the engineers at Koh Ker initiated a monumental building project constructing the largest embankment ever built across a major river in Khmer history. The construction raised all the levels of all the elements of adaptive capacity except for redundancy, which decreased as there were disproportionate amounts of water stored in state features. The dike could impound six times the amount of water of the previous system. The resulting reservoir likely acted as a symbol of Jayavarman's political prowess, bolstering the prestige of the new political center. This form of aggrandizing is seen elsewhere in Koh Ker through the modifications and additions made to temples within the city's core.

In this paper, I have observed how the decision to build an unprecedentedly large water structure influenced the dynamics of adaptive capacity. With the construction of the embankment, the royal engineers at Koh Ker increased the city's permanent water to accommodate the increases in population. The resulting reservoir stored up to six times the amount of water as the previous infrastructure, significantly enhanced the volume of water available for fish habitat, potentially increased the amount of land for flood-retreat agriculture, and stored water for non-agricultural and symbolic purposes. This increase in water enabled the city to recruit and support a large population and likely contributed to the city's ability to gain or maintain control of the Khmer empire. However, by building such a large feature, they decreased redundancy and introduced risk to the system that left it extremely vulnerable to failure. When the embankment did breach, the course of the river rerouted to the North. This breach undermined the reservoir's utility as a source of water and protein by over 85%. Further, its failure would have undermined any associated attempts at statecraft.

Koh Ker highlights the risk of decreasing redundancy in water management systems. Jayavarman IV invested significant amounts of labor into a single, unprecedentedly large item of physical infrastructure instead of building up the system's assets and capabilities steadily. Together, the Rahal and embankment stored approximately 93% of the system's water in two highly centralized features. Based on our calculations for natural capital, the Rahal provided storage for approximately 50% of the water stored in reservoirs before the construction of the 7-km long embankment. This suggests that a centralized water management feature, which doubled the water storage of the system was within the capabilities of the royal engineers, but that a septupling was not. The dike represented an extreme effort at centralization, likely intended to increase both prestige and access to water. However, it was risky. When the dike failed, the entire system was compromised and no longer met the social or utilitarian needs of the center.

While the failure of the embankment appears to precede the return of the political center of the Khmer Empire to Angkor, it is important to note that the area was not entirely abandoned. Local farmers returned to their original forms of subsistence, relying on reservoirs scattered throughout the landscape, and continued to farm the land for centuries. This was sufficient for the social-environmental needs of the rural and smaller urban population of Koh Ker for over 1,400 years. These types of decentralized systems are often championed for their resilient nature. However, in the case of Koh Ker, it was impractical and unable to meet the transformed approach of Koh Ker water managers when it became an imperial seat. This failure highlights the importance of moderating one’s investments in physical infrastructure so as not to exceed one’s capacity to absorb the consequences of the inevitable errors inherent in any new design. Unfortunately, the response to an increased need of harnessed water for social and utilitarian purposes introduced risk that undermined the ability of the system to function.

CHAPTER 5:

CONCLUSION

This study synthesizes new data with data that has been collected over decades into an integrated framework that has allowed me to evaluate the resilience of the water management systems in the long term. In this project, I have traced the emergence, florescence, and decline of the water management systems of two medieval Angkorian cities, Angkor and Koh Ker. This project has three stand-alone papers and an appendix. Together, these studies have helped redefine the urban morphology and agricultural system of the two cities over the course of centuries and has provided a data-driven approach to critically evaluate the resilience and adaptive capacity of water management systems in the long term.

In Appendix I and Chapter 2, I put forth a diachronic urban morphology building on decades of mapping and survey work by multi-national research teams in the greater Angkor region. As part of this project, I compiled a significant amount of new and pre-existing data in a comprehensive spatiotemporal database. In Appendix I, I used a combination of multiple-linear regression and semi-supervised machine learning to date over one thousand temples in Cambodia. In Chapter 2, I assigned dates to mapped polygons of archaeological features in the greater Angkor landscape based on their association with temples and dated hydraulic features. With this data, I created georectified and chronologically ordered maps that provide greater insight into the urban development of Angkor.

These diachronic maps trace the founding of temple communities in relation to the emergence of epicenters (concentrations of public and ritual architecture) and state-sponsored hydraulic infrastructure on the landscape over time. The results indicate that temple communities cluster around existing and newly constructed hydraulic features sponsored by the state. The number of new temple foundations increases through the 10th century CE and begins to decline in the 11th century CE. By combining landscape data with inferences from inscriptions, I argue that there is increasing competition for land by the mid-11th century. At this time, inscriptional data indicates that there was a gradual accumulation of land by elites and upper elites, which subsumed smaller land grants associated with smaller temples into the holdings of large temple complexes. This change has significant implications for our understanding of the organization and operation of the agricultural system in medieval Angkor. For example, the agricultural system during the 10th and first half of the 11th centuries utilized the infrastructure sponsored by the state while maintaining local autonomy through hundreds of temple communities with control of local reservoirs and ricefield systems. However, I identified a shift in this system when land was increasingly bought from the temple communities by the state and upper elites. More research is needed to determine if the centralized landownership in the 12th and 13th centuries impacted the viability of the agricultural system.

Chapters 3 and 4 provide empirical evidence to understand the usefulness of adaptive capacity metrics for contemporary countries as they prepare for and respond to climate change through the diachronic analysis of adaptive capacity at Koh Ker and Angkor. The underlying assumption is that the stronger the positive impact of key elements of adaptive capacity are within a system, the greater a system's adaptive capacity, and thus resilience, is enhanced. However, this study suggests that we should have a more nuanced view of a basic axiom, which this data reveals to be much more complex. While adaptive capacity may be useful for identifying causal factors in the resilience of systems over the long term, it is not directly explanatory for either Angkor or Koh Ker. As such, if they are relying on metrics such as these and no others, contemporary countries should re-evaluate the metrics they use to assess their ability to adapt to climate change.

At Angkor, the elements of adaptive capacity changed little throughout the analysis. The one element that did differ significantly before the third period of drought was natural capital, which decreased by almost half. This suggests that the reduced amount of natural capital may have played a causal role in the decreased resilience of the system during the third drought. At Koh Ker, the construction of the dike increased all the elements of adaptive capacity except for redundancy. The water in the system before the construction of the dike was equally distributed between state features and local features across the landscape. With the construction of the dike, a disproportionate amount of water was stored in state-sponsored centralized features.

Angkor and Koh Ker both demonstrate the importance and warn of the danger of large centralized water management features. At both Angkor and Koh Ker there are local and state scales of hydraulic infrastructure. The West Baray contributed to the amounts of natural capital the system was able to store during the first and second droughts. However, it was no longer retaining water during the third drought. While the West Baray functioned for centuries, the dike at Koh Ker likely failed shortly after it was constructed. In both cases, there were large investments in physical capital in the form of centralized water storage features. And in both cases, whether due to failure or strategic decision, the largest of these features was no longer functioning when the epicenters declined.

Understanding both the long-term success and the ultimate failure of water management systems in the past opens promising new avenues to identifying solutions for the present and future. This project makes a broad methodological contribution to the assessment of water management systems in pre-modern cities. Through adaptive capacity, it is possible to have a more detailed understanding of how elements of water management systems interacted to make the system as a whole more or less resilient. Historic case-studies, like Angkor and Koh Ker, can demonstrate the long-term human and environmental impacts of water management systems that are developed and used over the course of centuries. Remarkably, Angkor was resilient to social and environmental challenges for over 600 years and is an exemplar for any large urban environment that is highly dependent on managing water. This study indicates that the water stored in large, centralized features increased the system's resilience, they also introduced risk as the failure and disuse of both features, coincided with the collapse of each urban center.

Future Work

The data produced in this study also creates hypotheses and lays the groundwork for more advanced, socially-driven environmental research at Angkor and in Southeast Asia. Here, I highlight three of these new avenues for future work:

More fine-grained analysis of institutions and entitlements

The first drought at Angkor coincides with the end of the exponential growth phase of temple communities. During this period, there were numerous temples on the landscape that maintained autonomy while utilizing large centralized features, like the East and West Barays. In contrast to what we would expect based on basic principles of adaptive capacity (Pettengell, 2010, p. 15), the institutions and entitlements that provided access to resources were not found to vary much over time and do not seem to be an impactful element of adaptive capacity. However, more work can be done to determine which types of temples had access to hydraulic infrastructure and whether access was related to the size and wealth of the institution. Similarly, more work can be done to determine if the state-sanctioned centralization of land in the later periods of Angkor impacted the resilience of the system.

Nexus between large amounts of human capital and large centralized water management features.

In addition to having less total human capital, the population during the first period of drought was comprised of more producers (98%) than the third period of drought (85%). This decrease in percentage of producers would have added stress to the agricultural system during the third drought, which would have been required to produce more rice for the non-producers living in the epicenters. While the decline of the epicenters at both sites coincides with the disuse of their largest hydraulic features, both sites have evidence for long occupation histories at the local level. This relationship suggests that there may be a functional and societal relationship between the construction of large, centralized hydraulic features, which can increase the catchment area of a region, and large populations of non-producers living in epicenters. However, more case studies are needed to substantiate this proposition.

Small world and Scale Free networks

Another interesting avenue that arose from the second chapter is a network analysis to determine if there is a network shift in the locations for new temple constructions over time. For example, is there a tipping point when temples shift from being constructed randomly on the landscape (small world networks) to hierarchically and in association with other temple communities (scale free networks).

Ancient cities share many of the issues that our cities face today; however, they afford a much longer-term perspective. While this study shows the relevance of ancient cities for identifying the nature of resilient water management, the same is true for many other social, economic, demographic, and political phenomena. As such, further research into the successes and failures of cities of the past, will give us a broader perspective for the future of cities in the present.

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APPENDIX I:

SEMI-SUPERVISED MACHINE LEARNING APPROACHES FOR PREDICTING THE CHRONOLOGY OF ARCHAEOLOGICAL SITES: A CASE STUDY OF TEMPLES FROM MEDIEVAL ANGKOR, CAMBODIA

Abstract

Archaeologists often need to date and group artifact types to discern typologies, chronologies, and classifications. For over a century, statisticians have been using classification and clustering techniques to infer patterns in data that can be defined by algorithms. In the case of archaeology, linear regression algorithms are often used to chronologically date features and sites, and pattern recognition is used to develop typologies and classifications. However, archaeological data is often expensive to collect, and analyses are often limited by poor sample sizes and datasets. Here we show that recent advances in computation allow archaeologists to use machine learning based on much of the same statistical theory to address more complex problems using increased computing power and larger and incomplete datasets. This paper approaches the problem of predicting the chronology of archaeological sites through a case study of medieval temples in Angkor, Cambodia. For this study, we have a large dataset of temples with known architectural elements and artifacts; however, less than ten percent of the sample of temples have known dates, and much of the attribute data is incomplete. Our results suggest that the algorithms can predict dates for temples from 821 – 1150 CE with a 49-66-year average absolute error. We find that this method surpasses traditional supervised and unsupervised statistical approaches for under-specified portions of the dataset and is a promising new method for anthropological inquiry.

Introduction

Archaeologists often rely on statistical methods to infer the chronology of and group archaeological sites, artifact types, and architecture. However, this can be limited by small sample sizes and incomplete datasets. In this paper, we introduce the use of semi-supervised machine learning algorithms for archaeological inquiry. Machine learning mimics human pattern recognition and learning processes through a series of complex mathematical computations to find structure and define algorithms for large datasets (Salazar, 2012, p. 1). In this scenario, algorithms refer to the equation, rules, or set of steps and pattern recognition necessary to transform the data (input) into the categories (output) (Alpaydin, 2014, p. 1). Pattern recognition is the process of finding structure in data that can be used to divide the data into discrete categories (Salazar, 2012, p. 2).

Our case study, Angkor, was the political center of the Khmer Empire (9th – 15th centuries CE) in present-day Cambodia for over five hundred years (Figure 1). During this time, over 1400 temples were constructed in the greater Angkor region that were economic and religious centers of residential hamlets. Several mapping projects have shown the relationship between temples and other urban features, like occupation mounds and reservoirs (Evans, 2016; Evans et al., 2013; Evans et al., 2007). We argue that by dating the temples, we can also date associated urban features to create historical models of urban morphology, which will allow us to conduct more sophisticated analyses of the development of the urban center over tiem. Ideally, we would like to create historical models for each one-hundred-year period for future studies evaluating changes in the landscape, water management system, and agricultural system over time.

Figure 1: Location of Angkor in Cambodia.

In this paper, we first introduce statistical learning paradigms and our archaeological case study and dataset. We then explore four classical mathematical approaches to find statistically significant predictors for temple construction dates. We find that k-means clustering, discriminant function analysis, and principle component analysis cannot accurately predict temple dates to within 100-year time periods. Multiple linear regression can predict temples with a low absolute average error. However, it only works on well-specified data-points and cannot predict dates for approximately half of the temples. We then introduce semi-supervised machine learning as a potential method to address some of the inadequacies of supervised and unsupervised statistical paradigms. Our results indicate that graph-based semi-supervised machine learning, unlike multiple linear regression, can predict dates for all the temples in the dataset. When combined with the results of the multiple linear regression for more-specified data, we can create a historical model of urban development in terms of temple construction at Angkor for temples constructed between 821 – 1149 CE with an absolute average error (AAE) of 49-66 years.

Statistical Paradigms

Statistical paradigms: supervised, unsupervised, and semi-supervised

The degree of completeness of a given dataset defines the type of statistical learning paradigms possible (Salazar, 2012, p. 2). As in traditional statistical analyses, the goal of machine learning algorithms is to infer information on the basis of incomplete data. One prototypical problem is to classify data points by assigning each data point a "label" reflecting a quantity of interest. For example, we are interested in dating temples; temples with known construction dates are considered labeled data and temples without known construction dates are considered unlabeled data. In general, there are three types of learning paradigms: supervised (all data are labeled), unsupervised (no data are labeled), and semi-supervised (a portion of the data are labeled).

In the following sections, we discuss the differences between supervised, unsupervised, and semi-supervised machine learning. Note that supervised and unsupervised paradigms also apply to non-machine learning statistical analyses. The analyses we performed in this paper encompassed both supervised and unsupervised paradigms.

Supervised machine learning

Analyses that use labeled data are "supervised" because we know the correct output, which allows us to correct errors in the algorithm (de Sa, 1993). Some examples of machine learning applications that use supervised paradigms are associations, classification, and regression. Machine learning *associations* identify conditional probability in sets of data among input variables and between input variables and outputs (Alpaydin, 2014, p. 4). For example, machine learning can associate products customers typically buy together, like cereal and milk. The association of cereal and milk can be used by companies to cross-sell and advertise milk to customers purchasing cereal.

Supervised machine learning can also *classify* data into discrete classes. Insurance companies use a wide assortment of data about insurance applicants (e.g., age, income, sex, history) to classify them into high and low-risk groups. This machine learning method relies on previously collected data about individuals including their attributes (e.g., age, income, sex, history) and their insurance claims. By classifying new customers into low or high-risk groups, the insurance provider can determine which types of insurance to offer and determine premium rates. Classification algorithms are created with pre-existing data, but they can be adjusted as future data become available to improve accuracy. Other examples of machine learning classification include image and text recognition (Alpaydin, 2014, pp. 5-9).

Regression is distinguished from classification because the output is continuous as opposed to discrete. For example, a machine learning regression can predict the price of houses based on a training set of houses' attributes (e.g., type of countertop, square feet, neighborhood) and known sale prices. Machine learning optimizes the algorithm, so the approximate error of the value is as minimal as possible based on the known prices of houses in the training set (Alpaydin, 2014, pp. 9-11).

Unsupervised machine learning For unsupervised learning, all the data are unlabeled (de Sa, 1993). Unsupervised learning works best for density estimation to identify underlying patterns or structures in data (Alpaydin, 2014, pp. 12-13; Chapelle et al., 2010, p. 1). While unsupervised learning is fundamentally used for estimating density, it can also be used for quantile estimation, clustering, outlier detection, and dimensionality reduction (Chapelle et al., 2010, p. 1). For example, companies can use unsupervised learning paradigms to group customers based on demographic information and purchasing habits. The companies can then target different groups for marketing and outliers can be identified as niche markets.

Semi-supervised machine learning Semi-supervised learning (SSL) lies between supervised and unsupervised learning paradigms by incorporating both labeled and unlabeled data. This approach is often used when labeled data points are few because they are time consuming or expensive to obtain. In many cases, a fully labeled dataset may be infeasible, whereas non-labeled data points may be easily obtained (Chapelle et al., 2010, p. xiii; Zhu et al., 2003). The internet, for example, has provided an avenue to easily and inexpensively obtaining unlabeled data through web crawlers. Web crawlers can scrape millions of photographs from the internet. However, to label these images would require much human effort to identify and record the content of each image by hand. SSL works to minimize the number of labels needed by learning from unlabeled data, thereby reducing the necessary human effort. One of the first SSL algorithms was developed to classify web pages (Blum & Mitchell, 1998).

SSL creates algorithms that use unlabeled data to improve the supervised learning algorithms (Blum & Mitchell, 1998, p. 1). It may seem counterintuitive to suggest that one can use unlabeled data to learn the labels of other data, but the distribution of unlabeled data in relation to labeled data can reveal a great deal of information. **Error! Reference source not found.** illustrates how unlabeled data can be used with labeled data to infer underlying patterns. In this example, there are two labeled data points, a circle and a diamond. Many statistical methods (e.g., Bayesian paradigms, regularization, minimum description length) would linearly divide the space as shown on the left. However, if we introduce unlabeled data, a geometric structure emerges that contradicts the linear divide. Instead, a circular classifier is preferred (Belkin et al., 2006, p. 2402).

Indeed, much of natural human learning occurs in SSL paradigms (Belkin et al., 2006, p. 2401). Take, for example, how children learn to classify objects. They are exposed to some labeled data, their parent pointing to a gray fluffy animal, “cat.” However, they also observe many animals that are not explicitly labeled. Over time, children combine both the labeled and unlabeled data as they learn to classify animals (Zhu & Goldberg, 2009, p. 1).

If the data are unlabeled, how do we know if SSL works? In some cases, it is possible to identify isolated errors. For example, the number of labeled data points for image recognition SSL is limited by the relatively expensive human component of hand labeling. In these cases, the labels are not truly unknown, only in the context of the training dataset used by the learning algorithm. As such, humans can easily verify the results by scanning through the classification of images and recognizing mistakes. Mistakes can then be rectified to improve the overall accuracy of the model. A classic example is the individuals incorrectly classified as gorillas by Google's image classifier in 2015. The individuals brought the error to the attention of Google engineers, who quickly rectified the mistake (Dougherty, 2015). When the labels are truly unknown, the standard way to evaluate machine learning algorithms and estimate prediction error is through cross-validation (Hastie et al., 2009, pp. 241-245).

Background: Case study and data

Angkor is a sprawling low-density urban complex with hundreds of temples and occupation mounds connected through a network of hydraulic infrastructure (Evans & Fletcher, 2015, p. 1402). Until recently, the full extent of the settlement was only partially understood. Much of the habitational space was constructed in non-durable organic materials that have since disintegrated. Decades of aerial mapping and other remote sensing, however, have revealed traces of archaeological features including ponds, occupation mounds, embankments, and channels on the landscape (Evans et al., 2007; Pottier, 1999). Evans and Pottier mapped much of the hinterlands and identified over 1400 temples (**Figure 2**). In this paper, we are interested in identifying the construction sequence of these temples so that we can date other urban features by proxy and create historical models of the urban development of the city.

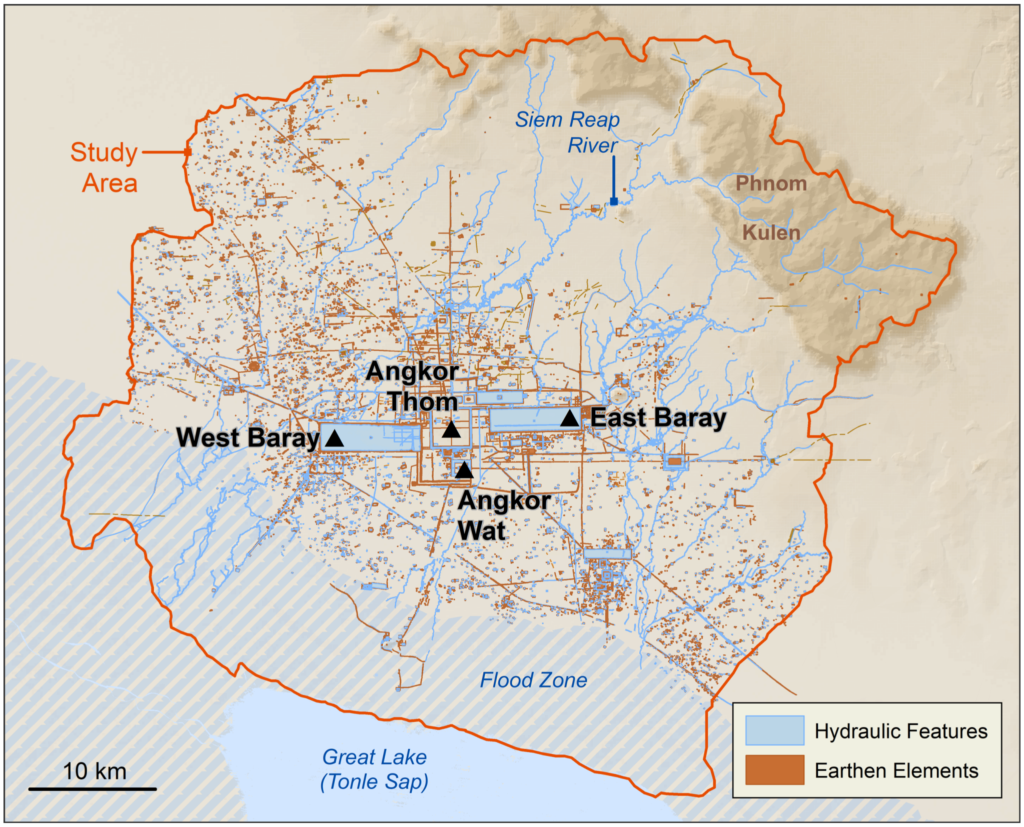

Figure 2: Map of Angkor created by Evans and Pottier. To be included as a supplementary image in a paper submitted for publication.

The archaeological record at Angkor is a palimpsest of thousands of years of human habitation, with early urban forms emerging in the Bronze and Iron Ages and developing, in the first millennium CE, into dispersed, low-density settlement complexes punctuated by high-density epicenters and nodes (Pottier & Bolle, 2009). The sheer scale and intensity of human transformation of the landscape, combined with persistent occupation and renovation of settlements over millennia, makes understanding the chronology of Angkor difficult. A single temple may have had multiple periods of occupation. Some were used for 100 years, then abandoned, and then re-purposed 300 years later. For example, one temple, *Kapilapura*, has inscriptions dating to 968 CE and 1200-1399 CE, suggesting at least two periods of occupation. Others were built over and obscured from our current record. Given the nature of the archaeological record, in most cases, it is easiest to determine when the temples were initially built, or *terminus post quem*. We do not expect to be able to identify multiple phases of occupation unless there are multiple art historical periods, inscriptions, or extensive excavation. When a temple went out of use, or *terminus ante quem*, is also difficult to determine. However, Greater Angkor Project (GAP) III ceramic data and excavations of temple sites by Pierre Bâty suggest degrees of longevity (Bâty, 2005). As a result, we treat the temple dates as cumulative, meaning that once built, a temple is in continued use unless we have specific spatiotemporal data to suggest it went into disuse.

Data

We derived known temple dates from Lustig's interpretation of temple inscriptions with listed dates and dates derived from Polkinghorne's dating of lintels (Lustig, 2009; Polkinghorne, 2007). Angkorian inscriptions were inscribed on stone in Khmer, Sanskrit, or both and often refer to temple foundations, including their establishment, administration, and support (Coedès, 1937-1966; Lustig et al., 2007). Similar inscriptions on contemporary pagodas indicate individual contributions to Pagoda foundations (**Figure 3**). When specific foundation dates were listed, Lustig converted the śaka dates to CE by adding 78 years. These dates are considered "certain." Where inscriptions were undated or a century or even two centuries are suggested, Lustig converted these to the approximate CE centuries (Coedès, 1966). For example, she converted 9th century śaka (800-899 śaka or 878-977 CE) to 10th century CE (900-999 CE). She further narrowed date ranges to specific reigns mentioned in the inscription. For example, if a king was mentioned by name, the date range was adjusted to the known dates of that king's reign. If a king's posthumous name was given, Lustig determined that inscription must have been written after his death and she adjusted the date range accordingly. Lustig considered dates with ranges "uncertain." Polkinghorne also used the designation of "certain" vs. "uncertain" for lintel dates; however, his designations are much more qualitative and nuanced, based on multiple lines of evidence, including the inscriptional data.

Figure 3: Contemporary Khmer pagodas list individuals who donated to the construction of the temple. For the statistical analysis, we are interested in identifying the date most

consistent with the current attributes of the temple. For example, it is possible that a sandstone temple from the 11th century CE was built on top of a small shrine dating to a much earlier period. If our attribute data for that temple represents the construction in the 11th century CE, we are interested in associating the temple with the 11th century CE date for the statistical analysis, regardless of whether there was an earlier foundation. Multiple periods of occupation are added to the model of urban development after we have conducted the statistical analysis. Where the date listed for each inscription or lintel was a range, we opted to use the median of the range.

Temples with multiple inscriptions and lintel dates were dated as follows with "certain" dates always prioritized over "uncertain" dates:

a) If there was only one lintel or inscription date, we used the date.
b) If there are multiple inscription and/or lintel dates that were within 65 years of each other, we used the median of the dates.
c) If there are no inscription or lintel dates, we use the dates found through literature searches.
d) When there are conflicting dates from the inscriptions and lintels where literature searches did not help, we prioritized the dates in the following order: lintels (certain), inscriptions (certain), lintels (uncertain), and inscriptions (uncertain). These have multiple periods of occupation.

Temple features like terraces, gates, and palaces that do not fit within the parameters of the study and would skew the results were excluded from the analysis. Other temples were excluded because their original foundations were built over by the city-block grid and the original morphology, moat, and primary reservoir are no longer apparent. We excluded 20 features mapped as temples from the analysis because of these limitations. In total, there are 1437 temples in Cambodia. Of these, 105 of the temples have known dates (Appendix 2). Our goal is to identify construction dates for the remaining 1332 undated temples.

In addition to the temple dates, there are six measures of similarity, or attributes, for each temple: 1) presence or absence of a primary reservoir (coded by Klassen) (**Figure 4**); 2) Building Materials (sandstone, pink sandstone, laterite, brick, thmaphom or mountain stone) (from database created by Evans); 3) azimuth (calculated by Klassen) (**Figure 5**); 4) area (calculated by Klassen) (**Figure 6**); 5) mound morphology (square, horseshoe (east), horseshoe (west), horseshoe (northern), two causeways, four causeways, blob, and undetermined) (coded by Klassen) (**Figure 7**); 6) presence or absence of a moat (coded by Klassen) (**Figure 8**) (Appendix 3). We did not use geographic coordinates or relative spatial data as metrics of similarity in this study. Meaning, we are not auto-correlating temples based on their geographic proximity to other temples.

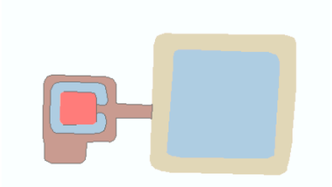

Figure 4: A temple (red) with a primary reservoir.

Figure 5: 65, 90, and 115 degree examples of temple (red) azimuths.

Figure 6: Example of temple (red) area. Note the large temple in the middle with small temples to the south and west indicated in red.

Square

2 causeways

4 causeways

Horseshoe (west)

Horseshoe (east)

Horseshoe (north)

Figure 7: Examples of square, two causeway, four causeway, horseshoe (west), horseshoe (east), and horseshoe (north) temple (red) mound morphology.

Figure 8: Examples of temples (red) with and without moats.

Results: Combining the results of multiple linear regression and GSSL

In this paper, we explore several statistical approaches that fall under supervised or unsupervised paradigms. In the case-study, there are 1332 undated temples (non-labeled data points) and 105 dated temples (labeled data points). Seriation like k-means clustering is unsupervised and uses data from all the temples but does not incorporate the known dates in the analysis. In contrast, MLR is supervised and uses the known dates to determine the algorithm, but is limited to approximately 10% of the dataset and could only predict dates for approximately half of the dataset (Alpaydin, 2014, p. 9). As a result, none of the analyses took full advantage of the dataset using information from both the labeled and unlabeled data to improve the algorithms. Since collecting data for all the undated temples, using excavation and traditional dating methods, would be prohibitively costly and time-consuming, a semi-supervised paradigm was a natural approach for our analysis to predict dates for the remaining temples that could not be dated using multiple linear regression. However, the GSSL model had a higher AAE than the multiple linear regression. As a result, we decided to merge the results from the GSSL and the MLR to combine the benefits of both approaches and determine estimated errors for different types of temples.

I expect GSSL performance to be worse for temples with incomplete data (lots of "null" columns) and for temples very dissimilar from all other temples. To test this hypothesis, we classified temples as either “well-specified” or “under-specified.” Any temple with more than five null columns was classified as “under-specified.” A temple was also called “under-specified” if there was no other temple with which it had a similarity of at least 10. For GSSL, “well-specified” temples had a 65-year AAE, and “under-specified” temples had a 92-year AAE. This analysis demonstrates the importance of complete datasets. We expect that the results can be improved in the future with a more-complete dataset. For the MLR, “well-specified” temples had a 60-year AAE, and “under-specified” temples had a 55-year AAE; however, dates were only predicted for 34 “under-specified” temples.

GSSL is also expected to underperform in predicting dates at either end of the range. In our sample, temples with known dates from 690 – 820 CE had an AAE of 137 years later than their true date from the GSSL predictions and 129 for the MLR predictions. Temples with known dates from 1150 – 1308 CE had an AAE of 132 years before their true date from the GSSL predictions and 92 for the MLR predictions. Temples with known dates from 821 – 1149 CE had an AAE of 56 years from the GSSL predictions and an AAE of 50 for the MLR predictions. In all scenarios, the MLR has lower AAE than the results of the GSSL. As a result, we chose to use the MLR predictions, where possible, and use the results from the GSSL for the remainder of the analysis (Appendix 4).

In Figure 9, we plotted the results from the analysis using bchron in R for a combination of GSSL and MLR dates and GSSL results alone. We plotted the results as follows for the GSSL dates: “well-specified” temples between 821 – 1149 CE, 49 years AAE; “well-specified” temples before 820 or after 1150 CE, 130 years AAE; “under-specified” temples between 821 – 1149 CE, 66 years AAE; “under-specified” temples before 820 or after 1150 CE, 139 years AAE. We plotted the results as follows for the MLR dates: “well-specified” temples between 821 – 1149 CE, 49 years AAE; “well-specified” temples before 820 or after 1150 CE, 107 years AAE; “under-specified” temples between 821 – 1149 CE, 57 years AAE; “under-specified” temples before 820 or after 1150 CE, 50 years AAE. Notably, the GSSL and MLR have the same AAE for “well-specified” temples between 821 – 1149 CE. For temples with known dates, we used the true date, rather than the inferred date, and included multiple occupation periods if there were separated by at least 20 years.

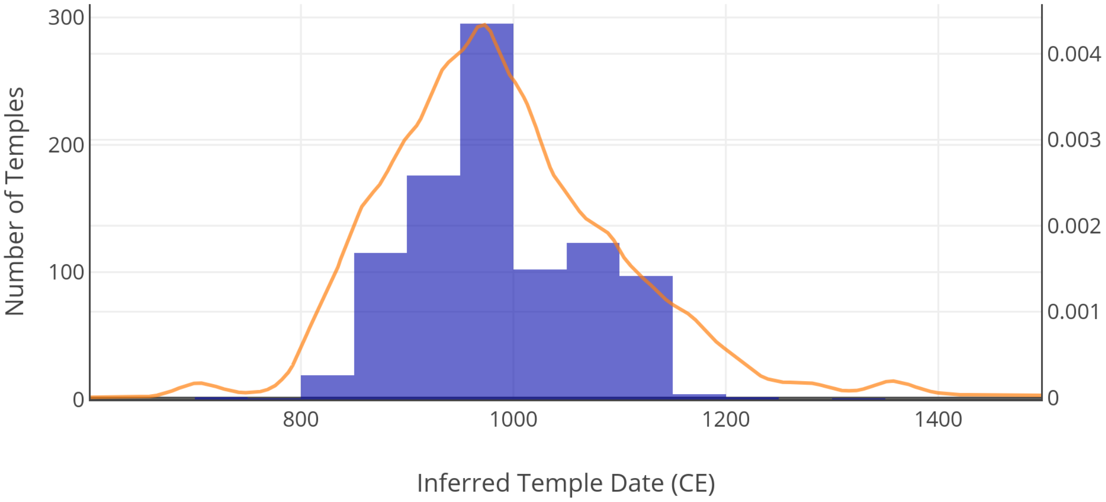

Figure 9: Bchron and histogram plot of inferred temple dates.

The results of the analysis suggest an increase in the number of temples founded until 11th century CE. After this, there is a decline in the number of new constructions through the 12th century CE and very few subsequent temple foundations. This pattern is noted with the disclaimer that GSSL methods tend to replicate the distribution that exists in the originally labeled dataset since it replicates the distribution of the original dataset to propagate known labels to the unknown set. It is possible that we are underestimating the number of temples in the first and last periods if the original set of labels also underestimated the proportion of temples from those time periods. We argue it is unlikely we are underestimating the number of temples with inscriptions for each period in our labeled dataset. We base this argument on the assumption that most of the inscriptions from Khmer temples have been identified and inventoried, representing an accurate distribution. Within our dataset, there were 12 temples with inscriptions from multiple periods. In six of these instances, there was one date from the period 821 – 1149 CE that was not used in favor of an earlier or later date. Only two dates before 821 CE were not used in the model in favor of a later date and only three dates after 1149 CE were not used in the model in favor of an earlier date. One limitation of our study is that Polkinghorne's database is constrained to lintels dating from before 1100 CE. As such, it is possible that temples that were dated by their lintels do not represent the entire distribution of temples across the landscape because of sampling bias in the original study.

Discussion and Conclusion

In the absence of detailed chronological models, the working assumption has always been that essentially all of the temples we see on the landscape were operational at the pinnacle of Angkor's development in the eleventh century, and the lack of chronological resolution has been a persistent obstacle to complex diachronic studies of social and environmental processes. By combining the results of GSSL and MLR, we were able to predict dates for otherwise undated temples from 821 – 1149 CE with a 49-66-year AAE. This data can be used to create historical models of urban development at Angkor by assigning dates to temples and other landscape features that are associated with the temples. These maps can then be used in future for diachronic analyses of human-environmental and urban dynamics in the Khmer world.

SSL is becoming a large research field yet is scarcely utilized by archaeologists. Archaeologists have begun using supervised and unsupervised machine learning approaches to classify archaeological soils (Oonk & Spijker, 2015), classify artifacts (Gansell et al., 2014; Hörr et al., 2009, 2014; van der Maaten et al., 2006), and identify archaeological features from remotely sensed data (Traviglia et al., 2016), but there are few examples of archaeologists using the semi-supervised paradigm. There are frequently disciplinary, cultural or knowledge-based barriers to the timely uptake of quantitative methods in archaeology, particularly when these involve some degree of automation in statistical analyses of massive datasets. For example, in the mid-1990s, Hare and Smith lamented archaeologists' reluctant uptake of quantitative seriation methods since the introduction of computers in the 1960s[1] (Hare & Smith, 1996, p. 283).

The natural application of SSL to archaeological datasets has been recognized by those in machine learning communities (Guyon et al., 2010; Mavroeidis et al., 2007). For example, archaeologists are highly interested in dates; however, C14 and OSL samples are expensive to collect and test. In contrast, sites can be identified and mapped through aerial imagery with much less effort and financial support than is required for excavation and survey. In one study (Mavroeidis et al., 2007), SSL was used to classify a collection of over 51, 000 administrative documents from the Dynasty of Ur in the 21st century BCE to determine which documents related to the water transport system. The authors used identified words relating to water transport (ship, boat, haul, river, and barge) and sorted the documents using a 2-way SSL clustering algorithm. The authors then dated the documents using a supervised learning Support Vector Machine (SVM) classifier based on kingdom era. Through this study, the authors determined which kingdom eras had the most documents related to water transportation. This study was part of the Discovery Challenge aimed at exploring Knowledge Discovery in Databases and applying data

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mining and machine learning methodologies to real-world problems. The authors conducted the study without collaboration with domain experts. In their conclusion, the authors highlight the value of data mining and machine learning in historical document analysis[2].

This analysis demonstrates the utility of GSSL for anthropological inquiry and allows archaeologists to streamline data collection methods and infer information using entire datasets, including labeled and unlabeled data, as well as make predictions for underspecified data. This analysis is also an extensible base for further input of new data; as we continue to contribute new data to the complex relational databases of archaeological features, the model will continue to improve in accuracy.

Given the nature of archaeological data, it is often difficult or expensive to get “labels,” for things like artifact typologies and site chronologies. While labeled datasets can be hard to obtain new methods of data collection and the very large scale of archaeological features are now often prohibitively large to rely on subjective manual classifications and traditional archaeological methods. Similarly, it is not realistic to excavate the tens of thousands of ponds, occupation mounds, and temples that we have identified using remotely sensed data in the greater Angkor region. Given these limitations of archaeological data and inquiry, we endeavor here to make a contribution

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[2] Mavroeidis et al., 2007 is the only archaeological application we could find utilizing SSL.

to the growing body of literature which explores the potential of semi-supervised routines and statistical inferences for archaeological inquiry.

Methods

To determine the foundation date of otherwise undated temples, we conducted k-means clustering, discriminant function analysis, multiple linear regression analysis, principal component analysis regression, and graph-based semi-supervised machine learning to determine if any morphological or architectural features were strong predictors of the temple dates. These analyses incorporate a variety of methods that produce either continuous-change (regression) or phase models (classification). Continuous values can be grouped into historical periods so that either technique will suffice for our purposes. Because we are interested in dividing the temples by century, each modeling approach was assessed on its ability to accurately predict the correct time period for temples with known dates. Classifications were considered satisfactory if they could successfully group temples with known dates with other temples from the same 100-year range and regressions were considered ideal if they could predict dates for temples with an AAE of 50 years or less and successful if they could predict dates for temples with an AAE of 75 years or less. For these analyses, we introduced dummy variables to represent categorical data. Dummy variables are independent variables that represent categorical or nominal variables and are coded to allow for statistical analyses (Hardy, 1993).

K-means clustering The first statistical method we used to estimate the chronological development of Angkorian period temples was k-means clustering using distances scores based on attributes. K-means is a non-hierarchical clustering technique that attempts to maximize the similarity of data points within each group. The clustering technique considers multiple variables and measures of similarity for each temple and makes no assumptions or stipulations about whether the variables are dependent or independent (Shennan, 1997). It is an unsupervised learning technique that often provides intuitive groups, with the number of groups specified by the user.

We performed the analysis with a varying number of clusters (2-6) but did not find any clusters that were chronologically distinct. For each of the five analyses (clusters 2-6), one cluster dominated the sample set with many of the temples with known dates. The k-means analysis for clusters (2-4) did not have any temples with dates outside of the dominant cluster. We compared the clusters against the known dates of temples, and the dates between clusters (5 and 6) did not differ significantly (ANOVA ps corrected > 0.7 and 0.98) (**Figure 10**).

Discriminant function analysis we next attempted seriation using discriminant analysis to group data into discrete classes. Seriation using discriminant function analysis is differentiated from k-means clustering because of the presupposition in seriation that there is a fixed number of groups based on one criterion. For this analysis, data are allocated into the most appropriate groups based the criterion and then assessed to determine if another independent criterion in the set of variables is also effective in predicting group membership (Shennan, 1997, p. 350). This method has been used in association with Bayesian analysis to develop chronologies for ceramic assemblages (Huster & Smith, 2015).

Unlike most archaeological samples that have multiple lines of chronological evidence, the only known chronological information for our analysis are the dates of a select group of temples. Using known dates, we defined three clusters: before 889 CE, 889-1164 CE, and after 1165 CE. These three-time periods were chosen based on three notable kings of Angkor: before Yasovarman, before Suryavarman II, and after Suryavarman II. The model was then fitted with all the temples with known dates to predict the clusters of the rest using Latent Dirichlet allocation (LDA).

Some archaeological studies, with additional chronological information like provenienced C14 dates, have used Bayesian modeling to cross-validate and assign absolute dates to resulting clusters. Bayesian modeling is well suited to archaeological studies of chronology because they can incorporate known factors, probability curves, and contextual information into a single probability curve (Huster & Smith, 2015). Because we used the known temple dates to form the initial clusters, we have no secondary chronological information remaining to cross-validate the results. Instead, we used k-fold cross-validation. K-fold cross-validation splits the labeled data into K equal-sized parts and withholds the kth part of the labeled data from the analysis. In doing so, a portion of the data is used to fit the model, and a different portion of the data is used to test it. When $k = n$, the cross-validation withholds one labeled data point from the learning procedure and tries to infer its label from the rest of the sample. This procedure is known as *leave-one-out* cross-validation. Leave-one-out is more precise for prediction error; however, it has high variance and is more computationally expensive because it requires running the analysis *n* times. When running *n* analyses is too computationally burdensome, and a lower variance is preferred, higher *k* values are chosen (Hastie et al., 2009, pp. 241-245). Using leave-one-out cross-validation, we determined that only 35.2% of the cross-validated grouped cases were correctly classified by the model. This suggests that discriminant function analysis is not a very reliable method for accurately dating unknown temples to our five time periods (Figure 11 and Figure 12).

Multiple regression analysis Multiple linear regression analysis determines the relationship between a single dependent variable (temple date) and multiple independent variables. Linear regression analysis assumes there is a linear relationship between variables that can be used to predict the output from the input values. This statistical approach assumes that the data are linear and the model utilizes a least-squares criterion (Shennan, 1997, pp. 182 - 185). Linear regression does not work well when data are grouped in clusters or when there is no clear linear relationship. Multiple linear regression is often used to identify constituent components in archaeological collections. For example, the technique has been used to determine periods of occupation from ceramic assemblages (Kohler & Blinman, 1987).

We fitted a multiple linear regression model with the all of the temple attributes. One limitation of multiple linear regression is that it cannot process temples with missing pieces of data. For example, if there is no known azimuth for a temple, the temple cannot be included in the analysis. Removing temples with missing data reduces the number of temples with known dates and complete datasets to 16. If we remove the pedestal type from the analysis, the number of temples included in the analysis increases to 73. The results from the linear model including all temple data except pedestals was statistically significant (R squared = 0.5892, adjusted R squared = 0.4883, F = 5.84, p = 0.00). The AAE in the predicted values from a leave-one-out cross evaluation is 60 years. Unfortunately, this method requires complete datasets. Much of our data is incomplete in the elements that were recorded during pedestrian survey or mapped using remotely sensed data. As such, we could only use the model to predict dates for approximately half of the sample (755 of 1437 temples).

Principal component analysis we next tried principal component analysis (PCA). The goal of PCA is to simplify the data matrix, by reducing dimensionality, to identify inter-relationships among variables. PCA defines uncorrelated axes of variability (components) and evaluates the correlation between the original variables and the components. Each coordinate and group is given a "score" that can be used to assign coordinates to groups. PCA works best with interval level data with a normal distribution and few outliers (Shennan, 1997, pp. 265-307). PCA can be used as a preliminary methodology to decrease collinearity and replace mutually unrelated factors with mutually correlated predictors for subsequent regression.

To determine the sampling adequacy for the overall data set, we first conducted a Kaiser-Meyer-Olkin (KMO) test. Unfortunately, the overall KMO for the dataset was 0.41, which means that it was unacceptable for PCA analysis. However, there were two groups of correlated variables (group one: laterite, horseshoe mound (east), pedestal type A3, moat, and square; group two: Pedestal types A1, A2, and A4). We re-ran the PCA analysis, which had an overall KMO of .645 for group one and .369 for group two. Based on the KMO scores, we decided to proceed with group one and conducted Bartlett's test of sphericity to ensure that there are no correlations between variables. The Bartlett's test was statistically significant ($p < 0.00$), indicating that the data was likely factorable. The analysis revealed three components that explained 49.3%, 22.7%, and 17.1% of the total variance, respectively. We then calculated a Pearson correlation coefficient for the year and three components. The first component (PCC = 0.278, p-value = 0.004) and the second component (PCC = 0.314, p-value = 0.001) were statistically significant; however, the third component was not statistically significant (0.168, p-value = 0.09).

We then fitted a multiple linear regression model with various combinations of the three components. The linear models were statistically significant ($p < 0.001$) for all combinations of the three components except for the second component alone ($p = 0.090$). The linear model using all three of the components explained 20.4% of the variance (R = 0.452, adjusted R squared =0.181, F=8.6, p= 0.000), the first and second components explained 17.6% of the variance (R = 0.420, adjusted R squared = 0.160, F =10.9, p = 0.000), the first component alone explained 7.7% of the variance (R = 0.278, adjusted R squared =0.068, F=8.6, p= 0.004), and the second component alone explained 9.9% of the variance (R = 0.314, adjusted R squared =0.090, F=11.3, p= 0.001). Unfortunately, the PCA did not explain more of the variance than the multiple linear regression.

Graph-Based SSL (GSSL) Graph-based SSL (GSSL) constructs a graph from training data to understand the underlying structure and relationships in the data (Zhu &

Goldberg, 2009, p. 43). A graph is a collection of mathematical objects with vertices connected by edges. In GSSL models, each vertex is a labeled or unlabeled data point in the training dataset. The number of vertices in the graph is determined by the total number of data points, and the number of edges is at most the square of the number of data points. The weights of the edges are determined by the amount of similarity between the two data points. In general, graph-based approaches are transductive and do not extend to data beyond the sample used in the graph (Belkin et al., 2006, p. 2416).

GSSL models propagate labels to unlabeled data based on edge weights; the larger the edge weight the more similar the data points. First, a measure of similarity is defined between data points. One typical example is the Hamming distance, which measures the difference between data points by the number of attributes on which they differ (Norouzi et al., 2012). These similarity measures are then converted to edge weights; often, this is accomplished via a Gaussian kernel, which puts significantly more weight on edges connecting data points which are very similar (Zhu et al., 2003). Finally, labels are assigned to vertices to minimize the total penalty arising from a mathematical object known as the "graph Laplacian." This penalty is similar to the least-squares formula used in linear regression; however, it replaces the assumption of linearity by a more flexible assumption on the so-called "manifold structure" of the data set (Seeger, 2001). To define the edge weights, many GSSL methods use a Gaussian kernel applied to the Hamming distance (Zhu et al., 2003). GSSL methods are quire flexible and can be used for both binary or multi-way classification (Blum & Chawla, 2001).

A classic example showing the utility of GSSL is the “swiss roll” data set (Figure 13). It is easy to see that this dataset has some structure, but the structure cannot be picked up by either linear regression or seriation. For example, imagine that the dark blue points in the swiss roll dataset are from the 9th century CE, and the yellow points are from the 12th century CE, but we do not know the dates of the other points represented in the first image as black dots. If we were to run a classification procedure based on the yellow and dark blue points alone, we would not understand the underlying geometry. However, if we include all the unlabeled data, we can build a graph by drawing lines between points that are very similar and trace out the correct shape of the data. We can then smoothly propagate the labels we know onto the labels we do not know to predict color, as in the case of the swiss roll, or dates, as in the present study.

GSSL works best when the labels between data points vary smoothly across the graph and when data points with large edge weight have the same or similar labels (Zhu & Goldberg, 2009, p. 51) and have the same distribution (Tian et al., 2004). Similarly, GSSL is expected to underperform for data at either end of the range because the procedure attempts to intelligently “average” the known labels in the dataset. As a result, the procedure will never assign a date outside the range of the dates present in the original labeled set. Hence, if we remove the earliest or latest temple from the sample, it is impossible for it to be assigned the correct label in a k-fold hold out procedure.

We conducted the analysis using NumPy, a scientific computing package for Python. After collection and sanitization, the data was loaded into an SQLite database and manipulated via the Python SQLAlchemy package. We first normalized numeric data (azimuth and area), so each entry lay between 0 and 1. We then calculated the similarity between data points by using the Hamming distance (with L2 distance for area and azimuth)[3]. Using these results, we built a weighted graph with edge weights assigned via a Gaussian kernel to put progressively greater weight on objects that are closer. Finally, we assigned years to unlabeled temples to minimize total penalty arising from graph Laplacian.

To cross-validate our results, we used a standard k-fold leave-one-out validation, as described in the discriminant function analysis section. We conducted the procedure in a combination of Python and Bash where $k = n$ (Hastie et al., 2009, pp. 241-245): for each temple for which we know the true date, we removed its label and tried to infer it from all the other labels. We repeated the process 105 times, once for every labeled temple in our dataset. We chose to use $k = n$ because it has a lower bias than some lower values of k, even though the variance is higher. The cross-validation suggests that our AAE for the entire dataset is 74 years from the original label (median absolute error is 50 years).

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[3] Explicitly, the similarity between two temples was defined as the number of non-numeric fields on which they agreed plus 2, minus the L2 distance between the two temples' normalized azimuth and area fields ($(\text{azimuth}_1 - \text{azimuth}_2)^2 + (\text{area}_1 - \text{area}_2)^2$). If either temple was missing azimuth or area data, the corresponding entry for that temple was replaced by .5. With this definition, the similarity for each pair of temples lay between 0 and 11.

To test whether the labeled and non-labeled temples are from the same distribution, we compared temples with inscriptions to temples with lintels but no inscriptions in our labeled dataset. If the labeled and unlabeled temples do represent different distributions, it could undermine the effectiveness of the GSSL model (Tian et al., 2004). Temples with inscriptions are often fundamentally different from temples without inscriptions. Inscriptions were expensive to commission and, as such, were often written for and by the elite (Lustig et al., 2007). We argue that temples without inscriptions that were dated by their lintels are more likely to represent the non-royal and non-elite temples. There were 35 labeled temples that did not have inscriptions; AAE for these temples is 54-years, which suggests that the GSSL works better for them than it did for the entire sample.

SUPPLEMENTAL FIGURES

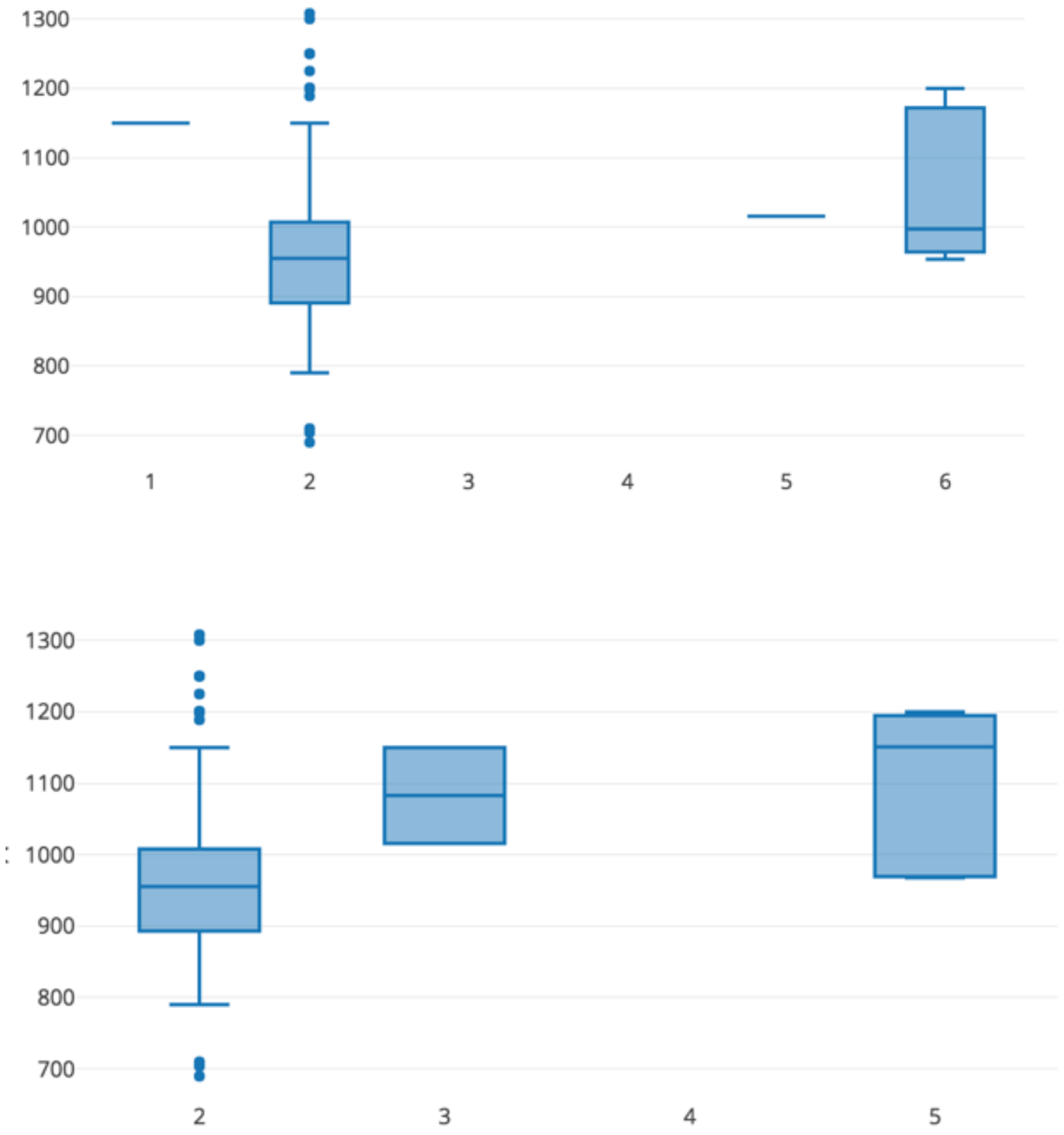


Figure 10: Box plots of four K-means clusters for five and six clusters.

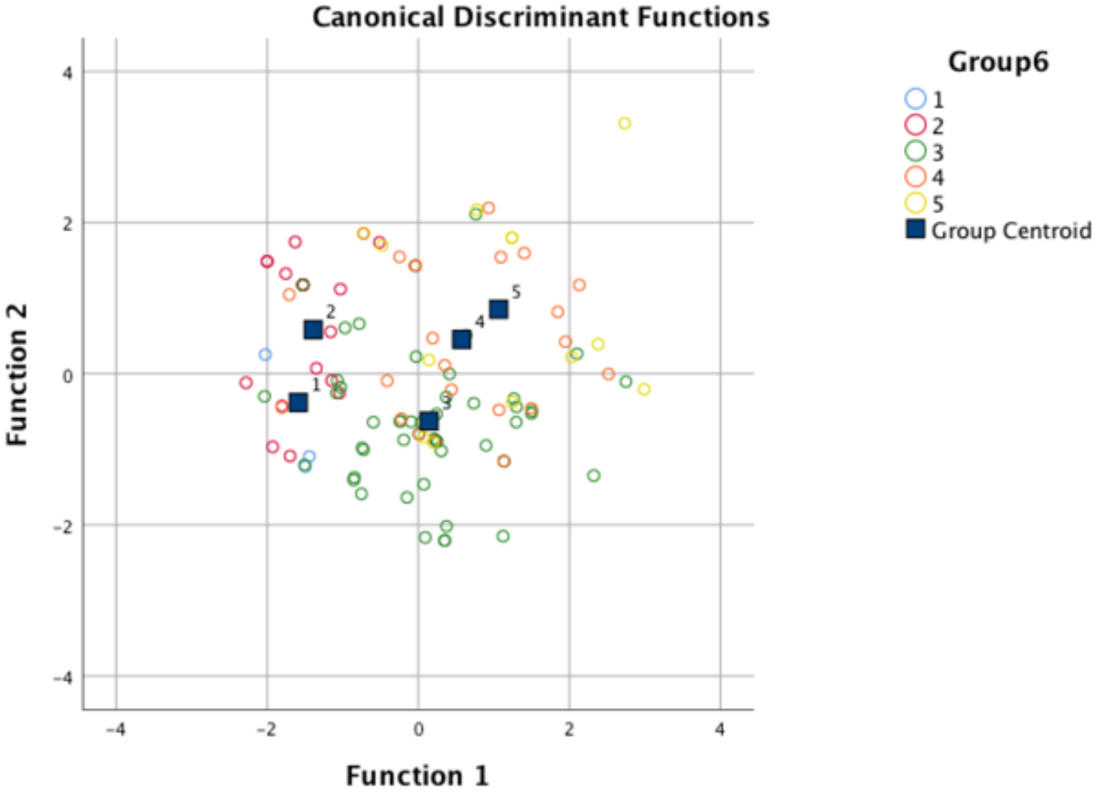
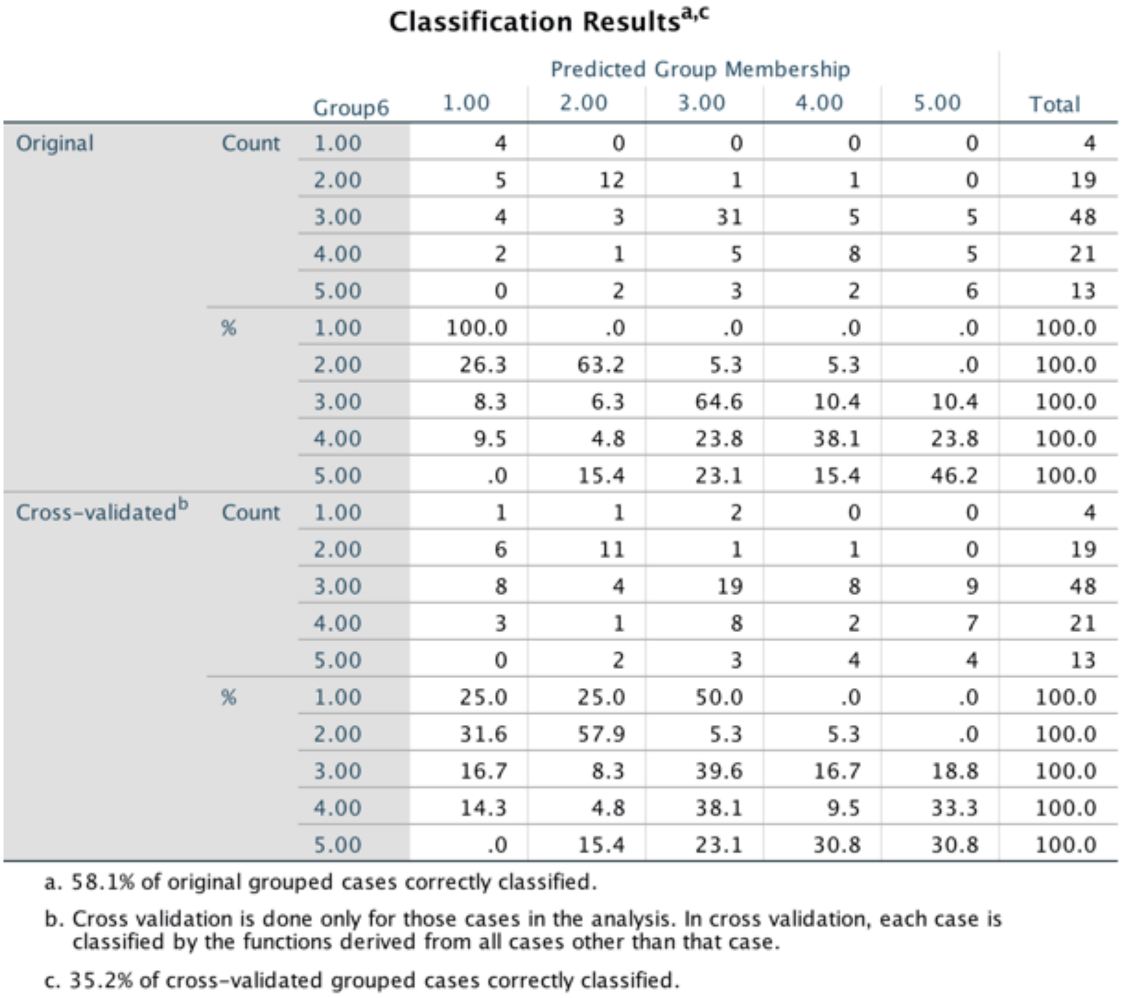


Figure 11: Canonical discriminant functions of temples for five-time periods at Angkor.



Classification Results[a,c]

			Predicted Group Membership					
		Group6	1.00	2.00	3.00	4.00	5.00	Total
Original	Count	1.00	4	0	0	0	0	4
		2.00	5	12	1	1	0	19
		3.00	4	3	31	5	5	48
		4.00	2	1	5	8	5	21
		5.00	0	2	3	2	6	13
	%	1.00	100.0	.0	.0	.0	.0	100.0
		2.00	26.3	63.2	5.3	5.3	.0	100.0
		3.00	8.3	6.3	64.6	10.4	10.4	100.0
		4.00	9.5	4.8	23.8	38.1	23.8	100.0
		5.00	.0	15.4	23.1	15.4	46.2	100.0
Cross-validated[b]	Count	1.00	1	1	2	0	0	4
		2.00	6	11	1	1	0	19
		3.00	8	4	19	8	9	48
		4.00	3	1	8	2	7	21
		5.00	0	2	3	4	4	13
	%	1.00	25.0	25.0	50.0	.0	.0	100.0
		2.00	31.6	57.9	5.3	5.3	.0	100.0
		3.00	16.7	8.3	39.6	16.7	18.8	100.0
		4.00	14.3	4.8	38.1	9.5	33.3	100.0
		5.00	.0	15.4	23.1	30.8	30.8	100.0

a. 58.1% of original grouped cases correctly classified.

b. Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.

c. 35.2% of cross-validated grouped cases correctly classified.

Figure 12: Results from the discriminant function analysis with leave-one-out cross-validation. Groups represent the following time periods ordered from 1 through 5, pre-802 CE, 803-889 CE, 890 – 1001 CE, 1002 – 1164 CE, and 1165 – 1320 CE.

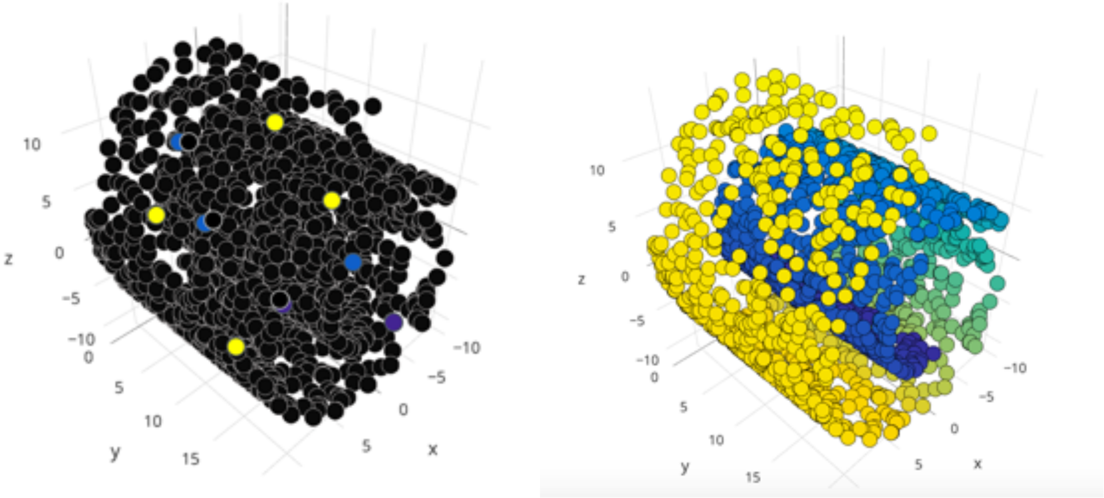


Figure 13: Swiss Roll dataset. The partially labeled (colored) dataset is shown on the left, and the fully labeled dataset is shown on the right.

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APPENDIX II:

COMPLETE LIST OF TEMPLES IN CAMBODIA WITH KNOWN DATES

APPENDIX III:

MEASURES OF SIMILARITY FOR EACH TEMPLE

APPENDIX IV:

COMPLETE LIST OF TEMPLES IN CAMBODIA WITH KNOWN AND PREDICTED DATES

The temple ID references the internal identification of the temples used in this dissertation. These IDs can be cross-referenced with the name of the temple, Lustig Site ID, Archsite ID, and Pelle Object ID in Appendix III.