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The Political Economy of Bread and Circuses: Weather Shocks and Classic Maya Monument Construction*

Melissa Rubio-Ramos† Christian Isendahl‡ Ola Olsson§

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Abstract

In early states, government elites provided both productivity-enhancing infrastructure, such as irrigation systems, as well as seemingly non-productive monumental architecture like temples and pyramids. The nature of this "bread-and-circuses"-tradeoff is not well understood. In this paper, we examine this phenomenon in the Classic Maya civilization (c. 250-950 CE) where city-state elites chose between investing in essential water management infrastructure (reservoirs, canals), and monumental architecture. We analyze information from 870 dated monuments from 110 cities. Correlating this dataset with a proxy record for variations in annual rainfall, we find–perhaps counter-intuitively–that monumental construction activity was more intense during drought years. A text analysis of 2.2 million words from deciphered hieroglyphic inscriptions on monuments, further shows higher frequencies of terms associated with war or violent conflict during periods of drought. We propose that in the Classic Maya setting, with numerous small city-states, monument construction functioned as a costly signaling device about state capacity, designed to attract labor for future control of revenue.

Keywords: bread and circuses, public goods, monumental architecture, drought, Maya

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1 Introduction

As noted by the Roman poet Juvenal in his *Satires* from the 2nd century CE, rulers are prone to try to pacify their population by offering *bread* and *circuses* (Rudd et al., 1999).[1] Although Juvenal was disdainful of both of these cravings (he thought Roman citizens should engage more in public policy, like in the old days), it is a standard assumption in economics and biology that people are primarily concerned with their own and their close kin's consumption of basic goods like food that provide necessary calories, proteins, and nutrients (i.e., improving their physical *fitness*) for survival and reproduction. A more difficult question from an economics point of view is why past societal elites often chose to allocate substantial resources to public goods like amphitheaters, ballcourts, pyramids, and statues. Unlike investments in landesque capital such as cleared and irrigated fields, monumental architecture does not increase the productivity of food production systems per se but instead constitutes a large opportunity cost since the resources spent on "circuses" could instead have been used for investments that actually increased the direct physical and reproductive fitness of the population. [2]

In this paper, we examine what principal factors may have been driving the propensity to make investments in monumental architecture, using the Classic Maya Lowlands (c. 250–950 CE) as a case. It is often assumed that such investments are more common when agricultural production is high and centrally collected resources abound. As an exogenous source of temporal variation in agricultural productivity, we use a recent high-resolution dataset on long-term interannual variation in precipitation on the Maya Lowlands over the Classic Period and correlate these patterns with trends in the construction of ceremonial monuments like ballcourts, lintels and stelae, dated from deciphered hieroglyphic inscriptions across 110 Maya cities. At odds with the common assumption, we find robust evidence that monument construction tended to be more intense during dry years when the productivity of the agricultural economy was relatively low.

In order to track the behavioral mechanism behind these results, we analyze the topical content of inscriptions on monuments. From a total sample of more than two million words, we extract information

[1]The Latin expression *panem et circenses* (bread and circuses) was introduced by the Roman poet Juvenal in *Satire X*, written in the 2nd century CE. It describes in a satirical way the common practice of Roman rulers to provide free grain (or bread) and spectacles as a means to pacify the people. The former practice is usually referred to as *Cura Annonae*, which was a government program during the Late Republic and most of the Imperial Period that provided subsidized or free grain to Rome's low-income male population. Public spectacles included gladiator games, fights with ferocious beasts (*venationes*), reproductions of naval battles (*naumachia*), chariot races, athletic contests, and theater performances. These games often had a religious background in Roman festivals but would later have the important role of manifesting the strong link between the ruler and the restless populace living at the expense of the state.

[2]Dutta et al. (2018) is one of the few papers in economics that explicitly model a tradeoff between the production and consumption of bread and circuses in this sense, as discussed further below.

about the relative share of terms categorized as being related to *religion, war, politics*, or *agriculture*, assuming that these semantic domains can be expected to become more common during years of hardship. We find a consistent pattern that dry periods are strongly associated with war references, whereas references to religion, politics, and agriculture are uncorrelated with droughts. When we extend our analysis to specific types of monuments, we find some evidence for a greater probability of the construction of ballcourts during droughts. When we also study the last phase of the Classic Maya Period, we find that settlements with low average levels of rainfall and several neighboring communities, tended to enter their terminal decline relatively late. We interpret these results as indicating that Maya elites displayed a proclivity for erecting monuments and for signaling military state capacity during years of hardship. A plausible reason for this tendency was the inherent competition between city-states to attract a mobile agricultural labor force for future extraction of revenue.

In the second half of the paper, we outline a general theoretical model of bread-and-circuses-like public good provisioning in early state societies that is aimed at providing a more rigorous analytical framework for the patterns revealed in the empirical analysis. In the model, ruling city-state elites compete to attract a relatively mobile population of farmers to settle within the jurisdiction of their polity. In this competition for labor force and revenue, rulers either attempt to make credible commitments to future food production capacity (bread) by investing in water management infrastructure or to construct monumental architecture (circuses), where the latter signals state capacity, the illusion of a strong economy, and mobilizes in-group identity. Our model proposes that there is more available (underemployed) labor in drought years since there are fewer crops to harvest. If expected rainfall is relatively low and reservoir storage capacity is high, the marginal payoff of investing further in water management infrastructure is low, and rulers will instead focus on attracting people to settle within their jurisdiction by building monuments to increase the stock of labor and future revenue. Clearly, expectations of interannual rainfall variation, based on lived experience and social memory (Hassan, 2000), is a pivotal variable of these adaptations. Arguably, expectations of beneficial long-term climatic conditions with high and stable precipitation rates will typically attract people to a city, implying a greater availability of labor to invest in public goods. Short-term weather variations, such as inter-annual variations in the length and intensity of the rain season, will mainly cause a substitution of labor between agriculture and public goods construction.

Longer term variations in weather patterns, such as the extended drought that affected the Maya Lowlands after 800 CE, plausibly generated radically different responses, including people's beliefs about future food production potential, undermining social cohesion and trust in the socio-political order and contributing to the collapse of elite hegemony and a halt in monumental construction. Within 3-4 generations, depopulation and abandonment of many Classic Maya cities of the Central Lowlands ensued. Shorter and less severe dry periods to which the subsistence economy was adapted to, on the other hand, plausibly gave rise to a greater availability of corvée labor and an opportunity for more monument construction. We suggest that these results of a negative short-run association between rainfall and monument building activity can be reconciled with the general observation of large-scale sociopolitical changes in the Central Maya Lowlands (the "Classic Maya Collapse") coinciding with a severe, multiannual drought during the 9th century CE (Hodell et al., 1995; Kennett et al., 2012).

Our results also link to the broader question of the political economy and the tradeoff involved in ruling elites' decision to choose between providing bread or circuses as public goods. Circuses are more likely to be prioritized in times of food shortage and underemployment in the agricultural food production, but if food shortage becomes too extensive, people are incentivized to consider alternative options to secure sustenance, including migrating to other polities, setting in motion a spiral of degrowth in the political economy that potentially leads to the polity's inability to mobilize labor and an incresing risk of state failure, and that neither type of public good will be provided.

Investments in monumental architecture have not been extensively studied in economics. Nonetheless, archaeological evidence suggests that demand for constructions like communal houses, shrines, and temples appears to have been a pervasive phenomenon in the evolution of complex societies (Flannery and Marcus, 2012). Dutta et al. (2018) explicitly model a bread-and-circuses tradeoff where it is assumed that households derive utility from two private goods – bread and "wine" – the latter used to indicate all goods that enhance utility but which are not required for subsistence and which do not affect fertility. When a subsistence minimum is satisfied, households might choose to devote more resources to produce and consume more wine, which arguably increases standards of living but holds back population growth. Our analysis is very different since we consider the decision to provide bread-and-circus-like public goods to be made by a ruling elite, similar to in Juvenal's Imperial Rome. The population in our model accepts a social contract where they provide labor in addition to the household's subsistence economy focused on agricultural production in exchange for productivity-enhancing water infrastructure or monumental public infrastructure. Their expectations of the elite's commitment to future public goods provisioning determine their decision to stay in, or leave, the city and/or a particular city-state polity.

A number of articles in political economy focus on elite response to external shocks. Allen et al. (2023) study random shifts in ancient Mesopotamia and show that a displacement of a river away from a city created a demand for public canal construction and the origin of governments. Belloc et al. (2016) find that earthquakes in northern Italy during 1000-1300 CE delayed a transition to self-governance in cities where the religious and political centers of power were distinct. They also show that earthquakes were often interpreted as a manifestation of the outrage of God, and that tended to lead to increased construction and ornamentation of religious buildings. In a similar vein, Chaney (2013) shows that religious leaders in Mamluk Egypt 1169-1425 CE were less likely to be replaced and that more religious structures were built when Nile floods were either abnormally high or low. Sinding Bentzen (2019) demonstrates that increasing religiosity increases in the wake of natural disasters, appears to be a common cross-cultural pattern.

Outside economics, there is a relatively extensive discourse on how material culture is used to signal status, prestige, power, or capacity. The sociologist Thorstein Veblen famously described the upper classes' *conspicuous consumption* of luxury goods as a means of publicly manifesting their social power and prestige (Veblen, 1899). In anthropology and archaeology, the practice of erecting public monuments like temples, palaces, and tombs have often been interpreted as an important strategy to foster in-group identity, offering a complement to ritual services (Flannery and Marcus, 2012). For instance, Bruce Trigger (Trigger, 1990) notes that investments in monuments in early chiefdoms and states greatly exceeded what can be described as an energy-minimizing "least effort" or what was required for any practical needs. He suggested that these were designed and constructed by elites to deter inter- and intrapolity competitors from claiming rule. The notion of *costly signaling* as a theory for understanding status-seeking behaviors, was further developed by Bliege Bird and Smith (2005).[3] In a Maya context, Neiman (1997) argued that monumental construction was a form of *wasteful advertising* with the purpose of signaling the ability of local ruling elites in a highly competitive political environment with numerous local rivals and a general inability to constrain the mobility of the population. Brian Hayden (1990) suggested that the use of abundant harvests and other productive resources in *competitive feasting* was a central political strategy for prospective "big men" in early hunter-gatherer communities to attain and maintain positions of power, a behavior that plausibly contributed to the emergence of agriculture (Hayden, 1990). Our model includes several intuitive insights from these approaches to understand monumentality in early complex societies, as detailed below.

Numerous studies suggest that extreme and prolonged weather events or anomalies have played a decisive role in causing political instability and even collapse in the past[4], with the collapse of Classic

[3] In economics, the literature on signaling goes back at least to Spence (1973).

[4] See for instance Cullen et al. (2000); Diamond (2005); Buckley et al. (2010); Cline (2014); Hsiang et al. (2013); Weiss

Maya city-states on the southern Yucatan Peninsula often highlighted as one of several flagship examples (Hodell et al., 1995; Haug et al., 2003; Kennett et al., 2012; Douglas et al., 2016). Like us, Carleton et al. (2017) study a measure of conflict as an intermediate mechanism in the decline of the Maya but find that it was warm temperatures rather than low rainfall that explain inter-city conflict, using a 25-year temporal resolution. Particular attention has been paid to examine the role of multi-annual droughts as one of the main factors precipitating system collapse, with a series of paleoclimatic proxy records indicating increased frequencies of extended droughts in the Maya Lowlands during the 9th century CE. It is often implicitly suggested that incidents of severe and prolonged drought lead to both tax shortfalls and shortages of food and potable water that not only caused wide-scale human suffering but also threatened the stability of society. If a linear relationship, reduced availability of resources would cause a marked decrease in socioeconomic activity, which can be assumed to be mirrored in the archaeological record by a decrease in material culture, including of large-scale monumental building construction. Although there are several settlement-focused investigations that track how these droughts may have impacted the economic and political integrity of individual cities, few systematic empirical studies examine the mechanisms of drought-induced systemic change at the regional scale.[5]

In our analysis, we use a detailed paleoclimatic record from a cave in the eastern part of the Maya Lowlands to estimate rainfall and, by extension, estimating agricultural productivity and food availability over time (Akers et al., 2016). We correlate this time series with monument construction activity dated by hieroglyphic inscriptions at 110 Maya settlements during the Classic Maya period, 250-950 CE from Kennett et al (2012), and with keywords in inscriptions extracted from the Maya Hieroglyphic Database (MHD, 2024). We further use GIS data from standard open sources on the topography of Maya settlements in terms of elevation, slope conditions, and their distance to other settlements, as well as contemporary records of local precipitation and temperature, in order to control for local geographical variation. In an analysis of the date of last monument construction, we show that settlements with relatively low average levels of rainfall and many close neighboring communities tended to decline later, suggesting stronger resilience than settlements with more abundant rain. Our study is, to our knowledge, the first to employ time series econometrics and detailed information on geographical variables to analyze long-term trends in socioeconomic activity across the Maya Lowlands.

Water management and the provision of a *blue infrastructure*, plays a key role in the political econ-

(2017); Mayoral and Olsson (2024)

[5]For instance, neither Kennett et al. (2012) nor Akers et al. (2016) provide any elaborate time series correlations. An exception is Neiman (1997) who found that monument construction appears to have ceased earlier at settlements with relatively high precipitation.

omy of Classic Maya cities (Scarborough, 1998; Isendahl, 2011; Lucero et al., 2011; Scarborough et al., 2012; Isendahl et al., 2024). For instance, without the construction of artificial reservoirs, sustaining a population of up to 60,000 people in a city like Tikal would not have been possible. Our model features a reservoir and a canal infrastructure that is gradually depreciated without collective dredging efforts. However, the model's assumptions may also apply to other kinds of infrastructures, such as irrigation systems, networks of drainage ditches, or protective walls against water or enemies. Such "economically useful" public goods were surprisingly often crowded out in history by non-productivity-enhancing pyramids and statues.

Lastly, this study draws on recent papers in economics on the political economy of monument symbolism, placement, construction, and removal. Rozenas and Vlasenko (2022) study the electoral impact of the removal of Soviet monuments and symbols in Ukraine in 2014 and suggest that the removals were interpreted as a signal indicating the weaker status of a Soviet cultural heritage and mobilized voting for politicians that were sympathetic to this heritage. Analyzing Confederate monuments in the US South, Ferlenga (2023) finds that counties with higher monument frequencies experienced a sharp decline in the African-American share of the population after their construction in the early 20th century. Both studies emphasize the powerful signaling potential of monuments, a pillar in our theoretical model.

2 Background

2.1 Historical overview

The history of early states among the pre-Columbian Maya unfolded over two millennia until a very different set of boundary conditions for political history, economic systems, and social change emerged following European contact and conquest in the 16th century CE. Located to the east of the Isthmus of Tehuantepec in what today is eastern Mexico, Guatemala, Belize, and parts of Honduras and El Salvador, the Maya was the southern- and easternmost of a series of Mesoamerican complex societies—including the Olmecs, the Zapotecs, Teotihuacán, and the Aztecs, among others—that developed early state-level urban polities (see Figure 1). At latitudes between 13 and 22 N, the Maya occupied the tropical environments of the Pacific Coastal Plain in the south, the Maya Highlands, and the Maya Lowlands that cover the Yucatan Peninsula in the north. The Maya Lowlands was the main region for the development of Late Preclassic, Classic, and Postclassic Maya state-level urban polities. The environment of the Maya Lowlands is highly heterogeneous owing to variations in topography, altitude, soil cover, geological structure, vegetation, and precipitation, with distinct physiographic sub-regions, to some significant extent mirroring cultural historical diversity among the numerous urban polities that emerged and demised throughout the region over the course of the pre-Columbian period (Dunning and Beach, 2011).

The abundance of city-state polities notwithstanding and even though there at no time existed a regional Maya polity, there are some general trends in the overall developmental history of the pre-Columbian Maya Lowlands. Although the evidence is sparse, small bands of hunter-gatherers plausibly entered the lowlands as part of the populating of the Americas at the end of the Pleistocene and into the early Holocene. With the stabilizing of a warmer and wetter Holocene climate, the domestication and spread of food plants, and the development of agriculture during the course of the Archaic Period (c. 8000–2000 BCE) and the Initial Preclassic (c. 2000–1200 BCE), sedentary villages appeared, principally in landscapes with high bioproductivity and easy access to potable water, such as along rivers in the coastal zone of the Caribbean Sea. Following population growth, increasing social complexity, and subsequent emergence of Mesoamerican early state urban polities—initially in the Isthmian region of the Southern Gulf Lowlands (e.g., Olmec San Lorenzo and La Venta)—during the Early Preclassic (c. 1200–800 BCE), incipient urbanization and early state formation processes followed elsewhere during the Middle Preclassic (c. 800–300 BCE) to grow rapidly in the Maya Lowlands during the Late Preclassic (c. 300 BCE – 250 CE). Pre-Columbian Maya society remained largely urbanized until the Conquest, but with considerable variation in extent among different subregions and periods as well as over time. This diversity notwithstanding (and despite a few idiosyncratic cases), the urban spatial morphology of most Classic Maya cities followed the same pattern: a civic-ceremonial core of monumental architecture with public spaces such as plazas and associated buildings, temples, palaces, elite residences, and ceremonial causeways. Radiating out from the center were the household residences of commoners, each with associated farming spaces, thus essentially forming urban farmsteads. The general outline of Maya cities does not follow an orthogonal model of densely placed settlement blocks, but instead display a relatively dispersed pattern of residential household groups interfingering with farming space and have been labelled "agro-urban landscapes" (Isendahl, 2012).

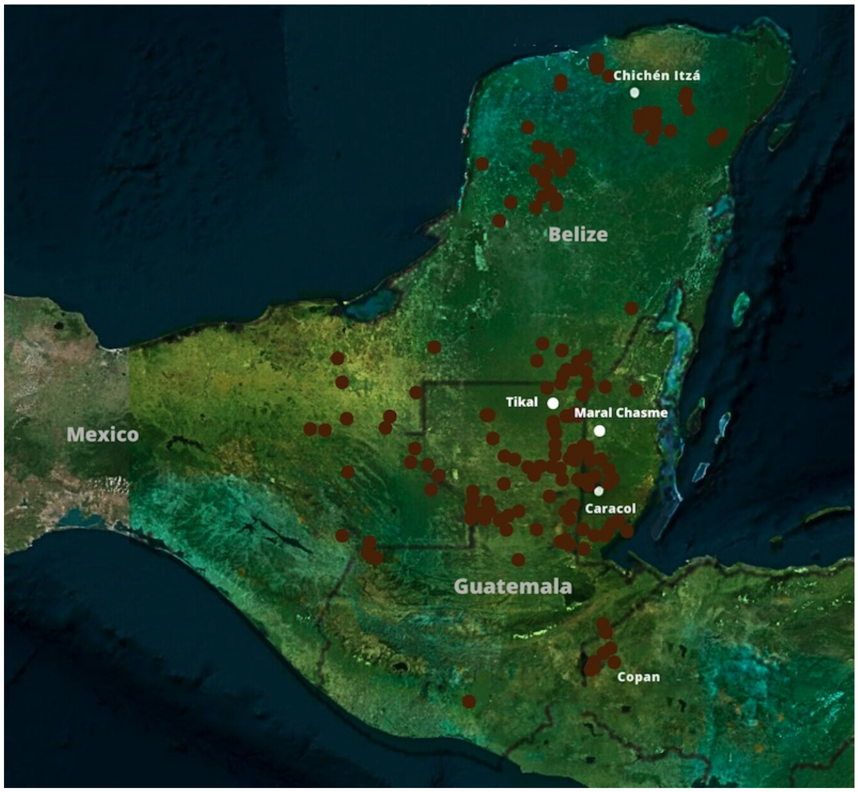
By the Early (250–550 CE) and Late Classic (550–800 CE), numerous city-state polities had been established, including (but not limited to) the megacities of Calakmul, Caracol, and Tikal in the Central Maya Lowlands of today's southern Mexican state of Campeche, Belize, and Guatemala's northern Petén District, the core region of Classic Maya civilization. Each city-state was governed by a royal elite, but the spatial extent of polities and the political jurisdiction of power changed as alliances were made or competitors defeated. The hieroglyphic record suggests considerable inter- and intra-polity antagonism between power lineages in the Central Lowlands during the Classic Period. Plausibly, conflicts were fueled by elite lineages' competition to control the wealth pump that provided the basis for capital accumulation: opportunities to control the principal means of production in the agricultural economy (i.e., labor and land) and/or the yields manufactured from these resources as well as to tap prestige-goods trade networks.

Following a long-term pattern of conjunctures (c. 100–300 years) oscillating between urban growth and degrowth, most large Classic Period cities of the Central Maya Lowlands suffered a crisis during the 9th century CE from which they did not recover (Isendahl et al., 2024). Following a period of massive growth at the tail end of the Late Classic, investments in public architecture came to a ground halt, hieroglyphic inscriptions manifesting elite accomplishments were no longer made, and civic-ceremonial centers were abandoned. However, the non-elite farming population seem to have remained in place for another 3 or 4 generations. The causes of this Classic Maya Collapse have been a matter of debate among Mayanists for half a century, but there is a relative degree of consensus that political disintegration followed from a series of interacting factors, including mounting conspicuous consumption by the elite, resource overshoot, inter-polity competition, social unrest, and conflict, with extended droughts potentially a triggering effect.

2.2 Food production

Maya agriculture was based on the cultivation of maize crops, with beans and squash also being important components of the diet, and with a host of other domesticated and wild plants harvested to make up the primarily vegetative diet, supplemented with fish, birds and meat from deer and turkey and hunted game, deer in particular. Maize constituted at least 70 percent of the Maya diet and is a relatively thirsty plant compared to, for instance, millet or sorghum. Rain-fed agrosystems focused on crops with high demand for soil humidity are vulnerable in areas prone to variation in the annual precipitation pattern. The major Maya staples were planted when the rainy season began in May. A delay in the onset of rains would shorten the growing period and lower the harvest. Some Maya Lowland regions experience an irregular midsummer drought, which may kill the tender plants, either resulting in the loss of the harvest altogether or the need to replant but with diminished yields. Too dry conditions during plant growth might cause fungus species to proliferate, leading to a poisoning of the maize Lucero et al. (2011). Not only too little rain was a risk to agricultural production, but also too much of it. From August to October tropical storms or hurricanes may form over the Caribbean Sea, and their stormtrack (though relatively local in impact compared to drought incidents) may bring heavy rainfall and wind potentially destroying growing plants and/or stored harvests. Furthermore, the humid climate of the Maya Lowlands was a challenge for storing food supplies for extended periods, an environmental constraint different from early states in semi-arid environments, e.g., in Mesopotamia, Egypt or the Indus Valley Scarborough and Isendahl (2022).

Figure 1: Maya cities during Classic Period



Note: Each dot is one of 110 Maya cities (or settlements). Select cities and country names are indicated in white. Own figure using Google Earth.

Maya agriculture was well adapted to these challenges however, and was able to feed a total population of perhaps 7-11 million people in the Southern Lowlands alone, implying a population density of around 100 persons/km2. Tikal, one of the largest Late Classic cities, had an estimated population of around 60,000 people and at least 12,000 structures, visible through remote sensing technology (Canuto et al., 2018; Isendahl et al., 2024).

2.3 Maya water management

Variations in how the humid but seasonally dry tropical climate and the karstic geological structure played out in the Maya Lowlands, resulted in considerable adaptive variety in how different challenges and opportunities to freshwater security were addressed (Isendahl et al. 2019). In the Central Maya

Lowlands, urban populations were strongly reliant on elaborate water management systems, including large-scale artificial reservoirs, to maintain urban livelihoods. Relying on water reservoirs, major cities like Tikal could support large populations despite a 6-month dry season, no freshwater sources such as perennial rivers or lakes and aquifers at too great depths for general groundwater access.

Scarborough (1998) describes Tikal as a ”water mountain” with the urban core of the main plazas, temples and palaces at the top of hills, and associated with “central precinct reservoirs”, plausibly under direct elite control. Through a sophisticated system of canals, some underground, large amounts of rain water were directed into reservoirs. By opening sluice gates, water could be allowed to flow downhill to lower-lying reservoirs. In low-lying terrain, cultivation was probably intensive at the margins of extensive wetlands (or *bajos*). At the bottom of the water mountain was typically a dam or a series of dams, as well as more extensive wetlands where water was sometimes available year-round (Scarborough, 1998; Dunning et al., 1999).

During the wet season agricultural labor was intense with planting and weeding, but the dry season freed up labour for various non-agricultural activities, such as monument and reservoir construction and maintenance, production of pottery and other goods, religious ceremonies, trade, and market activity. During these months, labour could be invested in construction and maintenance work of the water management system, for instance constructing new reservoirs, canals, or sluice gates, and, particularly towards the end of the dry season when reservoir capacity had been exhausted, extending or improving existing ones by plastering the surface to control seepage. The soil and stone from the reservoir construction were often recycled in the construction of public monuments at the urban core such as temples, palaces, causeways, and, vice versa, quarries were sometimes further elaborated into reservoirs. In order to ensure high water quality in reservoirs, aquatic ecosystem management included the introduction of water lilies and other plants that kept the water clean and potable (Scarborough, 1998; Lucero et al., 2011; Scarborough et al., 2012).

It is not surprising that the few natural sources of potable water there were, such as springs and caves, functioned as early attractors for human settlement and took on great symbolic significance in the Maya perception of landscape. At Tikal, for instance, the central civic-ceremonial precincts of the city's political and religious elite were constructed on a series of hilltops with fresh water springs. The association between those water sources and the elite's claim of power over place likely appeared in founder narratives. The city's elite literally built on these narratives, constructing a vertically organized rain-fed water management system of catchment surfaces, distribution canals, check-dams, storage reservoirs, and purification devices that together formed the water mountain (Scarborough, 1998). Concentrating and providing access to a fundamental resource, thereby offsetting the centrifugal tendency in a population, the reservoir infrastructure was not only a critical economic asset but also a political instrument for retaining fiscal control over a large farming population (Dunning et al., 1999). Hence, if the rain-fed water management system would fail owing to prolonged severe drought, the consequences of that breakdown would reverberate throughout the very fabric of urban society.

3 Data

This section describes the data sets from inscriptions on stone monuments that provide information on their construction, as well as the paleoclimatic data, based on the chemical composition of stalagmites, that similarly can be dated with high precision.

3.1 Monument data

We use archeological data on the distribution of 110 settlements throughout the Maya Lowlands collected by Kennett et al. (2012), including not only large cities like Tikal, Calakmul, Caracol, Copan and Palenque but also lesser centers. Major cities were largely independent political units in a similar way as the Mesopotamian or Greek city-states and were at no time a single unified macro-state under one political jurisdiction. Maya city-state polities were often at war with each other but as often unified in various combinations in political alliances, as reflected in numerous inscriptions. In addition, geographical and climatic conditions were very different across the Maya Lowlands. Although the political relationships (e.g., allies, in conflict, etc) among the 110 settlements in the database clearly varied over time, we argue that it is reasonable to study each settlement as an independent unit of observation with potentially unique trends in socioeconomic development. All 110 settlements have been georeferenced (see Figure 1).

Monuments of different character conveyed information that expressed the power and glory of elites. Some of the most important features of the Maya plazas and other spaces for public and/or elite ceremonies include stelae (an erected limestone slab with hieroglyphic text and iconographic ornamentation) and altars. Figure 2 shows an example of a stela (left) and an altar (right) from Copan. We have been classified monuments into different categories. The result is a list of 870 monuments containing information that suggests the time of their construction. Table 1 shows that the most common type of monument was the stela. Also common were altars, lintels, and thrones. We consider the presence of a monument at a certain date as an indication of an existing "city state"-like polity, controlled by a royal elite that has a fiscal and organizational capacity that goes beyond that of a village-head or tribal chief (Trigger, 2003).

Figure 2: Stela and altar from Copan

Note: The picture to the left shows Stela A (731 CE) from Copan and the picture to the right shows Altar Q (776 CE) from Copan.

Since there is no monument construction activity during several individual years, we aggregate the 700-year time interval into 140 5-year periods, resulting in a sample of 15,400 settlement-period observations. Figure 3 presents the temporal distribution of monumental construction within five-year intervals for the Classic Maya period (250 to 950 CE), comprising the Early, Late and Terminal Classic Periods. Before 650 CE there were relatively few dated monuments, and the mean annual frequency was 4.3. A steady increase followed, reaching almost 25 at the end of the 700s CE. After this time, the number of dated monuments rapidly falls. By the start of the 10th century, is down to zero.

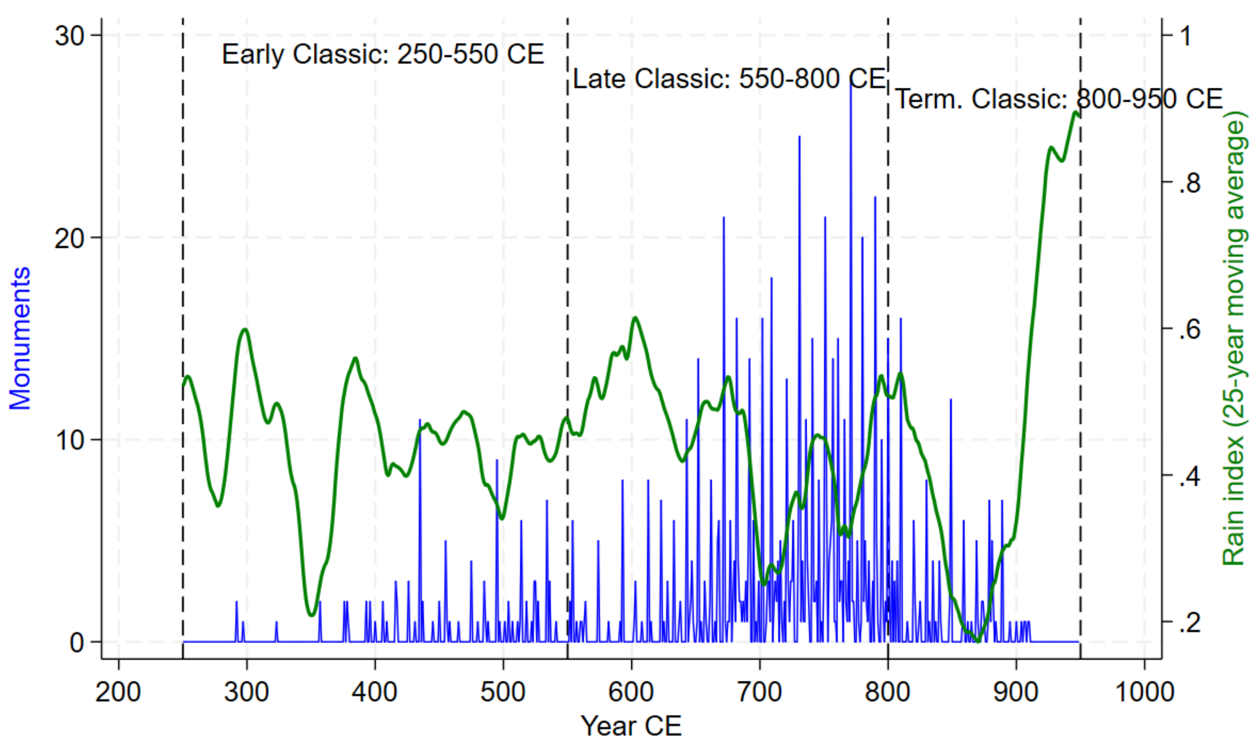
The second source of monument data come from the *Maya Hieroglyphic Database* (Looper and Macri, 2024). This dataset contains deciphered transcriptions of Classic Maya hieroglyphic inscriptions on stone monuments. Figure B1 in the Appendix shows an example of glyphs from Palenque. From the roughly two million hieroglyphic words inscribed on Maya monuments, we calculate the relative frequency of certain categories of messages related to religion, war, politics and agriculture, as described further below.

Table 1: Types of monuments

Type	Frequency	Percent
Stela	457	52.53
Altar	91	10.46
Lintel	83	9.54
Throne	32	3.68
Drawing	26	2.99
Panel	19	2.18
Bench	12	1.38
Ballcourt	6	0.69
Sculptures	4	0.46
Other	140	16.09
Total	870	100.00

Note: The table shows the distribution of different types of 870 monuments over the whole time period 250-950 CE.

Figure 3: Rainfall and Maya monument construction, 250-950 CE



Note: The figure shows the number of monuments constructed during a particular time period in blue on the vertical axis to the left and our Rain index in green on the vertical axis to the right. The horizontal axis shows year CE. The three main Classic periods are indicated with vertical lines. See text for explanations and sources of the data.

3.2 Climate data

Proxy records of past variation in annual rainfall over the Maya Lowlands, is our key source of exogenous temporal variation. We use collected time series on sediment layers in caves such as stalactites and stalagmites (speleothem), which have often been used in the scientific literature as proxies for historical precipitation (Blyth et al., 2016).

There are three main speleothem data archives in the Maya Lowlands that can be used to understand the variation in precipitation during the Classic Maya Period. One is the δ^{18}O-record from a sediment core in Lake Chichancanab in Mexico, initially sampled and analyzed by Hodell et al. (1995). δ^{18}O measures the oxygen isotope ratio in temporally defined segments of the speleothem where more negative values indicate relatively wetter years. This was one of the first studies to indicate a severe drought in the Maya Lowlands around 800-1000 CE. A drawback of the record, however, is that the lake is located in northern Yucatan where annual precipitation volumes are lower than in the southern Maya core area.

A second proxy record, also based on the oxygen isotope ratio δ^{18}O, was extracted from a stalagmite in the cave Yok Balum in southern Belize, which is securely dated to cover the entire Classic Period and with a high temporal resolution at 0.5 years (Kennett et al., 2012). This cave is located 1.5 km from the settlement Uxbenká and with Tikal and other major Classic Period population centres (such as Caracol, Copan, and Calakmul) within 200 km.

Our preferred indicator is a multi-proxy record from cave sediments in the Macal Chasm on the Vaca Plateau in southwestern Belize (see Figure 1), presented originally by Webster et al. (2007) and extended by Akers et al. (2016). Macal Chasm is located at the Maya settlement of Ixchel, 15 km north of the major city of Caracol and about 50 km from Tikal. Our main main climate proxy is the δ^{18}O from this cave. Also available from the Macal Chasm stalagmite are other paleoclimatic proxies such as carbon isotope data (δ^{13}C), natural light reflectance, and ultraviolet-stimulated luminescence. All four of these series follow the same basic trends as the δ^{18}O-series. Although the greater proximity of Macal Chasm to the core of the Classic Maya area is an advantage, the less certain anchoring of dates compared to the archive in Yok Balum is a potential drawback. In our empirical analysis, we check the robustness of our results by using the Yok Balum-series and the δ^{13}C-series from Macal Chasm as alternative proxies for variations in precipitation in the past.

For illustrative purposes, we have re-scaled the main δ^{18}O-series from Macal Chasm to a more intuitive *Rain index* with 1 indicating the highest rainfall reported, and zero the lowest. How the index changes over time is shown in the green line in Figure 3. The monument trend for all settlements is plotted in the blue line. Following Chaney (2013), we define shock events as equal to 1 for drought or flood extremes that are in the bottom or top 10 percent of the distribution. We use a non-linear trend in the empirical specification. Figure 3 suggests that weather shocks were primarily driven by stochastic high-frequency variation which could not have been predicted by the Maya.

Since the groundwater table was at depth out of reach in most of inland Maya Lowlands save the northern coastal plain, most Maya settlements had to rely on captured and stored rain water in artificial reservoirs. As discussed above, given very high levels of annual evaporation, there is a relatively weak temporal persistence in reservoir levels and they will typically depend on rainfall during the last few years.

We have also collected detailed geographical data for each of our 110 Maya settlements. We extract information about elevation and slope characteristics at the centroid of a settlement, as well as within 1km and 5km radiuses. As a measure of geographical closeness among settlements, we calculated the distance (in km) from each settlement to its nearest neighbors. We extracted information about contemporary average levels of precipitation and temperature for each settlement and month of the year. This allowed us to construct measures of typical rainfall and temperature during wet and dry seasons respectively. See Tables B1 and B2 in the Appendix for descriptive statistics about the data.

4 Empirical Analysis

In the following section, we outline the empirical strategy and present the results of our panel data regression analysis.

4.1 Empirical strategy

In studies of the impact of climate change on past societies ((Weiss, 2017) it is frequently assumed that there is a causal relationship between drought, resource shortfalls, and decrease in socioeconomic activity. Arguably, lower activity would result in a decrease in the production of material culture, and therefore potentially visible in the archaeological record. To test this prediction, we estimate the following regression:

$$m_{it} = \beta P_t + \sum_{l=1}^{L} \gamma_{t-l} m_{it-l} + \alpha_i + \delta_t + \epsilon_{it} \quad (1)$$

The dependent variable m_{it} is either a binary dummy for the construction of any monument or the log number (+1) of monument construction in a 5-year period t in settlement i. P_t is the proxy for rainfall for the whole area in year t (usually an index based on δ^{18}O-observations from Macal Chasm). α_i denotes settlement fixed effects, which will absorb the impact of any time-invariant settlement characteristics, for instance related to geographical or climatic characteristics such as average precipitation levels. δ_t denotes time trend variables. The error term ϵ_{it} includes all other time-varying unobservable shocks to monument construction. The specification also includes lags of monuments on the right-hand side to control for pre-trends in monument construction (see Acemoglu et al. (2019), for a similar specification).

A standard assumption when dealing with linear dynamic panel models is sequential exogeneity. Thus, we assume that past monument construction is orthogonal to contemporaneous and future shocks to monuments as in Acemoglu et al. (2019). Intuitively, this implies that settlements experiencing low or high rainfall are not on a different monument construction trend relative to others with similar monument construction in the past years (captured by the lags of monuments), and similar levels of long-run state capacity (captured by settlement fixed effects). Given that rainfall is arguably exogenous, we believe this is a reasonable assumption.

In some of the tables below, we will vary the structure of eq. (1). In one instance, we will address the absence of information about settlement-specific past precipitation by interacting P_t with a variable measuring average contemporary precipitation levels at individual settlements; $\bar{P}_i$. The implicit assumption is that $\bar{P}_i$ should be an acceptable proxy for average historical (unobserved) individual precipitation levels.

Instead of the panel structure, we sometimes aggregate all individual settlements into a macro time series where the dependent variable $m_\tau = \sum_{i=1}^{M} m_{i\tau}$ is the total amount of monuments in the entire region built during a particular year τ, rather than a 5-year period t. In that case, our specification is:

$$m_\tau = \beta P_\tau + \sum_{l=1}^{L} \gamma_{\tau-l} m_{\tau-l} + \delta_\tau + \epsilon_\tau \quad (2)$$

4.2 Main results

Table 2 reports our main results for the impact of our *Rain index*-variable, controlling for different numbers of lags in the dependent variable. The dependent variable is a dummy for any monument (Mon. dummy = 1) in period t in columns (1)-(2) and the log of (1+) the number of monuments in columns (3)-(6). Throughout all regressions, we estimate fixed effects at the settlement level and the coefficient for *Rain index* thus captures the intra-settlement intertemporal variation in monument construction activity.

The first column of the table presents the linear probability (extensive-margin) relationship between rainfall and a dummy for any monument construction without any lags or trends. The negative and significant estimate implies that higher rainfall has an immediate impact of lower monument construction. For instance, a one standard deviation increase in the rainfall index (.194) is associated with a 0.8 percent lower probability of any monument being constructed. The estimate is statistically significant but the magnitude of the marginal effect is rather small. The coefficient decreases to -0.027 in column (2) but is still strongly significant despite the inclusion of four lags in the dependent variable and a non-linear time trend.

Table 2: Effect of rainfall on monument construction among 110 Maya cities, 250-950 CE

	Dependent variable:					
	Mon. dummy (t) = 1		**Log Monuments (t)**			
	(1)	(2)	(3)	(4)	(5)	(6)
Rain index (t)	-0.041***	-0.027***	-0.036***	-0.029***	-0.020***	-0.021***
	(0.007)	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)
Mon. dummy ($t-1$)		0.134***				
		(0.022)				
Mon. dummy ($t-2$)		0.170***				
		(0.022)				
Mon. dummy ($t-3$)		0.058***				
		(0.021)				
Mon. dummy ($t-4$)		0.160***				
		(0.019)				
Log Monuments ($t-1$)				0.268***	0.166***	0.165***
				(0.048)	(0.031)	(0.031)
Log Monuments ($t-2$)					0.200***	0.199***
					(0.026)	(0.026)
Log Monuments ($t-3$)					0.043	0.041
					(0.026)	(0.026)
Log Monuments ($t-4$)					0.175***	0.173***
					(0.030)	(0.030)
Settlement FE	Yes	Yes	Yes	Yes	Yes	Yes
Non-linear trends	No	Yes	No	No	No	Yes
Observations	15,400	15,400	15,400	15,400	15,400	15,400
Settlements	110	110	110	110	110	110

Note: The table presents the within estimates of our Rain index on a binary dummy for monument construction in columns (1)-(2) and on Log Monument construction in columns (3)-(6) for 110 Maya cities over 140 5-year periods during 250-950 CE. Estimates of all included lags of the dependent variable are shown in all columns. Standard errors, clustered at the settlement level, are in parentheses. In each specification, we control for a full set of settlement fixed effects and for non-linear time trends in columns (2) and (6). *** p<0.01, ** p<0.05, * p<0.1.

A similar pattern is found in columns (3)-(6) with Log Monuments as the dependent variable. The estimate for rain is consistently negative and significant. In a pattern common to all of the results that we present, we find in column (3) a sizable amount of persistence in monument construction, with a coefficient on lagged (log) monuments of 0.268. Consistent with the stationarity assumption, this coefficient is significantly less than 1. Finally, column (6) shows that controlling for a non-linear trend does not change the magnitude of the effect.

In Table B3 in the Appendix, we account for the settlement fixed effects generated in Table 2, using climatological and geographical data from contemporary conditions at the settlement. Average annual and dry season temperature at individual settlements are positively associated with monument construction in columns (2)-(3). The slope gradient closest to the summit (within 1 km) has a negative and weakly significant impact in column (2). Notably, there are no indications that average rainfall levels at individual settlements (proxied by contemporary levels) affect monument construction activity. Distance to neighbors does not seem to have any impact either. The main take-away appears to be that geographical factors have a poor explanatory power for understanding why mean monument construction activity was higher in certain cities than in others. Most of the variation must be attributed to unobserved differences.

4.3 Robustness

In Table 3, we introduce a number of alternative proxies of historical rainfall. In column (2), we interact our historical Rain index for the Maya Lowlands with contemporary total levels of rainfall at each settlement. We do so in order to check if variations in average rainfall levels across settlements played a role for reactions at each settlement in terms of monument construction activity. As the table shows, the interaction term is close to zero and not significant.[6]

In columns (3)-(5), we include the dummy variables for the 10-percent worst drought- and flood-periods in the distribution of the Rain index. The pattern is clear also here: Drought years are associated with more monument construction whereas the reverse is true for years of heavy rainfall.

We also include two other paleoclimate proxies for historical rainfall in the Maya Lowlands: The δ^{13}C-series from Macal Chasm and a calculation of reservoir levels based on the Rain index. The former carbon isotope series is often used as an alternative proxy for precipitation to the δ^{18}O-series, although the carbon isotope ratio is believed to also reflect the extent of vegetational cover in the vicinity of the cave and, more precisely, the relative importance of cultivated crops vs forest growth (Akers et al., 2016). A high value of δ^{13}C might thus indicate a drought and/or a situation with a more intensive maize cultivation and potential deforestation. Once again, the coefficient and impact is small but positive and significant at the 5-percent level, indicating that droughts and/or a relatively greater dominance of crops over forest, are associated with greater monument construction.

[6] A similar zero result is also obtained if we instead use only wet season average rainfall levels at each settlement.

Table 3: Alternative measurements of rainfall

	Dependent variable: Log Monuments (t)					
	(1)	(2)	(3)	(4)	(5)	(6)
Rain index (t)	-0.021***	-0.036**				
	(0.005)	(0.018)				
Int. Rain index (t)		0.000				
x Annual rain (i)		(0.000)				
Drought (t)			0.012***		0.010**	
			(0.004)		(0.005)	
Flood (t)				-0.015***	-0.013***	
				(0.003)	(0.003)	
δ^{13}C (Macal Chasm) (t)						0.001**
						(0.001)
Log Monument lags	4	4	4	4	4	4
Settlement FE	Yes	Yes	Yes	Yes	Yes	Yes
Non-linear trends	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,400	15,400	15,400	15,400	15,400	15,400
Settlements	110	110	110	110	110	110

Note: The table presents the within estimates of alternative proxies of rainfall intensity (see discussion in text) on Log Monument (+1) construction for 110 Maya cities over 140 5-year periods during 250-950 CE. Information about the number of included lags of the dependent variable are summarized in the lower part. Standard errors, clustered at the settlement level, are in parentheses. In each specification, we control for a full set of settlement fixed effects and non-linear. *** p<0.01, ** p<0.05, * p<0.1.

In Table 4, we move to an aggregate macro level where the dependent variable is all monuments built in the Maya Lowlands during a particular year. The time resolution is thus single years (denominated as τ) rather than 5-year periods t, as in the tables above. Over the time period 250-950 CE, this gives us 700 annual observations of monument construction and four different rainfall proxies.

Also in this setting, the Rain index is negative and significant, regardless of lags, in columns (1)-(2). The absolute level of the estimate is higher (0.35-0.40) than before (0.02-0.036), which is not surprising given that the dependent variable now is all constructed monuments during a given year. The shorter time frame could imply that monument construction did not have time to respond immediately to annual rainfall variations. For this reason, we include a moving average of rainfall five years back in columns (3)-(4). The estimates are marginally lower but still negative and significant at the 5-percent level. The carbon isotope alternative proxy δ^{13}C has a positive estimate as before.

The key result to notice is that the δ^{18}O paleoclimate time series from Yok Balum (Kennett et al.,

Table 4: Macro level time series analysis using annual data, 250-950 CE

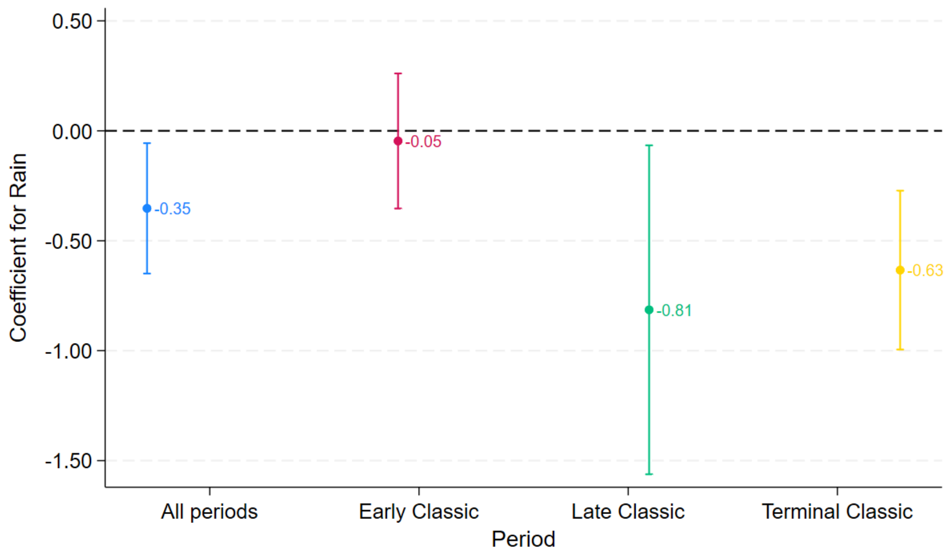
	Dependent variable: Log Monuments (τ)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rain index (τ)	-0.400**	-0.353**						
	(0.171)	(0.151)						
Rain index MA ($\tau - 4$,τ)			-0.392**	-0.333**				
			(0.174)	(0.154)				
δ^{13}C(τ) (Macal Chasm)					0.048***	0.042***		
					(0.017)	(0.015)		
δ^{18}O (τ) (Yok Balum)							0.566***	0.490***
							(0.181)	(0.171)
Monument lags	1	4	1	4	1	4	1	4
Non-linear trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	700	700	700	700	700	700	700	700

Note: The dependent variable is the log of the aggregate number of monuments (+1) dated to a particular year τ in the Maya Lowlands. Annual observations (700) during 250-950 CE. The number of lags in the dependent variable and the inclusion of non-linear time trends, are indicated in the table. The estimator is Newey-West, assuming a lag structure of 10 years. Standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1.

2012) show a very similar relationship to monument construction as our preferred proxy from Macal Chasm. Higher levels of δ^{18}O (indicating drier years) are associated with more monument construction. The estimates are significant at the 1-percent level in columns (7)-(8). This result goes against the basic interpretation in Kennett et al. (2012) whose results suggested that when using 25-year periods, there appeared to be a positive relationship between monument construction and rainfall and that an extended period of drought effectively ended the Classic Maya civilization. In the section below, we will discuss how our different results might be reconciled.

Was the impact of rainfall on monument construction homogeneous across time? In Figure 4, we disaggregate the full time interval into the standard Maya periods the Early Classic (250-550 CE), the Late Classic (550-800 CE), and the Terminal Classic (800-950 CE) and run the same specification as in Table 4, column (2) for each period, excluding the trend component. Figure 4 shows how the estimated coefficient β for rain changes over time. The overall negative estimate -0.35 to the left is primarily driven by the negative and significant estimates for the Late and Terminal Classic Periods, whereas there appears to be no relationship between rain and monument construction during the Early Classic, when there was far lower monument construction in general.

Figure 4: Temporal parameter heterogeneity across Maya periods



Note: The figure shows the coefficient and 95-percent confidence interval for the main Rain index-variable in the annual, macro level sample in Table 4 when disaggregating over the three time periods Early Classic (250-550 CE), Late Classic (550-800), and Terminal Classic (800-950 CE). The dependent variable is log (+1) monuments built during a year. The blue coefficient to the left is equivalent to the one in Table 4, column (2), including four monument lags and a non-linear time trend. The remaining coefficients to the right are from regressions with four monument lags but without non-linear time trends.

In the Appendix, we carry out two additional robustness tests. In Table B3, we check whether our results improve when we introduce a lag in our main Rain index-variable. In general, it appears that the level of rain in the same period gives the clearest results. When four lags in the dependent variable and a non-linear time trend are included, the lagged Rain index is not significant. In Table B4, we use the number of monuments, rather than the log of (1+) the number of monuments, as the dependent variable. As before, the results indicate a significant but quite small negative impact of rainfall on monument construction activity.

5 Mechanisms

5.1 Inscriptions on monuments

In the previous section, we showed that monument construction was more prevalent in dry years everywhere. This tendency also holds when we instead include dummies for the 10 percent most extreme drought and flood periods and control for alternative measures of precipitation. In this section, we investigate in more detail some plausible interpretations of these results. What kind of capacities did the ruling elite try to signal to the population by erecting monuments?

In order to answer this question, we analyze information about the glyphic inscriptions on geolocated Maya monuments. During the Classic Period, Maya elites had the tradition of recording historical events on stone monuments, using long count calendar dates that can be precisely translated to the Gregorian calendar. As mentioned above, we rely on the *Maya Hieroglyphic Database* (Looper and Macri, 2024), which is a comprehensive record of events inscribed in monuments, with their location, semantic, and chronological information.[7] Our unit of analysis are more than two million identified words with different meanings inscribed on Maya monuments during the Classic Period 250-950 CE.

There are many factors that might have contributed to the construction of monuments during drought periods. For instance, Belloc et al. (2016) and Chaney (2013) suggest that religion could have played a key role. We use proxies for and examine the frequency of four categories of words related to the social domains of: *religion, war, politics,* and *agricultural activity.* We start by searching for keywords that relate directly to Maya practices for each of the relevant topics. The meaning of the words in Maya language were derived from the "Spanish-Maya Dictionary" at the University of Yucatan, Mexico and used to classify the words in the texts.

For instance, regarding the religious category, relevant words were selected from what Mayanists have identified as themes of the Maya religion, including gods, deities, spiritual forces, rituals, mythical characters, figures associated to sacredness and holiness, and supernatural beings (Taube, 1992; Houston, 1999). Examples of words that we categorize as religious include "k'uhul" (holy), "k'uh" (sacred/deity), "na'at" (divine), "ka'an" (heaven), "k'iin" (priest), "nah k'uh" (temple), and "k'aam" (offering). In total, we found 238,687 religious words, distributed across hundreds of monuments and places over 700 years.

In a similar manner, we searched for words with a meaning associated with the other three categories. Within the *war*-category, we included words like "chuk" (to capture or tie up), "bate'el" (warrior), "bak" or "baak" (prisoner or captive), "pak" (defense walls), "ba'ate'el" or "ba'ate'il" (war or fighting), "pul kaabal", or "lúubs" (bring down or demolish), and "táanxel kaahil" (foreigner, outsider). Words related to war and conflict made up the least common category with only 13,351 words, whereas political words like "k'asa'an" (despot), wíinik (aristocrat) and agricultural words like "kol" (farmer), "hooch" (harvest), and "ya'abtal" (fertil), made up 35,864 and 25,645 words respectively. In total, about 2,24 million words

[7] The Project was initiated by Martha Macri at the University of Davis, California in the 1980s, and now is managed by Matthew Looper. More information can be found here: https://www.mayadatabase.org/about

were included in the database.[8]

On the basis of this data, we create measures of the proportion or the number of all glyphs that appear in the monument during 5-year periods and that belong to one of the four categories. For instance, religious words appear in 99 out of 140 5-year periods in the sample. Given that at least some religious word is mentioned, they make up on average 16.5 percent of all words. Words related to war only appear in 59 periods and the average proportion of words (given any reference to war) is relatively small at 2.2 percent.

In Table 5 below, we study the extensive margin of any reference to our four categories during a period. The dependent variables are thus dummies = 1 if there was any reference to religion, war, politics or agriculture during our 140 periods. In every odd column, we only regress our dummies on the Rain index, whereas we also control for the total number of monuments from the previous section, in every even column. Admittedly, Monuments is potentially a bad control since it was shown to be associated with rainfall in the previous section, but we think it might still be useful to include it in order to keep constant the aggregate level of monument construction activity during periods.

The estimates in the table show that War is consistently negative and significant whereas also the other variables have negative estimates but are not significant. Using the coefficient in column (3), we find that a one standard deviation decrease in our Rain index (0.196) increases the probability of war-related inscriptions during a period with about 11 percent. This result in consistent with archaeological, osteological, and radiocarbon evidence that prolonged drought escalated rival factions tensions (Kennett et al., 2022).

In Table 6, we use the proportion of words among all inscriptions during a period that are classified as related to religion, war, politics and agriculture respectively. The estimates for religious, political and agricultural terms are always quite close to zero and never significant. More or less rainfall thus does not appear to influence the the elite's propensity for signaling such messages on monuments. Hence, the results from the two tables in this section do not support the hypothesis that the Maya tended to lean on religious signals to gods more in times of failing rains, or that political or agricultural topics became more common during droughts.

However, the proportion of words associated with war and conflict once again have a clear negative association with rainfall. The result in column (3) implies that a one standard deviation decrease in our rain measure is associated with a 0.68 percentage units higher share of war-related words. Considering

[8] In addition, we have performed robustness checks, in which we remove articles, prepositions, auxiliary verbs, and conjunctions, often referred to as "stop words" in the text analysis jargon. The reason is that these words are often the most occurring words and carry little semantic meaning on their own, so we can focus on words with informative content.

Table 5: Types of inscriptions in monuments: Extensive margin

	Dependent variable: Dummy for type of inscription							
	Religion (t)		**War (t)**		**Politics (t)**		**Agriculture (t)**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rain index (t)	-0.307*	-0.231	-0.564***	-0.427***	-0.161	-0.027	-0.187	-0.024
	(0.173)	(0.170)	(0.167)	(0.154)	(0.175)	(0.164)	(0.167)	(0.148)
Monuments (t)		0.012***		0.021***		0.021***		0.026***
		(0.004)		(0.004)		(0.005)		(0.005)
Non-linear trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140	140	140	140	140	140	140	140
R-squared	0.38	0.42	0.36	0.45	0.37	0.46	0.30	0.43

Note: The dependent variables are dummies = 1 if there is any word within each of the four categories of inscriptions during a 5-year period for the Maya civilization as a whole during 250-950 CE. Linear regression using OLS. Non-linear time trends are included in every regression with unreported coefficients. *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Proportion of type of inscriptions

	Dependent variable: Proportion of inscriptions							
	Religion (t)		**War (t)**		**Politics (t)**		**Agriculture (t)**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rain index (t)	-0.999	-0.723	-3.530***	-3.559***	-0.393	-0.077	0.315	0.465
	(8.263)	(8.645)	(1.133)	(1.178)	(0.893)	(0.759)	(0.465)	(0.469)
Monuments (t)		0.043		-0.005		0.050*		0.024
		(0.113)		(0.015)		(0.028)		(0.017)
Non-linear trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140	140	140	140	140	140	140	140

Note: The dependent variables are the proportion (in percent) of all inscriptions for each of the four categories of inscriptions during a 5-year period for the Maya civilization as a whole during 250-950 CE. Non-linear time trends are included in every regression with unreported coefficients. Newey-West estimator, using 10 lags. *** p<0.01, ** p<0.05, * p<0.1.

that the mean is 0.95 percent, this is a non-negligible impact. In summary, these findings support the interpretation that most monuments or messages on monuments are unrelated to weather except for the conflict-related messages and monuments. When rainfall is low, elites show a tendency to emphasize their own military capacity to a greater extent.

5.2 Types of monuments

In this subsection, we explore how monuments with different societal functions – ranging from religious and ceremonial, to war-related and infrastructural purposes – may have been influenced by fluctuations in our proxy for rainfall. To this end, we use the same *Maya Hieroglyphic Database* as in the previous section to categorize monuments into four distinct classifications: *religion, war, community* and *infrastructure*. In total there are 779 unique monuments (440 religious, 47 war-related, 199 community-related, and 15 infrastructural monuments).

i) Religious monuments: This category encompasses structures dedicated to straightforward religious practices and beliefs, including altars, temples, thrones, tombs, and graves. These monuments served as sacred spaces for rituals, ceremonies, and the veneration of deities (Lucero, 2007).

ii) War-related monuments: This category comprises defensive structures and fortifications such as protective walls. These monuments were erected for strategic purposes, safeguarding settlements and ceremonial centers from external threats and conflicts (Kennett et al., 2022).

iii) Community monuments: Within this classification, we include monuments designed for public games and ceremonies such as ballcourts, and identity-enhancing artistic representations such as stucco, murals, and sculptures. These monuments often served to strengthen the social cohesion of the local community and showcased artistic expressions of mythological narratives and scenes of daily life (Scarborough, 1991).

iv) Infrastructural monuments: This category encompasses a diverse range of productivity-enhancing public goods serving practical functions for the Maya society. It includes monuments related to water management, residential buildings, and architectural support systems. These monuments facilitated essential aspects of daily life, such as irrigation, housing, and structural stability, contributing to the physical fitness and economic development of Maya communities (Walsh, 1916).

The dependent variable in Table 7 is the total number of monuments within the specific category. Specifications in even columns (i.e. columns 2, 4, 6, and 8) control for the total number of monuments and non-linear trends and is our preferred line-up. The results from a Poisson estimation show that there was no significant increase in the construction of religious monuments, war-related monuments (defensive walls), or infrastructure buildings during dry periods, once we control for total number of monuments. However, the negative estimate in column (6) suggests that there was a significant increase in community monuments during periods of drought. One potential explanation for the rise in community monuments, including ballcourts, may be linked to their different roles in Maya society.

Table 7: Types of monuments

	Dependent variable: Types of monuments							
	Religion (t)		**War** (t)		**Community** (t)		**Infrastructure** (t)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rain index (t)	-1.113***	-0.351	-3.998	2.247	-2.112***	-1.085***	0.164	0.840
	(0.256)	(0.261)	(6.016)	(2.004)	(0.396)	(0.375)	(1.314)	(1.480)
Monument (t)		0.059***		-0.128		0.064***		0.033
		(0.005)		(3.205)		(0.007)		(0.027)
Mean	3.14	3.14	0.01	0.01	1.42	1.42	0.10	0.10
Monuments	No	Yes	No	Yes	No	Yes	No	Yes
Non-linear trends	No	Yes	No	Yes	No	Yes	No	Yes
Observations	140	140	140	140	140	140	140	140

Note: The dependent variables the number of monument types with a purpose related to religion, war, community, or infrastructure during a 5-year periods for the Maya civilization as a whole during 250-290 CE. Non-linear time trends are included in every regression with unreported coefficients. *** p<0.01, ** p<0.05, * p<0.1.

Ballcourts were emblematic features of the Maya as well as other pre-Columbian Mesoamerican complex societies, characterized by a narrow central playing area flanked by two parallel walls (Scarborough, 1991). These structures served as venues for ceremonies and entertainment within Maya society. The game played in these ballcourts involved solid rubber balls, typically crafted from the rubber tree *Castilla elastica*. Due to their weight, players often wore layers of protective padding, and the game required them to strike the ball using their bodies rather than their hands or feet (Blomster and Chávez, 2020).[9] The game was a public spectacle characterized by rich and visual iconographic elements. The architectural design of the ballcourts provided a platform for artistic manifestations. Their walls served as murals, and they were adorned with carvings, sculptures, murals, and decorative elements such as stuccos and lintels (Scarborough, 1991).

The archaeological interpretation suggests that the presence of large-scale public architecture is an indicator of political hegemony, prestige, wealth, and power. The symbolism associated with the Mesoamerican ballgame was used to convey messages of strength, dominance and divine favor (Stark and Stoner, 2017). Thus, ballcourts were predominantly situated within urban centres, often adjacent to other buildings for communal and royal engagement. The ballgame was executed for many reasons, which include social functions, for recreation, for the mediation of conflict, such as acting as a forum for the oppos-

[9] Figure B2 illustrates a detailed depiction of ballcourt.

ing groups to compete for political status. In particular, the game provided opportunities for rulers to negotiate treaties, settle disputes, or solidify alliances (Fox, 1996).

Scarborough (1991) posits that the ballgame also functioned as an instrument of community integration, bridging societal divides through communal participation. Furthermore, it served as an expression for Maya ideology and group solidarity. Even members of the nobility, including the monarchy, often prided themselves as players (Scarborough, 1991). However, the ballcourt game also held a significant social role that extended beyond mere entertainment to encompass political dimensions. It played a role in resource mobilization and taxation. People lived relatively dispersed in spatial extensive agro-urban landscapes (Isendahl, 2012), and this made it challenging for rulers to organize work parties, feasts, and ceremonial events and extract surplus. For this reason, rulers funded large events in ballcourts to attract labor from the hinterland communities (Lucero, 2003).

The Maya ballcourts and their associated ballgame display several similarities to the spectacles and circuses of Imperial Rome. Similar to gladiator games at the Colosseum, the ballgame featured controlled competition, displays of individual skill, and entertainment in front of large audiences, intertwined with elements of religion and community-building. A key purpose of the Roman spectacles was clearly to keep the restless populace at peace and establish bonds between the emperor and the urban population. Although we do not know as much about the function of the Maya ballgame, it is likely that it played a similar role in the growing and increasingly complex city-states of Maya society.

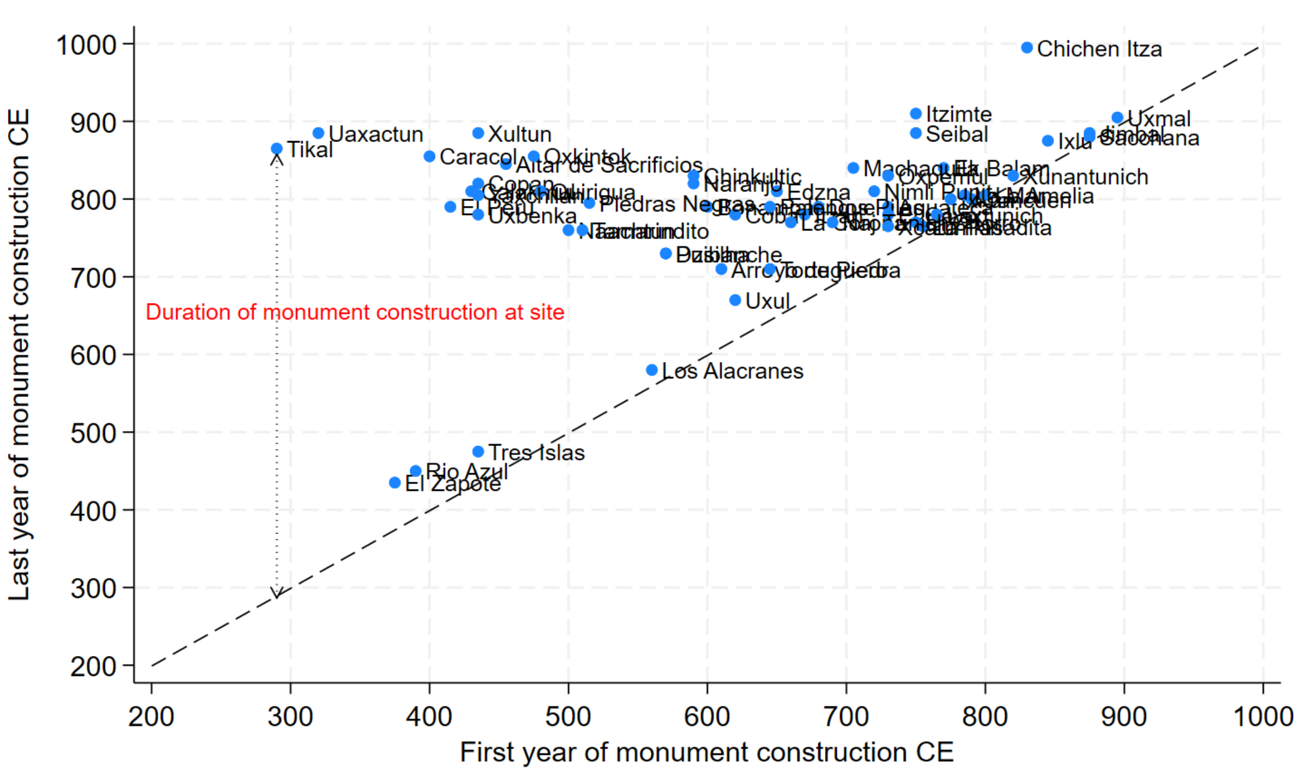
6 The Terminal Decline

In this last empirical section, we analyze the characteristics of the Classic decline that set in primarily in the Central Maya Lowlands somewhat before 800 CE and accelerated in the Terminal Classic Period (800-950 CE). Figure 5 shows a scatter plot of the first and last recorded date of monument construction among 56 Maya settlements where monument construction prevailed for more than a single year. The figure demonstrates that most communities constructed their last recorded monument in the late 700s and early 800s (the median date is 800 CE). The vertical distance between each settlement observation in the figure and the "45-degree line", indicates the duration of monument construction at the settlement. For the major settlement Tikal, for instance, monuments were erected from the late 200s to 865 CE, whereas Uxmal, to the upper right, had a much shorter duration, having its first monument in 895 and its last in 905 CE. There is also a separate group in the lower left part of the figure, including El Zapote and Tres

Islas, that exited early from monument history.

There are two main takeaways from this figure. First, that the practice of dating monuments disappeared at most settlements over a relatively short time span of 200 years. Second, the duration of previous monument construction does not appear to have played a major role for the resilience of settlements. Major ancient communities such as Tikal and Caracol had their last monuments erected at almost the same time as a cluster of much more recently founded settlements to the right.

Figure 5: First and last date of monument construction among 56 Maya settlements



Note: The figure shows a histogram of the last recorded dates of any monument construction in the 110 Maya settlements.

In Figure B3 in the Appendix, we take a closer look of the monument construction dynamic at four settlements with the largest number of monuments over the Classic Period: Copan (91 monuments), Yaxchilan (81), Tikal (54), and Calakmul (50). Together, these four settlements hosted 31.7 percent of all monuments in the database. The dynamics at the four settlements are quite different. Copan had a stable high production of monuments during 640-770 CE, whereas Yaxchilan had a feverishly intense period during just two decades 745-765 CE, Tikal had two distinct peaks in 500 and 750 CE, and Calakmul flourished 660-750 CE, with a second peak around 800 CE when their main competitor Tikal had started to decline. These cycles of rise and decline among the major city-states suggest inter-polity competition and conflict, as reflected in frequent war messages on monuments, but is also related to a series of other interacting socioecological factors, including drought (Isendahl et al., 2024).

To further examine the Terminal Classic decline, we run a cross-section regression with the date of the last period of monument construction as the dependent variable. We exclude all settlements with only one period of monument construction and also four settlements that have no evidence of dated monuments before 600 CE (see Figure 5). This leaves us with a sample of 52 ”durable” settlements. We correlate the date of last construction with a number of settlement-specific geographical characteristics. The results are shown in Table 8.

Table 8: Determinants of last year monument

	Dependent variable: Last period with monument (t)			
	(1)	(2)	(3)	(4)
Rain annual (mm)	-0.024**	-0.032**	-0.036***	-0.029*
	(0.012)	(0.012)	(0.013)	(0.015)
Temperature (mean C)		-8.251*	-6.795	-6.018
		(4.212)	(9.034)	(9.720)
Elevation (m)			0.035	0.048
			(0.037)	(0.046)
Slope 1 km			-2.845	-2.968
			(1.933)	(2.073)
Distance to neighbors (km)			-0.936***	-0.987***
			(0.324)	(0.308)
Latitude				3.584
				(8.927)
Longitude				4.917
				(8.230)
Constant	866.597***	1,090.132***	1,101.268***	1,444.271**
	(32.242)	(111.279)	(244.508)	(702.571)
Settlements	52	52	52	52
R-squared	0.09	0.12	0.24	0.25

Note: The dependent variable is the last year of monument construction among 52 Maya settlements with more than one year with monument construction and with a last period later than 600 CE. *** p<0.01, ** p<0.05, * p<0.1.

The main variable of interest is Rain annual, which measures the average total precipitation at a settlement (in mm) in modern times. This variable serves as a proxy for settlement-specific typical rainfall during the Classic Period. The mean level of precipitation among these settlements across the

Maya Lowlands is 2,266 mm and the standard deviation is 709 mm. Throughout the four columns, the coefficient for Rain annual is negative and significant at least at the 10-percent level, even when all correlates are included in column 4. The significant estimate in column 3 implies that a one-standard deviation increase in precipitation is associated with a 25.6 years earlier end of monument construction. The partial scatter plot is shown in Figure B4 in the Appendix. The results indicate that settlements with lower average rainfall tended to have stronger resilience to declining.

The estimate for Temperature is negative in columns 2-4, but given the high correlation with other variables such as elevation and latitude, it is not surprising that it is not significant in most columns. The second key takeaway is that a settlement's distance to its five closest neighbor settlements has a negative and significant estimate. Increasing the distance to neighbors by one standard deviation (21.7 km) is associated with a 20.3 year earlier instance of the last dated monument. The density of neighboring settlements thus also appears to have delayed the onset of decline. More isolated settlements declined earlier.

When discussing explanations for the specific timing of the general Classic Maya decline after 800 CE, it is reasonable to also reflect on the fact that the 800s CE had the most severe and extended drought throughout the era studied, followed by an equally extreme wet period from around 900 CE (see Figure 3). Visual inspection of Figure 3 suggests a close correspondence between the onset of drought and the dramatic general decline in monument construction in the Terminal Classic. Although the evidence presented here is far from conclusive, it is consistent with many other recent studies suggesting that the major drought played a key role in the ultimate decline of many Classic Maya polities.

7 Monument Construction as Costly Signaling

Here we present a theoretical framework that rationalizes the results from the empirical section concerning a negative short-run relationship between monument construction and rainfall. In particular, we demonstrate that there are compelling reasons for why it is not necessarily the case that more rain and more food resources in the short run should imply more public goods. The model is primarily tailored for the Classic Maya but may also be used to shed light on other historical communities where food production depended to a significant extent on investments in public goods such as water management infrastructures.

7.1 Key assumptions

Our model has a number of key assumptions: (i) Food is non-storable and non-transparent and cannot be taxed by the ruling elite. The elite extract taxes in the form of corvée labor from labor surpluses. (ii) Corvée labor can be used either for improving water infrastructure or for monument construction. (iii) Citizens are mobile across cities and the elite cannot constrain them from leaving or entering their city. (iv) Citizens accept to provide corvée labor in return for the elite's provision of a food production-enhancing water infrastructure (equivalent to "bread") and monuments that distract the population and that signal strong elite capacity ("circuses"). (v) People are attracted to cities by future food production opportunities and by the amount of monuments, but get direct utility only from food. (vi) Food production is a function of soil quality, productivity, labor, rainfall, and water infrastructure. (vii) Monument construction can be made in small, incremental investments whereas water infrastructure investment is "lumpy" in character and can only be carried out with a substantial labor force.

The sequence of events in the model is as follows: In a first stage, citizens determine their labor allocation to food production. In a second stage, the elite determines whether a labor surplus should be devoted to monument construction or water infrastructure investments. In a third stage, the city population and people from neighboring communities decide whether to leave, remain in, or migrate to the city in the next period.

7.2 Food production

Let us now go into the specifics of the model from the assumptions above. The elite provides a useful infrastructure that enhances productivity in food production. Examples of such public goods might be roads, irrigation channels or granaries for storing grain. In our specific Maya setting, we consider water infrastructure in the form of a reservoir for water capture, storage, and distribution. If water is not captured, it dissipates and is useless. The reservoir has a surface area of $a > 0$ and a time-varying depth of d_t so that the maximum water capacity in the reservoir has a volume $\bar{R}_t = ad_t$. After construction or dredging efforts, debris continuously falls into the reservoir in a predictable pattern which gradually diminishes its depth according to a function

$$d_t = (1 - \delta)d_{t-1} + I_t^d \tag{3}$$

where $\delta > 0$ is the periodical natural deposition of debris (sediment, organic material, waste, etc) from

$t-1$ to t which decreases depth.[10] The maximum reservoir capacity thus normally slowly depreciates with time unless dredging is carried out. However, by making an infrastructure investment I_t^d, such as a dredging effort, the level of d_t can be improved. This is however a difficult and costly endeavour which requires a substantial labor force. We will come back to the choice of investment below.

The actual volume of water in the reservoir that is available for food production at time t is $R_t \in [0, \bar{R}_t]$. The level of water is recharged every period with precipitation levels P_t, minus human consumption C_t^w. The volume of precipiation into the reservoir is given by $P_t = ar_t$ where r_t is the rain level in mms. As discussed above, evaporation is very high in tropical environments such as the Maya Lowlands, in particular during the warm season. We assume here that the population use the whole storage of water for either direct consumption or for food production before it evaporates. For simplicity, we assume henceforth that the surface area is $a = 1$.

Human water consumption C_t^w captures direct household usage (for drinking, cleaning, etc) rather than for food production purposes. In the longer term, a city's water demand should be proportional to the size of the population in a city but it should also be relatively smooth over time since it is a very basic commodity. In the short run (from one year to the next), household water consumption levels should be more or less identical. For simplicity, let us initially assume that people consume a constant level $C_t^w = c$.

In line with the simplified assumptions above, a normal year should be characterized by $R_t = P_t - c > 0$, which in turn means we can reformulate the following expression for the water reservoir level at each point in time:

$$R_t = \min\{P_t - c, \bar{R}_t - c\} = \min\{r_t, d_t\} - c \tag{4}$$

In the event that $\min\{r_t, d_t\} < c$, then $R_t = 0$.

In a first stage during period t, the citizens of the city determine how much of their labor to devote to food production. Food F_t is produced according to a production function:

$$F_t = \gamma R_t L_t^{\alpha} = \gamma(\min\{r_t, d_t\} - c) L_t^{\alpha} \tag{5}$$

During years of moderate rainfall when $r_t < d_t$, the production function is $\gamma(r_t - c)L_t^{\alpha}$ where $\gamma > 0$ is an agricultural productivity parameter (for instance capturing soil quality) and L_t is the amount of labor employed in agriculture. The output elasticity of labor is $\alpha < 1$, implying the usual diminishing

[10] In a different environment, this depreciation function could describe the wear and tear of a road or the silting of an irrigation channel.

returns. Food production increases linearly with rainfall r_t and decreases with water consumption c. In the catastrophic event that $\min\{r_t, d_t\} < c$, then $R_t = 0$ and hence $F_t = 0$. This scenario implies a community collapse.[11] When rainfall is high such that $r_t > d_t$, then $R_t = \bar{R}_t = d_t$ and food production stays at its upper bound $\gamma d_t L_t^\alpha = \gamma((1-\delta)d_{t-1} + I_t^d)L_t^\alpha$.

Rainfall r_t is a random, normally distributed variable where the expected level is $E_{t-1}(r_t) = r > 0$ for all t. We think of r as reflecting the state of the long-term *climate* whereas the yearly realization r_t reflects random weather draws around the mean. Figure B5 in the Appendix illustrates a stylized reservoir with the assumptions above.

The members of the community make two choices every year: First, they decide how much labor to allocate to food production given an observed amount of rain and reservoir capacity. Second, a migration decision whether to move to, remain in, or leave the community for next year. The second decision also involve people from neighboring communities who consider moving to the city.

The first decision involves finding the level of labor in food production $L_t \in (0, \bar{L}_t]$ that maximizes households' utility. The utility of a representative myopic household is

$$U_t = F_t - \eta L_t + c = \gamma R_t L_t^\alpha - \eta L_t + c. \tag{6}$$

In this expression, the left-hand side F_t is simply the amount of food produced and consumed, the middle expression ηL_t reflects the calorie marginal disutility of working $\eta > 0$, times the amount of labor supplied, and the last term c is the fixed level of water consumption. The equilibrium allocation of labor is found by rearranging the usual first-order condition for maximum:

$$L_t^* = \left(\frac{\alpha\gamma R_t}{\eta}\right)^{\frac{1}{1-\alpha}} = \left(\frac{\alpha\gamma}{\eta}\right)^{\frac{1}{1-\alpha}} (\min\{r_t, d_t\} - c)^{\frac{1}{1-\alpha}} \tag{7}$$

Labor supply to agriculture hence decreases with marginal calorie cost of working η and with water consumption c, increases with productivity γ, and with rainfall r_t or reservoir depth d_t during that year. Note further that a natural constraint is that $0 < L_t^* \leq \bar{L}_t$.

Total equilibrium food production in year t is thus

$$F_t^* = \gamma R_t (L_t^*)^\alpha = \gamma^{\frac{1}{1-\alpha}} \left(\frac{\alpha}{\eta}\right)^{\frac{\alpha}{1-\alpha}} R_t^{\frac{1}{1-\alpha}} = \phi(\min\{r_t, d_t\} - c)^{\frac{1}{1-\alpha}} \tag{8}$$

[11] In order to save notation, we will not mention this drastic possibility in all equations below.

where $\phi = \gamma^{\frac{1}{1-\alpha}} \left(\frac{\alpha}{\eta}\right)^{\frac{\alpha}{1-\alpha}} > 0$.

7.3 Costly signaling

The household migration decision is the third stage, but we will nonetheless analyze this stage already here since the elite rationally takes household behavior into account in the second stage. The migration decision determines the total population in the city next year, $\bar{L}_{t+1}$. We assume that there are numerous other localities to migrate to or from and that the aggregate level of available household labor in year $t+1$ is given by a welfare function ω of two factors: Expected levels of food production next year $E_t(F^*_{t+1})$ and the number of monuments constructed during the present year t, M_t (like lintels, stelae, ballcourts):

$$\begin{aligned} \bar{L}_{t+1} &= \omega(E_t(F^*_{t+1}), M_t) = \omega(\phi E_t(R_{t+1})^{\frac{1}{1-\alpha}}, M_t) = \\ &= \omega(\phi(\min\{r, d_t(1-\delta) + I^d_{t+1}\} - c)^{\frac{1}{1-\alpha}}, M_t) \end{aligned} \tag{9}$$

Note that the expression makes use of the optimal labor supply in eq. (7) and the facts that $E_t(r_{t+1}) = r$ and $E_t(d_{t+1}) = d_t(1-\delta)+I_{t+1}$. We assume that $\omega(0, M_t) = 0$ and that $\omega(E_t(F^*_{t+1}), 0) > 0$. This implies that a positive expected level of food production is essential for anyone to inhabit the settlement but that monuments are not essential in the same way. We further make the standard assumption that the marginal welfare from food and monuments are such that partial derivatives are $\omega_F > 0$ and $\omega_M > 0$. This *bread and circuses*-assumption in our model, that city populations are attracted in their decision of where to live by both food and monuments, is a novelty in the literature, as far as we can tell, and we will therefore motivate it below.

We argue that there are several reasons why it is necessary to consider a broader set of motivations for people's historical choice of location than just the availability of food and other basic goods. First, we know from the archaeological and historical records that erecting public monuments like obelisks, statues, and community houses have an important role for fostering in-group identity, providing ritual services, and for enhancing social capital in general (Flannery and Marcus, 2012; Olsson, 2024). Second, in large communities with tens of thousands of citizens where citizens do not personally know their ruler, monuments can serve as a signalling device of ruler capacity. Monuments often signal ruler capacities in several dimensions such as control of artistic talent, military prowess, access to valuable materials, generosity, discipline, and connections to divine powers. The signaling is costly since the opportunity cost of monument construction is investments in infrastructure which have a direct positive effect on the population's production potential and hence their fitness (Trigger, 1990; Neiman, 1997; Bliege Bird and Smith, 2005). Third, we know from numerous sources how rulers throughout history used bread and circuses strategically for pacifying large urban populations, most famously in Rome but also in many other places.

After the actual weather outcome has been realized, household labor in food production has been allocated, and harvests have been made, but before people make their migration decision, the ruling elite in the second stage consider what to do with the (corvée) surplus labor from the citizens that they control and which is now observable. We assume that the goal of the ruling elite at time t is simply to amass as many citizens as possible in their city during next period, i.e. to maximize $\bar{L}_{t+1}$. They can do so by either directing work to increase maximum reservoir capacity in the next period $\bar{R}_{t+1}$ or by constructing monuments M_t. Knowing the populations' reaction function to their decisions in eq. (9) in the third stage, the ruling elite maximizes its own welfare in the second stage (by backward induction). The corvée labor that it has at its disposal is the aggregate labor surplus from agriculture, i.e. the total labor available minus agricultural labor supply:

$$\begin{aligned} L_{t+1}^c =& \bar{L}_{t+1} - L_{t+1}^* = \omega(\phi E_t(R_{t+1})^{\frac{1}{1-\alpha}}, M_t) - \left(\frac{\alpha\gamma R_{t+1}}{\eta}\right)^{\frac{1}{1-\alpha}} = \\ &= \omega(\phi(\min\{r, d_t(1-\delta) + I_{t+1}^d\} - c)^{\frac{1}{1-\alpha}}, M_t) - \left(\frac{\alpha\gamma}{\eta}\right)^{\frac{1}{1-\alpha}} (\min\{r_{t+1}, d_{t+1}\} - c)^{\frac{1}{1-\alpha}} \geq 0 \end{aligned} \tag{10}$$

The expression has a number of implications. A key general insight from eq. (10) is that the size of the corvée labor force L_{t+1}^c increases with the expected level of rain r but has a negative association with contemporary actual rainfall r_{t+1}. The intuition is simply that more expected rain (given by the prevailing *climate*) at the settlement increased the size of the labor force that chose to live there in the previous period whereas more actual contemporary rain (i.e. determined by the *weather*) with a given labor force, increases agricultural productivity and pushes workers into farming activities, which means that less labor is left for public goods provision. Note further that if $L_{t+1}^* = \bar{L}_{t+1}$, then $L_{t+1}^c = 0$. This might happen during years with exceptionally abundant rain. $L_{t+1}^c = 0$ would also occur during extremely low levels of water access when $E(F^*) = 0$ so that $\bar{L}_{t+1} = 0$.

7.4 Public goods provision

How will the ruler use the corvée labor L_{t+1}^c in order to maximize $\bar{L}_{t+1}$ in eq. (9)? Our assumption above was that such labor can be used either for reservoir infrastructure investments I_{t+1}^d that increase reservoir depth in $t+1$, or for monument construction in t. Only I^d_{t+1} contributes to the material living standards of the population (i.e. the *bread* of the population) but M_t is still valuable as a distraction of the population and as a signaling device for the capacity of the ruler (i.e. *circuses*). We also assumed above that all investments $I^d_{t+1} > 0$ were lumpy in character and associated with adjustment costs, whereas M_t was like a normal status good that might come in any amount.

Let us capture these characteristics in a simple way by assuming that investment that increases reservoir capacity in the coming period can be made in line with a linear function $I^d_{t+1} = \lambda L^c_t$ if $L^c_t \geq L^I_{min}$ where $L^I_{min} > 0$ is the minimum size of corvée labor that can carry out a complicated large-scale water infrastructure investment such as dredging the reservoir. Regarding M_t, we propose a similarly simple production function such that $M_t = L^c_t$. Furthermore, during a given year, L^c_t can be devoted *either* to reservoir investment or monument construction.

The optimal choice of whether to devote labor to I^d_{t+1} or to M_t for the maximization of $\bar{L}_{t+1}$, thus boils down to four potential outcomes:

Proposition 1 *The optimal monument or water infrastructure construction activities are as follows:*

$$\begin{aligned} &\textit{(i)} \quad M^*_t = 0, \quad I^*_{t+1} = 0 \quad \textit{if} \quad L^c_t = 0 \\ &\textit{(ii)} \quad M^*_t = L^c_t > 0, \quad I^*_{t+1} = 0 \quad \textit{if} \quad L^c_t > 0, \quad d_t(1-\delta) > r \\ &\textit{(iii)} \quad M^*_t = L^c_t > 0, \quad I^*_{t+1} = 0 \quad \textit{if} \quad L^c_t \in (0, L^I_{min}), \quad d_t(1-\delta) < r \\ &\textit{(iv)} \quad M^*_t = 0, \quad I^*_{t+1} = \lambda L^c_t > 0 \quad \textit{if} \quad L^c_t \geq L^I_{min}, \quad d_t(1-\delta) < r \end{aligned} \tag{11}$$

The proof of this proposition follows from logical deduction on the basis of eq. (10)

In the top row (i), $L^c_t = 0$ might for instance happen if optimal labor allocation to food production was unexpectedly high due to heavy rainfall ($r_t > r$) that could still be captured by the reservoirs if $r_t < d_t$. During such good years, the population is occupied with food production, need no distractions, and rulers optimally provide no public goods. It could also happen in a year when water access is so low that $E(F^*) = 0$ and the whole community has collapsed.

In case (ii), we have what we believe was the standard situation during the Classic Maya period: Some available labor surplus from food production and a deep enough reservoir so that there is no expected utility gain from investing in I_{t+1} since it will not affect the expected level of water in the reservoir and neither therefore people's migration choice. In this case, the utility maximizing choice is to allocate all surplus labor to monument construction.

In case (iii), reservoir capacity is low and rainfall is expected to overflow next year ($d_t(1-\delta) < r$). This speaks for organizing a collective dredging effort $I_{t+1} > 0$ but this will still not be optimal since the available level of corvée labor is too low for such a major effort: $L_t^c < L_{min}^I$. The elite therefore needs to bide their time until a future year with little rain and a greater available supply of corvée labor. This latter scenario ultimately materializes in the fourth row (iv), when $L_t^c \geq L_{min}^I$ and $d_t(1-\delta) < r$. The collective dredging effort will then finally be carried out, which increases next year's reservoir capacity d_{t+1}.

In our empirical analysis, we do not have systematic data on reservoir investments but only on monument construction. If we focus on the second row in eq. (11), with available corvée labor and a decent reservoir capacity, the optimal level of monument construction will be:

$$M_t^* = L_t^c = \omega(\phi(r-c)^{\frac{1}{1-\alpha}}, M_{t-1}) - \left(\frac{\alpha\gamma}{\eta}\right)^{\frac{1}{1-\alpha}} (\min\{r_t, d_t\} - c)^{\frac{1}{1-\alpha}} \tag{12}$$

Since M_t is a linear function of L_t^c, we will have the important result below:

Proposition 2 *Given $L_t^c > 0$ and $d_t(1-\delta) > r$, the (intensive margin) level of monument construction M_t^* has a negative relationship with contemporary rainfall r_t for all rain levels $r_t < d_t$.*

The proof of this proposition is straightforward from visual inspection of eq. (12).

The intuition behind this result is, once again, that lower rainfall frees up labor from agriculture into public goods provision. When rains are expected to be lower than reservoir capacity, the ruling elite have no incentives for reservoir investments and optimally only invest in monuments that contribute to attracting a greater population in the next period.

We argue that this is indeed the main and most plausible reason for the negative short-run (intensive margin) relationship between our historical proxies for rain and monument construction that we observed in the empirical section. However, it is also noteworthy that long-run climate change, manifested in movements in expected rainfall r, has a positive relationship with M_t. The intuition is simply that more expected rain will attract people to move to the city, which means a larger work force to employ. Hence, somewhat paradoxically, the short-run (weather) effect of r_t on M_t is negative while the long-run climatic effect of r is positive.

After these decisions regarding public goods provision by the ruling elite, people react by moving to or leaving the city in the third stage. In $t+1$, the sequence of stages is then repeated and a population of size L_{t+1} observe weather shocks and the state of the reservoir and decide on labor supply to agriculture (stage 1), the ruling elite uses surplus labor for public good provision (stage 2), and the population makes migration decisions (stage 3).

7.5 Extension: Climate change

Let us now consider a scenario where the actual climate shifts for an extended time period so that the distribution of precipitation moves to the left, resulting in a lower mean level $r_{low} < r$. Such a change will in most periods lead to lower levels of annual rainfall r_t. However, given that the Maya population does not have perfect foresight, it should take some time before they realize that the climate has truly changed. As long as their expectation is $E_t(r_{t+1}) = r$, then $\bar{L}_{t+1}$ in eq. (10) will remain relatively high since people expect rains to return, whereas L^*_{t+1} will be low due to the low actual rains, resulting in a persistently large corvée labor force L^c_{t+1}. This high level of corvée labor increases the likelihood of case (iv) in Proposition 1, i.e. that $L^c_t \geq L^I_{min}$ and that the elite choose to invest in water infrastructure although it is not really necessary. After such an investment, case (ii) will be the most likely outcome with a high L^c_t and a high d_t, resulting in an intense period of monument construction. According to eq. (12), an initial phase of a more adverse climate will thus be characterized by a flurry of monument construction activity.

Eventually, depending on the exact assumptions regarding the updating of expectations, the accurate expectation $E_t(r_{t+1}) = r_{low}$ should prevail. When that new expectation sets in, population's belief in future food production capacity will fall and people will start leaving the city. Also reservoir capacity d_t will fall below (r_{low}). Even relatively normal higher levels of rain would then go to waste. Before that shift in climatic occurred, this would have resulted in a corvée labor force of a minimum size L^I_{min} was put to work in renewed dredging efforts. But if it is obviously the case that the largest possible remaining corvée labor force will always be lower than the minimum required for water infrastructure investments, then people should foresee that no future improvements will occur. When the community deteriorates into an expectation $E_t(F^*_{t+1}) = 0$, the settlement is abandoned.

In the short run, several years of drought in the wake of a long-term shift in climate towards lower precipitation, might thus initially result in people staying and being engaged in intense monument construction activity since the state elite could not keep their population busy in any other way. Eventually, the situation would nonetheless become unsustainable and result in a breakdown of the social contract between city elite and population. We propose that this scenario bears some resemblance to the initial years of the great drought around 830 CE in Figure 3, where a relatively high level of monument construction activity was kept up through the 850s, before it finally crashed in the late 800s. The uniquely long duration of the climate deterioration in the 800s, most likely contributed importantly to this collapse. We suggest the interpretation above effectively reconciles our theoretical model and the evidence in our empirical analysis with the argument in Kennett et al. (2012) on the detrimental effects of the extended 9th century drought on Classic Maya society.

7.6 Discussion

How generally applicable is this analysis to what we know about other early state societies? We believe our empirical analysis and theoretical model are most closely related to the city-state environment in the third millennium BCE in Mesopotamia.[12] In their analysis of random shifts in the flow of the Euphrates and Tigris, Allen et al. (2023) find that river shifts away from a settlement unleashed a "demand-driven" provision of public goods such as canals, defensive walls, ziggurats and temples. The authors interpret this evidence as demonstrating that random shocks to water access appear to have effectively caused the origins of a new type of state organization. Our analysis has similar implications in the sense that negative shocks to water access appears to have increased the intensity of monument construction among the Maya. Defensive walls became more common during such times in Mesopotamia and war-related messages became more common among the Maya. Unlike Allen et al. (2023), our analysis focuses on the distinction between productivity-enhancing and non-productivity-enhancing public goods.

The setting in the Maya Lowlands was quite different in several ways from territorial early states such as Ancient Egypt. Building on Carneiro (1970), several studies argue that the environmental circumscription of the entire Nile Valley and the more predictable floods, fostered the emergence of a single unitary state that extracted tributes from the population on the basis a highly transparent and appropriable agricultural production of wheat and barley (Allen, 1997; Mayshar et al., 2017; Mayoral and Olsson, 2024). Mayoral and Olsson (2024) show that political stability was stronger in years with favorable Nile floods, suggesting that the strength of a centralized Egyptian state was mainly determined by "supply-side" conditions. In the Maya Lowlands, on the other hand, mobility between independent cities was substantial, long-term storage of maize harvests was not feasible, and monument construction was more intense during droughts.

In summary, these cases clearly indicate the importance of carefully taking into account the details

[12]The city states of ancient Greece and Italy before the dominance of Rome, are potentially also relevant for comparison with the Maya Lowlands, but we do not yet have suitable data for an analysis of weather shocks and monument construction in those environments.

of environmental settings to understand the nature and mechanisms of public goods provisioning in early states.

8 Conclusion

In this paper, we explored two main research questions: How was the tradeoff between productivity-enhancing public goods such as irrigation infrastructure, and monumental architecture such as temples and statues, determined in early states? The common provision of the latter type of ”wasteful” public goods does not square well with models in economics and biology emphasizing the evolutionary advantages of an efficient food production and physical fitness for the long-term survival of societies. How was this tradeoff, in turn, affected by short-run weather shocks and long-term climate change?

Using the Classic Maya as a case study, we revisited existing data on dated monument construction among 110 Maya urban settlements during 250-950 CE and combined it with novel data on the content of messages on Maya monuments and a new paleoclimatic proxy for rainfall variation. Our results show that monument construction activity was more prevalent during years of drought and that droughts were also associated with more intense use of war-related terms. settlements with relatively low mean levels of rainfall and connections to neighboring communities, appeared to have entered their terminal decline later. In our theoretical model, we argue that monumental architecture had the primary role of signalling state capacity and in-group identity to the highly mobile city populations of Maya society. These results have similarities with recent findings from ancient Mesopotamia and suggest that state elites were became more active in difficult times. More research on similar historical settings should be able to shed light on whether this was indeed a universal phenomenon among decentralized historical polities.

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Appendices

A Water balance equation

Given the central role of water management in this study, it is useful to consider the Maya hydraulic system in some detail. A natural point of departure is a standard water balance equation for a water system, adapted to describe a water reservoir:

$$\Delta R_t = R_t - R_{t-1} = P_t - F_t - E_t - C_t^w \tag{13}$$

In this equation, R_t is the level of water storage in the reservoir at the end of year t, P_t is precipitation during t, F_t is net streamflow and seepage (outflow minus inflow), E_t is annual evaporation, and C_t^w is human water consumption during t. Precipitation is measured as annual precipitation (in mm) multiplied by area of the water reservoir surface. If, for instance, the area of the reservoir surface is 1 hectare (100*100 m) and annual rainfall is 2000 mm (a common level in Yucatan), then the amount of water that recharges the reservoir through precipitation during a year is 10,000*2 m=20,000 m^3. Net streamflow F_t will usually be positive or zero at hilltop reservoirs (where outflow downwards exceeds inflow) and negative at lower reservoirs. Through the construction of sluice gates and canals at hilltop reservoirs, the Maya had a certain degree of control of the flow downwards. Periods or instances with extraordinary rainfall (such as associated with tropical storms or hurricanes), hilltop reservoirs will be inundated and there will be an inevitable spontaneous outflow. In a stable and sustainable reservoir system, F_t should be close to zero.

Evaporation E_t is very high in tropical environments such as Maya Lowlands, in particular during the warm season. The level of evaporation can be modelled as a fraction of the existing level in the reservoir such that $E_t = eR_t$ where $0 < e < 1$ is the evaporation rate. This rate will depend on several factors, such as exposure to sun, temperature, and the relative size of the surface area to total volume. For simplicity, we assume that the rate is fixed here. Human water consumption C_t^w satisfies two basic needs: Direct household usage (for drinking, cleaning, etc) and for watering trees and crops cultivated for food production. Generally, variations in water demands over time should be proportional to the level of the population but it should also be relatively smooth over time since it is a very basic commodity. In the short run (from one year to the next), water household consumption levels should be close to constant.

In line with the assumptions above, we can rewrite the dynamic equation in 13 into a simplified expression for the level of reservoir water at each point in time:

$$R_t = P_t + R_{t-1}(1 - e) - C_t^w \tag{14}$$

The feasible levels of water in the reservoir system are further bounded from below at 0 and from above at some maximum level $\bar{R} > 0$.

Kuil et al. (2016) have estimated annual evaporation rates in the Maya area to be quite high, around 0.4. Hence, the persistence of water in the reservoir system is not very strong. For instance, after five years, only 7.8 percent of a cubic meter of water would not have evaporated ($(1-0.4)^5 = 0.078$). Furthermore, since annual human water consumption C_t^w is likely to be more or less constant from one year to another, the main source of intertemporal variation in reservoir levels at the end of year t is simply the annual level of precipitation P_t. Hence, we should expect to find a relatively rapid turnover in reservoir levels in response to rainfall shocks.

B Additional tables and figures

From the panel specification in eq. (1), is is possible to predict the settlement fixed effects $\bar{\eta}_i$ which should summarize a lot of information about fixed settlement characteristics that are relevant for understanding the average level of monument construction at the settlement. In order to account for this information, we also run a "second-stage" cross-sectional regression of the form

$$\bar{\eta}_i = \omega + \kappa \bar{P}_i + \theta X_i + \epsilon_i.$$

In this equation, $\bar{P}_i$ is average contemporary precipitation levels, as above, and X_i is a vector of fixed geographical characteristics of each settlement, including for instance latitude, longitude, distance to nearest neighbor settlement, elevation and slope characteristics. Table B3 below shows the results from these regressions.

Table B1: Description of variables

Monument variables:

Mon. dummy: Dummy = 1 in period with any monument in settlement (i) or in whole region (Kennett et al., 2012)

Log Monuments: Log of number of monuments (+1) in settlement (i) or in whole region (Kennett et al., 2012)

Dummy for type of inscription : Dummy = 1 for period with any monument in whole region with inscriptions related to religion, war, politics, or agriculture. Based on data from Looper and Macri (2024).

Proportion of inscriptions: Proportion (in percent) of all inscriptions of the four categories of inscriptions related to religion, war, politics, or agriculture, during a particular year. Based on data fron Looper and Macri (2024).

Type of monuments: Number of monuments categorized as having a purpose related to religion, war, community, or infrastructure in the whole region. Based on data from Looper and Macri (2024).

Last period with monument: Last year of any monument (in CE years) among 52 Maya settlements, including those with more than one year with monument construction and with a terminal period later than 600 CE (Kennett et al., 2012)

Climate variables:

Rain index: Normalized, continuous rain index over 250-950 CE for the Maya Lowlands where 1 indicates highest and 0 lowest rain levels. Based on interpolated $\delta^{18}O$-data from Macal Chasm (Akers et al., 2016).

Drought: Dummy = 1 in period with lowest 10 percent observations of Rain index, based on Akers et al. (2016).

Flood: Dummy = 1 in period with top 10 percent observations of Rain index, based on Akers et al. (201

$\delta^{13}C$ **(Macal Chasm)**: Interpolated carbon isotope ratio-series based on data from Macal Chasm (Akers et al., 2016).

Rain index MA: Five-year, retrospective moving average of Rain index for Maya Lowlands $(\tau - 4, \tau)$, based on $\delta^{18}O$-data from Macal Chasm (Akers et al., 2016).

$\delta^{18}O$ **(Yok Balum)**: Interpolated oxygen isotope ratio-series based on data from Yok Balum (Kennett et al., 2012).

Geographical variables:

Rain annual (mm): Average total annual precipitation levels (in mm) in 1900-2015 CE across Maya settlements. Based on data from the University of Delaware Terrestrial Precipitation data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov

Rain wet season (mm): Average total annual precipitation levels (in mm) for May-September in 1900-2015 CE across Maya settlements. Based on data from the University of Delaware Terrestrial Precipitation data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov

Temperature (mean C): Mean contemporary annual temperature across Maya settlements. Based on data from the University of Delaware Terrestrial Precipitation data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov

Elevation 1 and 5 km (m): Elevation over sea level in a 1 km or 5 km circle around centroid at settler (in m) across Maya settlements. Based on data from the Spatial Data Access Tool (SDAT) from NASA. We rely on the Shuttle Radar Topography Mission (SRTM) Near-global Digital Elevation Models (DEMs) https://webmap.ornl.gov/wcsdown/dataset.jsp?dg$_i d = 10008_1$

Slope 1 and 5 km: Slope (or "hillyness") measure across Maya settlements in a 1 km or 5 km circle around centroid. Based on data from the Digital Evelavation Database from NASA https://srtm.csi.cgiar.c

Distance to neighbors (km): Total distance to five nearest settlements (in km) across Maya settlements was calculated using ArcGis.

Latitude and Longitude: Latitude and longitude degree of Maya settlements come from geo-referenced work by Ebert and Kennett. (2012) on 91 Mayan sites, for the rest of the sites we have geo-referenced them manually in Google Earth(map)

Note: This table provides definitions of variables included in the empirical panel and time series samples with primary data sources in parenthesis.

Table B2: Descriptive statistics

	N	Mean	St. dev	Min	Max
Panel variables					
Mon. dummy	15,400	0.033	0.179	0	1
Monuments	15,400	0.054	0.380	0	16
Log Monuments	15,400	0.029	0.171	0	2.83
Rain index	15,400	0.404	0.195	0	1
Int. Rain index x Annual rain	15,400	95.49	54.43	0	365.5
Drought	15,400	0.093	0.290	0	1
Flood	15,400	0.079	0.269	0	1
$\delta^{13}C$ (Macal Chasm)	15,400	-9.11	1.77	-12.18	-5.12
Aggregate time series variables					
Log Monuments	700	0.411	0.072	0	3.37
Rain index	700	0.447	0.179	0	1
Rain index MA	700	0.446	0.168	0.046	0.971
$\delta^{13}C$ (Macal Chasm)	700	-9.11	1.831	-12.4	-4.9
$\delta^{18}O$ (Yok Balum)	700	-3.86	0.257	-4.47	- 3.35
Dummy for type of inscription: Religion	140	0.664	0.474	0	1
Dummy for type of inscription: War	140	0.421	0.496	0	1
Dummy for type of inscription: Politics	140	0.493	0.502	0	1
Dummy for type of inscription: Agriculture	140	0.471	0.501	0	1
Proportion of inscriptions: Religion	140	9.852	11.593	1	100
Proportion of inscriptions: War	140	0.950	2.401	0	20
Proportion of inscriptions: Politics	140	1.444	2.179	0	13.65
Proportion of inscriptions: Agriculture	140	1.109	1.710	0	8.71
Number of monuments: Religion	140	3.14	4.63	0	26
Number of monuments: War	140	0.01	0.084	0	1
Number of monuments: Community	140	1.42	3.30	0	22
Number of monuments: Infrastructure	140	0.107	0.45	0	4
Settlement-specific variables					
Last year monument	52	810	57.67	670	995
Rain annual (mm)	109	2266.8	709.0	852.8	3774.4
Rain wet season (mm)	109	1943.4	126.6	1371.5	2344.5
Temperature (mean C)	109	25.31	1.73	17.45	28.06
Temperature wet season (mean C)	109	24.13	1.56	16.5	28.5
Elevation 1 km	110	256.8	326.7	0	1572
Elevation 5 km	110	261.8	325.0	0	1600.7
Slope 1 km	110	3.72	3.36	0	14.99
Slope 5 km	110	3.82	3.35	0	20.93
Distance to neighbors	110	38.28	26.78	10.80	189.4
Latitude	110	17.56	1.54	14.46	21.52
Longitude	110	-89.95	1.00	-92.50	-87.71

Table B3: Accounting for settlement fixed effects in monument construction

	Dependent variable: Predicted settlement FE		
	(1)	(2)	(3)
Rain annual (mm)	-0.000	-0.000	
	(0.000)	(0.000)	
Rain wet season (mm)			0.000
			(0.002)
Temperature (mean C)	0.026	0.117**	
	(0.047)	(0.052)	
Temperature wet season			0.084
			(0.209)
Elevation 1 km		0.001*	
		(0.000)	
Elevation 5 km			0.001*
			(0.000)
Slope 1 km		-0.055*	
		(0.030)	
Slope 5 km			-0.057**
			(0.027)
Distance to neighbors (km)		0.001	0.001
		(0.003)	(0.003)
Latitude		-0.125	-0.078
		(0.082)	(0.077)
Longitude		-0.078	-0.066
		(0.082)	(0.087)
Settlements	109	109	109
R-squared	0.01	0.09	0.07

Note: The table presents OLS results using the generated fixed effects from column 6, Table 2 as the dependent variable in a cross-section of 109 settlements. Included geographical and climatological covariate variables are discussed in text. Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1.

Table B4: Accounting for lags in Rain index

	Dependent variable: Log Monuments (t)			
	(1)	(2)	(3)	(4)
Rain index (t)	-0.024***	-0.024***	-0.013	-0.016*
	(0.009)	(0.009)	(0.009)	(0.009)
Rain index ($t-1$)	-0.016*	-0.007	-0.009	-0.008
	(0.009)	(0.009)	(0.010)	(0.010)
Log Monument lags	0	1	4	4
Settlement FE	Yes	Yes	Yes	Yes
Non-linear trends	No	No	No	Yes
Observations	15,400	15,400	15,400	15,400
settlements	110	110	110	110

Note: The table presents the within estimates of our Rain index and lagged Rain index on Log Monument construction for 110 Maya settlements over 140 5-year periods during 250-950 CE. Number of included lags of the dependent variable are indicated in all columns. Standard errors, clustered at the settlement level, are in parentheses. In each specification, we control for a full set of settlement fixed effects and for non-linear time trends in columns (2) and (6). *** p<0.01, ** p<0.05, * p<0.1.

Table B5: Number of monuments as dependent variable

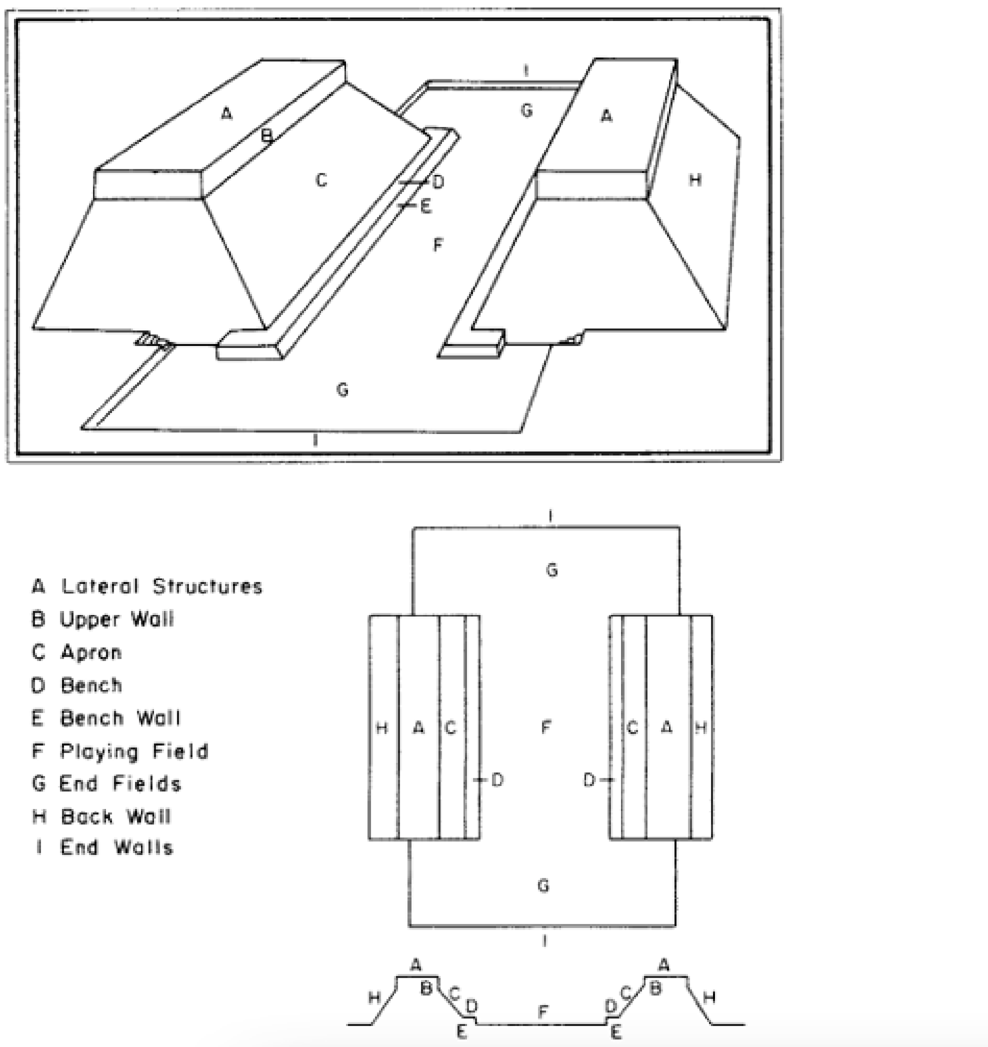
	Dependent variable: Monuments			
	(1)	(2)	(3)	(4)
Rain index (t)	-0.063***	-0.048***	-0.033***	-0.035***
	(0.013)	(0.011)	(0.009)	(0.009)
Monument (t-1)		0.321***	0.229***	0.228***
		(0.092)	(0.080)	(0.080)
Monument (t-2)			0.204***	0.203***
			(0.037)	(0.037)
Monument (t-3)			0.003	0.001
			(0.027)	(0.026)
Monument (t-4)			0.137***	0.135***
			(0.047)	(0.047)
Settlement FE	Yes	Yes	Yes	Yes
Non-linear trends	No	No	No	Yes
Observations	15,400	15,400	15,400	15,400
Settlements	110	110	110	110

Note: The table presents OLS results using the generated fixed effects from column 4, Table 3 as the dependent variable in a cross-section of 110 settlements. Included geographical and climatological covariate variables are discussed in text. Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1.

Figure B1: Example of Maya glyph from Palenque

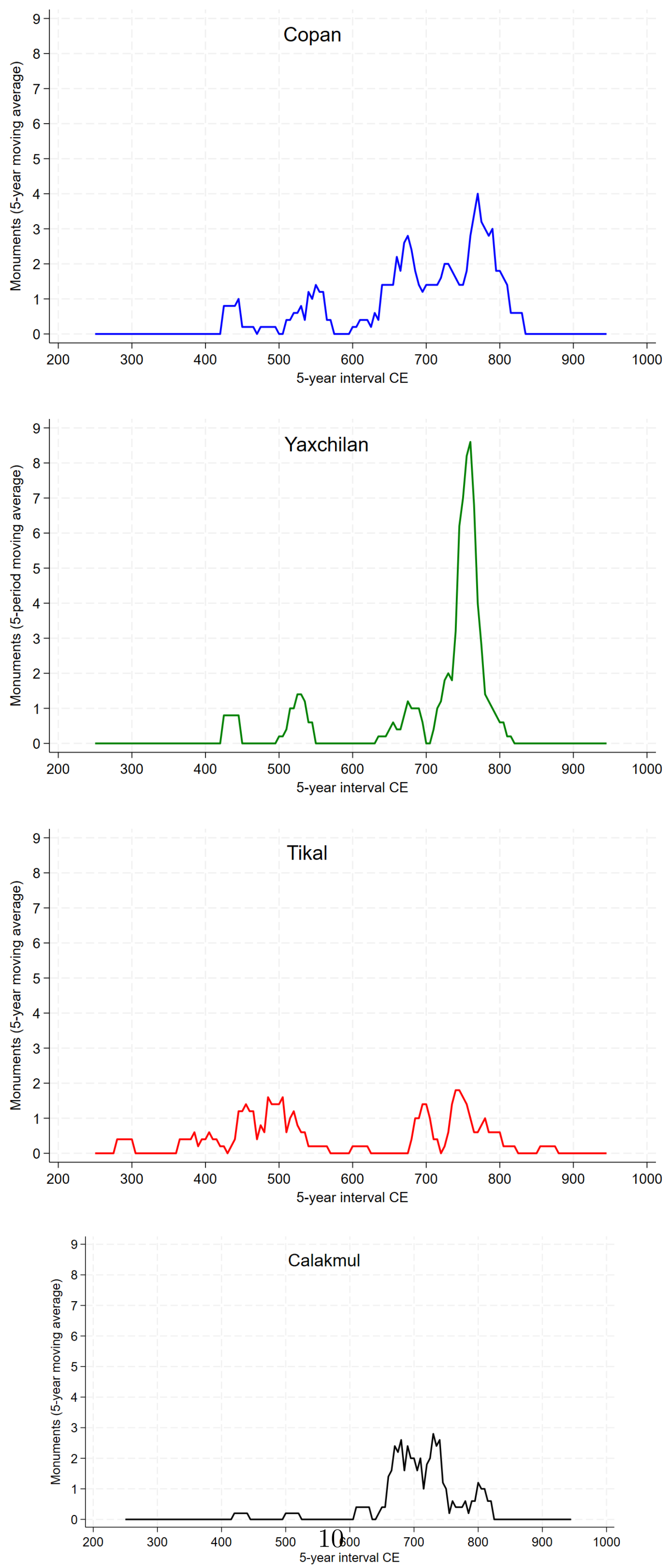
The picture shows an example of Maya glyphs from Palenque. Source: Palenque Site Museum Alberto Ruz LHuillier

Figure B2: Structure of a ball court



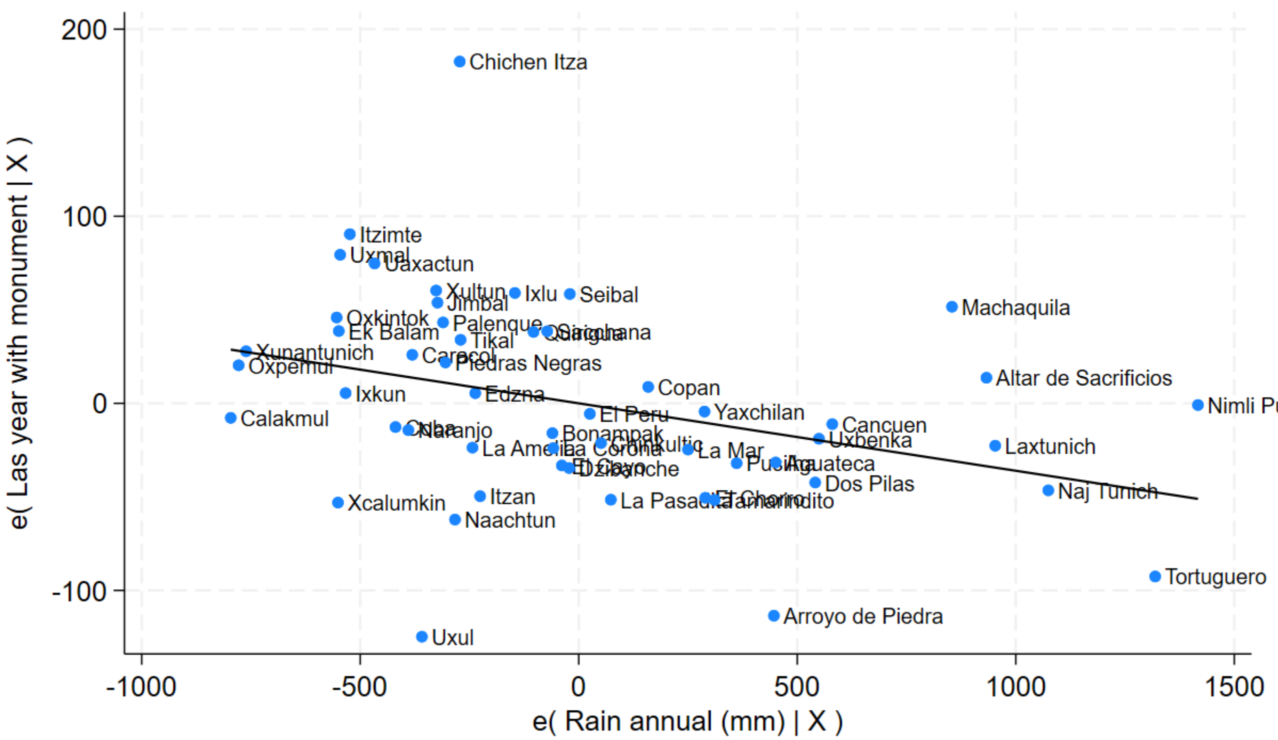
Source: Taladoire (2001)

Figure B3: Monument construction over time in four major settlements



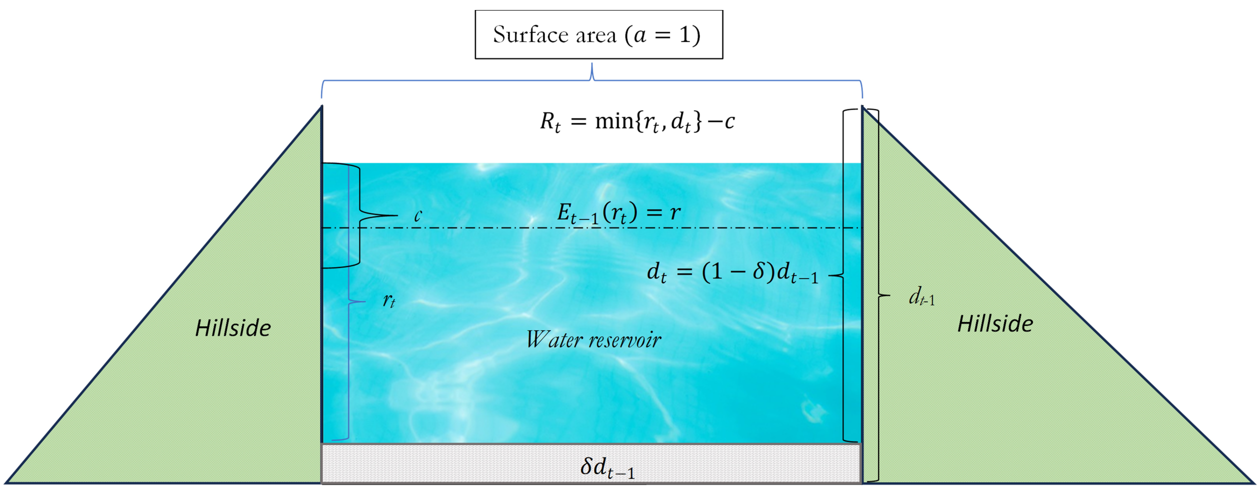
The figure shows a 5-period (25-year) moving average in monument construction in the four settlements with

Figure B4: Residual scatter plot Last year with monument vs Rain annual



The figure shows the partial residual scatter plot with Last year monument as the dependent variable and Rain annual as the covariate variable, from the specification in Table 8, column 3. The sample includes 52 Maya settlements with monument construction for more than a single year and Last year monument exceeding 600 CE.

Figure B5: Illustration of stylized water reservoir



The figure shows a stylized reservoir including the assumptions in the text.