Rainfall and circular moated sites in north-east Thailand

Glen Scott & Dougald O'Reilly*

The existence of moated mounds in the archaeological record of north-east Thailand has long been known, the majority constructed during the earlier first millennium AD. Despite considerable research, the purpose of the substantial and sometimes multiple moats surrounding raised occupation mounds has remained a mystery. Combining locational, hydrological and rainfall data with the archaeological evidence, this study of the moated mounds of the Khorat Plateau seeks to resolve the question through statistical analysis. The results suggest that water storage may have been the primary purpose of the moats, enabling communities to survive dry seasons and droughts.

Keywords: Thailand, Iron Age, moat, rainfall, water management, irrigation, statistical analysis

Introduction

Irregular mounds surrounded by moats and embankments were first noted in north-east Thailand over a century ago (Damrong Rajanubhap 1995). Since then these sites have continued to be the focus of archaeological interest (Williams-Hunt 1950; Vallibhotama 1984; Moore 1988; Welch 1989; Higham 1998, 2014; Talbot & Janthed 2001). The sites typically include a raised occupation mound surrounded by at least one moat (often as wide as *c.* 100m) and a raised embankment. Some sites have up to five encircling moats and embankments. One hundred and fifty-one of these sites have been identified by several projects since 1950 (Williams-Hunt 1950; Vallibhotama 1984; Moore 1988; Welch & McNeill 1988–89; Higham 1998; McGrath & Boyd 2001; Talbot & Janthed 2001; Higham 2011) but a further 146 sites are now known (Scott 2013; O'Reilly & Scott 2015). The majority were constructed in the mid- to late Iron Age (*c.* AD 1–600) (McGrath & Boyd 2001), although some were first inhabited during the Bronze Age (*c.* eleventh

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century BC) and at least one is known to have been occupied during the Neolithic period (*c.* seventeenth century BC) (McGrath & Boyd 2001; Higham & Kijngam 2013). At these early sites, however, the moats were later additions constructed during the Iron Age phases of occupation.

Despite considerable research (Vallibhotama 1984; Moore 1988; McNeill & Welch 1991; Higham 1998), the purpose of the moats remains unresolved. Here we present evidence of a correlation between the location and morphology of these sites and rainfall patterns, which suggests that moats and embankments were created to retain water. We will begin by discussing the geography and hydrology of the Khorat Plateau in north-east Thailand before offering a brief review of recent research that has identified many more moated sites on the plateau than were previously known. The methodology for assessing the distribution of moated sites will then be outlined; this is based on statistical analyses that incorporate rainfall patterns and variables including site size, location and the number of moats surrounding a site. Finally we present our interpretation of the data.

Geography and hydrology of the Khorat Plateau

The Khorat Plateau of north-east Thailand covers an area of 170 226km^2 (Moore 1988: 13) and is bounded on the west by the Phetchabun Mountains and to the south by the Dangrek Mountains (Figure 1). The Phetchabun Mountain range reaches a height of 1780m and produces a rain shadow effect over the western parts of the Plateau (Riethmuller 1988: 78; Supapoj *et al.* 1998: 162). The Khorat Plateau comprises two major drainage basins: the Sakon Nakhon Basin to the north and the Khorat Basin to the south. The vast majority of moated sites are found in the Khorat Basin, which is drained by the Mun and Chi rivers. These flow eastward to join the Mekong River, which forms the eastern and northern boundaries of the Plateau. The geography of the Mun and Chi valleys is characterised by broad, gently sloping floodplains. Precipitation on the Khorat Plateau increases in volume from west to east, ranging from an annual average of 1000–2400mm. Modern rainfall data are generally applicable to the past due to evidence of broad consistency in weather patterns in this region since the Iron Age (Riethmuller 1988: 78; Kealhofer & Penny 1998: 91; Boyd & McGrath 2001: 309; Penny 2001: 126; Maxwell 2004: 235). Data collected between 1981 and 2010 indicate that the western portion of the Khorat Plateau

Figure 1. Map of Southeast Asia with survey area marked (image from National Geographic, Esri).

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receives an average 1200mm less precipitation than the east (Figure 2). Rainfall is heaviest during the wet season, between May and September (Supapoj *et al.* 1998: 162), but annual fluctuations in the duration and intensity of the wet season are well documented and can have a significant impact on crop yield (Paul 1984; Bruins *et al.* 1986; Parnwell 1988; Fox & Ledgerwood 1999).

Much of the research focused on the Khorat Plateau has aimed to understand alterations in the hydrology of the Plateau throughout the Holocene (Boyd & McGrath 2001; McGrath & Boyd 2001: 360; Boyd 2007; Boyd & Habberfield-Short 2007; McGrath *et al.* 2008). Boyd and McGrath (2001: 309) have noted that the current hydrology of the region is very different to that of the early Holocene. It is accepted that at the beginning of the Iron Age (*c.* 2500 years ago), the Khorat Plateau shifted from a system of deep, single-channel waterways to one of multiple short-lived, narrow and shallow drainage channels (Boyd & Habberfield-Short 2007: 24–25). This is cited as evidence for a decline in rainwater run-off and the beginning of a climate similar to that of the present day, with a marked difference between dry and wet seasons (Boyd & Habberfield-Short 2007; McGrath *et al.* 2008). This environmental change is supported by recent oxygen isotopic research (King *et al.* 2013). Samples were taken from human dental enamel sourced from burials at Ban Non Wat to indicate the level of fractionation occurring in the water during the Iron Age (King *et al.* 2013: 1684). The results of the analysis showed an increase in δO^{18} since the Iron Age, which reflects a drier environment with higher levels of water lost through evaporation (King *et al.* 2013: 1888).

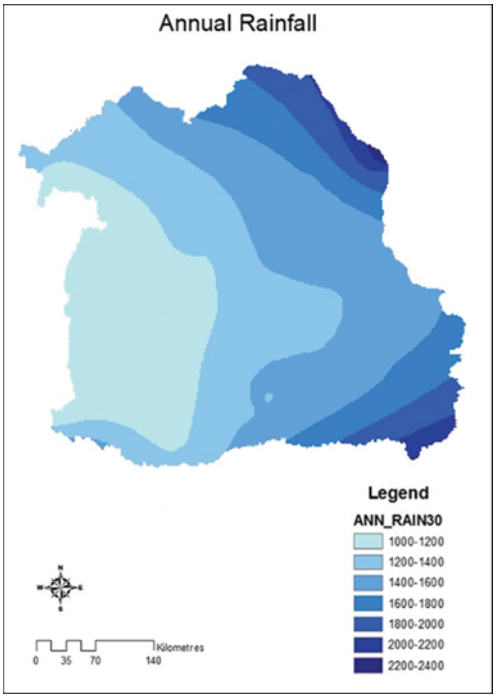

Figure 2. Annual rainfall distribution in the Khorat Plateau; average rainfall recorded from 1976–2004 (GIS data from the Thai Meteorology Department).

Recent research identifying moated sites

Building on the work undertaken by previous researchers (Moore 1988; Welch 1989), we undertook a remote visual survey of the entire area of the Khorat Plateau, using Google Earth® to produce a comprehensive dataset of site locations and the structure of individual sites (O'Reilly & Scott 2015). The objective was to produce a dataset of moated sites detailing for each site: soil texture, precipitation rates and aspects of construction, including location, size and number of moats.

Sites were recorded where they met the following well-established criteria: presence of a demonstrable raised central mound and a visible moat or embankment system encircling

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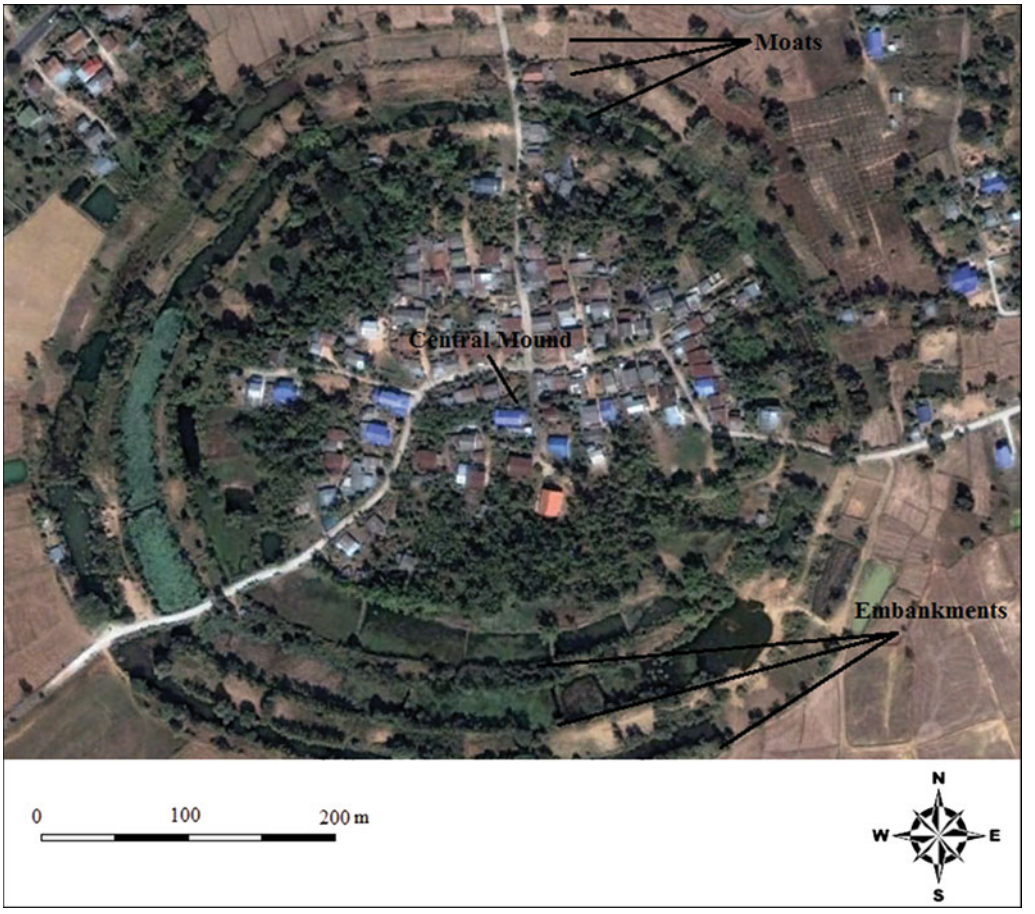

Figure 3. A site surrounded by moats and embankments in north-east Thailand (15° 0'0 N, 102°49'23 E).

the central mound (Moore 1988; Boyd *et al.* 1999; Talbot & Janthed 2001; Higham 2011). In cases where sites had been degraded or altered they were included in the dataset if at least one third of the circumference of the mound was encircled by a moat. Sites that are no longer extant but were recorded by Moore (1988) and Higham (2011) were also included in the current dataset.

The survey identified 297 circular moated sites, the majority of which are located in the southern portion of the Khorat Plateau, particularly in the Mun River Basin. Most are surrounded by one or two moats but some have as many as five (Figure 3). The area of the occupation mound at these sites, as delimited by the innermost moat, ranges from 0.5–171ha; within that range however, 50% of sites have an occupation mound between 6.2 and 19.7ha, with a mean area of 15.9ha.

Statistical methodology

The identification of moated sites and their mapping demonstrated several intuitively recognisable distribution patterns. In particular, the GIS software (ArcGIS) applied a kernel

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density model to the data that confirmed that the greatest density of sites of this type was in the Mun River valley. Site density is not consistent throughout the valley and clusters of occupation were noted. Several statistical analyses were applied to the data including a k-means analysis, a chi-squared test of independence and a residual maximum likelihood (REML) model. The first of these was applied to the site location data to confirm clusters that were identified in the kernel density model. The potential for site density to be associated with rainfall was analysed using chi-squared tests of independence. To evaluate the influence of rainfall on the size of sites a residual maximum likelihood analysis was undertaken; this demonstrated whether site size and geographic location were related to rainfall.

K-means analysis

As noted above, a kernel density model (Figure 4) revealed variations in the density of circular moated sites across the landscape. This is true of the entire Khorat Plateau, and is also evident on a finer scale along the Mun River. In order to explore these apparent groupings, a k-means analysis for non-hierarchical clustering was applied to the site location data using the Euclidean distance metric. This utilised locational data for sites, converted into the Universal Transverse Mercator (UTM) coordinate system, to chart sites by longitude and latitude. The k-means analysis produced a series of 10 models with a range of 5–15 site groups (clusters) from the data. The sums-of-squares criterion values decrease as the number of clusters increase until a point of consistency is reached, where the trend levels off (Figure 5). For this set of data the point where the criterion value ceases to decrease by any real degree is achieved with the model set at eight clusters; dividing the data into more clusters does not change how well the groups are statistically separated. This finding was used as the basis to divide the moated sites into eight distinct groups.

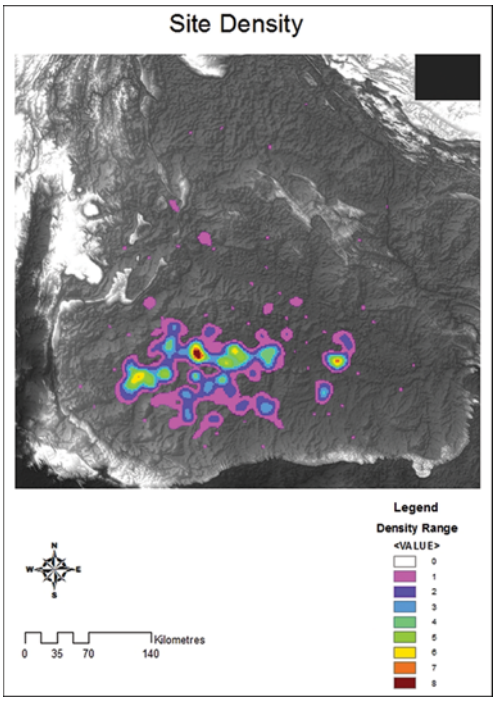

Figure 4. Kernel density model of circular moated sites in the Khorat Plateau; the model demonstrates several clusters of densely packed sites along the Mun River (DEM from the ASTER GDEM project).

Chi-squared test of independence

A chi-squared test provides a measure of the degree to which patterns in data are likely to represent real relationships rather than having occurred by chance. As such, a significant

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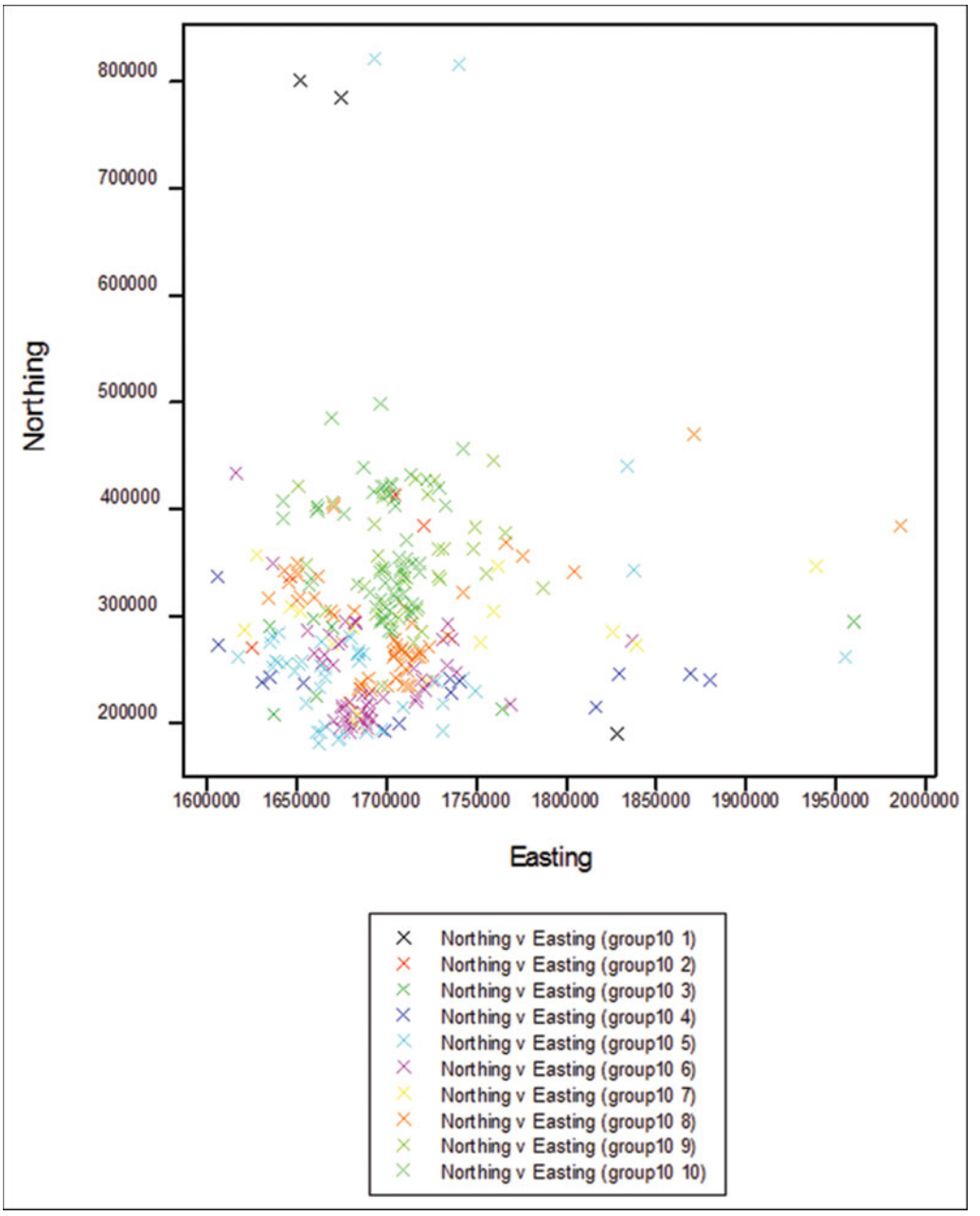

Figure 5. Criterion values for the k-means test with the number of groups set from 5–15.

χ^2 value indicates that the pattern present reflects a real association between the factors (Drennan 2004: 183). The P value obtained through the chi-squared test shows if the pattern is statistically significant (P = 0.05 or less); whereas Cramer's V is used to show the strength of the relationship. Cramer's V ranges from 0–1, with 1 indicating a very strong relationship (Drennan 2004: 199). For all the chi-squared tests, measures were taken

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Table 1. Wald and F statistics showing the contribution of each explanatory variable after the other terms have been included in the model (sequentially adding terms to fixed model).

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Elevation	0.43	1	0.43	266.0	0.514
Rainfall	31.77	3	10.59	266.0	<0.001
Fertility	6.55	2	3.28	266.0	0.039
Texture	1.51	3	0.50	266.0	0.680

Table 2. The second stage of the residual maximum likelihood individually analysing each variable (dropping individual terms from full fixed model).

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Elevation	10.01	1	10.01	266.0	0.002
Rainfall	3.55	3	1.18	266.0	0.317
Fertility	2.16	2	1.08	266.0	0.340
Texture	2.63	3	0.88	266.0	0.453

to eliminate as many nil (0) values as possible. This involved grouping together small categories with few values in the data (i.e. values for 4 or 5 moats per site were grouped into one class). A single small value (e.g. less than 5) in a chi-squared table will have some effect on the chi-squared test, but will not impact greatly on the conclusion unless the result is of borderline significance.

Residual maximum likelihood (REML)

Relationships between site size, rainfall, fertility and soil texture (e.g. silt, clay or sand) were tested using a REML. In order to fit the requirements for the analysis, the values for site area were standardised using a natural log transformation (Jiang 1996). This removed the issue of heterogeneity in the residuals (the difference between the observed and predicted values for each data point) and created a normal distribution curve. The 'test for fixed effects' in the REML analysis is divided into two parts: sequentially adding terms to the model and dropping individual terms (while leaving the other terms in the model). Table 1 presents the Wald and F statistics showing the contribution of each explanatory variable after the other terms have been included in the model. In this first stage of the analysis rainfall is the only variable shown to have a significant relationship to site size. The second stage of the REML drops the terms to individually analyse each variable. At this stage it is revealed that elevation is significantly related to site size (Table 2). From this initial analysis a second REML was run using only rainfall and elevation. Table 3 shows that, when considered together, both variables (rainfall and elevation) demonstrate clearly significant relationships with site size.

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Table 3. Residual maximum likelihood: showing elevation and rainfall together (remaining terms from full fixed model).

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Elevation	11.80	1	11.80	292.0	<0.001
Rainfall	30.84	3	10.28	292.0	<0.001

The particular effect of each variable on site size can also be assessed in more detail by examining its table of means.

Results of statistical analyses

Relationship between rainfall and site density

Overlaying the distribution of moated sites on a rainfall distribution map (Figure 6) indicates that the majority of moated sites are located in regions with the lowest precipitation, those receiving *c.* 1000–1200mm and 1200–1400mm annually (Figure 7). This is confirmed by the kernel density model.

Relationship between rainfall and site size

Assuming a correlation between the areal extent of the archaeological mounds and population size, it was reasoned that site size may have varied in relation to the amount of precipitation. Arid areas would not be able to support large populations and so the size of sites in relation to the amount of rainfall was also examined. Table 4 illustrates the change in the predicted average site size according to each rainfall category. The predicted mean size of sites is smallest in the area of the Khorat Plateau receiving the least annual rainfall. The table shows that there is very little difference between the predicted means for the rain bands ranging from 1200–1400ml and 1400–1600ml, which contain the sites with the largest average area. The average site area then drops off slightly in the band receiving the most rainfall (1600–2000ml), although it should be noted that only four sites fall in this region. In order to identify a statistically significant difference the value for the average standard error of difference (0.3377) is multiplied by 2 to produce the least significant difference (LSD) to measure

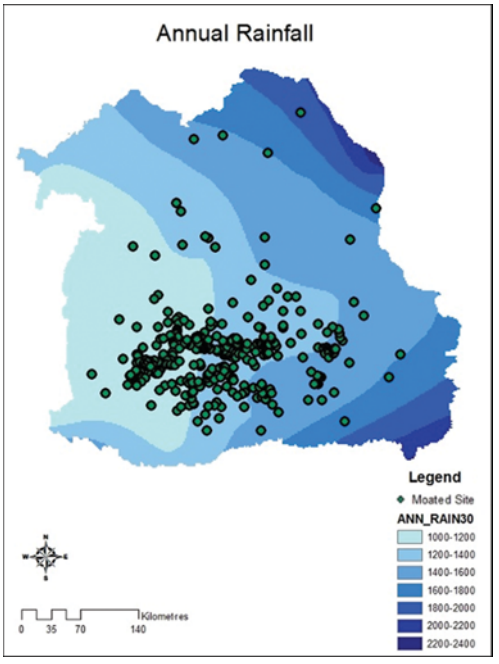

Figure 6. Rainfall map with circular moated sites overlayed.

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Table 4. Means for rainfall: showing changes in predicted mean for site size in each category.

Rainfall (mm)	1000–1200	1200–1400	1400–1600	1600–2000
Predicted Mean size	1.948	2.596	2.685	2.240
Average standard error of difference = 0.3377, LSD = 0.6754				

against. This produces an LSD value of 0.6754, which means that only the difference between the first and third rainfall bands is statistically significant. In addition, the difference between the first and second band is only just outside the statistically significant range. This demonstrates a trend in which sites are generally larger in the areas of greater rainfall.

Relationship between rainfall and the number of moats at a site

The pattern of distribution noted above may indicate that moats were constructed around these sites to collect and store water; if so it would stand to reason that sites in the driest areas would have multiple moats to collect as much water as possible. To test the validity of this hypothesis, we undertook statistical analyses on the number of moats per site. A chi-squared test of independence was applied to the data. To fulfil the requirements for the test, sites with four and five moats were merged into one group and all bands of rainfall of 1400mm and above were brought into one band (Table 5). The χ^2 value obtained (13.6) is statistically significant (P = 0.034). The value for Cramer's V, however, which gauges the strength of the pattern, is only 0.15. This suggests that the amount of annual rainfall has a slight influence on the number of moats at a site. It can be expected that, on average, sites in regions of less annual rainfall have more moats than those in areas of more plentiful rainfall.

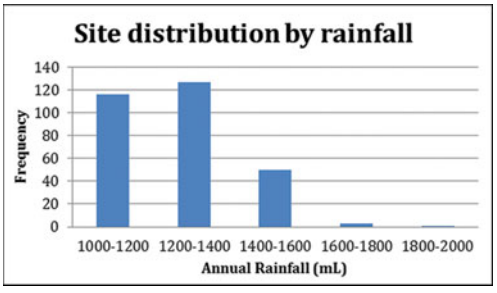

Figure 7. Frequency of circular moated sites by amount of rainfall.

Water loss is another consideration that must be taken into account. Water can be lost either through evaporation or through the soil. It is contended that if water was being lost, it must have been due to variable soil permeability across the landscape, because the meteorological parameters, and therefore evaporation rates, are broadly similar across the Khorat Plateau (Ohba & Ponsana 1987). The permeability of the soil on which the sites are located also plays a role in determining possible moat function. Moats being used to store water for extended periods of time would function most efficiently if seepage were at a minimum. Indeed most of the moated sites (95.6%) in the Mun floodplain are located on soils with low or low–medium permeability (Figure 8). Only 3.4% of sites are found in areas with high soil permeability.

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Table 5. Chi-squared observed values table for number of moats and rainfall.

	Rainfall mm			
No. of moats	1000–1200	1200–1400	1400	Row Total
1	55	58	21	134
2	30	46	27	103
3	26	16	5	47
4–5	5	7	1	13
Column total	**116**	**127**	**54**	**297**
$\chi^2 = 13.6$	d.f. = 6	P = 0.034	Cramer's V = 0.15	

The results of the statistical testing demonstrate several significant trends in estimated rainfall and in the distribution and morphology of circular moated sites. It is apparent that the majority of moated sites on the Khorat Plateau (81.8%) lie in areas with low annual precipitation (Figure 7). A slight relationship was identified between the amount of annual precipitation and the number of moats surrounding a site, with multi-moat sites being more common in areas of low precipitation. We have also seen that the amount of rainfall had a relationship to site size, with sites increasing in size as the amount of annual rainfall increases.

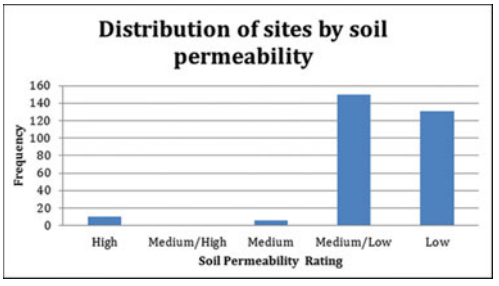

Figure 8. Frequency of circular moated sites by permeability of the soil.

Possible functions of moats

Several theories have been offered to explain the function of moats and embankments on the Khorat plateau including defence, intra-moat agriculture or aquaculture, symbolism, flood defence and water storage. Each of these hypotheses may be challenged on various grounds but the latter seems the most plausible, although it is possible that moats had multiple uses.

The defensive theory for the moat and embankment system was first suggested by Williams-Hunt who referred to them as "defended towns characterized by multiple, concentric earthworks and very regular, almost circular construction" (1950: 32). Others, including Vallibhotama (1984) and Nitta (1991) have put forward this possibility as well. There is evidence that several centuries after the moats and embankments were constructed there were military incursions into the region. A Sanskrit inscription from Phnom Hanchey (K. 81), dating to the sixth century, mentions that fighting was undertaken during the dry season when moats were waterless (Parry 1992: 13). The moats referred to in the inscription may not be those around Iron Age sites, as the text slightly post-dates the period under examination here, but it does hint that moats did serve as a deterrent against military aggression. If the moats were indeed empty during the dry season that would, however, greatly diminish their credibility as defensive features.

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Further reducing their efficacy for defence is the shape of the moats around these sites. Boyd *et al.* (1999) analysed the profiles, revealing broad U-shaped bottoms that would not greatly hinder an attacker. A moat with a V-shaped base is better at slowing attackers (Boyd *et al.* 1999; O'Reilly 2008: 380). Furthermore, there is no evidence for palisades or other protective structures atop the embankments that one would expect to find were the features defensive in nature (Higham 2011).

If the moats and embankments were constructed for defensive purposes then arguably the number of moats per site should increase proportionately with the density of neighbouring sites. Conversely, sites with only one or two moats should be found in areas of low site density. A density analysis on the moated sites of north-east Thailand indicates that site density does not demonstrate any relationship to the number of moats encircling a site (Scott 2013). There is some evidence for conflict during the period when the moats were constructed (Higham 2014), but given the weight of the evidence it appears unlikely that the moats were primarily defensive in nature.

Vallibhotama (1984) and Higham (1998) have suggested an agricultural or aquacultural function in which the moats were dug to grow wet-rice (in effect the moat served as a paddy field) or to keep fish. The argument for rice cultivation is problematic in that the moats surrounding these sites would have been much deeper during the Iron Age than they are today (Boyd *et al.* 1999; O'Reilly 2008: 380). The depth exceeds that appropriate for growing paddy rice and, in any case, the amount of rice that could be grown within the area of the moats would have been negligible. Fish farming would require the moats to be full of water for the entire year, which may not have been the case.

The possibility that the moats are symbolic in nature has been explored by one of the present authors (O'Reilly 2008) who suggested that the moats functioned to delineate territorial claims. While this explanation cannot be ruled out, it also cannot be confirmed and remains hypothetical. Again, the possibility of dual or multiple functions should be considered.

McGrath *et al.* (2008) have suggested that the moats served to protect sites from flooding. Given the climatic evidence we have for increasing periods of drought it seems doubtful that such a massive investment would have been made to ensure against an unlikely flood.

The use of moats for water management in which water would have been stored for domestic consumption and released, when needed, to irrigate surrounding fields in times of drought, has more recently been suggested (O'Reilly 2014). This argument contends that the majority of these sites were surrounded by moats with sufficient cubic capacity to irrigate paddies that could grow sufficient rice to feed the site's population. One issue is that, to date, no irrigation channels or outlets have been identified at the moated sites of the Khorat Plateau. Historic and pre-historic agricultural systems documented elsewhere in the world do, however, use moats to store water and irrigate fields without irrigation channels (Nabhan 1979; Paul 1984; Bruins *et al.* 1986; Hatibu & Mahoo 1999; Dominguez & Kolm 2005, Mupangwa *et al.* 2006; Mbilinyi *et al.* 2007). Such systems are generally found in regions that are similar to the Khorat Plateau in that they experience a distinct wet and dry season (Bruins *et al.* 1986; Prinz 2002). It must be noted, however, that further research is required to clarify whether the gradient from the moats to the rice paddies is sufficient to irrigate the fields.

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Given the results of the statistical analyses presented here relating rainfall patterns to site location, site size and the number of moats that surrounded these mounds, it is suggested that water storage is the most plausible primary explanation for the creation of the moats and embankments.

Conclusion

Our geographic study of Iron Age moated sites in north-east Thailand has examined 297 sites on the Khorat Plateau and their rainfall patterns. This analysis shows that the vast majority of moated mound sites are located in the Mun and Chi valleys. Furthermore, several interesting relationships have been revealed between site location, morphology and precipitation rates. The majority of moated sites are located in the two areas of lowest annual rainfall, with very few sites located in the high rainfall areas. This suggests that sites were constructed in areas where communities could not rely on regular rainfall. Statistical associations support this hypothesis, including the level of rainfall and number of moats, and level of rainfall and frequency and size of sites. Patterns in the data demonstrate that the average size of sites (and therefore the population that would have been supported) increased in areas of greater rainfall. They also show that rates of precipitation are correlated with the number of moats per site, with more moats at sites in areas of lower rainfall. The accumulated evidence suggests moats were necessary for water storage, acting as buffer supplies for irregular wet seasons and long periods of drought. It should be stressed, however, that moats may have been multi-purpose and also potentially have served a symbolic role. There is the possibility therefore, that multiple secondary functions, such as symbolism, may have diluted an even stronger correlation in the statistical relationships of variables, particularly that between rainfall and the number of moats at a site.

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References

Boyd, W. 2007. The geoarchaeology of Noen U-Loke and Non Muang Kao, in C.F.W. Higham, A. Kijngam & S. Talbot (ed.) *The origins of the civilization of Angkor: the excavation of Noen U-Loke and Non Muang Kao* (volume 3): 29–53. Bangkok: The Fine Arts Department of Thailand.

Boyd, W.E. & J. Habberfield-Short. 2007. Geoarchaeological landscape model of the Iron Age settlements of the upper Mun River floodplain, in C.F.W. Higham, A. Kijngam & S. Talbot (ed.) *The origins of the civilization of Angkor: the excavation of Noen U-Loke and Non Muang Kao* (volume 3): 1–28. Bangkok: The Fine Arts Department of Thailand.

Boyd, W., C. Higham & R. McGrath. 1999. The geoarchaeology of Iron Age 'moated' sites of the Upper Mae Nam Mun Valley, NE Thailand I: Palaeodrainage, site–landscape relationships and the origins of the 'moats'. *Geoarchaeology* 14: 675–716. http://dx.doi.org/10.1002/(SICI)1520–6548(199910)14:7<675::AID-GEA4>3.0.CO;2-G

Boyd, W. & R. McGrath. 2001. The geoarchaeology of the prehistoric ditched sites of the upper Mae Nam Mun Valley, NE Thailand, III: Late Holocene vegetation history. *Palaeogeography, Palaeoclimatology, Palaeoecology* 171: 307–28.

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https://doi.org/10.15184/aqy.2015.130 Published online by Cambridge University Press

BOYD, W., R. MCGRATH & C. HIGHAM. 1999. The geoarchaeology of the prehistoric ditched sites of the Upper Mae Nam Mun Valley, NE Thailand, II: stratigraphy and morphological sections of the encircling earthworks. *Bulletin of the Indo Pacific Prehistory Association* 18: 169–79. http://dx.doi.org/10.7152/bippa.v18i0.11712

BRUINS, H.J., M. EVENARI & U. NESSLER. 1986. Rainwater-harvesting agriculture for food production in arid zones: the challenge of the African famine. *Applied Geography* 6: 13–32. http://dx.doi.org/10.1016/0143-6228(86)90026-3

DAMRONG RAJANUBHAP, HRH Prince. 1995. *Visitations in Monthon Nakhon Rajasima and Monthon Udon Isarn in Rattanakosin 125 and B.E. 2449*. Bangkok: Diskul Foundation (in Thai).

DOMINGUEZ, S. & K.E. KOLM. 2005. Beyond water harvesting: a soil hydrology perspective on traditional southwestern agricultural technology. *American Antiquity* 70: 732–65. http://dx.doi.org/10.2307/40035872

DRENNAN, R.D. 2004. *Statistics for archaeologists, a common sense approach*. New York: Springer.

FOX, J.J. & J. LEDGERWOOD. 1999. Dry-season flood-recession rice in the Mekong Delta: two thousand years of sustainable agriculture? *Asian Perspectives* 38: 37–50.

HATIBU, N. & H. MAHOO. 1999. Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania, in P.G. Kaumbutho & T.E. Simalenga (ed.) *Conservation tillage with animal traction*: 161–71. Harare: Animal Traction Network for Eastern and Southern Africa.

HIGHAM, C. 1998. The transition from prehistory to the historic period in the Upper Mun Valley. *The transition to history in Southeast Asia, part I: Cambodia and Thailand* 2(3): 235–60.

– 2011. The Iron Age of the Mun Valley, Thailand. *The Antiquaries Journal* 91: 1–44.

– 2014. From the Iron Age to Angkor: new light on the origins of a state. *Antiquity* 88: 822–35. http://dx.doi.org/10.1017/S0003598×00050717

HIGHAM, C. & A. KIJNGAM (ed.). 2013. *The excavation of Ban Non Wat: the Iron Age* (volume 6). Bangkok: The Thai Fine Arts Department.

JIANG, J. 1996. REML estimation: asymptotic behavior and related topics. *Annals of Statistics* 24: 255–86. http://dx.doi.org/10.1214/aos/1033066209

KEALHOFER, L. & D. PENNY. 1998. A combined pollen and phytolith record for fourteen thousand years of vegetation change in northeastern Thailand. *Review of Palaeobotany and Palynology* 103: 83–93. http://dx.doi.org/10.1016/S0034-6667(98)00029-3

KING, C., A. BENTLEY, N. TAYLES, U.S. VIÐARSDÓTTIR, G. NOWELL & C. MACPHERSON. 2013. Moving peoples, changing diets: isotopic differences highlight migration and subsistence changes in the Upper Mun River valley, Thailand. *Journal of Archaeological Science* 40: 1681–88. http://dx.doi.org/10.1016/j.jas.2012.11.013

MAXWELL, A. 2004. Fire regimes in north-eastern Cambodian monsoonal forests, with a 9300-year sediment charcoal record. *Journal of Biogeography* 31: 225–39.

MBILINYI, B.P., S.D. TUMBO, H.F. MAHOO & F.O. MKIRAMWINYI. 2007. GIS-based decision support system for identifying potential sites for rainwater harvesting. *Physics and Chemistry of the Earth* 32: 1074–81. http://dx.doi.org/10.1016/j.pce.2007.07.014

MCGRATH, R. & W. BOYD. 2001. The chronology of the Iron Age 'moats' of northeast Thailand. *Antiquity* 75: 349–60. http://dx.doi.org/10.1017/S0003598×00061007

MCGRATH, R.J., W.E. BOYD & R.T. BUSH. 2008. The paleohydrological context of the Iron Age floodplain sites of the Mun River Valley, northeast Thailand. *Geoarchaeology* 23: 151–72. http://dx.doi.org/10.1002/gea.20210

MCNEILL, J. & D. WELCH. 1991. Regional and interregional interaction on the Khorat Plateau. *Bulletin of the Indo-Pacific Prehistory Association* 10: 327–40.

MOORE, E. 1988. *Moated sites in early north east Thailand* (British Archaeological Reports international series 400). Oxford: Hedges.

MUPANGWA, W., D. LOVE & S. TWOMLOW. 2006. Soil-water conservation and rainwater-harvesting strategies in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. *Physics and Chemistry of the Earth* 31: 893–900. http://dx.doi.org/10.1016/j.pce.2006.08.042

NABHAN, G.P. 1979. The ecology of floodwater farming in arid southwestern North America. *Agro-Ecosystems* 5: 245–55. http://dx.doi.org/10.1016/0304-3746(79)90004-0

NITTA, E. 1991. Archaeological study on the ancient iron-smelting and salt-making industries in the northeast of Thailand. Preliminary report on the excavations of Non Yang and Ban Don Phlong. *Journal of Southeast Asian Archaeology* 11: 1–46.

OHBA, K. & P. PONSANA. 1987. Evapotranspiration in the northeast district of Thailand as estimated by Morton method. *Journal of Agricultural Meteorology* 42: 329–36. http://dx.doi.org/10.2480/agrmet.42.329

O'REILLY, D. 2008. Multivallate sites and socio-economic change: Thailand and Britain in their Iron Ages. *Antiquity* 82: 377–89. http://dx.doi.org/10.1017/S0003598×00096873

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https://doi.org/10.15184/aqy.2015.130 Published online by Cambridge University Press

– 2014. Increasing complexity and the political economy model: a consideration of Iron Age moated sites in Thailand. *Journal of Anthropological Archaeology* 35: 298–309.

O'Reilly, D. & G. Scott. 2015. Multi-vallate sites of the Iron Age in the Mun River valley, Thailand: new discoveries using Google Earth. *Journal of Field Archaeology*.

Parnwell, M.J.G. 1988. Rural poverty, development and the environment: the case of north-east Thailand. *Journal of Biogeography* 15: 199–208. http://dx.doi.org/10.2307/2845060

Parry, J. 1992. The investigative role of Landsat-TM in the examination of pre- and proto-historic water management sites in northeast Thailand. *Geocarto International* 7(4): 5–24. http://dx.doi.org/10.1080/10106049209354385

Paul, B.K. 1984. Perception of and agricultural adjustment to floods in Jamuna floodplain, Bangladesh. *Human Ecology* 12: 3–19. http://dx.doi.org/10.1007/BF01531281

Penny, D. 2001. A 40,000 year palynological record from north-east Thailand; implications for biogeography and palaeo-environmental reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology* 171(3–4): 97–128. http://dx.doi.org/10.1016/S0031-0182(01)00242-5

Prinz, D. 2002. The role of water harvesting in alleviating water scarcity in arid areas (keynote lecture), in *Proceedings of the international conference on water resources management in arid regions. 23–27 March, 2002* (volume 3): 107–22. Kuwait: Kuwait Institute for Scientific Research.

Riethmuller, R. 1988. Differentiation and dynamics of land-use systems in a mountain-valley environment: a case study of new colonization areas in the upper Mae Nam Pa Sak catchment area, Thailand, in W. Manshard & W.B. Morgan (ed.) *Agricultural expansion and pioneer settlements in the humid tropics*: 74–99. Tokyo: United Nations University.

Scott, G. 2013. Examining the function of circular moated sites in north east Thailand: agriculture, defence or water storage? A landscape analysis. Unpublished BA dissertation, Australian National University.

Supapoj, N., K. Naklang & Y. Konboon. 1998. Using organic material to improve soil productivity in rainfed lowland rice in northeast Thailand, in J.K. Ladha, L. Wade, A. Dobermann, W. Reirchardt, G.J.D. Kirk & C. Piggin (ed.) *Rainfed lowland rice: advances in nutrient management research*: 161–68. Los Banos: International Rice Research Institute.

Talbot, S. & C. Janthed. 2001. Northeast Thailand before Angkor: evidence from an archaeological excavation at the Prasat Him Phimai. *Asian Perspectives* 40(2): 179–94. http://dx.doi.org/10.1353/asi.2001.0027

Vallibhotama, S. 1984. The relevance of moated settlements to the formation of states in Thailand, in D. Bayard (ed.) *Southeast Asian archaeology at the XV Pacific Science Congress: papers presented in symposium K.1e, the origins of agriculture, metallurgy, and the state of mainland Southeast Asia, Dunedin, New Zealand, 8–10 February 1983* (University of Otago studies in prehistoric anthropology 16): 123–28. Dunedin: Department of Anthropology, University of Otago.

Welch, D.J. 1989. Late Prehistoric and Early Historic exchange patterns in the Phimai region, Thailand. *Journal of Southeast Asian Studies* 20: 11–26. http://dx.doi.org/10.1017/S0022463400019810

Welch, D.J. & J.R. McNeill. 1988–1989. Excavations at Ban Tamyae and Non Ban Kham, Phimai region, northeast Thailand. *Asian Perspectives* 28: 99–123.

Williams-Hunt, P.D.R. 1950. Irregular earthworks in eastern Siam: a review. *Antiquity* 24: 30–36. http://dx.doi.org/10.1017/S0003598×00022821

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