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## **Anthropogenic contribution to the geological and geomorphological record: A case study from Great Yarmouth, Norfolk, UK.**

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### **Abstract**

Reconstruction of artificial or anthropogenic topographies, sediment thicknesses and volumes provides a mechanism for quantifying anthropogenic changes to sedimentary systems in the context of the proposed Anthropocene epoch. We present a methodology for determining the volumetric contribution of anthropogenic deposits to the geological and geomorphological record and apply it to the Great Yarmouth area of Norfolk, UK.

115 boreholes, drilled to a maximum depth of 6 m below ground level, were used to determine the thickness and distribution of seven geo-archaeological units comprising natural and anthropogenic deposits in the central Great Yarmouth area. This was supplemented by additional depth information derived from 467 existing ground investigation boreholes and published 1:50 000 scale geological maps.

The top and base of each geo-archaeological unit were modelled from elevations recorded in the borehole data. Grids were produced using a natural neighbour analysis with a 25 m cell size using MapInfo 8.0 Vertical Mapper 3.1 to produce palaeotopographical surfaces.

Maximum, minimum and average elevations for each geo-archaeological unit generally increase with decreasing age with the exception of the Early-Medieval palaeotopographical surface which locally occurs at higher elevations than that of the younger Late-Medieval unit.

The total sediment volume for the combined Modern, Post-Medieval, Late-Medieval and Early-Medieval geo-archaeological units is  $10.91 \times 10^5 \text{ m}^3$ . The total sediment volume for the Aeolian, River Terrace and Marine geo-archaeological units combined is  $65.58 \times 10^5 \text{ m}^3$ .

Anthropogenic sedimentation rates were calculated to increase from  $\sim 590 \text{ m}^3/\text{yr}$  during the Early-Medieval period,  $\sim 1500 \text{ m}^3/\text{yr}$  during the Post-Medieval period and  $\sim 2300 \text{ m}^3/\text{yr}$  during the Modern period.

It is estimated that the combined anthropogenic geo-archaeological units contribute approximately 15% of the total volume of sediments that would have been traditionally considered natural Holocene deposits in the Great Yarmouth area. The results indicate that an approach combining geological and archaeological deposits modelling can be used to quantify anthropogenic landscape impact and its associated sediment flux.

## **Keywords**

Anthropogenic deposits; artificial ground; anthropogenic geomorphology, palaeotopography; urban geoscience; Anthropocene.

## **1. Introduction**

Humans are leaving an ever-increasing footprint on the Earth's atmosphere, biosphere and lithosphere. This anthropogenic impact is developing to such an extent that proposals are being taken forward for a geological epoch defined by the action of humans: the Anthropocene (Crutzen & Stoermer, 2000; Steffen et al., 2007; Zalasiewicz et al., 2010). Consensus is yet to be reached on how best to define and characterise this proposed epoch (Zalasiewicz et al., 2010, 2011a; Certini & Scalenghe, 2011). However, a number of indicators exist which can be used to quantify the impact of human activity. These include atmospheric greenhouse gas concentrations (Steffen et al., 2011); rates of human-induced animal extinctions (Zalasiewicz et al., 2011b) and; the distribution and type of anthropogenic deposits in the geological record (Price et al., 2011). It is this latter indicator that forms the focus of this paper. The geological and geomorphological significance of humans as landscape transforming agents is described further in Price et al., (2011) and Ford et al., 2014.

Anthropogenic deposits may comprise 'natural' deposits that have been reworked by humans and/or manufactured and processed materials such as those found in household rubbish and building rubble. The systematic geological and geomorphological characterisation, classification and volumetric assessment of anthropogenic deposits and landforms is limited. Landforms may be shown on topographical maps along with anthropogenic features

including roads, canals and buildings. Landforms and associated deposits are shown on 1:50 000 scale geological maps in the UK based on their geomorphology and origin.

Anthropogenic landforms and deposits are considered together as artificially modified ground and divided into classes of Made Ground, Worked Ground, Disturbed Ground, Landscaped Ground or Infilled Ground (Ford et al., 2010). These classes are further subdivided into progressively more detailed types and units. Buildings and infrastructure at the ground surface could also be considered as anthropogenic deposits, although extant construction materials used in dwellings and infrastructure are excluded. Processes that occur in anthropogenically modified environments but that do not result in the direct emplacement of anthropogenic deposits are excluded from the classification of artificially modified ground considered here. These processes include agricultural ploughing and the creation of warp from deliberate sediment trapping during flooding in coastal or low lying areas.

Characterisation and classification of anthropogenic deposits created by direct human emplacement of modification, beyond the UK, is often undertaken on the basis of their lithology, landform or soil properties. For example, Dávid, (2010) and Sütő (2010) describe a system for the geomorphological classification of quarrying and mineral extraction. The geomorphological impact of military activity including construction of defensive structures has been described Rose, (2005). The relative proportion of anthropogenic (technic) material within a soil can be used as one property on which to base the classification of soils. The World Reference Base for Soils recognises two major reference soil groups of anthropogenic soils; Anthrosols and Technosols (Rossiter, 2007). The description and classification of Technosols has been used as a basis to map anthropogenic deposits in countries including Uruguay (Nerei et al., 2014; Mezzano & Huelmo, 2011) and Lithuania (Satkūnas et al.,

2011). Researchers in Japan characterise anthropogenic deposits on the basis of their lithology and bounding surfaces (Nerei et al., 2012).

The current study presents a methodology for assessing the sedimentary contribution of anthropogenic activity to the geological and geomorphological record of a given region. By applying this methodology to the Great Yarmouth area, Norfolk, UK, natural and anthropogenic palaeotopographies are modelled, deposit thicknesses and volumes are calculated and the contribution of anthropogenic deposits to the geological and geomorphological record is determined. Such an approach proves useful in quantifying the magnitude of direct anthropogenic modification to the local sedimentary system and the degree of human-landscape interaction. The methodology described here can be readily applied to different anthropogenic classification or characterisation schemes used in the UK and beyond, on the basis of geomorphology and sedimentology.

### **1.1 The Great Yarmouth study area**

The central area of the town of Great Yarmouth, Norfolk, on the east coast of England (Fig. 1) was chosen for the current study as a result of its relatively dense borehole coverage and well documented occupation history (Swinden, 1772; Chambers, 1829, Crisp, 1871; Rogerson, 1976; Ashwin and Davison, 2005). The area under examination extends from National Grid Reference (NGR) 652272 308025 in the north to Middlegate [NGR 652585 306987] in the south and in an east-west alignment between Dene Street [NGR 652576 307431] and Hall Quay [NGR 652205 307555] covering a total of  $2.84 \times 10^5 \text{ m}^2$  (not accounting for topography). Maximum elevations of 7 m OD are reached in the east of the study area in the vicinity of Dene Street and then decrease at shallow angles to the west and south.

The study area lies on the Great Yarmouth spit, a natural coastal promontory joined to the mainland at Caister-on-Sea [NGR 652813, 312146] that projects southwards to Gorleston-on-Sea [NGR 653296, 303763]. This natural spit is bounded by the River Yare to the west and by the North Sea to the east. A coastal barrier has existed in the location of the Great Yarmouth spit since the first few centuries AD, following marine incursion into the southern North Sea in the early Holocene (Arthurton et al., 1994). Throughout this time, the barrier has varied in its geomorphology from an offshore sandbank to a coastal spit. Between 1199 and 1216 AD the spit was recorded as reaching as far south as Lowestoft. The current spit length of ~8 km was determined by the cutting of the current river mouth between 1559 and 1567 AD (Manship, 1845).

The Quaternary geology of the study area is characterised by sporadic Holocene wind-blown deposits mantling sand and subordinate gravels of the North Denes Formation (Table 1). These in turn rest unconformably upon estuarine clays, silts, peats and sands of the Breydon Formation (Arthurton et al., 1994). Interdigitation of deposits of the North Denes and Breydon formations occurs locally. Underlying these Holocene deposits are the Late Pleistocene gravels and subordinate sand of the Yare Valley Formation and Late Pliocene to Early Pleistocene shallow marine sediments of the Crag Group. Natural superficial deposits are overlain locally by artificial ground comprising Made, Worked, Disturbed, Landscaped and Infilled Ground.

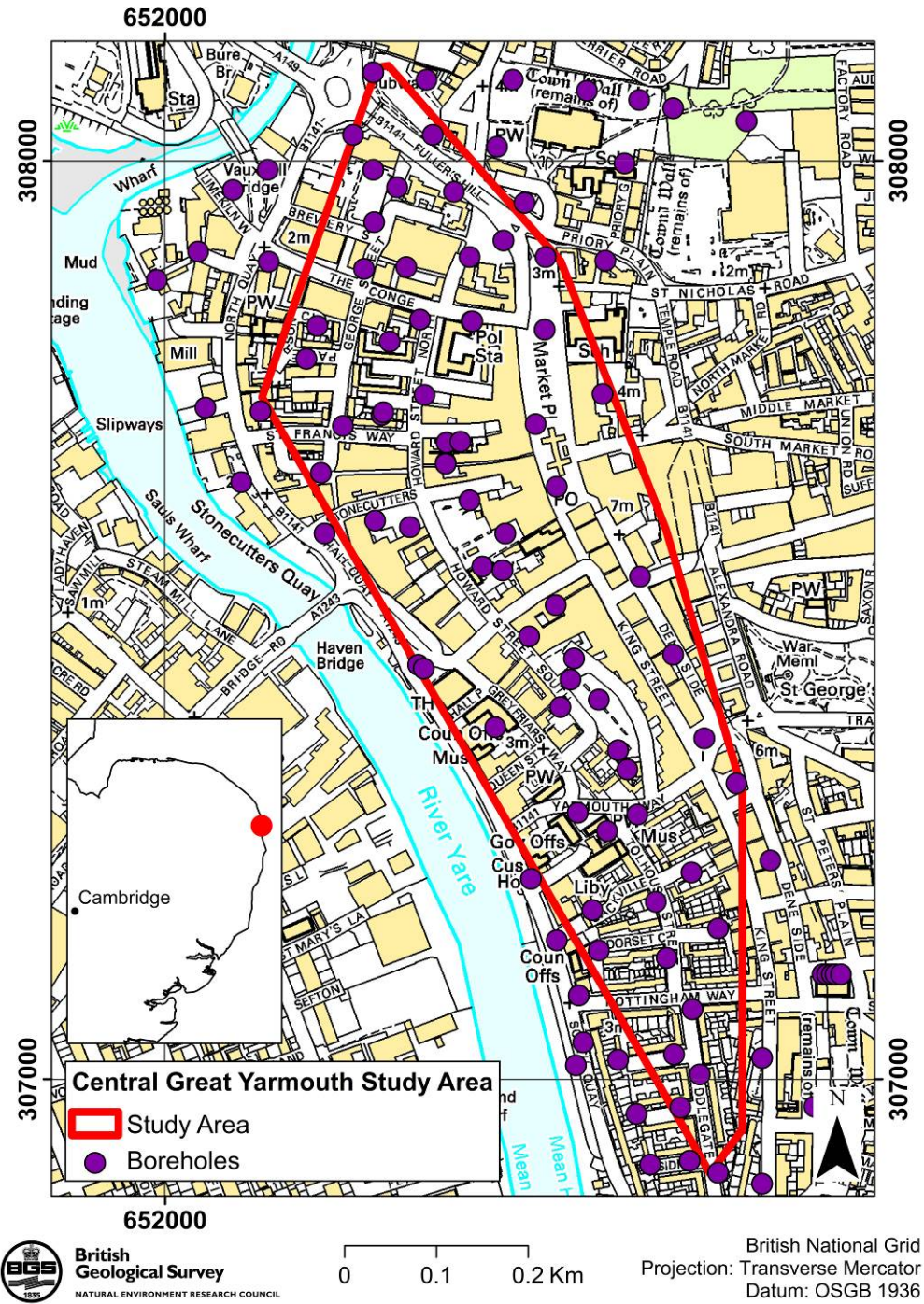


Figure 1. The central Great Yarmouth study area and location of boreholes drilled for the Great Yarmouth Archaeological Map. Inset: point denotes location of study area in Eastern England. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

System/ Period	Chronology/Geochronology		Formation/Group	Characteristics	
	Series/Epoch	Age/Stage			
Quaternary		<i>Anthropocene</i>	<i>Artificial Ground</i>	Artificial material or reworked older ‘natural’ material as Made, Worked, Disturbed, Landscaped and Infilled Ground	
	Holocene		Blown Sand	Aeolian Sand	
			Alluvium (Undifferentiated)	Sand and silt	
			North Denes Formation	Beach sand and subordinate gravel	
			Breydon Formation	Estuarine clays, silts, peats and subordinate sands	
	Pleistocene		Devensian	River Terrace Deposits (Undifferentiated)	Sand and gravel
			?Devensian	Yare Valley Formation	Gravel and subordinate sand
			Anglian	Lowestoft Till Formation	Chalky sandy till
				Corton Formation	Sand, some sandy clay
	Quaternary/ Tertiary	Pleistocene/ Pliocene	Crag Group	Shallow marine sands, partly shelly, some silt clay	

Table 1. The Quaternary sequence within the Great Yarmouth area, adapted from Arthurton et al., (1994). Artificial ground categories as in Ford et al., (2010). Proposed Ages and Formation/ Groups denoted in italics.

## 2. Methodology

115 boreholes were drilled using a Dando Terrier window sampler and rotary mast to a maximum depth of 6 m below ground surface to produce the Great Yarmouth Archaeological Map (<http://www.heritage.norfolk.gov.uk/gyam>) (Fig. 1). These were logged to British Standard 5930:1999 (British Standards Institution, 1999) and the position and type of



archaeological artefacts were recorded. Recovered pottery fragments were dated by comparison of type through relative dating. Wood samples were identified by optical microscopy before undergoing AMS radiocarbon dating (Bronk Ramsey et al., 2004) with acid-alkali-acid pre-treatment (de Vries method, Goh & Molloy (1972) using 2% NaOH on waterlogged wood). The deposits were then categorised into seven geo-archaeological units based on the stratigraphical and dating evidence: Modern, Post-Medieval, Late-Medieval, Early Medieval, Aeolian, River Terrace and Marine (Table 2).

The Aeolian, River Terrace and Marine horizons were interpreted to represent natural deposits whilst Modern, Post-Medieval and Late-Medieval sediments are largely of anthropogenic origin, including ‘natural’ deposits that have been reworked by humans and/or ‘artificial’ material such as building rubble. Early-Medieval sediments encompass a combination of natural and artificial deposits.

<b>Unit</b>	<b>Age</b>	<b>Lithology</b>	<b>Artefacts</b>	<b>Formation/Group</b>
Modern	1950- 2008	Artificial material &/or reworked fine- to-medium-grained sand, clay or clayey silt.	Concrete, asphalt, brick, rubble and topsoil.	<i>Artificial Ground</i> ( <i>Anthropocene</i> )
Post-Medieval	1650- 1950	Reworked fine-to- coarse-grained sand, clay, clayey/sandy silt or peat.	Brick, rubble, pottery, bone and wood.	<i>Artificial Ground</i> ( <i>Anthropocene</i> )

Late-Medieval	1350- 1650	Reworked gravel, fine-to-medium- grained sand, clay, sandy silt or peat.	Ash, pottery and bone dated.	<i>Artificial Ground</i> <i>(Anthropocene)</i>
Early-Medieval	1050- 1350	Fine-to-medium- grained sand, clay, clayey silt or peat.	Ash, pottery, bone and furnace slag.	<i>Artificial Ground</i> <i>(Anthropocene)</i> ; Blown Sand, Alluvium, Breydon Formation (Holocene)
Aeolian	Pre- 1050	Fine-to-medium- grained sand	None	Blown Sand (Holocene)
River Terrace	Pre- 1050	Fine-to-medium- grained sand, clay or clayey silt.	None	Alluvium (Holocene)
Marine	Pre- 1050	Fine-to-coarse-grained sand or clayey silt.	None	Breydon Formation & some interdigitated North Denes Formation (Holocene)

Table 2. Lithology and age characteristics of the seven geo-archaeological units identified in the central Great Yarmouth area, Norfolk, UK. Proposed Ages and Formation/ Groups denoted in italics.

The top and base surfaces of each of the geo-archaeological units were modelled from the borehole elevation data. Grids were created by interpolation from this data using natural neighbour analysis (cell size 25 m, aggradation distance 50 m) in MapInfo 8.0 Vertical

Mapper 3.1. This led to the production of seven palaeotopographical surfaces for the central Great Yarmouth area, corresponding to ground surface elevations in 2008 AD (Modern unit top), 1950 AD (Modern unit base/ Post-Medieval unit top), 1650 AD (Post-Medieval unit base/ Late-Medieval unit top), 1350 AD (Late-Medieval unit base/ Early-Medieval unit top), 1050 AD (Early-Medieval unit base/ Aeolian unit top), pre-1050a AD (Aeolian unit base/ River Terrace unit top) and pre-1050b AD (River Terrace unit base/ Marine unit top).

Locally, deposits of older geo-archaeological units appeared topographically higher than those of younger units during modelling which was interpreted to be an artefact of the interpolation process where borehole density is relatively low. In these cases, the older unit was modelled to the level of the base of the younger deposit to minimise elevation errors.

As a result of the varying proportions of natural and anthropogenic material in the different geo-archaeological units outlined in Table 2, two scenarios were defined for the calculation of anthropogenic deposit thickness (Table 3). Thickness grids were created for these scenarios by subtracting the elevation for the top surface of the stratigraphically higher unit from that of the base surface of the stratigraphically lower unit using Vertical Mapper 3.1 in MapInfo 8.0. The volume of anthropogenic deposits within the study area was also calculated for each scenario by multiplying deposit thickness by area of the central Great Yarmouth area.

<b>Scenario Number</b>	<b>Characteristics</b>	<b>Unit surfaces used</b>
A1	All potential anthropogenic deposits	Modern top, Early-Medieval base

A2	All definite anthropogenic deposits	Modern top, Late-Medieval base
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Table 3. Anthropogenic deposit thickness scenarios for the central Great Yarmouth area, Norfolk, UK.

In order to assess the contribution of anthropogenic deposits to the geological and geomorphological record, the thickness of the area's Holocene deposits was also modelled. The Breydon Formation characterises the Early Holocene in the Great Yarmouth region (Table 1) and elevations derived from the base surface of this unit are a useful indicator of the onset of Holocene conditions. These elevations provide a base surface for the Marine geoarchaeological unit.

Pre-existing borehole records held within the British Geological Survey's (BGS) Single Onshore Borehole Index (SOBI) were interrogated for a study area lying between NGR 649830, 303159 (southwest corner) and NGR 655932, 312799 (northeast corner) (Fig. 2). This larger area was chosen for the modelling of natural Holocene deposits to account for the low frequency of boreholes containing sediments of the Breydon Formation in the central Great Yarmouth study area itself. Approximately 1496 boreholes occur within this larger area (not including those drilled for the Great Yarmouth Archaeological Map. Of the boreholes in the larger area, 467 contain sediments interpreted as Breydon Formation. These were divided into boreholes proving the base of the Breydon Formation (totalling 310) and those with Breydon Formation sediments at borehole termination depth (157). Thickness and volume calculations were performed using a sub-set of this larger study area, matching that of the central Great Yarmouth study area.

Deposits included on BGS 1:50 000 geological maps typically have a thickness of at least 1 m. The edge of the Breydon Formation mapped on the BGS 1:50 000 Geological Map Sheet 162 (British Geological Survey, 1994), therefore, provides additional data points at which the thickness of the Breydon Formation is interpreted to be at least 1 m and where the base surface elevation of the Breydon Formation at these points was calculated by subtracting this thickness from NEXTMap® DSM elevation data (©Intermap Technologies). Areas in which the NEXTMap® DSM data clearly represented the elevations of buildings rather than the ground surface were avoided, where possible. These points were digitised at a scale of 1:2000 within ESRI ArcMap 9.2.

Similarly, additional data points were added to the offshore portion of the model by digitising the meeting point of the Crag and Breydon Formation deposits from the BGS 1:50 000 Geological Map Sheet 162 (British Geological Survey, 1994). The thickness of the Breydon Formation at these points is interpreted to be at least 1 m and elevations for the base of the Breydon Formation were derived by subtracting this thickness from UK Hydrographic Office bathymetric data (UK Hydrographic Office, 2009). The Crag Group was used to represent pre-Holocene deposits as the late Pleistocene Yare Valley Formation is less easily separated in these areas (having only been recognised tentatively offshore in shallow seismic profiles). Areas where the mapped Breydon Formation limits abut stratigraphically younger units were not used to delimit Breydon Formation extent as the younger deposits may mask a continuation of the Breydon Formation at depth. The onshore and offshore constraint data were added to the model as additional base proven points; a total of 539 data points.

Using Vertical Mapper 3.1 in MapInfo 8.0, natural neighbour analysis (cell size 25 m, aggradation distance 50 m) was performed on the data where the base of the Breydon

Formation was proven in order to interpolate its basal surface. The resulting grid of the base of Holocene deposits was refined by ensuring that minimum Breydon Formation depths identified in borehole records with Breydon Formation at termination depth were correctly represented in the model.

Holocene deposit thickness was calculated as outlined in Table 4. A thickness grid was created by subtracting the elevation for the top surface of the stratigraphically higher unit from that of the base surface of stratigraphically lower unit using Vertical Mapper 3.1 in MapInfo 8.0 (cell size 25 m, aggradation distance 50 m). The volume of Holocene deposits within the study area was also calculated by multiplying deposit thickness by area of the central Great Yarmouth region.

<b>Scenario Number</b>	<b>Characteristics</b>	<b>Unit surfaces used</b>
H1	All Holocene deposits	Modern top, Holocene base

Table 4. Holocene deposit thickness scenario for the central Great Yarmouth area, Norfolk, UK.

As the Early-Medieval unit may contain both natural and anthropogenic material, Scenario A2 is likely to provide a more realistic indication of anthropogenic deposits in the central Great Yarmouth area than Scenario A1 which includes Early-Medieval material. In light of this, the scenario outlined in Table 5 was used to examine the ratio of anthropogenic to natural deposits within the study area. Vertical Mapper 3.1 in MapInfo 8.0 (cell size 25 m, aggradation distance 50 m) was used to create a grid for the ratio of anthropogenic to Holocene deposit thicknesses.

<b>Scenario Number</b>	<b>Characteristics</b>	<b>Unit surfaces used</b>
R1	Ratio of all anthropogenic deposits, excluding Early-Medieval, (A2) to all Holocene deposits (H1)	Modern top, Late Medieval bottom: Modern top, Holocene base

Table 5. Scenario for the ratio of anthropogenic to Holocene deposits thickness in the central Great Yarmouth area, Norfolk, UK.

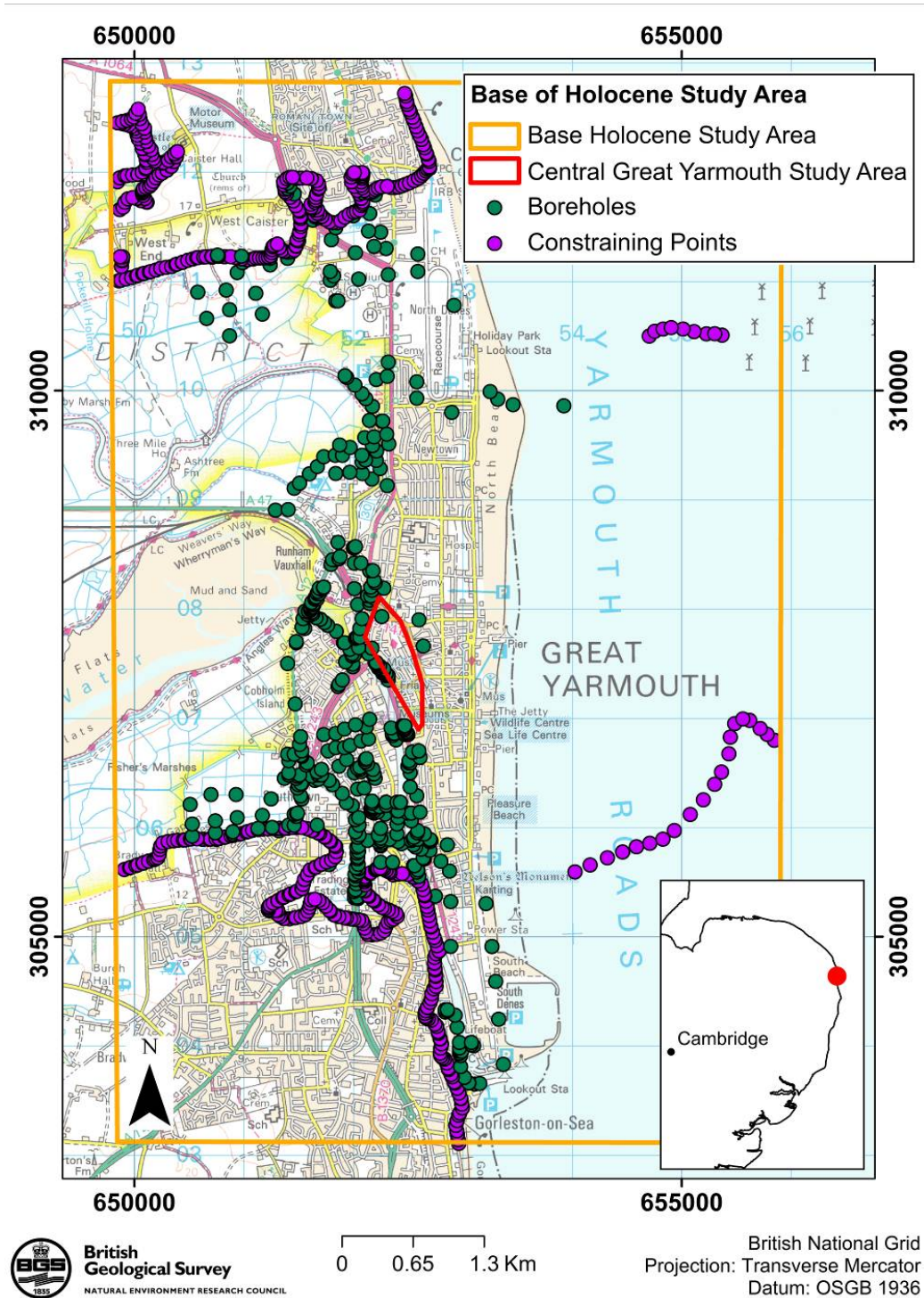


Figure 2. The base of Holocene deposits study area, Great Yarmouth, Norfolk, UK. Boreholes from the BGS's Single Onshore Borehole Index and constraining points are shown. Inset: point denotes location of study area in Eastern England. The National Grid



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### **3. Anthropogenic and natural deposit elevation in the Great Yarmouth area**

At any given site, deposits of younger geo-archaeological units generally overlie those of older units. For all geo-archaeological units, the range of elevations of the unit's top surface across the study area overlaps with those of at least one other unit across different sites (Fig. 3). Typically, maximum top surface elevation of the geo-archaeological units increases with decreasing age with the exception of the Early-Medieval geo-archaeological unit which locally achieves a greater maximum top surface elevation than that of Late-Medieval deposits. This may reflect a combination of natural and anthropogenic processes operating in the Early and Late-Medieval periods. Minimum top surface elevations of the geo-archaeological units also typically increase with decreasing age.

Spatial variations in top surface elevations between the different geo-archaeological units can also be seen (Fig. 4). Grid references for the places referred to in the remainder of this section and Section 4 and shown in figs. 4, 5, 7, 9, 11 and 12 are outlined in Table 6. Top surface elevations for the Modern and Post-Medieval geo-archaeological units reach a maximum in the eastern portion of the study area, in the vicinity of King Street and decrease westwards. The Post-Medieval unit displays a slightly larger region of decreased top surface elevations to the northwest of Tolhouse Street than the Modern unit. The distribution of top surface elevations of the Late-Medieval geo-archaeological unit is increasingly patchy. Three distinct areas of increased elevations can be seen centred upon Fuller's Hill, King Street and the area to the north of Greyfriars Way. Top surface elevations for the Early-Medieval geo-

archaeological unit are similar with the exception of the area just to the north of Market Place where it occurs at lower elevations.

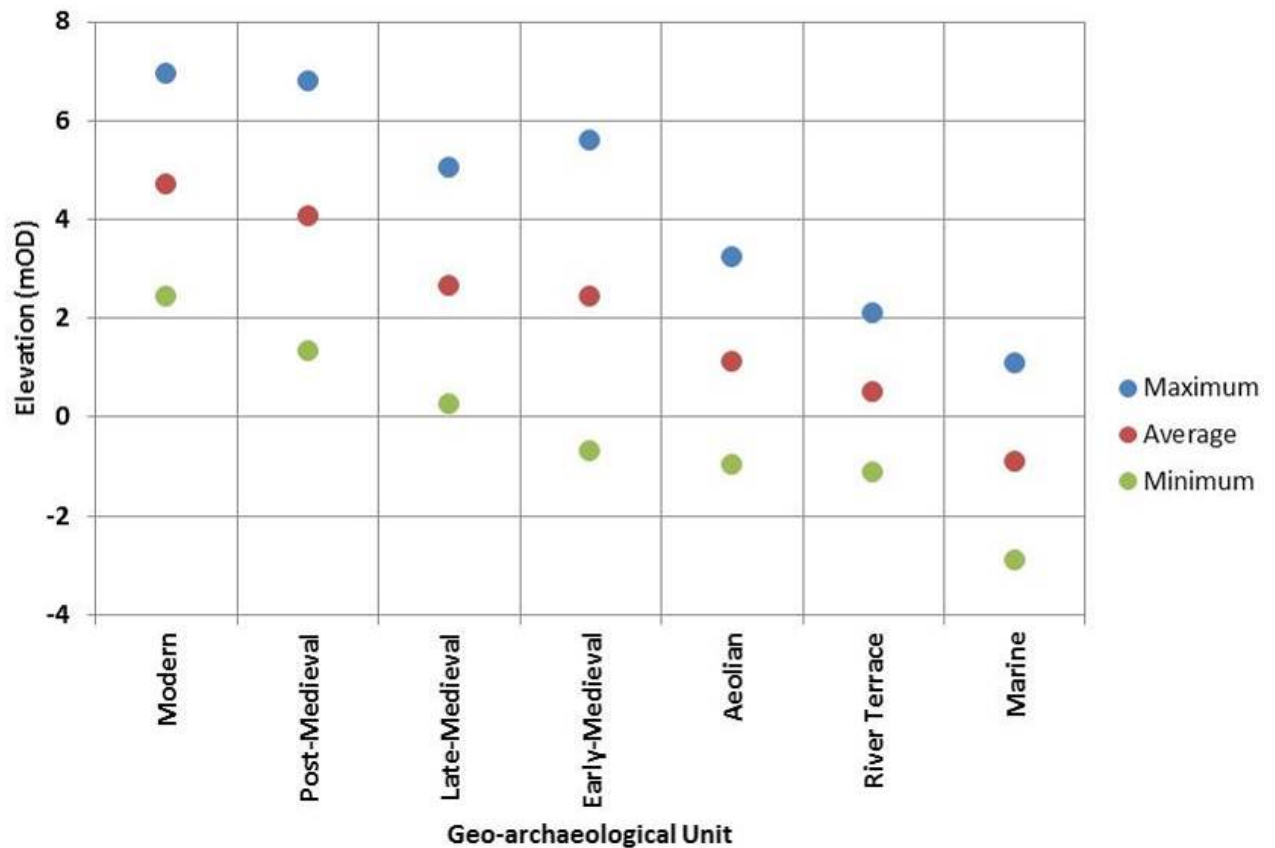


Figure 3. Variation in maximum, mean and minimum elevation of the top surface of the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK.

Elevations of the top of the Aeolian geo-archaeological unit are greatest around Fuller’s Hill and King Street. Peaks in top surface elevations for the River Terrace geo-archaeological unit extend further north than those for the Aeolian unit, towards the northern end of Market Place. Finally, the elevation of the top of the Marine geo-archaeological unit is greatest in the central portion of the study area. Four main centres of increased elevation can be seen in the

northern extremity of the study area around Fuller’s Hill; Tolhouse Street; to the north of Greyfriars Way and north east of Stonecutters.

<b>Place Name</b>	<b>National Grid Reference</b>	<b>Label in figs. 4, 5, 7, 9, 11 and 12</b>
Fuller’s Hill	652306 307994	A
Market Place	652411 307761	B
King Street	652527 307449	C
Tolhouse Street	652541 307188	D
Middlegate	652585 306987	E
Greyfriars Way	652381 307399	F
Stonecutters	652210 307627	G
The Conge	652195 307868	H

Table 6. National Grid References for places referred to in sections 3 and 4 and figs. 4, 5, 7, 9, 11 and 12.

Elevations for the base of Holocene deposits vary throughout the study area (Fig. 5). A pronounced topographic low can be seen in the north of the study area around Fuller’s Hill where the minimum elevation is -27.07 m OD. Holocene deposits are also found at relatively low elevations in the south of the study area in the region of Middlegate. The base surface of Holocene deposits reaches a topographic high approximately 130 m to the northwest of Greyfriars Way and approximately 160 m north east of Stonecutters. In the central and eastern sections of the central Great Yarmouth study area the base surface of the Holocene deposits can be found at around -17 m OD.

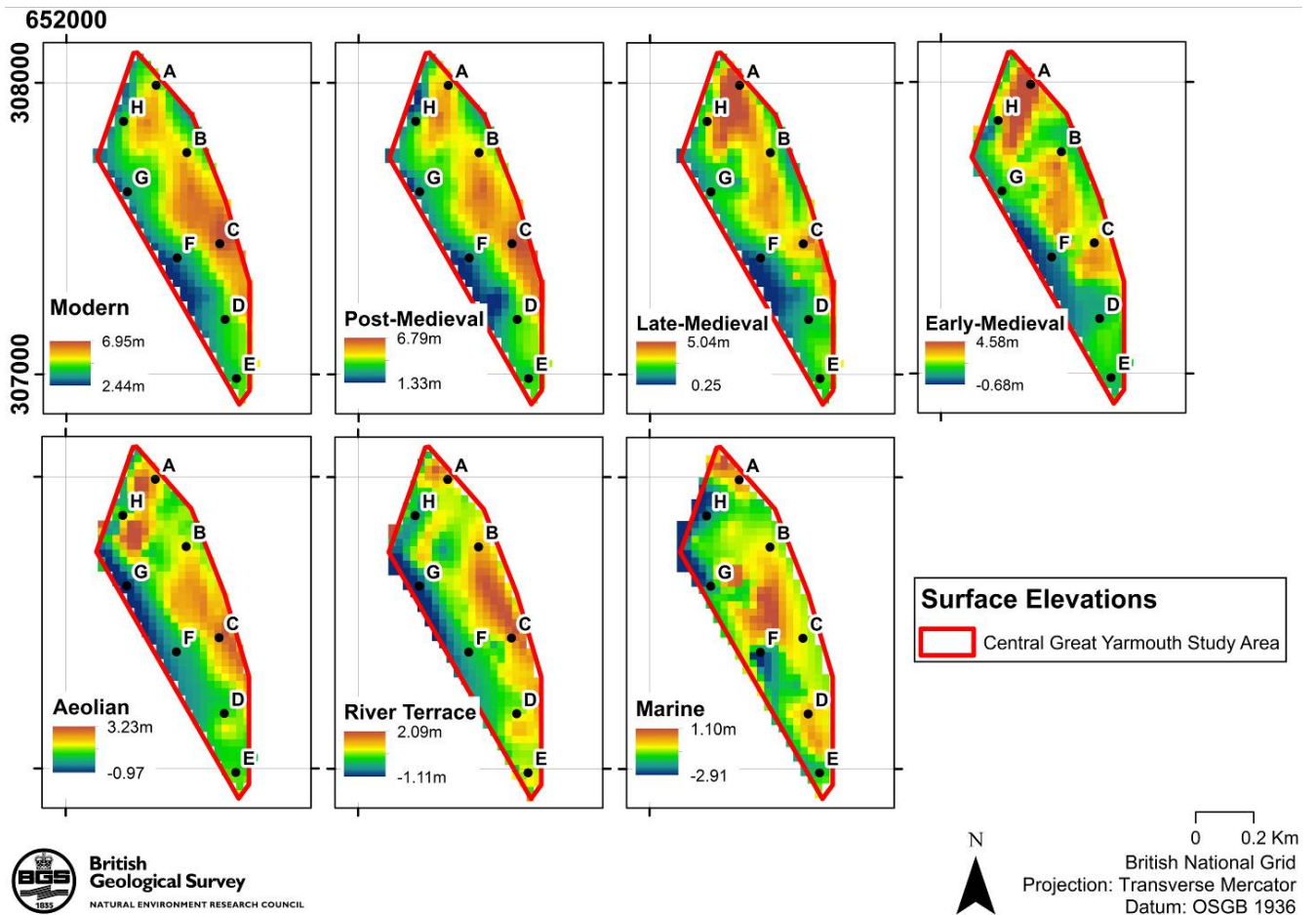


Figure 4. Surface elevations for the top of the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK. All elevations are metres above Ordnance Datum Newlyn. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

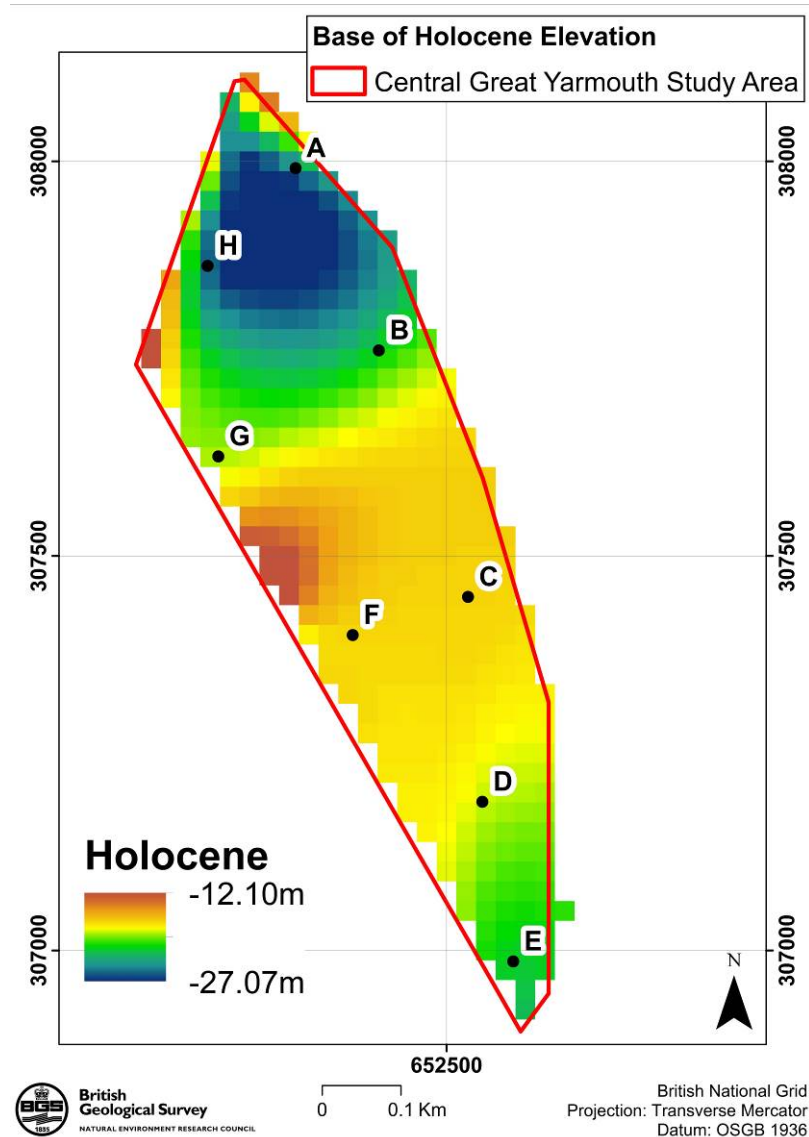


Figure 5. Base surface elevations of Holocene deposits within the central Great Yarmouth area, Norfolk, UK. All elevations are metres above Ordnance Datum Newlyn (mOD). Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

#### 4. Anthropogenic and natural deposit thickness and volume in the Great Yarmouth area

All geo-archaeological units, with the exception of the Marine unit, display minimum thickness values of 0 m (Table 7). Deposits of the River Terrace, Aeolian and Early-Medieval geo-archaeological units are absent from 80.58%, 75.73% and 60.19% of the boreholes, respectively. Deposits of the Modern, Post-Medieval, Late-Medieval and Marine geo-archaeological units are more widespread where they are proved in 78.64 to 100.00% of the borehole records. Deposits of the Marine geo-archaeological unit reach a minimum thickness of 10.80 m.

<b>Unit</b>	<b>Minimum thickness (m)</b>	<b>Maximum thickness (m)</b>	<b>Mean Thickness (m)</b>	<b>Volume (<math>\times 10^5 \text{ m}^3</math>)</b>
Modern	0.00	1.77	0.46	1.32
Post-Medieval	0.00	3.37	1.60	4.56
Late Medieval	0.00	2.97	1.14	3.25
Early-Medieval	0.00	3.05	0.63	1.78
Aeolian	0.00	2.43	0.29	0.83
River Terrace	0.00	3.32	0.96	2.73
Marine	10.80	26.23	19.01	46.69

Table 7. Geo-archaeological unit thickness and volume statistics for the central Great Yarmouth area, Norfolk, UK.

Whilst there is no significant temporal trend in geo-archaeological unit thickness or volume characteristics (Table 7), sediment accumulation rates vary more consistently with time (Fig.

6). Calculation of sediment accumulation rates for the Aeolian, River Terrace and Marine geological units individually was not possible given the relatively poor age constraints for these units. Instead, these units were treated together as a Pre-Early-Medieval unit and 11,700 yr before 2000 AD was adopted for the start of the Holocene (Walker et al., 2009).

Successive increases in sediment accumulation rates through time are visible. The rate of this increase also increased dramatically after the deposition of Early-Medieval deposits.

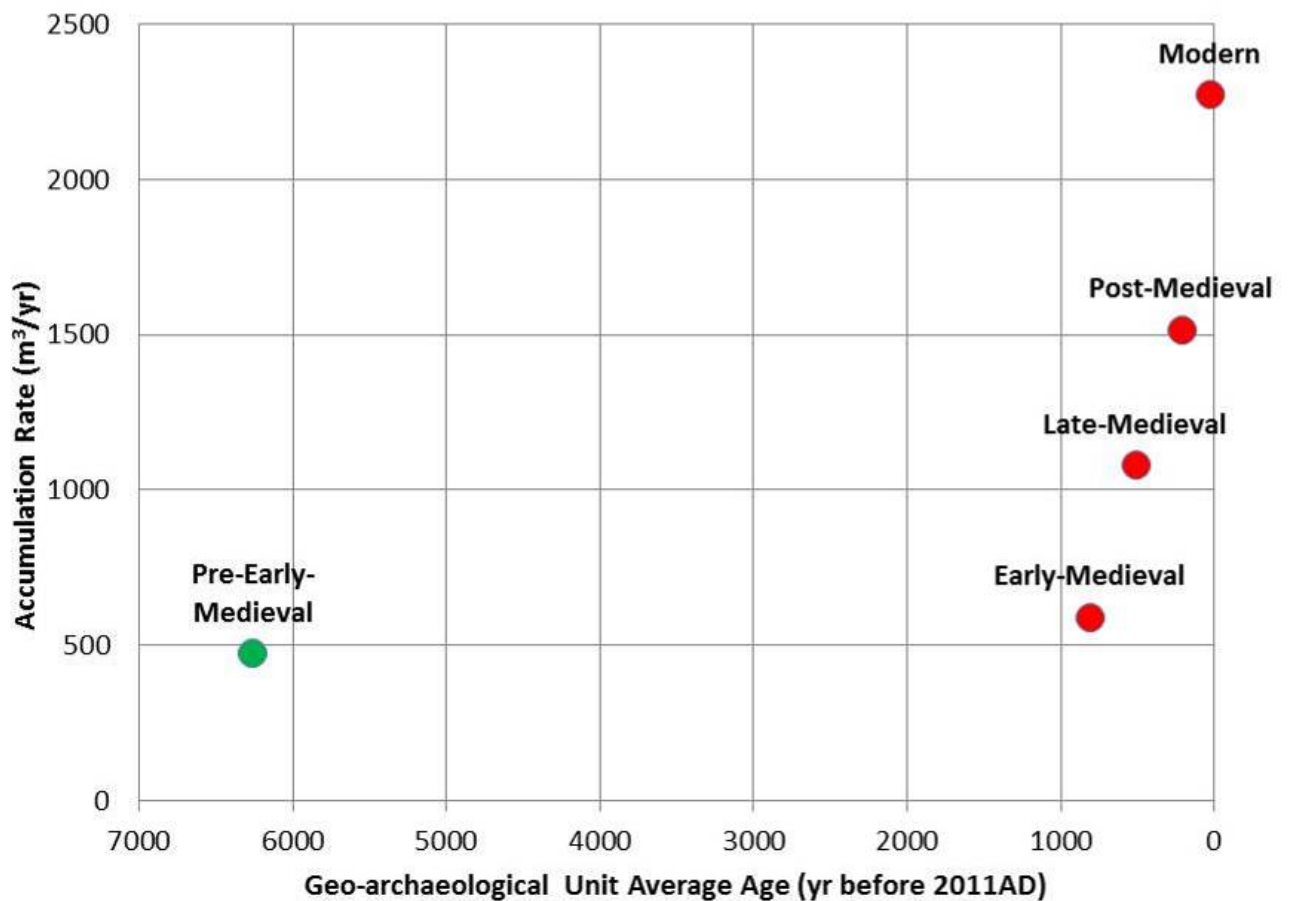


Figure 6. Average annual sediment accumulation rates within the central Great Yarmouth area, Norfolk, UK. Geo-archaeological unit average ages derived from age ranges in Table 2

and converted to years before 2011AD. Green point denotes natural geo-archaeological unit; red point denotes geo-archaeological units containing anthropogenic material.

Deposit thickness of the different geo-archaeological units is spatially variable (Fig. 7).

Deposit thicknesses for the Modern unit reveal discrete centres of increased thickness in the region of King Street, The Conge and Tolhouse Street. Post-Medieval deposits are increasingly thick in the eastern portion of the study area around King Street. The distribution of Late-Medieval deposits is more similar to that of the Modern unit rather than Post-Medieval deposits in that several discrete centres of increased deposit accumulation can be seen. In this case the greatest deposit concentrations are observed in the vicinity of Market Place and to the north west of Greyfriars Way. The Early-Medieval geo-archaeological unit displays very low thickness towards the south of the study area with increased concentration instead lying around Stonecutters in the west and Fuller's Hill to the north. The Aeolian geo-archaeological unit possesses clear centres of increased deposit thickness at The Conge and Fuller's Hill whilst River Terrace deposits are thicker north and west of The Conge and in the vicinity of Greyfriars Way, Middlegate and Market Place. Deposits of the marine geo-archaeological unit are thickest in the north of the study area around Fuller's Hill and The Conge.

Anthropogenic and natural Holocene deposit thickness and volume statistics for scenarios A1, A2, and H1 (see Tables 3 and 4 for definition of scenarios) are presented in Table 8. The inclusion of Early-Medieval deposits (A1) as a possible source of artificial material does not significantly alter maximum anthropogenic deposit thicknesses but does lead to an increased minimum thickness. Anthropogenic deposit volumes are increased by approximately 16% when deposits of the Early-Medieval geo-archaeological unit are included.



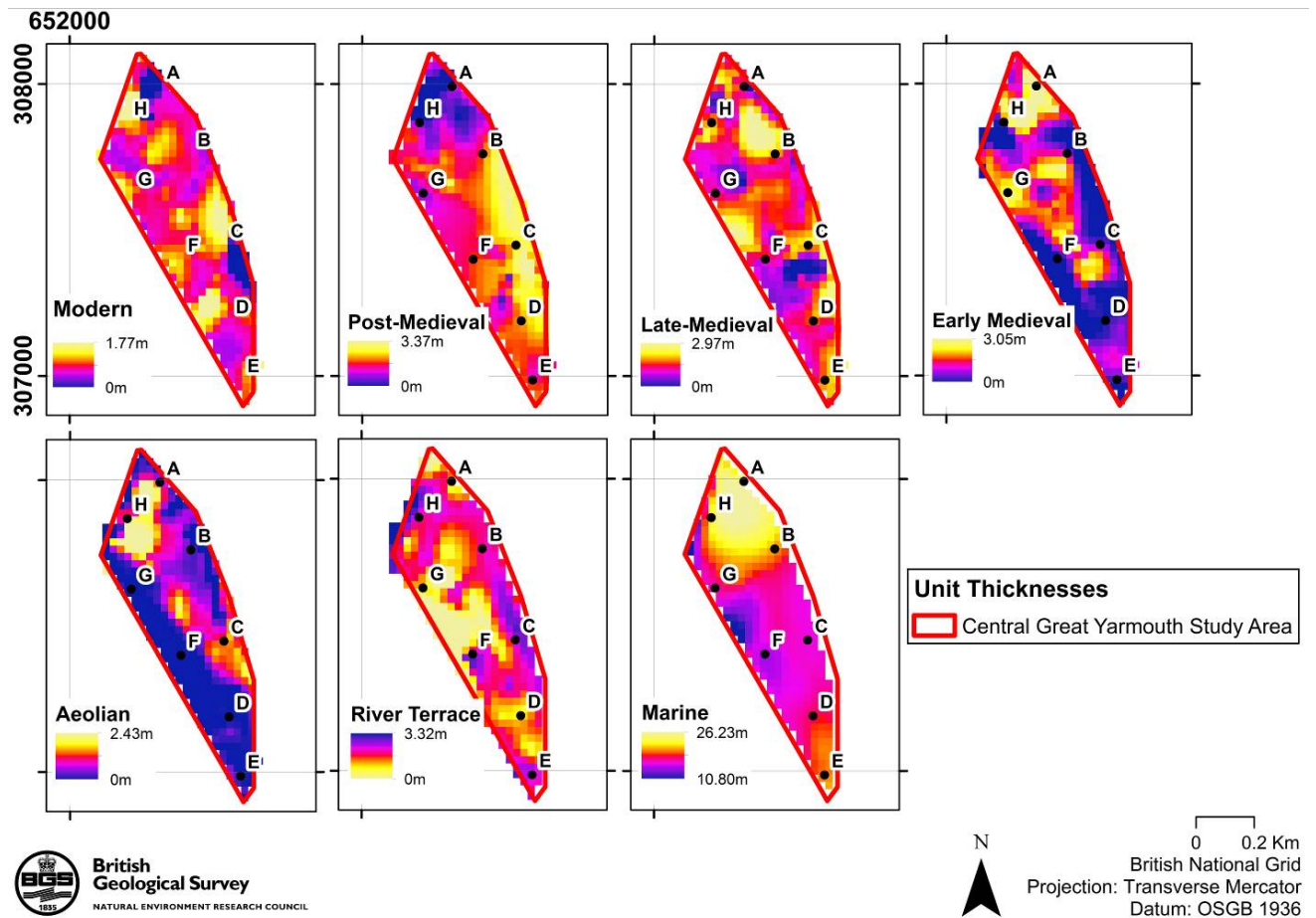


Figure 7. Deposit thicknesses for the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

The percentage contributions of the individual geo-archaeological units to anthropogenic deposit volumes in scenarios A1 and A2 are shown in Fig. 8. Under both scenarios Post-Medieval deposits provide nearly half of the sediment volume and Late-Medieval deposits represent the second largest contributor.

Deposit Type	Scenario	Minimum	Maximum	Mean	Volume
		thickness	thickness	Thickness	(x10 <sup>5</sup> m <sup>3</sup> )
		(m)	(m)	(m)	
Anthropogenic	A1	2.20	5.08	3.84	10.91
	A2	1.04	5.08	3.21	9.13
Natural	H1	15.42	32.68	24.18	65.58
Holocene					

Table 8. Anthropogenic and Holocene deposit thickness and volume statistics for the central Great Yarmouth area, Norfolk, UK. Scenarios A1-A2 as detailed in Table 3 and H1 as in Table 4.

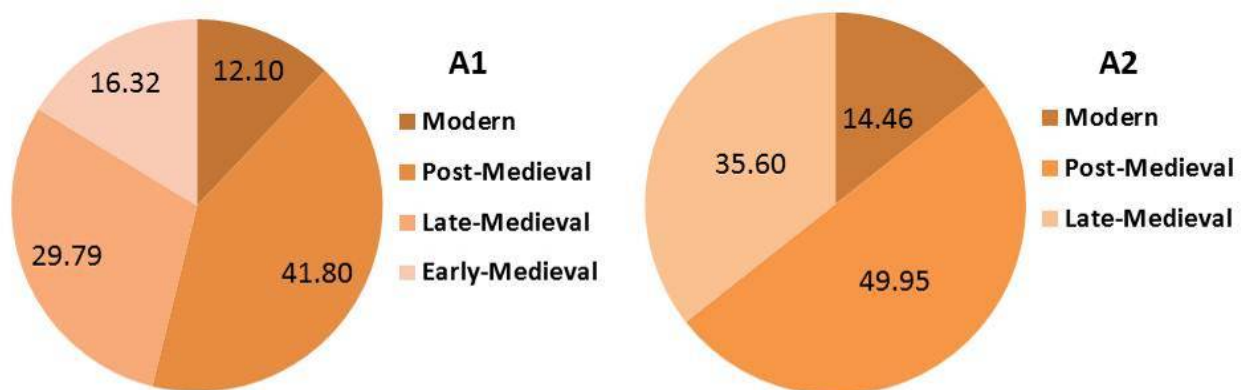


Figure 8. Percentage contributions of geo-archaeological units containing anthropogenic material to anthropogenic deposit volume in scenarios A1 and A2. Scenarios A1-A2 as detailed in Table 3.

Scenarios A1 and A2 demonstrate the presence of anthropogenic deposits throughout the study area; minimum anthropogenic deposit thicknesses equal 2.20 m in A1 and 1.04 m in

A2. In both scenarios, greatest thicknesses of anthropogenic deposits are found towards the east and in the centre of the study area around King Street (Fig. 9). In these areas the buried natural Holocene sediments may be masked by as much as 5.08 m of artificial deposits. Both anthropogenic deposit scenarios display relatively low sediment thicknesses around Fuller’s Hill although this is slightly less pronounced in scenario A1. The most prominent differences between the two scenarios arise around Stonecutters Way and east of the Conge where anthropogenic deposit thicknesses are significantly greater in A1 than A2.

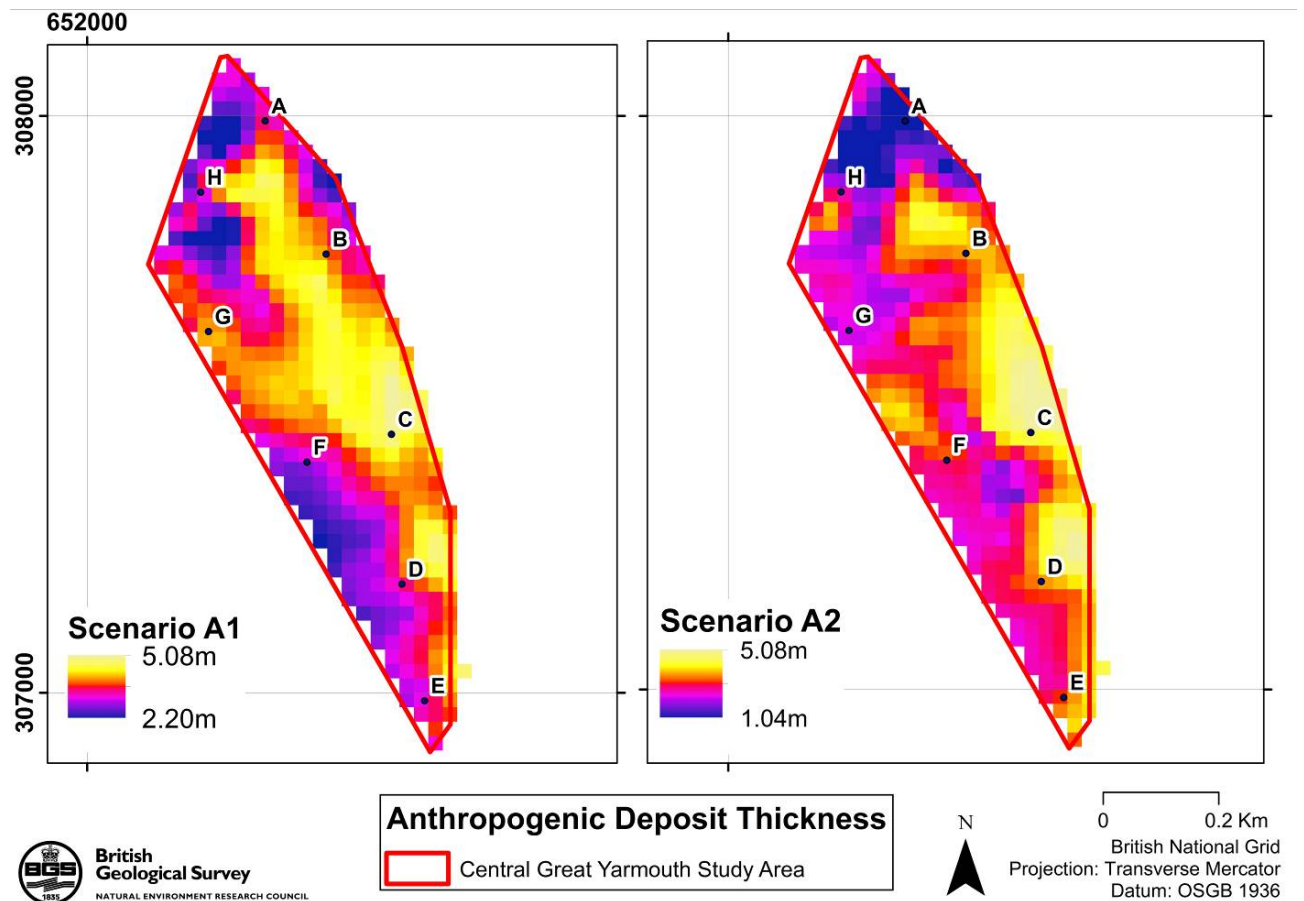


Figure 9. Anthropogenic deposit thicknesses in the central Great Yarmouth area, Norfolk, UK. Scenarios A1-A2 as detailed in Table 3. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

The percentage contributions of the individual geo-archaeological units to Holocene deposit volume in Scenarios H1 are shown in Fig. 10. Marine deposits are by far the largest component of Holocene sediment volumes in the study area; sediments of the Post-Medieval and Late-Medieval geo-archaeological units provide the second and third largest components, respectively.

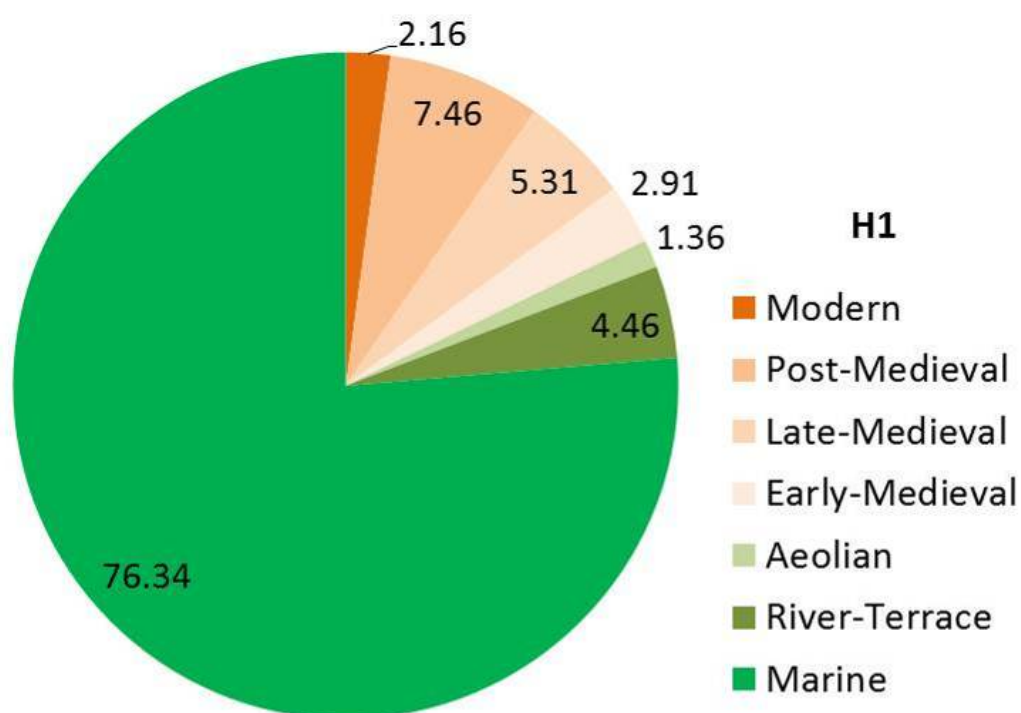


Figure 10. Percentage contributions of the seven geo-archaeological units to Holocene volume in Scenario H1. Scenarios H1 as detailed in Table 4.

Total Holocene deposit thicknesses vary across the study area. Thicker deposits are present near Fuller’s Hill and at Middlegate (Fig. 11). Thinner deposits are evident in the Greyfriars Way area.



fact be derived from anthropogenic sources including domestic refuse, building rubble or anthropogenically-reworked natural deposits. If it is assumed that Early-Medieval deposits comprise solely anthropogenic deposits, this figure increases to 17.84%.

<b>Holocene Scenario</b>	<b>Anthropogenic Scenario</b>	
	A1	A2
H1	17.84	14.93

Table 9. Percentage contribution of anthropogenic deposit volume (scenarios A1 and A2 as in Table 3) to Holocene sediment volume (Scenario H1 as in Table 4) in the central Great Yarmouth area, Norfolk, UK.

Spatial variability in the proportion of anthropogenic to natural Holocene deposits can also be seen within the study area (Fig. 12). The greatest anthropogenic to Holocene deposit ratio is present in central and southern regions of the study area. Four distinct highs can be seen, centred upon Kings Street, Tolhouse Street, Greyfriars Way and the region approximately 130 m east of Stonecutters. Low ratios, i.e. greater proportion of natural Holocene compared to anthropogenic deposits are focussed near Fuller’s Hill and The Conge.

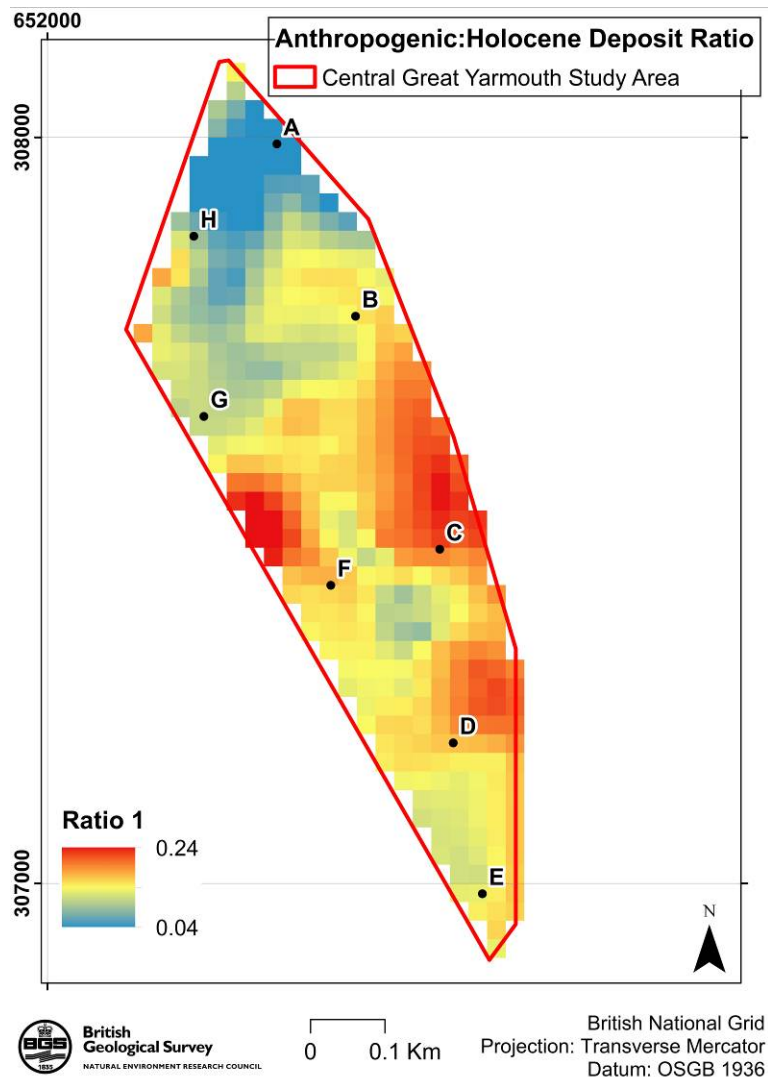


Figure 12. Ratio of anthropogenic to natural Holocene deposits within the central Great Yarmouth area, Norfolk, UK based on Scenario R1 in Table 5. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

## 5. Discussion

Significant temporal and spatial variations in geo-archaeological unit elevation, thickness and volume have been demonstrated in Sections 3 and 4. These may be due to temporal and

spatial variations in the amount of sediment deposition, the density of the sediment deposited, post-depositional reworking, post-depositional compaction and/or post-depositional erosion.

Stratigraphical and dating evidence demonstrates that the predominant depositional processes operating in the study area have varied through time from marine, fluvial and aeolian to anthropogenic activity. Anthropogenic activity may include the processes of ground excavation, waste deposition including partial or complete backfilling of excavations and raising ground level for development and foundations. Successive increases in sediment accumulation rate with time (Fig. 6) and especially from the Late-Medieval period onwards suggest that increasing levels of anthropogenic activity in the region through time, evidenced by increased population (Manship, H. 1845; Palmer, C. J. 1853; Anonymous, 2013) may have facilitated increased levels of sediment deposition. Indeed, anthropogenic activity is an extremely efficient agent of sediment transport and deposition (Hooke, 2000; Price et al., 2011) and may be less limited by proximity to sediment supply than more natural processes. Whilst the Modern geo-archaeological unit shows the greatest accumulation rate, deposits of the Post-Medieval unit provide the largest contribution to the area's anthropogenic deposits. This is due to the relative lengths of the periods used in the study: 300 years for the Post-Medieval period versus 58 years for the Modern equivalent.

Map evidence suggests that post-1800 AD, the rate of expansion of the town of Great Yarmouth beyond the limits of the town walls increased rapidly (Trinity House, 1801; British Admiralty, 1846; British Admiralty, 1866) and to a certain extent Great Yarmouth's population statistics may reflect this rather than an increase in population in the central Great Yarmouth study area itself. Large-scale destruction of the original high density tenements during the Second World War (English Heritage, 2002) and their post-war replacement with



the current, lower density street pattern in the central study area will have compounded this. This appears to have had little effect on sediment accumulation rate and continued increases in the rate after this period may reflect changing anthropogenic practices. For example, borehole records demonstrate that demolition rubble from bombing during the Second World War was crushed and re-deposited on site, potentially leading to an increased thickness of deposits in the Post-Medieval (1650-1950 AD) and Modern (1950-2008 AD) geo-archaeological units. Short-term depopulations reported for 1370-1380 AD (Saul, 1982) and 1940-1970 (Anonymous, 2013) plus longer-term post-Black Death depression of population growth rates (Platt, 1996) appear to have had little effect on sediment accumulation rates (Fig. 6).

Deposits of the seven geo-archaeological units found within the Central Great Yarmouth study area are generally distributed in stratigraphical order throughout the sequences investigated. This may be in part a result of the methodology used to reduce elevation errors produced by the interpolation process. Locally however, differences in relative elevation occur where the elevation of the top palaeosurface of the Early-Medieval geo-archaeological unit occurs at a higher elevation than the younger Late-Medieval unit. This may be the result of a combination of anthropogenic and natural processes. Sediment accumulation through anthropogenic processes including deposition of waste and construction of town wall defences and foundations during the Early-Medieval period may account for sediment thickening. Lateral changes in sediment thickness are interpreted to have created an undulating palaeosurface. Sediment accumulation in the Late-Medieval period may have infilled areas of low elevation between thicker Early-Medieval sediment mounds. The same effect may also be produced by ground excavation and back-filling in the Late-Medieval period. There is historical evidence of Late-Medieval wall reinforcement using domestic

refuse (Manship, 1845) which may account for thickening of sediment but there is no evidence of re-use of Early-Medieval material in construction. The Early-Medieval geo-archaeological also includes natural deposits. Rogerson (1976) records evidence of deposition of aeolian sand during this time which may account for sediment thickening and the production of an undulating Early-Medieval palaeosurface surface. As the dated artefacts lie generally in stratigraphical order throughout in the sediments proved in borehole drilling, evidence of significant post-depositional reworking by natural or human activity seems to be lacking in central Great Yarmouth area. It is possible that locally, Late-Medieval sediments were deposited in topographical lows of the undulating Early-Medieval palaeosurface.

Post-depositional compaction of the anthropogenic and Holocene deposits may also affect unit elevations, thicknesses and volumes. Geo-archaeological units at greater depths, overlain by greater thicknesses of deposits are likely to be particularly affected. As such, this process is likely to impact more on the older natural Holocene deposits than the overlying anthropogenic units. Peat layers present within the Breydon Formation are likely to be particularly prone. Arthurton et al., (1994) demonstrated a conspicuous vertical displacement of 1.5 m of the Breydon Formation surface in the vicinity of Mautby [NGR 648061 312384]. They regarded this displacement as being largely due to progressive natural loading of the Breydon Formation sediments, especially the middle peat, combined with consolidation resulting from artificial dewatering of the uppermost few metres of the formation. Mautby lies approximately 5 km north-east of the central Great Yarmouth study area and whilst the Breydon Formation in the vicinity of Mautby is exposed at surface, that in the current study area is overlain by the North Denes Formation and anthropogenic deposits. The magnitude of post-depositional compaction at Mautby is therefore unlikely to be applicable to the central Great Yarmouth study area.

Post-depositional erosion is also likely to have affected geo-archaeological unit elevations, thicknesses and volumes. The temporal and spatial variations in erosion processes are harder to quantify, especially from borehole records where erosional features are less likely to be identified than from exposed sections. The following general trends can be observed:

- 1) By definition, coastal erosion requires proximity to the coastline. Periods of inundation interspersed with by the re-establishment of terrestrial conditions have been identified in the region throughout the Holocene (Arthurton et al., 1994). Generally, however, the eastern extent of the study area is likely to have been most exposed to coastal processes. Shoreface and beach deposits are demonstrated to have prograded south- and eastwards since the 13<sup>th</sup> Century (Arthurton et al., 1994) demonstrating negligible coastal erosion during this period in the central Great Yarmouth study area;
- 2) Relatively rapid sea-level rise modelled during the early Holocene (Shennan et al., 2006) will have helped to reduce the effect of coastal erosion on deposits of the Breydon Formation (Marine geo-archaeological unit), especially in eastern areas as sediments deposited in shallow water depths are likely to have become rapidly out of reach of wave action and the shallower tidal currents.
- 3) Areas exposed to the southwest are likely to have been most prone to wind erosion, at least during the period of operation of the current wind climate.
- 4) Deposits of the Late-Medieval, Post-Medieval and Modern geo-archaeological units are likely to have been relatively unaffected by wind erosion as closure of the town walls in 1396 AD (Potter, 2008) may have gone some way to sheltering the central Great Yarmouth area. Conversely, the completion of the town walls is also likely to have reduced deposition of wind-blown sediment.

5) Erosion by anthropogenic activity, in the form of excavation of the ground which may be subsequently partly or wholly back-filled, is likely to have increased in line with the increasing population and changing anthropogenic practices examined above, although modern planning regulations may have checked this to some extent in recent years. However, the effects of anthropogenic erosion may have been outweighed by high anthropogenic deposition rates.

Selected methodological procedures may also impact upon the geo-archaeological unit and scenario data presented above. When calculating statistics, MapInfo 8.0 includes only grid cells that are completely contained within the study area and so the volume calculations presented above are likely to be an underestimate of the total. However, any underestimate of unit volumes caused by this process is likely to be within the margin of error caused by interpolation between borehole locations. In addition, the methodology outlined above records predominantly the effect of anthropogenic activity on the geological record where deposition of material results. As such, areas of worked ground which are characterised by removal of material are likely to be less well represented. Anthropogenically-induced forms of post-depositional compaction are also unconstrained in the methodology. The impact of anthropogenic activity on an area's geological record and geomorphology are, therefore, likely to be greater than demonstrated above.

Over the study area as a whole, anthropogenic deposits represent a significant contribution to the Holocene geological record of Great Yarmouth. This occurs despite the period of deposition of the anthropogenic deposits (1350-2008AD) representing only 5.69% of the time-span of the Holocene (11,700BP-present). Using even the most conservative of the scenarios presented above, measurable thicknesses and quantifiable volumes of artificial

deposits are present, substantially impacting the region's geological and geomorphological record. These deposits could be used as one measure on which to characterise the proposed Anthropocene epoch. It is recommended that this methodology is applied to other locations in the UK and worldwide in order to assess the effects of population density, occupation length, agricultural practices and cultural tendencies on artificial sediment thickness and the anthropogenic contribution to the geological and geomorphological record.

## **6. Conclusions**

A methodology for determining anthropogenic deposit thickness and assessing the contribution of these deposits to the geomorphology and geological record of an area is presented here. Application of this methodology to a portion of Great Yarmouth, Norfolk, UK reveals significant human-landscape interaction and anthropogenic modification of the local sedimentary environment. The natural topography may be masked by up to 5.08 m of anthropogenic deposits and approximately 15% of what would traditionally be regarded as the area's Holocene deposit volume may in fact be derived from anthropogenic sources such as rubbish, building rubble or anthropogenically-reworked natural deposits.

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Anthony Cooper and Vanessa Banks (BGS) are thanked for invaluable discussion throughout the preparation of the article. HJ, RL and SJP publish with the permission of the Executive Director of the British Geological Survey (Natural Environment Research Council). Funding provided to HJ through the 2009 Crown Estate-Caird Research Fellowship is gratefully acknowledged. Boreholes drilled for the Great Yarmouth Archaeological Map were funded

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## **Tables**

Table 1. The Quaternary sequence within the Great Yarmouth area, adapted from Arthurton et al., (1994). Artificial ground categories as in Ford et al., (2010). Proposed Ages and Formation/ Groups denoted in italics.

Table 2. Lithology and age characteristics of the seven geo-archaeological units identified in the central Great Yarmouth area, Norfolk, UK. Proposed Ages and Formation/ Groups denoted in italics.

Table 3. Anthropogenic deposit thickness scenarios for the central Great Yarmouth area, Norfolk, UK.

Table 4. Holocene deposit thickness scenario for the central Great Yarmouth area, Norfolk, UK.

Table 5. Scenario for the ratio of anthropogenic to Holocene deposits thickness in the central Great Yarmouth area, Norfolk, UK.

Table 6. National Grid References for places referred to in sections 3 and 4 and figures 4, 5, 7, 9, 11 and 12.

Table 7. Geo-archaeological unit thickness and volume statistics for the central Great Yarmouth area, Norfolk, UK.

Table 8. Anthropogenic and Holocene deposit thickness and volume statistics for the central Great Yarmouth area, Norfolk, UK. Scenarios A1-A2 as detailed in Table 3 and H1 as in Table 4.

Table 9. Percentage contribution of anthropogenic deposit volume (scenarios A1 and A2 as in Table 3) to Holocene sediment volume (Scenario H1 as in Table 4) in the central Great Yarmouth area, Norfolk, UK.

## **Figures**

Figure 1. The central Great Yarmouth study area and location of boreholes drilled for the Great Yarmouth Archaeological Map. Inset: point denotes location of study area in Eastern

England. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 2. The base of Holocene deposits study area, Great Yarmouth, Norfolk, UK.

Boreholes from the BGS's Single Onshore Borehole Index and constraining points are shown. Inset: point denotes location of study area in Eastern England. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 3. Variation in maximum, mean and minimum elevation of the top surface of the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK.

Figure 4. Surface elevations for the top of the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK. All elevations are metres above Ordnance Datum Newlyn. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 5. Base surface elevations of Holocene deposits within the central Great Yarmouth area, Norfolk, UK. All elevations are metres above Ordnance Datum Newlyn. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 6. Average annual sediment accumulation rates within the central Great Yarmouth area, Norfolk, UK. Geo-archaeological unit average ages derived from age ranges in Table 2 and converted to years before 2011AD. Green point denotes natural geo-archaeological unit; red point denotes geo-archaeological units containing anthropogenic material.

Figure 7. Deposit thicknesses for the seven geo-archaeological units identified within the central Great Yarmouth area, Norfolk, UK. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 8. Percentage contributions of geo-archaeological units containing anthropogenic material to anthropogenic deposit volume in scenarios A1 and A2. Scenarios A1-A2 as detailed in Table 3.

Figure 9. Anthropogenic deposit thicknesses in the central Great Yarmouth area, Norfolk, UK. Scenarios A1-A2 as detailed in Table 3. Locations A to H as Table 6. The National Grid and other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

Figure 10. Percentage contributions of the seven geo-archaeological units to Holocene volume in Scenario H1. Scenarios H1 as detailed in Table 4.

Figure 11. Holocene deposit thicknesses in the central Great Yarmouth area, Norfolk, UK. Scenario H1 as detailed in Table 4. Locations A to H as Table 6. The National Grid and

other Ordnance Survey data © Crown Copyright and database rights 2013. Ordnance Survey Licence No. 100021290.

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