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History of Mid- and Late Holocene Palaeofloods in the Yangtze Coastal Lowlands, East China: Evaluation of Non-Pollen Palynomorph Evidence, Review and Synthesis

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Abstract: The surface of the lowland deltaic plain around Taihu (Lake Tai), south of the Yangtze river mouth in eastern China, lies near sea level and until recent drainage and development by human societies was mostly covered by wetlands of various types. It was created by regular overbank flooding, mainly from the Yangtze, and the deposition of mostly mineral sediments over the several millennia since sea level regained its current altitude in the early mid-Holocene and progradation of the Yangtze delta began. Fluvial activity has therefore been the dominant influence on sedimentation in the Taihu lowlands, and in the lower Yangtze valley generally, and has determined the character of the mainly inorganic sediment sequences that have accumulated there, with autochthonous deposition of organic sediments within the local wetland plant communities playing a minor role. The presence of both clastic flood horizons and peat layers within the deposits of the Taihu plain attests to great variability in the magnitude of fluvial input from the Yangtze, with repeated extreme floods occurring at some periods, but with periods when the growth of peat layers shows low water tables, little exogenic sediment input and so little fluvial influence. We have examined the published evidence for these different depositional environments in the lower Yangtze and the Taihu plain during the Holocene, comparing the flood history with the middle and upper reaches of the Yangtze catchment. Discrete phases of high or low flooding influence are recognised, and these correspond with large-scale Holocene climate history. Intensified human land use in recent millennia has complicated this relationship, amplifying the flooding signal. Our palynological research shows that algal microfossil type and abundance is a useful proxy for changing water depth and quality in the aquatic environments of the Holocene Taihu wetlands, and can recognise flooding events that are not registered in the floodplain lithological sequences.

Keywords: Yangtze river; Holocene; palaeofloods; non-pollen palynomorphs

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1. Introduction

It can be no surprise that the coastal lowlands around Lake Tai (Taihu), to the west of Shanghai in eastern China, have been greatly influenced by fluvial action in the mid- and Late Holocene, as their surface altitude is very low, mostly between 2 and 5 m above sea level, and they lie between the Yangtze (Changjiang) river to the north, one of the largest rivers in the world, and the major Qiantang river to the south, which empties into Hangzhou Bay (Figure 1). There are also several minor rivers that drain the uplands of Tian-Mu-Shan, that fringe the plain to the west, or run between Taihu and the sea, for example the Tiaoxi, Nanxi and Wusongjiang rivers to the south, west and east of the Taihu lake respectively [1,2]. These, and many lesser streams and creeks, have formed an intricate network of drainage channels across the Taihu lowland [3–5] which also had the potential to contribute fluvial sediments to the plain's depositional facies. The Taihu lowland, and nearby coastal lowlands in the area such as the Ningshao plain south of Hangzhou Bay, is an alluvial floodplain that, since its creation about 7000 years ago and its subsequent progradation [6], has always experienced high groundwater tables and surface waterlogging, including many shallow lakes [7,8], and so naturally has supported wetland vegetation of various types [9–11].

These wetlands have been much altered and reduced by agricultural development, eutrophication, drainage and urbanisation over the last two millennia but particularly in recent times [7,8,12–16], and the plain's hydrology is likely to be even more affected in future because of recent major damming of the middle Yangtze [17,18], which will result in greatly reduced water discharge in the river's lower reaches, with reduced fluvial sediment input in the Taihu area [19–22]. Throughout mid- and late Holocene times, however, sedimentation in the low-lying coastal plain to the south of the main Yangtze river channel has been massive, and has produced the prograding Yangtze Delta [23–27]. Sedimentation in the Taihu plain has been naturally governed by three main processes: marine influence through fluctuations in sea level and storm surges, autochthonous depositional regimes within freshwater wetlands, and fluvial input from the Yangtze and the smaller rivers that drained the area. Of these, flooding from the Yangtze has been the most important, certainly since postglacial sea-level readjustment was completed in the late mid-Holocene [28–33].

While moderate annual seasonal Yangtze flooding has been a constant factor, introducing fine-grained minerogenic sediment into the floodplain sequence, major floods have occurred regularly throughout the Holocene, continuing into modern times [34,35], with periods during which very extreme flood events affected the Taihu lowlands as well as many other parts of the Yangtze valley [36,37]. Such extreme flooding events were not confined to the Yangtze, although the huge Yangtze catchment and river water discharge rates would exacerbate them, and have been recorded throughout eastern Asia, as in north China [38–45], Japan [46,47] and Korea [48–50]. As the timings of the major flooding phases in all these places correlate closely, it is clear that a regional external driver of extreme freshwater flooding has been involved, with some periods during the Holocene particularly affected. Periods of extreme flooding often had major repercussions for human culture and settlement [51,52], including migration and wars [53–57]. Occasionally major floods were triggered by other factors such as destabilisation and failure of valley palaeolake debris dams [58,59], causing outburst flooding. In almost all cases, however, the linkage of flood events to climate variability and extreme rainfall seems established [60], and the history of the East Asian Summer Monsoon (EASM) [61–63] is central to this, with human land use, especially deforestation, an exacerbating factor in more recent times [64–68]. In this paper we review the evidence for major river flooding and its impacts in the lower Yangtze, primarily in the lowland plain around the Taihu lake, and present new data regarding the value of microfossil assemblages as subtle indicators of past water level changes, and hence for the recognition of major fluvial discharge events.

2. The Study Area—Geological and Environmental Settings

2.1. The Yangtze Delta and the Taihu Lowlands

The Yangtze Delta is a sedimentary feature of relatively recent, mid-Holocene origin [69–71] (Figure 1), and owes its creation mainly to fluvial transport and deposition of clastic sediment derived from erosion in the catchment of the lower parts of the river system [23,72]. Beneath the Holocene sediments of the Taihu plain, however, are many metres of clastic sediments of pre-Holocene age [73,74], some of which are also of fluvial origin [75]. During the main glacial, Lateglacial and earliest Holocene periods floodplain wetland deposits were confined to the deeply incised valleys of the Yangtze and Quiantang rivers [76–79]. Sea level rose swiftly in the early Holocene [30,31,33,80] until about 7000 years ago, after which major deceleration of the rate of sea-level rise greatly reduced the Yangtze's rate of flow and it changed to an aggrading fluvial system, thus becoming prone to flooding.

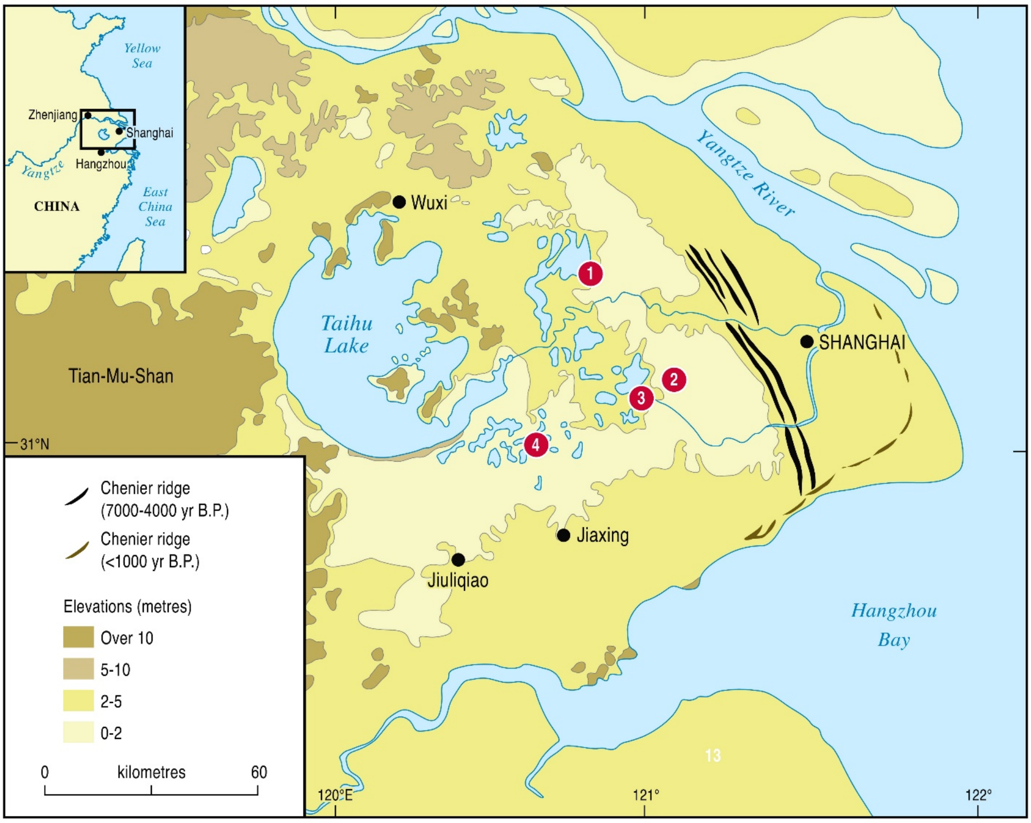

Figure 1. Location of the study area to the east of Taihu Lake in the Yangtze coastal plain, showing the topography, location of smaller lakes and the position of the four study sites 1. Chuodun 2. Tianyilu 3. Dianshan 4. Pingwang. Adapted from Innes et al. [81] with permission from Elsevier.

The delta began to form [82] as the new high, stable sea level encouraged the fluvial input of water and its entrained sediment from the river into the lowlands to the south of the Yangtze mouth [83–85]. This annual alluvial sediment supply maintained the growth of the delta [86], both eastwards into the sea but also the vertical accretion of sediment within the wetland ecosystems that developed upon it, affecting delta surface morphology [87,88]. Delta expansion continued throughout the Holocene until very recently, when reduction in the river's water discharge and in fluvial sediment supply to the delta has followed the construction of many reservoirs in the Yangtze catchment in recent times, causing greatly reduced delta progradation rates [22,86,89,90]. Since the construction of the Three Gorges Dam in 2003 sediment deposition has ceased at the subaqueous delta front, which is now eroding [17,91–96].

The freshwater wetlands of the Taihu lowland owed their formation to the culmination of rapid Holocene sea-level rise to near its present level, meaning that from about 7000 cal. BP marine sedimentation in the Yangtze delta would occur only during periods of more minor and temporary positive fluctuation in sea level, and would be confined to limited areas around the delta front and to the creeks and inlets which penetrated the deltaic lowlands [5,97], such as a brief but rapid positive pulse in sea level that has been recorded on both sides of Hangzhou Bay between about 4500 and 4400 cal. BP [98–100]. The Taihu lowland has a concave morphology, forming a shallow depression [101] with the centre now occupied by the modern Lake Taihu, and with slightly higher altitude lips to both north and south. This architecture and the creation of chenier barrier ridges to the east [102–104] prevented marine inundation of the bulk of the Taihu lowland during these periodic pulses of higher sea level. Continuous high sea level, however, kept groundwater tables in this very low-lying floodplain area at or above the land surface, initiating and maintaining freshwater wetlands, with semi-aquatic and aquatic vegetation communities [105], except on the occasional small higher areas that rise out of the plain, where woodland developed.

The natural wetland ecosystems in the Yangtze delta area [15] would have been complex, mainly comprising palustrine marshland dominated by reedswamp with emergent taxa such as Cyperaceae, *Phragmites* and *Zizania* depending upon the water depth, then sedge fen with *Carex* and *Typha*, and swamp-carr communities with *Salix* and *Alnus* as hydroseral succession progressed [106,107] and terrestrialisation ensued as autochthonous sediment accumulated. Limnic clays containing plant roots are typical sediments deposited in these shallow water marsh habitats, and pollen data from several sites suggest that the Poaceae-dominated reedswamps were the most common plant community across the delta plain. In topographically lower areas, however, or when river floods occurred, deeper water existed, with aquatic plants such as *Potamogeton*, *Myriophyllum*, *Salvinia*, *Nelumbo* and *Typha latifolia*.

These lower areas formed many lakes during periods of increased rainfall and enhanced fluvial discharge during the mid-Holocene [108–110], and particularly at the time of the later Holocene (c. 4.2 ka BP) climatic deterioration [111], when Lake Taihu and many of the Yangtze lakes came into being or expanded [83,84,109,112–120], encouraged by a slow rise in sea level that started at this time [31,109]. Throughout most of the Holocene therefore, the Taihu lowland was primarily a mosaic of aquatic habitats of a range of water depths, but usually shallow marshland, undergoing hydroseral succession through sedimentation but regularly affected by hydrological disturbance through the input of fluvial water and sediment from the Yangtze, a river with regular floods but periodically of the most extreme kind [121]. As alluvial wetlands, those of the Taihu plain would have been flood-adapted and were capable of expanding greatly in size as well as depth because of sudden flooding [122], absorbing floodwaters [123], and converting areas of higher ground to wetland.

2.2. Recognition of Past Hydrological Changes

There are various ways to recognise fluvial events in the sedimentary archive, but perhaps the easiest way of gathering information on extreme fluvial conditions and palaeofloods in the lower Yangtze in the past, at least in historical dynastic times, is to accept documentary records of such events and use them to reconstruct flood history [124–131], as has been done elsewhere in China [132]. These are often detailed and there is no reason to consider them any less accurate than modern flood records [133,134]. For example, multiple phases of greatly increased water discharge from the Yangtze into the Chaohu Lake basin at the end of the Han dynasty, for which the flooding might have been at least partly responsible, and in the later Ming and Qing dynasties are noted in contemporary historical annals as extreme flooding events which disrupted settlement and agriculture there [135,136]. Yi et al. [137] noted that their documentary records of floods matched their lithostratigraphic and geochemical evidence for Yangtze floods very well, and correspondence of historical records with such palaeoenvironmental evidence is strong support for its accuracy [138].

Lithostratigraphic analyses can be highly diagnostic of overbank flood events with changes in the grain-size of minerogenic sediments, usually coarsening due to high discharge energy [39,45,119,136–146], and exogenic clastic layers within organic sediment profiles indicating sudden changes in depositional regime [147–149]. Finer-grained, sorted and well-bedded layers often represent fluvial slackwater deposits [38,43,75,140,150–160]. Soil erosion in the river catchments by increased rainfall volume, intensity and runoff was usually the cause [161,162], enhanced in the last few millennia by human land-use activity [21,98], leading to greatly increased delivery of sediment to the lower reaches, the delta and subaqueous delta front sandbars [163,164]. Lithofacies and particle-size characteristics of floodplain sediments have been shown to be sensitive to sedimentation changes and flooding in the valleys of other major rivers [165] and have had an important role in recognising flood deposits in the Yangtze valley through their pedostratigraphy [160,166], usually a well-sorted sandy silt, although sometimes of coarser grain size, even gravel. Chemical signatures in clastic layers are also diagnostic of their flood origin [35,142,148], while magnetic anomalies in Lake Tai sediments have been interpreted as flood proxy records [167,168]. Minerogenic sediment layers in recent floodplain facies correspond closely with high magnitude flood events, as at Tongling and Nanjing in the lower Yangtze area [156], and will have done so in this area in the past [117,160,169], as has been shown in other regional studies of Holocene flood histories (e.g. [41,43,47,148,170]).

Other evidence that has been interpreted as recording flood events is the presence of debris, notably tree trunks and branches that are referred to as 'palaeotrees', that occur within the clastic flood layers. That these are often mixed with coarse-grained sand and gravel sediment [141,145] indicates high-energy flash flooding and transport of material by torrents of flood water, as well as the sudden destruction of local standing trees [52,112,171–174]. The many local water bodies of the Yangtze Delta area, such as Lakes Taihu and Dianshan [141], would also have rapidly expanded [83,117,120]. That these layers of clay and silt, often sealing cultural horizons and even major cultural sites, are archaeologically 'sterile' indicates that the scale of the flooding was sufficient to bring local human settlement to an end, and even terminate whole archaeological cultures in the lower Yangtze. Although not every buried tree trunk will have been deposited because of freshwater flooding, the ages of many palaeotrees do correspond to periods of known heavy rainstorms and floods [34,52] and when found in numbers are therefore likely to be a good indicator of past high-magnitude flood events.

Where flooding did not cause major change in lithology, such as within swamps or lacustrine systems where it might have only resulted in increased water levels, deeper water should be discernable through changes in the microfossil assemblages preserved within the limnic or fluvial sediment. Some pollen and spore types, particularly *Pinus* and Filicales, are buoyant and can be transported long distances with floodwater [175]. A high pollen producer, the sudden abundance of *Pinus* pollen, particularly in slackwater deposits, may be an indicator of hydrodynamic processes and flooding [176], rather than climatic deterioration as it is often interpreted, although climate instability might have been a driver for the flooding [175,177,178].

Pollen and spores of marsh or aquatic plants might be useful where their water depth preferences are known, and their pollen is unlikely to have been transported significant distances from where the plants grew. Algal spore assemblages, however, could be the most sensitive indicators of changes in water depth [179–182] as they live in situ in the water column, although there is necessarily some overlap in their tolerances [183] so that depth interpretations can not be precise, with direction of depth changes a more reliable interpretation. Also, other variables including trophic status and temperature will have influenced algal abundance. Nevertheless, analysis of freshwater algal spore assemblages can have strong indicator value regarding increases in water depth [184]. They have been used in previous research in China [178,185] including the Yangtze Delta [186,187] and Ningshao Plain [188,189] to reconstruct water depth, for example increased *Pediastrum* or *Botryococcus* levels interpreted as indicating a rise in lake levels and/or increased precipitation [181,190–195], and although *Pediastrum* might represent eutrophication [196], that would itself be a likely result of the input of silt-laden Yangtze flood water. The blue-green alga *Gloeotrichia* is sensitive to light levels and prefers clear, open water, but not too deep, as does Volvocaceae [197]. Spores of *Zygnema* are likely to represent waterlogged marsh environments or very shallow water rather than open water [198–200]. *Mougeotia* and *Spirogyra* are common in fluvial sediments and are more likely to represent less deep open water, although their affinities are less well known [185]. Algal assemblages have been an important element in palaeoenvironmental reconstruction in wetland archaeology and palaeolimnology, including floodplain wetlands, in other parts of the world for some time [199–206].

2.3. Climate and Precipitation Changes

The dominance of the East Asian Summer Monsoon (EASM) over climate [61,207] in the lower Yangtze area is such that the great majority of water and sediment discharge to the deltaic plain takes place during the summer flood season [208–210], with much of the transported fluvial sediment retained within the sedimentary sequences there [71,177,211], and the rest deposited offshore of the delta front [22,66,98,212]. Meteorological conditions suitable for heavy rainfall in the mid- and lower reaches of the Yangtze occur when East Asian atmospheric circulation patterns and pressure systems [213] conspire to reinforce the monsoon, producing persistent and intense rainfall, and annual precipitation variability during the summer monsoon months [214,215], with high amplitude peaks in wet years, causes extreme rainfall events and major flooding [127,216–219]. These frequent and extreme floods are responsible for the acceleration of sedimentation rates [220] in the lower Yangtze lowlands, and the evolution of the floodplain in the Taihu area [156].

Increased fluvial discharge and flooding in the lower Yangtze has therefore been intimately connected with fluctuations in climate and therefore in catchment rainfall [221,222], and these were governed primarily by changes in the strength of the EASM and its interactions with the El Niño-Southern Oscillation (ENSO) events [160,161,216,223–234]. Regional research on this connection [48,49,164,217,235–237] suggests that major hydrological changes in the Yangtze valley are consistent with a stronger ENSO and weaker EASM, so that the monsoon rain belt does not penetrate far north in China and remains static over the Yangtze river, concentrating rainfall there and producing long rainstorms and extreme flood events [160,227]. Blender et al. [162] showed strong correlation between ENSO and Tibetan snow-melt, influencing runoff and hydrology in the Yangtze catchment, and Yangtze floods still correlate with ENSO [212]. Weak EASM and strong ENSO conditions also correlate well with a cold climate in eastern China [238], as shown in the $\delta^{18}O$ record from Shanbao cave [239] to the west of the Taihu plain, which agrees with the other reconstructions of monsoon history and climatic change for east China [216,228,240–243].

Li et al. [244] have produced a pollen-based reconstruction of rainfall and temperature history for the lower Yangtze region, showing that the early and mid-Holocene had a warm, wet and humid climate with a strong EASM, with a cooling and drying climate after about 5000 cal. BP as the EASM gradually weakened. This supports previous climate research in the area [176,233,245–248]. Periods of lower rainfall did occur, as between 7500 and 6500 cal. BP [249], but several high amplitude cold events are the most notable Holocene climatic features [233], occurring particularly around 8200, 5500, 4200 and 2800 cal. BP, the later examples corresponding with the stronger ENSO, and this record of abrupt climatic fluctuations confirms previous findings [120,234,250]. These climate deterioration events were global phenomena. The 8200 cal. BP event [251,252] was of considerable significance in China [228,253,254] including the Taihu region [164,233] but the major cold event starting at 4200 cal. BP was particularly pronounced [111,164,255–258] and represents the transition to the Late Holocene neoglacial period [259,260], and is now officially recognised as such [261].

As well as being much colder, there was extreme variability in precipitation from this time onwards [221,262,263], with high amplitude fluctuations leading to severe flooding, as is common during periods of climate transition and instability [264]. Such an abrupt climate change must have had a significant impact [265–269] on human settlement and agriculture in eastern China, no matter how resilient their society [270], including the Yangtze delta where the high population of the well-developed Neolithic Liangzhu culture [271–274] depended on benign climate, stable hydrological conditions and water management [275] for its subsistence. Another abrupt phase of climatic deterioration occurred after the 2800 cal. BP event with the lakes that came into being around 4000 cal. BP [225] expanding due to increased rainfall [244,276,277], magnified by river floods [151], and lasting to about 1200 cal. BP [278]. This 2800 cal. BP climate deterioration is marked in stalagmite records in China [161,242] and India [217,279], and in global environmental archives [280,281], and is one of the largest drivers of Holocene hydrodynamic instability and flooding.

2.4. Yangtze Floods

The Yangtze has always been prone to some moderate seasonal flooding because of increased monsoonal rainfall during the summer months [72,210,282], although to a limited degree and varying from year to year. There has therefore been an annual small to moderate input of river floodwater into the Taihu floodplain during the Holocene, but one that usually would not carry a large sediment load [156]. However, the Yangtze valley is a part of China notorious for great floods [283,284] and some extreme examples have occurred in the last two millennia [131], including in recent times [63,168,222]. Zheng et al. [127] have noted that great floods in late dynastic times were common between 900 and 600 cal. BP, and Wu et al. [285] and Luo et al. [286] noted that many major flood events occurred during the Ming and Qing dynasties after 600 cal. BP during an extended cold phase corresponding to the Little Ice Age [62,75,129,287,288].

High-intensity flooding has also occurred regularly in the last two centuries [35,156,289], and floods in the 19th and 20th centuries have been as bad as any in the last 1500 years. As recently as 1889, 1954 and 1998, the greatest magnitude floods have been recorded in both the mid- and lower Yangtze [146,160,168,220,290,291], with flood deposits of the 1998 event widespread [119]. The EASM rain belt has moved southwards in recent decades, bringing heavy rains and floods to the lower Yangtze [221,292,293], such as the extreme rainfall there in 2015 [219]. Usually such recent high magnitude floods have left a lithostratigraphic signature in floodplain and lake sediments [156,294]. These more recent examples provide analogues for mid- to late Holocene flood history, as the ancient and modern flood deposits are morphologically very similar [295] and represent similar depositional environments and processes [138].

3. Materials and Methods

Sub-samples from the cores were prepared for palynological analysis at five-centimetre intervals, using standard laboratory techniques [296]. Alkali digestion with NaOH was followed by sieving at 180 μm, removal of silicate mineral material with hydrofluoric acid, and acetolysis. The residue was stained before mounting on microscope slides. Although designed for pollen and spores, the work of Clarke [297] has shown that these procedures do little to affect the preservation of most other microfossils, such as algae or fungal spores. Microfossils are defined as palynomorphs which passed through the 180 μm sieve. Reference keys were used to aid identification of pollen and spores, primarily Wang et al. [298] for pollen and Zhang et al. [299] for pteridophyte spores. At least 200 land pollen grains were counted at each level, often more, as well as all aquatic pollen, pteridophyte and bryophyte spores that were present.

Full pollen data are not presented in this paper because the taphonomy of pollen grains means that they will represent extra-local as well as in situ plant communities, so providing a spatially composite pollen assemblage that derives from several plant communities in the wider area. It therefore might well not record hydrological changes at a particular site itself, and would blur any signal of rapid water depth changes, as caused by flooding events, but would record a mosaic of wetland habitats [176]. It is important to note, however, that several pollen taxa were recorded in every diagram that indicated local wetland environments of deposition, including organic soil, reedswamp and marsh, or more open water. These included Poaceae (grass) pollen grains below 40 μm, which are likely to originate from wild reedswamp and marsh grasses such as *Phragmites* and *Zizania* [298,300], and Cyperaceae, as well as the emergent aquatic *Typha angustifolia*, an important element of past Taihu wetland vegetation [11,178,301,302]. Obligate aquatic pollen types were also occasionally present in very low frequencies, notably including *Myriophyllum* and *Typha latifolia*, indicating areas of deeper water. A combined curve for aquatic pollen, which is comprised mainly of *T. angustifolia*, is shown on the diagrams, calculated as percentages of total land pollen.

The pollen data from the sites in this paper have been published previously either in full [81,260] or summary form [85,303]. In this paper we concentrate on the record of non-pollen palynomorphs (NPPs), mainly comprising algal and fungal spores [304], which are much more likely to reflect in situ hydrological conditions such as water depth. Fungal NPPs would have been produced in situ at the core sampling point and usually are hardly transported from their point of production to point of deposition [305], unless redistributed by a force such as a fluvial flooding event which might affect algal spores living in aquatic environments, which are the subject of this paper.

At least 100 algal and fungal spores were counted at each level, and their identification was achieved by reference to the illustrations and descriptions in several published papers [180,306–308] although, as many NPPs have not yet been identified and remain known only by their Type (HdV) number in the Hugo de Vries Laboratory catalogue in Amsterdam, taxonomic identification was not always possible, although the palaeoecology of individual types is well known from previous research [304,308]. HdV numbers are shown on the microfossil diagrams and with the first mention of an NPP type in the text. In this paper microfossil diagrams for each site show only the curves for selected individual NPP taxa that are present in substantial frequencies and are sensitive to water level, calculated as percentages of the total NPP counting sum. The ratio between algal and fungal spores should provide an indication of water table changes, with rises in fully aquatic algal spore frequencies showing increased water depth whereas fungal spore taxa and marsh algae represent more stable semi-terrestrial or shallow marsh conditions. Rapid rises in open water aquatic algal taxa can be interpreted as recording flooding events. Following the literature cited above, Volvocaceae (HdV-128), *Spirogyra* (HdV-130), *Gloeotrichia* (HdV-146), *Mougeotia* (HdV-313) and *Pediastrum* (HdV-760) are considered fully aquatic while *Zygnema* (HdV-58), HdV-306 and HdV-708 are considered shallow wetland reedswamp or marsh taxa. *Mougeotia* may signify less eutrophic conditions [309]. Common fungal spores considered as indicating wet semi-terrestrial conditions are Sordariaceae (HdV-55A) and *Coniochaeta* cf. *ligniaria* (HdV-172). To provide an independent measure of spore abundance for individual taxa in aquatic sediments [310,311], spore concentrations are also shown, calculated as numbers of spores per cc. of wet sediment using the *Lycopodium* exotic marker technique [312]. Stable concentration rates indicate stable sedimentation rates, so that changes in frequencies reflect real changes in microfossil proportions in the assemblage.

Radiocarbon (AMS) dates are from Beta-Analytic, Miami, on pollen (organic) residues or peat, which previously have produced consistent results [311,313]. Alluvial sediment samples are avoided as these can produce anomalous dates [314]. Dates were calibrated using Calib 7.1 and IntCal13 [315]. Microfossil diagrams were constructed using TILIA [316].

4. Results

Microfossil data from four sites in the Taihu lowlands have been chosen to illustrate NPP evidence for increases in water depth that almost certainly correspond to flooding episodes. Their locations are shown on Figure 1. Results from Pingwang and Dianshan have been presented elsewhere [81,260], whereas data from Chuodun and Tianyilu have been published only in summary form [303]. A different sediment profile at Chuodun has been investigated by Long et al. [317]. The core lithostratigraphies of the four sites are shown in Table 1.

4.1. Chuodun

Chuodun lies in the northern part of the central Taihu plain to the east of Lake Yangcheng, at 31°24′16′′ N; 120°50′37′′ E, with a ground surface altitude of 2.5 m YSD (Yellow Sea Datum). The selected taxa microfossil diagram is presented as Figure 2. The site supported shallow marsh wetland habitats, as shown by the dominance of NPP taxa indicating reedswamp or wet semi-terrestrial conditions until around 1964 cal. BP when the more terrestrial indicators decline and are replaced by increasingly high percentages of open water algae, particularly Volvocaceae. Although the lithostratigraphy is clay throughout this section of the core, around 92 cm depth there is a change to less organic clay, marking the switch from a shallow marsh to deeper open water and fully aquatic environments at the site. Floating aquatic herbs including *Myriophyllum* and *Potamogeton* are present during the open water phase, suggesting quite eutrophic conditions presumably stimulated by the silt and nutrient content of the floodwaters, which is supported by the absence of

Mougeotia, which prefers less eutrophic conditions. Total aquatic pollen frequencies are very low, however, indicating deep open water. The evidence from Chuodun suggests a flooding phase which increased water depth and therefore changed ecological communities at the site. Pollen concentration data show no rapid changes in sedimentation rate, and emphasise the abundance of Volvocaceae in the aquatic algal community.

Table 1. Core lithostratigraphy for the four sites.

Site	Depth (m)	Description
Chuodun	0.00–0.30	Agricultural soil
	0.30–0.50	Yellow-grey firm silt and clay with organic matter
	0.50–0.95	Green-grey soft clay
	0.95–1.20	Black-grey soft clay
	1.20–1.38	Green-grey soft clay
	1.38–1.50	Hard clay
Tianyilu	0.00–0.50	Organic soil
	0.50–1.60	Brown-grey firm silt and clay, rich in organic matter and herbaceous roots
	1.60–2.00	Black-grey soft silt and clay
	2.00–2.30	Green-grey soft silt and clay
Dianshan	0.00–1.00	Agricultural soil
	1.00–1.15	Brown-yellow silt
	1.15–1.90	Green-grey mud
	1.90–2.20	Dark grey mud
	2.20–2.45	Green-grey highly organic mud
	2.45–2.60	Black peat
	2.60–2.65	Brown-black peaty mud
	2.65–3.05	Green-grey mud
	3.05–3.45	Grey mud with calcium carbonate patches
	3.45–3.50	Hard clay
Pingwang	0.00–0.45	Organic soils
	0.45–1.10	Brown-yellow grey firm clay
	1.10–1.25	Black-grey soft clay
	1.25–1.80	Green-grey soft clay
	1.80–2.10	Brown-grey soft organic-rich clay
	2.10–3.10	Dark grey soft organic-rich clay with small shells in the upper part
	3.10–3.70	Green-grey soft silt and clay
	3.70–3.80	Black-brown peat
	3.80–4.00	Hard clay

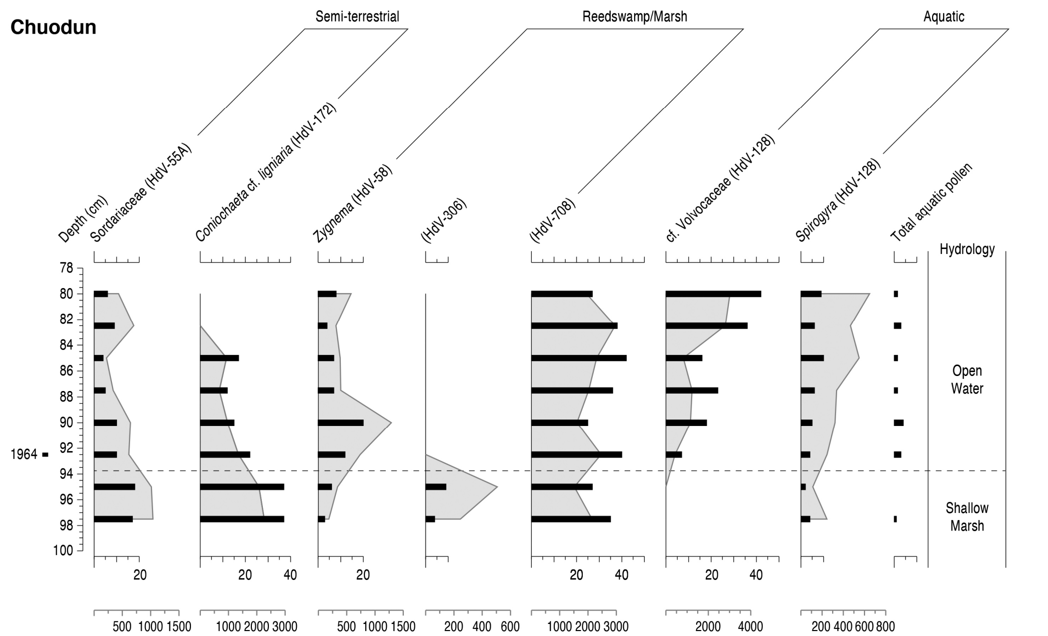

Figure 2. Frequencies of selected NPP taxa (histogram bars calculated as % total NPPs) from Chuodun. A combined aquatic pollen curve is also shown, calculated as percentages of total land pollen. Pollen concentration values for the NPPs are shown as shaded curves (numbers of grains per cc. on the secondary x-axis).

4.2. Tianyilu

Tianyilu lies 600 m east of Siqian village, to the east of Lake Dianshan at 31°11′54″ N; 121°6′40″ E with a ground surface altitude of 1.9 m YSD. The selected taxa microfossil diagram is presented as Figure 3. The site supported shallow marsh wetland habitats, as shown by the high frequencies of taxa indicative of wet surface marsh or shallow reedswamp, until 4000 cal. BP when the curves for fully aquatic taxa increase sharply, particularly Volvocaceae, *Spirogyra* and *Mougeotia*. *Coniochaeta* cf. *ligniaria* and HdV-708 are especially reduced, while Sordariaceae percentages decline more gradually, this general decomposer of plant material remained present in the locality. Pollen of floating and emergent aquatic plants occurs in low frequencies in this open water phase of the core, including *Myriophyllum* and *Nelumbo*, while *Typha* percentages are low to moderate. The total aquatic pollen curve comprises mainly *Typha*. The change in hydrological regime with significantly increased water depth at 4000 cal. BP was quite swift and represents one or more major fluvial flooding events. Concentration rates mirror the percentage changes well, and changes in taxa frequencies reflect changes in proportions in the assemblage, notably the switch from *Coniochaeta* to Volvocaceae as water levels deepened significantly. The age of 4000 cal. BP is significant in that it falls within a phase of climatic deterioration that has considerable evidence for flooding in most parts of the Yangtze catchment, as discussed below.

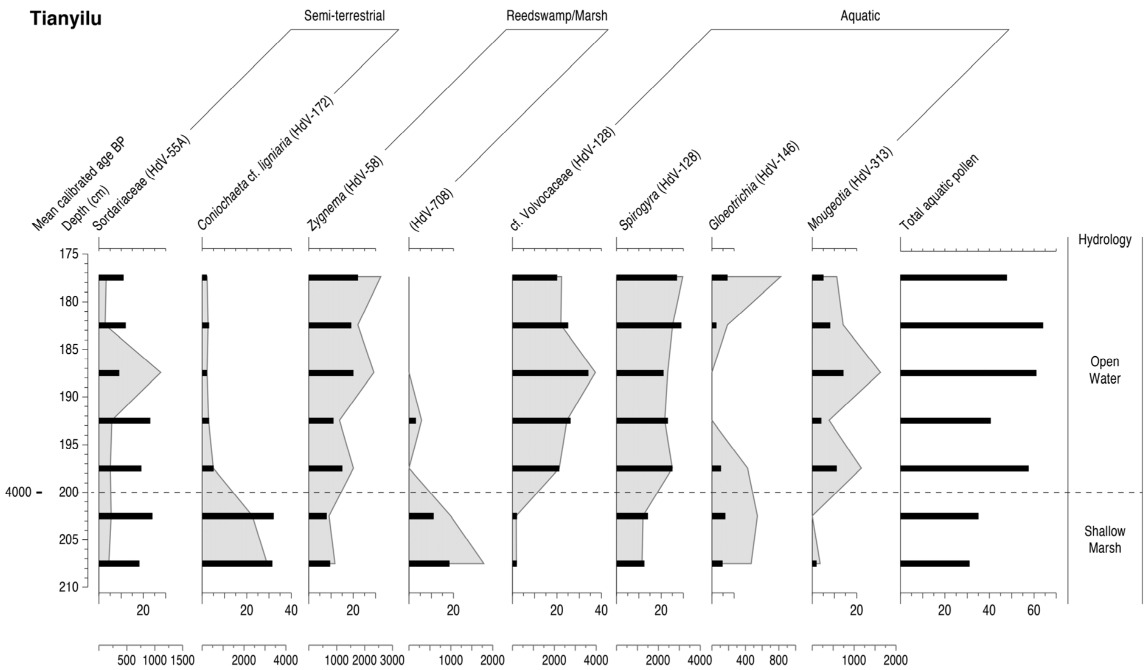

Figure 3. Frequencies of selected NPP taxa (histogram bars calculated as % total NPPs) from Tianyilu. A combined aquatic pollen curve is also shown, calculated as percentages of total land pollen. Pollen concentration values for the NPPs are shown as shaded curves (numbers of grains per cc. on the secondary x-axis).

4.3. Dianshan

Dianshan lies on the eastern shore of Dianshan Lake at 31°05′35″ N; 120°59′0″ E with a ground surface altitude of 2 m YSD. The selected taxa microfossil diagram is presented as Figure 4. The site supported wetland marsh habitats depositing organic sediments in shallow reedswamp environments until around 1514 cal. BP when a transition to open water began. Reedswamp types HdV-306 and HdV-708 decline. Algal taxa increase with HdV-119 added to the assemblage, *Gloeotrichia* high and Volvocaceae percentages rising. Pollen of fully aquatic plants *Nelumbo*, *Myriophyllum* and *Potamogeton* occur in the open water phase of Figure 4 and record significant water depth, although *Typha* is the most common in the low total aquatic curve. The introduction of *Pediastrum* and

Botryococcus, and peaks of *Aphanizomenon*, indicate that water depth continued to increase and some eutrophication occurred. The succession suggests perhaps two phases of fluvial flooding that changed shallow reedswamp to open water and then to increased water depth. Flooding was perhaps of repeated and major type but not extreme, as the shift to more aquatic systems was not sudden, but continuous. The location of the site adjacent to the large lake Dianshan will have made it susceptible to the effects of flooding and water level rises and it may have been subsumed within the lake [81]. The concentration curves are similar to the percentage changes, suggesting stable sedimentation rates, with Volvocaceae and *Gloeotrichia* the most abundant assemblage components.

4.4. Pingwang

Pingwang lies to the south-east of Lake Taihu at 30°57′30′′ N; 120°38′25′′ E, with a ground surface altitude of 1.6 m YSD. The selected taxa microfossil diagram is presented as Figure 5. The lower part of the core contains a thin peat which probably formed under higher saltmarsh conditions [260], followed by shallow water reedswamp and marsh as water tables continued to rise, shown by high frequencies of HdV-306, HdV-708 and semi-terrestrial fungal taxa. Some aquatic spores are present but do not dominate the assemblage and indicate the progression to shallow water. The semi-terrestrial and reedswamp taxa fall until about 7650 cal. BP when an increase in water depth occurs, with deeper water indicators Volvocaceae, *Gloeotrichia* and *Pediastrum* increasing. Floating aquatic pollen taxa *Myriophyllum, Potamogeton* and *Nelumbo* occur in low values, with *Salvinia* also present, but most of the low total aquatic pollen curve comprises *Typha*. Concentrations are generally high but mirror the percentage changes, indicating slow and stable sediment accumulation. Although not a dramatic change, the evidence suggests a significant increase in water depth, and possibly also eutrophication, that is most likely to represent substantial flooding. Evidence for floods of this age is not common in the lower Yangtze area, but this date corresponds to the date of 7700 cal. BP recorded by Song et al. [176] for a major flood in a core in the Yangtze valley just to the north of Nanjing, during a brief period of climatic deterioration.

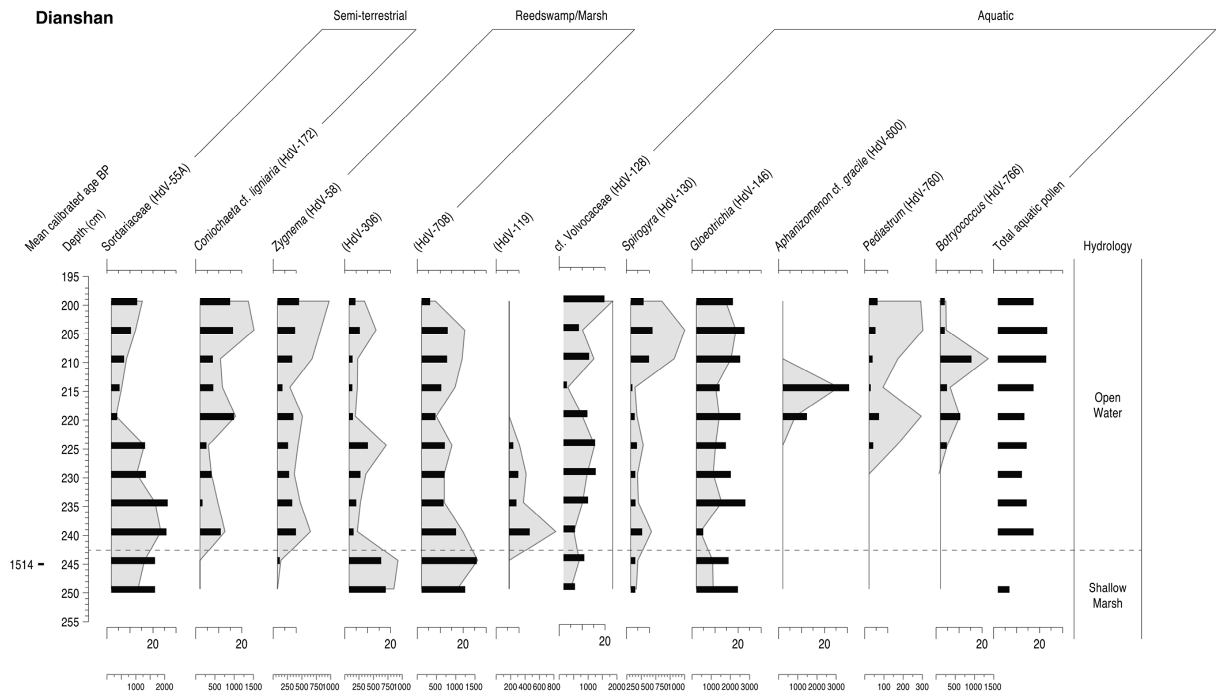

Figure 4. Frequencies of selected NPP taxa (histogram bars calculated as % total NPPs) from Dianshan. A combined aquatic pollen curve is also shown, calculated as percentages of total land pollen. Pollen concentration values for the NPPs are shown as shaded curves (numbers of grains per cc. on the secondary x-axis).

4.5. Summary

These four examples from the Taihu lowland differ in the timing and magnitude of the evidence for flooding at each site, but they have demonstrated the ability of algal assemblages to recognize significant increases in water level that are not apparent in the lithostratigraphy, indicating rapid increases in water depth in already aquatic locations, although the ecological tolerances and preferences of these taxa are not exact and should be interpreted in assemblage terms, rather than individually. The curves for total aquatic pollen vary between the sites, although are never high, and mainly comprise *Typha*, common in the Taihu lowlands throughout the Holocene at a range of water depths.

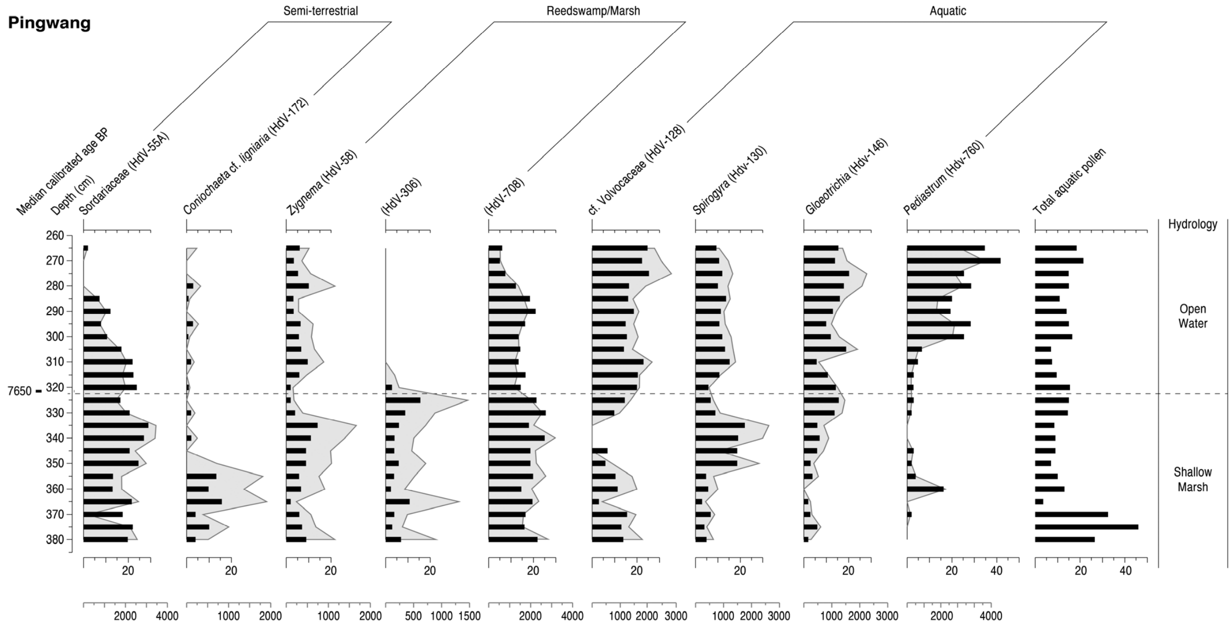

Figure 5. Frequencies of selected NPP taxa (histogram bars calculated as % total NPPs) from Pingwang. A combined aquatic pollen curve is also shown, calculated as percentages of total land pollen. Pollen concentration values for the NPPs are shown as shaded curves (numbers of grains per cc. on the secondary x-axis).

These aquatic pollen curves largely reflect *Typha* pollen taphonomy and the distance from the coring site of *Typha* beds. They do not reflect conditions at the sites themselves. These sites occur across a significant time range through most of the Holocene, and can be compared with the existing evidence for lower Yangtze floods, and all four fall within the age ranges for flooding phases in the Taihu plain discussed below, that are derived from synthesis of the published literature. They show that the use of aquatic algal microfossils can be an important additional proxy method in the study of floodplain hydrology and flood history, particularly when used in association with other techniques.

5. Discussion

5.1. Hydrology of the Taihu Lowland Plain

The overall postglacial lithostratigraphy of the Taihu lowland plain can be reconstructed from the many boreholes that have been completed there and in deltaic offshore cores, and comprises several facies, including lacustrine, riverine, deltaic, floodplain, marsh, lagoonal and estuarine-marine units [77,275,318–320]. Changes between these sedimentary units in site lithologies reflect changes in depositional environments and therefore in hydrological regimes. Freshwater floodplain sedimentation in the Yangtze delta lowland is governed by accretion rate, with high rates of fluvial sediment supply usually producing mineral-dominated deposits with low organic content [321], as most sedimentation in such environments occurs during low-intensity, regular river floods [26]. Most Yangtze delta deposits are therefore floodplain clays and silts of alluvial origin [188,322,323] and the presence of in situ plant remains in most of them indicates steady accumulation of wetland sediments within shallow-water, hydrologically stable fen and swamp environments, as the delta gradually accreted vertically and prograded laterally. This type of autogenic hydrological succession through increasingly terrestrial wetland plant communities would have been the natural ecosystem in the lower Yangtze valley and the Taihu/delta lowlands [1].

Annual low-scale flooding from the river system would have had only moderate effects, raising the water table and laying down organic muds and clays in areas of lower altitude where semi-aquatic habitats would be maintained, and temporarily flooding more terrestrial land surfaces. In periods of low rainfall, or at slightly higher altitudes in the floodplain, fully organic peats would form under the process of terrestrialisation, and surface altitude would have been an important regulator of sedimentation type in the floodplain areas. Most sediments in the lower Yangtze and Taihu lowland represent these stable hydrological conditions [105], deposited in a range of wetland types with various water depths, but undergoing autogenic sedimentation.

The four examples shown in this paper, despite their differences in age, are alike in showing significant and sometimes rapid changes in local hydrology which must have been generated by major, or even extreme, flood events with significantly increased water depth causing a switch between a macrophyte-dominated marsh or shallow water fen-swamp state to an algae-dominated open water state, similar to hydrological successions in some recent shallow Yangtze lakes [7,15], including present-day Lake Taihu [116]. They also illustrate the types of evidence that can be diagnostic of such a rapid environmental change. Such major inputs of fluvial water during great flood events would suddenly alter the hydrology [324], increasing water depth and reversing the natural sedimentation regime, so that shallow aquatic marsh habitats would become deep, and semi-terrestrial wetlands would become fully aquatic, perhaps subsumed into the many already existing lakes of the floodplain, as the *Pediastrum* record [192] indicates for Pingwang. These sudden shifts in water depth would often be expressed in the sedimentary lithology, and lake sediments can be very good archives for preserving palaeoflood stratigraphies [325], using techniques such as magnetic measurements and grain-size analysis, as in Lake Taihu [168]. At already aquatic but shallow sites, however, the change might well be most observable in the biostratigraphy with deeper water micro-organisms becoming favoured, particularly algae, exacerbated by increased eutrophication as major amounts of sediment and nutrient-rich water were swept into the aquatic ecosystem, encouraging microphytic diversity and algal blooms for taxa including *Pediastrum* [196].

In the following sections we present the evidence for periods of hydrological stability and peat formation (Table 2) and for phases of major or extreme flood events (Table 3) in the lower Yangtze valley and Taihu lowlands/Ningshao plain, deduced from the published literature. A synthesis of the data is shown in Figure 6, divided into the phases when great floods were either common or rare. These broad phases can not be considered mutually exclusive, as exceptions to the general trend will occur within them, and they will be modified by future research. The existing dataset is large enough, however, to come to general conclusions regarding Holocene flood history in the study area. For correlation with climate, graphs of fluctuations in temperature (and monsoon precipitation) during the Holocene in the study area are also shown on Figure 6, derived from Shao et al. [239] at Shanbao Cave, the $\delta^{18}O$ record closest to the Taihu lowland and at the same latitude, and from the Lianhua Cave [242], which has a record that continues up to the present day, unlike the Shanbao record which does not continue beyond about 2000 cal. BP.

5.2. Terrestrialisation and Peat Formation

Peat deposits indicate sedimentation at or near the wetland surface, deriving from plants of the 'in situ' marsh vegetation [204], and there are peat layers of various ages within the stratigraphic sequences of the lower Yangtze and Taihu lowlands, including some dated to the Lateglacial and to the very beginning of the Holocene [77,319], although the oldest is 32,325 cal. BP at Hemudu south of Hangzhou Bay at 36 m depth [188]. In a borehole offshore of the present Yangtze mouth Zhao et al. [326] recorded a floodplain freshwater marsh peat almost a metre thick that was dated as forming from 19,000 to 11,300 cal. BP, Stanley et al. [327] recorded a thin peat dated to about 15,800 cal. BP resting upon the stiff Pleistocene clay at core YZ-1, 30 km west of Shanghai, Li and Wang [318] recorded peats dated to about 13,500 cal. BP on the north bank of the Yangtze, Liu et al. [322] recorded a thin peat dated around 12,758 cal. BP at 36 m depth at Qidong at the seaward end of the delta, Liu et al. [188] reported a peat dated to 12,647 cal. BP at 30 m depth at Hemudu, while Qin et al. [328] recorded a peat dated about 12,568 cal. BP in a core offshore of the Yangtze delta. Zhang et al. [2] and Cheng and Ye [329] have reported peat at more than 18 m depth dated to 11,004 cal. BP at Beihu, south of Taihu on the upper Tiaoxi River near Hangzhou. Zhang et al. [79] recorded deep peat layers dated to 10,859 and 10,087 cal. BP, towards the end of the Lateglacial, at Xiaoshan in the incised Qiantang valley, as have Lin et al. [78,330] of similar age.

It is clear that fluvial floodplain freshwater marsh environments have a very long history in the area of the present lower Yangtze and delta, many forming during the Lateglacial. Many more, however, have formed at various stages throughout the Holocene (Table 2). All such peats will have formed within floodplain, marsh-lacustrine or back-barrier lagoonal environments, but will represent near-surface autogenic organic sediment accumulation in a paludified freshwater marsh stage of hydroseral development [1], rather than in a deeper water aquatic environment. Their presence therefore implies phases in which water levels are not significantly elevated by extreme flood events. Examples of Lateglacial and earlier Holocene date are usually basal peats resting upon terrestrial, fluvial sediments, and will have formed in response to rising sea levels which were driving freshwater perimarine zone water tables higher [85,331], until waterlogging and organic sediment accumulation occurred in freshwater marsh and lagoonal areas. This sea-level rise created many of the shallow lakes that formed in the Taihu lowlands in the mid-Holocene [109,114,248]. The high water tables at this time caused many peats to accumulate (Table 2) in the Taihu lake area and around Hangzhou Bay in the early to mid-Holocene [332,333], but several more recent ones also occur [173,246,332,334]. In some cases, peats, some of which will have formed in the high upper saltmarsh zone [11], were then overtaken by rising marine waters which deposited estuarine clay and silt facies above them. Most were buried by freshwater and alluvial deposits, however, as sedimentation in floodplain wetlands in the mid-Holocene generally kept pace with any sea-level rise and chenier barrier ridges came into being [74,103,104], both preventing marine penetration [30,85].

The formation of marsh peats within floodplain wetlands requires conditions of low riverine input coupled with developed marsh vegetation and continuous organic accumulation [204]. The presence of peat in sediment columns in the Taihu lowlands must therefore indicate phases of low fluvial influence and vegetation-covered marshland surfaces. Periods during which such peat accumulation was dominant and fluvial sediments were rare will correspond to times when fluvial input was low, and so probably with low rainfall intensity. Dated examples of peat beds in the lower Yangtze and Taihu floodplain lowland are listed in Table 2. Derived from these data, periods during which peat formation was the norm are shown on Figure 6. It is clear that during the early and mid-Holocene, and into the late Holocene, hydrological conditions were largely stable, and while some significant flood events will have occurred, these were unusual and probably not of extreme strength. Low energy marsh, swamp and peat-forming wetland environments were the norm, with sediments of variable organic content, and these mid-Holocene conditions were very attractive for human settlement [335]. High sea level, and minor replenishment from fluvial sources, maintained freshwater floodplain marshes in most areas between the areas of open water represented by the floodplain's many lakes. There were, however, periods of exception to this stable norm when major floods did occur.

Table 2. Chronology of phases of Holocene peat formation (surface water table) in the Taihu lowland/lower Yangtze area. Dates are in calibrated years BP. Age ranges may include several dates.

Site	Median Age of Peat
D2 [327]	1050
Yaojiang [146]	1321
T-1 [336]	1350
Longnan [337]	1500–1400
Dianshan [81]	1514
D2 [327]	1700
Taihu plain [332]	1710–1414
Qingpu [313]	2500
Yushan [98]	2540
YZ-1 [327]	2651
Taihu plain [332]	3110–2818
Dongjing [52]	3177–3111
Taihu plain [332]	3630
Dongjing [52]	3657–3639
Guoyuancun [303]	3795–3710
Baiwaitan [52]	4291
Maoshan [149]	4464
Banxiangchan [52]	4577
Liangzhu (LZ-1) [273]	4620
Wuguishan [338]	4630
Yangxi [30]	4700
HB3 [339]	4886
Hemudu [188]	4924–4603
Luojiang [5,311]	4940–4620
Yushan [340]	4903
Taihu plain [332]	5129–4346
Liangzhu (LZ-4) [273]	5175
Jingtoushan [341]	5200– 5000
Tianluoshan [11]	5326
Yaojiang [25]	5386
Shisanzuqiao [332]	5434–5347
Tiaoxi valley [1]	5445
Xiaofengyang [52]	5517
Fengjing [52]	5680
Wuguishan [338]	5815
Hemudu [342]	6255
Jingtoushan [341]	6350–6200
Hemudu [178]	6470–6255
Wujincheng [52]	6494
Yaojiang [177]	6509
Jingtoushan [341]	6650–6500
Xinjie [221]	6713
Gehu Lake [30]	6800–6500
Hemudu 1501 [189]	6932
Luotuodun [343]	7000
Yuyao [344]	7000
Xinjie [221]	7210
Longnan [337]	7410
Wujiabang [5]	7509–7499
Taihu plain [332]	7554–7134
Beihu [2]	7914
Beihuqiao [329]	7989–7883
Beihu [2]	7990
Maqiao [52]	8069
Hongkou [52]	8156
Beihu [2]	8348
Beihuqiao [329]	8356
ZX-1 [327]	8481
ZX-1 [250,323]	8690–8512
Pingwang [260]	c.8850
Zhaoxiang [52]	9072–8847
HL81063 [339]	10,027

5.3. Major Palaeofloods

With the regularity and strength of recent flooding events as shown by historical records [345], it is to be expected that the basins and floodplains of the river were subject to major floods many times earlier in the Holocene, and there is considerable evidence that these have occurred. Clastic layers which represent flooding horizons occur in many early and mid- Holocene sediment sequences throughout the valley of the Yangtze [275] and in its tributary valleys [158,159,346–349], as well as in more recent, including historical, times [28]. Many of these earlier clastic units have been confirmed as flood layers by sedimentological research [159,164,350], and their ages, established by various dating techniques including radiocarbon, can be shown to correspond with periods of climatic change with higher rainfall and temperature fluctuation by analyses of several other forms of sedimentary archive [130,351–354], particularly cave speleothem records [161,228,239,242,353,355,356].

5.3.1. The Lower Yangtze and Delta

Tables 2 and 3 and Figure 6 show that the first three Holocene millennia were characterized by stable hydrological conditions, with gradually rising sea level encouraging rising water tables, surface soil waterlogging and the formation of peats in many low-lying parts of the Yangtze Delta and Hangzhou Bay area. While the Delta area was accreting rather than prograding between 10,000 and 7000 cal. BP, it was a warm, humid period with high rainfall as shown by biomarker and other research in the Yangtze valley [357–359]. It is only during the few centuries around the 8200 cal. BP cold and wet climatic deterioration [342] that there is evidence of major freshwater flooding from the Yangtze, labelled phase 'a' on Figure 6. Otherwise, the very few records of flooding is a reflection of the minor role the incised Yangtze river played in the area's hydrology in the early Holocene, with rising groundwater driven by sea-level rise leading to autochthonous lacustrine and peat deposition, often of the upper saltmarsh type as at Pingwang around 8850 cal. BP, in lagoonal and perimarine wetlands. During brief phases of less stable climate during this period, however, occasional floods did occur, such as the event around 7700 cal. BP recorded by Song et al. [176], which is reflected in the evidence for water depth rise at Pingwang at the same time.

After the Yangtze Delta floodplain was established and began to prograde after about 7000 cal. BP, river floods occurred more often, although variability of climate and rainfall allowed long periods of stability when peat still formed. Patalano et al. [249] have shown that climate between c.7500 and c.6500 cal. BP was relatively dry and, while peat could still form in the wetlands, floods did not occur (Table 3). A significant phase with major flood events occurred around the centuries around 6000 cal. BP, phase 'b' on Figure 6, again corresponding broadly with climatic deterioration and colder, wet conditions, as recorded at Hemudu south of Hangzhou Bay [342]. It was followed by a long period of humid climate [233] and hydrological stability with peat formation (Table 2), high lake levels [360], and only occasional floods, that lasted until about 4200 cal. BP. Overall, in the first six thousand years of the Holocene the lower Yangtze and Delta area can be categorized as hydrologically stable during the warm and wet Holocene climatic optimum [245], with relatively brief phases when major floods occurred and fluvial input was dramatically increased from that of the low-intensity seasonal EASM.

Table 3. Chronology of Holocene fluvial flood events (rapid water level rises) in the Taihu lowland/lower Yangtze area. Dates are in calibrated years BP. Age ranges may include several dates. Some dates are reliable estimates based on other data.

Site	Median Age of Flood Events
Lake Taihu [168]	400–0
Dianshan [81]	800
Jiang-nan [127]	800–400
Jiang-nan [127]	1400–1200
Longnan [337]	1300–1200
Chaohu Lake [135]	1300
Shangshan [361]	1710
Longnan [337]	1800–1700
Chuodun [303]	1964
Chaohu Lake [135]	2200, 1800
Guangfulin [311]	2400
Qingfeng [246]	3900
Maqiao [362]	4000–3800
Maoshan [149]	4000–3900
Maoshan [154]	4000–3900
Chuodun [363]	c.4000
Dadong [363]	c.4000
Dasanjin [363]	c.4000
Guoyuancun [363]	c.4000
Liangzhu [363,364]	c.4000
Longtanhu [363]	c.4000
Shuitianfan [363]	c.4000
Tangwanli [363]	c.4000
Tenghualuo [142]	c.4000
Taihu plain [365]	c.4000
Yuanjiadi [363]	c.4000
Wangjiashan [363]	c.4000
Xuxiang [363]	c.4000
Yuecheng [363]	c.4000
Tianyilu [303]	4030
Yuhuicun [366]	4100
XL [367]	4200
Caoxieshan [246]	5250
Baohuashan [246]	5860
Fuquanshan [246]	6020
Songze [246]	6170
Huaihe valley [368]	6250–5500
Qingfeng [139]	6400–5500
Jingtoushan [341]	6500
Pingwang [260]	7650
HG01 [176]	7700
Taihu plain [139]	8100–7700
Lower Yangtze [141]	9200–8000

While some major flood events occurred in the Yangtze coastal lowlands in the early and mid-Holocene, it is with the great climatic deterioration that started around 4.2 ka cal. BP [111,234], and which marks the transition to the colder Upper Holocene (Meghalayan) sub-epoch [261], that the most severe and repeated flood events occurred [136,145,225,265,268,369]. While much of China became more arid, field evidence as well as modelling [370] shows that the middle and lower Yangtze valley became wetter.

While the transition towards cooler conditions began around 6000, and especially after 5500 cal. BP [247,371,372], it is the major climatic shift around 4000 cal. BP, marked as phase 'c' on Figure 6, that marks the end of the warm and wet mid-Holocene climate optimum [266,359,373] and the beginning of centuries of low temperatures, climatic variability and increased rainfall intensity [120,256,259]. Evidence of this major flooding phase is recorded in sedimentary sequences throughout the Yangtze catchment, including the delta lowlands (Table 3) as recorded at Tianyilu [303], and it clearly had major hydrological consequences [181,268,374]. Several sites experienced repeated flooding during this climatically transitional period [375], and some of the floods were very extreme events. Lake levels increased markedly at this time [278,376].

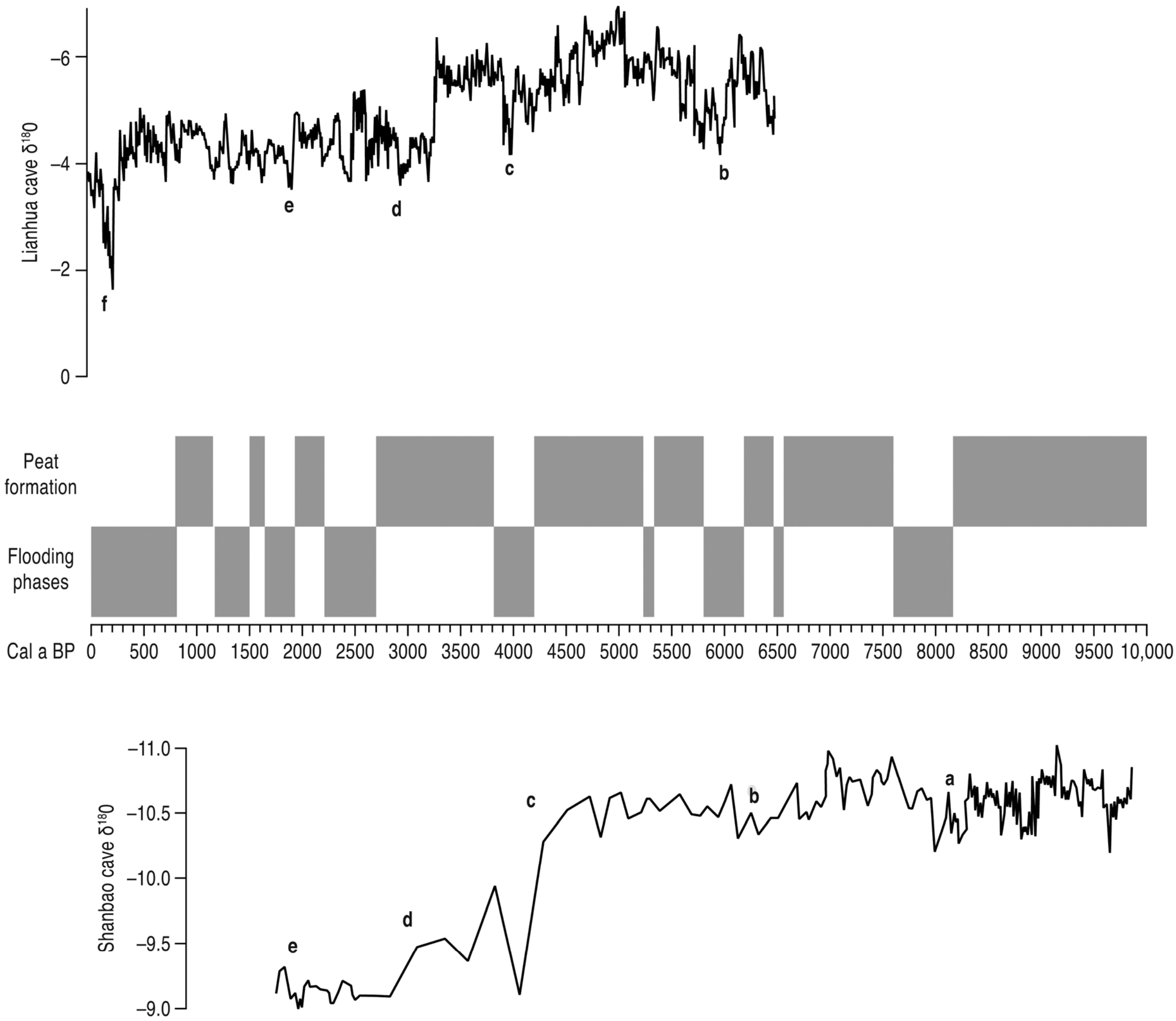

Figure 6. Phases of flooding and peat formation in the Lower Yangtze valley/Taihu lowland region, derived from Tables 2 and 3. Two graphs of temperature fluctuations (and monsoon precipitation) during the Holocene in eastern China are also shown, derived from Cosford et al. [242] at Lianhua Cave and Shao et al. [239] at Shanbao Cave, which is the $\delta^{18}O$ record closest to the Taihu lowland and at the same latitude. Major climatic deterioration events are dated to (a) 8.2 (b) 6.2 (c) 4.2 (d) 2.8 (e) 1.8 cal. ka BP and (f) since c.500 cal. BP (Little Ice Age).

For more than a millennium after the end of phase 'c' on Figure 6 at about 3800 cal. BP there was relative hydrological stability in the study area, with many records of peat formation (Table 2) and no evidence of major flood events (Table 3). It corresponds to colder conditions under which the wetland communities of the Delta floodplain developed without exceptional fluvial input. Clearly shown on Figure 6, the next phase of major flooding in the lower Yangtze and Delta began at about 3000 to 2800 cal. BP, when climate deteriorated rapidly and became extremely variable, with rainfall volume and intensity increasing greatly [244,278,358]. This 2.8 ka cal. BP event and the preceding one at 4.2 ka cal. BP have been identified by Donges et al. [356] as one of the major non-linear climatic regime shifts in the Holocene, with very rapid climate change and high-amplitude variability in eastern China, with severe rainstorm events.

Although climate change and the strength and character of the EASM remained a vital driver of rainfall in the Yangtze valley, with increased variability and rainstorm intensity in the Late Holocene [62], a complicating factor in palaeoflood history in the last three millennia has been the much increased impact of human activity in agriculture, deforestation and increasing runoff, erosion and flooding [34,64,65,67,68,311,377–379], particularly starting before 2500 cal. BP, in the centuries before the Qin dynasty [311] and having the effect of greatly increasing progradation rates of the Delta [72]. This human factor amplified the effects of climate in the last two millennia [135–137,380], a period during which climate, particularly rainfall, variability has been marked [62,124,221], especially so in the last half millennium and leading up to the very heavy rainfall intensity of modern times [381–383].

As Table 3 and Figure 6 show, from before 2500 to about 800 cal. BP relatively short periods of a few centuries' duration occurred, agreeing with the findings of Lu et al. [221] of extreme rainfall variability on centennial scales in the lower Yangtze, which had alternate dominance of flooding and peat formation with the centuries between 2000 and 1700 cal. BP (climatic phase 'e') notable for cold and wet climate and major flood events [153], as recorded at Chuodun [303]. At Chaohu Lake between 2250 and 2100 cal. BP fine sand occurs in the lacustrine sediment column, signifying soil erosion caused by significant flooding, probably a combination of heavy rainfall and Yangtze floods [135], probably exacerbated by an increase in human impacts on the vegetation from this time onwards [384]. Major floods occurred in the Taihu area between about 1500 and 1200 cal. BP, with rising lake levels, as recorded at Dianshan [81]. Flooding has seriously affected the Yangtze Delta area in the last millennium [385] and Table 3 shows that since 800 cal. BP major flooding has been common under deteriorating climate [81,127,128,168], with a particularly cold climate excursion in recent centuries represented as phase 'f' in the Lianhua Cave evidence (Figure 6), corresponding to the 'Little Ice Age' cold phase [287]. Overall, Figure 6 shows that major flooding phases in the lower Yangtze and Taihu plain correspond well [36,338] to periods of Holocene climatic instability and deterioration. The dates of the increases in water depth at the four Taihu Plain sites presented in this paper fall within the age ranges of major flood phases (Figure 6).

5.3.2. The Upper and Middle Yangtze

The main focus of this paper is the fluvial flood history of the lower Yangtze, and especially the delta lowlands around lake Taihu, but for comparative purposes it is important also to consider the flood history of the upper and middle reaches of the Yangtze valley and its tributary headwaters, and also because increased river flow and discharge in those areas of the catchment will have had an input into the situation downstream. Now much reclaimed for agriculture [7,386], the major lakes and other wetlands in the mid-Yangtze area, particularly Dongting Lake and Poyang Lake, would have expanded and provided accommodation space for floodwater and sediment from upstream [8,134,360,376,387–392], but a considerable amount would still have entered the lower Yangtze valley, adding to overbank flooding and sedimentation in the study area. Records of major floods in the upper and mid-Yangtze region and in tributary headwaters are listed in Table 4. As with the Lower Yangtze, it is clear that flood events have occurred in the higher and middle reaches of the river at intervals throughout the Holocene [376,393–395]. Zhang et al. [351] have demonstrated that all sections of the Yangtze valley have had the same monsoon, and therefore climate, history and so have been subject to the same external environmental drivers. They should therefore have had similar Holocene flood histories.

Comparison of Tables 3 and 4 shows this mostly to be the case, although the middle and lower Yangtze appear to have suffered widespread great floods most particularly during the great climate deterioration and instability of 'Holocene Event 3' between 4200 and 3800 cal. BP [36,294,376,387,391], with flood clays deposited [376,393] and with multiple clastic layers at some sites, such as Hongqiaocun in the Upper Yangtze Chengdu Plain [170], experiencing several extreme flood events. It is clear that the Neolithic societies of the

Middle Yangtze valley suffered major decline at this time [396,397], exemplified by the abandonment of the large Neolithic site of Chengtoushan on the west bank of Dongting Lake at 4000 cal. BP [369,398]. Many sites of the Baodun culture in the Chengdu Plain [399] were abandoned during this period. Further major flooding occurred at intervals during the similar, severe climatic deterioration that started around 2800 and lasted until 1700 cal. BP, for example the flood event at Majie in the Chengdu Plain [400]. It began a period of heavier rainfall [358] and increased flooding intensity that has lasted until the present day, as seen in the Poyang Lake area [401,402].

Table 4. Chronology of Holocene fluvial flood events (water level rises) in the upper and mid-Yangtze valley, and in Yangtze tributary headwaters. Dates are in calibrated years BP. Age ranges may include several dates. Some dates are reliable estimates based on other data.

Site	Median Age of Flood Event
Wufeng [349]	400
Weibicun [160]	600
Poyang [401]	800–0
Nanchang [288]	840–772
Weibicun [160]	1000–800
Luojiatan [153]	1800–1700
Liaowadian [151,166]	1800
Weibicun [160]	1800
Zhangjiawan [403]	1800
Xintancun [166]	1900–1700
Weibicun [160]	2200
Liaowadian [151,166]	2200
Majie [400]	2610
Longgan Lake [278]	2700
Hanjiang TJW [158]	c.3000
Weihe GCZ [158]	c.3100
Luojiatan [153,166]	3200–2800
East Dongting [387]	3900
Baodun [399]	4000–3800
Caitai [376]	c.4000
Chengtoushan [369]	c.4000
Longgan Lake [278]	c.4000
Dongting [391]	c.4000
Lajia [404]	c.4000
Jianghan [171]	c.4000
Hongqiacun [170]	c.4000
Jinsha [145,170]	c.4000
Mangcheng [399]	c.4000
Three Gorges [29]	c.4000
Shuanghe [399]	c.4000
Zhongba [148]	c.4000
Yichang [405]	c.4000
Yuxi [375]	c.4000
Wulinji [376]	c.4000
Zhongqiao [119,170]	4100–3800
Zhongqiao [119,170]	4168
Tanjialing [294]	4200–4000
Luojiatan [153]	4200
Zhongqiao [119]	4900–4600
Dongting [391]	5800
T0403 Yuxi [295]	6800–6300
T0403 Yuxi [295]	7600–7250
Dajiuhu [354]	9500–7500

References cited in Table 4 show that great floods were common in the period between 1900 and 1700 cal. BP and again from 1000 cal. BP to modern times. Lake levels in the middle Yangtze were at their highest during these Late Holocene flooding phases [277,278]. Extreme floods seem not to have occurred so much in the earlier Holocene, with examples dated to around the 8.2 ka cal. BP event not present, although this might well just be an expression of the distribution of research effort and the availability of suitable sedimentary archives in those regions. Alternatively, the character of the 8.2 ka event in China remains poorly understood [406], and it may be that the climate event was cold but without increased rainfall, precluding major floods. Future research might well yield data which modify this assessment.

5.4. Influence of Hydrology on Human Settlement and Land Use

It is clear that hydrology was the dominant environmental factor in the Taihu lowlands since the creation and development of the Yangtze delta, and while the wetland environments would have been attractive to human occupation and subsistence with many food and other resources, at times of hydrological instability a human presence amongst the floodplain wetlands might not have been viable. Much of the evidence for past fluvial activity in the Yangtze valley has therefore been derived from studies in environmental archaeology at ancient cultural sites and the relative hydrological stability (site formation and stable wetlands) and instability (river flooding and site abandonment) that occurred [52,136,143,258,369,391,407–410].

Evidence from sites in the area shows that in the Taihu-Hangzhou lowland many human settlements were located upon stable, organic marsh soils, some on surface peats [98,335] and others on piles in shallow water [342,411–413]. Here rice agriculture would be reliable and could be supplemented by the exploitation of wild plant and animal resources from the deeper water lakes and swamps that would have existed nearby [414–418]. During most of the Neolithic the Taihu plain supported dense and economically wealthy settlement [335], of which the sites at Kuahuqiao, Guangfulin, Hemudu, Majiabang, Siqian, Tianluoshan, Songze and Liangzhu are major examples [271,344, 365]. In the later Neolithic around 4200 cal. BP freshwater flooding was apparently an increasing problem with earthworks for flood defence built at the Liangzhu site [141,273,275,317]. The dramatic increase in the incidence and magnitude of river valley flooding [135,136,369,374], where settlement and agriculture tended to be located, made people very vulnerable to rapid water level rise [143,399] and would force the abandonment of cultivated fields as well as settlements [148,267,391], including in the Delta area [363,419].

Evidence shows that at the end of the Neolithic many sites were submerged by a dramatic elevation of water levels, by lake or river floods, or covered by rapidly growing marsh peat [154,265,327], often with clastic flood layers, usually yellow clay and silt [2,145,149,334,366,375], which can be up to a metre thick [275], sealing cultural occupation horizons [142,154,258,363,376,396,420–422]. These flooding horizons were devoid of archaeological material [169,366,423,424], so that there appears to have been a cultural interruption as humans evacuated the area, with major sites such as Qingpu [313], Maqiao [362] and Liangzhu [364,419] abandoned. Zhang et al. [363] have listed several sites where such flooding horizons occur in the Taihu lowlands.

As occurred with agriculturally-based societies world-wide [425], in China cultures including the Liangzhu, Longshan, Qujialing and Shijiahe collapsed at this time [52,111,132, 142,294,366,376,409,426,427], perhaps following a period of decline [428], due to repeated extreme floods. Cultural interruption of this kind because of severe climate change is not confined to the Yangtze region, but has been noted at several sites on the Yellow River and elsewhere in northern China [169,429–431] at the time of the 4.2 ka event, such as at Erlitou. As well as by flood events, however, in that region cultural disruption was sometimes caused by severe drought, as noted by Wu and Liu [265], caused by the weakening of the EASM [170,234,429]. In some cases, whole settlements could be at risk of destruction because of flood and debris flow after extreme rainfall at the time of the 4.2 ka climate event, as in the headwaters of the Yellow River [432].

The locations of middle and late Neolithic human settlements of all sizes were also strongly influenced by hydrology, so that they were situated on higher ground near smaller water bodies [51,136,409], away from areas likely to be badly affected by flooding. For example, no settlements in the Chaohu lake basin in the lower Yangtze valley were below 10 m above sea level during that period, nor in the subsequent Shang and Zhou dynasties [372]. Changes in river and lake level, and even movement of river channels [433,434], often forced relocation of Neolithic settlements to higher, safer ground [169,174,303,361,363,365,435], such as the small isolated uplands within the Taihu marshes or the coastal ridges to the east (Figure 1), a process which occurred in the middle as well as the lower reaches of the Yangtze [358,376,391,392,427]. Archaeological site distribution was therefore closely linked to environmental, mainly hydrological, factors and local topography [51,344,358,368,436–438]. Serious fluvial impacts occurred during post-Neolithic times also, with examples of increased frequency and severity of flooding disrupting settlement and food production, as at Guangfulin around 2400 cal. BP [311]. Bronze Age and Iron Age cultures in the Dajiuhu region of the central Yangtze valley [272] also came to an end during periods of major flooding [358]. Yin et al. [131] have discussed the impacts of climate change on dynastic history in the last two millennia, identifying centennial-scale warm and cold periods during which social and economic stability was maintained or destabilised [439,440]. This periodicity correlates well with the peat/flood phases shown on Tables 2 and 3 and Figure 6, illustrating the important role of great floods in Late Holocene cultural history in this part of the Yangtze valley, increasingly so in the last 800 years.

Although most flooding events that terminated occupation at cultural sites were fluvial, there are examples where marine flooding was responsible [10,99,174,340,441], as at Wuguishan [338] and Yushan near the southern coast of Hangzhou Bay [98] where an inundation event caused by storms laid down thick muddy marine sand deposits. These seal Neolithic cultural levels, which occur within a wooded freshwater marsh peat, as do similar typhoon-induced coastal flood deposits at nearby Xiawangdu in the mid-Holocene [100]. Marine inundation also swamped cultural levels at the earlier Neolithic site of Kuahuqiao on the southern shore of the lower Qiantang River [301,442]. Although not the subject of this paper, marine inundation, especially driven by exceptional typhoon events, would have been an important force in the Yangtze delta area in the mid- and late Holocene.

6. Conclusions

Much of the lowland plain between the Yangtze River and Hangzhou Bay was created by fluvial activity due to progradation of the Yangtze delta from the early mid-Holocene onwards, and rests upon terrestrial sediments of pre-Holocene age, some of which are fluvial. Although also subject to marine influence, particularly in the early to mid-Holocene but also more recently, the varying input through time of fluvial water and suspended sediment discharge from the Yangtze has been dominant in governing the history of depositional regimes in this coastal plain since the mid-Holocene [23,209]. Combined with fluvial input from the other large rivers of the area, primarily the Qiantang but also the myriad of lesser drainage channels and creeks which cover the plain [1,5], deposits comprising minerogenic fluvial material dominate most of the sedimentary sequences in the Taihu lowlands, particularly to the east and south of the lake. Seasonal Yangtze floods must account for some of these exogenic clastic facies, but much of this material was introduced during great flood events, occasionally very extreme, which have occurred periodically during the Holocene. The Taihu lowland is the creation of the Yangtze.

Although allochthonous flood deposits are most important, also highly significant are the autochthonous deposits that have formed in the wetlands of the Taihu lowland—usually expressed as more organic units in the sediment column—within lakes, swamps, marshes and other freshwater aquatic systems. In particular, the occasional peat layers provide dateable marker horizons that signify periods of local hydrological stability and slower sedimentation when more extreme Yangtze floods were absent. Analysis of lithologies and microfossil content, particularly of aquatic plants and algae, from sites around Lake Taihu has allowed the reconstruction of water level movements that can be interpreted as proxies for greater or lesser flooding influence, especially from the Yangtze but also from other watercourses. Although occasional major floods could occur at any time, periods with many great floods were broadly around 8000, 6000, 4000 and after 2800 cal. BP, especially since c. 800 cal. BP, the later events often amplified by the hydrological effects of human activities in the catchment during a period of deteriorating climate.

Overall, the timing of major fluvial floods in the lower Yangtze and Taihu/Ningshao plains corresponds well with periods of Holocene climatic instability and deterioration, with six major phases of climate change and severe flooding recognized. Increased human settlement, its location and major land use in this coastal floodplain lowland were closely tied to local topography and to times when, mainly due to climatic factors, more extreme flooding events were rare, hydrological regimes were stable and ground surface conditions permitted extensive and intensive agriculture.

In this study, non-pollen palynomorphs, as they are generated very close to their site of deposition, have proven to be good diagnostic indicators of very local environmental conditions. At our four research sites, high frequencies of fungal spores correlated well with stable organic marsh soils with on-site vegetation and surface or shallow water, while aquatic algae that lived in the local water column increased in abundance when major flooding caused increases in water depth, replacing the fungal spores in the NPP assemblage. Although further analysis is required, it seems that the relative abundance of algal spores and algal assemblage composition in floodplain sediments can be used to recognize the occurrence of major freshwater flooding events. This will be of particular use in already aquatic environments, where the environment of deposition switches from shallow to deep water, and where other evidence of hydrological change, such as in sedimentary facies, does not occur.

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