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Hydrogeological Modelling of Water-Level Changes in an Area of Archaeological Significance: A Case Study from Flag Fen, Cambridgeshire, UK

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Concern exists regarding the long-term viability of the internationally important archaeological remains of the Flag Fen peatland basin near Peterborough. The delicate organic remains at the site are thought to be degrading as a result of drying out due to lowering of the water table. This paper describes a hydrogeological model of the Flag Fen site and surrounding area. The numerical groundwater model has been used to understand the current groundwater situation with regard to the archaeology and also to explore potential future scenarios, including external threats and potential water level management schemes. Observed and modelled groundwater levels have been interpreted using three zones: the 'dry' zone 1 above the seasonal maximum water table; zone 2 of seasonal water table fluctuation which is intermittently wet and dry; and a deeper zone 3 of permanent saturation. Archaeological wood is best preserved in Zone 3 and least well preserved in Zone 1. Much of the Bronze Age wooden structure at Flag Fen is located within Zone 2 (or even in Zone 1). The hydrological conditions are therefore not ideal for the long-term *in situ* preservation of the material. Groundwater modelling indicates that the main factor controlling groundwater levels in the Flag Fen area is artificial drainage.

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Drainage has lowered groundwater levels in what would naturally be a wet fenland area. Modelled climate change and potential nearby development pressures have minimal influence on water levels. If groundwater levels are to be further raised at Flag Fen then it will be necessary to address the problem of artificial drainage. Preliminary modelling of potential management options, including the creation of a wetland (through ditch blocking) to the south of Flag Fen and the diversion of drainage ditches away from the archaeological features was undertaken. The research outlined in this paper has considerable implications for the way in which wet-preserved archaeological sites can be addressed in the future. AQ4

KEYWORDS hydrogeology modelling, preservation in peat, groundwater-level fluctuation

Introduction

Wetland archaeological sites are generally poorly understood in terms of hydrology despite the high potential for preservation. Hence, the importance of understanding the potential for preservation through proxy approaches has been previously documented (Chapman & Cheetham, 2002). One of the best-known wetland archaeological sites is that of Flag Fen. The Flag Fen Basin is an area of low-lying flat land (Figure 1) which forms a part of the larger Fenland basin. At the beginning of the Bronze Age, the River Nene flowed along the southern edge of what is now known as the Flag Fen Basin. Sea levels rose during the Holocene era. Over time, the ground became saturated, peat began to form, and the Fens were created. People continued to live in this new area of marshland. They retreated to higher ground and built walkways to link together 'islands' that emerged.

In the seventeenth century, ditches were installed to drain the land for agriculture. Active drainage continues at present, with ditches maintained by Internal Drainage Boards (IDB) and the Environment Agency. The Mustdyke, a major ditch passing through the eastern end of the Flag Fen site, was enlarged and deepened in 1972 in order to accommodate floodwater from eastern Peterborough (Pryor, 1992). It was further deepened in 1982 (Pryor, 1992), and this led to the discovery of the Bronze Age wooden structures of Flag Fen Scheduled Ancient Monument (SAM) timber platform and post alignment (causeway). These wooden structures are believed to be under threat due to long-term declining water levels. Excavation in 2012 of the eastern part of the trackway indicated that the base of the archaeology was often close to the base of the zone of water-table fluctuations (DigVentures, 2012) The relationship between groundwater levels and the preservation of archaeological remains is summarized using the three-zone model after Chapman & Cheetham (2002), and is illustrated in Figure 2. This paper describes hydrogeological conceptualization and numerical groundwater modelling of the site undertaken for Historic England, full details of which are provided in JBA (2015).

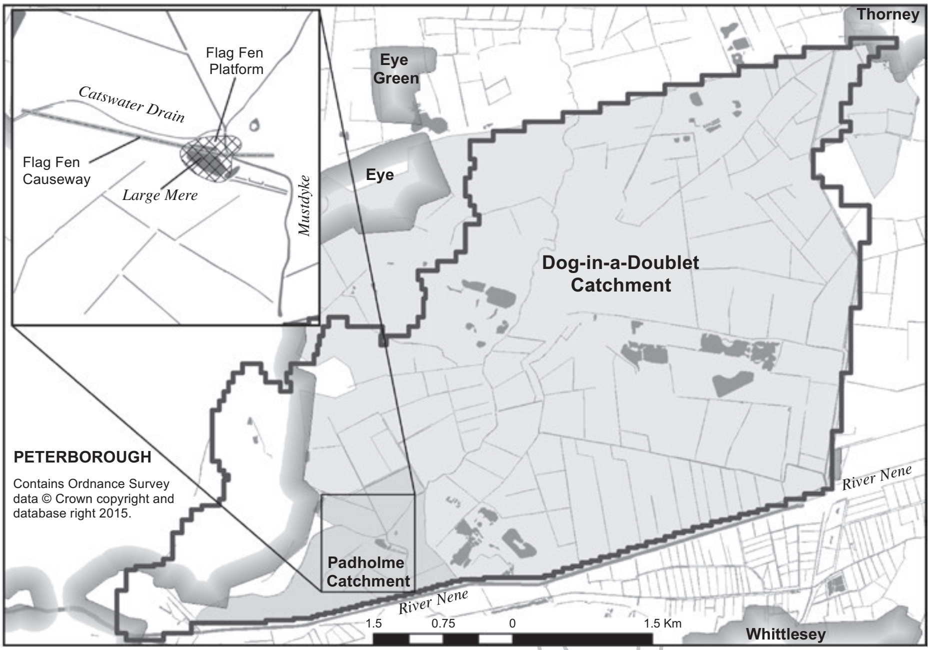

FIGURE 1 Site location (showing model domain).
Graph by the authors

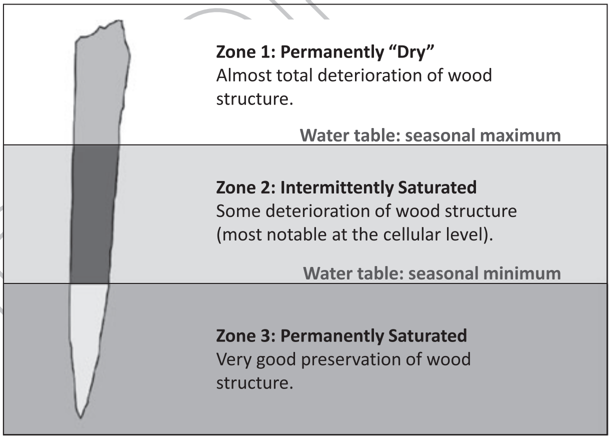

FIGURE 2 Three-zone model illustrating the link between groundwater levels and the preservation of archaeological wood.
After Chapman & Cheetham (2002)

Study Area

The study reviewed existing reports on the area and consulted with the North Level IDB and the Environment Agency (EA) in order to understand the hydrogeology, hydrology, geology, soils, and drainage management of the area.

The vast majority of the study area comprises arable farmland. Peterborough, including the Fengate industrial area extends into the west of the area with Eye village located in the northwest. The total average annual rainfall based on MORECS (Meteorological Office Rainfall and Evaporation Calculation System) data is 615 mm.

Most of the study area is underlain by bedrock belonging to the Jurassic Oxford Clay Formation. The superficial Quaternary succession comprises glacial and interglacial Pleistocene deposits including glacial lake deposits, till, glacial sand and gravel, fluvial gravel terraces, and marine gravels. These are overlain by Flandrian sediments including alluvium, peat, and tidal flat deposits that cover most of the low-lying Fenlands. Table 1 summarizes the geology in the area and the hydrogeological characteristics of the key units.

The Fenlands are drained by the River Welland in the north, and the Nene in the south. Between these rivers, drainage is achieved using a network of ditches and dykes mostly managed by the North Level District IDB, with most of the study area within the Dog-in-a-Doublet catchment. The smaller Padholme catchment contains the Flag Fen site and is managed by the EA. It discharges water by pumping to the fresh water River Nene. The Mustdyke comes into being at Flag Fen at the confluence of Catswater Drain to the west, an unnamed drain to the north (which does receive some water from Peterborough City), and Catswater Drain South to the northeast. The western extent of the study area falls within the Peterborough City District and is under the control of Anglian Water and is largely hydrologically separate from the rest of the study area.

At the Flag Fen visitor centre is an artificial pond named Large Mere constructed in 1987. Located where the Bronze Age platform was believed to exist, it was designed to keep the underlying ground saturated (Pryor, 1991, 1992). The water is topped up from the nearby Mustdyke. Pryor (1992) stated that the Large Mere covered about two-thirds of the Bronze Age platform; however, more recent investigations suggest that the platform may not extend as far west as previously thought, or that it may be discontinuous (DigVentures, 2012).

Two historical abstraction rates for Mustdyke were obtained from the Environment Agency to provide an indication of how much water was used to top up the Large Mere against losses to ground (leakage) and evaporation: 16,180 m^3/yr (2008) and 6,248 m^3/yr (2009). Most other abstraction licences in the area are for spray irrigation; these are likely to lower ditch water levels in summer (JBA, 2015). A variety of sources of groundwater-level data within the study area were also reviewed (JBA, 2015).

Methods

Site conceptualization

Using the data obtained, a conceptual understanding of the groundwater system at Flag Fen was developed (JBA, 2015). Figures 3 and 4 summarize the key aspects of the groundwater conceptualization at a regional and local scale. The main features of the conceptual model are:

- beneath Flag Fen, the top of the Oxford Clay aquitard forms an effective base to the shallow groundwater flow system. West of Flag Fen other Jurassic strata

Table 1
MAIN HYDROGEOLOGY UNITS UNDERLYING THE STUDY AREA

Age/Group	Unit	Hydrogeological role	Thickness	Groundwater Flow and storage characteristics	Hydraulic Conductivity used in the model K_{xy}, K_z [m/d]
Quaternary Flandrian	Alluvium	Secondary A Aquifer	<1.6 m	Intergranular flow and storage	0.132, 0.0132
	Peat	Aquifer/Aquitard	<2.7 m	Peat will store significant volumes of water. Hydraulic properties depend upon drying/cracking etc.	0.66, 0.0066
	Barroway Drove Beds - Clays	Aquitard		Vertical hydraulic gradient across these deposits	0.00132, 0.000132
Quaternary Pleistocene	River Terrace Deposits	Secondary A Aquifer	<6.2 m	Intergranular flow and storage	10.56, 1
	March Gravels Member	Secondary A Aquifer	<6.8 m	Intergranular flow and storage	10.56, 1
Jurassic Ancholme Group (bedrock)	West Walton Formation - Mudstone	Aquitard	<30 m		0.00132, 0.000132
	Oxford Clay Formation - Mudstone	Aquitard	63–65 m	Hydraulic base to the area	0.000132, 1.32×10^{-5}
	Kellaways Sand Member	Secondary A Aquifer	1.9–4.6 m	Intergranular flow and storage	0.00132, 0.000132
	Kellaways Clay Member	Aquitard	1.4–5.8 m		0.000132, 1.32×10^{-5}
Jurassic Great Oolite Group	Cornbrash Formation - Limestone	Secondary A Aquifer	1.2–4.3 m	Flow and storage mainly within fractures	0.0066, 0.00066
	Blisworth Clay Formation	Aquitard	3–6 m		0.000132, 1.32×10^{-5}
	Blisworth Limestone Formation	Principal Aquifer	1.9–5.1 m	Flow and storage mainly within fractures	0.0066, 0.00066
	Rutland Formation - Mudstone	Secondary B Aquifer	6–14 m		0.00132, 0.000132

Notes: An aquifer is a permeable sediment or rock that can store and transmit significant quantities of water. In contrast, an aquitard is a low permeability sediment or rock that allows only slow groundwater seepage.
K_{xy} = Horizontal hydraulic conductivity.
K_z = Vertical hydraulic conductivity.
It should be noted that not every geological unit is described in the above table where its relevance to the model is not considered to be significant.

Sources.
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BGS Geological Memoir: Geology of the Peterborough District (Horton, 1989).
Environment Agency website.

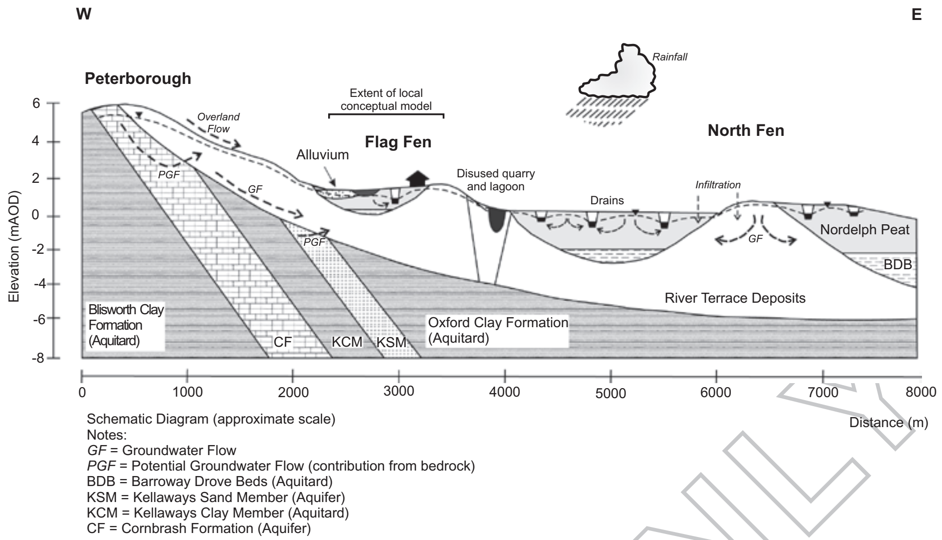

FIGURE 3 Hydrogeological conceptualization of the study area showing the relationship between the bedrock strata and the overlying superficial deposits.
Graph by the authors

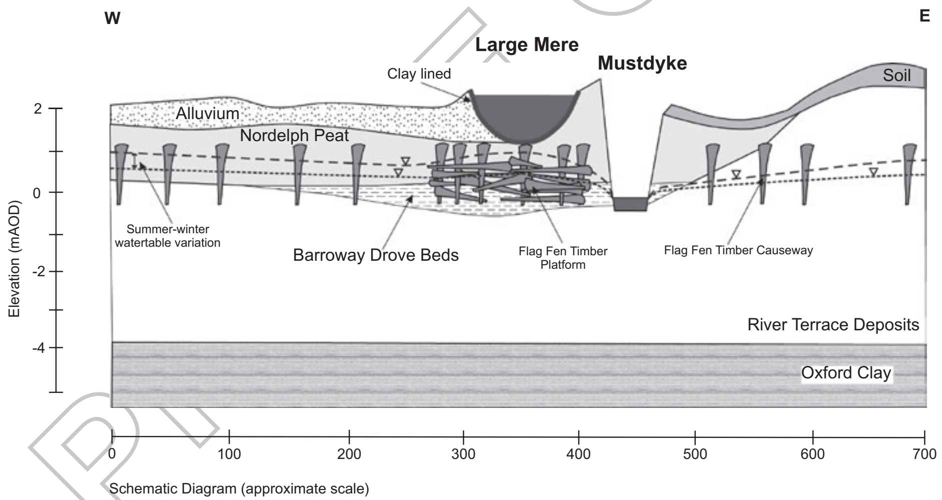

FIGURE 4 Hydrogeological conceptualization of the area around Flag Fen showing the relationship between the water table and the Bronze Age wooden structures.
Graph by the authors

outcrop, some of which behave as aquifers and may discharge water to shallow groundwater in the superficial deposits;

- the thickness of the superficial aquifer varies from 0 to approximately 6 m. The aquifer unit is the River Terrace Deposits composed of sand and gravel. Overlying alluvial deposits and peat deposits are likely to act as aquifers and/or aquitards;

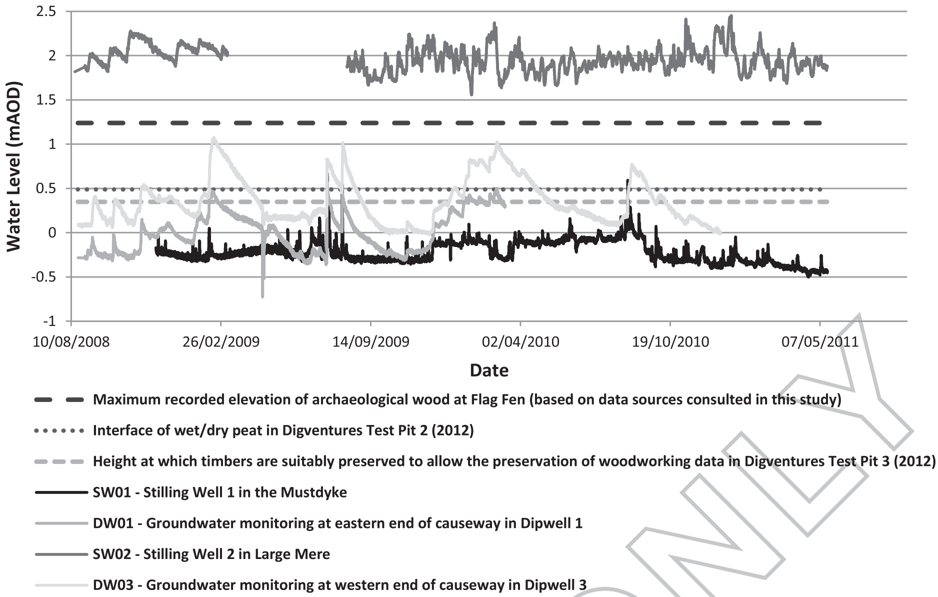

FIGURE 5 Summary of groundwater level monitoring at Flag Fen.
Graph by the authors

- the superficial deposits are drained by an extensive network of artificial drainage ditches;
- groundwater levels in the vicinity of Flag Fen fluctuate seasonally mainly between 1 and −0.5 mAOD as shown in Figure 4. The water level in Large Mere is maintained significantly above local groundwater levels and the Mustdyke level. However, it is not known whether the ground profile beneath the Large Mere is fully saturated, or whether (as shown in Figure 4) there is an unsaturated zone above a groundwater mound;
- Flag Fen timber posts are believed to have a maximum survival height of approximately 1.1 m AOD. Posts that allow the preservation of woodworking data are believed to exist at a height of between 0.47 and 0.35 m AOD.

Figure 5 shows water levels at Flag Fen from August 2008 to May 2011 based upon data provided by English Heritage. To summarize, the water level in the Large Mere is consistently above the archaeology, the water level in the Mustdyke is typically about 1.5 m below the top of the archaeology, and other traces representing groundwater are predominantly below the top of the archaeology.

Numerical modelling of groundwater

A groundwater model was constructed using Groundwater Vistas (ESI, 2011), which is a Graphical User Interface (GUI) for the United States Geological Survey's MODFLOW code (McDonald & Harbaugh, 1984, 1988; Harbaugh & McDonald, 1996a, 1996b; Harbaugh, et al., 2000; Harbaugh, 2005).

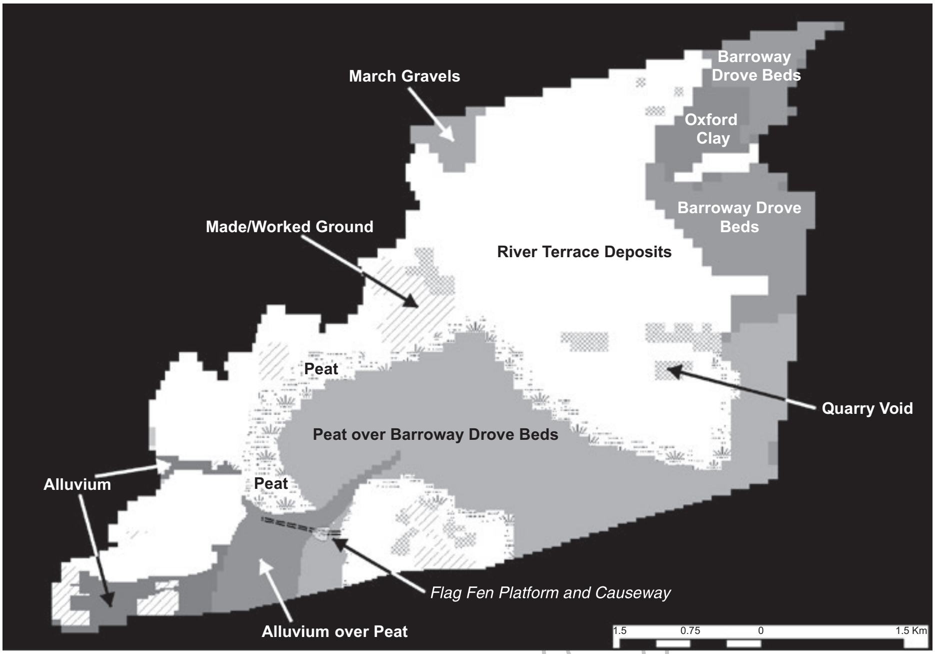

FIGURE 6 Hydraulic conductivity zones used in Layer 1 of the numerical MODFLOW groundwater model. Labels illustrate the geology each zone is representing.
Adapted from Horton (1989)

The numerical model represents the ground as a three-dimensional grid of cells. Each rectangular cell is assigned particular properties (such as recharge, hydraulic conductivity, and storage properties) and certain cells are also set to represent hydrological features such as rivers. The model grid was defined with a uniform spacing of 100 m, which was refined in the vicinity of Flag Fen to 20 m. The model domain can be seen in Figure 6, illustrating the hydraulic conductivity zones used in Layer 1 of the model. The model contains four layers:

1. peat, alluvium, and made ground;
2. Barroway Drove Beds (or clay/silt-rich layer at the base of the peat or top of the river terrace deposits);
3. river terrace deposits and March Gravels;
4. layer to represent bedrock (allowing for influence of permeable bedrock in the west).

External model boundaries were specified: the River Thorney to the east; the River Nene to the south; a drainage divide to the north was represented by general head boundary cells; and the western boundary was a no-flow boundary at the edge of permeable superficial deposits.

Within the model area, MODFLOW drain and river cells are used to represent watercourses. Drain cells can only take water from the model. River cells were used for watercourses that may lose or gain water, including the Large Mere at Flag Fen.

The steady-state model was calibrated using observed groundwater levels from twenty-nine locations across the study site. The quality of this data was variable, with continuous data sets available from some locations and point data available from others. The earliest data dates back to 1991, though the bulk of the data is post-2002. Continuous data sets were generally available for time periods ranging from one year to three years in length. Model parameters were varied until a good match was obtained between observed and modelled groundwater levels, and sensitivity analysis undertaken. Across the whole model, the groundwater-level targets were matched to within 0.5 m, and commonly to within 0.3 m. Around the Flag Fen platform and causeway, most of the targets have been matched to within 0.2 m in Layer 1 and 0.1 m in Layer 2.

Model flow rates were compared with known flows. The 'main' recharge rate is about 15% of the long-term average rainfall (10 to 20% would be expected). An upper estimate of the IDB pumping rate for Dog-in-a-Doublet is 8,896 m^3 per day based on pumping hours and pump capacity. The IDB catchment is similar to the model area, and the modelled flow of groundwater to drains is 4,890 m^3 per day (i.e. 55% of the pumping volume). This is reasonable, given that some of the pumped water will have come from runoff rather than groundwater input. The modelled leakage rate from the Large Mere to ground is 26 m^3 per day, which is within the likely range of 10 to 40 m^3 per day (based upon abstraction data).

The model was run transiently, with rainfall recharge varied seasonally. The resulting seasonal variation in water level was calibrated to the annual variation in water levels in the peat and river terrace deposits.

Figure 7 shows the modelled transient baseline groundwater levels at key locations across the site, and displays them alongside critical heights of archaeology. The following conclusions can be drawn:

1. the main archaeological interest at Flag Fen is concentrated between about 1.2 m AOD and −0.6 m AOD;
2. seasonal fluctuations in groundwater level mean that the upper parts of the archaeological structure at Flag Fen are typically located within (or even above) the zone of water table fluctuation. On average, the base of the archaeology is close to the base of the zone of fluctuation;
3. the exception is the area beneath the Large Mere, where modelling suggests that leakage from the pond is maintaining groundwater levels above the highest elevation of the nearby archaeology.

The calibrated transient model has been used to run the following six scenarios:

1. climate change sensitivity (a): recharge profile adjusted to that of a dry year (2011: 64% of average rainfall);
2. climate change sensitivity (b): recharge profile of average year applied, but with recharge values at 50% of average values;
3. effect of proposed nearby development area represented with an average recharge equal to 0.25 of the baseline value (assuming 75% hardstanding and all runoff from hardstanding areas routed directly to the surface water drainage system);
4. wetland created to the southwest of Flag Fen by removing/blocking the drains in this area (deleting them from the model);

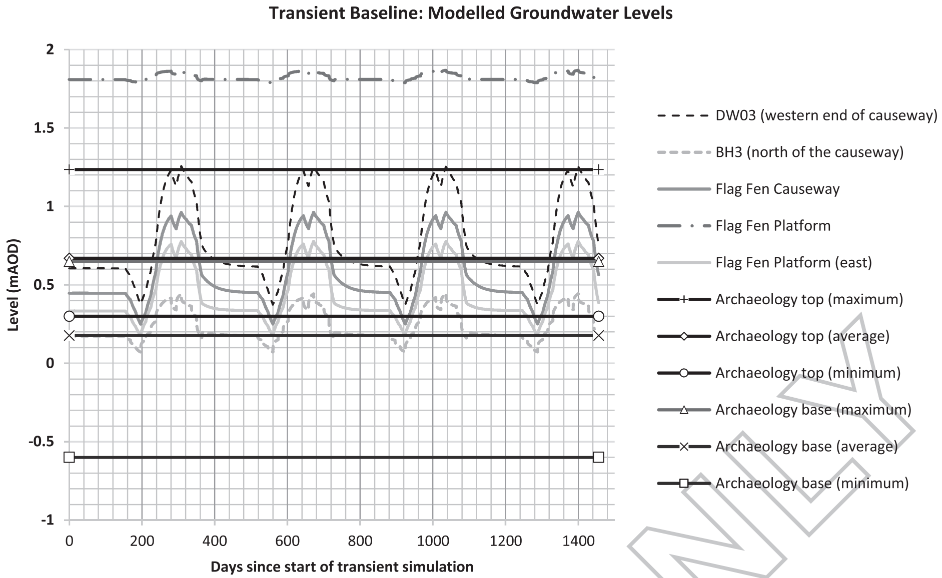

FIGURE 7 Modelled transient baseline groundwater levels (4 years hydrographs) compared to archaeological interest (maximum, average, minimum top and base levels — the horizontal lines). *Graph by the authors*

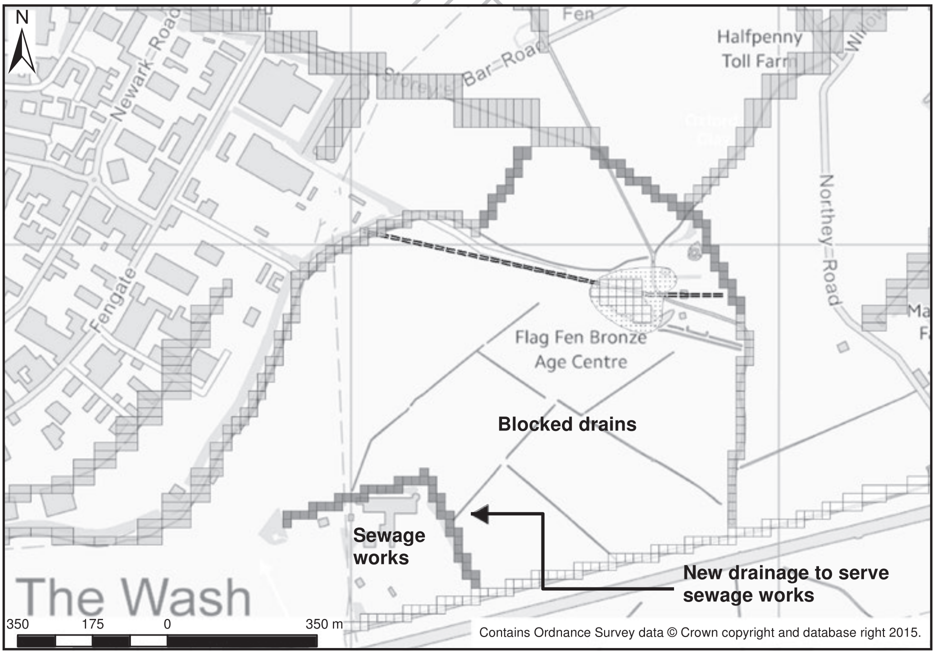

FIGURE 8 Ditch diversion modelling scenario 1 new drains shown in dark grey. *Graph by the authors*

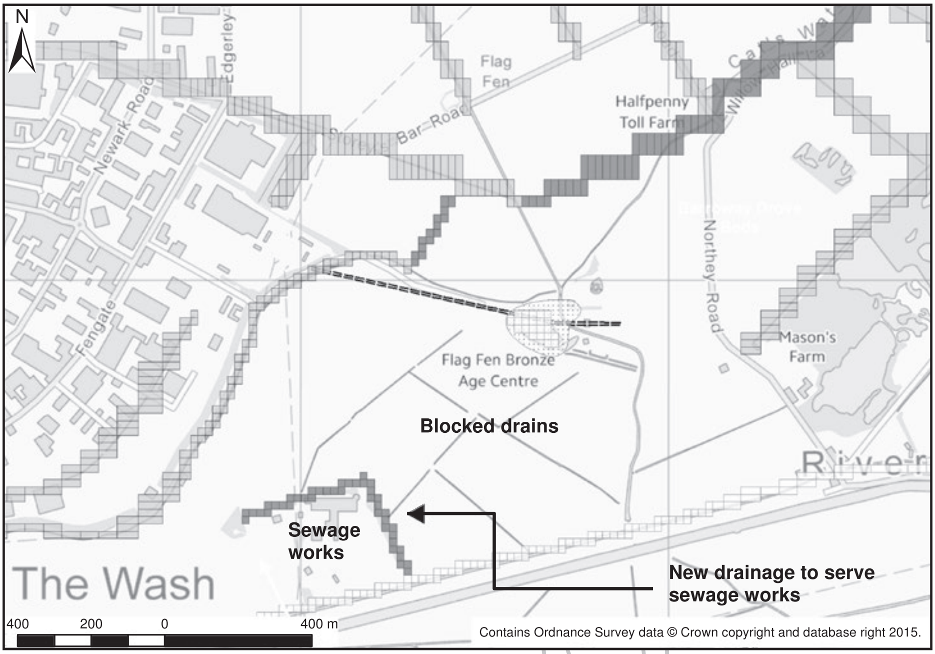

FIGURE 9 Ditch diversion modelling scenario 2 new or deepened drains shown in dark grey. *Graph by the authors*

5. diversion 1 — shown in Figure 8: diverting Catswater Drainater and part of the Mustdyke within the Padholme catchment and blocking drains to the southwest of Flag Fen; AQ5
6. diversion 2 — shown in Figure 9: diverting water from Padholme catchment into the IDB catchment and blocking drains to the southwest of Flag Fen, as well as the Mustdyke and part of Catswater Drain.

For each scenario the transient model was set to simulate a four-year period (following an initial 'run-in' period to establish the starting groundwater levels).

Results and discussion

The modelling results suggest the following:

- the upper parts of the wooden structure at Flag Fen are typically located within (or even above) the zone of seasonal water table fluctuation, i.e. within Zone 2 (or Zone 1) in the three-zone model of Chapman & Cheetham (2002). The results of the present study therefore suggest that the current hydrological conditions are suboptimal for the long-term *in situ* preservation of the wooden platform and causeway at Flag Fen;
- the Large Mere may be fulfilling its function as an artificial recharge basin (Pryor, 1991, 1992), maintaining higher groundwater levels beneath it. However, the extent to which this is benefiting the Bronze Age platform is unclear. The location and

extent of the platform are uncertain, and the Mustdyke — which is known to cut through the archaeology — is draining the ground adjacent to its channel. Also, the artificial recharge will not have any effect east of the Mustdyke, which will act as a hydraulic barrier to shallow groundwater flow;

- if the observed basal elevation of the eastern part of the Bronze Age structure is representative then, on average, the base of the archaeology is close to the base of the zone of water-table fluctuation (base of Zone 2). The implication is that much of the archaeological wood located outside the immediate area covered by the Large Mere is within the zone of fluctuating groundwater levels and therefore potentially at risk of enhanced degradation (relative to Zone 3);
- the main factor controlling groundwater levels in the Flag Fen area is artificial drainage. Climate seems to be less of an influence. Catswater Drain has less of an influence as the reach that runs alongside the Flag Fen causeway generally does not flow along its entire length (thereby reducing the drainage effect). However, it may still limit maximum groundwater levels;
- hardstanding associated with the proposed development to the east is unlikely to have a significant influence on groundwater levels at Flag Fen. By extension, other developments which involve only a small 'footprint' of impermeable or low permeability, structures are unlikely to pose a significant threat to groundwater levels at Flag Fen;
- blocking ditches to create a wetland southwest of Flag Fen could potentially raise groundwater levels in the vicinity of the causeway and platform, but not to above the top of all the archaeology all year. Further field investigations and modelling would be required to confirm this;
- the ditch diversion scenarios give the best results in terms of raising groundwater levels at Flag Fen with the potential to return much of the archaeology to the zone of permanent saturation. Different combinations of ditches give different rises in groundwater levels: the greatest rise is given by the second diversion scenario.

Conclusion and future investigations

Low groundwater levels at Flag Fen put at risk the long-term *in situ* preservation of the Bronze Age wooden structures. Modelling provides a way of evaluating the groundwater conditions around the structures and assessing options for long-term water management to aid preservation. Modelling of water management options suggests that drain blockage and diversion have the potential to return much of the archaeology to the zone of permanent saturation. The development of a wetland to the south of Flag Fen would also be helpful for raising water levels but this alone would not raise water levels permanently above the remains. Modelled groundwater levels are relatively insensitive to a lowering of groundwater recharge: whether a general reduction such as could be due to climate change; or a local reduction, potentially due to nearby development with hardstanding reducing infiltration.

Further investigation should include additional monitoring of groundwater, particularly between Flag Fen and Mustdyke and beneath the Large Mere. This should include assessment of the chemical impact (including oxygen levels) of the infiltration of water beneath the Large Mere.

Potential wetland creation and/or ditch diversion proposals should be further investigated and their feasibility discussed with the Environment Agency and the IDB. The detailed design of any scheme needs to consider flood risk impacts.

Archaeological investigations could further constrain the spatial distribution of the Bronze Age wooden structures at Flag Fen. It is important always to record the elevation (in m AOD or m below ground level) of archaeological wood encountered within trenches to enable comparison with groundwater-level monitoring.

The modelling approach used, comprising pre-existing data, has been demonstrated to be effective for both understanding the current state of the resource, and for exploring different management scenarios. Hence, whilst this research has focussed on the internationally important site of Flag Fen, the approach has considerable implications for understanding wetland archaeology globally.

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Jim Williams is the senior science advisor, Zoe Outram is the East of England science advisor, and Debbie Priddy is the inspector of Ancient Monuments.

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