The Sizewell C Project

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ATKINS, 2019. TECHNICAL NOTE SIZEWELL C. HYDROLOGICAL IMPACTS ON THE MINSMERE SSSI

SNC·LAVALIN ATKINS Member of the SNC-Lavalin Group

Technical Note

Project:	Sizewell C
Subject:	Sizewell C Hydrological Impacts on the Minsmere SSSI
Author:	Scott Haworth

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Rev 1.0	Information	Scott Haworth	Stuart Smith	Mark Lee	Mark Lee	14/05/2019
Rev 2.1	Update following EDF review and discussion with stakeholders	Scott Haworth	Stuart Smith	Mark Lee	Mark Lee	17/07/2019

Introduction to this technical note

This technical note has been prepared to provide a basis for discussing an issue raised by the RSPB in its response to pre-application consultation undertaken on the proposed Sizewell C development. It draws together materials presented to date and will ultimately provide a common understanding of the hydrological systems to the north of the proposed Sizewell C Power Station.

The systems of particular interest are the Minsmere River (New Cut and Old River), Leiston Drain, Scott's Hall Drain and IDB Drain No 7. These systems drain towards the Minsmere Sluice from where they discharge to sea. The significant concerns pertain to changes in the flow regime of the Leiston Drain having an impact on the nature of flows and inundation of the Minsmere to Walberswick Heaths and Marshes Site of Special Scientific Interest (SSSI) as a result of prolonged back flooding of the Scott's Hall Drain (Figure 1). Figure 1 is reproduced from the PEI Report (Figure 2.11.1, November 2018) and it does not show the connection between IDB Drain No 7 and Leiston Drain.

The RSPB is concerned that if the flows within the Leiston Drain are increased, this would cause excessive back flooding of the Scott's Hall Drain. This back flooding can result in increased inundation of the scrape, Lowered Reed Beds and Dowleys and North Levels drainage units which could potentially affect waterfowl that utilise the area.

The note considers the channels, the various water level control structures, and the potential mechanisms by which water levels and flows in the different systems interact. The note demonstrates there is limited potential for increased inundation to occur as a result of the proposed works due to the structure of the Minsmere Sluice and the relationships between the watercourses that discharge via it.

The draft content of the technical note was summarised in a workshop on 21st May 2019. Two extensions to the scope were requested include the following considerations

- wider effects from changes at Minsmere Sluice (e.g. on Minsmere River)
- means of attenuating flow and controlling water quality within the water management zones.

A detailed consideration of the function of the water management zones is beyond the scope of this note and the environmental impact assessment. Instead, the work is framed around the performance of the proposed water management strategy and the anticipated off-site effects. However, the desire of our stakeholders for further information to be provided on the water management zones has been noted.

Minsmere Sluice and the contributing catchments

The Minsmere Sluice (Figure 2, reproduced from the PEI Report (2.12.1, November 2018)) is the main control structure governing the flow and water level regimes of the Minsmere New Cut, Leiston Drain and Scott's Hall Drains. The contributing catchments cross the low-lying coastal plain inland of the sluice, which discharges to the North Sea. The sluice was last modified on behalf of the Environment Agency in 2013/14 to improve the durability and operation of the structure. The sluice is divided into two chambers, each with its own gravity-outlet culvert. The northern chamber receives flows from the Minsmere New Cut, while the southern chamber receives flows from Leiston Drain and Scott's Hall Drains. The southern chamber is also connected to the Minsmere New Cut through its southern culvert, which includes a penstock at its upstream face. This inlet valve is only opened during times of excessive back flooding upstream of the structure within the Minsmere River catchment. When river levels exceed sea levels (low tide), water flows from river to sea. Importantly, when sea levels exceed river levels (high tide), river flow will cease, with water stored upstream of the sluice (termed tide locking). Some ingress of seawater into the freshwater system has been factored into the design. This controlled saline intrusion replicates the conditions created by the original, unintentionally leaky structure.

The Leiston Drain provides a relatively small hydrological input and supplies approximately 18% of the total contributing catchment of the Minsmere Sluice. The Leiston Drain catchment has the following contributing sub-catchments: Leiston Drain, Sizewell Drain, IDB Drain DRN16390201 and IDB Drain No. 7. The vast majority of the Main Site Boundary (as shown on Figure 2) is within the Leiston Drain catchment.
IDB Drain No. 7 is not shown on Figure 2 and whilst it is not a Main River, it should have been shown as an 'Other watercourse'. From a geomorphological perspective, the Leiston Drain has been artificially modified, is uniform and trapezoidal in shape with near-vertical banks and has a gentle longitudinal profile.

Groundwater and surface water are in the same range within the catchment of the Leiston Drain, varying between 0.2m and 1.2m AOD. Stage and flow monitoring at location G1 (in Leiston Drain, close to the proposed SSSI crossing), shows that during dry periods, the recorded surface water level is lower than the groundwater level at the closest monitoring point. This indicates that groundwater is contributing to surface water. In addition to data in Leiston Drain illustrating seasonal fluctuations, there are also numerous flow reversals, which are linked to tidal cycles.

Summary of proposals and potential mechanisms of effect

As part of the construction phase, the Sizewell Drain (a tributary of the Leiston Drain) would be diverted, parallel to the base of the platform slope. At its northern extent, it would discharge to the Leiston Drain upstream of the proposed SSSI crossing. In addition, revised water level management may be required for the drainage units and watercourses adjacent to the construction site (Sizewell Belts and Marshes). This would require the inclusion of additional water level control structures and potentially the revised operation of other existing structures. The design of the structures includes interfaces with other drains and ditches and is aimed to ensure the existing water balance of the surrounding wetlands is maintained. The enhanced water level control within the Sizewell Belts and Marshes would allow for fine tuning of the management regime over time.

Greater volumes of water may need to discharge down the Leiston Drain to ensure the SSSI water levels behind the water management structures are maintained. This change in the hydrological regime will be proportionately greatest when the tidal influence on water levels in the Leiston Drain are at a minimum (i.e. when fluvial flows dominate the overall water balance at Minsmere Sluice). In addition, the predicted change in fluvial flows will be most significant during low flows (i.e. when overall fluvial flows are lowest, the predicted change in hydrological regime associated with the construction phase will be proportionally greatest). Proportionally smaller changes in water levels would occur when fluvial flows are higher and when the system is tide locked.

Uncontrolled increase in runoff during construction works could, in theory, also increase flows in the Leiston Drain. Finally, changes to the percentage of hardened surfaces (proposed Sizewell C campus) within the catchment of the IDB Drain No. 7 could, in theory, also influence the flow regime within the lower reaches of the Leiston Drain. Embedded mitigation measures are intended to ensure that these theoretical effects are minimised.

The only credible cause of an observable effect in watercourses other than the Leiston Drain is if the increased discharge flows are sufficient to reduce available capacity in the southern chamber of the Minsmere Sluice. In this case, back flooding may be caused within the Scott's Hall Drain. The back flooding could lead to adverse impacts on the Minsmere to Walberswick SSSI. For the Minsmere River (New Cut and Old River), the only potential cause of change in flow regime would be if the available capacity of the southern chamber caused the overtopping of the divider between the northern and southern chambers of Minsmere Sluice. A series of embedded mitigation measures have been considered to prevent these effects from occurring.

Embedded mitigation measures

Mitigation measures have been embedded into the design of the Sizewell C MDS to manage surface water discharges from the site adequately, during both the construction and operational phases that could potentially affect the flow regime of the systems and include:

- A perimeter ditch/swale and bund would be constructed to prevent untreated surface water run-off from leaving the site. Oil/petrol interceptors would be incorporated into the drainage design.
- Where complete infiltration to ground is not feasible, water management zones (WMZs) have been embedded into the design. These would intercept surface water run-off, sediment and contaminants. The WMZs would incorporate an underground piped network and storage tanks and ponds. These systems would be designed to discharge treated water to the surface water drainage network at greenfield run-off rates.
- Foul water would be pumped to a central treatment plant, prior to discharge to sea. This would prevent the contamination of surface waters with sewage effluent during construction.
- A cut-off wall would be anchored into the London Clay Formation, to limit the extent of drawdown associated with dewatering during construction works in the main platform area. The cut-off wall may be breached towards the end of the construction period to enable groundwater levels across the area to recover as close as possible to original conditions.
- An operational phase drainage system would be implemented, including SuDS measures to intercept water, sediment and contaminants.
- Rainfall falling onto the power station site would be managed through an engineered drainage system. Forecourt separators would be provided at all locations where fuel handling takes place. Bypass separators would be provided for car parks of a size greater than $800m^2$ or with more than 50 spaces if the car park discharges via drains to a water body. Bypass separators are also required for other areas where there is a risk of oil/hydrocarbon contamination in surface water run-off. This water would be discharged to sea with the cooling water and will therefore no longer influence flow/water level of the Leiston Drain.
- At the western perimeter of the site, a filter drain would be installed to capture surface water run-off and prevent direct discharge to Sizewell Drain. The realigned Sizewell Drain will remain during the operational phase as described in the construction phase.

- Foul effluent would be discharged to the existing local foul water system located in the south east corner of the site. Treated effluent would be pumped to the cooling water outfall tunnel and disposed to sea.

The mitigation measures above, combined with the proposed Sizewell Drain realignment, largely isolate the Sizewell C MDS from the surrounding areas. The mitigation measures also ensure that any flows discharged to an existing surface water receptor would have passed through water quality treatment measures and will be discharged at greenfield rates. It is anticipated that the Sizewell C MDS should create no significant effect on the flow regime of the existing surface water receptors.

We note that RSPB has expressed concerns regarding the WMZs and the change to the hydrological regime that their implementation will have at Minsmere Sluice. The following outlines potential effects under different scenarios:

- Under day to day weather events, all water would infiltrate meaning there would be no off-site effects. Influence on the tidal drain network solely via groundwater (i.e. as per present conditions).
- High magnitude events up to the maximum design event (i.e. up to a 1 in 30 year return period), infiltration with discharge at greenfield runoff rates.
  - For low magnitude events (high rainfall but not exceeding annual maximum events), the relative balance of infiltration and surface discharge will depend upon antecedent conditions but it is feasible that a greater proportion of the water budget will discharge into the tidal drainage network via surface runoff than at present. It is unlikely that these conditions would cause a meaningful alteration of the water balance at Minsmere Sluice or have implications for the management of water levels in Scott's Hall Drain or Minsmere River due to the relatively small change from existing flows.
  - For higher magnitude events (still within maximum design event), as the magnitude of an event increases, the relative balance of drainage will shift from infiltration to discharge at greenfield runoff rates. As the magnitude of event increases, the degree of control exerted by the WMZs will increase, meaning that within-storm runoff is likely to be lower than would be anticipated under current conditions (i.e. this water will be held on site and discharged more slowly than would occur naturally). No significant effects are predicted for Minsmere Sluice, pending finalisation of design, modelling and assessment work.
- High magnitude events beyond the maximum design event (1 in 30 year return period) to a 1 in 100 year event. The effectiveness of the drainage network within the site will decrease affecting site operations, but discharge from the site will still be restricted to greenfield runoff rates. Consequently, we anticipate that runoff will be lower than would occur under existing conditions.
- Beyond a 1 in 100 magnitude event, the drainage system will be exceeded and runoff from the site will not be controlled. The effects of extremely high magnitude, extremely low probability events have not been assessed as they are beyond the requirements of site drainage for reasonably foreseeable events, however it is not considered that the flows at the Minsmere Sluice would be different from pre-development conditions.
- Under scenarios where greenfield runoff rates are greater than runoff would otherwise be under existing conditions e.g. following a storm event as the retained water is discharged, the principal control on water levels in Leiston Drain and Scott's Hall Drain is still tidal conditions. This is because it is only when Minsmere Sluice is tide locked that the Scott's Hall and Leiston Drain 'compete' to discharge via the southern chamber of Minsmere Sluice. The magnitude of effect from the proposed changes relative to this tidal control is small. A similar conclusion can be drawn regarding the relative influence of fluvial flows and tidal levels on the interaction of the northern and southern chambers.
- Under scenarios where greenfield runoff rates are less than would occur under existing conditions, high water levels would be anticipated in the wider network draining via Minsmere Sluice. As levels recede post event, runoff from the main site would continue for longer than would occur under existing conditions. The magnitude of this change is unlikely to be as large. In effect the rate of discharge is lower, but occurs over a longer period. For the reasons stated above when the wider network is discharging under day to day conditions the effect of an increase in discharge to the Leiston Drain at greenfield rates is small, and not considered likely to impact on the function of the other catchments draining to the Minsmere Sluice.

The management of water levels within the Sizewell Belts and Marshes may result in increased flow volumes discharging down the Leiston Drain towards the Minsmere sluice, which would be similar to the current hydrograph during an intense rainfall event in the catchment. These flash flows would be of a short duration. It is important to note that the flat topography of Sizewell Marshes, together with the inter-connected nature of the drainage network, means that the variations in the flow of water will be relatively modest and driven by seasonal and local variations in water level. The drainage pattern could also be modified through simple changes in water level management and channel maintenance. Such changes would need to be made with reference to an agreed programme of monitoring and mitigation, targeted to minimise effects on Sizewell Marshes SSSI and other downstream receptors.

Further mitigation measures have been embedded into the design to minimise the significance of changes to the percentage of hardened surfaces (proposed Sizewell C campus) within the catchment of the IDB Drain No. 7. The following mitigation measures that have been embedded in the design of the campus facility:

- During the construction phase Water Management Zones (WMZs) will ensure runoff from the vicinity of the campus are returned to groundwater via infiltration, with any excess surface water runoff not exceeding greenfield runoff rates. Oil/petrol interceptors would be incorporated into the drainage design.
- An operational phase drainage system would be implemented, including Sustainable Drainage Systems (SuDS) measures to intercept water, sediment and contaminants for separation and treatment. Where infiltration is feasible, this would be the preferred means of discharge, with surface discharge restricted to greenfield runoff rates. The SuDS capacity will be exceeded during extreme events and in this situation, some uncontrolled runoff will occur. Flood risk modelling and assessment work will compare pre-development and post-development scenarios, including during extreme events. We will share these results, when available, to ensure that effects are adequately characterised and described.

Conclusions

Based upon currently available information, it is concluded that the main site construction and operation should not lead to any significant effects on the flow regime[1] of the Sizewell Drain, Leiston Drain and IDB Drain DRN163G0201. This coupled with the fact that the relatively small contribution from Leiston Drain to the overall flow at Minsmere Sluice, limited effects on the flow regime and capacity of the southern chamber of the Minsmere Sluice are anticipated and thus no significant effect is predicted for the Scott's Hall Drain and associated upstream drainage network.

[1] Other impacts on Sizewell Drain such as physical change and alteration/disruption of geomorphological processes may be significant.

Figure 2.11.1 Surface water channels and drainage units

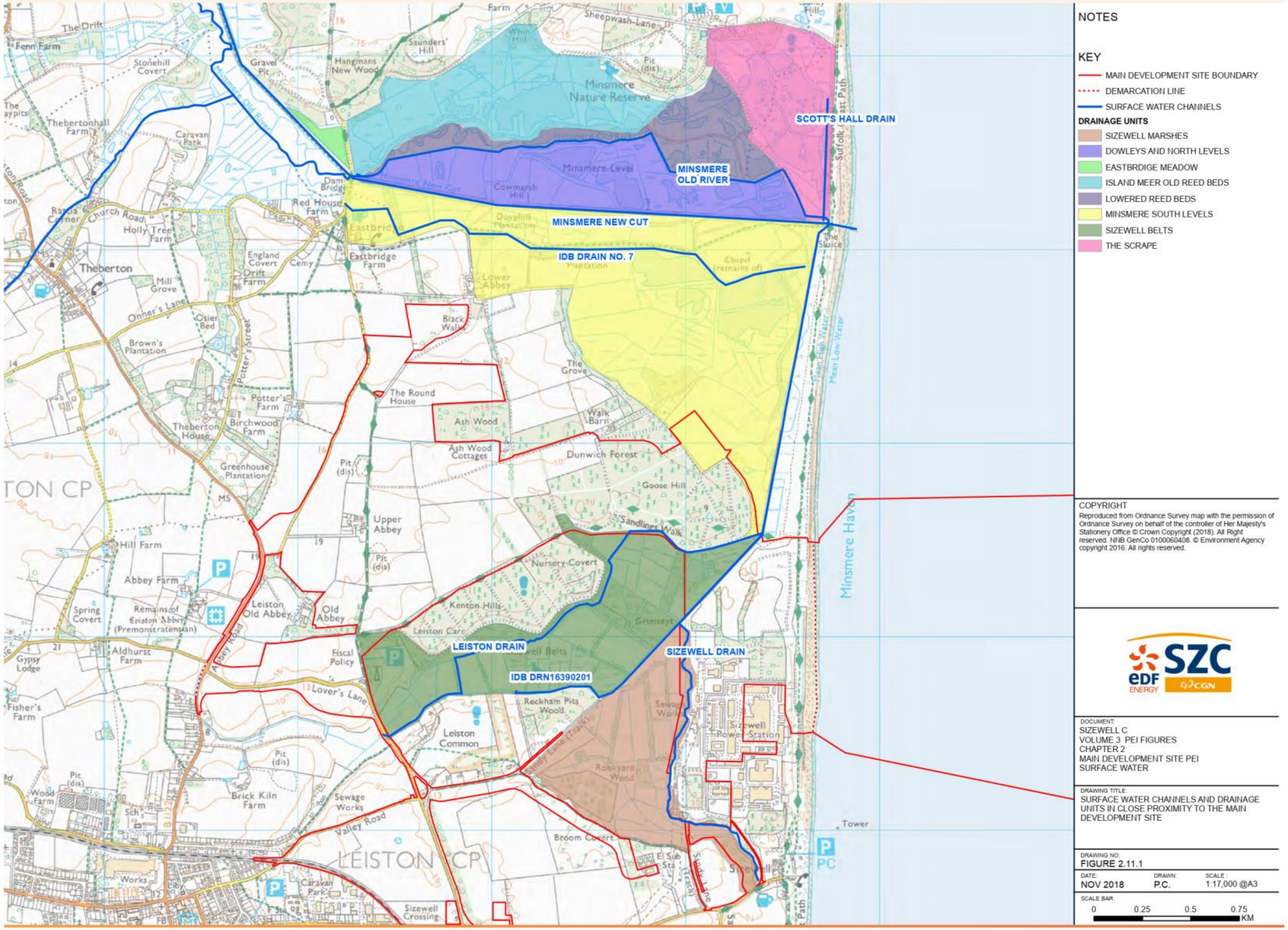

Figure 1 Surface water features and drainage units that drain towards the Minsmere Sluice (reproduced from PEIR)

Figure 2.12.1 Summary plan of key catchment features and locations

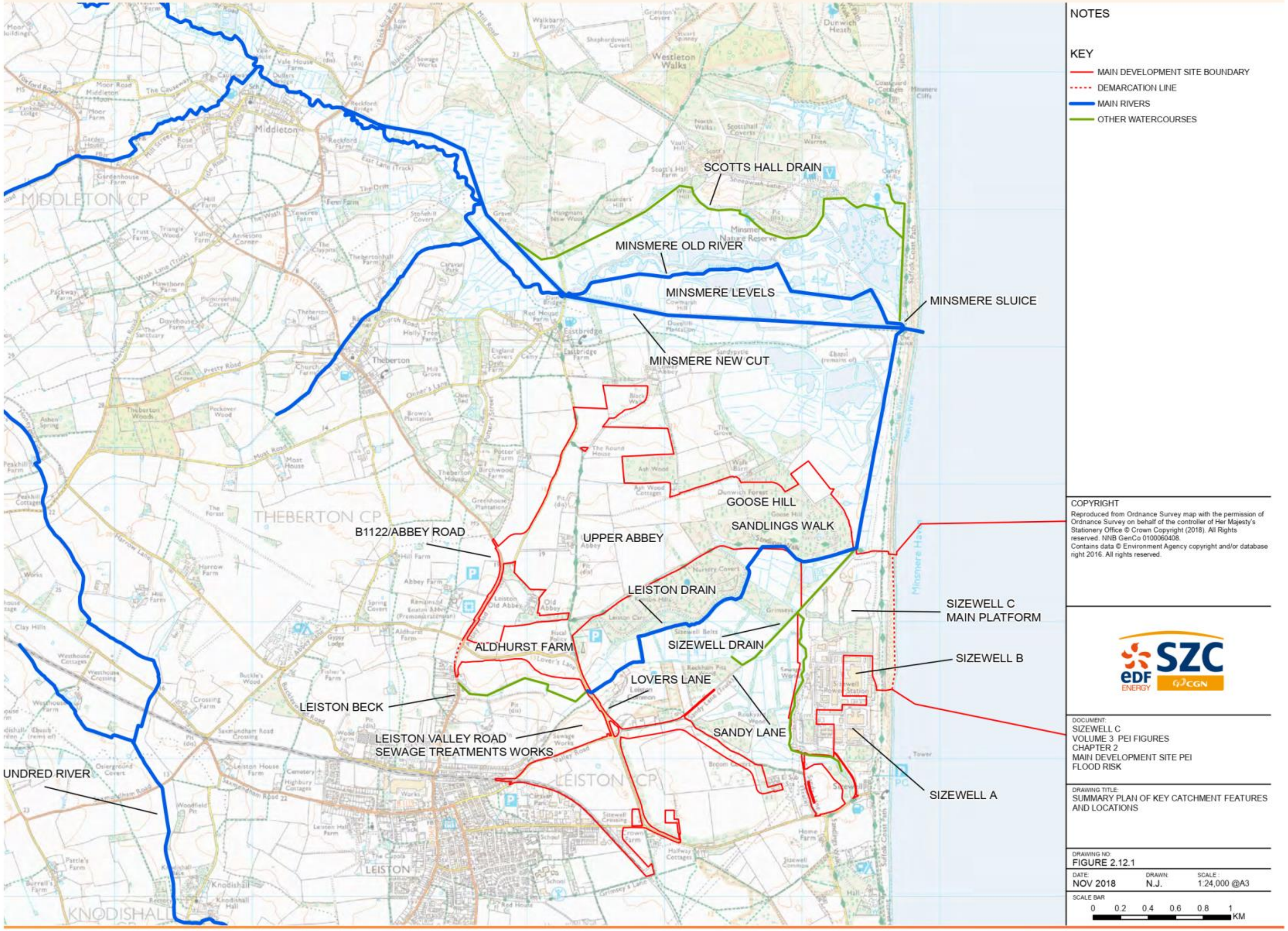

Figure 2 Summary plan of key catchment features and locations (reproduced from PEIR)

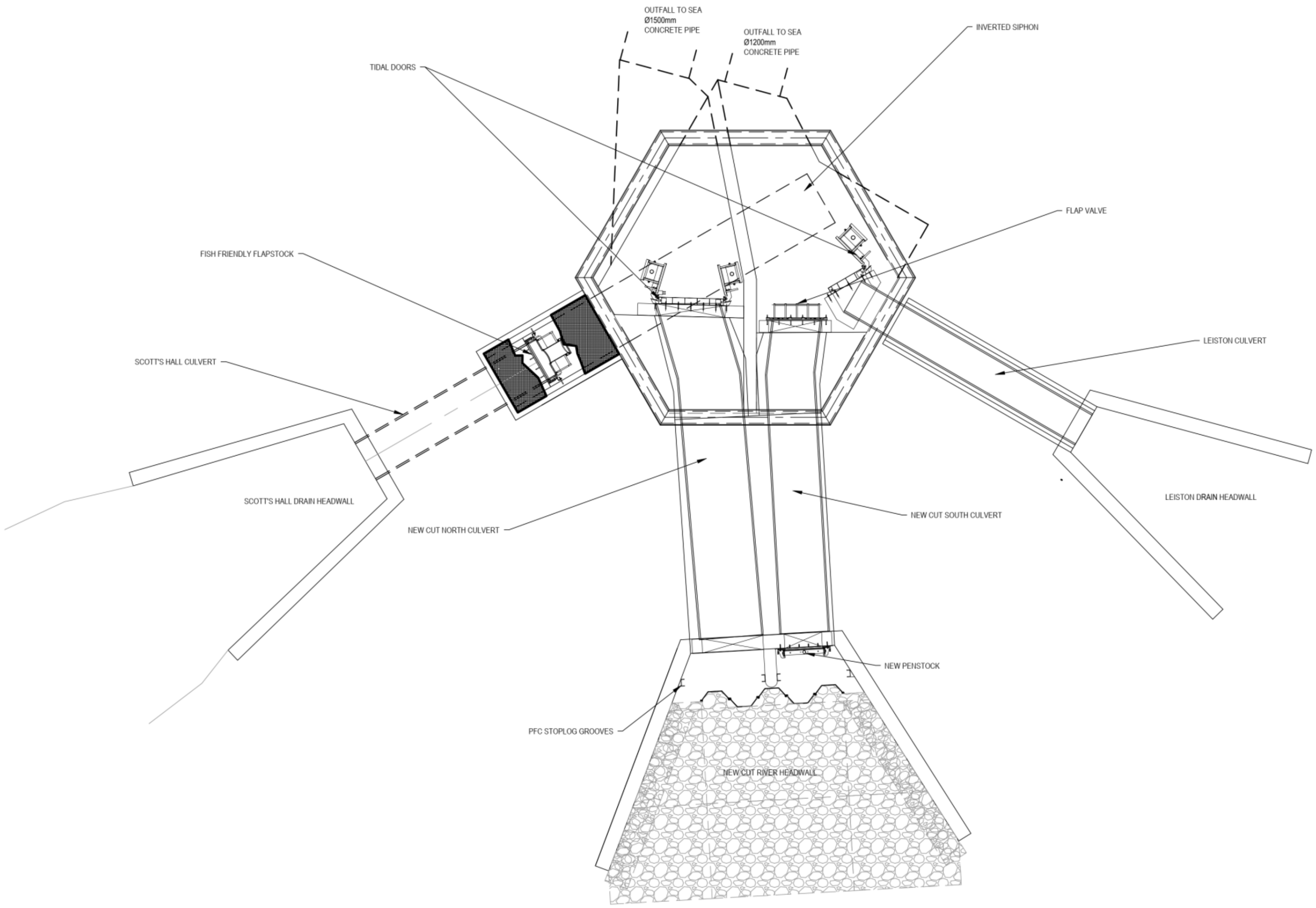

Figure 3 Design of the Minsmere Sluice

BECC, 2014, BECC SCOPING PAPER, HOW TO DEFINE CREDIBLE MAXIMUM SEA LEVEL CHANGE SCENARIOS FOR THE UK COAST

British Energy Estuarine & Marine Studies

Scientific Advisory Report Series 2014 no. 024

How to define credible maximum sea-level change scenarios for the UK coast

British Energy Climate Change Working Group

Production Date: December 2014
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Science Advisory Report No 024

How to define credible maximum sea-level change scenarios for the UK coast

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BECC WG membership

Professor Rob Wilby (Chair)	Loughborough University
Dr Richard Dawson	Newcastle University
Professor Chris Kilsby	Newcastle University
Professor Robert Nicholls	Southampton University
Dr Rachel Warren	University of East Anglia

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List of acronyms

Acronym	Definition
A1B	Greenhouse gas emissions scenario under very rapid economic growth
A1FI	Fossil fuel intensive greenhouse gas emissions scenario
AIS	Antarctic ice sheet
AOGCM	Atmosphere-ocean general circulation model
AR4	Fourth Assessment Report (of the IPCC) published in 2007
AR5	Fifth Assessment Report (of the IPCC) published in 2013
CMIP3	Third Climate Model Intercomparison Project (used in AR4)
CMIP5	Fifth Climate Model Intercomparison Project (used in AR5)
EA	Environment Agency
EIA	US Energy Information Administration (EIA)
EMIC	Earth System Model of Intermediate Complexity
ENSO	El Niño Southern Oscillation
EPR	East Pacific Rise (earthquake zone)
ES	Environmental Statement (under the European Environmental Impact Assessment Directive)
GIS	Greenland ice sheet
HLO	High level option
IPC	Infrastructure Planning Commission
IPCC	Intergovernmental Panel on Climate Change
MOC	Meridional overturning circulation
NFIP	US National Flood Insurance Programme
NNB	New nuclear build
NPCC	New York City Panel on Climate Change
ONR	Office for Nuclear Regulation
RCP	Representative Concentration Pathway
SLR	Sea-level rise
SRES	Special Report on Emissions Scenarios (of the IPCC)
TAG	Technical Assessment Guide
TE2100	Thames Estuary 2100 Project
UKCP09	2009 UK Climate Projections
USACE	US Army Corps of Engineers
WAIS	West Antarctic ice sheet

Executive Summary

This report synthesizes the current scientific knowledge on climate risks, particularly relative sea-level rise (SLR) in order to inform the planning, design and operational processes of new nuclear build (NNB). SLR is already occurring, and such risks would have to be managed until at least the middle of the 22nd century. The Office for Nuclear Regulation (ONR) and Environment Agency (EA) (2013) advise that a precautionary approach is taken, which should be based on the “credible maximum scenario”. The synthesis provided herein establishes terms of reference for evaluating such scenarios, examines high-end scenarios of SLR in the scientific literature, provides case studies that illustrate how sea level and surge can be combined into credible maximum scenarios, and lastly provides a worked example for the east coast of England. The site is intentionally unspecified in order to avoid uncritical application of derived levels.

Relatively little research on climate change has been carried out beyond year 2100 (BECC, 2011). However the whole lifetime must be considered when identifying mitigation and adaptation measures of new infrastructure applications. There are, however, no such national projections that cover the full lifetime of NNB. IPCC AR4 stated that high-end SLR scenarios could not be evaluated (BECC, 2011). However, it did provide two scenarios projected through to 2300, with forcing held constant from 2100. Thermal expansion contributed to increasing SLR beyond 2100 in these projections. Other studies have indicated that SLR could increase by 11.4 m by year 3000 (Lenton et al., 2006), or up to 3.3 m by 2500 (Nicholls et al., 2006). The more recent IPCC AR5 report presents climate models which give a global mean SLR of up to 2 m by 2200 although semi-empirical models give greater SLR, but there is lower confidence in these results (Church and Clark, 2013).

Recent advances in SLR research include analysis of palaeoclimate analogues, ice mass-balance changes, multi-centennial experiments, regional SLR and local tide-surge interactions. Before high-end scenarios can be applied in a decision-making context, these separate components of extreme water level have to be assembled in a defensible and transparent way. Three case studies are presented which have developed high-end scenarios for adaptation planning, incorporating these new advances. These are the Netherlands Delta Committee, New York City Panel in Climate Change (NPCC and NPCC2), and the Thames Estuary 2100 Project. These projects had different overall objectives and socio-economic contexts, but they shared several common features. These principles could be adopted in future studies to help infrastructure decisions in the coastal zone:

- Scientific evidence is drawn from a range of sources including dynamic and empirical models, palaeoclimatic data, expert judgement, climate model projections, and lessons learnt by others responding to rapid SLR;
- The plausibility and uncertainty scenarios is corroborated with respect to other recent high-end estimates;
- Where feasible estimates are constrained by physically plausible upper bounds;
- Narratives are used in place of likelihoods to qualitatively describe high-end scenarios;
- Participatory approaches are deployed to capture the perspectives of different stakeholders;
- Significant resources are invested commensurate with the scale of climate risks involved;
- Expert panels have clear terms of reference and are multi-disciplinary, drawing on different perspectives;
- Every step of the analysis is carefully documented and supported by evidence tested by panel and/or peer review;
- Monitoring systems track sea-level changes to give sufficient lead time to re-evaluate flood risk and implement measures;
- Management structures capture and internalise emerging scientific evidence as part of an open-ended, institutional learning process.

These case studies illustrate two ways of specifying credible maximum sea levels. The first is transparent and straightforward to scrutinize and involves aggregating the components of extreme water levels, assuming independence of the elements (e.g. Delta Committee, NPCC2). The ‘extremeness’ of each

building block can be modulated by the level of risk aversion, or willingness to accept outlier opinions about highly uncertain future conditions. The values are also readily updated as the science evolves and further factors can be applied to enable exploration of "cliff edge" effects, or to include new scientific findings.

The second approach uses narratives or representative climate futures (e.g. NPCC, Thames Estuary 2100). Adaptation strategies and design assumptions can then be tested against bespoke situations such as 'rapid ice melt', 'submarine landslide' and 'a 4 degree Celsius world'. Likelihood or timing is not attached to the scenario, yet the assumed climate parameters may still be drawn from a range of sources (i.e. observations, models, palaeo-data and expert opinion). This approach can also accommodate credible, long-term institutional scenarios that might influence the range of options available for decision-makers.

Both methods of specifying credible maximum sea levels have their limitations. Aggregating high-end contributions may appear more objective but linear addition of extreme components can imply coincidental occurrence of the components, which has infinitesimally small likelihoods. There is also a loss of internal consistency when component values are derived from different lines of evidence. On the other hand, the narrative approach is always open to the criticism of subjectivity. With these points in mind, an example is provided here for the east coast of England. This example includes the following components of credible maximum water level elevation:

- Global mean thermal expansion
- Local steric anomaly
- Small ice caps and glacier melt
- Antarctic ice sheet melt
- Greenland ice sheet melt
- Correction for gravitational fingerprint
- Aquifer dewatering
- Vertical land movement
- Surge

These different components give a total SLR range by 2100 of 1.55–3.20 m, and by 2200 of 2.55–5.00 m.

This report has focused attention on the quantitative definition of credible maximum (or high-end) scenarios. As has been shown, this is not an entirely objective exercise because the variable reliability of different sources and expert opinions must be combined with the risk tolerance and intended application of the scenario. The task is further complicated by the volume and breadth of research that must be assimilated. This spans different techniques as well as various scientific disciplines. The three case studies show that constructions of credible maximum scenarios for sea level and surge should:

- Cast the net for evidence far and wide
- Weigh different lines of evidence
- Constrain scenarios using physical limits where feasible
- Avoid the language of likelihood or probability
- Employ participatory consultation processes
- Allocate appropriate levels of time and resource to the task
- Draw on the expertise of panels of specialists
- Document and test assumptions by peer review
- Invest in targeted monitoring systems to track and learn from indicators of coastal change, and
- Establish institutional structures that can systematically harvest and implement latest scientific understanding of the issues.

The worked example for a site on the east coast of England shows how various components of a credible maximum scenario can be assembled in a transparent way. This transparency establishes the provenance of data, exposing embedded assumptions and showing methods of working, and providing tabulated values of the components of potential future relative sea-level rise provides a basis for peer review and further refinement. Individual components may subsequently be adjusted in line with evolving scientific knowledge.

1 Introduction

Accepting that the operational phase of NNB in the UK begins in the 2020s and that no geological disposal facility is found, at-site climate risks would have to be managed until at least the mid-22nd century. Joint advice issued by the ONR and EA (2013) assumes that the full lifetime of a new station (including operation, spent fuel storage, and decommissioning) will be 160 years. Relative SLR is already occurring and the regional consequences of anthropogenic climate change are expected to accelerate during this time frame (Haigh et al., 2014), so the consequences must be factored into the design and safety planning of NNB (Defra, 2011; Kopytko et al., 2011; Wilby et al., 2011).

The ONR/EA (2013) joint advice sets out a framework for parties involved in NNB pre-planning and safety discussions. This includes: (i) consideration of climate change in energy infrastructure and planning; (ii) reference to Government guidance and data to support adaptation within flood and coastal management; and (iii) elements of a managed adaptive approach. A precautionary approach is required *where there is potential for adverse consequences to people, property and the environment* (p.3). This should be based on the **credible maximum scenario** defined therein as *a peer-reviewed, high-end, plausible scenario* (ONR/EA, 2013:13).

Phrases such as “upper bound” (Sriver et al., 2012), “maximum plausible” (NOAA, 2012), “high end” (Jevrejeva et al., 2014), “high impact/low-probability” (Katsman et al., 2011) have all been used in the context of relative SLR and associated impacts. **For the purpose of this report the credible maximum sea-level is defined as a scenario based on assumed rapid climate change, resulting from high rates of greenhouse gas emissions and responses in each of the major contributions to SLR that are in line with current scientific knowledge, but nevertheless towards the upper end of the expected sensitivity in these responses.**

ONR/EA advice refers to credible maximum scenario in five contexts (Table 1):

i. flood-risk assessment;

ii. evaluating flood mitigation measures

iii. reflecting latest scientific knowledge in periodic safety cases

iv. assessing “cliff-edge” effects in the design, and

v. taking a managed adaptive approach throughout the life-time of the site

ONR Technical Assessment Guide 13 (TAG, 2014) also states that *due consideration needs to be given to the effects of climate change over the remaining lifetime of the facility*.

ONR TAG 13 (2011:11) further signals that for the design of new facilities, *a conservative choice is adopted, although not necessarily the most conservative, and an appreciation of the sensitivity of the design to changes is gained. In addition, it is prudent to ensure that there are not features of the design which are completely undermined by more radical changes to the climate*.

Table 1 References to the credible maximum scenario by ONR/EA (2013).

Context	**Advice**
Flood/coastal risk assessment (p.6)	*the effects of climate change over the lifetime of the site, assessed using the most up-to-date credible projections*
Flood risk mitigation measures (p.9)	*mitigation measures should take account of the potential effects of the credible maximum scenario in the most recent marine and coastal flood projects*
Safety cases (p.9)	*allow for any future credible projections that might arise during the life of the station and the interim spent fuel stores*
Assessing “cliff-edge” effects (p.12)	*ensure that there are not features of the design which are completely undermined by more radical changes in climate*
Managed adaptive approach (p.13 & 14)	*understanding the full range of risks that might need to be managed*

This report provides a synthesis of scientific knowledge on climate risks to inform the planning and design (flood-risk assessment), and operational phases (safety case) of NNB. Given that all proposed sites for NNB in the UK are situated on the coast, the focus is on future sea-level extremes. Ten components of credible maximum water level elevation are covered:

i) global mean thermal expansion

ii) local steric effects (thermal and salinity)

iii) small ice caps and glacier melt

iv) Antarctic ice sheet melt

v) Greenland ice sheet melt;

vi) elastic and gravitational effects

vii) aquifer dewatering

viii) vertical land movements

ix) surge, and

x) tsunami

Note that tsunamis are considered because there is a small but growing body of evidence about the potential for climatic forcing of submarine mass movements, earthquakes and tidal waves.

Section 2 establishes some terms of reference for evaluating knowledge about credible maximum scenarios. Section 3 surveys the scientific literature beginning with the headline messages of the IPCC Fifth Assessment Report (AR5) then examines drivers of global mean SLR, regional SLR, local surge and coastal geo-hazards. Given the volume of material, the focus of the survey is on peer-reviewed research into low likelihood, high-impact scenarios. Section 4 summarises three case studies that illustrate various ways in which evidence of sea level and surge components can be assembled into credible maximum scenarios for long-lived infrastructure projects. Section 5 then provides a worked example for the east coast of England. Section 6 concludes the report with a summary of the practical insights gained from the case studies and worked example.

2 Establishing credible high-end scenarios

Given the heterogeneity of scientific methods, knowledge of credible maximum sea-level scenarios could be drawn from palaeo-climate research, extrapolations of observed rates of environmental change, empirical and process-based models of the Earth System. However, one thing is clear: there is relatively little research on climate change beyond year 2100 (BECC, 2011). On the other hand, the Overarching National Policy Statement for Energy (Box 1) stipulates that the latest UK Climate Projections available should be applied when identifying mitigation and adaptation measures for the lifetime of the new infrastructure (ie, to the 2140s). At this point in time, there are no such national projections that cover the full lifetime of NNB.

Box 1 Overarching National Policy Statement for Energy (EN-1, sec 4.8.6)

The IPC should be satisfied that applicants for new energy infrastructure have taken into account the potential impacts of climate change using the latest UK Climate Projections available at the time the ES was prepared, to ensure they have identified appropriate mitigation or adaptation measures. This should cover the estimated lifetime of the new infrastructure. Should a new set of UK Climate Projections become available after the preparation of the ES, the IPC should consider whether they need to request further information from the applicant.

What principles might, therefore, be applied in good faith to available climate change information beyond 2100? Expert elicitation has become an established technique for pooling views on very uncertain components of climate projections. For example, based on surveyed expert judgements, Bamber and Aspinall (2013) established a median and 95th percentile estimate for ice-sheet contributions to sea level of 29 cm and 84 cm respectively by year 2100. However, political and peer pressure, cultural processes and the scientific norm of restraint can cause scientists to err on the side of less alarming predictions when, in fact, *some phenomena in nature are dramatic* (Brysse et al., 2013: 335). Even complex arrangements for scientific assessment can lead to exclusion of extreme projections (e.g., O'Reilly et al., 2012) or redaction of material that is scientifically robust yet regarded by some governments as 'too toxic' (Victor et al, 2014:35).

Moreover, judging the quality of climate science based on the calibre of the researchers involved is controversial. This is because objective classification of climate expertise is far from straightforward. One study categorized researchers based on their publication and citation data (Anderegg et al., 2010) and attracted strong criticism (e.g., Bodenstein, 2010). Expertise may also be weighed by the underlying motivations of the scientist. For instance, Pielke Jr. (2007) identifies five types of practice ranging from the pure scientist through to the 'stealth issue advocate'. In between are the honest brokers who try to offer decision-makers a range of options based on available evidence but in non-prescriptive ways.

Cash et al. (2003) and Tang and Dessai (2012) take a different approach, focusing instead on the 'usability' of the (climate) science assessed by three criteria:

- **Credibility** is the stakeholders' perceptions of the quality of science underpinning the disseminated information;
- **Legitimacy** is the stakeholders' perceptions of the level of transparency and bias of the individuals and institutions involved in the development of the science;
- **Saliency** is the stakeholders' perceptions of the relevance of the science to their requirements.

Tang and Dessai (2012) sampled the perceptions of three stakeholder groups (knowledge producers, knowledge translators and knowledge users vested with responsibilities for adaptation) regarding the 2009 UK Climate Projections (UKCP09). Six indicators of credibility and legitimacy emerged for users:

i. source(s) of funding behind the projections

ii. national and international recognition of the research

iii. endorsement by government and/or regulatory bodies

iv. peer review

v. comparable to other research, and

vi. transparent modes of research production and dissemination

This list provides a rubric for evaluating the scientific basis of credible maximum scenarios. For example, even the UK Government's credible maximum scenario for SLR and storm surge up to year 2100 (the H++ scenario) falters on one or two of these criteria. Early development of H++ was supported by the EA (criteria i), the scenarios are nationally recognised and endorsed by Defra (criteria ii, iii), but some aspects of H++ (such as exclusion of gravitational effects) were not made fully explicit (criteria vi). Although drawing on peer-assessed ensemble projections from IPCC AR4 models, the full H++ methodology has only recently been published in the peer-reviewed scientific literature (criteria iv) (Nicholls et al., 2014).

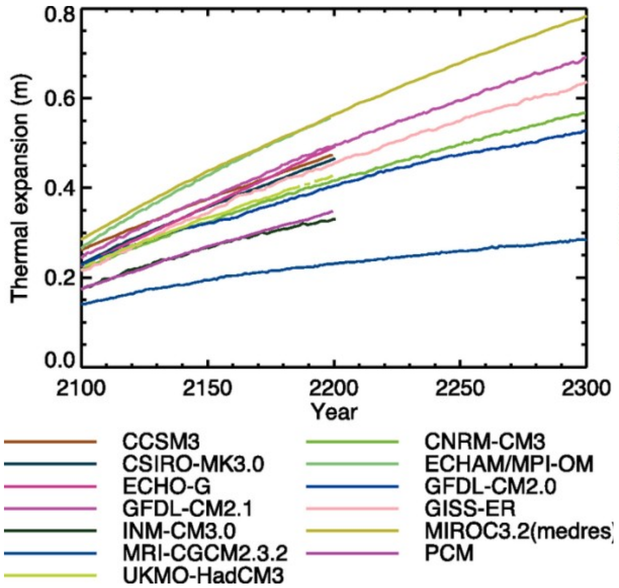
As well as criteria for assessing credibility, a robust process is also needed for systematically harvesting new scientific evidence as it emerges in the future. Burney et al. (2014) suggest that investment will be needed to set up 'knowledge action networks' to organize information sharing and disseminate best practice. Periodic safety-case reviews will provide opportunities to revisit evidence on a decadal basis. In between, higher-frequency reviews could be performed by boundary organisations such as BECC. The following section provides a synthesis of relevant climate science published since 2007.

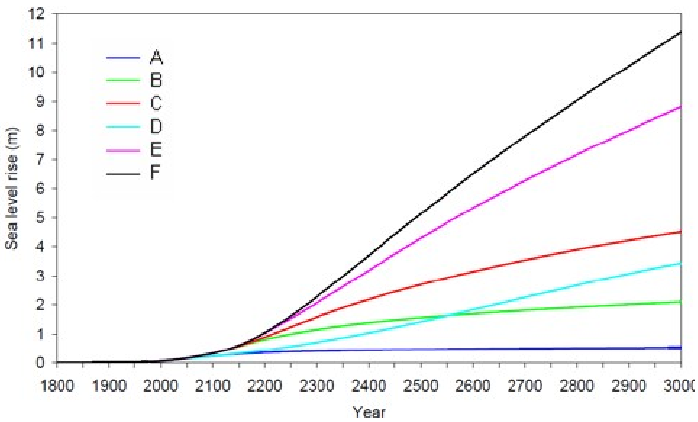
3 Summary of recent scientific developments

The IPCC AR4 had nothing to say about *high-end* SLR scenarios beyond 2100 apart from stating that they could not be evaluated (BECC, 2011). However, SRES A1B and B1 scenarios were projected through to 2300, with forcing held constant by stabilising atmospheric concentrations at 550 ppm CO_2 (B1) and 700 ppm CO_2 (A1B) from 2100. Thermal expansion of the ocean was projected to contribute 0.3 m to 0.8 m to SLR by 2300 and to continue for centuries beyond (Figure 1, left).

One early study applied two Earth System Models of Intermediate Complexity (EMICs) to evaluate the impact of six emissions scenarios to year 3000 (Lenton et al., 2006). The models predicted 1.2 to 15.6°C global warming and SLR of up to 11.4 m on the millennial timescale (Figure 1, right). Another early multi-centennial model experiment showed that burning conventional fossil-fuel reserves could yield SLR of 0.35 m to 3.3 m by the year 2500 (Nicholls et al., 2006).

The IPCC AR5 report collates recent research into the likely range of global mean SLR and new model evidence on climate change beyond 2100 (Church and Clark, 2013). A new set of radiative forcing scenarios (ranging from 2.6 to 8.5 $W.m^{-2}$) termed Representative Concentration Pathways (RCPs) were developed for the 21st century and extended to 2300 (Meinshaussen et al., 2011). Process-based climate models suggest global mean SLR of up to 2 m by 2200 under high greenhouse gas concentrations (Figure 2); semi-empirical models show consistently greater SLR over the same period but there is lower confidence in these results (Box 2).





Key to emissions scenarios: **(A)** minimum emissions (1130GtC); **(B)** business as usual followed by a rapid cessation in emissions (2660GtC); **(C)** rapid and **(D)** slow combustion of all 4000GtC conventional fossil-fuel reserves; **(E, F)** additional combustion of 'exotic' fossil fuel reserves (e.g. methane hydrates) yielding total emissions of 9210GtC or 15000GtC.

Figure 1 Left: global mean SLR from thermal expansion relative to the period 1980 to 1999 for an A1B commitment experiment run with 13 AOGCMs (IPCC AR4 section 10.7). Right: SLR projected by GENIE-1 due to thermal expansion and Greenland ice-sheet melt but excluding changes in the mass balance of Antarctic ice sheets (Lenton et al., 2006).

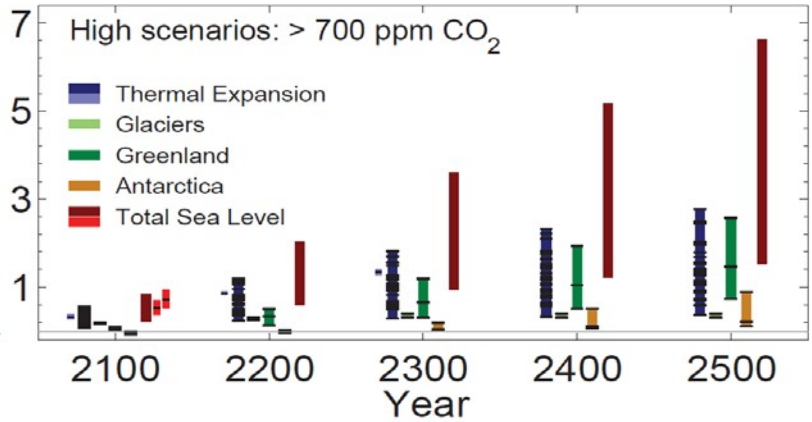


Figure 2 Sea-level projections (change in m) beyond 2100 under the high concentration scenario showing contributions from thermal expansion, glaciers, Greenland and Antarctic ice sheets, and their total. Sourced from Church and Clark (2013).

Research has advanced in five areas that inform the present critique of credible maximum SLR scenarios. These are: palaeoclimate analogues, ice mass-balance changes, multi-centennial climate experiments, regional SLR, and local tide-surge interactions. Each is discussed below. For a review of the different mechanisms contributing to sea-level change and alternative ways of combining this information for impact and adaptation assessment, see Nicholls et al. (2014). For a compendium of research on sea level rise and European coastlines, see BAS (2013).

Box 2 Headline messages about global mean SLR from the IPCC AR5 (Church and Clark, 2013)

• The 5% to 95% range of process-based models under RCP8.5 (total radiative forcing of 8.5 $W.m^{-2}$) gives *likely* SLR of 0.53–0.97 m by 2100. This implies that there is up to a 33% likelihood of SLR exceeding 0.97 m by 2100. However, there is insufficient evidence to evaluate the probability of specific levels above the likely range. [Note that von Storch and Zwiers (2013) advocate a *descriptive approach* rather than statistical terminology when communicating certainty in ensembles of climate-change scenarios].

• Collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean SLR substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a metre of sea level rise during the 21st century. [See O'Reilly et al. (2012) for a critique of evolving scientific and cultural processes behind statements about Antarctic Ice Sheet disintegration].

• Some semi-empirical models project a range that overlaps the process-based *likely* range, while others project a median and 95-percentile that are about twice as large as the process-based models. In nearly every case, the semi-empirical model 95-percentile is higher than the process-based *likely* range.

• There is low agreement about the reliability and low confidence in the projections of semi-empirical models for the 21st century. Confidence is low in the projections of semi-empirical models because they are extrapolating beyond the range of correlations between observed changes in global mean temperature and SLR.

• The few available process-based models project global mean SLR by 2200 of up to 2 m for greenhouse gas emissions that exceed 700 ppm in the 22nd century. Some semi-empirical models show SLR exceeding 3 m over the same period.

3.1 Palaeo-climate analogues and maximum rates of SLR

Multi-centennial global-mean temperature scenarios (as in Figure 1) fall within the range reconstructed from palaeo-environmental evidence for the previous (~125,000 years ago) and beginning of the present (~12,000 to 7,000 years ago) inter-glacial stages. Hence, it has been suggested that these events could provide upper bounds for maximum rates of SLR associated with processes that are poorly understood. For example, Berger (2013) reports typical SLR of 1.2 m per century during the last inter-glacial (Eemian), but some data from deep-ocean sediments suggest that more than 5 m/century is possible. The H++ scenario in UKCP09 is based on a high-resolution oxygen isotope record for the Red Sea which gives average rates of SLR of 1.6 ± 0.8 m/century (Rohling et al., 2008) (the purple lines in Figure 3). Others use palaeo-evidence to indicate rapid, multi-centennial SLR (McNeall et al., 2011; Stanford et al., 2011). For instance, melt-water pulses from decaying ice-sheets ~8,200 years ago have been linked to SLR of 1.6 to 3.9 m over 300 years in the Netherlands plus regional cooling triggered by perturbation of the North Atlantic circulation (Carlson and Clark, 2012; Tornqvist and Hijma, 2012).

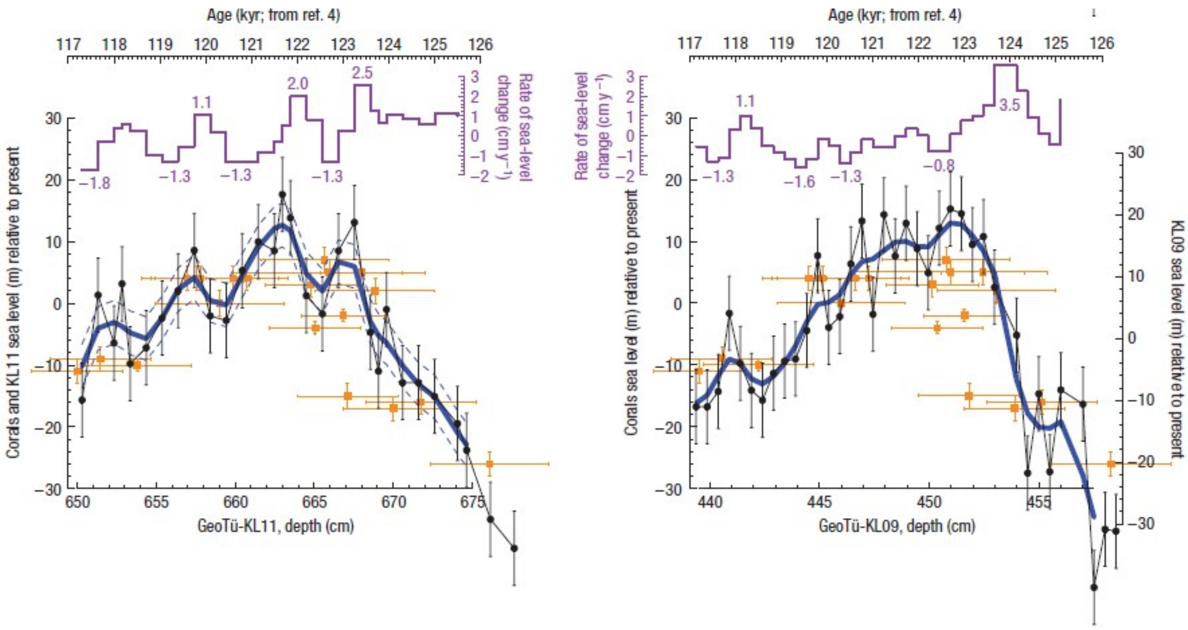


Figure 3 Sea-level reconstructions from oxygen isotope analysis of Red Sea coral data (KL11 and KL09) and surface-water dwelling planktonic foraminifera (Rohling et al., 2008).

Four factors affect the utility of analogues. First, palaeo-climate records do not always agree with each other very well, and inferred rates of local sea-level change may be difficult to interpret as a record of global sea level. Second, seasonal impacts and rates of SLR produced by externally forced climate change (ie, triggered by orbital variations) are not equivalent to radiative forcing by greenhouse gases. Third, there is uncertainty about potential negative feedbacks in major Earth systems due to rapid ice melt, freshwater fluxes and changed ocean circulation patterns (Masson-Delmotte et al., 2012; McNeall et al., 2011). Fourth, the initial state of the system (such as the volume and distribution of ice masses, or thermal profile of the deep ocean) was not the same as the present state. Nonetheless, analogues provide some insights into those physical processes capable of yielding high-end rates of global mean SLR.

3.2 Ice-sheet mass balance contributions to SLR

According to Hanna et al. (2013:51) mass-balance changes in ice-sheets are defined as the net result of mass gains (primarily snow accumulation) and mass losses (primarily meltwater runoff and solid ice dynamic discharge across the grounding line). The contribution of dynamic ice-sheets to future SLR was recognised as a knowledge gap in IPCC AR4. Technical advances have since been made in ice-flow modelling (equations and resolution), as well as in satellite and ground-based observations of ice velocities, surface elevation and thickness (Hanna et al., 2013). The disparity of mass-balance estimates between different techniques is less for recent studies and overall mass-budget methods give the most negative changes for both Antarctica and Greenland (Figure 4). The sum of all contributions now agrees well with observed SLR (Jones, 2013), and shows that the flux from the cryosphere increased between 1972 and 2008 (Church et al., 2011a).

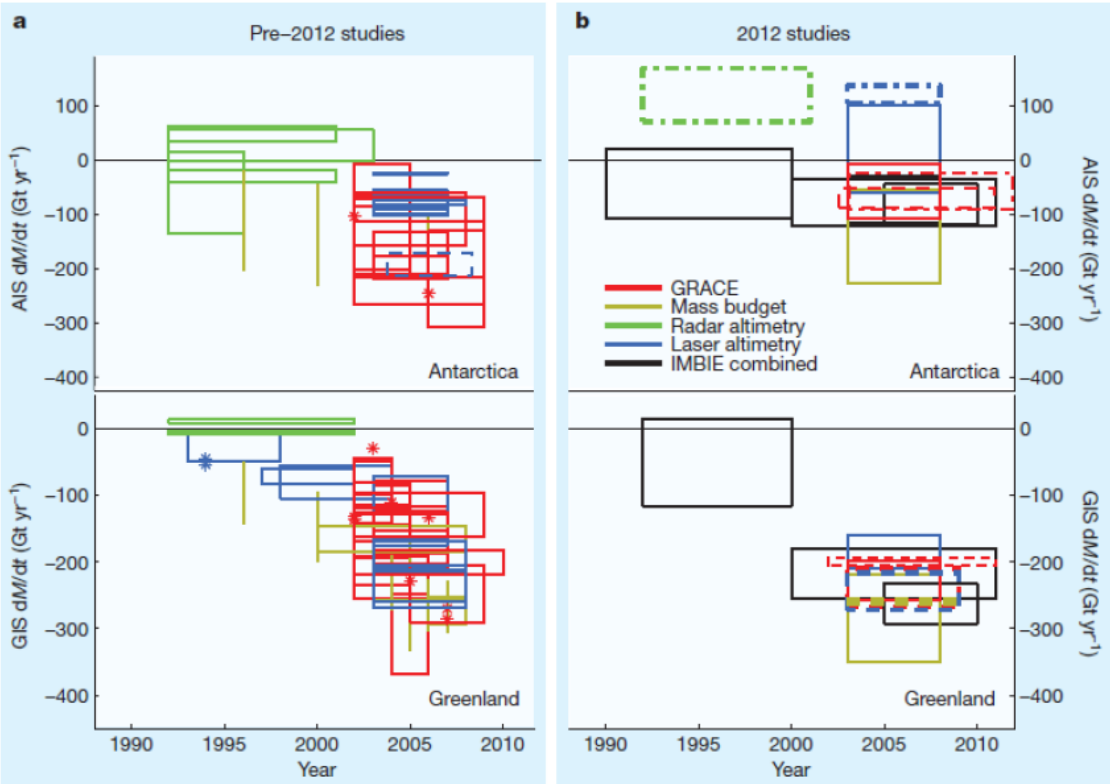


Figure 4 Estimates of rates of ice-mass change for Antarctica and Greenland. Box width represents the time-period studied and box height indicates the error estimate. Source: Hanna et al. (2013).

Recent estimates of current Antarctic ice loss are lower than in earlier studies but remain highly uncertain, particularly for West Antarctica and the Antarctic Peninsula (Hanna et al., 2013). However, new observations are establishing a clear association between increased heat-delivery to ice-sheet margins and accelerating ice loss (Joughin et al., 2012; Miles et al., 2013). In fact, basal melting of ice shelves around Antarctica contributes more to SLR than ice calving, with half of all measured ablation originating from just 10 small shelves (Rignot et al., 2013). Even so, new probabilistic assessments highlight the importance of the need to explicitly account for mass balance uncertainties over the entire ice sheet rather than extrapolating from a few presently active basins (Little et al., 2013a; b).

Total ice wastage added 0.71 ± 0.08 mm/year to global SLR between 2003 and 2009 (Gardner et al., 2013) with polar ice sheets contributing 0.59 ± 0.20 mm/yr between 1992/93 and 2008/11 (Shepherd et al., 2012), and a significant fraction originating from Greenland's marine-terminating outlet glaciers (Straneo et al., 2013). Estimates for the future dynamic contribution to SLR by Greenland vary widely: from 45 mm by 2100 (Price et al., 2011), to 29 to 49 mm by 2200 (Nick et al., 2013), to as much as 467 mm by 2100 (Pfeffer et al., 2008). When estimates of all ice contributions to SLR are constrained by physically plausible conditions (such as maximum rates of ice flow and surface melt), the total SLR to 2100 could lie between 785 and 2008 mm (Pfeffer et al., 2008). To place this in context, the current rate of all contributions to SLR is equivalent to 311 ± 56 mm/century (including ice-sheet mass change, glacier and ice-cap melt, ocean thermal expansion and terrestrial water storage), and estimates resulting from tide gauges and satellite altimetry indicate SLR of 322 ± 41 mm/century (1993–2008) (Hanna et al., 2013).

Hansen and Sato (2012) and Hansen et al. (2013) raise the possibility of a multi-metre SLR scenario, based on the premise that the Greenland and Arctic ice sheets were, in the past, unstable at those global mean temperatures projected to occur in the 21st century. This possibility becomes plausible and pertinent over the 160 year time horizon relevant to NNB. Hansen (2007) originally claimed that SLR of 5 m by 2100 is possible under a business-as-usual emissions scenario, assuming non-linear (exponential) ice-sheet disintegration with 10-year doubling time. Reference was made to elevated shoreline deposits from the Pliocene as evidence that eustatic sea level was 25 m higher than today when the global mean temperature was 1–2°C warmer than the pre-industrial Holocene. However, Rowley et al. (2013) argued that this apparent high stage is explicable by glacial isostatic adjustment and topographic dynamics, driven by mantle convection during the intervening three million years.

3.3 Multi-centennial climate model experiments and irreversible SLR

At the time of the AR4, there were only a handful of climate model runs which produced outputs beyond 2100; a short-coming that has since been addressed by a raft of new studies (Table 2).

Table 2 Example projections of global mean SLR to 2100 and beyond (published since 2007).

Model(s)	Forcing	Global mean SLR (cm)			Sources
		2100	2200	2300	
Expert survey	Low scenario (< 2°C) High scenario (4.5°C,8°C)	40–60 70–120		60–100 200–300	Horton et al. (2014)
Semi-empirical	RCP3PD, RCP8.5	36–165			Jevrejeva et al. (2012)
Semi-empirical	RCP4.5	64–121		212–527	Schaeffer et al. (2012)
MAGIC	450 ppm stabilisation 1000 ppm stabilisation	8–49 13–64		8–120 23–244	Wigley et al. (2009)
CMIP5	RCP2.6, RCP8.5			21–119	Yin (2012)
MAGICC	489 GtC,1146 GtC	63–120	117–332		Zecca and Chiari (2012)
MAGICC6 Semi-empirical	RCP4.5, RCP8.5	31–70 66–143			Perrette et al. (2013)
CMIP5 Semi-empirical	RCP8.5 >700 ppm in 22nd century RCP4.5 A1B	53–97 21–83 43–124 32–156	58–203	92–359	Church and Clark (2013)

Multi-centennial climate model experiments consistently show unabated SLR for many centuries to come even if emissions are cut aggressively or constrained by fossil fuel depletion (e.g. Körper et al., 2013). This reflects the thermal inertia of the deep ocean, which continues to act as a heat sink, plus continued ice melt and disintegration even after radiative forcing has been stabilised (Boucher et al., 2012; Caeser et al., 2013; Frohlicher and Joos, 2010; Levermann et al., 2013; Meehl et al., 2012). According to the latest estimates of the US Energy Information Administration (EIA)[1], global CO_2 emissions from the consumption of energy exceeded 32 billion metric tonnes in 2011. Hence, despite the economic downturn of the last few years, the current emission trajectory lies above the pessimistic SRES A1FI scenario, strengthening the case for experiments with more extreme emissions scenarios (e.g. Sanderson et al., 2011).

More simulations are now available for the end of the millennium (and beyond) to quantify the amount of SLR (Church and Clark, 2013). For example, Goelzer et al. (2012) report SLR in the range 2.1 to 6.8 m by 3000, depending on the concentration at which greenhouse gases are stabilized by year 2100. Even if concentrations are held at year 2000 levels the committed SLR is still projected to be 1.1 m by 3000. Likewise, Solomon et al. (2009) suggest an irreversible component of SLR, due to thermal expansion, of 0.4 to 1.0 m if 21st century CO_2 concentrations exceed 600 ppmv, or 0.6 to 1.9 m if concentrations exceed 1,000 ppmv. Some assert that halting or reversing thermal expansion of the ocean on a centennial time-scale might only be possible by deploying geoengineering techniques (Bouttes et al., 2013; Jevrejeva et al., 2012).

Other authors focus on tipping points within the climate system. For example, Charbit et al. (2008) used a climate-ice sheet model forced with various CO_2 emission scenarios to show that irreversible melt of the Greenland ice sheet could be triggered by cumulative emissions above 3000 GtC, implying an eventual SLR commitment of several metres. Rae et al. (2012) find that the surface mass balance of Greenland becomes negative under a near surface temperature change of ~2 °C. Ridley et al. (2010) used high-resolution ice-sheet models to evaluate pathways of Greenland ice sheet evolution under a higher range of steady state global mean temperature rises (3 to 6 °C). A threshold for irreversible melt was found at ~80 to 90% original ice sheet volume – a point of no return that could be reached in a few hundred years. Beyond this threshold the ice sheet does not fully recover even under a pre-industrial climate state, implying irreversible SLR of 1.3 m for 20% melt. By comparison, the Gravity Recovery and Climate Experiment (GRACE) satellite system indicates that the Greenland ice sheet lost 263 ± 30 Gt/yr between 2005 and 2010 (Hanna et al., 2013). Although this amounts only to ~0.1% total mass lost per decade, the rate of melting is accelerating (Svendsen et al., 2013).

Zickfield et al. (2012) found that the amount of SLR due to thermal expansion is dependent on the emission pathway (unlike global mean temperature rise which is proportional to cumulative CO_2 emissions). Orlic and Pasaric (2013) showed that SLR projections from semi-empirical models (based on temperature-SLR relationships) far exceed those from process-based models. This is partly due to the dynamics considered by the models and partly because the former (semi-empirical models) do not typically correct SLR for impounded water and artificial transfers from aquifers to the ocean. For example, Wada et al. (2012) report that groundwater depletion was adding 0.57 ± 0.09 mm/yr to global mean SLR in 2000 and, when adjusted for water retention behind dams, the terrestrial flux could be equivalent to 31 ± 11 mm by 2050. [Note that groundwater abstraction, water-table lowering and soil oxidation can further contribute to local SLR through loss of elevation and ground subsidence (Phien-wej et al., 2006) but these processes are not relevant to any NNB site in the UK].

3.4 Regional variations in SLR

Climate model projections of SLR for the 21st century show limited agreement at the regional scale, increasing overall uncertainty in associated risks. Regional SLR departs from the global mean due to gravitational and meteo-oceanographic factors (Church et al., 2011b; Nicholls et al., 2014). Regional 'hotspots' of observed SLR can be three to four times higher than the global average (Sallenger et al., 2012).

[1] http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8

One analysis of the IPCC AR4 A1B ensemble found that local relative sea-level changes vary by -3.91 to +0.79 m about a global mean of +0.47 m were when accounting for land ice mass changes and steric effects to 2100 (Slangen et al., 2012).

Melting of terrestrial ice causes the solid Earth to deform and thereby affects the pattern of relative SLR. Redistribution of sea mass and associated gravitational effects could contribute up to 3 cm of SLR to continental shelves by 2100 (Richter et al., 2013). However, estimates of the local gravitational 'fingerprint' (i.e. gravitational pull due to the mass of ice sheets) depend on the melt scenario. For example, Gomez et al. (2010) predicted peak enhancements to SLR along the coast of the United States and around the Indian Ocean for West Antarctic melt, and along the south Atlantic and northwest Pacific coasts for East Antarctic melt. Spada et al. (2013) estimate that a mid-range scenario of Greenland and Antarctic ice melt could add 25 cm to SLR by 2100 in equatorial oceans. Mitrovica et al. (2011) find that West Antarctic Ice Sheet (WAIS) thinning produces a SLR fingerprint of 25% more eustatic SLR in the north Pacific and 20% more in the North Atlantic (Figure 5). According to Perrette et al. (2013) Greenland ice-melt contributions are effectively suppressed north of 55°N by associated reductions in gravitational pull. Large dams further complicate the fingerprint of glacial unloading by locally depressing the earth's surface and by gravity effects (Fielder and Conrad, 2010).

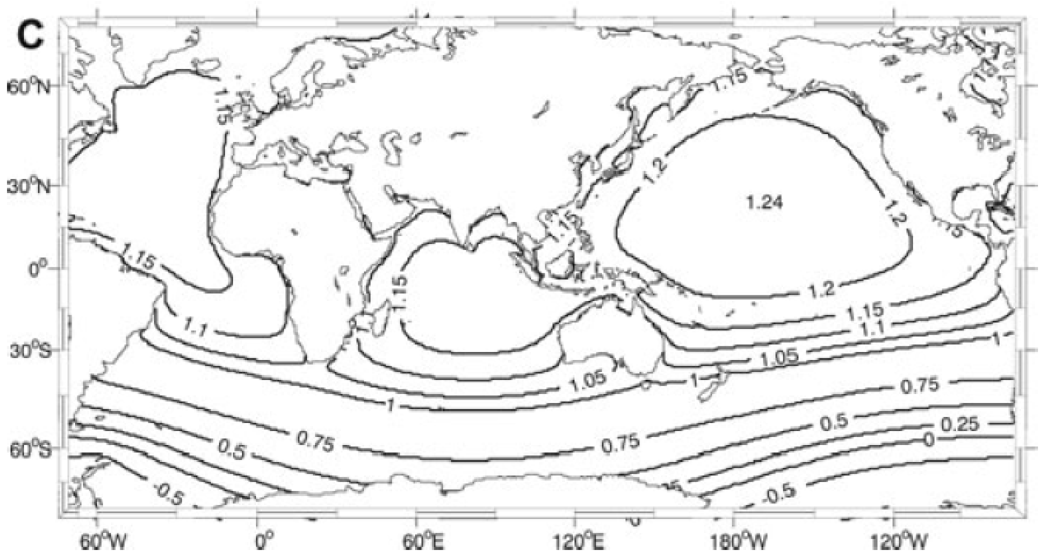


Figure 5 Sea-level fingerprint for a rapid, uniform thinning across the WAIS, normalized by eustatic sea-level change. Source: Mitrovica et al. (2011).

Regional variations in ocean temperature (thermal expansion), salinity, ocean circulation and atmospheric pressure patterns also modify local SLR. Körper et al. (2009) used a coupled ocean-atmosphere model to investigate thermal and saline effects on SLR in the North Atlantic. Changes in ocean salinity were found to have greater significance in the 22nd century by reducing the meridional density gradient, thereby preventing recovery of meridional overturning circulation (MOC).

Pardaens et al. (2011) also find that spatial variations in SLR across the North Atlantic are influenced by the extent of MOC weakening. Lorbacher et al. (2010) showed that an artificially induced decline in modelled MOC (from about 11 to 6 Sverdrups [Sv] over five decades) induces regional increases in North Atlantic sea-surface elevation of 20 cm – approximately 2 mm/yr in the vicinity of the British Isles (Figure 6).

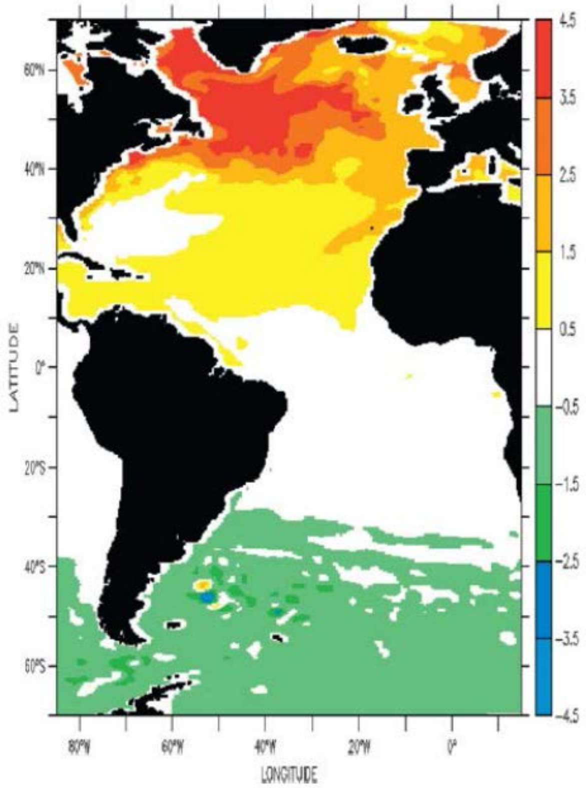


Figure 6 Modelled sea-surface elevation changes (mm/yr) associated with multi-decadal MOC decline, caused by artificially increasing precipitation over the North Atlantic by 15-20% (equivalent to increasing the freshwater flux by ~0.08 Sv). Source: Lorbacher et al. (2010).

Hunter et al. (2013) produced regional allowances for SLR under the A1FI emissions scenario by combining spatially varying projections of SLR from the IPCC AR4, at a local scale for extreme tide levels, the spatially and temporally varying gravitational fingerprint of Mitrovica et al. (2011) and a glacial isostatic adjustment based on careful measurement of local crustal movements. For the east coast of England, the glacio-isostatic component is estimated to be ~100 mm/century (Bradley et al., 2009; 2011). Although of little consequence in the UK, variations in vertical land movements can also arise from local sediment compaction and consolidation, as well as from subsidence due to dewatering of coastal aquifers.

3.5 Local SLR, wave and surge interactions

Site-specific extreme coastal water levels reflect the global and regional controls discussed above, as well as local tide-surge interactions and effects associated with waves. Local SLR and surge interactions are considered below but it is noted in passing that there is a growing body of literature on the wind and wave environment. Moreover, it is important to distinguish between the signatures of climate *variability* and climate *change* on extreme water levels. For the former, Weisse et al. (2012) find much inter-decadal variability but no evidence of long-term trends in observed wave heights in the North Sea. Weisse et al. (2014) further assert that observed increases in sea levels over the last 100 years around Europe are mainly driven by trends in mean sea levels with decadal variations in storm climate superimposed. Conversely, Young et al. (2011) report more extreme wind speeds and increased significant wave heights around the British Isles. Izaguirre et al. (2011) demonstrate that a unit rise in the Arctic Oscillation index adds up to 70 cm to extreme wave heights observed south of Iceland.

Some climate model projections of wind-wave environment point to increased extreme wave heights in the North Atlantic (Mori et al., 2013; Debernard and Røed, 2008), as well as for the east (Chini et al., 2010; Grabemann and Weisse, 2008) and southwest coasts of England (Zacharioudaki et al., 2011). Others find reduced wave heights or changes that are within natural variability (Dobrynin et al., 2012). Hence, it is generally accepted that wind-wave scenarios are highly method dependent (Hemer et al., 2013; Church and Clark, 2013). This reflects poor understanding of waves and their high natural variability, plus limited observational data and outputs of simulations.

Future tidal surge risk around the UK coast will depend on the amount of SLR combined with Atlantic storm frequency and intensity (which varies over annual to centennial timescales). Observations and climate model experiments suggest no long-term trend in surge in the North Sea (Sterl et al., 2009; Weisse et al., 2012). According to UKCP09 future climate-driven changes in surges are expected to lie within historic variability. However, sea-level scenario H++ in UKCP09 does refer to one climate model (Lowe et al., 2009) that suggests increased storminess and an upper-end change in surge of 1.4 m for the east coast by 2100 (Figure 7). Later studies confirm an increased risk of extreme surge by 2100 in Liverpool Bay (Brown et al., 2012) and more rapid propagation of modelled surges in the Thames Estuary (Howard et al., 2010). One climate model experiment found that change in storminess could add about 15 cm to the height of the 50-year surge on the west coast of the Jutland Peninsula under A1B emissions by 2100 (Howard et al., 2014a).

Potential SLR-tide-surge interactions are also feasible. The “skew surge” is widely used to quantify the difference between the highest measured water level in a tidal cycle (irrespective of timing) and the expected astronomical high water (e.g. Lowe et al., 2009). Maximum residuals between measured and expected water levels typically occur 3 to 5 hours before predicted high tide along the North Sea coastline (Horsburgh and Wilson, 2007). Experiments with the Dutch Continental Shelf Model for +2 m and +10 m SLR scenarios produced spatially non-uniform change in spring tide amplitudes, with large decreases in the Bristol Channel (Pickering et al., 2012). Others have shown that variability in the *duration* of extreme tide-surge events can influence the volumes overflowing defences and associated flood damages (Quinn et al., 2014).

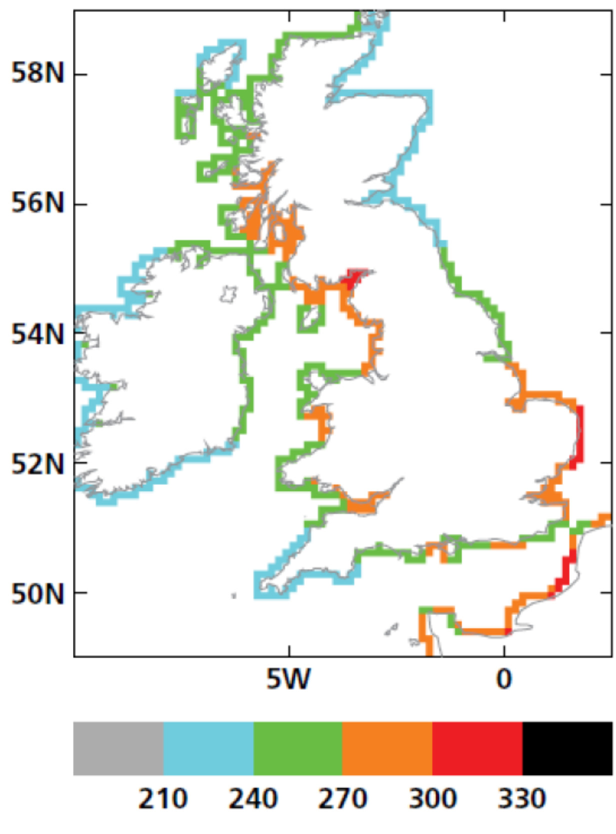


Figure 7 H++ extreme sea-level change scenario for 2100 reflecting the combination of high-end SLR combined with high-end surge estimate. Source: Lowe et al. (2009).

The relationships of coastal morphological change, SLR and surge are poorly understood even for observed climate variability (Montreuil and Bullard, 2012; Nicholls et al., 2013). Nonetheless, several studies have applied dynamic modelling to explore interactions between SLR and surge properties (Gonnert and Sossidi, 2011), although this depends on the application and level accepted of risks. Some assume that simple linear addition of mean SLR and surge is acceptable (e.g. Howard et al., 2010; Hunter, 2012; Obeysekera and Park, 2013; Tebaldi et al., 2012), whereas others report strong non-linear interactions between surge and SLR in shallow waters (e.g. Weisse et al., 2012; Zhang et al., 2013). Non-linear responses might be expected when the inundation zone is shifted by SLR thereby altering bed friction and wind-surface stress. Furthermore, distributions of extreme water levels and inundation may vary spatially because of complex relationships between storm surges and coastal bathymetry/topography (Zhang et al., 2013: 497) as well as local influence of coastal defences (e.g. Purvis et al., 2008).

Even if there is no change in surge and wave components, the return period for extreme water levels would still reduce non-linearly with increasing total change in local sea-level. Changes in frequency may be particularly marked in locations where the difference in water levels between presently rare and common events is modest. For example, Tebaldi et al. (2012) show that with assumed global mean SLR of 0.32 m by 2050, some coastal locations in the United States may experience high water levels annually that previously had return periods of 100 years. Likewise, under a SLR scenario of 0.28 m by 2050, the 100-year return period extreme sea level at Southend in the Thames Estuary has its return period lowered to 20 years (see Table 1 in HR Wallingford [2008]).

3.6 Climate change and coastal geo-hazards

Coastal geo-hazards are considered here because there is growing speculation about the potential for climatic forcing of submarine mass movements, earthquakes, tsunamis, destabilisation of methane clathrates, and volcanic eruptions (Liggins et al., 2010; McGuire and Maslin, 2013; Svejdar et al., 2011). For example, Guillas et al. (2010) present evidence of a statistical association between the El Niño-Southern Oscillation (ENSO) and the frequency of earthquakes on the East Pacific Rise (EPR). They hypothesised that ENSO drives sea-surface gradients that reduce ocean-bottom pressure on the EPR which in turn triggers plate flexure and seismicity (peaking at a lag of 6 months). This implies that pressure changes (whether due to shifting atmospheric or ocean loads) in a warmer world could trigger earthquakes in major submarine faults that are close to being triggered.

The Indian Ocean (2004) and Japanese (2011) tsunamis highlight the risks that are already posed by geo-hazards to coastal infrastructure in some parts of the world, so it is not unreasonable to speculate about a tsunami threat to the UK. Even with wave spreading and energy dissipation, a repeat of the 1755 Lisbon earthquake could generate high water levels at the UK coastline that are comparable to a severe winter storm (Horsburgh et al., 2008). Furthermore, coastal fen and lake deposits in the Shetland Islands reveal evidence of three North Sea tsunamis (~1500, 5500 and 8100 cal year BP) with an inferred run-up height for the youngest event of 5–6 m above present high tide (Bondevik et al., 2005). The causes of the oldest tsunami (the Storegga event, see below) are well established, but the origins of the more recent events have yet to be determined.

Rapid planetary warming, ice-sheet melt, modified patterns of rainfall, associated load pressure changes and increased pore-water pressures are all factors which collectively might help.trigger further submarine landslides and tsunamis in the NE Atlantic region (McGuire, 2010; Tappin, 2010). For instance, the Storegga Slide off the coast of Norway ~8200 years ago has been linked to a strong earthquake caused by the isostatic rebound of Fennoscandia (Bondevik et al., 2003; Bryn et al., 2005). This landslide generated tsunami deposits that are 20 m above modern sea level in the Shetland Islands, 10–12 m above the coast in Norway, and 4–6 m in northeast Scotland (see Figure 8). However, the geomorphological and sedimentary context of the continental margin was very different because global mean sea level was lower at that time (Stanford et al., 2011). One study shows that local sea level was approximately 18 m below present in the east of England (Bradley et al., 2011).

The significance of climate factors as a preconditioning and/or trigger mechanism for major submarine mass failures (‘megaslides’) depends on the submarine depositional environment of (glacial) sediments and the level of sediment instability. Moreover, the present limited evidence for tsunamis in the North Atlantic may be misleading given the difficulty in locating, identifying, coring and dating preserved sediments, and the small number of actual case studies. Based on the modest quantity of records available, Urlaub et al. (2013) find no proof of a significant correlation (at the global scale) between sea-level changes and frequency of large submarine landslides over the last 30,000 years (Figure 8). However, they acknowledge that individual landslide responses may be masked in a global data set.

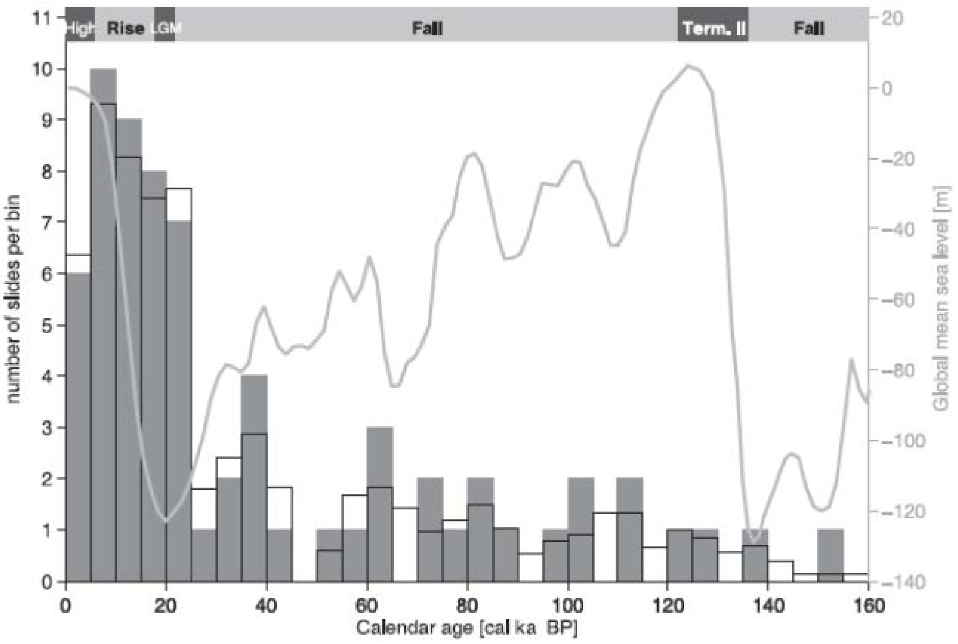


Figure 8 Global mean sea level (grey line) and frequency of submarine landslides based on most likely ages (dark grey bars) with uncertainty interval (open bars). Note the maximum frequency ~8 ka BP. Source: Urlaub et al. (2013).

McGuire (2010: 2338) recommends a three-pronged approach to improve knowledge and reduce uncertainty about climate change as a driver of future geo-hazards. The first two involve statistical analysis of climate-geological data and detailed process modelling of the effects of changing environmental conditions. The third priority is for *monitoring of specific locations perceived already to be demonstrating a climate-change response or that are deemed sensitive enough to do so in the short to medium term*. Model evidence presented by Hampel et al. (2010) indicates that the frequency of earthquakes along the Greenland coastal margin could increase as the ice-sheet continues to melt over time scales of 10–100 years.

McGuire (*pers. comm.*) asserts that the potential for renewed earthquake activity beneath Greenland to trigger tsunamis capable of impacting the UK will depend, in part, upon earthquake magnitude and the availability of a sufficiently large and unstable submarine sediment source. In relation to the former, it is noteworthy that the lengths of fault ruptures driving post-glacial Scandinavian earthquakes suggest magnitudes approaching or in excess of M=8 (Stewart et al. 2000). The submarine sediment situation is poorly constrained due to the fact that parts of the Greenland coastal margin have not been mapped in sufficient detail. Hence, coastal geo-hazards is an area where urgent work is required to establish even the baseline risk.

4 Applying high-end SLR and surge scenarios

As the preceding commentary demonstrates, evidence of long-term SLR and surge risk is spread across a large body of scientific literature. Hence, before high-end scenarios can be applied in a decision-making context, the components of extreme water level have to be assembled in a defensible and transparent way.

This section refers to three cases in which adaptation planning for long-lived coastal protection and flood infrastructure took high-end climate change scenarios into account. Shared features are identified from the adaptation frameworks applied in the Delta Committee's plan to flood-proof the Netherlands, New York City's sustainability plan and the EA Thames Estuary 2100 project. The discussion draws out the distinctive features of each strategy rather than elaborating the detailed values attached to the various elements associates with climate change. Note that other agencies are also developing procedures to evaluate future SLR (e.g. USACE, 2013).

4.1 Netherlands Delta Committee

The Delta Committee was established on 18 February 1953 in the immediate aftermath of a catastrophic surge that struck low-lying coastal areas of northwest Europe (Gerritson, 2005). In 2007 the Dutch Government tasked the committee with providing recommendations on how to flood-proof and safeguard freshwater supplies for the Netherlands into the next century (Stive et al., 2011). A year later the Committee delivered an integrated plan based on high-end regional SLR scenarios for 2100 and 2200, as created by a panel of 20 international scientists (Delta Committee, 2009; Katsman et al., 2011). Their analysis yielded high-end estimates of global mean SLR in the range 0.55 to 1.10 m by 2100, and 1.5 to 3.5 m by 2200, assuming high rates of global warming (with temperature rise scenarios of up to 6°C by 2100 and 8°C by 2200), and increased rates of ice discharge. These translate into local scenarios of SLR along the coast of the Netherlands of up to 1.20 m by 2100 and 4 m by 2200.

The approach taken by the Delta Committee summed high-end – but not always the highest – estimates for 'building blocks' of global mean and regional SLR including:

- thermal expansion of the upper ocean
- melt from small ice caps and glaciers
- melt from the Greenland and Antarctic ice sheets (ie, mass balance contribution)
- scaled discharge from ice sheets (ie, dynamic contribution)
- two gravitational scenarios
- terrestrial water storage
- regional steric (ocean temperature and salinity(effects, and
- vertical land movements (comprising local isostatic rebound, tectonic subsidence and deep-layer compaction).

Sources of evidence for all elements were auditable and accompanied by uncertainty bounds (Figure 9).

Scenarios for SLR were not linked to specific emission scenarios. Instead, by adapting the approach of Rahmstorf (2007), global-mean thermal expansion was predicted using two variants of a semi-empirical linear relationship between atmospheric temperature and SLR, in various climate simulations. Scaled rates of melt from ice sheets were consistent with the low-end estimate of Pfeffer et al. (2008). Various gravitational fingerprints were applied by scaling global-mean mass-balance contributions from glaciers and ice sheets using the factors in Figure 9 (representing different melt scenarios for Greenland [GIS] and the Antarctic [AIS]). 'Modest' and 'severe' scenarios were calculated for the Antarctic contribution; the latter envisages a collapse of the WAIS with accelerating melt and glacier flow.

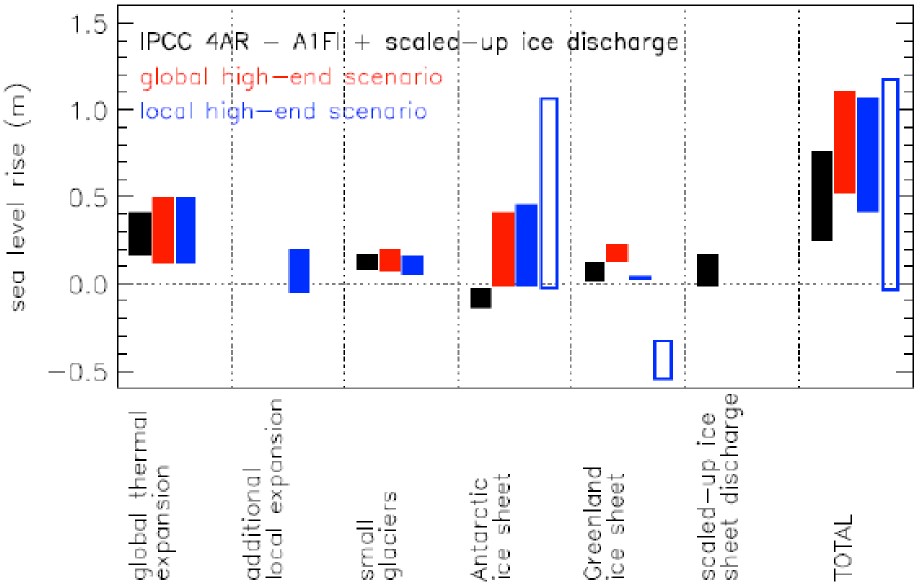


Figure 9 Ranges for individual contributions and total high-end scenarios for SLR by 2100 (black: global mean SLR for the A1FI scenario of IPCC AR4, including scaled-up ice discharge; red: high-end scenario for global-mean SLR; blue: high-end scenario for local sea-level rise along the Dutch coast (scaling factors used to translate the global-mean contributions from land-based ice masses to local variations are (solid bars): AIS = 1.1; GIS = 0.2, based on Mitrovica et al. (2001); (open bars): AIS = 2.6; GIS = −2.5. Source: Katsman et al. (2011).

Total mean SLR to 2100 was calculated by summing median values of individual components and summing their uncertainties quadratically, all rounded to the nearest 0.05 m (Katsman et al., 2011). Values for global mean SLR were corroborated against palaeoclimatic evidence. The same approach was applied for 2200 except that: a) a higher upper bound was applied for atmospheric temperature forcing (8°C instead of 6°C); and b) it included the possibility of a shutdown of the MOC and associated local expansion of the North Atlantic Ocean. The resulting high-end scenarios are precautionary but draw back from the most extreme values where there is sufficient doubt or contention in the peer-reviewed literature. [Climate-driven landslides and tsunami were not included in their extreme water levels but the likelihood of coincident surge and tsunami would be exceedingly low].

Some have criticised the way in which the Delta Committee downplayed the epistemic uncertainty in their projections. Enserink et al. (2013:8) contest that the 'worst case scenario' was partly shaped by a desirable image of the future in which the Netherlands stays safe 'no matter what'. Their accusation was that ambiguity about the assumed value systems was neglected when communicating with the public, so the Delta Committee study served for *agenda-setting, safeguarding expenditures and for creating urgency for improving coastal and river defences*. The counter view is that such extreme scenarios are justified given the serious consequences of inundating low-lying areas of the Netherlands.

4.2 New York City Panel on Climate Change

Mayor Bloomberg assembled a New York City Panel on Climate Change (NPCC) in 2008 to advise his office of the potential climate risks to critical infrastructure in the city and wider hinterland, regarding communication, energy, transport, water and waste systems. The expert panel convened a range of academic disciplines to cover various relevant disciplines, including physical science and humanities, and engaged in what was described as a *multi-jurisdictional stakeholder-scientist process* (Rosenzweig et al., 2011:97).

To clarify roles and responsibilities, care was taken to separate the functions of knowledge provision from those of adaptation planning and action. The panel also explicitly communicated with stakeholders about different types of uncertainty arising from the choice of emission pathways, assumed sensitivity of the climate system to greenhouse gas forcing and the partial scientific understanding of those physical processes governing the melting of Greenland and WAIS. The resulting adaptation plan for SLR and surge risk was published two years later (Rosenzweig and Solecki, 2010).

The first set of SLR scenarios for New York City were based on global climate-model simulations from the IPCC AR4, using the central 67% range of the ensemble for the 2020s, 2050s and 2080s (Figure 10). These yielded SLR projections of 50 to 125 mm, 175 to 300 mm, and 300 to 575 mm respectively. The approach was analogous to the flood-risk allowances developed for England and Wales (EA, 2011).

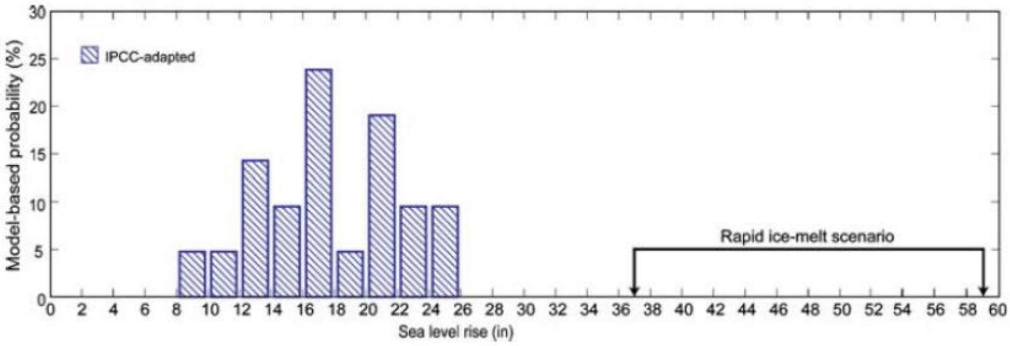


Figure 10 Comparison of sea-level rise (inches) for New York City for the 2080s, resulting from various scenarios of rapid ice-melt. The histogram is built from an ensemble of seven climate models and three emissions scenarios. Note that the full range of projections is shown, rather than just the central tendency. The rapid ice-melt scenario does not have likelihoods attached due to the high level of uncertainty. Source: Horton and Rosenzweig (2010).

The IPCC projections were supplemented by a 'rapid ice-melt' scenario to acknowledge the possibility of more extreme SLR scenarios (which would be driven by higher emissions, carbon and methane cycle feedbacks, and changes in ocean circulation and ice-sheet dynamics). Under the rapid ice-melt scenario, glaciers and ice sheets were assumed to melt at rates reconstructed for the last deglaciation – equivalent to 1.0 to 1.2 mm/yr of eustatic SLR by 2100. The melt rate was increased exponentially to this point; other components such as thermal expansion, ocean circulation and local land movements were added as before. This yielded a high-end rapid ice-melt scenario of ~950 mm (37 inches) to 1500 mm (59 inches) by the 2080s (Figure 10).

Projections for 2200 were regarded as too uncertain to quantify. However, the expectation was that temperature increases and SLR would continue, because of the great inertia of the climate system. Even with stabilization, dynamically-induced melting of Greenland and West Antarctica would increase the likelihood of contributions by these sources to SLR (as indicated by Solomon et al. [2009]).

Although changes in storm intensity, frequency and duration were thought to be more likely in the future, changes in coastal flooding frequency reflected only the SLR component. This simple approach was then used to generate revised maps of the 1 in 100-year flood zones for the 2020s, 2050s and 2080s under the IPCC and rapid-melt scenarios. These showed a significant landward expansion of the flood-risk zone and potential inclusion of new communities in the National Flood Insurance Program (NFIP). As a consequence of the NPCC work, the Department of Environmental Protection raised pumps and electrical equipment in the Far Rockaway Wastewater Treatment Plant from below sea level to more than 4 m above sea level (Rosenzweig et al., 2011).

A second set of SLR scenarios (NPCC2) has recently been published (NPCC, 2013). These were developed using a component-by-component analysis that includes changes in local ocean height; thermal expansion; vertical land movements; loss of ice from glaciers, ice caps and land-based ice sheets; gravitational, isostatic, and rotational effects resulting from decreased ice-mass; and storage of water on land. Based on the CMIP5 ensemble (RCP4.5 and RCP8.5 runs), the high-end (90th percentile) SLR estimate was ~800 mm (31 inches) by the 2050s. When combined with a 1 in 500-year storm, the still-water flood height in lower Manhattan was projected to be 5180 mm (17 feet) above datum. NPCC also produced future flood maps and stressed the need for transparency of the mapping process to improve users' understanding of what the maps convey with respect to future coastal flood risks (NPCC, 2013:28). No projections were provided beyond the 2050s.

4.3 Thames Estuary 2100 Project

The Thames Estuary 2100 Project (TE2100) was led by the Environment Agency of England and Wales, ran from 2002 for 10 years and produced a flood-risk management plan for London at a cost of ~£16 million (Ranger et al., 2013). Key drivers behind TE2100 were the need to replace deteriorating assets and upgrade the Thames Barrier to meet future SLR and surge risk. The current barrier and flood-defence system have a standard of protection of more than 1 in 1000 years to 2030 but without action this standard would deteriorate to unacceptably low levels given the large number of lives and property at risk. Renewal of flood defence assets creates opportunities to consider climate change in a carefully planned and systematic way (Penning-Rowsell et al., 2013).

TE2100 commissioned research to improve understanding of potential climate-change effects on extreme water levels in the tidal regions of the Thames. This work established that the key threat is posed by SLR; conversely, modelled changes in surge risk were statistically indistinguishable from decadal variability (Lowe et al., 2009). This meant that the analysis could focus on SLR (Figure 11). The H++ narrative scenario was subsequently conceived for testing the robustness of adaptation options in TE2100 under a plausible high-end SLR for 2100. In addition, a scenario for extreme water levels was obtained from the first set of national allowances for climate change issued by Defra (2006) [and now superseded by EA (2011)].

The H++ scenario was based on expert judgement, observed SLR, palaeoclimatic data and assumptions about ice-sheet behaviour (EA, 2009; Ranger et al., 2013). According to Lowe et al. (2009:12), the *H++ scenario is an attempt to quantify emerging understanding of dynamic ice-sheet processes described, but not fully quantified, in the IPCC Fourth Assessment Report and of storminess changes projected in the IPCC Fourth Assessment Report but beyond the range simulated in the Met Office models* (Murphy et al., 2007). For the UK, the absolute SLR estimate for H++ is between 0.93 m and 1.90 m by 2100. An upper bound in the region of 2 m was judged to be consistent with the available palaeoclimatic evidence (Rohling et al., 2008) and understanding of ice-sheet dynamics (Pfeffer et al., 2008) at that time.

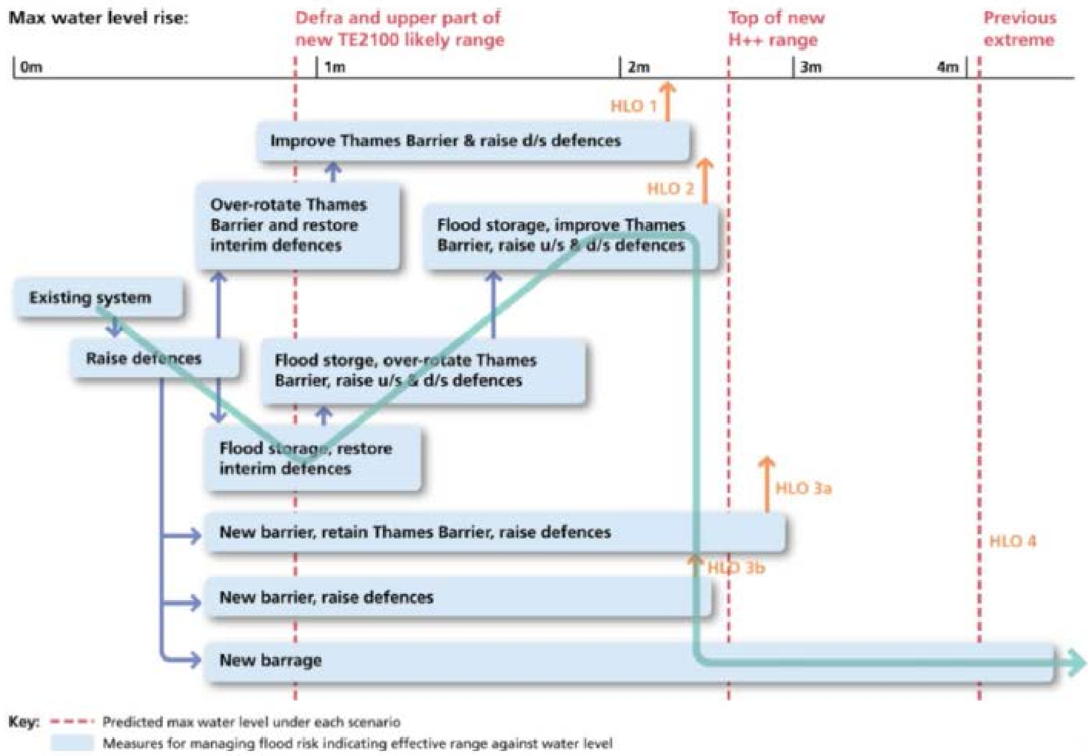


Figure 11 High-level management options (HLO) and pathways developed by TE2100 related to threshold increases in extreme water level (horizontal axis). The green line illustrates an example ‘route’ by which a decision-maker initially follows HLO2 then switches to HLO4 when mean sea level was found to increase faster than predicted. The maximum water level rise incorporates all components of sea level, including local land movement. Source: EA (2009).

Given the existing long-term commitment to global mean temperature increases and SLR, the TE2100 strategy had to be open-ended. Another innovation of TE2100 was that no specific timeframes were attached to given amounts of SLR (see the horizontal axis in Figure 11). This encourages decision-makers to devise a flexible strategy for adaptation (Wilby and Dessai, 2010). The envisaged approach of adaptive management involves careful monitoring of evolving climate risks and systematic appraisal of the performance of structural and non-structural measures (Dawson et al., 2011). The resulting adaptation pathway will also be shaped by the evolving scientific evidence and societal attitudes to risk (Figure 11). For example, scheduling of alternative flood-defence options within the TE2100 Plan would depend on future changes in key components of flood risk (ie, SLR, surge, fluvial flooding, and urban flash-flooding).

Large degrees of uncertainty are attached to all elements, so the TRE2100 Plan was broken down into three phases:

1) maintaining and improving existing flood defences, plus safeguarding spaces for future flood management (2010-2034),

2) renewal and replacement of existing tidal defences (2035-2070),

3) continued maintenance of the existing system or construction of a new barrier (2070 onwards).

The Plan is flexible and responsive to changing climate because interventions can be brought forward or delayed, alternative option pathways are not excluded, the design of structures can be modified, plus land has been set aside for flood-water storage, new defences and habitat creation (EA, 2009). Ten “triggers for change" will be monitored throughout the life of the Plan: if rapid change is detected in any indicator (such as mean sea level) the adaptation pathway can be adjusted accordingly.

4.4 Features shared by the case studies

Although the three case studies are very different in terms of their overall objectives, socio-economic and geographic contexts, there are several features in common. The following general principles might be adopted by others seeking to apply high-end climate change scenarios to infrastructure decisions in the coastal zone:

- Scientific evidence is drawn from a range of sources including dynamic and empirical models (for ice melt and thermal expansion of the ocean), palaeoclimatic data, expert judgement, climate model projections, and lessons learnt by others responding to rapid SLR;
- The plausibility and uncertainty of each scenario is corroborated with respect to other recent high-end estimates;
- Where feasible estimates are constrained by physically plausible upper bounds (such as total global mean sea level equivalent, or limits to outlet glacier velocities in Greenland and the Antarctic);
- Narratives are used in place of likelihoods to qualitatively describe high-end scenarios (e.g. 'collapse of the WAIS', 'rapid ice-melt', 'H++');
- Participatory approaches are deployed to capture the perspectives of different stakeholders;
- Significant resources are invested (in terms of time and number of experts in each panel assessment) commensurate with the scale of climate risks involved;
- Expert panels have clear terms of reference and are multi-disciplinary, drawing on climatological, oceanographic, geological, social scientific, economic, legal, insurance, risk management, private swector and public sector perspectives;
- Every step of the analysis is carefully documented and supported by auditable lines of evidence that has been tested by panel and/or peer review;
- Monitoring systems are installed to track sea-level changes and other indicators to give sufficient lead time to re-evaluate flood risk and to implement measures along an adaptation pathway at appropriate times;
- Management structures are established to capture and internalise emerging scientific evidence as part of an open-ended, institutional learning process.

5 Worked example

The case studies illustrate two ways of specifying credible maximum sea levels. The first involves aggregating the components of extreme water levels, assuming independence of the elements (e.g. Delta Committee, NPCC2). The advantage of the approach is that it is transparent and straightforward to scrutinize. The 'extremeness' of each building block can be modulated by the level of risk aversion, or willingness to accept outlier opinions about highly uncertain future conditions. The values are also readily updated as the science evolves. Moreover, additional factors can be applied to enable exploration of "cliff edge" effects (defined in Table 1), or to include new scientific findings (such as climate-driven geohazards). For instance, it is possible to conceive even higher emissions scenarios than SRES A1FI (driven by greater population growth, different energy mixes and more carbon intensive economies) with likely consequences for SLR (Sanderson et al., 2011).

The second approach uses narratives or representative climate futures (e.g. NPCC Thames Estuary 2100). Adaptation strategies and design assumptions can then be tested against bespoke situations such as 'rapid ice melt', 'submarine landslide', or 'a 4 degree Celsius world' (e.g. Nicholls et al., 2011). No attempt is made to attach a likelihood or timing to the scenario, yet the assumed climate parameters may still be drawn from a range of sources (ie, observations, models, palaeo-data and expert opinion). Furthermore, this approach can also accommodate credible, long-term institutional scenarios that might influence the range of options available for decision-makers. For example, the existence of an active national nuclear waste repository could limit the time horizon (and hence range of uncertainty) of the climate risk assessment by removing the need for on-site storage. Likewise, other narratives could describe the wider contingencies related to the adaptation actions of other neighbours along the coast.

Both methods of specifying credible maximum sea levels have their limitations. Aggregating high-end contributions may appear more objective but linear addition of extreme components can imply coincidental occurrence of the components, which has infinitesimally small likelihoods. There is also a loss of internal consistency when component values are derived from different lines of evidence. On the other hand, the narrative approach is open to the criticism of subjectivity. With these points in mind, a worked example is provided here for the east coast of England.

Following the methods of the Delta Committee (2009), a mixture of sources is used to estimate credible maximum SLR scenarios for years 2100 and 2200. Evidence behind the value of each component of sea-level change is drawn from peer-reviewed literature, process-based models, semi-empirical models, palaeo-data (ocean sediments) and expert judgement; no primary data analysis has been performed except for recalculation of the combined uncertainty (see below). Upper and lower bounds are provided to reflect uncertainties in future global mean temperature, the veracity of climate modelling, glacier and ice-sheet volumes, gravitational fingerprint and measurement errors (terrestrial water contributions and vertical land movements).

It is not possible to assign likelihoods to individual components and their respective uncertainties are assumed to be independent. The overall central estimate for SLR is obtained by adding central estimates of components, assuming that all ranges are Gaussian (Delta Committee, 2009: 23). Following Katsman et al. (2011), Tables 3 and 4 show combined uncertainty in net SLR calculated using quadratic summation of uncertainties (square root of the sum of squared uncertainty ranges for all the individual components). Given the gross simplifying assumptions made elsewhere when constructing high-end scenarios of sea-level change, this level of sophistication was deemed to be proportionate (Katsman, *pers. comm.*). More elaborate Monte Carlo approaches can be applied to estimate upper and lower bounds if uncertainties in components are specified as dependent (Meehl et al., 2007). This is mentioned to show that not only do the individual components contain uncertainty, but that there is also embedded uncertainty in how best to combine the components' uncertainties (i.e. whether by quadrature, or linearly, independently or dependently).

5.1 Credible maximum sea level to 2100

For 2100, the UKCP09 H++ SLR scenario is presented as a range for the UK, from 0.93 m up to 1.9 m (EA, 2011:15). In this case, the lower bound originates from the IPCC AR4 high emissions scenario with an adjustment for accelerated ice flow from Greenland and the Antarctic. Local departures from global SLR due to water density and transport were neglected but recent modelling suggests that this component of dynamic sea level change in the North Atlantic amounts to just 3 cm by 2100 (Howard et al., 2014b).

The upper bound is based on palaeo-data adjusted for elastic and gravitational effects (Lowe et al., 2009). These values were combined with published rates of contemporary global aquifer dewatering and vertical land movement in east England. Finally, a range of potential changes in skew surge were added, based on analyses undertaken by Lowe et al. (2009). The total range of high-end SLR for 2100 (excluding tsunami and waves) is 1.55 m to 3.20 m (Table 3). This is higher than the range of Katsman et al. (2011) for the Dutch coast (0.40 m to 1.05 m) because the Dutch estimate did not include terrestrial water fluxes, vertical land movements or surge in their high-end projections for 2100.

Jevrejeva et al. (2014) arrived at an upper limit of 1.9 m by linear summation of the highest estimates of individual global SLR components simulated by process models under RCP8.5 (i.e. thermal expansion, glaciers, GIS, AIS and land water contributions but excluding regional factors such as local land movements and surge). The IPCC AR5 cites a range of 0.21 m to 0.83 m for global SLR components based on coarse resolution physical models under various high emissions scenarios (Church and Clark, 2013). For comparison, linear summation of components in Table 3 yields a range estimate of 1.0 m to 2.0 m for global mean SLR and 1.15 m to 3.60 m for east England.

5.2 Credible maximum sea level to 2200

For 2200, there are no UKCP09 H++ SLR scenarios, so projections were built from published values of global mean thermal expansion, local steric anomalies, melt from small ice caps, AIS and GIS (Table 4). [Note that these are unlikely to be independent variables because if the contribution from Greenland is at the upper end, so too might be the contributions from Antarctic and glacier melt, and from thermal expansion]. Elastic and gravitational factors have been applied (Mitrovica et al. (2011) as have the local steric effects of a slowdown of the North Atlantic MOC. Net additions to SLR from terrestrial water sources were assumed to continue at the same rate as to 2100, however the rate of groundwater exploitation and surface impoundment would not continue indefinitely. Likewise, rates of vertical land movement and the tidal surge component were assumed constant from 2100. These elements were combined by quadrature to give a high-end SLR for 2200 of 2.55 m to 5.00 m for east England (Table 4), which is higher than Katsman et al. (2011) because of the inclusion of surge and terrestrial water components.

For comparison, linear summation of components in Table 4 yields a range estimate of 1.15 m to 6.40 m for east England. The IPCC AR5 cites a range of 0.58 m to 2.03 m for global SLR components based on coarse resolution physical models under various high emissions scenarios (Church and Clark, 2013). The difference between IPCC AR5 and Table 4 (global change components) is largely due to the AIS contribution which is significantly smaller in the former. However, it is recognised that the IPCC AR5 values likely underestimate Antarctica's future contribution because the models have limited ability to reflect the grounding line motion of marine ice sheets. On the other hand, there is low confidence in semi-empirical model extrapolations of global sea level change beyond the forcing of the calibration period (Church and Clark, 2013).

Finally, multi-millennial projections of thermal expansion based on the coupled climate models used in IPCC AR4 yield a rate of sea level change in the range 0.20 to 0.63 m $°C^{-1}$ (or 0.38 m $°C^{-1}$ for a spatially uniform ocean warming) (Church and Clark, 2013). This spans the high-end rate of thermal expansion (0.23 m $°C^{-1}$) to 2200 inferred from Katsman et al (2011) and Table 4.

Table 3 Illustrative components of extreme sea levels (excluding tsunami) by 2100 for the east coast of England. Total SLR is with respect to 1990, rounded to the nearest 0.05 m.

Extreme sea-level component	Range by 2100 (m)	Assumptions	Sources
Global mean thermal expansion *plus* Local steric (thermal and salinity) anomaly *plus* Small ice caps and glacier melt *plus* Antarctic ice sheet melt *plus* Greenland ice sheet melt *with* Correction for gravitational fingerprint	0.95–1.90	H++ lower bound derived from IPCC AR4 high emissions scenario (SRES A1FI) 95th percentile global mean thermal expansion *plus* ice melt *plus* 0.17 m to account for accelerated ice flow from Greenland and Antarctica. Local steric, elastic and gravitational effects were not included. H++ upper bound derived from maximum rate of sea-level change inferred from Red Sea sediments (2.5 m) during the last interglacial, corrected for elastic and gravitational effects (-0.6 m). Local steric effects were not included.	Lowe et al. (2009: Table 3.3) Lowe et al. (2009:33) Lowe et al (2009: 32-33) Rohling et al. (2008) Tamisiea et al. (2001)
Aquifer dewatering	0.05–0.10	0.6 ± 0.1 mm/year global net effect of groundwater depletions minus impoundments.	Wada et al. (2012)
Vertical land movement	0.10–0.20	1.2 ± 0.4 mm/year GPS observations at Lowestoft.	Bradley et al. (2009:22); Shennan et al. (2012)
Tidal surge	0.05–1.40	Lower bound taken from UKCP09 (grid cell 14482) linear trend +0.325 mm/year for the 95 percentile 1 in 50 year skew surge under SRES A1B emissions. Upper bound inferred from Fig.4.11a of UKCP09 marine report (ie, 3.30 m minus 1.90 m) Both assume no change in surge-tide interactions.	UKCP09 H++ Lowe et al. (2009)
Total SLR	**1.55–3.20**	Individual elements combined (m).	Katsman et al. (2011)

Table 4 As in Table 3 but for 2200. Note that local gravitational adjustment depends on the assumed melt scenarios and 'fingerprints' for WAIS and GIS.

Extreme sea-level component	Range by 2200 (m)	Assumptions	Sources
Global mean thermal expansion	0.30–1.80	Range of estimates based on a semi-empirical relationship with global mean temperature for global mean temperature change of 2.5–8°C.	Katsman et al. (2011); Delta Committee (2009: 63-68)
Local steric (thermal and salinity) anomaly	0.00–0.60	Freshwater influx from melt-water and precipitation causes slowdown of the North Atlantic MOC.	Delta Committee (2009); Lorbacher et al. (2010)
Small ice caps and glacier melt	0.12–0.44	Temperature scaling relationship applied to global glacier volume.	Katsman et al. (2011)
Antarctic ice sheet melt	0.24–1.50	Accounting for surface mass balance and dynamical changes *with* scaling for elastic and gravitational affects (assuming WAIS factor 1.1).	Katsman et al. (2011); Mitrovica et al. (2011)
Greenland ice sheet melt	0.10–0.16	Accounting for surface mass balance and dynamical changes *with* scaling for elastic and gravitational affects (assuming GIS factor 0.2).	Katsman et al. (2011); Mitrovica et al. (2011)
Aquifer dewatering	0.10–0.15	0.6 ± 0.1 mm/year global net effect of groundwater depletions minus impoundments.	Wada et al. (2012)
Vertical land movement	0.17–0.34	1.2 ± 0.4 mm/year GPS observations at Lowestoft.	Bradley et al. (2009:22); Shennan et al. (2012)
Tidal surge	0.10–1.40	Upper and lower bound changes estimated as in 2100.	Lowe et al. (2009)
Total SLR	**2.55–5.00**	Individual elements combined (m).	Katsman et al. (2011)

6 Concluding remarks

This scoping paper offers a synthesis of knowledge of rising sea levels and tidal surge that is relevant to long-lived coastal infrastructure. The paper also touches on potential geohazards linked to climate change.

Global mean SLR occurs predominantly through the transfer of substantial heat into the ocean and/or movement of significant volumes of ice to the ocean. Advances in remote sensing have brought closer agreement amongst observed sea level, the sum of individual components, and model results for past SLR. Despite improvements in dynamic ice-sheet modelling, Church and Clark (2013) assert that there is currently insufficient evidence to evaluate the *probability* of specific levels above the *likely* range (such as might be produced by, for example, the collapse of marine-based sectors of the Antarctic ice sheet). Nonetheless, after accounting for inter-annual to multi-decadal variability, it may be possible to detect statistically significant acceleration in individual tide gauge records by the late 2010s or early 2020s (Haigh et al., 2014).

This report focused on the quantitative definition of credible maximum (or high-end) scenarios. As has been shown, this is not an entirely objective exercise because the variable reliability of different sources and expert opinions must be combined with the risk tolerance and intended application of the scenario. The task is further complicated by the volume and breadth of research that must be assimilated. This spans different techniques (observations, climate modelling and reconstruction of past sea levels) as well as various scientific disciplines.

Important lessons may be learnt from the three major infrastructure projects that have already grappled with these complex issues (Delta Committee, New York City and Thames Estuary). Construction of credible maximum scenarios for sea level and surge should:

1) cast the net for evidence far and wide

2) weigh different lines of evidence

3) constrain scenarios using physical limits where feasible

4) avoid the language of likelihood or probability

5) employ participatory consultation processes

6) allocate appropriate levels of time and resource to the task

7) draw on the expertise of panels of specialists

8) document and test assumptions by peer review

9) invest in targeted monitoring systems to track and learn from indicators of coastal change, and

10) establish institutional structures that can systematically harvest and implement latest scientific understanding of the issues.

The last point is important, because the institutional context also frames the *ways* in which scenarios are applied, no matter how they were derived.

The worked example for a hypothetical site on the east coast of England shows how various components of a credible maximum scenario can be assembled in a transparent way. **Transparency is critical for establishing the provenance of data, exposing embedded assumptions and showing methods of working**. Moreover, tabulated values of the components of potential future relative sea-level rise provide a basis for peer review and further refinement. Individual components may subsequently be adjusted in line with evolving scientific knowledge.

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Technical Report Series:	TR322: Update on Estimation of extreme sea levels at Sizewell
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Summary of Purpose & Value to BEEMS

This report is an update to BEEMS Technical Report TR252 on extreme sea levels at Sizewell and should be read in conjunction with that report which provides more background information on the various statistical approaches used to estimate extreme still water levels. This update presents the results of a revised assessment of extreme still water sea levels at Sizewell resulting from the interaction of astronomical tides and meteorological surges, based on a re-analysis of tide gauge records for Lowestoft relating to the period January 1964 to May 2014 (previously to October 2012 in TR252). Estimates are made of extreme sea levels with return periods of up to 1 in 10,000 years, taking into account the possible effects of climate change and sea level rise up to 2100. Waves are not considered.

The purpose of this reanalysis was to determine the effect of incorporating the observational data which was captured under the BEEMS programme from the storm surge tide of 5 December 2013 which reached 3.26 m OD at Lowestoft, including a skew surge of 2.06 m. These were the highest still water level and the largest skew surge values recorded in the period 1964-2014, however the surge event was not exceptional (and neither were the wave heights). The residual at high water (2.11 m) was only 9 cm higher than the event on 21 February 1993, and considerably lower than the estimate of 2.71 m for the 1953 storm surge. However, what was exceptional was that the surge occurred on a spring tide, and only 30 minutes before the predicted time of high water. This resulted in a maximum recorded water level of 3.26 m OD, 55 cm higher than the next largest recorded tide on 29 September 1969, and only 18 cm lower than the estimate for the 1953 storm surge.

Differences in the extreme water levels estimated in this report and in TR252 are due primarily to the inclusion of this large surge event, but also to a slightly revised value for mean sea level rise over the longer period of record. The results of this analysis further emphasise the relatively large effect on predicted extreme values of including even a single high magnitude event.

In the context of coastal flood risk there is a widely held view in previous studies that there is a low probability that maximum surges will coincide with predicted high water based upon a statistical analysis of the available short tidal records (e.g. Horsburgh & Wilson, 2007). BEEMS reports TR139 and TR252 had cast doubts on this assumption for the east coast and considered that there was no apparent *a priori* reason why a large surge could not coincide with predicted high water and cited several events recorded at Lowestoft since 1964 when the maximum surge occurred very close to the time of predicted high water. The 5th December 2013 surge was only 30 minutes from the prediction of high water.

In TR252 the sensitivity of the various statistical methods to the addition of additional extreme events into the data record was determined by adding simulated data for the 1953 and 3 other known historic surge events. In all cases the effect was to increase the predicted size of extreme events at the different probability levels. The analysis showed that the Joint Probability Analysis (JPA) estimates were less sensitive than the GPD estimates to the inclusion of data from additional extreme events. The effect of adding observed data from the December 2103 event followed the same pattern. The 1 in 10,000 year extreme level estimates indicated by JPA increased by 13 cm for the post 1964 recorded data, and by 15 cm for the modelling exercise including assumed values for four large tides representative of those which occurred in 1928, 1938, 1949 and 1953. The GPD estimates were affected to a greater extent by the inclusion of a single additional large value because this technique fits a distribution curve to only the top 3 to 4% of the data. The JPA in this context is the joint probability of tide and skew surge.

Estimates for 1 in 10,000 year still water level at Sizewell (m OD), obtained using different methods, for a range of climate change and sea level scenarios. Levels are based on the Lowestoft sea level records for the period 1964-2014, and high tide levels at Sizewell are assumed to be 15 cm higher than at Lowestoft.

Statistical method	2008	2100			
	(base year)	Medium Emissions 95% estimate (0.65 m SL rise)	High Emissions 95% estimate (0.80 m SL rise)	H++ scenario low estimate (0.93 m SL rise)	H++ scenario high estimate (1.90 m SL rise)
McMillan *et al* (2011a)	4.21 ± 0.6	4.86 ± 0.6	5.01 ± 0.6	5.14 ± 0.6	6.11 ± 0.6
JPA	4.64 ± 0.19	5.29 ± 0.21	5.44 ± 0.22	5.57 ± 0.22	6.54 ± 0.26
JPA (simulation including 4 events)	5.06 ± 0.14	5.71 ± 0.136	5.86 ± 0.17	5.99 ± 0.17	6.96 ± 0.20
HR Wallingford (2010)*	4.84 ± 0.57	5.49 ± 0.57	5.64 ± 0.57	5.77 ± 0.57	6.74 ± 0.57
GPD	5.18 ± 0.28	5.83 ± 0.31	5.98 ± 0.32	6.11 ± 0.33	7.08 ± 0.38
GPD (simulation including 4 events)	5.83 ± 0.29	6.48 ± 0.32	6.63 ± 0.33	6.76 ± 0.33	7.73 ± 0.38
Additive approach	5.73	6.38	6.53	6.66	7.63

Notes:
1. The McMillan and HR Wallingford results are those originally provided by the authors, i.e. the predictions have not been recalculated to include the December 2013 surge event.
2. The 95% confidence limits quoted for each return period in the above table relate to the mathematical curve-fitting procedure, and not to the true uncertainty in any return period. Due to the shortness of the tidal data record, the calculated confidence limits will invariably under-estimate the true uncertainty involved.

The report has provided a very clear demonstration of the sensitivity of existing statistical techniques for estimating extreme still water levels to the number of extreme events captured in the limited tidal data record.

Cefas Quality Assessor:	Liam Fernand
Signature:	
Position in Cefas / BEEMS:	BEEMS Physical Science Lead
Date:	5/9/2014

Estimation of Extreme Sea Levels at Sizewell: Addendum Report

Kenneth Pye & Simon J. Blott

External Investigation Report No. EX1723

26 June 2014

Kenneth Pye Associates Ltd.
Scientific research, consultancy and investigations

Estimation of Extreme Sea Levels at Sizewell: Addendum Report

Kenneth Pye & Simon J. Blott

External Investigation Report No. EX1723

This report was prepared by Professor Kenneth Pye ScD PhD MA CGeol FGS
and Simon James Blott PhD MRes BSc FGS

Report history

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Kenneth Pye Associates Ltd
Research, Consultancy and Investigations
Blythe Valley Innovation Centre
Central Boulevard
Blythe Valley Park
Solihull
B90 8AJ
United Kingdom
Telephone + 44 (0)121 506 9067
E-mail: info@kpal.co.uk
website: www.kpal.co.uk

CONTENTS

EXECUTIVE SUMMARY

This report is an Addendum to BEEMS Technical Report TR252. It presents the results of a revised assessment of extreme still water sea levels at Lowestoft (and by extrapolation at Sizewell) resulting from the interaction of astronomical tides and meteorological surges, based on a re-analysis of tide gauge records for Lowestoft relating to the period January 1964 to May 2014 . Estimates are made of extreme sea levels with return periods of up to 1 in 10,000 years, taking into account the possible effects of climate change and sea level rise up to 2100. Waves are not considered. The analysis presented previously in TR252, was based on water level data from the Lowestoft tide gauge for the shorter period January 1964 to October 2012. The new analysis incorporates data for the high storm surge tide of 5 December 2013, which reached 3.26 m OD at Lowestoft, including a skew surge of 2.06. These were the highest still water level and the largest skew surge values recorded in the period 1964-2014. Differences in the extreme water levels estimated in this report and in TR252 are due primarily to the inclusion of this large surge event, but also to a slightly revised value for mean sea level rise over the longer period of record. The results of the further analysis highlight the relatively large effect on predicted extreme values of including even a single high magnitude event.

Table EX1 provides a summary of the new results, obtained using Joint Probability Analysis (JPA) and Generalised Pareto Distribution (GPD) analysis methods applied to the measured data (de-trended for sea level rise), two model simulations using the measured data plus estimated values for four additional high magnitude events, and the 'worst case' additive approach described previously in TR252 (to which reference should be made for further information). Table EX2 shows the differences in levels obtained in this new analysis, compared with the analysis in TR252.

The new results show that the JPA estimates are less sensitive than the GPD estimates to the inclusion of the additional measured data for the period 2012 -2014The 1 in 10,000 year estimates indicated by JPA have increased by 13 cm for the post 1964 recorded data, and by 15 cm for the modelling exercise including assumed values for four large tides representative of those which occurred in 1928, 1938, 1949 and 1953. The GPD estimates are affected to a greater extent by the inclusion of a single additional large value because this technique fits a distribution curve to only the top 3 to 4% of the data.

No additional data for the Sizewell tide gauge were available for inclusion in the further analysis , and, based on comparisons of measured data for Lowestoft and Sizewell in the period 2009-2012, it has been assumed (as in TR252) that high water levels at Sizewell are 15 cm higher than those at Lowestoft. The estimated 1 in 10,000 year levels are increased by 29 cm for the post 1964 recorded data and by 30 cm for the simulation exercise. The 1 in 10,000 year extreme level estimates for Sizewell obtained using the additive approach, which considers the 'worst case' credible combination of events, is increased by 11 cm due to a 1 cm increase in the estimate of the highest astronomical tide (now taken to be 1.63 m, based on updated information provided by the National Oceanography Centre Proudman

Laboratory), and a 10 cm increase in the statistically estimate of the maximum possible skew surge (3.97 ± 0.14 m).

As concluded in TR252, a rise in mean sea level of 1.9 m by 2100 (H^{++} upper scenario) is considered extremely unlikely and arguably not credible. A rise of 0.93 m by 2100 (H^{++} lower scenario) is also unlikely but credible. It is therefore recommended that an extreme still water level of at least 6.66 m OD should be considered in the design of the general platform level for Sizewell C. This value is 11 cm higher than the value of 6.55 m OD recommended in TR252. For the period 2100 to 2185, a higher level of protection would be required to safeguard residual and more localised hazards such as those that might be associated with a spent fuel store. TR252 recommended an equivalent platform level for 2100 to 2185 of 7.5 m. Considering the significant uncertainties in extrapolation of sea levels beyond 2100, this recommended level of 7.5 m OD is retained in this Addendum. The additional effect of waves also needs to be considered in the specification of the sea defences.

Table EX1. Differences in estimates for 1 in 10,000 year still water level at Sizewell (m OD), between the data presented in Report TR252 (based on 1964-2012 data) and this Addendum report (based on 1964-2014 data).

Statistical method	2008 (base year)	2100			
		Medium Emissions 95% estimate (0.65 m SL rise)	High Emissions 95% estimate (0.80 m SL rise)	H++ scenario low estimate (0.93 m SL rise)	H++ scenario high estimate (1.90 m SL rise)
McMillan *et al* (2011a)	0.00	0.00	0.00	0.00	0.00
JPA	+0.13	+0.13	+0.13	+0.13	+0.13
JPA (simulation including 4 events)	+0.15	+0.15	+0.15	+0.15	+0.15
HR Wallingford (2010)*	0.00	0.00	0.00	0.00	0.00
GPD	+0.29	+0.29	+0.29	+0.29	+0.29
GPD (simulation including 4 events)	+0.30	+0.30	+0.30	+0.30	+0.30
Additive approach	+0.11	+0.11	+0.11	+0.11	+0.11

Table EX2. Estimates for 1 in 10,000 year still water level at Sizewell (m OD), obtained using different methods, for a range of climate change and sea level scenarios. Levels are based on the Lowestoft sea level records for the period 1964-2014, and high tide levels at Sizewell are assumed to be 15 cm higher than at Lowestoft.

Statistical method	2008 (base year)	2100			
		Medium Emissions 95% estimate (0.65 m SL rise)	High Emissions 95% estimate (0.80 m SL rise)	H++ scenario low estimate (0.93 m SL rise)	H++ scenario high estimate (1.90 m SL rise)
McMillan *et al* (2011a)	4.21 ± 0.6	4.86 ± 0.6	5.01 ± 0.6	5.14 ± 0.6	6.11 ± 0.6
JPA	4.64 ± 0.19	5.29 ± 0.21	5.44 ± 0.22	5.57 ± 0.22	6.54 ± 0.26
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HR Wallingford (2010)*	4.84 ± 0.57	5.49 ± 0.57	5.64 ± 0.57	5.77 ± 0.57	6.74 ± 0.57
GPD	5.18 ± 0.28	5.83 ± 0.31	5.98 ± 0.32	6.11 ± 0.33	7.08 ± 0.38
GPD (simulation including 4 events)	5.83 ± 0.29	6.48 ± 0.32	6.63 ± 0.33	6.76 ± 0.33	7.73 ± 0.38
Additive approach	5.73	6.38	6.53	6.66	7.63

* values calculated by HR Wallingford (2010) use a base year of 2010 rather than 2008.

Estimation of extreme sea levels at Sizewell

1.0 INTRODUCTION

This report presents the results of a revised assessment of extreme still water sea levels at Sizewell, Suffolk, resulting from the interaction of astronomical tides and meteorological surges. Waves are not considered. Estimates are made of extreme sea levels with return periods of up to 1 in 10,000 years relative to the base year 2008, taking into account the possible effects of climate change and sea level rise. The purpose of the report is to inform the design of the platform level for the proposed new nuclear build (NNB) station at Sizewell ‘C’.

This report represents an addendum to the previous BEEMS Technical Report TR252 on extreme still water levels at Sizewell which analysed data from the Lowestoft gauge in the period January 1964 to October 2012. This new analysis incorporates data up to May 2014 including the storm surge of 5 December 2013, which reached 3.26 m OD at Lowestoft, including a skew surge of 2.06 m (Table 1). This was the highest level and the largest skew surge recorded in the period 1964-2014. Analyses of records from other stations along the east coast of the UK are also shown in Table 1. It is apparent that the surge increased down the North Sea, with the maximum being observed at Lowestoft. The gauges at Harwich and Sheerness were unfortunately not operating, so these data do not show whether the surge increased or decreased to the south of Lowestoft. However, the Environment Agency gauge at Orford (in the Alde-Ore estuary, some 50 km south) recorded a maximum high water level 3.06 m OD at 01.45 on the 6th December, 71 minutes before the time of predicted HW, with an estimated skew surge of 1.66 m, indicating that the peak surge was probably observed in the Lowestoft area. Comparison with previous storms (Table 2) shows that the magnitude of the skew surge was not exceptional. However, what was exception was the timing of the event: only 30 minutes before high water, and on a spring tide. This coincidence produced the large observed water level of 3.26 m OD (the value de-trended for sea-level rise and the lunar nodal tidal cycle is 3.23 m OD).

The purpose of this Addendum is to assess the effect of including the additional data for the period 2012-2014, and in particular the large event on 5 December 2013. No further tide level data recorded at Sizewell Power Station have been provided, and levels at Lowestoft have been converted to levels at Sizewell on the basis of the relationships determined in TR252 using data for the period 2009-2012. In particular, high water levels are assumed to be 15 cm higher at Sizewell than they are at Lowestoft. Revised tables and figures are provided at the end of this Addendum. Reference should be made to TR252 for introductory material.

2.0 REVISED ANALYSIS

2.1 Lowestoft tidal record analysis

A re-analysis of the Lowestoft tide gauge record has been undertaken. Digital data available on the Permanent Service for Mean Sea Level (PSMSL) and National Tidal and National Tidal and Sea Level facility (NTSLF) websites have been analysed. TR252 used annual mean sea level data from PSMSL for the period 1955-2011. Since publication of TR252, PSMSL have revised their estimate of annual mean sea level for 2011, and have included an estimate for 2012. This Addendum therefore incorporates annual mean sea level values s for the period 1955-2012 (although there is no data for some years). Additional 15 minute observational data from NTSLF have been obtained for the period November 2012 to May 2014, and this Addendum therefore incorporates hourly observations covering the period January 1964 to December 1992 and 15 minute observations covering the period January 1993 to May 2014. As was the case for TR252, all analysis has been undertaken using Microsoft Excel® and Visual Basic programming routines, and the Mathwave EasyFit® programme for determining Generalised Pareto and other extreme value distributions.

A revised completeness record for the Lowestoft Gauge is shown in Figure 1. The period 2012-2014 saw very few gaps in the data record and are considered a very reliable addition to the previous data set.

2.2 Sizewell tidal record analysis

TR252 included a preliminary assessment of mean tidal levels recorded at the Sizewell Power Station tide gauge established as part of the BEEMS project, for the period February 2009 to October 2012 (recorded at 5 minute intervals). Updated data for the period after October 2012 were not available for use in this further assessment, and therefore the estimations made in TR252 have been retained, that high water levels with and without surge residuals are, on average, about 15 cm higher at Sizewell than they are at Lowestoft.

2.3 Sea level trends at Lowestoft

Revised average tidal levels are shown in Table 3, and temporal changes in annual mean water level, annual mean high water level and annual mean low water level are shown in Figure 52 and Table 4. To make reliable estimates of extreme water levels or surges, the data need to be de-trended for sea level rise. Additionally, high and low water need to be de-trended for the lunar nodal tidal cycle, which causes a rise and fall of high water levels by approximately 5 cm at Lowestoft on an 18.6 year timescale (TR252?). Further, predicted astronomical tidal levels supplied by NTSLF do not include a sea level rise component, but are based on a specified datum level of predictions (termed z_o). Up to and including 2006, no annual adjustment was made for sea level rise and the value of z_o was taken from an average of sea levels for the 18 year period from 1984 to 2002 (z_o = 0.114 m OD). All predicted tidal levels before 2006 used the same value of z_o. Between 2007 and 2010 the datum of predictions was calculated on an annual basis using observations for the preceding year: z_o = 0.162 for 2007, 0.195 for 2008, 0.175 for 2009 and 0.168 for 2010 (David Blackman, NOC, *pers. comm*. 2010). NTSLF have since made three further predictions of z_o: z_o = 0.174 for 2011-13, 0.156 for 2014, 0.161 for 2015 (Colin Bell, NOC, *pers. comm*. 2014). In this study, all values have been adjusted to a z_o value of 0.195 m OD, the level used for 2008, which the Environment Agency (2008) has recommended should be used as the base year in all coastal flood risk assessments.

A linear regression fitted to the record of annual mean sea levels since January 1964 indicates an average trend of 2.99 mm/yr (Figure 2a), a reduction from 3.03 mm/yr estimated for the period 1964-2012 in TR252, caused by mean sea levels in 2012-2013 being slightly lower than the previous average. Estimates of the trends for the more recent periods 1980-2011 and 1993-2011 have also been revised down (to 3.16 mm/yr and 3.73 mm/yr, respectively).

Temporal changes in annual mean high and mean low water levels are significantly affected by the lunar nodal tidal cycle (illustrated in Figure 2). Therefore, trends in these levels have been calculated by fitting a linear regression to data spanning two complete lunar nodal cycles, (37 years). It is possible to repeat this regression exercise 13 times for the Lowestoft dataset, i.e. for the periods 1964-2001, 1965-2002, 1966-2003 etc. The mean of the 13 linear regressions produces estimates of the average rise in mean high waters of 3.17 mm/yr, and the average rise in low waters of 3.59 mm/yr. These values have been used to de-trend high tide levels for sea level rise (illustrated in Figures 2e and 2f).

The annual contribution of the lunar nodal cycle (assumed to occur on 1 July each year) can be estimated by subtracting each de-trended annual mean predicted tidal level from the 2008 mean (0.195 m OD). The lunar nodal contribution for any 15 minute (or hourly) value can be estimated by interpolating between the adjacent annual contributions (for example, a value on 10 October 1985 will require interpolating between 1 July 1985 and 1 July 1986). The additional de-trending for the lunar nodal cycle results in the trends illustrated in Figures 2g and 2h, with a flat-line relationship for predicted high tides, and observed high water levels with no significant rising or falling trends over the period.

2.4 Frequency distribution of predicted and observed tidal levels at Lowestoft

All trends in frequency distributions of sea levels and surges have been re-calculated after inclusion of the 2012-2014 data, and tables 5 and 6 and Figures 4 to 9 re-plotted to show the revised distributions. Since the record has been extended by only 2.5 years (5% of the record) the changes in the aggregated values are not large, generally changing by 1 or 2 cm only. The most significant changes are the estimates of the maximum observed water level and surge for the record, which now represents the 5 December 2013 event.

Table 7 presents summary water levels and surge magnitudes recorded at Lowestoft for the largest storm surges on record, including the event on 5 December 2013. It is evident that while the skew surge of 2.06 m was the largest recorded at Lowestoft in the period 1964-2014, it was not exceptional. The residual at high water (2.11 m) was only 9 cm higher than the event on 21 February 1993, and considerably lower than the estimate of 2.71 m for the 1953 storm surge. However, what was exceptional was that the surge occurred on a spring tide, and only 30 minutes before the predicted time of high water. This results in a maximum recorded water level of 3.26 m OD, 55 cm higher than the next largest recorded tide on 29 September 1969, and only 18 cm lower than the estimate for the 1953 storm surge.

2.5 Estimation of extreme sea levels at Lowestoft using GPD and Joint Probability methods

The same method was used to calculate extreme water level estimates as in TR252, using the Mathwave EasyFit® programme for determining Generalised Pareto and other extreme value distributions. High tide levels, or high skew surge values, are fitted to the idealised distribution using a maximum likelihood method, with the shape of the curve represented by a set of three or four parameters (e.g. κ, σ and μ for the Generalised Pareto distribution). The generally accepted method of assessing the ‘goodness of fit’ to these curve-fitting operations is the Kolmogorov-Smirnov statistical test, which effectively produces a pass or fail result based on confidence limits (95% were chosen in this study). There is no conventional mathematical calculation which can calculate a confidence limit on any single point on the extreme value curve (i.e. any single estimated return period). However, the generally agreed method chosen to represent the “spread of values” around a single value (e.g. Miller and Miller, 2005) is to use the calculated curve parameters (κ, σ and μ etc.) to generate random distributions of extreme tidal levels, with the same number of data points as the original measured distribution. In this study, 30 of these seeded random distributions were generated for each calculated return period, and the 95% percentile values calculated from the 30 random values. Experimentation demonstrated that 30 random values was sufficient to produce a significant estimation of the 95% confidence interval, and using more than 30 distributions (up to 100 were tested) changed the calculated confidence interval by no more than 1 to 2 cm. It should therefore be noted that the 95% confidence limits quoted for each return period in the report relates to the mathematical curve-fitting procedure, and not to the true uncertainty in any return period generated, which would include uncertainties in the accuracy of the recorded tide data, adequacy of the length of data record, and the appropriateness of the curve type used.

Table 8 presents Generalised Pareto Distribution (GPD) extreme water level estimations for different threshold values. This method requires only high tides above a specified threshold level to determine the shape of the tail of the distribution. The threshold value to use is largely a pragmatic decision, based on the degree of fit determined by the Kolmogorov-Smirnov test, and the number of values used to determine the distribution. In general, with fewer values the fit will be better, and testing (Figures 10 and 11) has shown that very good statistical fits can made using less than 0.2% of the data (c. 60 values). Nevertheless, with fewer data, the calculated extreme values become less representative of the data record and influence of outlier values becomes even greater. Statistically, the best fit was found in this study by using a threshold value of 1.54 m OD, but this uses only 573 'events'. A more reliable estimate is likely to be obtained by using a threshold value of 1.44 m OD (1 cm different to the 1.43 m OD threshold used in TR252). Calculated estimates of extreme water levels are only a few cm different from those quotes TR252 for lower return periods (specify return periods), but the 1:10,000 year level is calculated to be 5.03 ± 0.27 (29 cm higher than the estimate of 4.74 ± 0.24 made in TR252).

Comparison of Kolmogorov-Smirnov goodness-of-fit tests has demonstrated that a Generalised Pareto distribution provides the best statistical fit to the Lowestoft high water level data (Table 9). Statistically significant fits can be obtained using Pearson 6, Weibull, Burr and Generalised Gamma distributions, but with much lower Kolmogorov-Smirnov values for goodness of fit.

Table 10 illustrates the results of GPD analysis performed on the distribution of skew surges at Lowestoft, employing three different threshold values. A GPD provides a much better fit to the distribution of surges than to the distribution of high water levels presented earlier, with Kolmogorov-Smirnov values of 1.0000, and varying the threshold value makes very little difference to the results. The 1 in 10,000 year skew surge is calculated to be 3.54 ± 0.18 m, 13 cm larger than the value determined from the 1964-2012 record in TR252 (3.41 ± 0.21 m). As described in section 4.4 above, the skew surge during the 5 December 2013 storm event was less exceptional than the observed water level due to the near coincidence with predicted spring tide high water. It is largely for this reason that the 1 in 10,000 year skew surge has increased by only 13 cm in this revised analysis compared with TR252, while the 1 in 10,000 extreme water level has risen by a much greater amount (29 cm).

Table 10 also shows the results of GPD - JPA performed using the de-trended tide gauge and skew surge data for data for the period 1964-2014, using the same three threshold values for skew surge. The predicted value for the 1 in 10,000 high water level is 4.49 ± 0.18 m OD, 13 cm higher than the estimate in TR252 (4.36 ± 0.21 m OD), caused by the fact that the 1:10,000 year skew surge is also 13 cm larger .

Revised estimates resulting from the modelling exercise which included estimated high water levels for the 1953 event and four other high surge tide events in 1928, 1938, 1949 and 1953 (Table 2) are shown in Tables 11 and 12. With the inclusion of the four additional extreme tides, the 1:10,000 year skew surge is 3.97 ± 0.14 m, 15 cm higher than the estimate made in TR252. The JPA 1 in 10,000 high extreme water level for the same scenario is 4.91 ± 0.14 m OD, again 15 cm higher than the estimate given in TR252. The GPD 1 in 10,000 high water level for the same modelled data set is 5.68 ± 0.28 m OD, 30 cm higher than the estimate in TR252.

2.6 Allowances for future climate change

No revised estimates of future sea level rise projections for the UK have been published since the publication of TR252, and estimates for the Sizewell area have been calculated using data on the UKCP09 user interface (http://ukclimateprojections.defra.gov.uk), themselves based partly on projections from the Fourth Scientific Assessment of the Inter-governmental Panel on Climate Change, are shown in Table 13. Additional extreme estimates of the lower estimate of the H^{++} scenario, and the higher estimate of the H^{++} scenario (Lowe *et al*., 2009) are still considered valid. 1:10,000 year high water levels at Sizewell in the year 2100, assuming the H^{++} lower estimate, are 6.11 ± 0.33 m OD based on GPD calculations, and 5.57 ± 0.22 m OD based on JPA. These values are again 29 cm and 13 cm higher than the estimates made in TR252.

3.0 ALTERNATIVE METHODS OF DETERMINING EXTREME HIGH WATER LEVEL ALLOWANCES

As was made clear in TR252, estimates of extreme high water levels based on conventional statistical analysis methods are highly dependent on the model parameterization chosen, and especially on the length and quality of the data record used to make the statistical assessments. Confidence limits were determined on the basis of the standard errors associated with the curve fitting will invariably under-estimate the true uncertainty involved.

An alternative approach to the issue of extreme water level risk is to consider the ‘worst case’ credible scenario, for example using an additive approach where the highest possible astronomical tide is combined with the estimated maximum possible 1 in 10, 000 year surge. Table 16 summaries revised estimates based on this additive approach. The maximum possible extreme water level at Sizewell in 2008 is considered to be 5.73 m OD. Assuming the H^{++} lower estimate of sea level rise, the level in 2100 is considered to be 6.66 m OD. These values are 11 cm higher than the estimates made in TR252, made up to a 1 cm increase in the highest astronomical tide (1.63 m OD, NTSLF estimate for 2008-2026) and a 10 cm increase in extreme skew surge (4.10 m, assuming the magnitude of skew surges is unaffected by sea level rise).

Although a rise in mean sea level of 1.9 m or more is by most authors to be very unlikely, and arguably implausible, by 2100, a rise of this magnitude could occur over a longer time period if large-scale melting of ice sheets in Greenland and Antarctica were to take place (Nicholls *et al*., 2011). A rise of the order of 0.93 m by 2100 m is also considered here to be unlikely but is plausible. For this reason, it was suggested in TR252 that , extreme still water levels values associated with the lower H^{++} climate change scenario should be considered in the design for the operational lifetime of Sizewell ‘C’ (i.e. up to approximately 2100).

4.0 CONCLUSIONS

Based on an updated analysis of observed and estimated extreme water levels recorded at Lowestoft between January 1964 and May 2014, an estimated difference in high water levels between Lowestoft and Sizewell of +15 cm, and taking into account possible but credible changes in mean sea level which may occur due to climate change by 2100, it is concluded that an extreme still water level of at least 6.66 OD should be considered in the design of the general platform level for Sizewell 'C'.

For the period extending beyond 2100 to 2185 a level of protection equivalent to a platform level of 7.5 m would be required to safeguard residual and more localised hazards such as those that might be associated with a spent fuel store. The additional effect of waves also needs to be considered in the specification of the sea defences.

It should be noted that these statistical assessments are based only on data for the period 1964 – 2014 and do not include the high magnitude 1953 event. Modelling has shown that the inclusion of this and other high magnitude events earlier in the 20th century leads to even higher estimates for the 1in 10000 year water level.

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Revised Tables

Table 1. Tidal levels recorded at East Coast Class A gauges during the 5-6 December 2013 storm surge. All times refer to 5 December 2013, except Dover which refer to 6 December 2013.

	Time of HW			Highest water level				Largest residual		
	Observed (hh:mm)	Predicted (hh:mm)	Difference (mins)	Observed (m OD)	Predicted (m OD)	Surge at HW (m)	Skew surge (m)	Time (hh:mm)	Difference from HW	Surge (m)
Wick	12:45	12:30	+15	2.437	2.092	0.346	0.345	11:45	-60	0.429
Aberdeen	15:00	14:45	+15	2.979	2.339	0.673	0.640	12:15	-165	0.741
Leith	15:15	16:00	-45	3.706	2.967	0.929	0.739	12:45	-150	1.024
North Shields	16:15	16:45	-30	3.975	2.794	1.26	1.181	15:15	-60	1.329
Whitby	17:15	17:30	-15	4.319	2.849	1.476	1.470	15:45	-90	1.631
Immingham	19:15	19:30	-15	5.216	3.693	1.527	1.523	17:30	-105	1.969
Cromer	19:45	20:00	-15	3.756	2.533	1.23	1.223	16:00	-225	1.787
Lowestoft	22:30	23:00	-30	3.264	1.202	2.106	2.062	22:00	-30	2.179
Harwich					gauge not working					
Sheerness					gauge not working					
Dover	00:45	00:45	0	4.779	3.252	1.527	1.527	00:45	0	1.527

Table 2. Tidal levels recorded on 5 December 2013 at Lowestoft, compared with previous high tide events. Data sources: (1) Waverley Committee (1954) values for Sheerness; (2) Rossiter (1954) estimated levels for the 1953 event; (3) values at Lowestoft estimated in this study from the values quoted for Sheerness.

Event	Values recorded at Sheerness[1]				Values estimated at Lowestoft[2,3]		
	Predicted high water level (m OD)	Observed high water level (m OD)	Maximum surge (m)	Skew surge (m)	Predicted high water level (m OD)	Observed high water level (m OD)	Skew surge (m)
Nov 1897	2.50	4.15	2.13	1.65	nd	nd	nd
Jan 1928	2.53	4.15	1.65	1.62	1.10	3.10	2.00
Feb 1938	2.35	4.18	1.98	1.83	1.00	3.25	2.25
Mar 1949	2.47	4.21	2.29	1.74	0.90	3.00	2.10
Jan 1953	2.53	4.69	2.59	2.16	1.00	3.44	2.44
Dec 2013	nd	nd	nd	nd	1.20	3.26	2.06

Table 3. Tidal levels on the Suffolk coast quoted by various sources, with data range for calculations where known: 2014 Admiralty Tide Tables (ATT) (UKHO, 2013); National Tidal and Sea Level Facility (NTSLF); HR Wallingford (2010) (HR); and the present study (KPAL). Elevations are expressed in m OD. Where values for MHW and MLW are not quoted, these levels are assumed to occur midway between MHWS and MHWN, and MLWN and MLWS.

Location	Source	HAT	MHWS	MHW	MHWN	MSL	MLWN	MLW	MLWS	LAT	CD	MSR	MNR
Lowestoft	ATT (1988-2007)	14	0.9	0.75	0.6	0.16	-0.5	-0.75	-10	-14	-15	19	11
	NTSLF (2008-2026)	148	108	0.91	0.74	nd	-0.34	-0.60	-0.86	-138	-150	194	108
	KPAL (1964-2014)	144	104	0.88	0.71	0.11	-0.40	-0.64	-0.87	-156	-150	191	111
Southwold	ATT	16	11	0.95	0.8	0.25	-0.4	-0.60	-0.8	-112	-13	19	12
Minsmere Sluice	ATT	15	0.8	0.60	0.4	-0.19	-0.8	-105	-13	-17	-16	2.1	12
Sizewell	KPAL (2009-2012)	162	120	104	0.87	0.12	-0.62	-0.88	-110	-169	nd	2.30	149
	HR	168	122	nd	0.83	0.16	-0.42	nd	-101	-161	-160	2.23	125
Aldeburgh	ATT	18	11	0.90	0.7	0.06	-0.7	-100	-13	-18	-16	2.4	14
Felixstowe	ATT (1994-2007)	2.25	185	150	115	0.13	-0.95	-125	-155	-2.1	-195	3.4	2.1
	NTSLF (2008-2026)	2.25	191	156	121	nd	-0.88	-119	-149	-197	-195	3.40	2.09

Table 4. Estimates of average rates of relative sea level rise and vertical land movements at Lowestoft, based linear regression over different averaging periods. Note that the values of 3.17 ± 0.39 for high waters and 3.59 ± 0.58 for low waters are based on thirteen running-means of 37 years (spanning two complete lunar nodal tidal cycles between 1964-2001 and 1976-2013), and are considered the most appropriate to use as the long-term trends over the period 1964-2013. Standard errors are also shown, where known.

Measure	Vertical change (mm/yr)	Source
Relative Mean Sea Level		
1956-1995 trend	1.81 ± 0.48	Woodworth et al. (1999)
1956-2006 trend	2.57 ± 0.33	Woodworth et al. (2009)
1956-2006 trend ('Master Station' method)	2.47 ± 0.23	Woodworth et al. (2009)
1956-2007 trend ('sea-level index' method)	2.24 ± 0.25	Haigh et al. (2009)
1956-2012 trend	2.66 ± 0.27	This study, from PSMSL values
1964-2012 trend	3.01 ± 0.32	This study, from PSMSL values
1964-2013 trend	2.99 ± 0.29	This study, from NTSLF values
1980-2013 trend	3.16 ± 0.38	This study, from NTSLF values
1993-2013 trend	3.73 ± 0.72	This study, from NTSLF values
Relative Mean High Water Level		
1964-2013 trend	2.75 ± 0.26	This study, from NTSLF values
1980-2013 trend	3.00 ± 0.40	This study, from NTSLF values
1993-2013 trend	2.20 ± 0.64	This study, from NTSLF values
1964-2013 trend, two lunar nodal cycles	3.17 ± 0.39	This study, from NTSLF values
Relative Mean Low Water Level		
1964-2013 trend	3.05 ± 0.39	This study, from NTSLF values
1980-2013 trend	3.29 ± 0.57	This study, from NTSLF values
1993-2013 trend	5.48 ± 1.14	This study, from NTSLF values
1964-2013 trend, two lunar nodal cycles	3.59 ± 0.58	This study, from NTSLF values
Vertical land movement		
Geology evidence by Shennan & Horton (2002)	−0.61	Woodworth et al. (2009)
GPS measurements 1999-2006	-1.17	Bradley et al. (2009)
GPS measurements 1999-2006	-1.2 ± 0.4 to -1.5 ± 0.6	Teferle et al. (2009)

Table 5. The 40 highest tides recorded at Lowestoft in the period January 1964 to May 2014. [1 & 2] High water levels were sustained over two successive tides during these two events. Values are as recorded, and have been de-trended for sea level rise over the period.

Time of observed high water	Observed high water level (m OD)	Predicted high water level (m OD)	Surge residual at observed time of high water (m)	Surge residual at predicted time of high water (m)	Skew surge at high water, SK_{HW} (m)
05/12/2013 22:30[2]	3.23	1.17	2.11	1.93	2.06
29/09/1969 10:00	2.85	1.25	1.66	1.49	1.60
01/02/1983 23:00	2.77	1.22	1.63	1.43	1.55
03/01/1976 21:00[1]	2.76	1.11	1.75	1.33	1.66
21/02/1993 09:00	2.72	0.82	1.97	1.76	1.91
09/11/2007 08:15	2.65	1.01	1.66	1.41	1.64
14/12/1973 00:00	2.58	1.19	1.29	1.29	1.39
28/01/1994 09:30	2.44	0.91	1.53	1.40	1.53
11/01/1978 23:00	2.40	1.25	1.06	1.06	1.15
21/11/1971 23:00	2.39	1.05	1.24	1.24	1.34
14/02/1989 06:00	2.39	0.87	2.03	0.87	1.52
01/01/1995 20:30	2.38	1.12	1.29	1.16	1.26
14/11/1993 21:00	2.36	1.14	1.22	1.15	1.22
27/11/2011 22:00	2.32	1.16	1.25	1.07	1.16
29/10/1996 10:30	2.31	1.14	1.16	1.04	1.17
12/12/1990 19:00	2.31	0.76	1.50	1.50	1.55
02/04/1973 20:00	2.30	0.98	1.26	1.03	1.33
03/01/1976 10:00[1]	2.28	0.94	1.31	1.06	1.35
10/12/1965 10:00	2.27	1.11	1.04	1.04	1.17
01/11/2006 05:15	2.27	0.85	1.45	1.40	1.41
19/11/1973 18:00	2.25	0.80	1.35	1.35	1.45
07/10/1990 10:00	2.25	1.33	0.95	0.79	0.92
15/12/2003 00:45	2.23	0.94	1.28	1.19	1.29
26/02/1990 22:00	2.21	1.20	0.96	0.96	1.01
12/01/2005 22:30	2.21	1.18	1.03	1.01	1.03
25/11/2007 09:15	2.21	1.25	0.96	0.96	0.96
30/01/2000 04:15	2.19	0.70	1.46	1.46	1.49
10/01/1995 05:15	2.18	0.75	1.59	1.19	1.44
18/03/2007 20:30	2.18	1.09	1.10	1.01	1.09
06/12/1973 19:00	2.17	0.80	1.27	1.27	1.37
12/01/2007 02:45	2.17	0.82	1.34	1.34	1.35
19/10/1970 12:00	2.14	1.06	0.97	0.97	1.08
25/01/1993 11:00	2.14	0.81	1.30	1.25	1.33
03/01/1984 21:00	2.13	1.02	1.09	0.90	1.11
01/03/2008 13:45	2.13	0.54	1.80	1.30	1.59
04/02/1999 23:30	2.13	1.06	1.09	0.95	1.07
25/11/1973 21:00	2.13	1.05	1.03	0.84	1.08
20/01/1976 23:00	2.12	1.19	0.88	0.75	0.93
05/01/2012 18:15	2.12	0.74	1.43	1.31	1.38
06/12/2013 11:15[2]	2.09	1.07	1.08	0.95	1.02

Table 6. The 40 largest positive skew surges at high water (SKHW) recorded at Lowestoft in the period January 1964 to May 2014. [1,2,3 & 4] High water levels were sustained over two successive tides during these four events. Values are as recorded, and have been de-trended for sea level rise over the period.

Time of observed high water	Observed high water level (m OD)	Predicted high water level (m OD)	Surge residual at observed time of high water (m)	Surge residual at predicted time of high water (m)	Skew surge at high water, SK_{HW} (m)
05/12/2013 22:30	3.23	1.17	2.11	1.93	2.06
21/02/1993 09:00	2.72	0.82	1.97	1.76	1.91
03/01/1976 21:00[1]	2.76	1.11	1.75	1.33	1.66
09/11/2007 08:15	2.65	1.01	1.66	1.41	1.64
29/09/1969 10:00	2.85	1.25	1.66	1.49	1.60
01/03/2008 13:45	2.13	0.54	1.80	1.30	1.59
01/02/1983 23:00	2.77	1.22	1.63	1.43	1.55
12/12/1990 19:00[2]	2.31	0.76	1.50	1.50	1.55
28/01/1994 09:30	2.44	0.91	1.53	1.40	1.53
14/02/1989 06:00	2.39	0.87	2.03	0.87	1.52
30/01/2000 04:15	2.19	0.70	1.46	1.46	1.49
19/11/1973 18:00	2.25	0.80	1.35	1.35	1.45
10/01/1995 05:15[3]	2.18	0.75	1.59	1.19	1.44
01/11/2006 05:15[4]	2.27	0.85	1.45	1.40	1.41
14/12/1973 00:00	2.58	1.19	1.29	1.29	1.39
06/03/1968 12:00	2.00	0.62	1.48	1.18	1.39
05/01/2012 18:15	2.12	0.74	1.43	1.31	1.38
06/12/1973 19:00	2.17	0.80	1.27	1.27	1.37
12/01/2007 02:45	2.17	0.82	1.34	1.34	1.35
03/01/1976 10:00[1]	2.28	0.94	1.31	1.06	1.35
21/11/1971 23:00	2.39	1.05	1.24	1.24	1.34
18/03/1967 13:00	1.97	0.63	1.27	1.19	1.34
25/01/1993 11:00	2.14	0.81	1.30	1.25	1.33
02/04/1973 20:00	2.30	0.98	1.26	1.03	1.33
18/01/1983 12:00	2.06	0.75	1.23	1.23	1.31
15/12/2003 00:45	2.23	0.94	1.28	1.19	1.29
01/01/1995 20:30	2.38	1.12	1.29	1.16	1.26
31/10/2006 20:15[4]	2.07	0.82	1.79	1.02	1.26
12/12/1990 06:00[2]	2.09	0.84	1.23	1.18	1.25
05/02/1999 11:45	1.96	0.73	1.35	1.09	1.23
14/11/1993 21:00	2.36	1.14	1.22	1.15	1.22
06/11/1985 05:00	1.95	0.76	1.51	1.03	1.19
29/10/1996 10:30	2.31	1.14	1.16	1.04	1.17
10/12/1965 10:00	2.27	1.11	1.04	1.04	1.17
24/11/1981 20:00	2.09	0.92	1.12	0.89	1.16
27/11/2011 22:00	2.32	1.16	1.25	1.07	1.16
12/01/1995 06:00[3]	1.80	0.65	1.11	1.11	1.15
11/01/1978 23:00	2.40	1.25	1.06	1.06	1.15
09/12/2011 08:45	1.96	0.81	1.16	1.14	1.15
23/02/1967 20:00	2.03	0.90	1.03	0.89	1.13

Table 7. Comparison of tidal levels recorded at various stations during the largest storm surges on record. Note: positive times indicate observed high waters occurred later than predicted high waters or peak residuals. Values are as recorded, and have not been de-trended for sea level rise.

Event	Location	Time of Observed High Water	Time of Predicted High Water	Time between observed and predicted high waters (mins)	Observed High Water (m OD)	Residual at Observed High Water (m)	Skew Surge (m)	Maximum residual (m)	Time between observed high water and max residual (mins)	Source
31 January - 1 February 1953	Gt Yarmouth	22:04	22:53	-49	3.29	2.71	nd	nd	nd	Rossiter (1954)
	Lowestoft	22:19	23:10	-51	3.44	nd	nd	2.53	nd	Rossiter (1954)
29 September 1969	Lowestoft	10:00	11:00	-60	2.71	1.78	1.61	1.79	+180	NTSLF
3 January 1976	Gt Yarmouth	nd	nd	nd	2.69	nd	nd	nd	nd	George (1994)
	Lowestoft	21:00	23:00	-120	2.68	1.85	1.66	2.02	+240	NTSLF
1 February 1983	Gt Yarmouth	nd	nd	nd	2.59	nd	nd	nd	nd	George (1994)
	Lowestoft	23:00	00:00	-60	2.69	1.71	1.55	1.71	0	NTSLF
21 February 1993	Gt Yarmouth	09:15	nd	nd	2.64	nd	nd	nd	nd	EA
	Lowestoft	09:00	09:45	-45	2.68	2.02	1.91	2.36	+240	NTSLF
	Southwold	09:30	nd	nd	2.56	nd	nd	nd	nd	EA
	Felixstowe	11:30	11:45	-15	2.99	1.31	nd	2.52	+315	NTSLF
31 October - 1 November 2006 (first high tide)	Gt Yarmouth	20:00	nd	nd	2.03	nd	nd	nd	nd	EA
	Lowestoft	20:15	17:00	+195	2.04	1.80	1.26	1.83	-15	EA
	Southwold	20:30	nd	nd	2.40	nd	nd	nd	nd	EA
	Felixstowe	20:15	18:30	+105	2.61	1.75	nd	1.86	-45	NTSLF
31 October - 1 November 2006 (second high tide)	Gt Yarmouth	05:00	nd	nd	2.49	nd	nd	nd	nd	EA
	Lowestoft	05:15	04:30	+45	2.24	1.45	1.41	1.83	+480	NTSLF
	Southwold	05:30	nd	nd	2.43	nd	nd	nd	nd	EA
	Felixstowe			Gauge not working						
9 November 2007	Gt Yarmouth	06:04	nd	nd	2.83	nd	nd	nd	nd	EA
	Lowestoft	08:15	08:45	-30	2.63	1.66	1.64	2.09	+315	NTSLF
	Southwold	08:15	nd	nd	2.52	nd	nd	nd	nd	EA
	Felixstowe	11:00	11:00	0	2.85	1.14	nd	2.25	+330	NTSLF
5 December 2013	Lowestoft	22:30	23:00	-30	3.26	2.11	2.06	2.18	-30	NTSLF
	Felixstowe			No longer a Class A gauge						
	Harwich			Gauge not working						

Table 8. Return periods of extreme water levels calculated for Lowestoft using Generalised Pareto Distributions with different thresholds, based on high tides recorded at Lowestoft during the period 1964-2014. Values have been are de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period, calculated using 2008 as the base year. Distribution parameters are indicated (κ, σ and μ), as are the probability values from Kolmogorov-Smirnov goodness of fit tests (K-S). Values in bold (i.e. using a threshold of 1.44 m OD and a base year of 2008) are adopted in this study on the basis that estimates based on a larger number of data points are likely to be more representative. All values are statistically significant at the 95% confidence level.

threshold =	>1.41 m OD	>1.43 m OD	**>1.44 m OD**	>1.45 m OD	>1.47 m OD	>1.54 m OD
n =	1193	1058	**990**	934	842	573
% =	3.4	3.0	**2.8**	2.7	2.4	1.6
κ =	0.08296	0.07657	**0.07310**	0.07351	0.07899	0.05851
Return σ =	0.17588	0.17980	**0.18191**	0.18254	0.18204	0.19482
Period μ =	1.40860	1.42870	**1.44000**	1.45070	1.47070	1.53820
(years) K-S =	0.8506	0.9460	**0.9472**	0.9351	0.8688	0.9817
1	2.05 ± 0.01	2.05 ± 0.01	**2.05 ± 0.01**	2.05 ± 0.01	2.05 ± 0.01	2.05 ± 0.01
2	2.21 ± 0.01	2.21 ± 0.02	**2.21 ± 0.01**	2.21 ± 0.01	2.21 ± 0.01	2.21 ± 0.01
5	2.44 ± 0.02	2.44 ± 0.03	**2.44 ± 0.02**	2.44 ± 0.02	2.44 ± 0.02	2.43 ± 0.02
10	2.63 ± 0.02	2.62 ± 0.04	**2.62 ± 0.03**	2.62 ± 0.03	2.62 ± 0.03	2.61 ± 0.03
20	2.83 ± 0.03	2.81 ± 0.05	**2.81 ± 0.04**	2.81 ± 0.05	2.82 ± 0.04	2.79 ± 0.05
50	3.11 ± 0.05	3.09 ± 0.07	**3.08 ± 0.05**	3.08 ± 0.07	3.09 ± 0.06	3.04 ± 0.07
100	3.33 ± 0.06	3.30 ± 0.09	**3.29 ± 0.07**	3.29 ± 0.09	3.31 ± 0.07	3.24 ± 0.09
200	3.57 ± 0.07	3.53 ± 0.12	**3.51 ± 0.09**	3.52 ± 0.11	3.55 ± 0.09	3.45 ± 0.11
500	3.91 ± 0.09	3.86 ± 0.15	**3.83 ± 0.12**	3.83 ± 0.16	3.88 ± 0.12	3.74 ± 0.15
1000	4.19 ± 0.11	4.12 ± 0.18	**4.08 ± 0.15**	4.09 ± 0.19	4.14 ± 0.15	3.97 ± 0.18
2000	4.48 ± 0.14	4.39 ± 0.22	**4.35 ± 0.18**	4.36 ± 0.23	4.42 ± 0.19	4.20 ± 0.21
5000	4.89 ± 0.17	4.78 ± 0.28	**4.73 ± 0.22**	4.73 ± 0.30	4.82 ± 0.24	4.53 ± 0.27
10000	5.22 ± 0.20	5.09 ± 0.33	**5.03 ± 0.27**	5.03 ± 0.36	5.13 ± 0.28	4.80 ± 0.32

Table 9. Return periods of extreme water levels calculated for Lowestoft using a number of extreme value distributions, based on tides above set thresholds and using the base year of 2008. All values have been de-trended for sea level rise assuming a rate of increase of 3.17 mm/yr in high waters over the period 1964-2014. Distribution parameters are indicated (κ, σ and μ), as are the probability values from Kolmogorov-Smirnov goodness of fit tests (K-S). All values are statistically significant at the 95% confidence limit. Values in bold (i.e. using a Generalised Pareto Distribution and a base year of 2008) are adopted in this study, due to the better fit provided by the distribution according to the Kolmogorov-Smirnov test.

		Base Year = 2008 (threshold at 1.44 m OD)				
		Gen. Pareto	**Pearson 6**	**Weibull**	**Burr**	**Gen. Gamma**
	n =	990	990	990	990	990
	% =	2.8	2.8	2.8	2.8	2.8
		κ = 0.0731	α1 = 0.91844	α = 0.94169	κ = 19.848	κ = 0.89778
Return		σ = 0.18191	α2 = 28.36	β = 0.18959	α = 0.96388	α = 1.1014
Period		μ =1.4400	β = 5.9047	γ = 1.4404	β = 4.064	β = 0.16318
			γ = 1.4404		γ = 1.4404	γ = 1.4404
(years)	K-S =	0.9472	0.7324	0.6786	0.6505	0.5331
1		**2.05 ± 0.01**	2.06 ± 0.02	2.05 ± 0.01	2.06 ± 0.01	2.03 ± 0.01
2		**2.21 ± 0.01**	2.22 ± 0.02	2.20 ± 0.02	2.22 ± 0.02	2.18 ± 0.02
5		**2.44 ± 0.02**	2.44 ± 0.04	2.40 ± 0.02	2.45 ± 0.03	2.38 ± 0.02
10		**2.62 ± 0.03**	2.61 ± 0.05	2.55 ± 0.03	2.63 ± 0.04	2.54 ± 0.03
20		**2.81 ± 0.04**	2.78 ± 0.07	2.71 ± 0.03	2.82 ± 0.05	2.70 ± 0.04
50		**3.08 ± 0.05**	3.01 ± 0.11	2.92 ± 0.04	3.08 ± 0.08	2.91 ± 0.05
100		**3.29 ± 0.07**	3.20 ± 0.14	3.07 ± 0.05	3.28 ± 0.10	3.07 ± 0.06
200		**3.51 ± 0.09**	3.39 ± 0.18	3.23 ± 0.05	3.50 ± 0.12	3.23 ± 0.07
500		**3.83 ± 0.12**	3.64 ± 0.24	3.44 ± 0.06	3.79 ± 0.16	3.44 ± 0.09
1000		**4.08 ± 0.15**	3.84 ± 0.30	3.60 ± 0.06	4.03 ± 0.20	3.61 ± 0.10
2000		**4.35 ± 0.18**	4.04 ± 0.37	3.77 ± 0.07	4.27 ± 0.24	3.77 ± 0.11
5000		**4.73 ± 0.22**	4.32 ± 0.48	3.98 ± 0.08	4.61 ± 0.31	4.00 ± 0.13
10000		**5.03 ± 0.27**	4.54 ± 0.58	4.14 ± 0.09	4.87 ± 0.37	4.17 ± 0.14

Table 10. Magnitude of skew surges and extreme tide plus skew surge with different return periods calculated for Lowestoft using Joint Probability Analysis and Generalised Pareto Distributions, based on tide gauge data for the period 1964-2014, de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period and using 2008 as the base year**.** Distribution parameters are indicated (κ, σ and μ), as are the probability values from Kolmogorov-Smirnov goodness of fit tests (K-S). Values in bold (i.e. joint probability water levels using a surge threshold of 0.41 m) are adopted in this study on the basis of the greatest number of data points and the precautionary principle that the largest values should be used. All values are statistically significant at the 95% confidence level.

		Skew Surges (m)			Joint Probability Water Levels (m OD)	
threshold =	>0.47 m	>0.44 m	**>0.41 m**	>0.47 m	>0.44 m	**>0.41 m**
n =	985	1144	**1337**	985	1144	**1337**
% =	2.8	3.3	**3.8**	2.8	3.3	**3.8**
κ =	0.03977	0.03922	**0.03925**	0.03977	0.03922	**0.03925**
Return σ =	0.19582	0.19486	**0.19366**	0.19582	0.19486	**0.19366**
Period μ =	0.46903	0.43971	**0.40946**	0.46903	0.43971	**0.40946**
(years) K-S =	1.0000	1.0000	**1.0000**	1.0000	1.0000	**1.0000**
1	1.09 ± 0.01	1.09 ± 0.01	**1.09 ± 0.01**	2.06 ± 0.01	2.06 ± 0.01	**2.06 ± 0.01**
2	1.25 ± 0.01	1.25 ± 0.01	**1.25 ± 0.01**	2.21 ± 0.01	2.21 ± 0.01	**2.22 ± 0.01**
5	1.46 ± 0.02	1.46 ± 0.02	**1.46 ± 0.02**	2.42 ± 0.02	2.42 ± 0.02	**2.43 ± 0.02**
10	1.62 ± 0.03	1.62 ± 0.03	**1.62 ± 0.02**	2.59 ± 0.03	2.59 ± 0.03	**2.59 ± 0.02**
20	1.79 ± 0.03	1.79 ± 0.04	**1.79 ± 0.03**	2.75 ± 0.03	2.75 ± 0.04	**2.76 ± 0.03**
50	2.02 ± 0.05	2.02 ± 0.06	**2.02 ± 0.04**	2.98 ± 0.05	2.98 ± 0.06	**2.99 ± 0.04**
100	2.21 ± 0.06	2.20 ± 0.08	**2.20 ± 0.05**	3.16 ± 0.06	3.16 ± 0.08	**3.16 ± 0.05**
200	2.39 ± 0.07	2.39 ± 0.09	**2.39 ± 0.07**	3.35 ± 0.07	3.35 ± 0.09	**3.35 ± 0.07**
500	2.65 ± 0.09	2.64 ± 0.12	**2.64 ± 0.09**	3.60 ± 0.09	3.60 ± 0.12	**3.60 ± 0.09**
1000	2.84 ± 0.11	2.84 ± 0.14	**2.84 ± 0.11**	3.80 ± 0.11	3.79 ± 0.14	**3.80 ± 0.11**
2000	3.05 ± 0.13	3.04 ± 0.17	**3.04 ± 0.13**	4.00 ± 0.13	4.00 ± 0.17	**4.00 ± 0.13**
5000	3.33 ± 0.16	3.32 ± 0.21	**3.32 ± 0.16**	4.28 ± 0.16	4.27 ± 0.21	**4.28 ± 0.16**
10000	3.54 ± 0.19	3.54 ± 0.24	**3.54 ± 0.18**	4.49 ± 0.19	4.49 ± 0.24	**4.49 ± 0.18**

Table 11. Modelling exercise of extreme skew surges at Lowestoft obtained using (a) Generalised Pareto distribution of observed skew surges larger than 0.41 m over the period 1964-2014; (b) the same as (a), but with the addition of one skew surge value of 2.44 m, the estimated value for the 1953 surge event; (c) an extended tide data set for the period 1914-2014 in which a distribution for 1914-1964 is assumed to be the same as that observed between 1964 and 2014, except for the inclusion of four assumed high surge levels (2.00, 2.25, 2.10 and 2.44 m OD) representative of the high tides which occurred in 1928, 1938, 1949 and 1953. All values are de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period 1964-2013, using 2008 as the base year. All values are statistically significant at the 95% confidence level.

	Skew Surges (m)		
	(a) as observed	(b) including 1953 event	(c) including four large events
threshold =	>0.41 m	>0.41 m	>0.41 m
n =	1337	1338	2678
% =	3.8	3.8	3.8
κ =	0.03925	0.05245	0.05983
Return σ =	0.19366	0.19195	0.19121
Period μ =	0.40946	0.40982	0.41003
(years) K-S =	1.0000	1.0000	0.9962
1	1.09 ± 0.01	1.10 ± 0.01	1.11 ± 0.01
2	1.25 ± 0.01	1.26 ± 0.01	1.27 ± 0.01
5	1.46 ± 0.02	1.48 ± 0.02	1.50 ± 0.01
10	1.62 ± 0.02	1.66 ± 0.03	1.68 ± 0.02
20	1.79 ± 0.03	1.84 ± 0.03	1.87 ± 0.03
50	2.02 ± 0.04	2.09 ± 0.05	2.13 ± 0.03
100	2.20 ± 0.05	2.29 ± 0.06	2.34 ± 0.04
200	2.39 ± 0.07	2.49 ± 0.07	2.56 ± 0.05
500	2.64 ± 0.09	2.78 ± 0.10	2.86 ± 0.07
1000	2.84 ± 0.11	3.00 ± 0.12	3.10 ± 0.08
2000	3.04 ± 0.13	3.23 ± 0.14	3.35 ± 0.10
5000	3.32 ± 0.16	3.55 ± 0.17	3.69 ± 0.12
10000	3.54 ± 0.18	3.80 ± 0.20	3.97 ± 0.14

Table 12. Modelling exercise of extreme water levels at Lowestoft obtained using an extended tide data set for the period 1914-2014 in which a distribution for 1914-1964 is assumed to be the same as that observed between 1964 and 2014, except for the inclusion of four assumed high tidal levels (3.0, 3.25, 3.10 and 3.44 m OD) representative of the high tides which occurred in 1928, 1938, 1949 and 1953. Levels are calculated using (a) Generalised Pareto distribution of observed water levels above 1.44 m OD, and (b) a Joint Probability Analysis of astronomical tides plus skew surges larger than 0.41 m. All values are de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period 1964-2013, using 2008 as the base year. All values are statistically significant at the 95% confidence level.

	(a) Generalised Pareto Distribution of observations above threshold		(b) Joint Probability Analysis of tides and skew surges above threshold	
	as observed	including four large tides	as observed	including four large tides
threshold =	**>1.44 m OD**	**>1.44 m OD**	**>0.41 m**	**>0.41 m**
n =	990	1984	1337	2678
% =	2.8	2.8	3.8	3.8
κ =	0.07310	0.09862	0.03925	0.05983
Return σ =	0.18191	0.17916	0.19366	0.19121
Period μ =	1.44000	1.44060	0.40946	0.41003
(years) K-S =	0.9472	0.5801	1.0000	0.9962
1	2.05 ± 0.01	2.07 ± 0.01	2.06 ± 0.01	2.08 ± 0.01
2	2.21 ± 0.01	2.24 ± 0.01	2.22 ± 0.01	2.24 ± 0.01
5	2.44 ± 0.02	2.49 ± 0.02	2.43 ± 0.02	2.46 ± 0.01
10	2.62 ± 0.03	2.69 ± 0.03	2.59 ± 0.02	2.64 ± 0.02
20	2.81 ± 0.04	2.91 ± 0.04	2.76 ± 0.03	2.83 ± 0.03
50	3.08 ± 0.05	3.22 ± 0.06	2.99 ± 0.04	3.09 ± 0.03
100	3.29 ± 0.07	3.47 ± 0.07	3.16 ± 0.05	3.30 ± 0.04
200	3.51 ± 0.09	3.74 ± 0.09	3.35 ± 0.07	3.51 ± 0.05
500	3.83 ± 0.12	4.13 ± 0.12	3.60 ± 0.09	3.81 ± 0.07
1000	4.08 ± 0.15	4.45 ± 0.15	3.80 ± 0.11	4.05 ± 0.08
2000	4.35 ± 0.18	4.79 ± 0.18	4.00 ± 0.13	4.30 ± 0.10
5000	4.73 ± 0.22	5.28 ± 0.24	4.28 ± 0.16	4.64 ± 0.12
10000	5.03 ± 0.27	5.68 ± 0.28	4.49 ± 0.18	4.91 ± 0.14

Table 13. Predictions of future increases in relative mean sea level at Sizewell, based on UKCP09 projections up to 2100 for Cell 21689 (assuming low, medium, high and H^{++} emissions scenarios). All increases are relative to 2008.

Year	Increase in sea level from 2008 **(values in cm)**										
	low emissions scenario			medium emissions scenario			high emissions scenario			H^{++} scenario	
	5%	50%	95%	5%	50%	95%	5%	50%	95%	lower estimate	higher estimate
2015	1.2	2.1	3.0	1.2	2.5	3.6	1.3	2.9	4.4	nd	nd
2030	3.8	7.0	10.1	4.1	8.2	12.3	4.4	9.7	14.9	nd	nd
2060	9.7	18.1	26.6	10.4	21.4	32.4	11.4	25.5	39.5	nd	nd
2100	18.7	36.0	53.3	20.1	42.8	65.4	22.2	51.1	79.8	93	190

Table 14. Return periods of extreme water levels calculated for Sizewell in 2008, and in 2100 based on three future sea level rise scenarios. The underlying distribution is based on a Generalised Pareto Distribution of high tides above 1.44 m OD recorded at Lowestoft during the period 1964-2014, with values de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period over the period 1964-2013, using 2008 as the base year. Projections to 2100 assume that high tide levels increase at the same rate as mean sea levels.

Return Period (years)	2008	2100			
		Medium Emissions 95% estimate	High Emissions 95% estimate	H++ scenario low estimate	H++ scenario high estimate
1	2.20 ± 0.01	2.85 ± 0.01	3.00 ± 0.01	3.13 ± 0.02	4.10 ± 0.02
2	2.36 ± 0.01	3.01 ± 0.01	3.16 ± 0.01	3.29 ± 0.02	4.26 ± 0.02
5	2.59 ± 0.02	3.24 ± 0.03	3.39 ± 0.03	3.52 ± 0.03	4.49 ± 0.04
10	2.77 ± 0.03	3.42 ± 0.04	3.57 ± 0.04	3.70 ± 0.04	4.67 ± 0.05
20	2.96 ± 0.04	3.61 ± 0.05	3.76 ± 0.05	3.89 ± 0.06	4.86 ± 0.07
50	3.23 ± 0.05	3.88 ± 0.06	4.03 ± 0.07	4.16 ± 0.07	5.13 ± 0.08
100	3.44 ± 0.07	4.09 ± 0.09	4.24 ± 0.09	4.37 ± 0.09	5.34 ± 0.11
200	3.66 ± 0.09	4.31 ± 0.11	4.46 ± 0.11	4.59 ± 0.12	5.56 ± 0.14
500	3.98 ± 0.12	4.63 ± 0.15	4.78 ± 0.15	4.91 ± 0.15	5.88 ± 0.18
1000	4.23 ± 0.16	4.88 ± 0.18	5.03 ± 0.18	5.16 ± 0.19	6.13 ± 0.23
2000	4.50 ± 0.19	5.15 ± 0.21	5.30 ± 0.22	5.43 ± 0.22	6.40 ± 0.26
5000	4.88 ± 0.23	5.53 ± 0.26	5.68 ± 0.26	5.81 ± 0.27	6.78 ± 0.32
10000	5.18 ± 0.28	5.83 ± 0.31	5.98 ± 0.32	6.11 ± 0.33	7.08 ± 0.38

Table 15. Return periods of extreme water levels calculated for Sizewell in 2008, and in 2100 based on three future sea level rise scenarios. The underlying distribution is based on a Joint Probability analysis of astronomical tides and a Generalised Pareto Distribution of skew surges above 0.41 m, with values de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period 1964-2013, using 2008 as the base year. Projections to 2100 assume that high tide levels increase at the same rate as mean sea levels.

Return Period (years)	2008	2100			
		Medium Emissions 95% estimate	High Emissions 95% estimate	H++ scenario low estimate	H++ scenario high estimate
1	2.21 ± 0.01	2.86 ± 0.01	3.01 ± 0.01	3.14 ± 0.02	4.11 ± 0.02
2	2.37 ± 0.01	3.02 ± 0.01	3.17 ± 0.01	3.30 ± 0.02	4.27 ± 0.02
5	2.58 ± 0.02	3.23 ± 0.03	3.38 ± 0.03	3.51 ± 0.03	4.48 ± 0.04
10	2.74 ± 0.02	3.39 ± 0.03	3.54 ± 0.03	3.67 ± 0.03	4.64 ± 0.04
20	2.91 ± 0.03	3.56 ± 0.04	3.71 ± 0.04	3.84 ± 0.04	4.81 ± 0.05
50	3.14 ± 0.04	3.79 ± 0.05	3.94 ± 0.05	4.07 ± 0.05	5.04 ± 0.07
100	3.31 ± 0.05	3.96 ± 0.06	4.11 ± 0.07	4.24 ± 0.07	5.21 ± 0.08
200	3.50 ± 0.07	4.15 ± 0.09	4.30 ± 0.09	4.43 ± 0.09	5.40 ± 0.11
500	3.75 ± 0.09	4.40 ± 0.11	4.55 ± 0.11	4.68 ± 0.12	5.65 ± 0.14
1000	3.95 ± 0.11	4.60 ± 0.13	4.75 ± 0.14	4.88 ± 0.14	5.85 ± 0.17
2000	4.15 ± 0.13	4.80 ± 0.16	4.95 ± 0.16	5.08 ± 0.17	6.05 ± 0.20
5000	4.43 ± 0.17	5.08 ± 0.19	5.23 ± 0.20	5.36 ± 0.20	6.33 ± 0.24
10000	4.64 ± 0.19	5.29 ± 0.21	5.44 ± 0.22	5.57 ± 0.22	6.54 ± 0.26

Table 16. Estimations of the highest plausible still water levels at Sizewell in 2100, relative to the base year 2008, for a range of UKCP09 and H^{++} sea level rise scenarios. The highest astronomical tide is taken from Table 3, assuming high tides are 0.15 m higher than Lowestoft at Sizewell. The highest plausible skew surge is taken from Table 11, using the extended tide record to 1916-2012 with four additional large surge events in 1928, 1938, 1949 and 1953. The sea level rise assumptions are taken from Table 14, based on UKCP09 projections.

Scenario	Highest astronomical tide (m OD)	Highest skew surge (m)	Sea level rise (m)	Total (m OD)
2008	1.63	4.10	0.00	5.73
2100 (low emissions scenario, 5%)	1.63	4.10	0.19	5.92
2100 (low emissions scenario, 50%)	1.63	4.10	0.36	6.09
2100 (low emissions scenario, 95%)	1.63	4.10	0.53	6.26
2100 (medium emissions scenario, 5%)	1.63	4.10	0.20	5.93
2100 (medium emissions scenario, 50%)	1.63	4.10	0.43	6.16
2100 (medium emissions scenario, 95%)	1.63	4.10	0.65	6.38
2100 (high emissions scenario, 5%)	1.63	4.10	0.22	5.95
2100 (high emissions scenario, 50%)	1.63	4.10	0.51	6.24
2100 (high emissions scenario, 95%)	1.63	4.10	0.80	6.53
2100 (H^{++} scenario, lower estimate)	1.63	4.10	0.93	6.66
2100 (H^{++} scenario, higher estimate)	1.63	4.10	1.90	7.63

Revised Figures

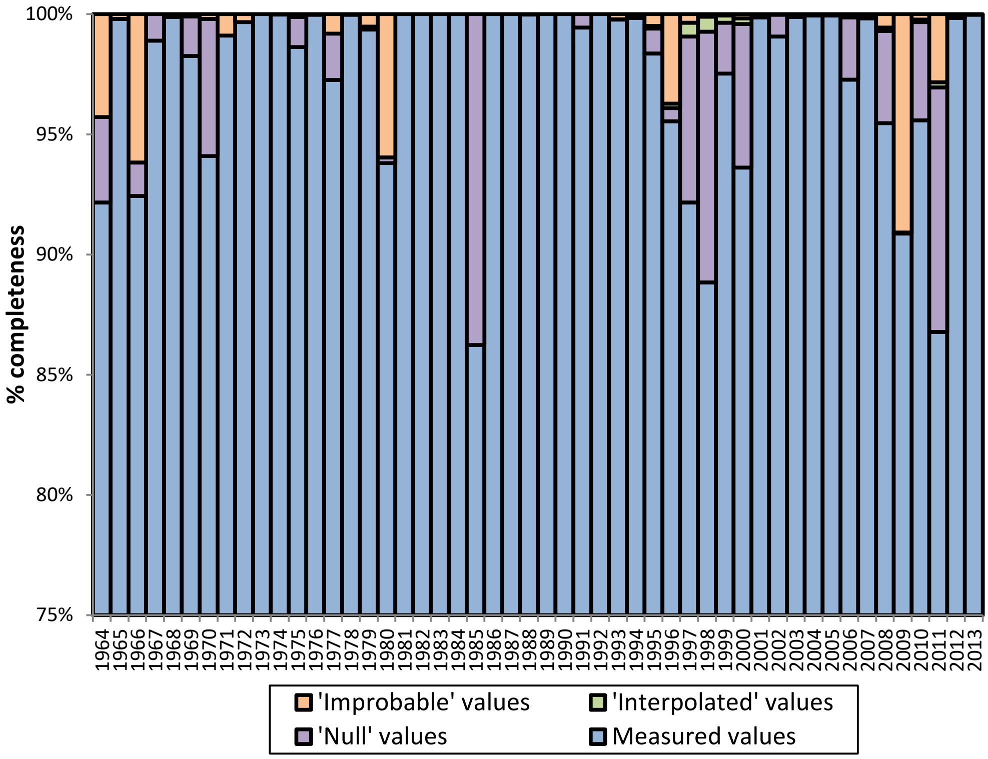


Figure 1. Data 'completeness' for the Lowestoft Class A tide gauge record 1964-2013 (annual percentages of data points recorded at 60 minute intervals between 1964 and 1992 and at 15 minute intervals from 1993 onwards). Only accepted measured values and interpolated values have been included in the statistical analysis performed in this study.

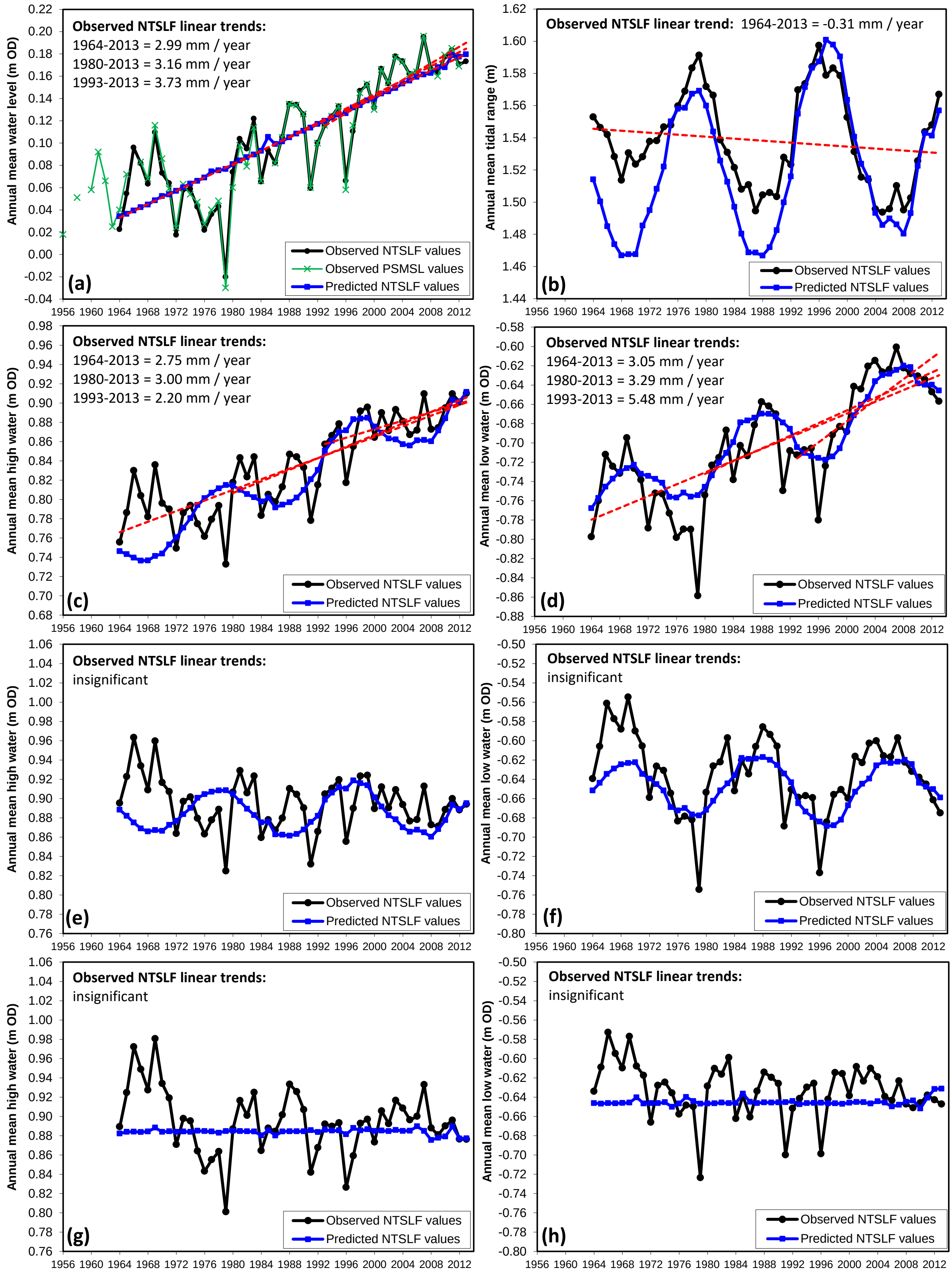


Figure 2. Trends in observed and predicted annual water levels at Lowestoft: (a) annual mean sea level; (b) annual mean tidal range; (c) annual mean high water; (d) annual mean low water; (e) annual mean high water de-trended for sea level rise; (f) annual mean low water de-trended for sea level rise; (g) annual mean high water de-trended for sea level rise and lunar nodal tidal cycle; (h) annual mean low water de-trended for sea level rise and lunar nodal tidal cycle. Original data sources: PSMSL (1956-2012) and NTSLF (1964-2013). Dotted red lines show the linear trend for 1964-2013, 1980-2013 and 1993-2013, where the trend is significant.

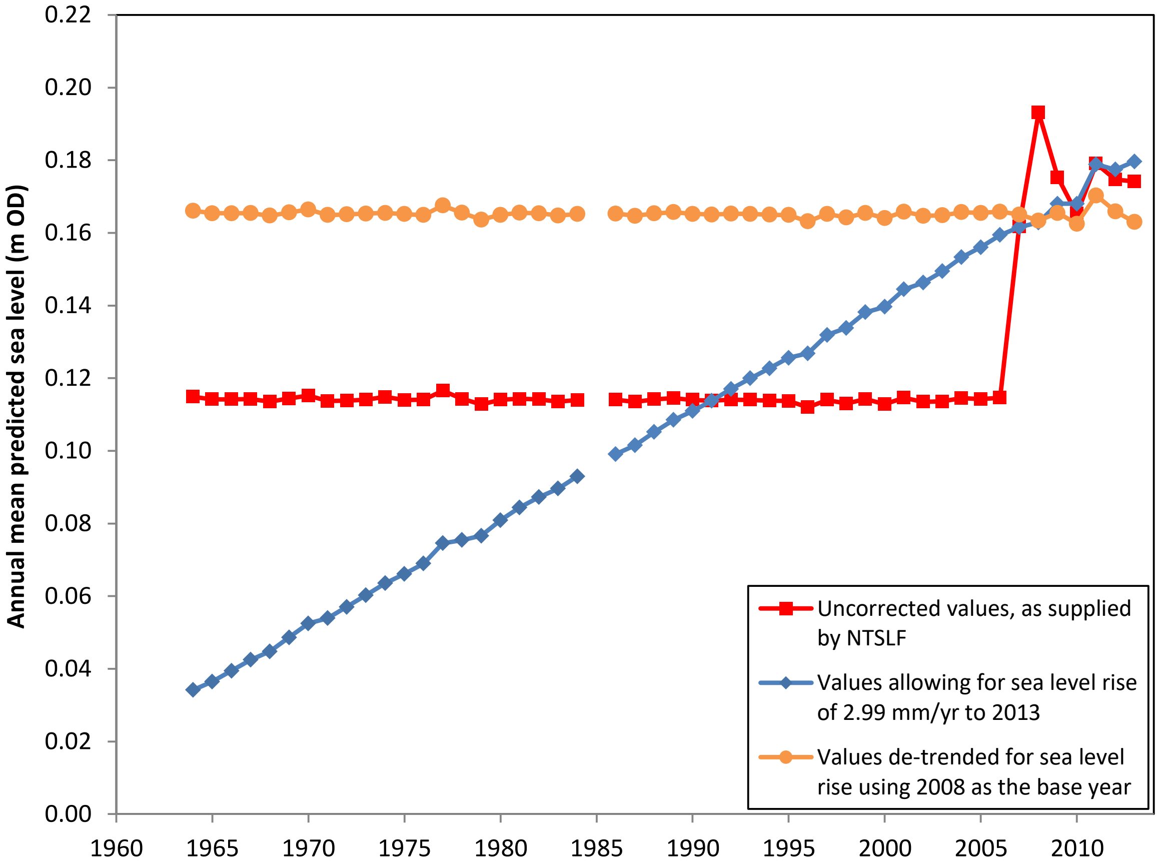


Figure 3. Annual mean predicted sea level at Lowestoft (1964-2013), showing corrections made in this study. Red line: values calculated using data observed and residual values supplied by NTSLF; Blue line: values corrected to allow for sea level rise of 2.99 mm/yr for the period 1964-2013, and used to re-calculate observed skew surges; Orange line: values de-trended for sea level rise, using a base year of 2008.

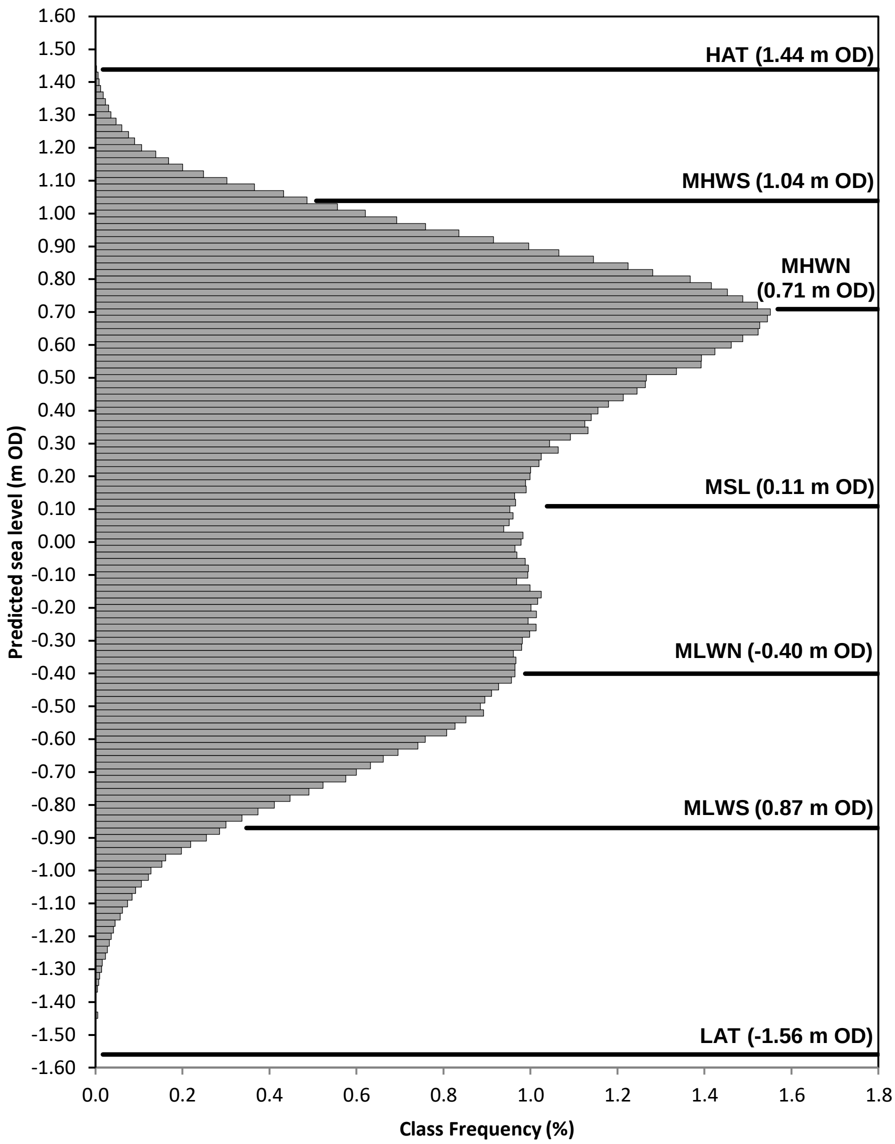


Figure 4. Frequency distribution of predicted water levels at Lowestoft (based on NTSLF predictions for January 1964 to May 2014, 250806 hourly and 730263 fifteen minute observations). All values have been de-trended for sea level rise assuming a rate of 2.99 mm/yr over the period, and expressed to a common datum in 2008. Original data source: NTSLF.

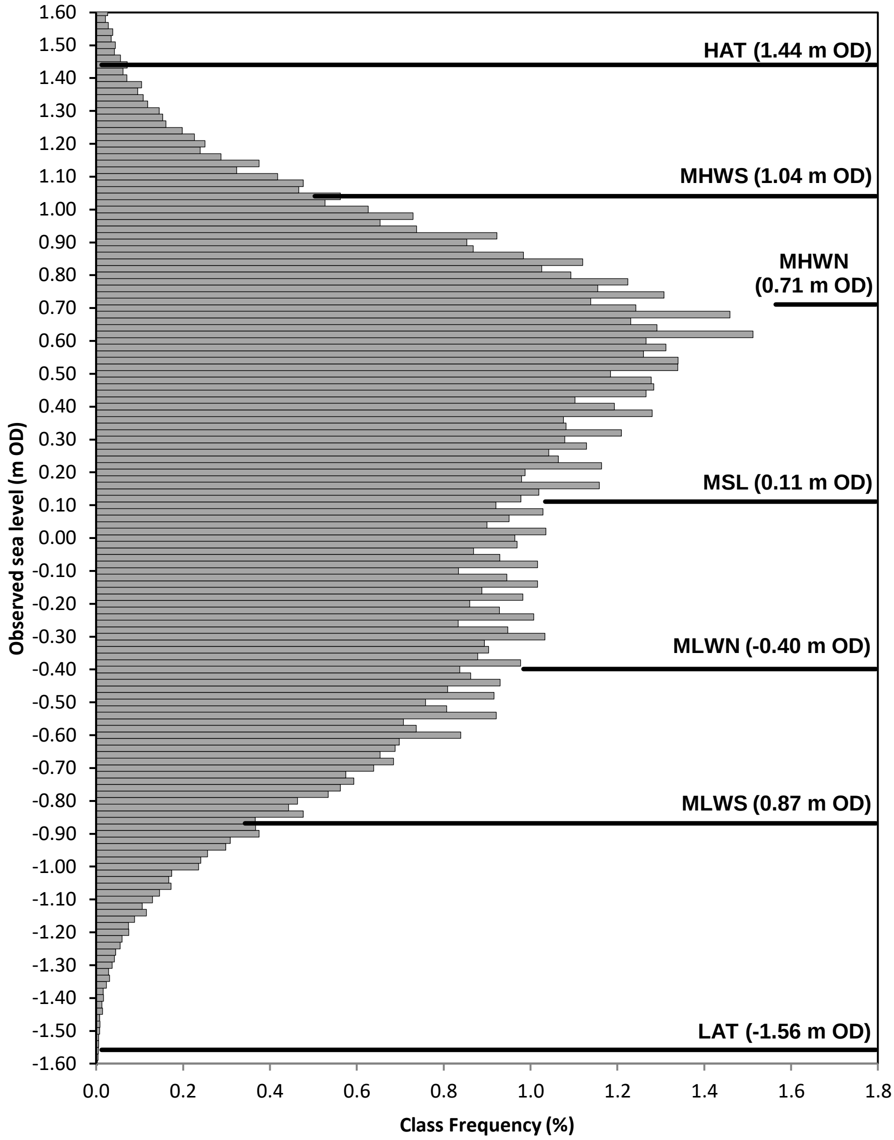
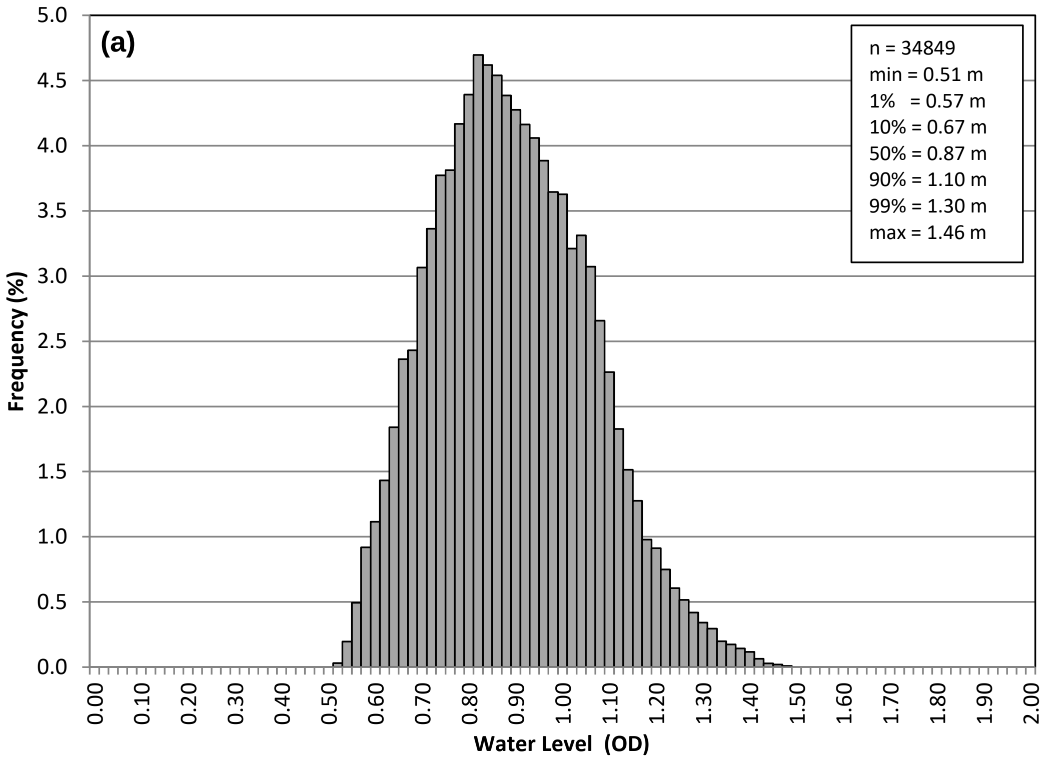


Figure 5. Frequency distribution of observed water levels at Lowestoft, recorded between January 1964 and May 2014 (250806 hourly and 730263 fifteen minute observations). All values have been de-trended for a mean sea level rise of 2.99 mm/yr over the period, and expressed to a common datum in 2008. Original data source: NTSLF.



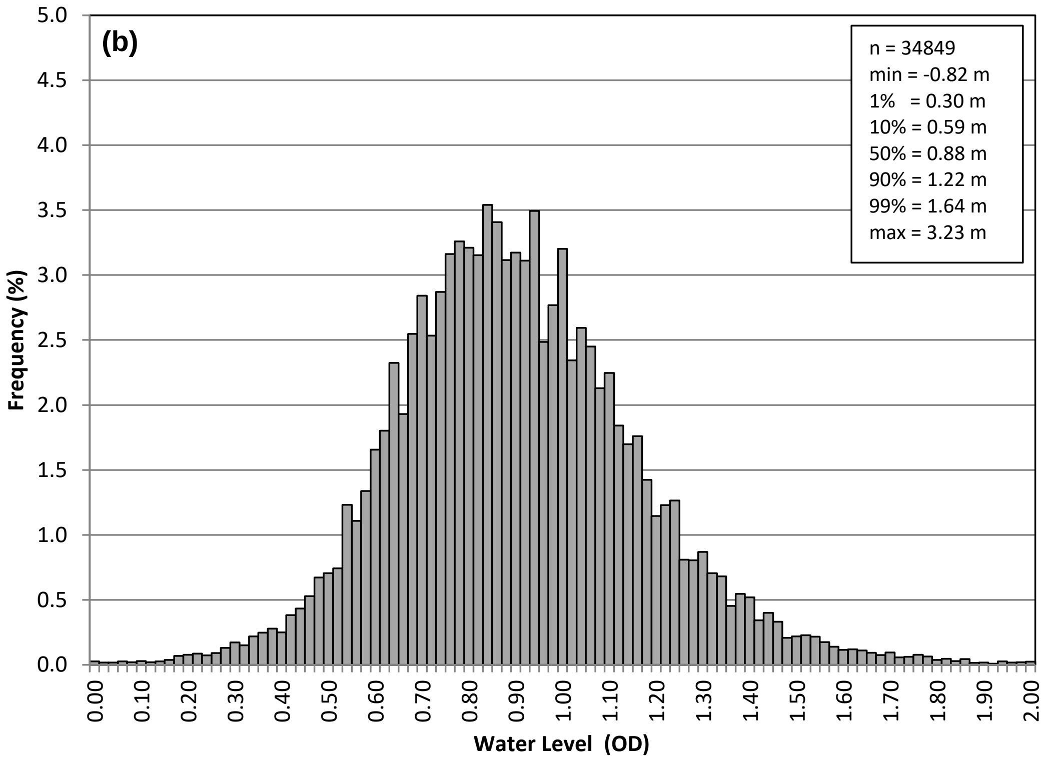


Figure 6. Frequency distributions of (a) predicted and (b) observed high water levels at Lowestoft between January 1964 and May 2014 (250799 hourly and 730263 fifteen minute observations). Values have been de-trended for a sea level rise of 3.17 mm/yr (observed values) and 3.23 mm/yr (predicted values), these being the average annual rate of increase derived from the linear trend in mean high waters for two lunar nodal tidal cycles (thirteen 37 year periods between 1964 and 2013). Original data source: NTSLF.

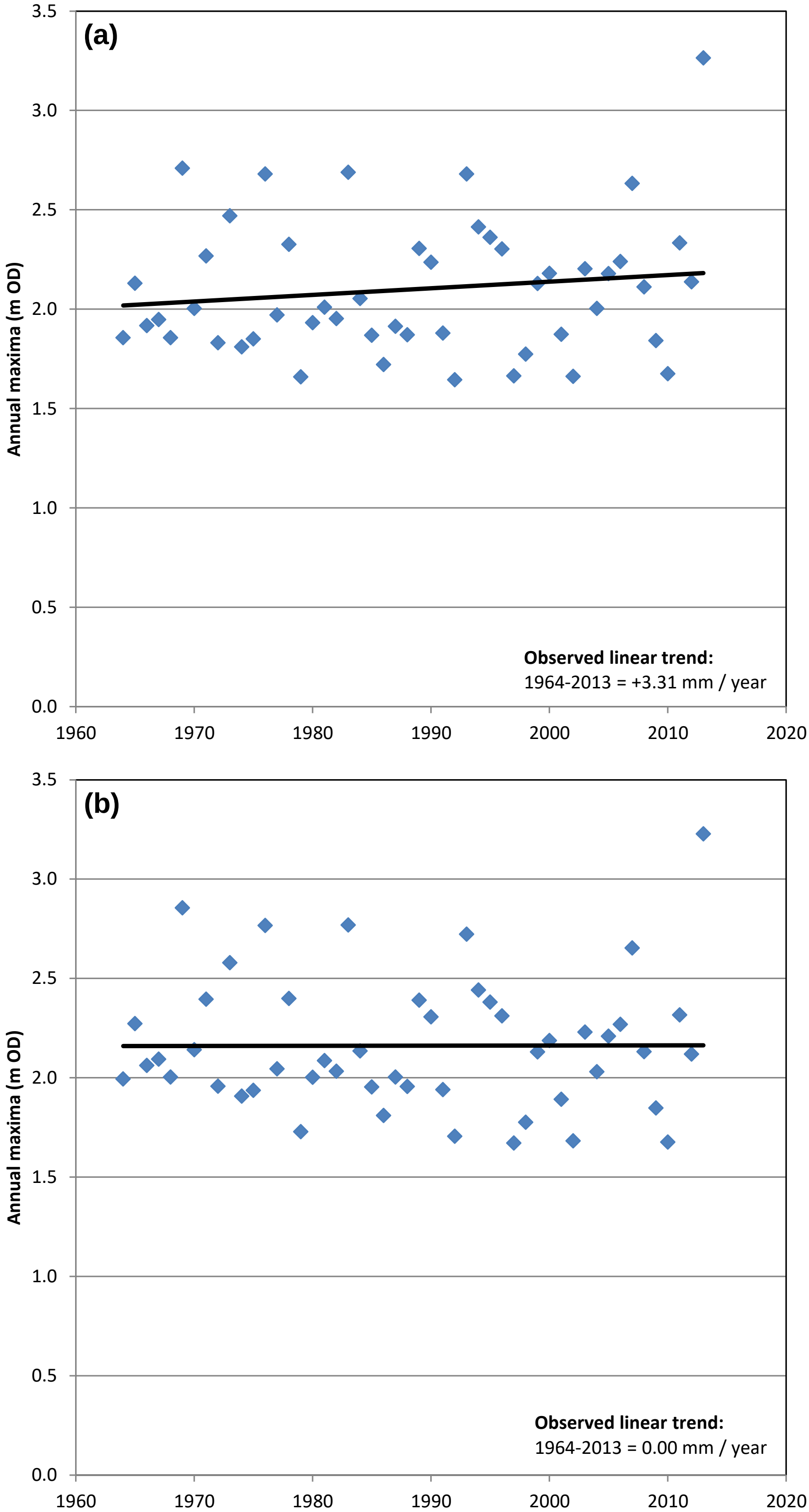


Figure 7. Annual maximum water levels recorded at Lowestoft during the period 1964-2013: (a) values as recorded; (b) values de-trended for sea level rise assuming a rate of 3.17 mm/yr in high waters over the period, and using 2008 as the base year.

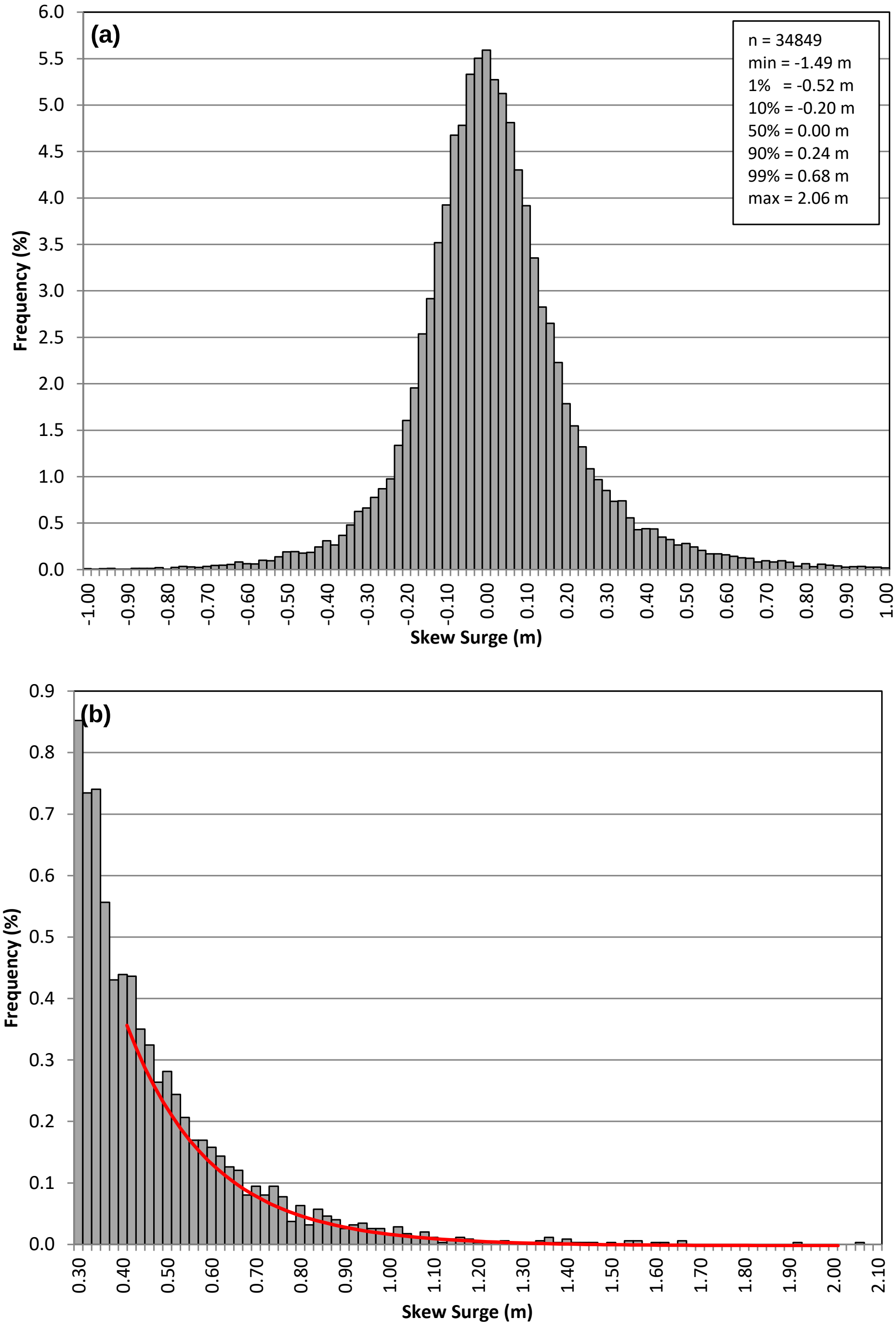


Figure 8. (a) Frequency distribution of skew surges recorded at Lowestoft between January 1964 and May 2014 (all values have been de-trended for annual mean sea level rise of 2.99 mm/year; (b) frequency distribution of the skew surges larger than 0.41 m with a fitted Generalised Pareto Distribution (1337 tides, 3.8% of the distribution) with a Kolmogorov-Smirnov goodness of fit probability value of 1.0000, a significant fit.

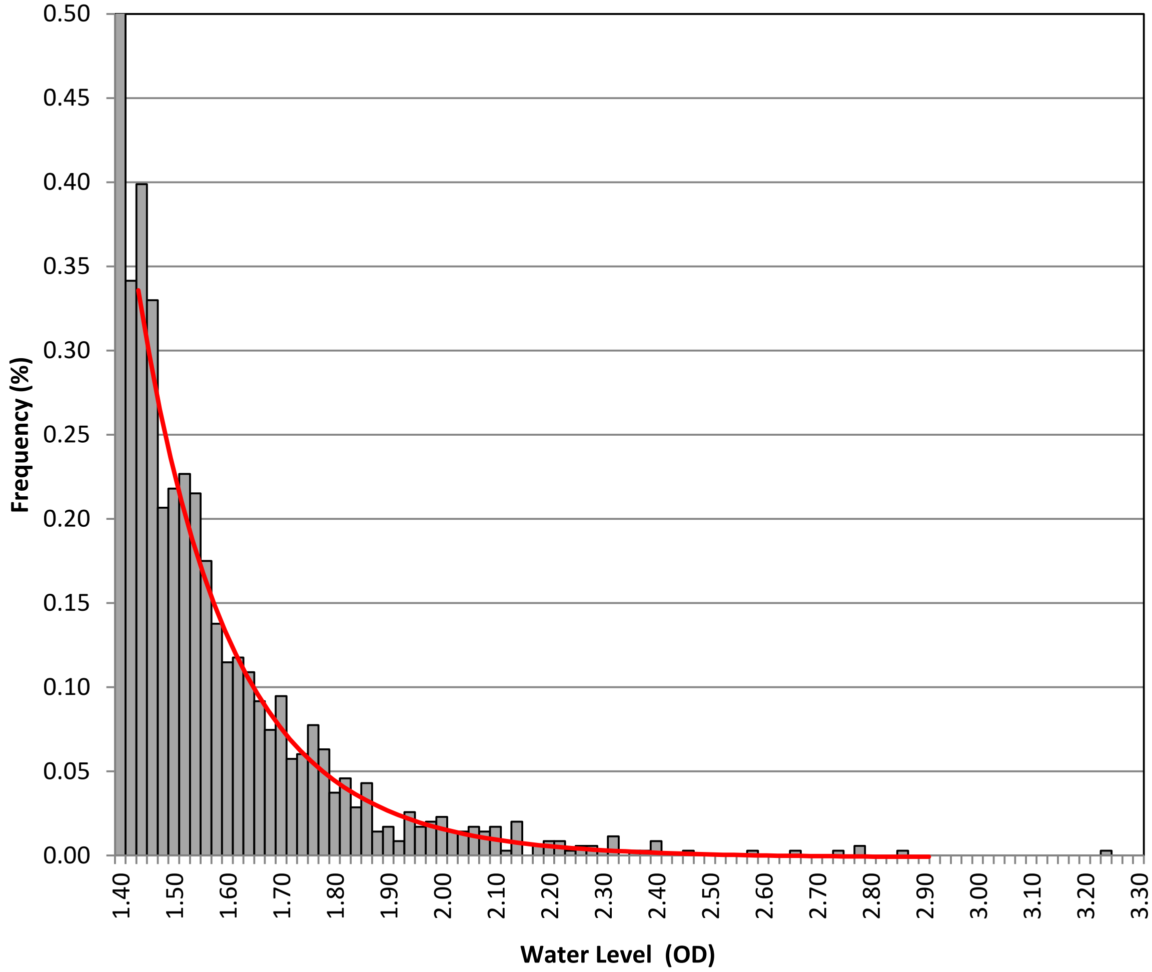


Figure 9. Frequency distribution of observed high water levels above 1.44 m OD at Lowestoft between January 1964 and May 2014. All values have been de-trended for sea level rise assuming a rate of 3.17 mm/year in high waters over the period 1964-2013, and using 2008 as the base year. A Generalised Pareto Distribution has been fitted to values above 1.44 m OD (990 tides, representing 2.8% of the distribution) with a Kolmogorov-Smirnov goodness of fit probability value of 0.9472, significant at the 95% level.

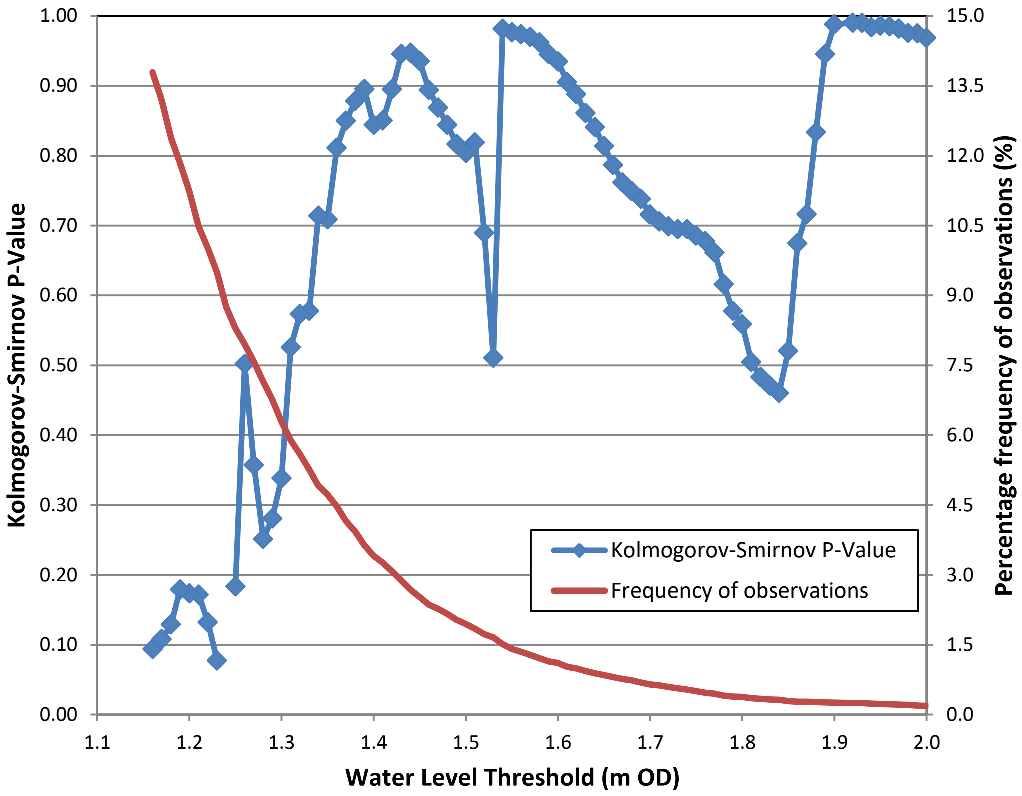


Figure 10. The goodness of fit (blue line), indicated by the Kolmogorov-Smirnov probability value, P, of Generalised Pareto Distributions fitted to observed high tide levels at Lowestoft between January 1964 and May 2014 above varying water level thresholds between 1.16 m OD (13.8% of the distribution) and 2.00 m OD (0.2% of the distribution). All values (except 1.24 m OD, omitted from the graph) are above 0.05 and are therefore statistically significant at the 95% confidence level. Also shown is the frequency of observations (red line) above each threshold value, as a percentage of all observations (34849 in total).

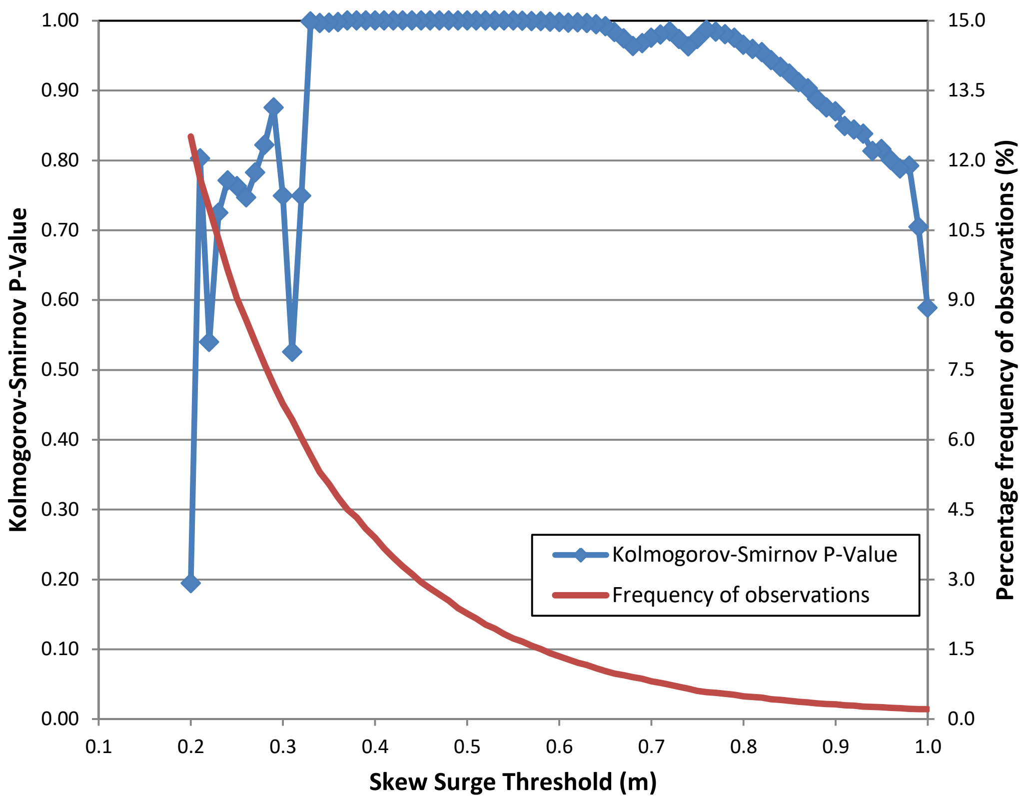


Figure 11. The goodness of fit (blue line), indicated by the Kolmogorov-Smirnov P-value, of Generalised Pareto Distributions fitted to observed skew surges at Lowestoft between January 1964 and May 2014 above varying thresholds between 0.2 m (12.5% of the distribution) and 1.00 m (0.2% of the distribution). All values are above 0.05 and are therefore statistically significant at the 95% confidence level. Also shown is the frequency of observations (red line) above each threshold value, as a percentage of all observations (34849 in total).

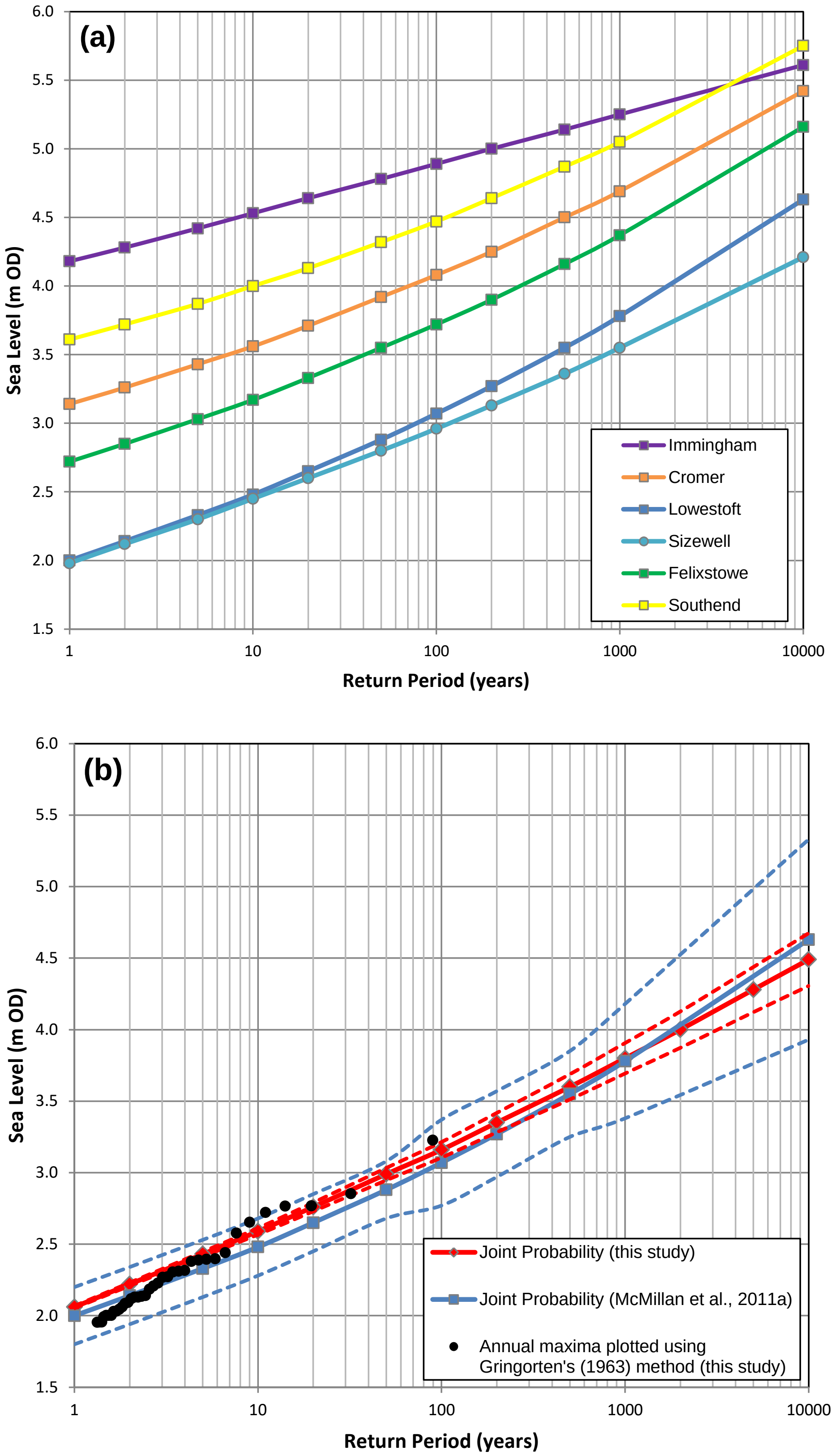


Figure 12. Return periods of extreme water levels, calculated using Joint Probability Analysis: (a) values for various sites quoted by McMillan *et al.* (2011a), confidence limits omitted for clarity; (b) values for Lowestoft calculated by McMillan *et al.* (2011a) and this study (1964-2014 data), with confidence limits shown as dashed lines.

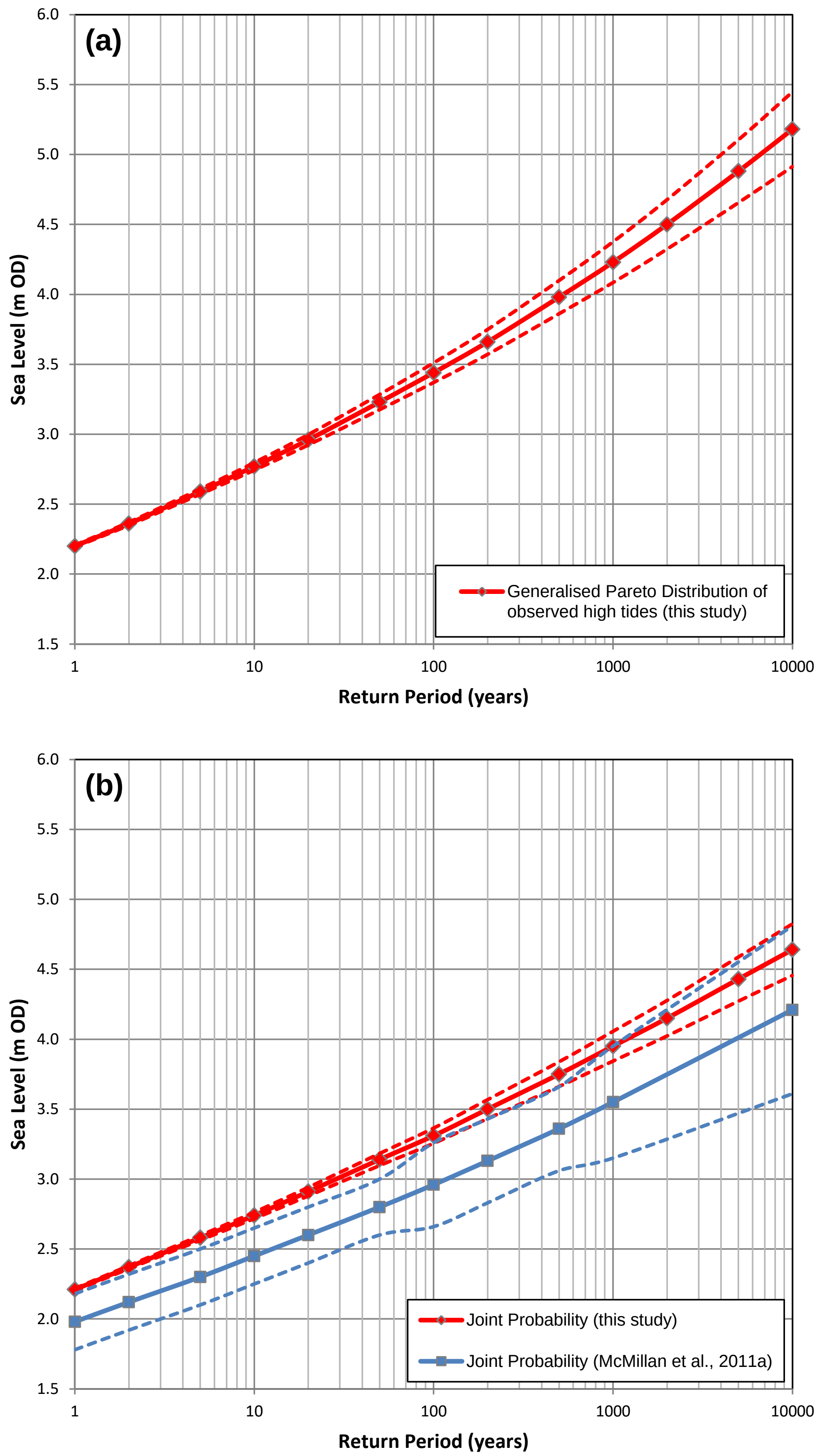


Figure 13. Return periods of extreme water levels at Sizewell, calculated using (a) Generalised Pareto Distribution of observed high tides above 1.44 m OD (2008 base year); (b) Joint Probability Analysis of skew surges and predicted tides by McMillan *et. al* (2011a) and this study. Confidence limits are shown as dashed lines. High waters at Sizewell are assumed to be 15 cm higher than at Lowestoft.

Estimation of Extreme Sea Levels at Sizewell: Addendum Report

Appendix A
Clarification following SZC FRA Technical Sub-Group Meeting on 13 Nov 2014

Kenneth Pye & Simon J. Blott

External Investigation Report No. EX1747

16 July 2015

Kenneth Pye Associates Ltd.
Scientific research, consultancy and investigations

Estimation of Extreme Sea Levels at Sizewell: Addendum Report

Appendix A
Clarification following SZC FRA Technical Sub-Group Meeting on 13 Nov 2014

Kenneth Pye & Simon J. Blott

External Investigation Report No. EX1747

This report was prepared by Professor Kenneth Pye ScD PhD MA CGeol FGS
and Simon James Blott PhD MRes BSc FGS

Report history

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Version 2.0	Revised	16 July 2015

Kenneth Pye Associates Ltd
Research, Consultancy and Investigations
Blythe Valley Innovation Centre
Central Boulevard
Blythe Valley Park
Solihull
B90 8AJ
United Kingdom
Telephone + 44 (0)121 506 9067
E-mail: info@kpal.co.uk
website: www.kpal.co.uk

CONTENTS

1.0 INTRODUCTION

Following a meeting of the Sizewell ‘C’ Flood Risk Assessment (SZC FRA) Technical Sub-Group on 13th November 2014, clarification has been requested regarding:

(1) the reasons for the difference in confidence estimates for a 10^4 year event quoted in TR252 and those calculated by McMillan *et al*. (2011a,b and associated shape files);

(2) how the additional simulated four extreme water level events were incorporated into the analysis presented in reports TR252 and TR322.

Additional clarification was also subsequently requested regarding Summary Table EX2 in the Executive Summary to TR322.

2.0 CLARIFICATION RELATING TO CONFIDENCE ESTIMATES

As explained in Section 2.5 of TR252, the procedure used by KPAL first involved fitting an extreme value distribution curve (e.g. Generalised Pareto Distribution, GPD) to a sub-set of the measured skew surge or high water data above a defined threshold value (only data for Lowestoft were used). To calculate the uncertainty associated with any single value on the fitted extreme value curve, the calculated curve parameters (κ, σ and μ etc.) were used to generate 30 additional random distributions. The number 30 was chosen because numerical experimentation using more than 30 sets was found to produce very little change (1 or 2 cm only) in the calculated 95% confidence levels. For each of the distributions the return periods for extreme skew surges and high waters were re-calculated, and the 95% confidence limits were then calculated as $\bar{x} \pm 1.96\sigma/\sqrt{n}$. As an example, Table A1 below shows the confidence limits determined for the GPD of skew surges and high waters based on recorded tide gauge data for Lowestoft 1964-2014.

The term ‘confidence interval’ was not used in TR252 but in TR322 was used to refer to the range between the confidence limits ($\bar{x} - 1.96\sigma/\sqrt{n}$ and $\bar{x} + 1.96\sigma/\sqrt{n}$). The term ‘confidence bound’ was not used either in TR252 or TR322, but confidence bounds are generally considered to define the upper and lower limits of the confidence interval, i.e. are equivalent to confidence limits.

McMillan *et al.* (2011b, Appendix 6) describe a similar approach to calculate what they term ‘95% confidence bounds’ for sites where the Skew Surge Joint Probability Method (SSJPM) was applied by them (this did not include Lowestoft). Unfortunately, there is confusion with the terminology used, as they use the term ‘confidence bound’ in the sense that KPAL (and most statistical textbooks, e.g. Miller & Miller, 2005) use the term’ confidence interval’. Table A6.4.1 in Appendix 6 of McMillan *et al.* (2011b) actually shows confidence interval values rather than confidence bounds (or confidence limits). The text of Appendix 6 also refers to dividing the "confidence bounds" by half to derive "confidence intervals", whereas the actual process was to divide the confidence interval to obtain the confidence limits. Table A6.2 in McMillan *et al's* Appendix 6 is headed "Modified Confidence Intervals for Raw SSJPM Sites", but in fact it shows confidence limits (although without +/- indicated).

Table A1. 95% confidence limits (metres) for skew surges larger than 0.41 m and observed high tides above 1.44 m OD for the period 1964-2014 calculated using the Generalised Pareto Distribution.

	Skew surges above 0.41 m	High waters above 1.44 m OD
1	±0.01	±0.01
2	±0.01	±0.01
5	±0.02	±0.02
10	±0.02	±0.03
20	±0.03	±0.04
50	±0.04	±0.05
100	±0.05	±0.07
200	±0.07	±0.09
500	±0.09	±0.12
1000	±0.11	±0.15
2000	±0.13	±0.18
5000	±0.16	±0.22
10000	±0.18	±0.27

McMillan *et al*. do not state how many random samples were used to determine the 95% confidence limits. Their analysis method was only possible at 31 sites where they considered that sufficient data existed to calculate SSJPM values (termed their 'SSJPM sites'). Lowestoft was not one of these sites because their analysis was found to produce an implausibly steep Generalised Pareto Distribution curve (a result not found in the independent analysis conducted by KPAL). Table A2 below shows the confidence intervals and limits for the two closest stations, Immingham and Dover, modified from McMillan *et al*. 2011 Appendix 6).

The confidence limits for Immingham and Dover shown in Table A2 for the 10^4 year event differ considerably, and both values are significantly higher than the 95% JPA confidence limits (+/- 0.19) calculated by KPAL using the Lowestoft record.

It should be noted that these statistical estimates of confidence limits do not include the full degree of uncertainty relating to the extrapolated values obtained, which would also reflect many other factors, including the accuracy of tidal predictions and measured tide data, the adequacy of the length of data record, and the appropriateness of the type of distribution fitted. McMillan *et al*. (2011a.b.) appear to recognise this and the need to be conservative in the values quoted. Minimum values were set at ± 0.1 m for a 1 year return period event, ± 0.2 m for a 10 year return period event, and ± 0.3 m for a 1000 year return period event. McMillan *et al.* (2011a.b.) do not explain how these 'minimum' figures were determined, or what minimum values were assumed for intermediate return periods, but these were used to create 'modified confidence intervals', rounding up the original values (such as those listed in

Table A2). This approach is described as ‘empirical’, using the original confidence intervals only as a ‘starting point’, the need to be ‘precautionary’, and ‘mindful of the geography’. The ‘modified confidence intervals’ therefore reflect a degree of human manipulation.

Table A2. 95% confidence intervals (referred to as “confidence bounds” by McMillan *et al*.2011a,b) and confidence limits (referred to as “original confidence intervals” by McMillan *et al*. 2011a,b), in metres, calculated for Immingham and Dover using data up to 2009 by McMillan *et al*. (N.B. they did not calculate values for the 2000 year and 5000 year events)

	Immingham		Dover	
	Confidence interval	Confidence limit	Confidence interval	Confidence limit
1	0.03	±0.02	0.04	±0.02
2	0.04	±0.02	0.05	±0.03
5	0.06	±0.03	0.07	±0.04
10	0.08	±0.04	0.09	±0.05
20	0.12	±0.06	0.11	±0.06
50	0.18	±0.09	0.15	±0.08
100	0.25	±0.13	0.20	±0.10
200	0.32	±0.18	0.24	±0.12
500	0.45	±0.23	0.32	±0.16
1000	0.55	±0.28	0.38	±0.19
2000	nd	nd	nd	nd
5000	nd	nd	nd	nd
10000	0.99	±0.50	0.63	±0.32

Since McMillan *et al.* (2011a,b) were only able to calculate ‘modified confidence intervals’ at their 31 SSJPM sites, values had to be estimated for all other locations (including Lowestoft) based on the estimates at neighbouring sites. Uncertainty in these assumptions increases with distance from the neighbouring sites, and therefore an additional ‘confidence interval add-on’ was applied for locations more than 50 km from a SSJPM site: an additional 0.1 m where the modified confidence interval is between 0.1 and 0.3 m; an additional 0.2 m where the modified confidence interval is between 0.4 and 0.6 m; an additional 0.3 m where the modified confidence interval is between 0.7 and 0.9 m; and an additional 0.4 m where the modified confidence interval is between 1.0 and 1.2 m. The final ‘confidence interval’ quoted by McMillan *et al.* (2011a,b) therefore bears little resemblance to the original calculation of mathematical uncertainty in curve-fitting, and relies to a great degree on the empirical assumptions applied with the ‘modified’ and ‘add-on’ values. No details are provided in their report regarding how these values have been determined. For illustration, the final confidence values for Immingham, Lowestoft and Dover are shown below in Table A3.

Table A3. 95% “confidence intervals”, in metres, calculated by McMillan *et al.* (2011a,b) using their SSJPM method for the same return periods quoted in TR322 (2000 year and 5000 year events were not calculated in the McMillan 2011a,b study). NB terms shown are as used by McMillan *et al*; all are confidence limits according to the terminology used by KPAL

	Immingham		Lowestoft	Dover	
	“Original confidence Interval”	“Modified confidence Interval”	Interpolated “Modified confidence Interval” including “add-on”	“Original confidence Interval”	“Modified confidence Interval”
1	±0.02	±0.1	±0.2	±0.02	±0.1
2	±0.02	±0.1	±0.2	±0.03	±0.1
5	±0.03	±0.1	±0.2	±0.04	±0.1
10	±0.04	±0.1	±0.2	±0.05	±0.1
20	±0.06	±0.1	±0.2	±0.06	±0.1
50	±0.09	±0.1	±0.2	±0.08	±0.1
100	±0.13	±0.2	±0.3	±0.10	±0.2
200	±0.18	±0.2	±0.3	±0.12	±0.2
500	±0.23	±0.3	±0.3	±0.16	±0.2
1000	±0.28	±0.3	±0.4	±0.19	±0.3
2000	nd	nd	nd	nd	nd
5000	nd	nd	nd	nd	nd
10000	±0.50	±0.5	±0.7	±0.32	±0.4

Considerable uncertainty surrounds the McMillan *et al.* (2011a,b) estimates for Lowestoft. Lowestoft is 274 chainage kilometres from Immingham and 250 chainage kilometres from Dover, well beyond the 50 km ‘buffer’ outside of which the ‘add-on’ confidence intervals apply. Further, it is unfortunate that further investigation was not made into why the Lowestoft record yielded poor GPD estimates of return periods. The gauge has a very high degree of completeness, compared with other gauges in the UK, and a long digital record (> 50 years). The omission of the Lowestoft record means that the secondary sites of Cromer and Felixstowe were used to interpolate the growth curve for this coastline. An analysis of the Cromer record by KPAL found significant errors (up to 20 cm) in the datum used at this gauge, and PSMSL has now flagged the entire record at Cromer as ‘suspect’. Similarly, the Felixstowe tide gauge was sited on the pier, which has since been condemned and access to the gauge has not been possible for health and safety reasons. It was not possible to check the accuracy of the gauge after 1999, and the gauge was abandoned completely in 2011.

In summary, the KPAL confidence estimates for both Lowestoft and Sizewell are based on analysis of the recorded water level data at Lowestoft, whereas the McMillan *et al*. estimates for this area are based on analysis of data for tide gauges which are relatively distant to Lowestoft and Sizewell, together with the addition of a number of empirical adjustment factors. The general point needs to be emphasised that statistical assessments resulting from mathematical curve fitting do not provide a true indication of the full uncertainty involved in estimating extreme water levels, and it is good practice to adopt a conservative approach.

3.0 SIMULATED EVENTS

The Lowestoft tide gauge record analysed in TR252 spanned the period 1964-2012. The highest water level recorded during this period occurred on 29th September 1969, when a level of 2.71 m OD was recorded. The period covered by TR322 (1964-2014) included the event on 5th December 2013, when a level of 3.26 m OD was recorded. However, it was conceded that even the 1964-2013 period was a relatively non-stormy period, and the data record did not include the large storm surge in 1953 (estimated from waterline and other evidence to be approximately 3.44 m OD in the Lowestoft area), or several other events, for example in 1928, 1938 and 1949. No tide gauge records for these events exist on this part of the coast, although there is some anecdotal information, such as descriptions as to the distance inland and height reached by waves and flood waters. Since the GPD and JPA methods employed require a statistical extrapolation of the data record, the resulting levels for different return period are highly dependent upon the number of extreme events in the data record.

In TR252 and TR322 modelling exercises were undertaken to evaluate the effects of incorporating additional high magnitude events into the data record. For the purposes of this demonstration exercise, it was assumed that the distribution of high water levels in the period 1914-1963 was identical to that recorded in the period 1964-2014, except that four additional high magnitude events were added to the 1914-1963 data record. The long-term record for Sheerness (Table 2 in TR252) recorded relatively high magnitude surge events in 1928, 1938, 1949 and 1953, and for the purposes of the modelling exercise undertaken high water levels of 2.00, 2.25, 2.10 and 2.44 m OD were assigned to these events at Lowestoft. The record for 1964-2014 originally contained 34849 high tides; the 1914-2014 record ultimately contained 696702 tides (34849 x 2 + 4). The combined 1914-2014 data record was then de-trended for sea level rise (assuming a constant average rate of 3.17 mm/yr over the period), and the GPD and JPA analyses were repeated. For the GPD method, for example, the original extrapolation for the period 1964-2014 used 990 tides above 1.44 m OD to determine the GPD fit, while the simulated 1914-2014 period used 1984 tides (990 x 2 + 4). Confidence limits for the 1914-2014 period were again determined using the calculated curve parameters to generate 30 random distributions of extreme tidal levels, with the same number of data points as the original measured distribution, and to calculate the 95% confidence limits.

4.0 SUMMARY OF 1:10,000 YEAR STILL WATER LEVEL ESTIMATES AT SIZEWELL

4.1 Revised summary table

The following section provides additional clarification regarding the 1 in 10,000 water levels and confidence limits summarised in Table EX2 of TR322. This table erroneously included a value (4.84 +/- 0.57 m) for the 1:100,000 year water level reported by HR Wallingford (2010), rather than the 1:10,000 year event (4.34 +/- 0.41). A revised and expanded version of the summary table is shown below. Each row of values in the Table is accompanied with a note describing how the values have been calculated (see section 4.2).

Table A4. Estimates of the 1:10,000 year still water level at Sizewell (m OD), obtained using different methods, for a range of climate change and sea level scenarios. Levels determined by KPAL are based on Lowestoft tide gauge records for the period 1964-2014, and high water levels at Sizewell are assumed to be 15 cm higher than at Lowestoft based on comparison of measured high waters at the two locations reported in TR252.

Statistical method		Base Year	2100				Notes
		(2008 or 2010)	Medium Emissions 95% estimate (0.65 m SL rise)	High Emissions 95% estimate (0.80 m SL rise)	H++ scenario low estimate (0.93 m SL rise)	H++ scenario high estimate (1.90 m SL rise)	
Previous studies							
McMillan *et al* (2011a) (Base year = 2008)	Calculated value ± "modified confidence interval":	**4.21** ± 0.6	nd	nd	nd	nd	1
HR Wallingford (2010) (Base year = 2010)	Calculated value ± "70% confidence limits":	**4.34** ± 0.41	**5.24** ± 0.41 (assuming sea level rise of 0.90 m)				2
This study (base year = 2008)							
JPA	Calculated value:	**4.64**	**5.29**	**5.44**	**5.57**	**6.54**	3
	Mean ± 95% confidence limits:	4.74 ± 0.19	5.39 ± 0.21	5.54 ± 0.22	5.67 ± 0.22	6.64 ± 0.26	4
JPA (simulation including 4 events)	Calculated value:	**5.06**	**5.71**	**5.86**	**5.99**	**6.96**	5
	Mean ± 95% confidence limits:	5.01 ± 0.14	5.66 ± 0.136	5.81 ± 0.17	5.94 ± 0.17	6.91 ± 0.20	6
GPD	Calculated value:	**5.18**	**5.83**	**5.98**	**6.11**	**7.08**	7
	Mean ± 95% confidence limits:	5.31 ± 0.28	5.96 ± 0.31	6.11 ± 0.32	6.24 ± 0.33	7.21 ± 0.38	8
GPD (simulation including 4 events)	Calculated value:	**5.83**	**6.48**	**6.63**	**6.76**	**7.73**	9
	Mean ± 95% confidence limits:	5.93 ± 0.29	6.58 ± 0.32	6.73 ± 0.33	6.86 ± 0.33	7.83 ± 0.38	10
Additive approach	Calculated value:	**5.73**	**6.38**	**6.53**	**6.66**	**7.63**	11

4.2 Explanatory notes

All of the principal extreme water level values in Table A4 (values in bold type) are calculated on the basis of the mathematical extrapolation of the frequency distribution of observed water levels or surges by reference to an extreme value curve. A single number is calculated based on the probability of the 1:10,000 year event. The confidence in the single value is represented by the ± value, but it should be noted that these confidence limits have been calculated in varying ways in the different studies referred to, as explained below.

Note 1: Values calculated by McMillan et al. (2011a)

The estimates for Sizewell made by McMillan *et al*. (2011a) were obtained by fitting a Generalized Pareto Distribution (GPD) to the highest 2.5% of skew surge records at the nearest available tide gauges (excluding Lowestoft) and performing a joint probability analysis of astronomical tides and skew surge (termed the "Skew Surge Joint Probability Method", SSJPM). Data for Sizewell are effectively interpolated from values at the adjoining stations of Cromer and Felixstowe. The method by which the 'modified confidence interval" is calculated is described above in Section 2 above. McMillan *et al.* (2011a) did not provide estimates of extreme water levels in 2100.

Note 2: Values calculated by HR Wallingford (2010)

The estimates of extreme still water levels reported by HR Wallingford (2010) were based on tide gauge data at Lowestoft for the period 1990 to 2009. They calculated a 1 in 1 year high water level of 2.29 m OD for Lowestoft based on the monthly maximum levels recorded during this period, de-trended for sea level rise to a base year of 2010, using a calculated average rate of rise in mean monthly water levels of 4.5 mm/ yr. They then increased the Lowestoft high water levels by a notional 10% to convert the values to levels at Sizewell. They used the calculated 1 in 1 year level, and interpolated extreme value growth curve values at Sizewell, based on values for Lowestoft and Aldeburgh previously published by Dixon and Tawn (1997), to estimate extreme levels at Sizewell for return periods of up to 1 in 100,000 years. HR Wallingford state that they used Dixon and Tawn's (1995) values for standard error (SE) at Lowestoft in order to calculate confidence limits. The Dixon and Tawn SE values were multiplied by 1.034% to obtain 70% "statistical inference confidence limits" (HR Wallingford, 2010, p16). Extreme level values for the year 2100 were estimated assuming a sea level rise of 90 cm between 2010 and 2100, based on DEFRA (2006) guidance. The central estimate extreme water level values calculated by HR Wallingford are lower than the levels calculated by KPAL (2014) principally because the Dixon and Tawn extreme value growth curve is less steep than that calculated by KPAL based on a longer run of data for the Lowestoft gauge.

Note 3: Values calculated by KPAL using Joint Probability Analysis (JPA)

All of the calculations in the KPAL study, described in TR252 and TR322, were made relative to a base year of 2008. High water level values for the period 1964 to 2011 at Lowestoft were de-trended to a base year of 2008, as recommended by the Environment Agency (2011), using a calculated average rate of rise of all high waters of 3.17 mm/yr. A GPD was fitted to the highest 3.8% of skew surges (i.e. those above 0.41 m). The estimated skew surge for the 1:10,000 year event at Lowestoft is 3.54 m. The joint probability of skew surges and astronomical tides at Lowestoft was calculated, the 1:10,000 value being 4.49 m OD. High waters at Sizewell were previously found (TR252) to be, on average, 15 cm higher than at Lowestoft, hence the present 1:10,000 year still water level at Sizewell was estimated to be 4.64 m OD (Table A4). Estimates for the 1:10,000 year level in 2100 were made by adding sea level rise estimates of 0.65, 0.80, 0.93 and 1.90 m to this value, representing a range of UKCP09 climate change scenarios, as detailed in TR252 and TR322.

Note 4: Confidence in the KPAL JPA values relative to the mean of 30 simulated distributions

Estimation of extreme skew surges required the fitting of an extreme value curve to the observed data set using a maximum likelihood method. The Kolmogorov-Smirnov 'goodness of fit' test was used to check that the fit was statistically valid at the 95% level. However, this test effectively checks the degree of fit of the observed data (i.e. which cover 50 years, not 10,000 years). As explained in Section 2 above, the uncertainty associated with any single value on the extrapolated extreme value curve was estimated by generating 30 additional random distributions using the calculated curve parameters (κ, σ and μ etc.). For each of the 30 distributions the return periods for extreme skew surges were recalculated, producing 30 new estimates of the 1:10,000 year level. The mean of these 30 values, when combined in a JPA with high water, was 4.74 m OD (being 10 cm higher than the value calculated from the original extreme value curve). 95% confidence limits around these 30 values (calculated as $\overline{x} \pm 1.96\sigma/\sqrt{n}$) were calculated as 0.19 m. Estimates for the levels in 2100 were calculated by adding sea level rise estimates of 0.65, 0.80, 0.93 and 1.90 m to this value to obtain estimates of 5.39, 5.54, 5.67 and 6.64 m OD in 2100 (Table A4). The confidence limits around each 2100 value were increased in proportion to the assumed increase in extreme sea levels; for example the 1 in 10,000 water level in 2100 under a 95 percentile high emissions scenario (5.44 m OD) is 117% of the level in 2008 (4.64 m OD), hence the confidence limits have been assumed also to be 117% higher, that is +/- 0.22 m in 2100 compared to +/- 0.19 m in 2008.

Notes 5 and 6: Values calculated by KPAL using Joint Probability Analysis (JPA) with a synthetic longer record including four additional simulated extreme events

The values in these rows were calculated using the same methods described in Notes 3 and 4 above. The difference is that the record length was increased to 1914 -2014 by assuming that the tidal record for the period 1914-1963 was identical to that for 1964-2014, with the addition of hypothetical large skew-surges events (2.00, 2.25, 2.10 and 2.44 m), broadly representing historical storm events which occurred on the East Anglian Coast in 1928, 1938, 1949 and 1953.

Note 7: Values calculated in KPAL using an extrapolated Generalized Pareto Distribution (GPD) of high tide levels

A Generalised Pareto Distribution was fitted to the largest 2.8% high waters (i.e. those above 1.44 m OD) recorded at Lowestoft in the period 1964-2014, with values de-trended for sea level rise using a base year of 2008. The high water value on the extreme value curve for the 1:10,000 year event is 5.03 m OD. High waters at Sizewell were found to be 15 cm higher than at Lowestoft, hence the 1:10,000 year level at Sizewell was calculated to be 5.18 m OD (Table A4). Estimates for the levels in 2100 are calculated by adding sea level rise estimates of 0.65, 0.80, 0.93 and 1.90 m to this value.

Note 8: Confidence in the GPD values relative to the mean of 30 simulated distributions

As with the JPA method, estimation of extreme high waters required the fitting of an extreme value curve to the observed data set using a maximum likelihood method, and the curve-fitting process passed the Kolmogorov-Smirnov ‘goodness of fit’ test in terms of observed values. The uncertainty associated with any single value on the extrapolated extreme value curve was estimated by generating 30 additional random distributions using the calculated curve parameters (κ, σ and μ etc.). For each of the distributions, the return periods for extreme high waters were recalculated, producing 30 new estimates of the 1:10,000 year level. The mean of these 30 values was 5.31 m OD, 13 cm higher than the value obtained from the original extreme value curve. 95% confidence limits around these 30 values (calculated as $\overline{x} \pm 1.96\sigma/\sqrt{n}$) were determined to be +/- 0.28 m. Estimates for the extreme water levels in 2100 were calculated by adding sea level rise estimates of 0.65, 0.80, 0.93 and 1.90 m. The confidence limits around each future extreme value were increased in proportion to the increase in extreme sea levels.

Notes 9 and 10: Values calculated by KPAL using an extrapolated Generalized Pareto Distribution (GPD) of high tide levels, including for additional hypothetical extreme events

The values in these rows have been calculated using the same methods described in Notes 7 and 8 above. The difference is that the record length was increased to 1914 - 2014 by assuming a tidal record for the period 1914-1963 identical to that for the period 1964-2014, with the addition of four hypothetical high tide levels (3.00, 3.25, 3.10 and 3.44 m OD) intended to represent simulated historical storm events in 1928, 1938, 1949 and 1953.

Note 11: Additive approach

The values calculated using the additive approach represent the ‘credible worst case scenario’ of the highest astronomical tide (1.48 m OD) coinciding with the highest skew surge (estimated to be 4.10 m), producing a combined 2008 1:10,000 water level of 5.58 m OD at Lowestoft and 5.73 m OD at Sizewell. Estimates for the 1:10,000 levels in 2100 were made by adding sea level rise increments for each of the four climate change scenarios considered.

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CEFAS, 2015. BEEMS TR319 EDITION 2, DERIVATION OF EXTREME WAVES AND SURGE AND INITIAL RESULTS OF COASTAL WAVE MODEL

Revision	Date	Prepared by	Checked by	Status	Reasons for revision	Approved by
5	16/05/17	LF	BJR	Ed 2 BPE	Response to client comments. SR request	
4	14/02/17	LF	BJR	Ed 2 Prel A	Includes synthesis of full model run set	
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2	13/05/15	LF	PJJ	Prel C	In response to Client comments	
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Sizewell – Derivation of extreme wave and surge events at Sizewell with results of the coastal wave modelling, climate change and geomorphic scenario runs.

Edition 2

Adrian Farcas, Liam Fernand, Steven Wallbridge, Ralph Brayne and John Bacon

Version and Quality Control

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Executive summary

As part of the planning application for the proposed Sizewell C (SZC) new nuclear build, EDF Energy need to undertake a Flood Risk Assessment (FRA) to meet planning requirements as prescribed in EN-1 and EN-6, consulting with the Environment Agency (EA) as the FRA progresses. Flood hazard analysis is also required for the nuclear site licence and ongoing safety case regulated by the Office of Nuclear Regulation (ONR). The EA and ONR have produced a joint advice note on how such assessments should be undertaken in order to ensure that the full range of risks are considered and that the two assessments display appropriate consistency:

> "*Flood hazard analysis and the necessary protection and management arrangements should be captured and reported by the developer (referred to as the duty holder) in different documents:*
>
> - *for the EA - in planning submissions and Flood Risk Assessments, and*
> - *for the ONR - in relevant nuclear safety case(s)*
>
> *The individual submissions may differ in detail but, there should be consistency between them. The submissions will respond to different regulatory requirements and expectations but where they overlap in their predictions of flooding effects on the site, the predictions should be consistent; differences in data, methods used and judgments should be reconcilable and justified between the two analyses. The analyses and protection arrangements that best address EA's requirements, for example, should be consistent with those needed to address nuclear safety criteria as regulated by the ONR."* (Defra 2016)

One element of the Sizewell flood risk assessment is to consider what combination of extreme waves, surge elevation and tides could result in a breach or overtopping of flood defences. Whilst 50 year high resolution records of tidal levels are available, long term continuous wave records are not available for most of the UK coast. However, open sea model hindcast (30 year duration) model results are available and these can be used to provide boundary conditions for more detailed (high resolution) coastal models using well proven tools such as TOMAWAC or SWAN. High resolution coastal wave modelling can replicate the behaviour of wave propagation over the complex bathymetry from the offshore to the nearshore and also allows the effect of potential future bathymetries resulting from geomorphological change to be investigated. The outputs of these models can be used in the near shore zone (<5m water depth) to feed run up and over topping models e.g. Amazon, or can be used to assess the potential for breach in the case of a soft defence e.g. via the Bradbury method.

This report explains the methodology used to generate the extreme wave and water level combinations which could occur under high tides and storm surges to use as boundary conditions for a TOMAWAC wave model of the Sizewell area. The methodology used to derive the input boundary conditions is the publicly available JOIN-SEA method which has been developed for and adopted by the Environment Agency to calculate the joint probability of waves and water levels (Hawkes 2005).

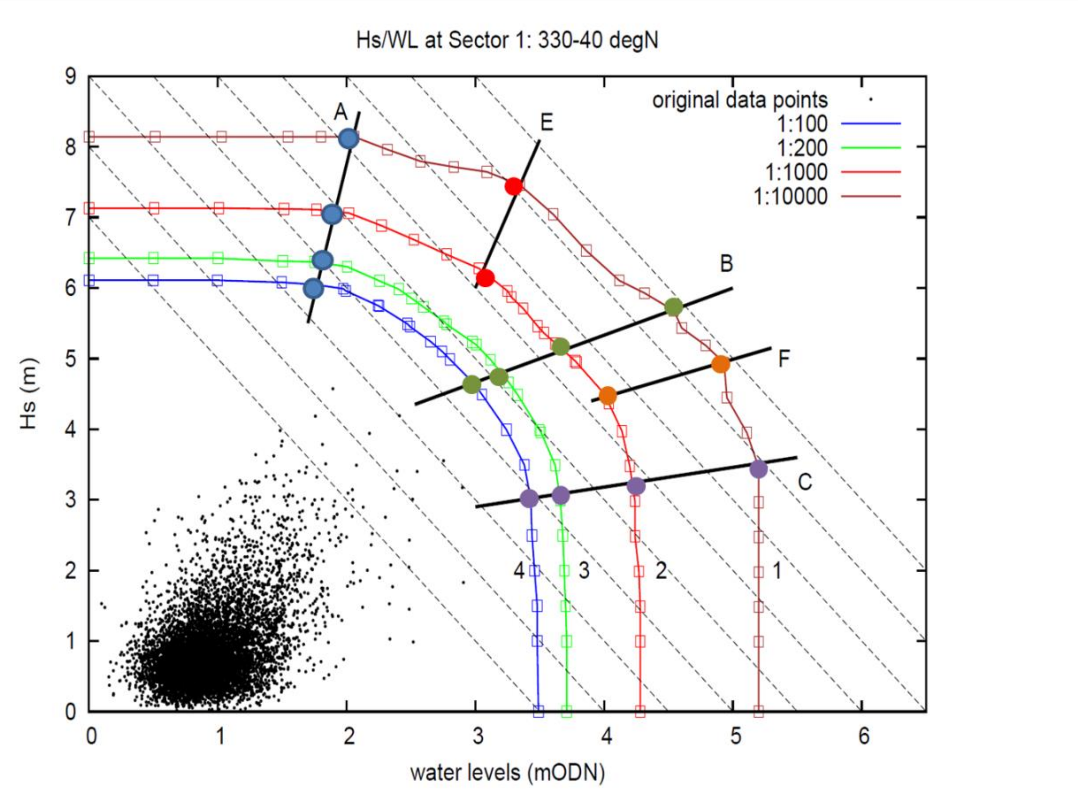
One of the most important aspects in defining wave height is the available fetch. This is usually dependent upon direction, thus in order to calculate the statistics of high return period events, the wave data is usually broken into groups by direction. For Sizewell two sets of directions (sectors) were found to be important, Sector 1: when waves at the coastal model boundary approach from 330 ^{0}N – 40 ^{0}N, and Sector 4: 136^{0}N – 210 ^{0}N.

For each of these sectors 5 conditions around the joint probability assessment (JPA) curve of water level and wave height were identified as worthy of modelling. 10 cases of different climate change related sea level rise and wind speed allowances have been considered and these are coupled to the present bathymetry and 5 geomorphological scenarios.

This report shows the results of applying high return period combinations of wave and water levels at the boundary of a high resolution coastal TOMAWAC wave model of Sizewell. Details of the setup and validation of the TOMAWAC wave model are available in BEEMS Technical Report TR232 Ed2.

Edition 1 of this report presented the method used to derive extreme water levels and the results of modelling waves from Sector 1 for the baseline case and for 1.8m of sea level rise (the credible maximum upper estimate for 2185, see Table 2 of this report). The full set of approximately 2000 models runs including the 5 geomorphological scenarios has subsequently been completed. It is not practical to present all of the results from these model runs and this edition 2 report presents a subset of the results which have been chosen to exemplify particular points. The full dataset has been archived should EDF Energy require access to specific model runs in future.

This report shows that for present bathymetry the joint probability assessment conditions of B and F (see figure below), result in the highest near shore wave heights, and when considered with water level, the highest combined extreme wave level comes from these conditions. Including the effects of climate change (increased water levels and wave height) gives increased waves at the shore line, with the B and F conditions resulting in largest combined extreme water levels.



Calculated joint probability curve of wave height and water level for sector 1 waves from 330-40 degrees North for different cases of sea level rise (1-4). The points along the lines A, E, B, F and C were the selected boundary (offshore) conditions for input to the BEEMS TOMAWAC wave model of Sizewell, which then predicts the inshore wave conditions.

The simulations of the geomorphological change scenarios show that it is only the lowered bank scenario that results in near shore wave increases in the vicinity of the proposed SZC site. Simulations run at low return periods (2 to 100 years) do show a near shore (at 1000m) increase in wave energy in the lowered bank simulations and by inference the importance of the present bank, although in the very near shore (<200m) there is little difference. However, for extreme waves (1:1000 return period), when sea levels are also raised there is little difference in the near shore between the geoscenarios and present bathymetry. Geoscenarios are necessarily artificial (albeit developed from the existing bathymetry), whereas the present bathymetry has been accurately surveyed. It would, therefore seem logical to focus wave run up calculations on the present bathymetry cases.

1 Background and basis for the flood risk assessment

1.1 ONR/EA Guidance

The Office of Nuclear Regulation (ONR) and the Environment Agency (EA) Joint Advice Note (Defra 2016) provides expectations for how coastal and flood risk assessments should be carried out. The Joint Advice Note stipulates that assessments should consider:

1. the potential for flooding due to, for example, heavy and prolonged and/or intense rainfall, high tides, storm surges, and tsunamis;
2. the combined effects of high tide, wind effects, wave actions, duration of the flood and flow conditions;
3. the potential for coastal erosion due to the above factors and other geological and geomorphological considerations;
4. the probability of failure of flood risk management measures, for example, the breach or over-topping of flood defences and the consequences of this happening;
5. the risk of foreshore lowering due to coastal processes undermining sea protection works;
6. the effects of climate change over the lifetime of the site, assessed using the most up to date credible projections;
7. Offsite flood and coastal erosion risks, for example to site access and egress routes.
8. Studies to address any significant uncertainties (as determined for example by sensitivity studies) that exist.
9. Any changes to flood and coastal erosion risk elsewhere as a result of works.

The purpose of this report is to explain the methodology used to generate the extreme waves and sea levels which can occur under high tides and storm surges that have been used as input parameters to the TOMAWAC model of Sizewell. The report shows the results of applying that model under the present bathymetry, climate change and geo scenarios. It in addresses either entirely or in part items; 2, 3, 6, 7 and 8. As such it is a feeder document to the site FRA and nuclear site licence.

Details of the setup and validation of the wave model (TOMAWAC) used in this report are available in BEEMS Technical Report TR232 Ed2.

1.2 Extreme sea levels

1.2.1 Coastal flood boundary conditions (McMillan *et al*. 2011)

"Successful risk-based flood and coastal erosion risk management requires the best available information on coastal flood boundary conditions, such as swell waves and sea levels. Current information is not consistent around the country and is becoming out of date. In April 2008, the Environment Agency took on the strategic overview of coasts in England, giving it an overarching role in the management of the English coastline. A practical guidance was created for the Environment Agency R&D project Coastal flood boundary conditions for UK mainland and islands. The aim of this project was to develop and apply improved methods to update these datasets, using a longer data record. The aims of the project were to:

- *Provide a consistent set of extreme sea levels around the coasts of England, Wales and Scotland (replacing advice given in the Proudman Oceanographic Laboratory Report 112).*

- *Provide a means of generating total storm tide curves for use with the extreme sea levels.*
- *Offer practical guidance on how to use these new datasets.*

This report provides practical guidance on how to view the findings of the extreme sea level and storm tide curve studies" (McMillan *et al*., 2011).

Whilst the above guidance is no doubt sufficient for many flood risk assessment purposes, for a nationally important infrastructure project such as at Sizewell C an additional analysis would be expected of the data and the underlying assumptions. Thus, for a robust assessment of water levels BEEMS analysed the McMillan work and found some issues with the approach for Sizewell (see BEEMS Technical Report TR252 for detail); in particular, the assumption of the quality of the Lowestoft data, which leads to lower estimates of extremes at Sizewell than at Lowestoft, despite the mean water level and tidal range being higher at Sizewell than Lowestoft (Figure 1).

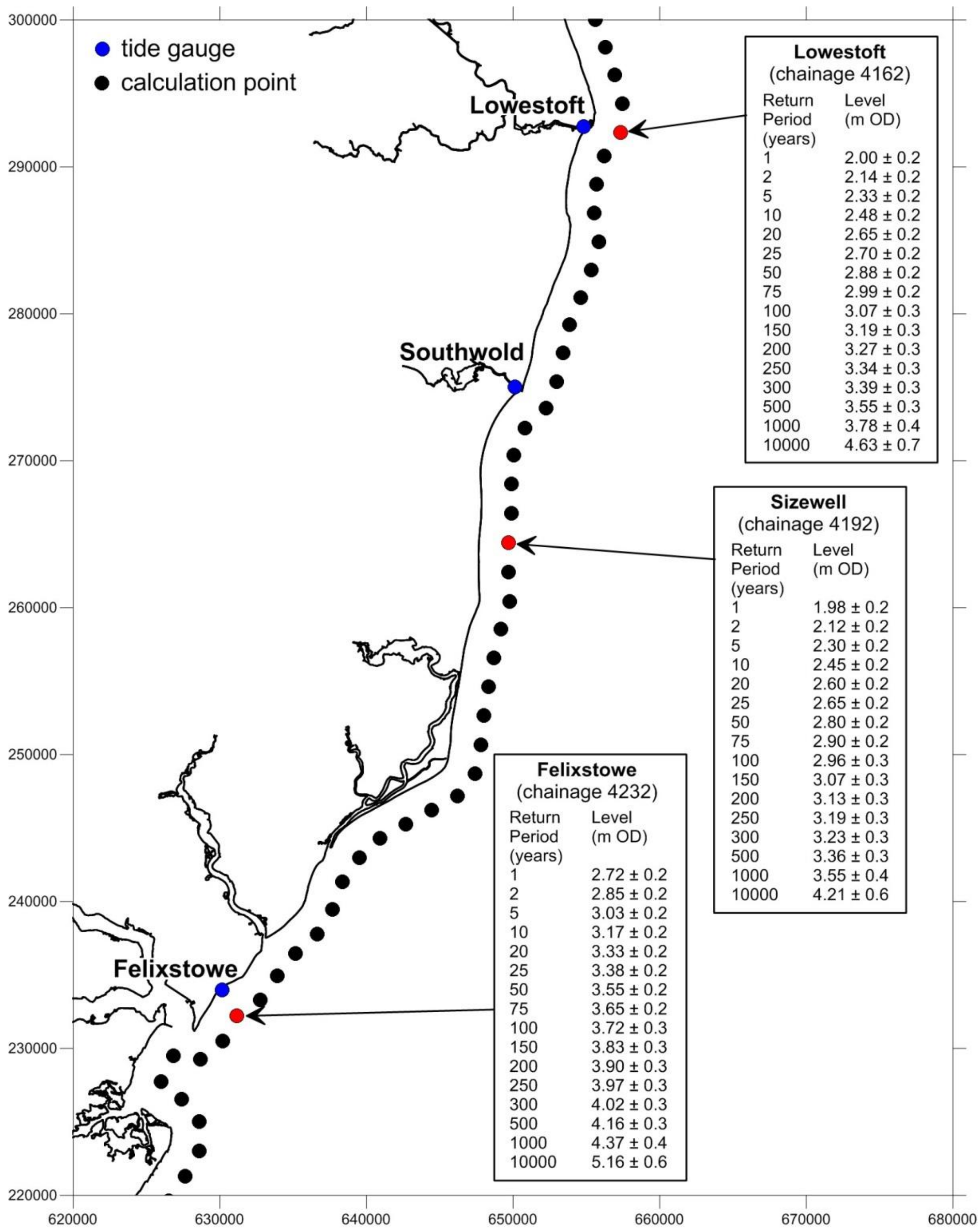


Figure 1 Estimates of extreme sea level from McMillan et al., (2011),

1.2.2 New estimates of extreme water level at Sizewell (From BEEMS TR252 and TR322)

In BEEMS Technical Report TR252 a number of methods to predict extreme still water levels using the 1964-2012 measurement record were presented. In order to assess the sensitivity of the predictions to the limited length of the data record, estimated data from 4 known historic surge events, including the 1953 event, were included in the data record and the predicted extreme still water levels were recalculated. Following the December 2013 East coast storm surge, the predictions were further recalculated in BEEMS Technical Report TR322 to include the 2013 measurement data. The latter increased the predicted 1 in 10,000 year still water level at Sizewell by approximately 15 cm (using joint probability analysis (JPA) of tide and skew surge).

Table 1 Estimates for the 1 in 10,000 year still water level at Sizewell (m OD), obtained using different methods for a range of climate change and sea level scenarios extracted from BEEMS Technical Report TR322.

	2008 Base year	Medium Emissions 95% estimate (0.65m SL rise)	High Emissions 95% estimate (0.80m SL rise)	H++ scenario low estimate (0.93 m SL rise)	H++ scenario high estimate (1.90 m SL rise)
		For 2100			
McMillian et al., (2011a)	4.21 ± 0.6	4.86 ± 0.6	5.01 ± 0.6	5.14 ± 0.6	6.11 ± 0.6
JPA	4.64 ± 0.19	5.29 ± 0.21	5.44 ± 0.22	5.57 ± 0.22	6.54 ± 0.26
JPA (simulation incl. 4 events	5.06 ± 0.14	5.71 ± 0.14	5.86 ± 0.14	5.99 ± 0.17	6.96 ± 0.20
HR Wallingford (2010)	4.34 ± 0.57	4.99 ± 0.57	5.14 ± 0.57	5.27 ± 0.57	6.24 ± 0.57
GPD	5.18 ± 0.28	5.83 ± 0.31	5.98 ± 0.32	6.11 ± 0.33	7.08 ± 0.38
GPD (simulation including 4 events	5.83 ± 0.29	6.48 ± 0.32	6.63 ± 0.33	6.76 ± 0.33	7.73 ± 0.38
Additive approach	5.73	6.38	6.53	6.66	7.63

The various statistical methods, including the December 2013 event, produce extreme elevation levels that range from 4.64 to 5.83m in the base year (2008). The McMillan and HR Wallingford, results do not include the December 2013 storm surge.

1.3 Future Sea Level Rise (SLR)

The 95th percentile for sea level rise using the UKCP09 scenarios for 2100 is 0.65m under the medium emissions scenario and 0.80m under the high emissions scenario. The H++ lower and higher scenario estimates for 2100 are 0.93m and 1.90m (Table 1). The EA/ONR joint advice note (Defra 2016, Appendix D) recommends the use of the 90th percentile for the medium emissions scenario, however, the more conservative 95th percentile is being used for the design basis of SZC, i.e. “the design base case”.

A recent paper on the credible maximum sea level by the BEEMS Climate Change working group (BEEMS SAR024) reviewed recent estimates of future sea level. The different components that contribute to mean Sea Level Rise (SLR) are;

- Global mean thermal expansion
- Local steric anomaly
- Small ice caps and glacier melt
- Antarctic ice sheet melt
- Greenland ice sheet melt
- Correction for gravitational fingerprint
- Aquifer dewatering
- Vertical land movement
- Surge

These different components give a total credible maximum SLR range by 2100 of 1.55–3.20 m, and by 2200 of 2.55–5.00 m. A fuller explanation of the climate change allowances to be used can be found with the report ‘Sizewell C Flood Risk Assessment Recommended Climate Change Allowances (2015)’.

1.3.1 Sea level elevations used in this modelling

In order to perform the modelling runs and develop a common and easily understood nomenclature, specific cases have been developed and these are colour coded in Table 2. The construction phase is not included in these runs. The key dates relevant to flood risk for the operation of the station are; the end of operation of the station at 2085, end of decommissioning at 2110, end of interim spent fuel store 2140, and end of theoretical maximum site lifetime 2185.

1. A large number of potential considerations are required, the design base case at each date, but also sensitivity runs (95th of High Emissions Scenario) and credible maximum values from different sources. As some of these conditions (at different times) produce similar sea level elevations these have been grouped together as shown in

Table 3 below.

Table 2 Recommended Sea level rise scenarios (in m) for model runs, relative to baseline of 2008. Adapted from EDF (2014) Sizewell FRA scoping report.

Year	Development Phase	Reasonably Foreseeable		Credible Maximum			
		Medium Emissions 95%ile (m)	**High Emissions 95%ile (m)**	**EA Upper-End Estimate with Land Motion + surge (m)**	**BECC Lower (m)**	**H^{++} with Land Motion + surge (m**	**BECC Upper (m)**
2008	Baseline Hydrological Datum	0.00	0.00				
2017	Start of construction	0.047	0.058				
2025	Commissioning	0.093	0.113				
2085	End of operation	0.522	0.637				
2110	End of decommissioning	0.744	0.908	1.105 + 0.7 = 1.805	1.55	2.12 + 1.0 = 3.12[1]	3.20
2140	Interim spent fuel store	1.014	1.238		1.95		3.92
2185	Theoretical maximum site lifetime	1.419	1.733	1.99 +1.0 = 2.99	2.550		5.00

2. In keeping with the approach applied for HPC, the credible maximum allowances adopted here are aligned with the upper H++ estimates for mean sea level rise and storm surge given in UKCP09 and the associated allowances in the EA guidance. The BECC scoping paper focusing on the SZC location found very similar values for the increase in extreme still water levels at the upper end of the credible maximum range (3.20m from 1990 to 2100 compared to 3.12m from 2008 to 2110)

Table 3 Summary of the sea level cases for consideration in the modelling, where values lie within 10-15 cm then these are treated as the same run for wave modelling purposes, with the upper value used as the sea level. Design base case is 95th % of Medium Emissions Scenario; sensitivity runs are 95th % of High Emissions Scenario. (Table 2 is the source for the sea level increase)

Case Name	Colour	Sea Level increase (m)	Comment	Comment
Baseline Case (2008) White	White	No increase	No offshore wave height increase	Baseline
Design Basis Case (2110)	Green	0.74m	10% increase to offshore wave height. .	From EA “Climate change allowance for planners” September 2013
Design Basis Case (2140) **Sensitivity Run (2110)**	Blue	1.01m 0.91m	10% increase to offshore wave height.	
Design Basis Case (2185) **Credible Maximum Case BECC Lower (2110)**	Purple	1.42m 1.55m	10% increase to offshore wave height	
Sensitivity Run (2140)	Dark Blue	1.24m	10% increase to offshore wave height	
Sensitivity Run (2185) **EA Credible Maximum Upper (2110)**	Brown	1.73m. 1.81m	10% increase to offshore wave height	
Credible Maximum Case BECC Lower (2185).	Yellow	2.55m	10% increase to offshore wave height	
Credible Maximum Case, BECC Upper (2110)	Red	3.20m	15% increase to offshore wave height	Sensitivity check for wave height increase.
Credible Maximum Case, BECC Upper (2185).	Black	5.00m	15% increase to offshore wave height.	
Credible Maximum Case (2110) **EA Upper Estimate (2185)**	Pink	3.12m 2.99m	10% increase to offshore wave height	

The colour coding is used as a label in the model runs to distinguish the scenarios.

1.4 Inference from previous work in relation to wave boundary conditions.

HR Wallingford (2010) laid out the methodology for developing the shape of the extreme profiles of wave height and water level combination at Sizewell (see Figure 2 below). They used the JOIN-SEA methodology (Hawkes 2005); the same methodology is used in this report.

A number of useful results can be inferred from the simulations performed by HR Wallingford. They broke the wave climate into 4 sectors, Sector 1: 330 ºN – 40 ºN, Sector 2: 41ºN -75ºN, Sector 3: 76ºN - 135ºN and

Sector: 4 136ºN – 210 ºN. HR Wallingford developed 8 separate cases of wave height and water level for each sector. They demonstrated that only two sectors, 1 and 4, produce large wave and surge conditions that warrant further investigation. An example is shown below.

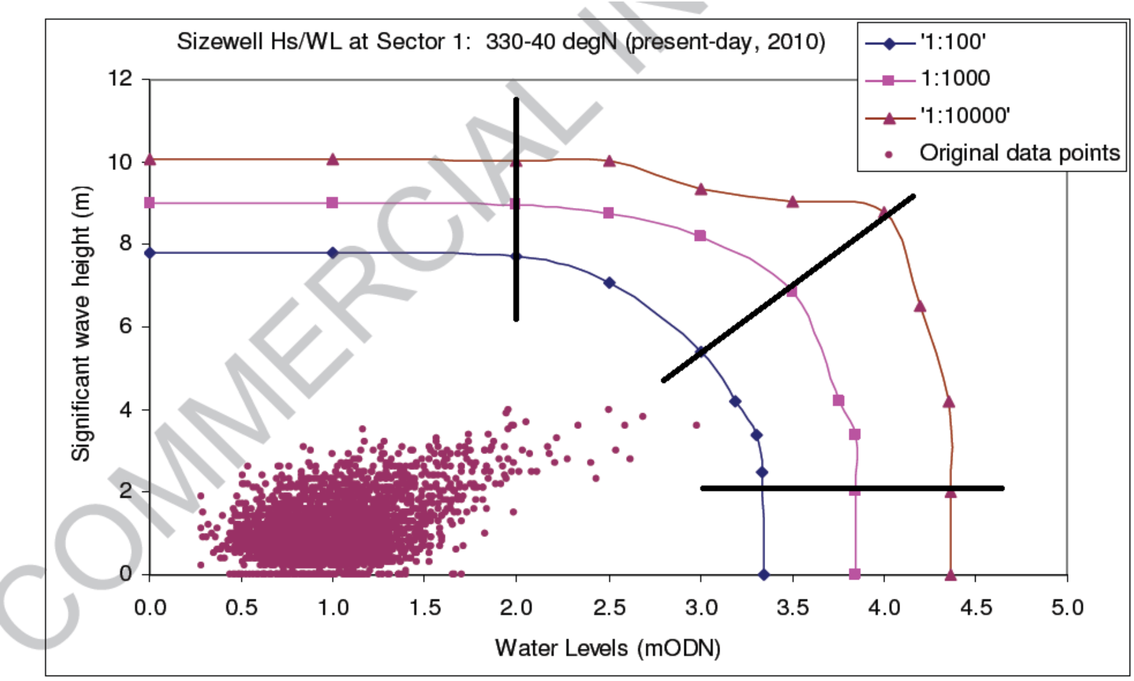


Figure 2 Extract from HR Wallingford (2010) report showing water level and wave heights for Sector 1

The values used for boundary conditions derived in the HR Wallingford work were not taken forward in this study for two main reasons:

- The wave model output available to HR Wallingford in 2010 was subsequently updated by the UK Met Office so that a longer record, and one that better replicated conditions in the relatively shallow water of the southern bight of the North Sea was available to Cefas in 2014.
- The exact model extents used in the BEEMS TOMAWAC model were slightly different from that of the HR Wallingford Swan model.

1.5 BEEMS analysis of joint probability waves and sea levels

The JOIN-SEA method of calculating the joint probability for combined waves and sea levels was developed by HR Wallingford funded by Defra/Environment Agency Flood and Coastal Defence R&D programme over a number of years. The methodology used here comes from “Use of Joint Probability Methods in Flood Management - A Guide to Best Practice. R&D Technical Report FD2308/TR2” (Hawkes 2005). This is the recommended EA approach. Since this was developed, other approaches (e.g. Gouldby *et al*., 2014) using radial bias functions have been applied which develop a methodology of extending a data set to the shore, however they effectively work as a lookup table and have limitations in that the exact application and location of the output has to be known beforehand. As the inclusion of geoscenarios is a requirement of this study then the Join-Sea method is the most appropriate.

i. Data preparation

The wave data for the northern Sector 1 was taken from the Met. Office European Wave Model prediction point 1069, while for the southern Sector 4, data from the prediction point 950 was used.

In each Sector case, 33-year (1980 to 2012) 1 and 3-hourly time series were considered and the waves from directions outside the sector were filtered out.

The water level time series used was that from the Lowestoft tide gauge, modified for use at Sizewell, as detailed in HR Wallingford report and in agreement with BEEMS Technical Report TR139.

For each sector the wave and water level datasets were combined in order to create simultaneous and independent records of wave height, period and water level. The requirement of independence of sequential records was addressed by extracting only consecutive high waters from the water level time series data. Where needed, wave height and period data were interpolated at the time of high waters in order to obtain simultaneous combined records.

ii. Modelling the distribution of marginal variables

For both marginal variables (i.e. the significant wave height and the water level), Generalised Pareto Distributions (GPD) were fitted to the values of the variables greater than specified thresholds (the top few percent), and empirical distribution functions were used to fit the values below the thresholds.

iii. Modelling the dependency between the variables

In order to model the dependence between variables, first the correlation between wave heights and sea levels was analysed. This dependence is then represented by fitting the data by either a single Bi-Variate Normal (BVN) distribution, or by a mixture of two BVN distributions. For the northern Sector 1, the data is represented by a mixture of two BVNs with correlation coefficients of 0.025 and 0.56, while for the southern Sector 4 the data is represented by a single BVN with a correlation coefficient of -0.025.

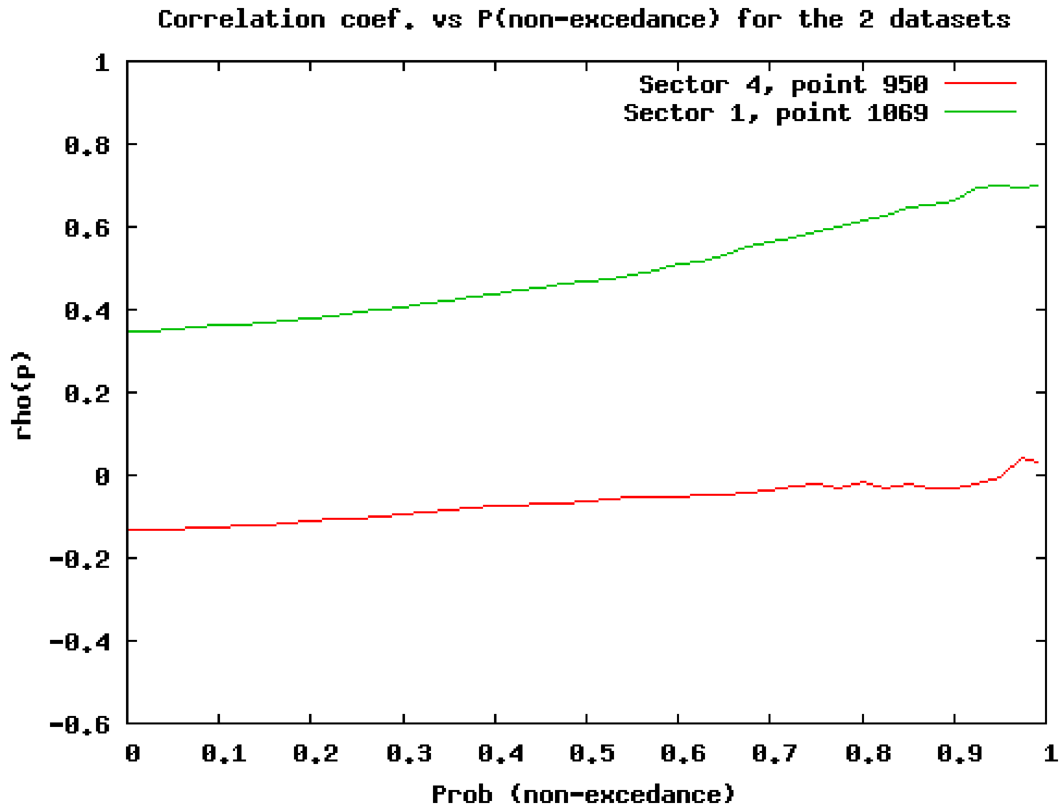


Figure 3 Correlation coefficient for sector 1 (correlated) and 4 (not correlated)

iv. Refine extreme marginal predictions (i.e. Weibull for Hs and GPD for elevation)

At this stage, the initial extreme variables, which are representative for the extreme end of the distributions fitted in Step 2, were based on GPDs fitted to the simultaneous data records only. Optionally, any refined knowledge of the marginal variable extremes (based on the full records, or from other sources) can be included in the representation and used for rescaling during the next step (the long-term simulation of data). Marginal extremes of wave height were calculated separately for sectors 1 and 4 by fitting three-parameter Weibull distributions to the wave datasets for the respective sectors (Figures 4 and 5). The Weibull method is explained in the Appendix A. The estimates of the extreme wave heights for 15 increasing return periods from 0.2 to 10,000 years are shown in Table 4 including the 95% confidence limits for each return period. The water level has been derived using the EA recommended method of joint probability (JPA) but using the time series that included the December 2013 storm surge. The method chosen for calculating the confidence intervals consists of using the fitted Weibull parameters to generate random distributions of significant wave heights H_s, with the same number of data points as the original (observational) distribution[1]. We have used 100 of these seeded random distributions for both Sector 1 and 4, to calculate a sample of 100 random H_s values for each return period, and the 95% percentile values were calculated from the 100 random values. This procedure is similar to the method used in BEEMS Technical Report TR252 to calculate the confidence limits of the extreme water levels.

[1] H_s is the mean of the highest 1/3 waves in the wave record

Table 4 Estimates of present-day (2008 baseline) extreme offshore significant wave heights calculated using Weibull distribution. All values are statistically significant at the 95% level.

Return period (years)	**Sector 1 Hs(m)**	**Sector 4 Hs(m)**	**Water Level (OD)**
0.2	3.20 ±0.07	3.03 ± 0.06	
0.5	3.60 ± 0.10	3.32 ± 0.07	
1	3.90 ± 0.12	3.53 ± 0.08	2.23 ± 0.01
2	4.20 ± 0.15	3.74 ± 0.09	2.39 ± 0.01
5	4.58 ± 0.18	4.01 ± 0.10	2.61 ± 0.01
10	4.87 ± 0.21	4.20 ± 0.11	2.79 ± 0.02
20	5.16 ± 0.23	4.39 ± 0.12	2.98 ± 0.03
50	5.53 ± 0.27	4.64 ± 0.14	3.24 ± 0.03
100	5.81 ± 0.30	4.82 ± 0.15	3.45 ± 0.04
200	6.09 ± 0.33	5.00 ± 0.16	3.66 ± 0.05
500	6.46 ± 0.37	5.23 ± 0.17	3.96 ± 0.07
1000	6.74 ± 0.40	5.40 ± 0.18	4.20 ± 0.08
2000	7.01 ± 0.43	5.56 ± 0.19	4.45 ± 0.10
5000	7.37 ± 0.47	5.78 ± 0.20	4.79 ±0.120
10000	7.64 ± 0.50	5.94 ± 0.21	5.06 ± 0.14

Water level marginal extremes are based on the values from BEEMS Technical Report TR322 Table 12, the JPA of tides plus skew surges and corrected for Sizewell by addition of 15 cm to account for the difference in mean High Waters.

For the purpose of rescaling the marginal extremes in the JOIN-SEA analysis procedure, as a precautionary approach values at the upper limit of the confidence intervals for both the wave heights and the water levels; have been used e.g. for sector 1 Hs of 8.14 m (7.64+0.50) and water level of 5.20 m (5.06+0.14) at 1: 10,000 return period.

Whilst the joint probability has been developed from present data, it is reasonable to assume that it is valid for future sea levels rise, so that the curve can be offset as the mean sea level increases. There have been some publications which indicate that surge may increase, and this has been accounted for in some sea level rise estimates. However, there are no publications in this area which inform the calculation of joint probability of wave height and extreme water levels.

v. Long-term simulation

A large sample (100,000 years) of synthetic records was created through Monte Carlo simulation, based on the distributions fitted and the optional information provided in the previous steps.

vi. Analysis of the joint extremes

The simulated data set was analysed by ordering the results and counting back from the top in order to derive joint exceedance probability combinations for 100, 200, 1,000 and 10,000 year joint return periods.

1.5.1 Fitting the analysis

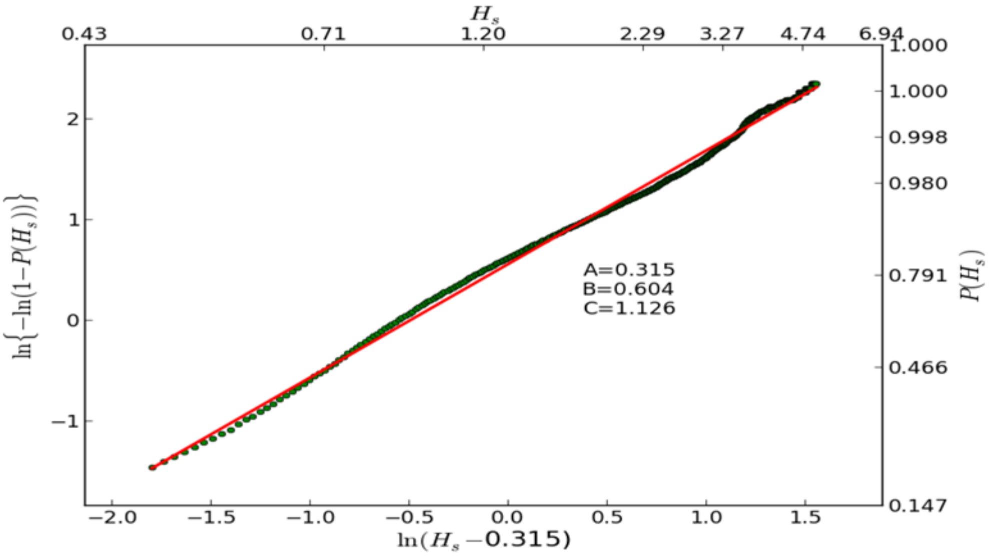


Figure 4 Weibull fit for waves for sector 1. A, B and C are coefficients in the Weibull parameterisation (Appendix A)

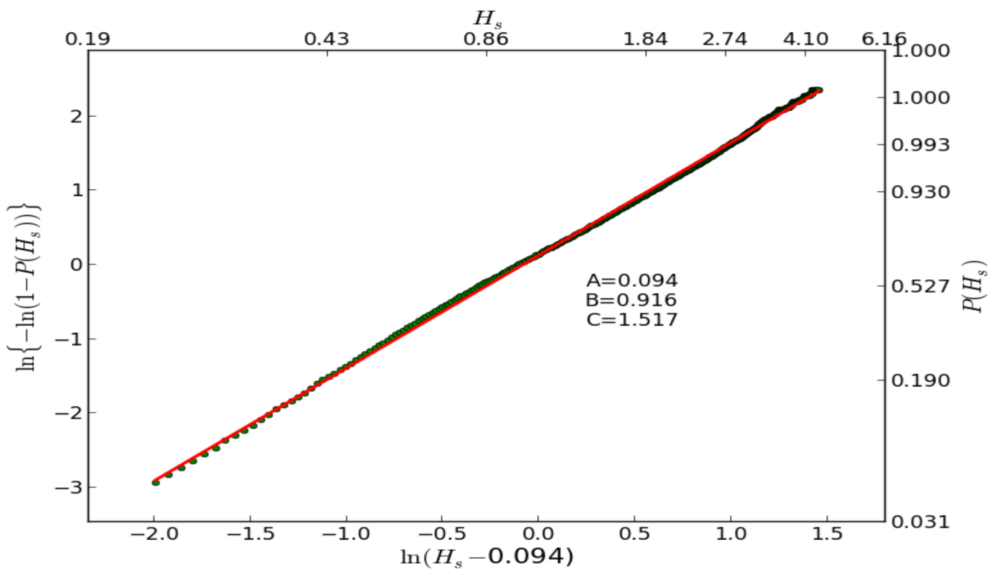


Figure 5 Weibull fit for waves for Sector 4. A, B and C are coefficients in the Weibull parameterisation

1.5.2 Joint probability of waves and water levels on the existing baseline (2008).

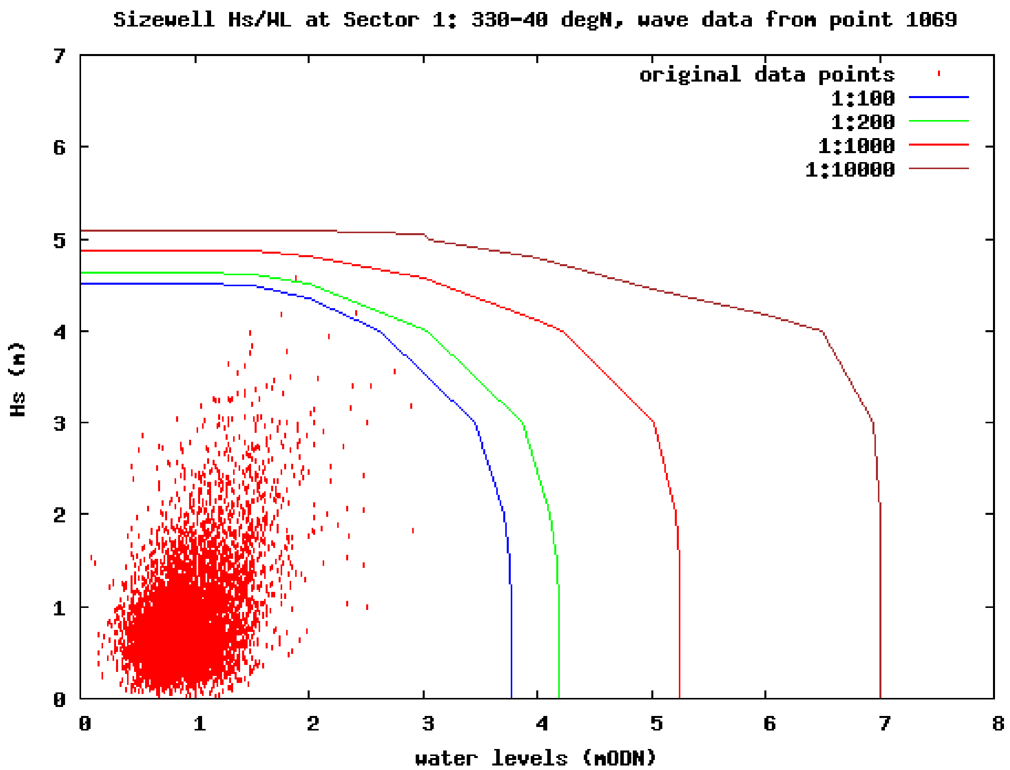


Figure 6 Joint probability assessment without scaling Sector 1. Note some observations occur in the 1:200 category.

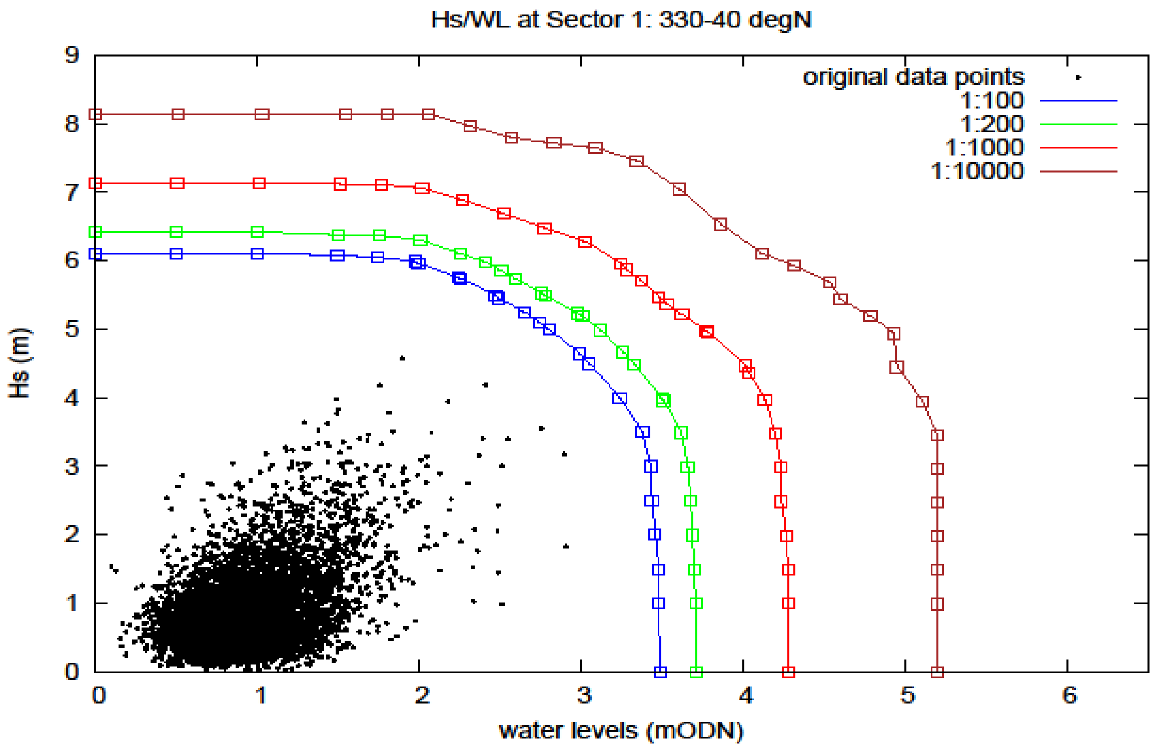


Figure 7 Joint probability assessment for Sector 1 with scaling of both wave height and water level.

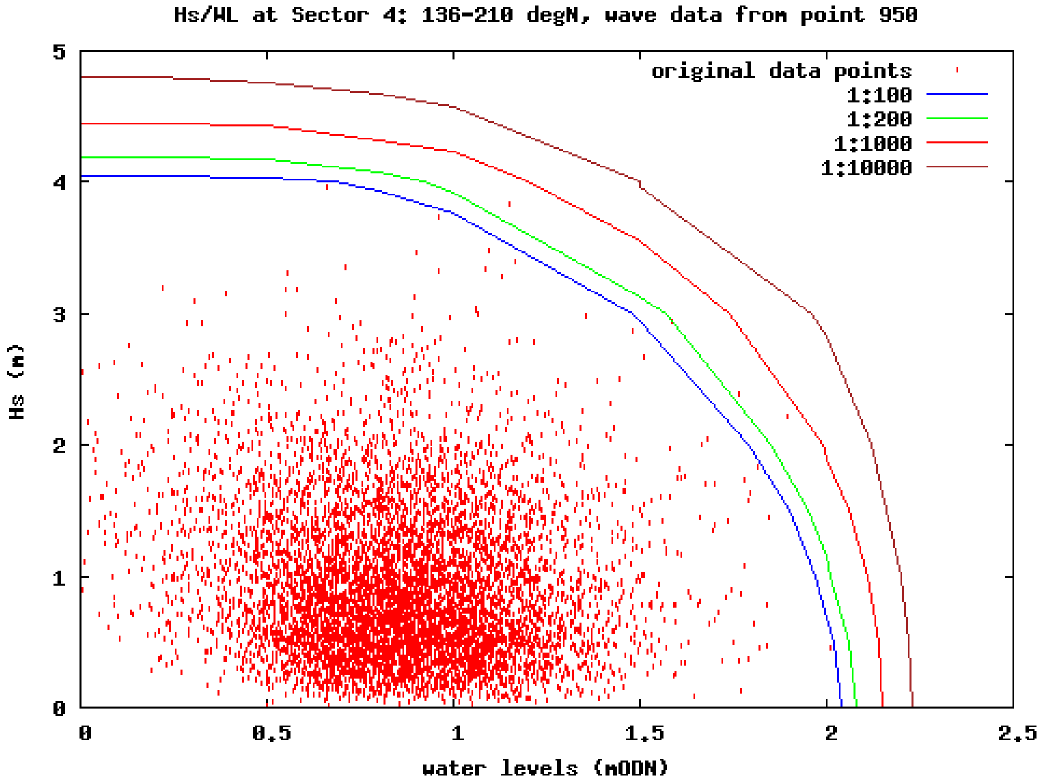


Figure 8 Joint probability assessment for sector 4 (no scaling).

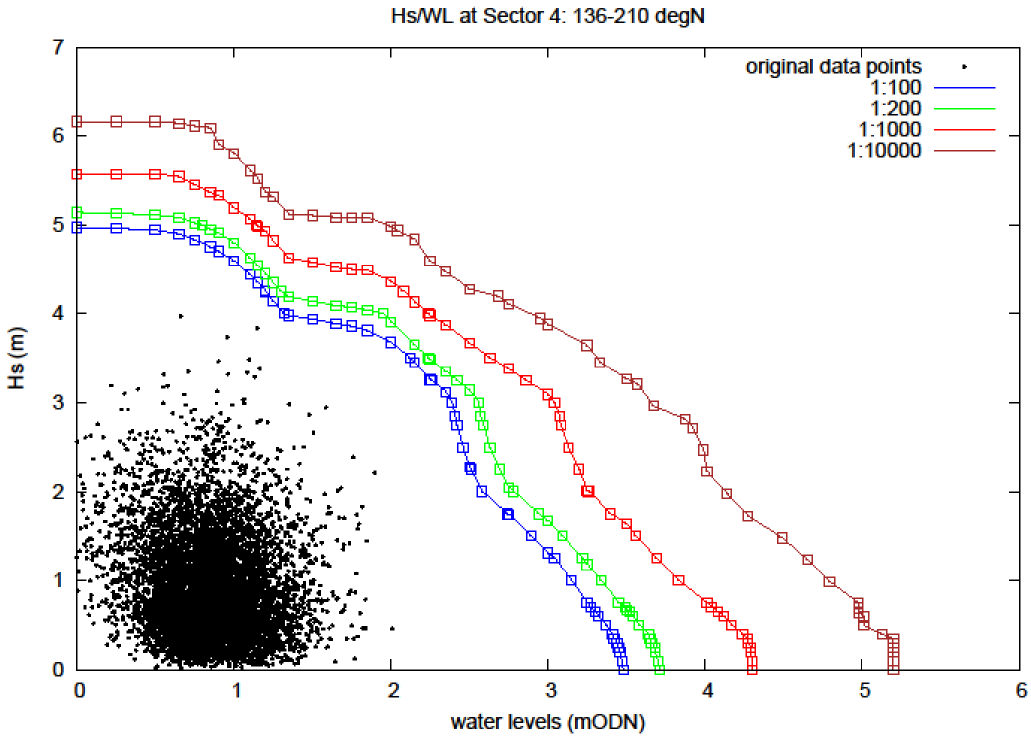


Figure 9 Joint probability assessment for Sector 4 including scaling of wave height and water level.

The same water level scaling has been used for Sector 1 and Sector 4 using the values given in Table 4 as described in section 1.5 iv. In the case of Sector 4 this leads to a stretching of the distribution at the high water level, low wave end.

1.6 Future Storminess

There is no definitive evidence to predict a change in future storminess. As a precautionary measure 10% was added to wave heights for all future scenarios, in accordance with EA guidelines (“Climate change allowances for planners” EA September 2013, except for the most extreme case when 15% has been added to inform the sensitivity of the potential site overtopping to increases in wave height beyond those required in EA/ONR guidance, for ”safety case” runs.

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1.7 Wind speed

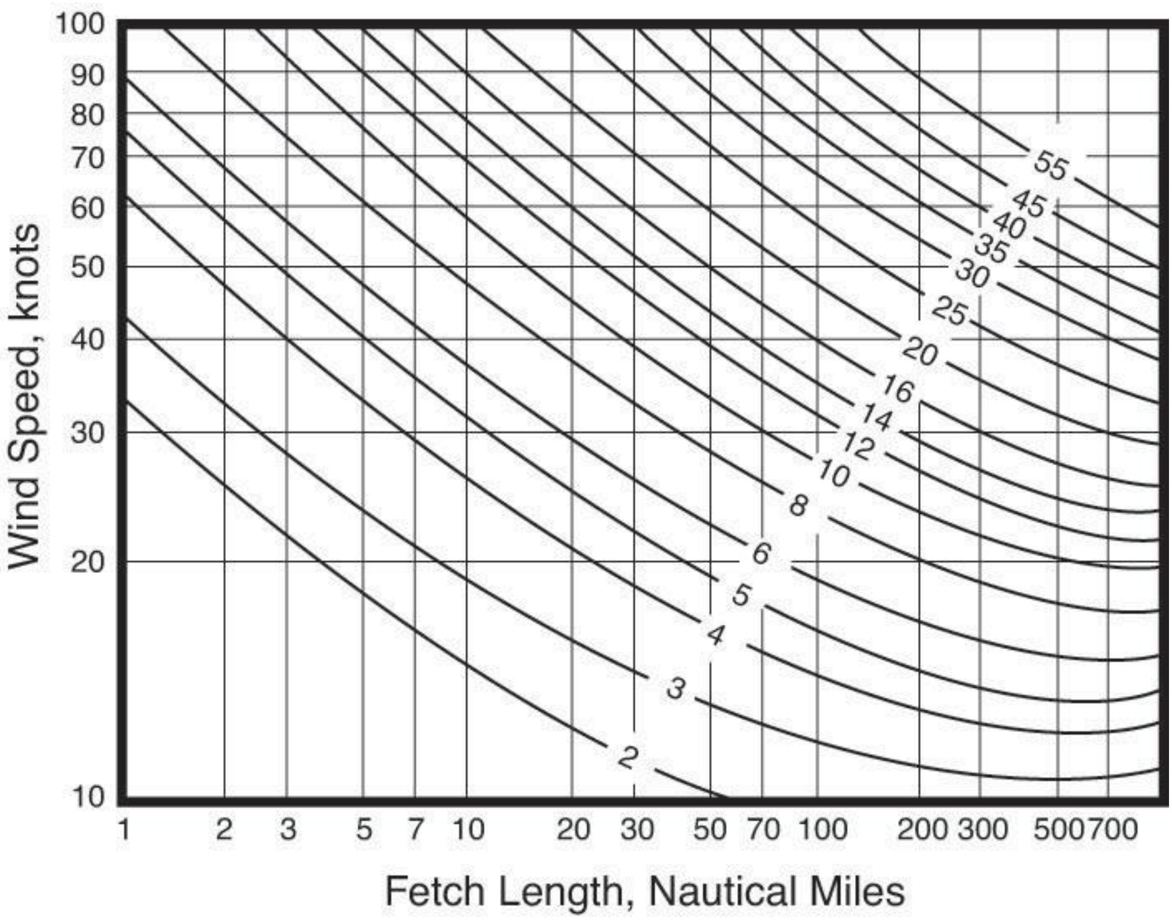

Figure 10 Relation between wave height (feet), wind speed (knots) and fetch (nautical miles)

The wind speeds used to drive the model are those which are appropriate to the wave condition assuming a fetch of 70nm for both sector 1 and sector 4 waves using the Sverdrup-Munk-Bretschneider relation (Sverdrup and Munk 1947).

1.8 Period – Wave Height relation

The period of the extremes waves is important to model, as the energy loss terms are strongly dependant on the period. The figures below give the wave height period relationship so that the extreme waves can be associated with an appropriate wave period. The difference in the relationship between the two curves is partly a reflection of the fetch from either direction. Sector 4 extreme waves have a shorter period for the same wave height.

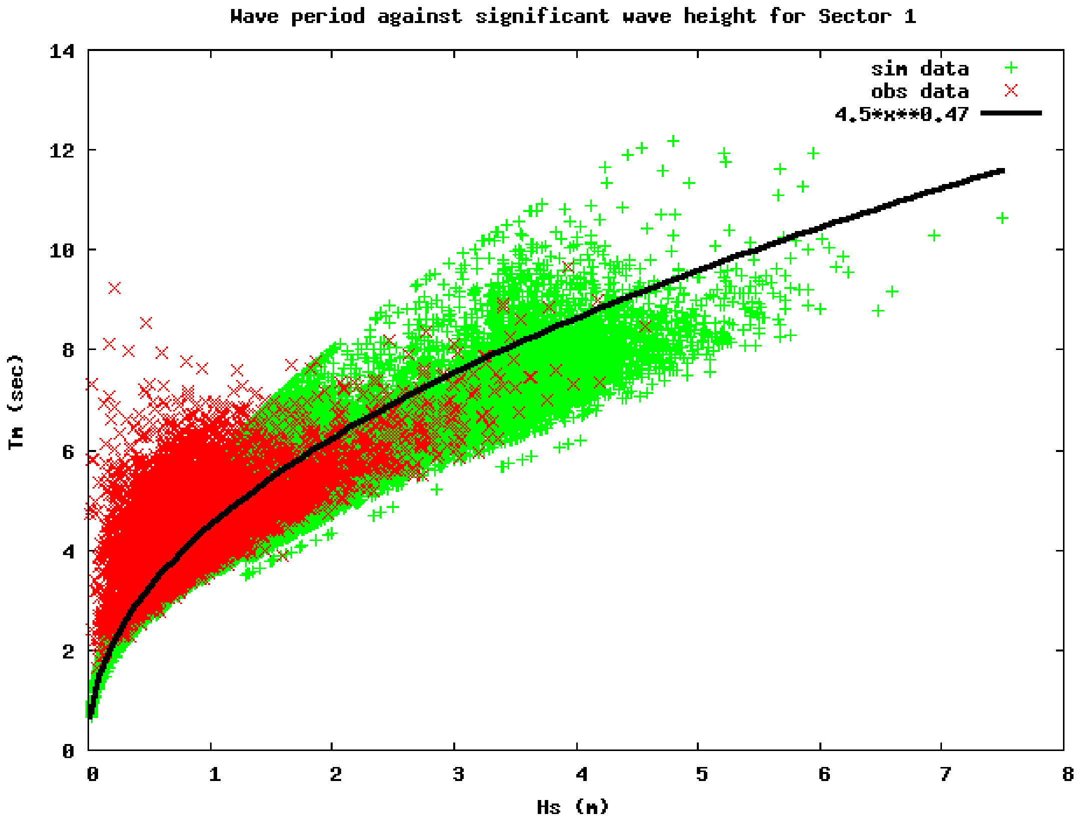

Figure 11 Mean wave period versus wave height for observed (red) and simulated (green) data for Sector 1

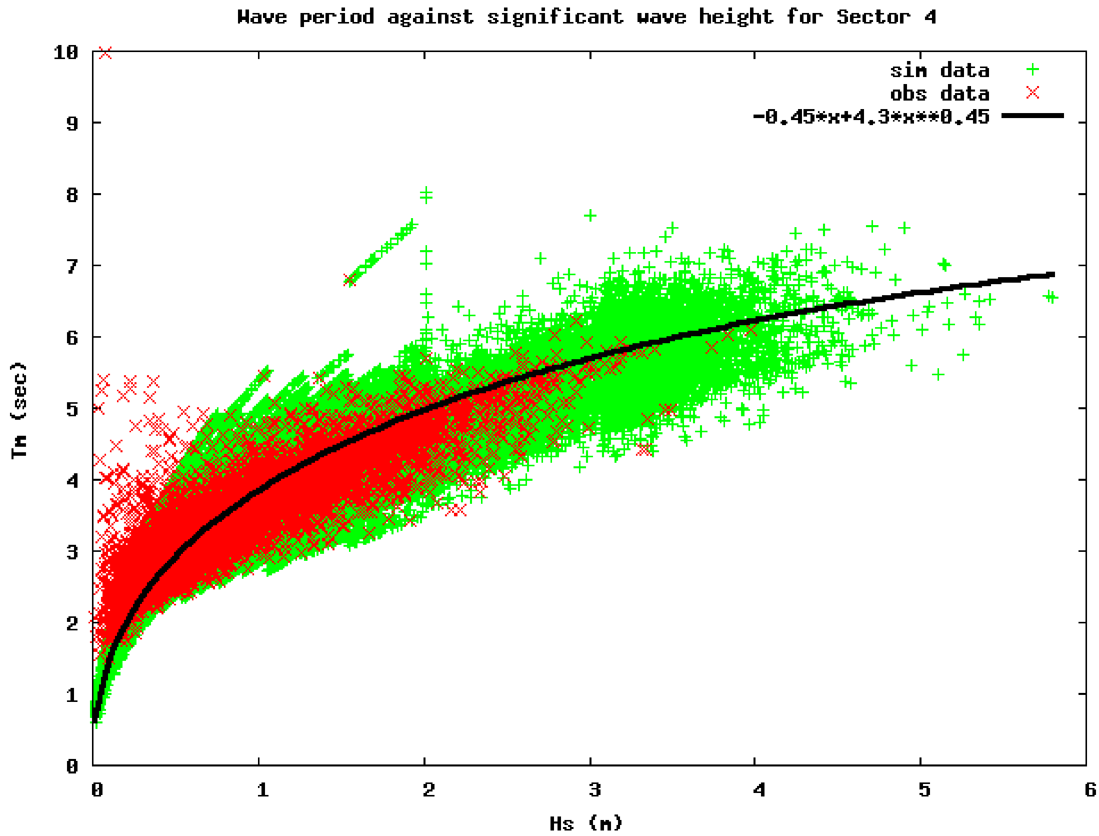

Figure 12 Mean wave period versus significant wave height (m) for Sector 4 (30 year hindcast observation red , simulation green).

1.9 Selection of conditions to run

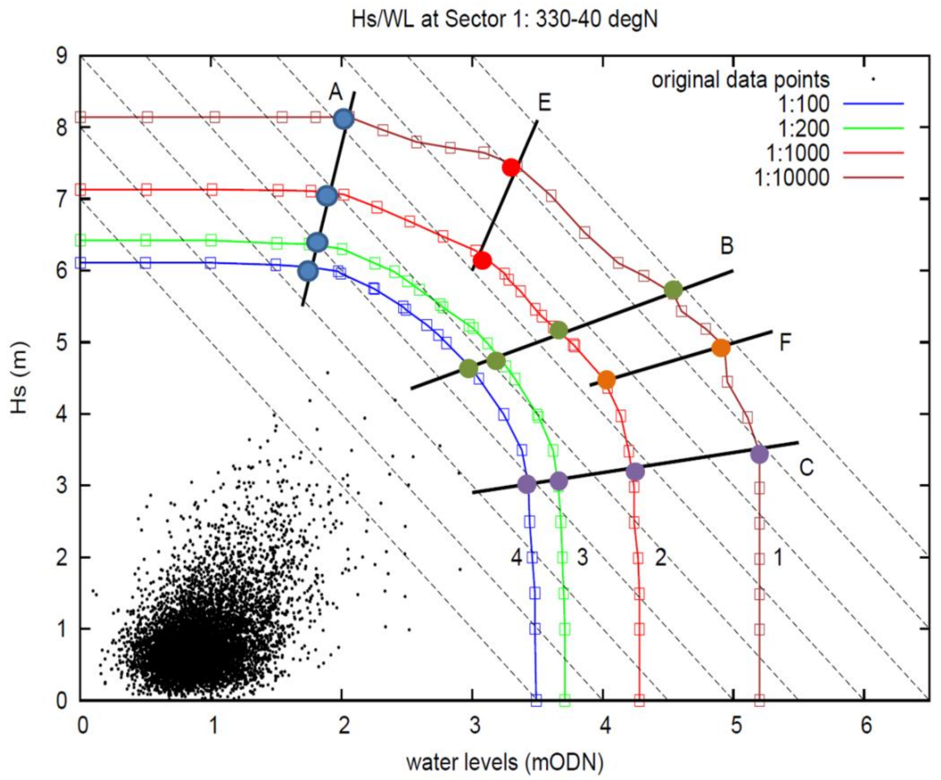

Figure 13 Selection of boundary conditions for Sector 1. Dashed lines mark the sum of half wave height and water level. Conditions are A, E, B, F, C and return periods are 1,2,3,4. Water levels are relative to the 2008 baseline.

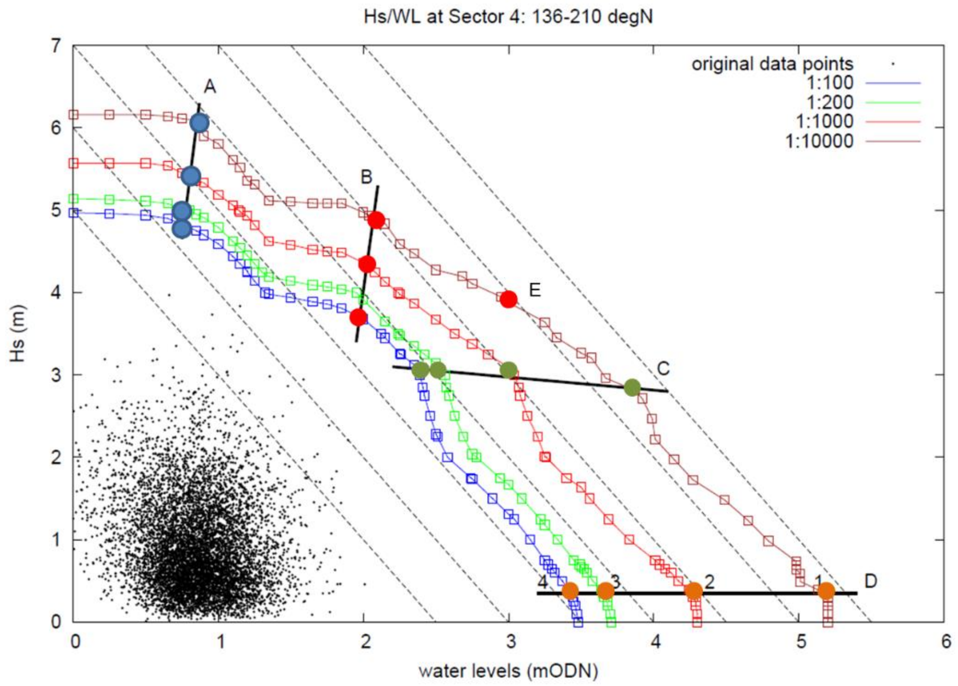

Figure 14 Selection of boundary conditions to run for Sector 4. Dashed lines mark the sum of half wave height and water level. Conditions are A, B, E, C, D and return periods are 1,2,3,4.

Having derived the shapes of the joint probability curves shown in Figures 13 and 14 using the method outlined in Section 1.5, the selection of appropriate conditions to model was undertaken. The dotted lines which mark the sum of half the wave height and the water level were used as a guide for maximum extreme water level ignoring wave run up. Thus, Case D in Sector 4 has the highest combined water level at a 1:10000 return period. Initially four conditions A, B, C and D were chosen for each sector and all four frequencies of occurrence considered (1:100, 1:200, 1:1000, 1:10000). Subsequently it was realised that for Sector 1 the D condition produced a similar extreme water level to the C condition and the D condition was therefore dropped. Where there were perceived gaps additional points were added for certain frequencies of occurrence i.e. in Sector 1 conditions E and F were added for 1:1000 and 1:10000 return periods and Sector 4 condition E was added for 1:10000 return periods.

However, wave run up is more dependent on wave energy flux and wave power. Wave power (E) is the square of wave height (a), and wave energy flux (P) is the wave power multiplied by the group velocity Cg.

$$E = \frac{1}{2} pga^2 \ \ and \ \ P_{energy} = ECg$$

Where p is density and g the acceleration due to gravity. The group velocity ($_{Cg}$) is a function of wave number, itself dependant on the wave length and hence wave period.

Thus, consideration of the “A” conditions is required even if their maximum combined water level is less than the “C” condition as the wave power or wave energy flux may be greater and hence wave run up and the potential for over-topping may also be greater. The values used in the modelling and the associated wave period and wind speed used are given in Table 4.

Table 5 Boundary conditions to run for present water levels (2008), the direction refers to the wave direction at the boundary of the model.

Probability	Condition A, B,C,E,F for present sea level (2008)				
Sector 1 (from 330 -40 ºN)	Name	Hs (m) Wave Height	Water Level (mODN, 2008)	Mean Period Tm01 (s)	Wind (m/s)
1:10000	A1	8.14	2.06	12.1	30
1:10000	E1	7.46	3.35	11.6	26
1:10000	B1	5.68	4.54	10.2	21
1:10000	F1	4.94	4.93	9.5	19
1:10000	C1	3.46	5.2	8.1	15
1:1000	A2	7.1	1.89	11.3	25
1:1000	E2	6.28	3.03	10.7	22
1:1000	B2	5.21	3.62	9.8	20
1:1000	F2	4.47	4.02	9.1	18
1:1000	C2	3.23	4.22	7.8	14
1:200	A3	6.38	1.76	10.8	23
1:200	B3	4.83	3.18	9.4	19
1:200	C3	3.05	3.66	7.6	13
Sector 4 (from 135 - 210 ºN)	Name	Hs (m) Wave Height	Water Level (mODN, 2008)	Mean Period Tm01 (s)	Wind (m/s)
1:10000	A1	6.09	0.85	6.9	22
1:10000	B1	4.94	2.04	6.6	19
1:10000	E1	3.88	3	6.2	16
1:10000	C1	2.81	3.87	5.6	12
1:10000	D1	0.35	5.2	2.5	0.5
1:1000	A2	5.4	0.8	6.7	21
1:1000	B2	4.3	2.04	6.5	17.5
1:1000	C2	3	3.04	5.7	13
1:1000	D2	0.35	4.27	2.5	0.5
1:200	A3	5.02	0.75	6.6	20
1:200	B3	3.95	2	6.2	16.5
1:200	C3	3.07	2.53	5.7	13
1:200	D3	0.35	3.65	2.5	0.5

2 Geoscenario modelling

2.1 The Geoscenarios

Four potential future geoscenarios were defined in BEEMS Technical Report TR108:

1. Tidal Inlet and Barrier Retreat
2. Elongate bank
3. Shallow Southern Trough
4. Bank Depletion (or lowered bank)

However, subsequent to the development of these scenarios, it became evident that the lowered bank scenario would be likely to represent the greatest wave exposure to the coastline. An additional series of lowered bank scenarios were, therefore, created by lowering of the bank with the material lost from the system. This is in contrast to the original bank depletion scenario where the material from the bank was deposited inshore. Net loss of material is included in this study as a worst case scenario for sensitivity testing in flood risk analyses. Although it is considered an extremely unlikely scenario during the lifetime of the site (based upon the past 180 years behavior of the system) it is plausible if there was a change in climatic conditions (wave climate) or to shoreline management (to the north of Sizewell) affecting sediment supply to the Sizewell - Dunwich Bank.

As well as the lowered bank scenarios, a migrated bank scenario has also been included whereby the present bank system has been migrated westwards by 700m. This scenario is of less interest to the flood risk analysis, as it was primarily developed as a worst case for the heat sink capacity relevant to siting the SZC cooling water discharge. These scenarios are described in BEEMS Technical Report TR105. As noted in Section 1.2 the EA/ONR require consideration of coastal erosion and foreshore lowering. Some of the scenarios therefore potentially have a relevance in this respect, in that they may change the directional bias of the wave spectrum and thus change the net longshore sediment transport and hence erosion or accretion patterns. Appendix C contains an analysis of the effect of the lowered bank scenario which is the scenario most likely to produce a change on the wave energy approaching the Sizewell frontage. The methodology associated with this coastline modelling is presented in BEEMS Technical Report TR329 Ed2, which also contains an analysis of changed wave conditions on the coastline. The tidal inlet scenario, whilst a relevant consideration for understanding of the potential future Sizewell – Minsmere coastline, has the least direct impact on the wave field with any change constrained to the zone near the breach itself when compared to the baseline bathymetry. It is, therefore, not considered further in relation to simulation of the extreme waves that could impact upon the Sizewell C frontage.

The scenarios that are therefore considered of potential importance during extreme waves are:

- Elongated Bank (Figures 15 and 16);
- Shallow southern trough (Figures 17 and 18);
- Lowered bank (Figures 19 and 20);
- Lowered bank including loss of material (Figures 21 and 22); and
- Migrated bank by 700m (Figures 23 and 24).

A number of additional scenarios of the lowered bank were also developed, which involved removing smaller amounts of material in 1m increments. i.e. 1m, 2m, 3m, 4m. For the migrated bank scenario, intermediate amounts of migration were also considered of 400m and 200m, model runs have been undertaken, but the results are omitted from this report for brevity.

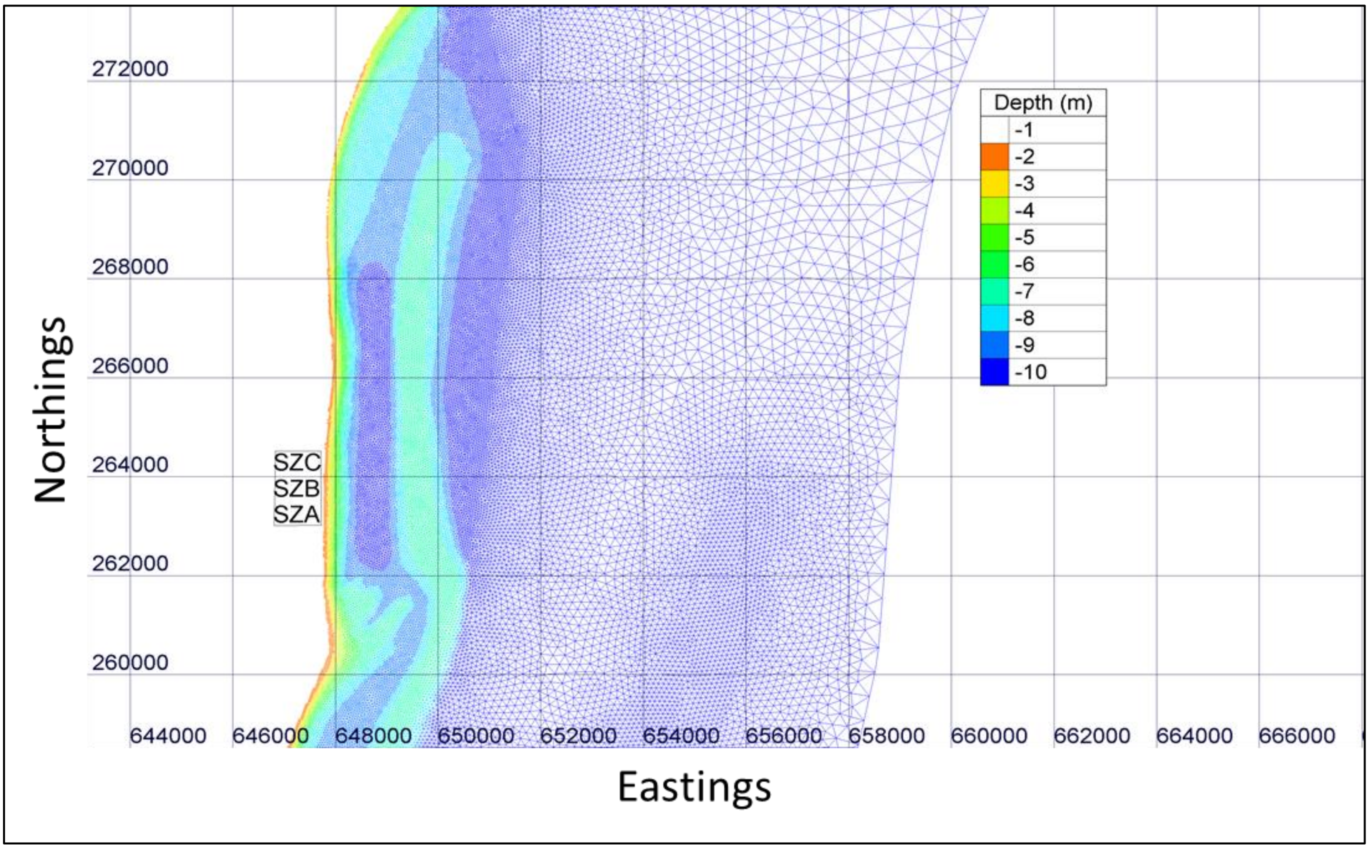

Figure 15 Elongated Bank Geoscenario, depths in meters ODN, BNG co-ordinate system.

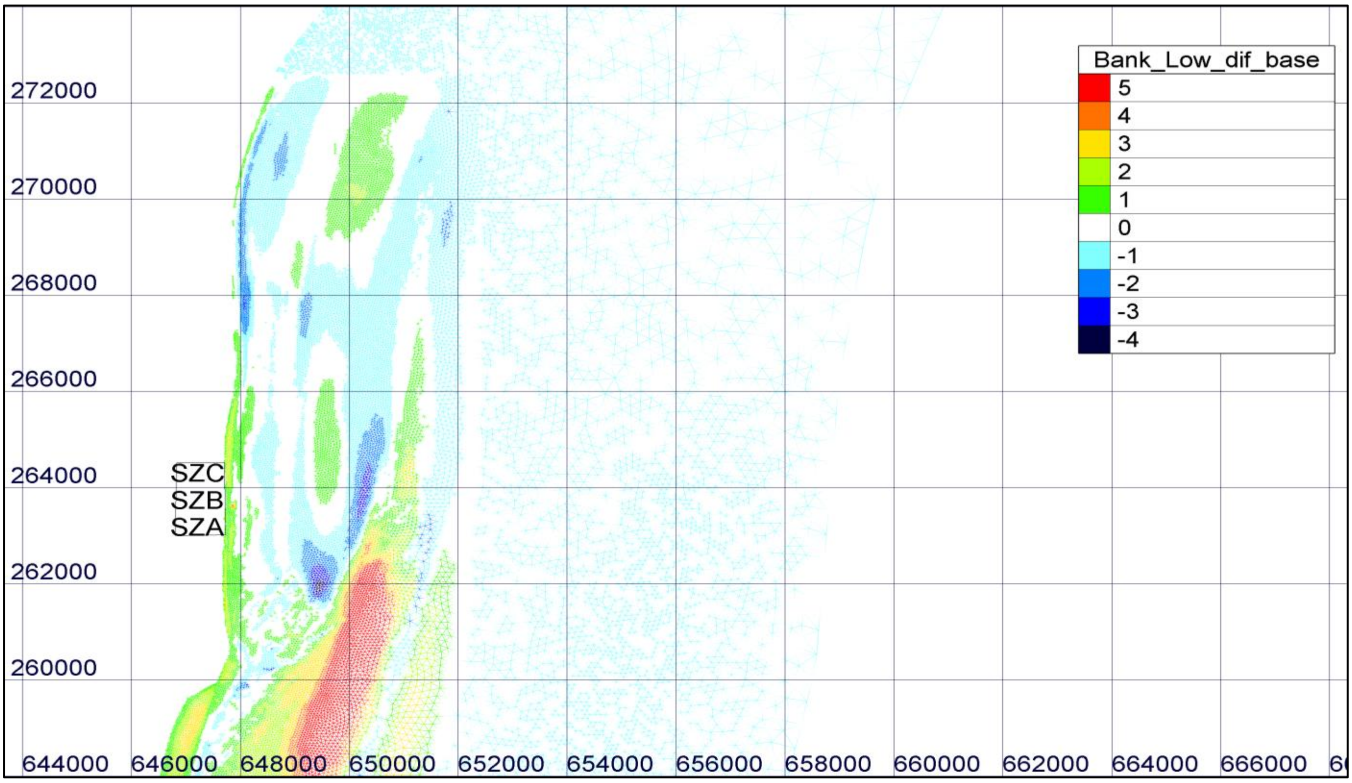

Figure 16 Elongated bank difference with baseline bathymetry (m). Horizontal axis Eastings, vertical axis Northings

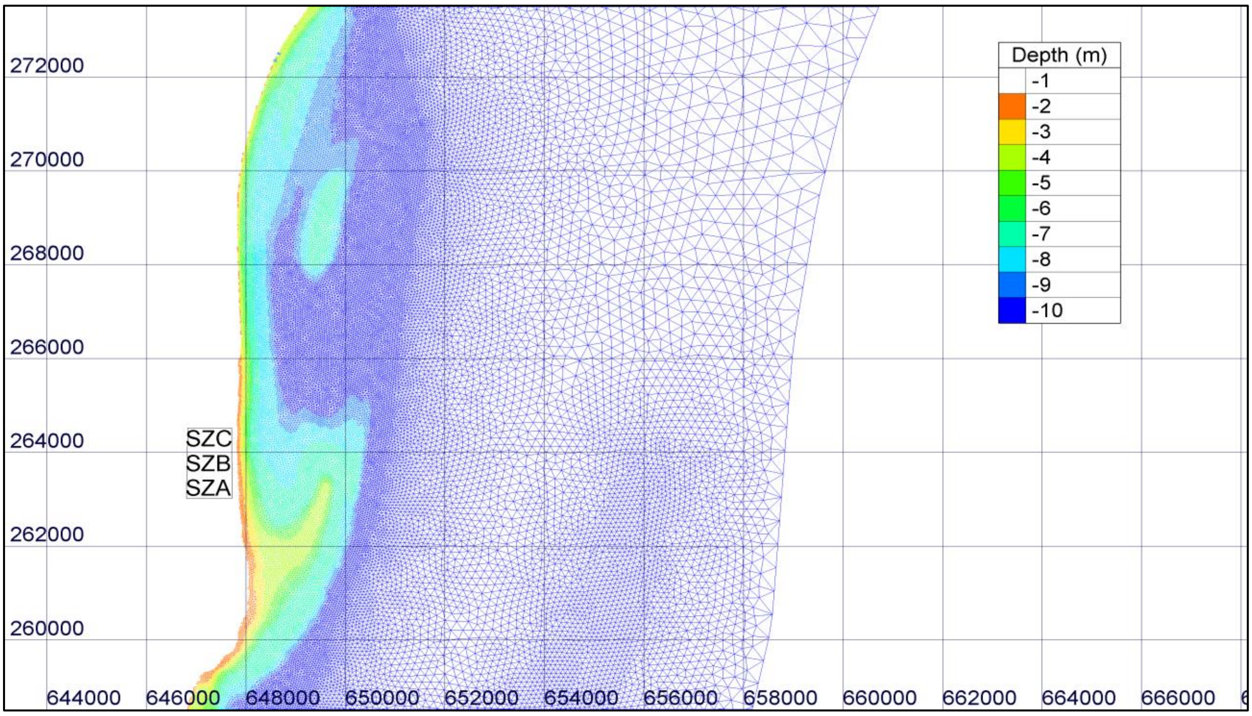

Figure 17 Shallow southern trough depths in meters ODN. Horizontal axis Eastings, vertical axis Northings

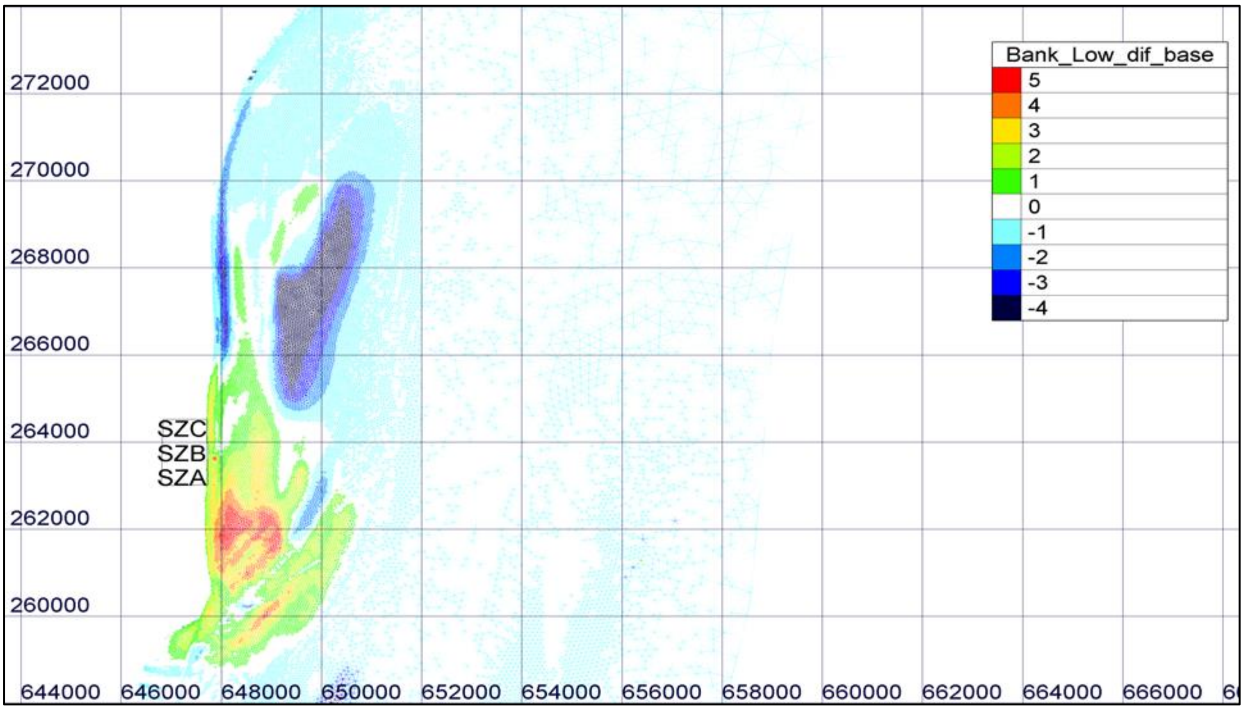

Figure 18 Difference in shallow trough scenario from the baseline in meters. Horizontal axis Eastings, vertical axis Northings

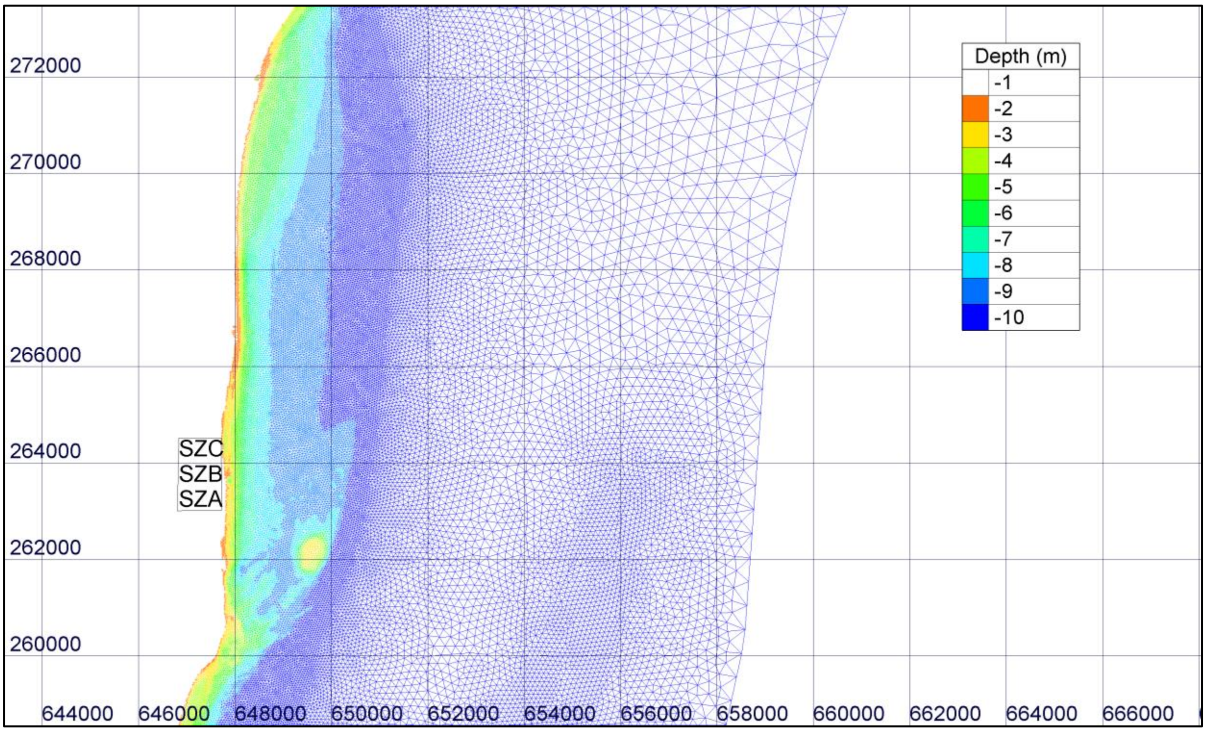

Figure 19 Bank removal and infill (depths in meters ODN). Horizontal axis Eastings, vertical axis Northings

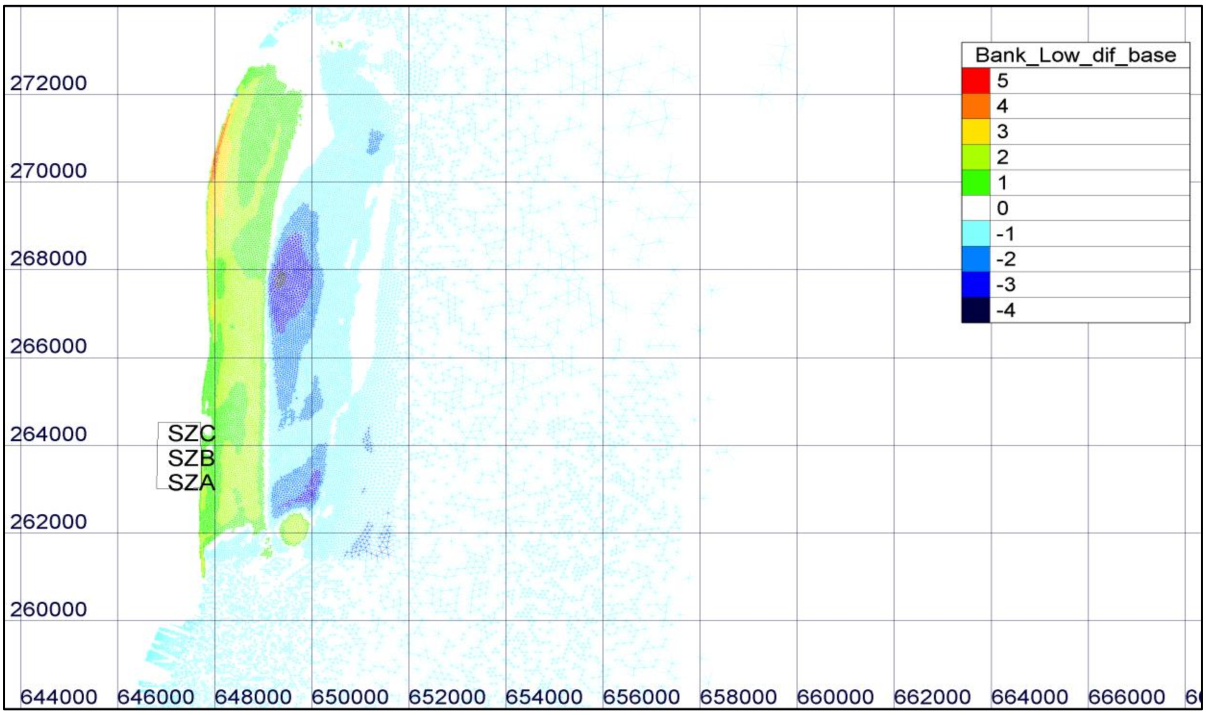

Figure 20 Bank removal and infill - difference with baseline (depth in meters), note reduction of Bank and infill of trough. Horizontal axis Eastings, vertical axis Northings

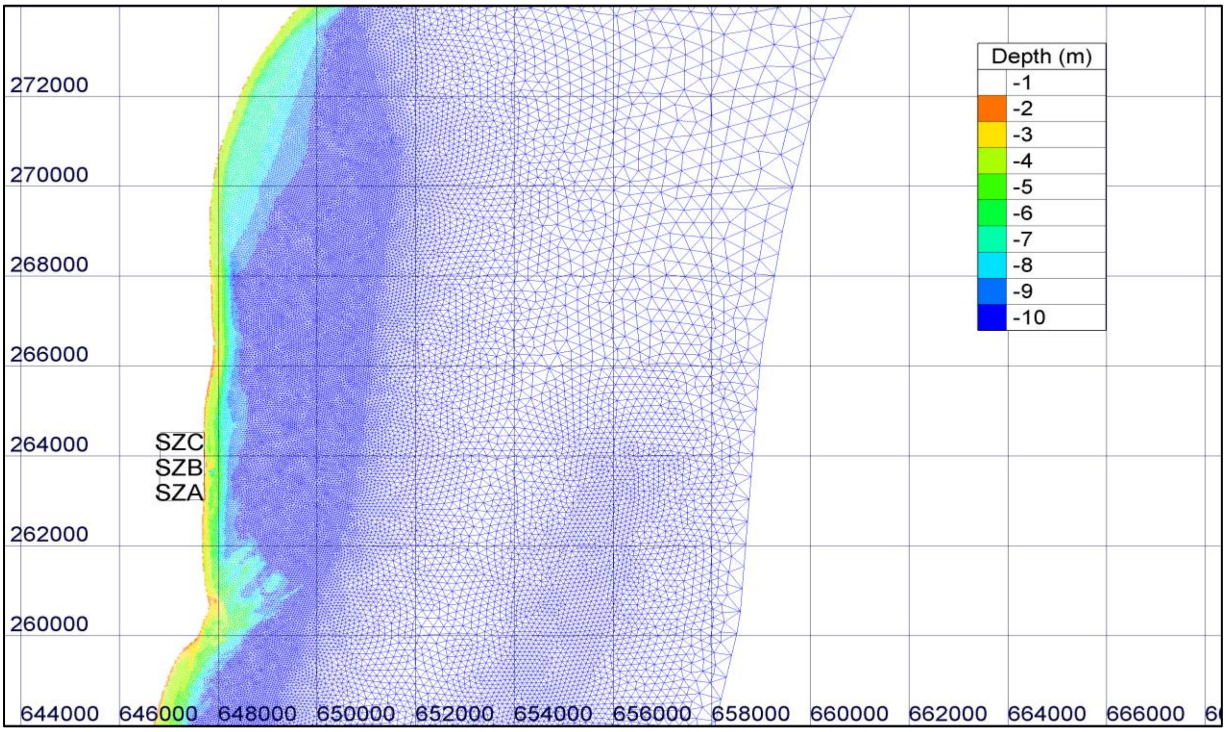

Figure 21 Bank lowering by 5m (Bank removal only) depths in meters ODN. Horizontal axis Eastings, vertical axis Northings

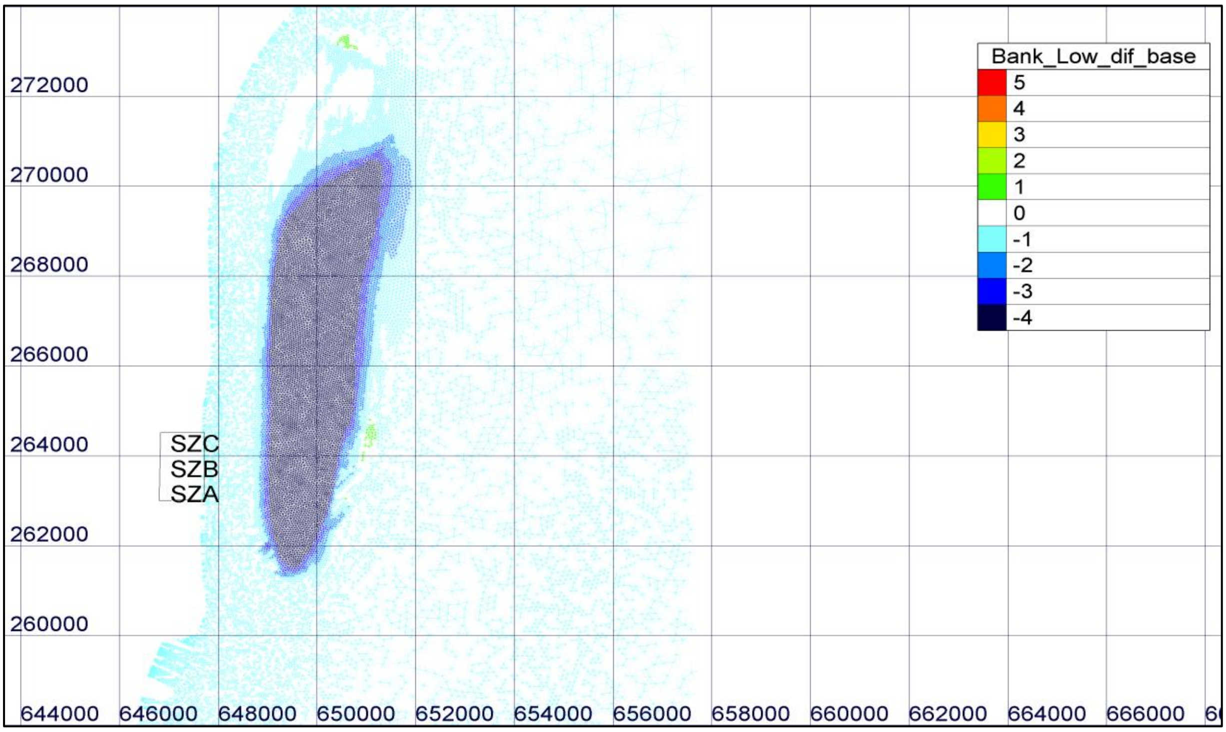

Figure 22 Bank lowering by 5m - difference with baseline, in meters. Horizontal axis Eastings, vertical axis Northings

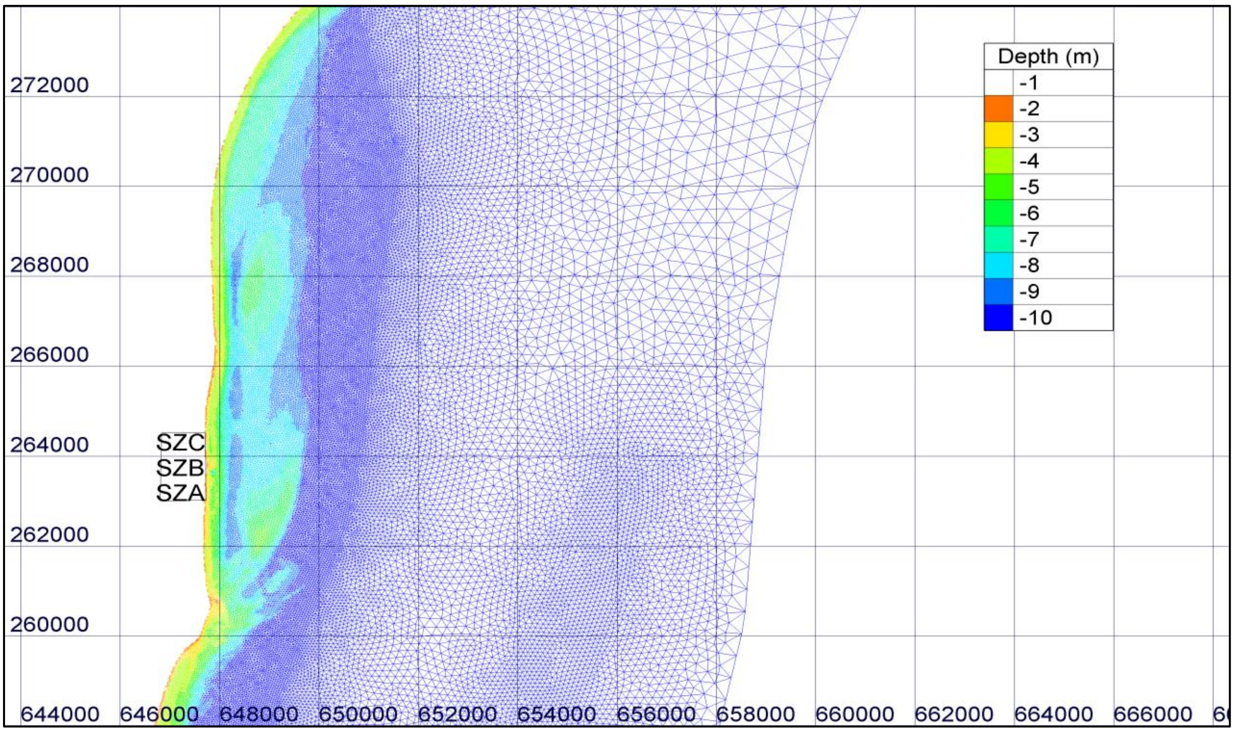

Figure 23 Bank migration by 700m, depths in meters ODN. Horizontal axis Eastings, vertical axis Northings

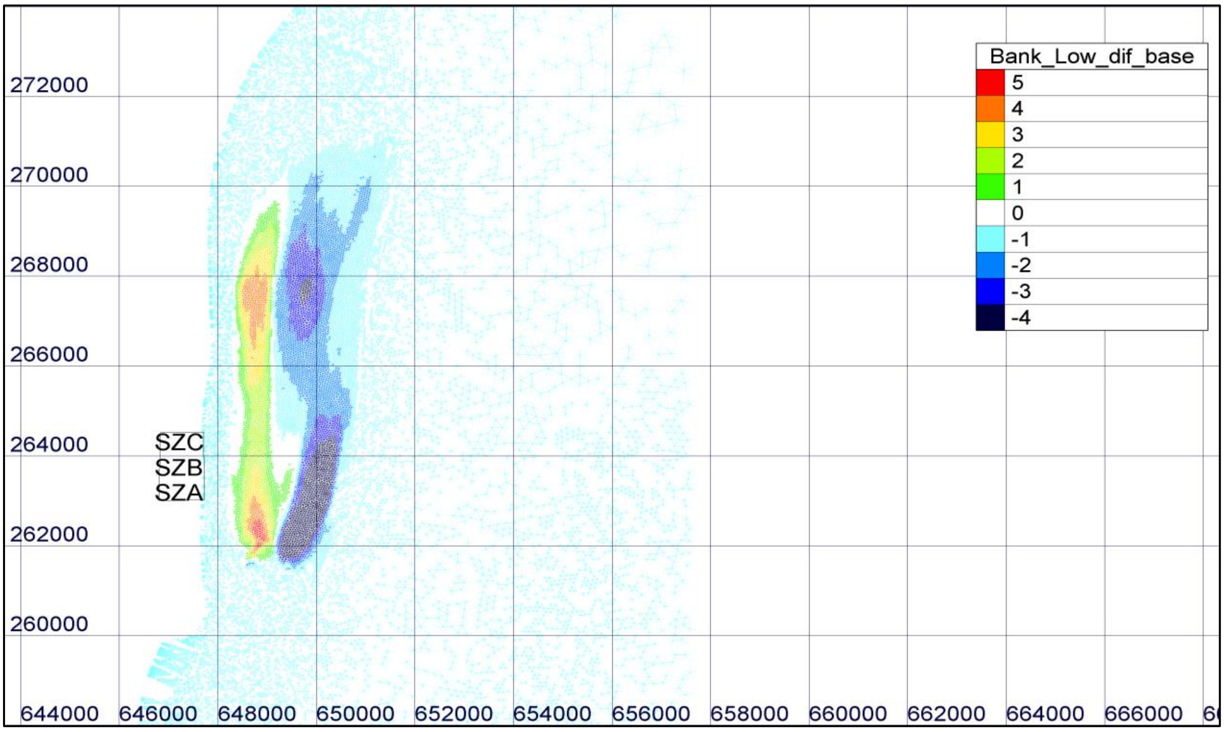

Figure 24 Bank migration (700m) - difference with baseline, in meters. Horizontal axis Eastings, vertical axis Northings

3 Results from Baseline, Climate change and Geoscenario modelling runs.

Approximately 2000 model runs have been undertaken for the combination of:

- extreme return periods (4); 1:100,1:200, 1:1000,1:10000
- location on the joint probability curve, for varying conditions;
- each sector (2);
- sea level rise cases due to climate change (10); and
- geomorphic scenario (5 + baseline).

In addition, a number of lower return periods (0.5 to 100 year) have been run for specific cases. Each of the 2000 model runs produces a number of parameters, Wave height, wave power, breaking fraction, and direction. Clearly it is unwieldy to show the results from all runs and all the parameters, the following sections therefore aims to show the most pertinent results to enable the reader to develop an overall holistic view.

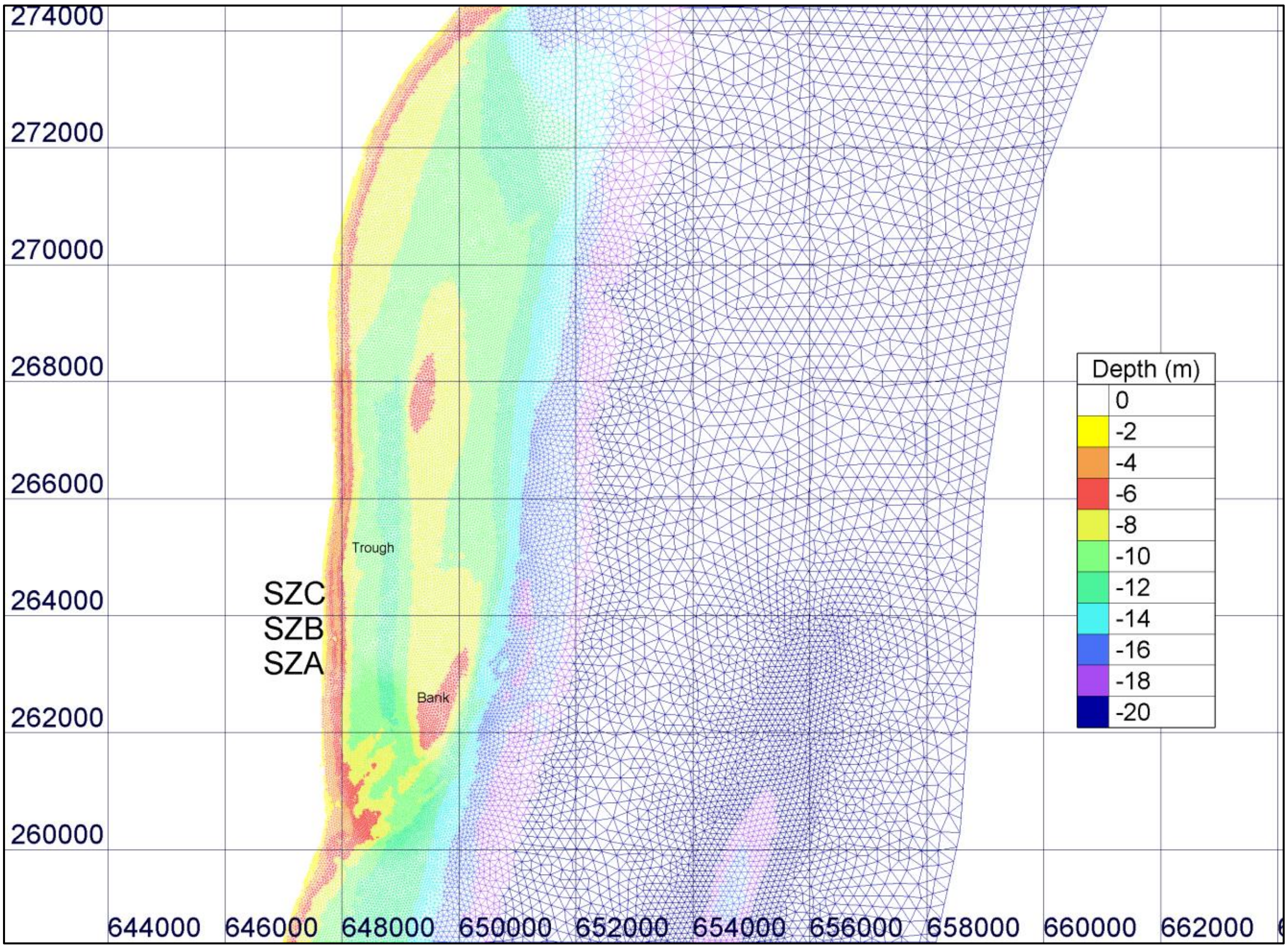

Figure 25 Present bathymetry ODN (and model grid nodes). BNG Co-ordinate system. Horizontal axis Eastings, vertical axis Northings.

3.1 Baseline – current sea level and bathymetry. Variation of the wave height water elevation relation for the same joint probability frequency event (1:1000)

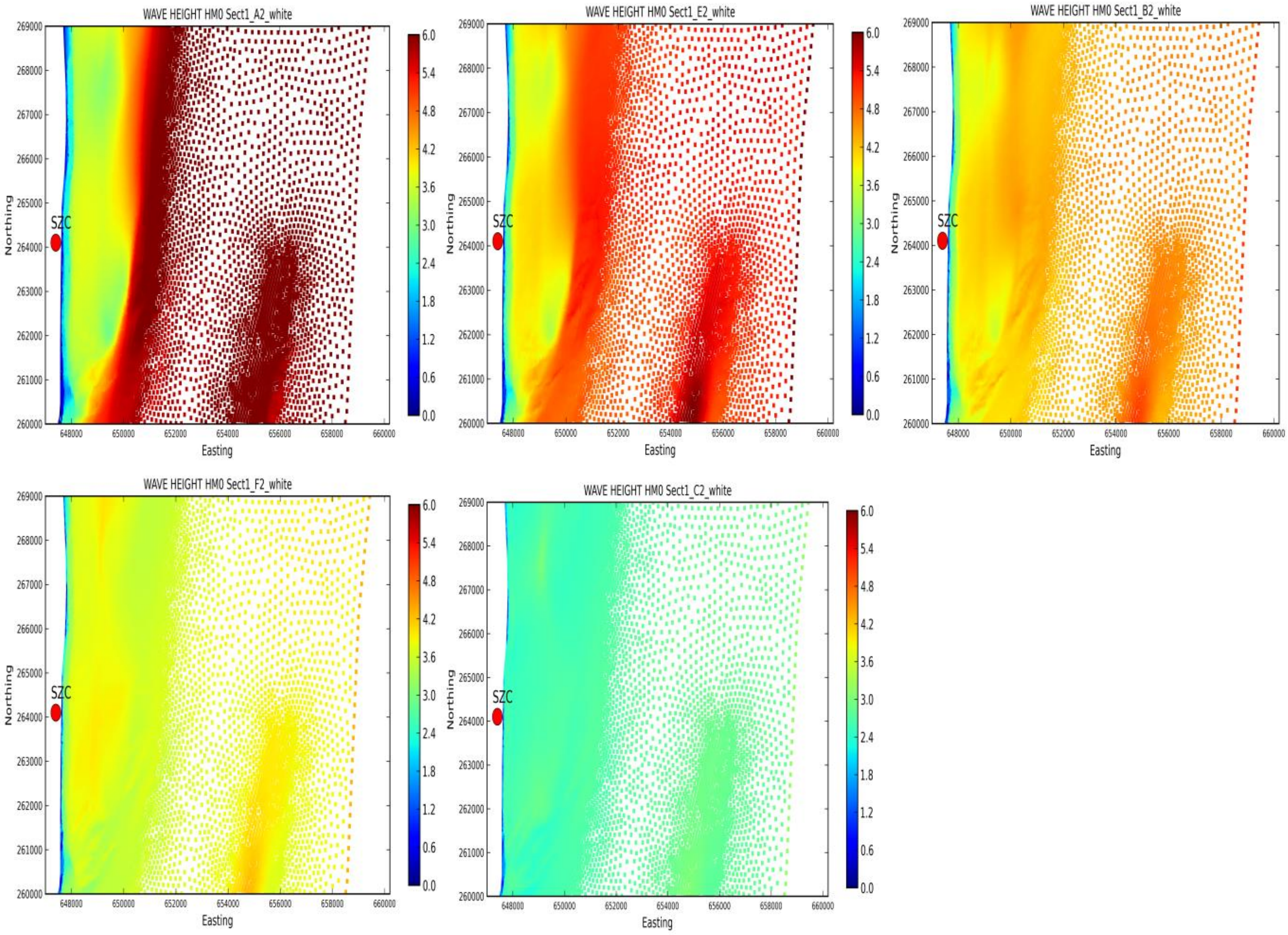

Figure 26 Wave height for present sea level (2008) and bathymetry (Baseline) for different points on the JPA curve (A,E,B,F,C) Sector 1. Please zoom figures to 160% to read better.

Condition A2 (Hs 7.1m, water elevation 1.89m at the boundary), shows the greatest effect of the bank with reduction in wave energy on the outside of the bank and on the inside. Condition E2 (Hs 6.28m, elevation 3.03m at the boundary), has less breaking on the banks and therefore results in near shore wave heights greater than in the A2 case. Condition B2 (Hs 5.21m, elevation 3.62m at the boundary), shows some breaking across the banks with waves above around 4m propagating to inside the bank. Condition F2 (Hs 4.47, elevation 4.02m at the boundary) shows the decrease across the bank, but interestingly a small increase inshore, due to wave - wave interactions coupled to local generation. Condition C2 (Hs 3.23m, elevation 4.22m at the boundary) has the highest surge element and with such a large surge there is little interaction with the bank as the waves, which are around 2.5 - 3m Hs, propagate inshore to the near coastal region with little change. A way to summarize this behavior is shown below which is an extraction of Hs along Northing 265000.

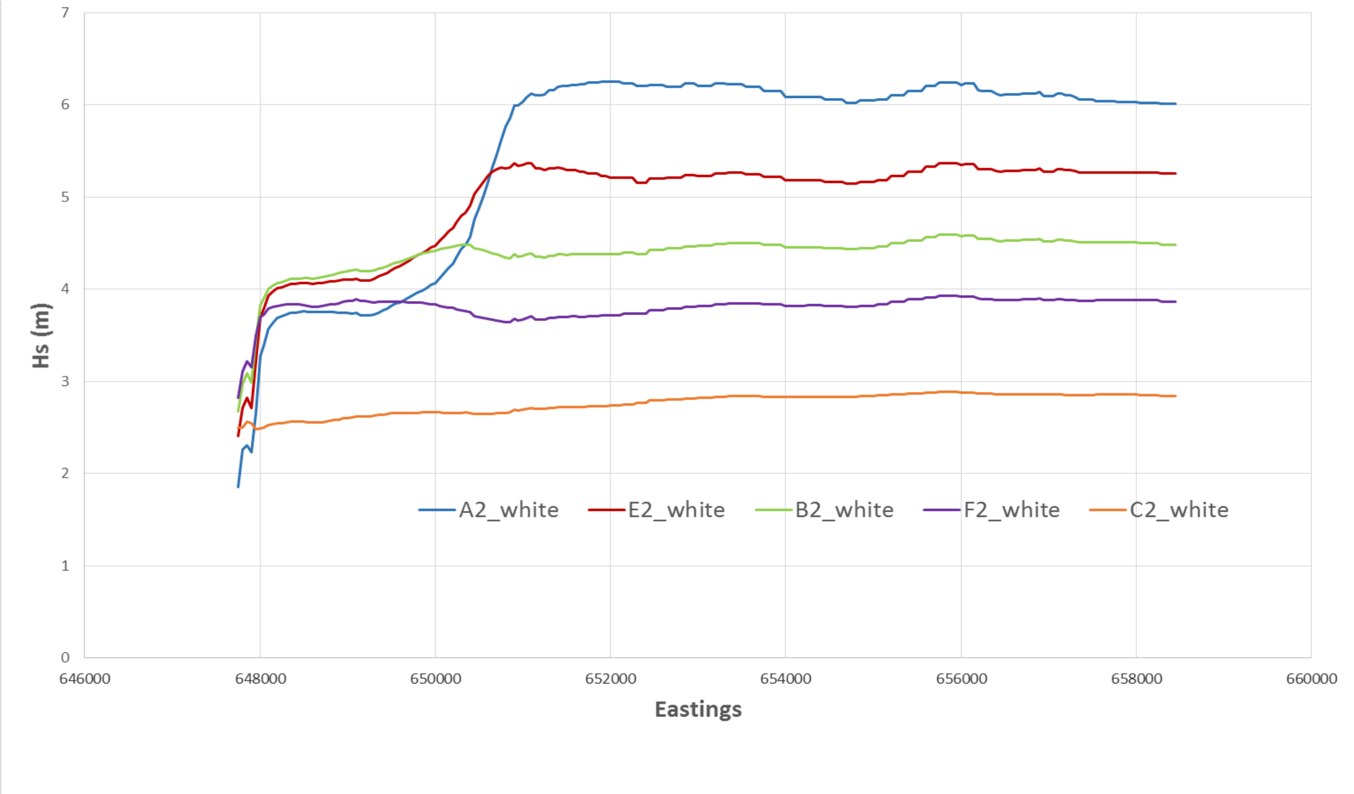

Figure 27 Significant wave height along Northing 265000 for present bathymetry case 1:1000. Sensitivity of near shore wave conditions to the boundary conditions for present bathymetry, Sector 1.

Evident from Figure 27 is that conditions E and B produce the highest wave heights in the region of the offshore bar at around easting 648000 which is approximately 300m from coastline at mean sea level. Onto the near shore bar and close by the beach condition F2 results in the highest wave heights onto the beach despite the initial wave height at the boundary being approximately 2m less than the A2 condition. Evident from Figure 25 is that the top of the Bank is between Eastings 649000 and 650000, however the steepest gradient occurs further east from 16m depth (Easting 651028) to 10m depth (Easting 650632) which is where the abrupt change in the A2 condition occurs.

While it is necessary to simulate extreme waves to comply with flood risk and site safety assessment requirements, more normal conditions need to be considered to understand the role of the banks and how waves vary inside of the trough. The results of Hs simulations are presented below for wave breaking and for wave power in Appendix B.

3.1.1 The role of the Sizewell Bank; wave breaking simulations for current conditions.

In order to understand where wave energy is expended in the present Sizewell system we undertook an investigation of the spatial distribution of the wave breaking and the associated effects on the distribution of wave height and wave power using a series of increasing wave heights with return periods from 0.2 to 100 years. The 9 values used in the modelling for Sectors 1 and 4, as well as the associated wave periods and wind speed are given in Table 6. In all cases the water levels were taken as 0.13m ODN (mean sea level) and the wave return periods were consistent with condition A. Condition A was chosen as the changes in wave power and energy flux are clearest with the highest waves, the figures associated with these outputs are shown in Appendix B. Only low return period events have been considered so that a comparison with known patterns of wave breaking can be undertaken.

Figure 28, shows one example of the distribution of wave breaking[2] for Sector 1 with a wave height return period of 50 years. Figure 29 and Figure 30 show the full wave breaking fractions for Sectors 1 and 4 respectively with a broadly similar behaviour of wave breaking demonstrated for both sectors. (the breaking fraction being the ratio of waves that have undergone breaking to those that haven't).

[2] As waves approach shallow water when the water depth decreases to one half of a wave's wavelength, the wave starts to "feel the bottom" forcing the wave height to increase. The base of the wave is slowed down by friction against the sea bottom, while the top of the wave rushes ahead, so the wave crest begins to lean more and more forward until it topples over, and breaks.

For the lowest wave heights considered, namely the 1 in 0.2 years W02 cases, only limited breaking takes place over the offshore banks and most wave breaking and hence energy dissipation is expended over the longshore bars. When considering higher waves and more extreme wave cases W02 – W10, a greater fraction of breaking occurs on the outside of the bank where the change in bathymetry is greatest. Interestingly for W20 – W100 return periods wave breaking occurs on the outside of the bank but also over a larger area over the whole of the bank, e.g. at Northing 26800.

Table 6. Boundary conditions run for current mean sea water levels.

Annual Probability				
Sector 1 (from 30deg N)	Name	Hs (m) Wave Height	Mean Period Tm01 (s)	Wind (m/s)
1: 0.2	W02	3.27	7.9	14
1: 0.5	W05	3.70	8.3	15
1: 1	W1	4.02	8.7	16
1: 2	W2	4.35	9.0	17
1: 5	W5	4.76	9.4	18
1: 10	W10	5.08	9.7	19
1: 20	W20	5.39	9.9	20
1: 50	W50	5.80	10.3	21
1: 100	W100	6.11	10.5	22
Sector 4 (from 150deg N)	Name	Hs (m) Wave Height	Mean Period Tm01 (s)	Wind (m/s)
1: 0.2	W02	3.09	5.8	13
1: 0.5	W05	3.39	5.9	14
1: 1	W1	3.61	6.0	15
1: 2	W2	3.83	6.1	15.5
1: 5	W5	4.11	6.3	16.5
1: 10	W10	4.31	6.6	17
1: 20	W20	4.51	6.4	17.5
1: 50	W50	4.78	6.5	18
1: 100	W100	4.97	6.6	18.5

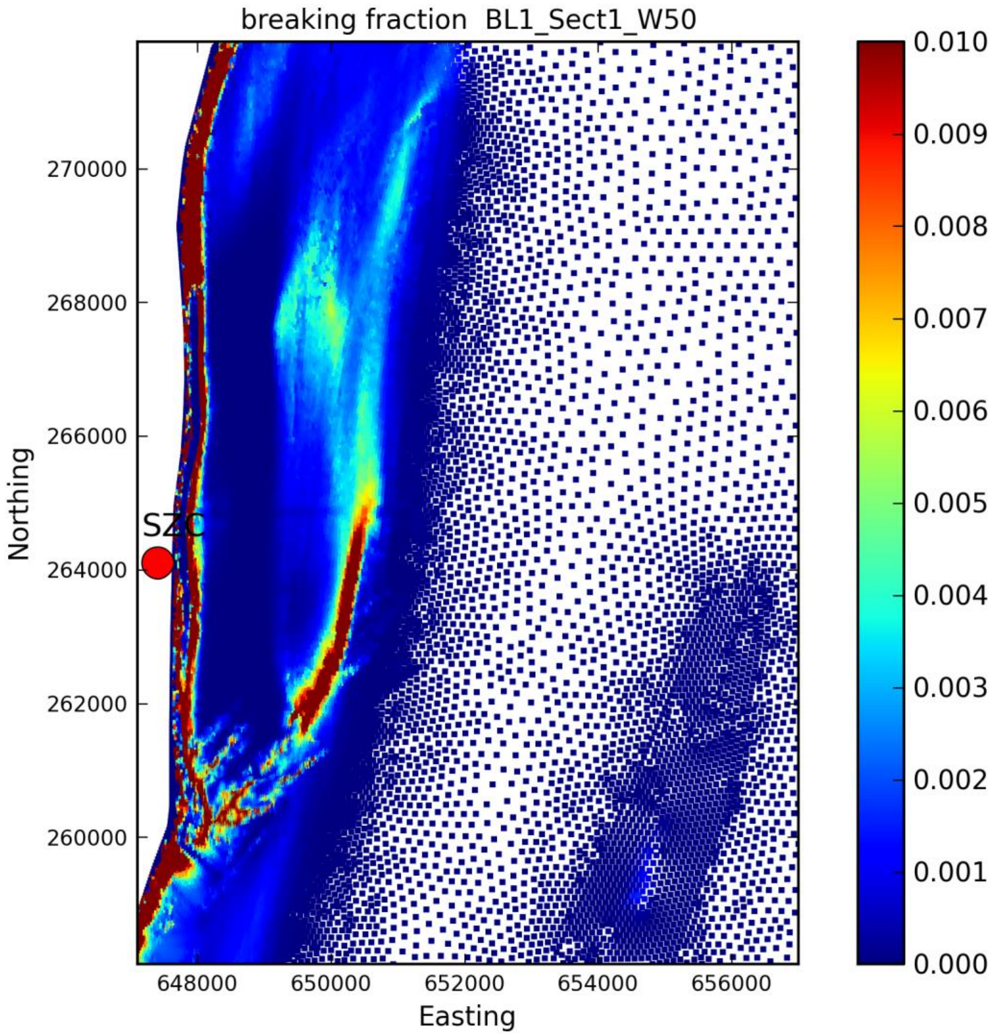

Figure 28 Breaking fraction for 1:50 year waves from Sector 1 (North). Note high breaking fraction on the outside of the Bank

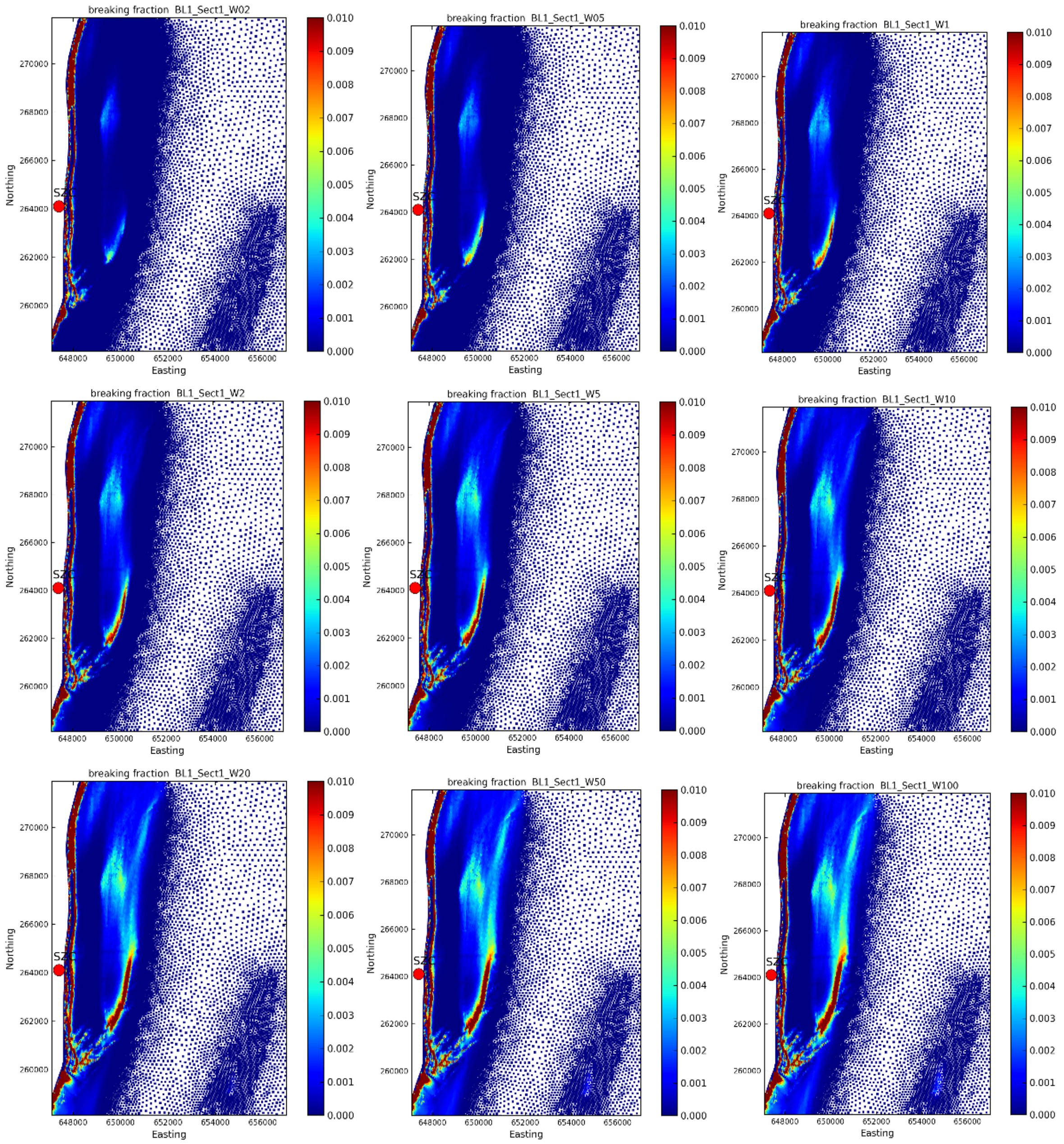

Figure 29. Wave breaking fraction for cases W02-W100, Sector 1 using present bathymetry

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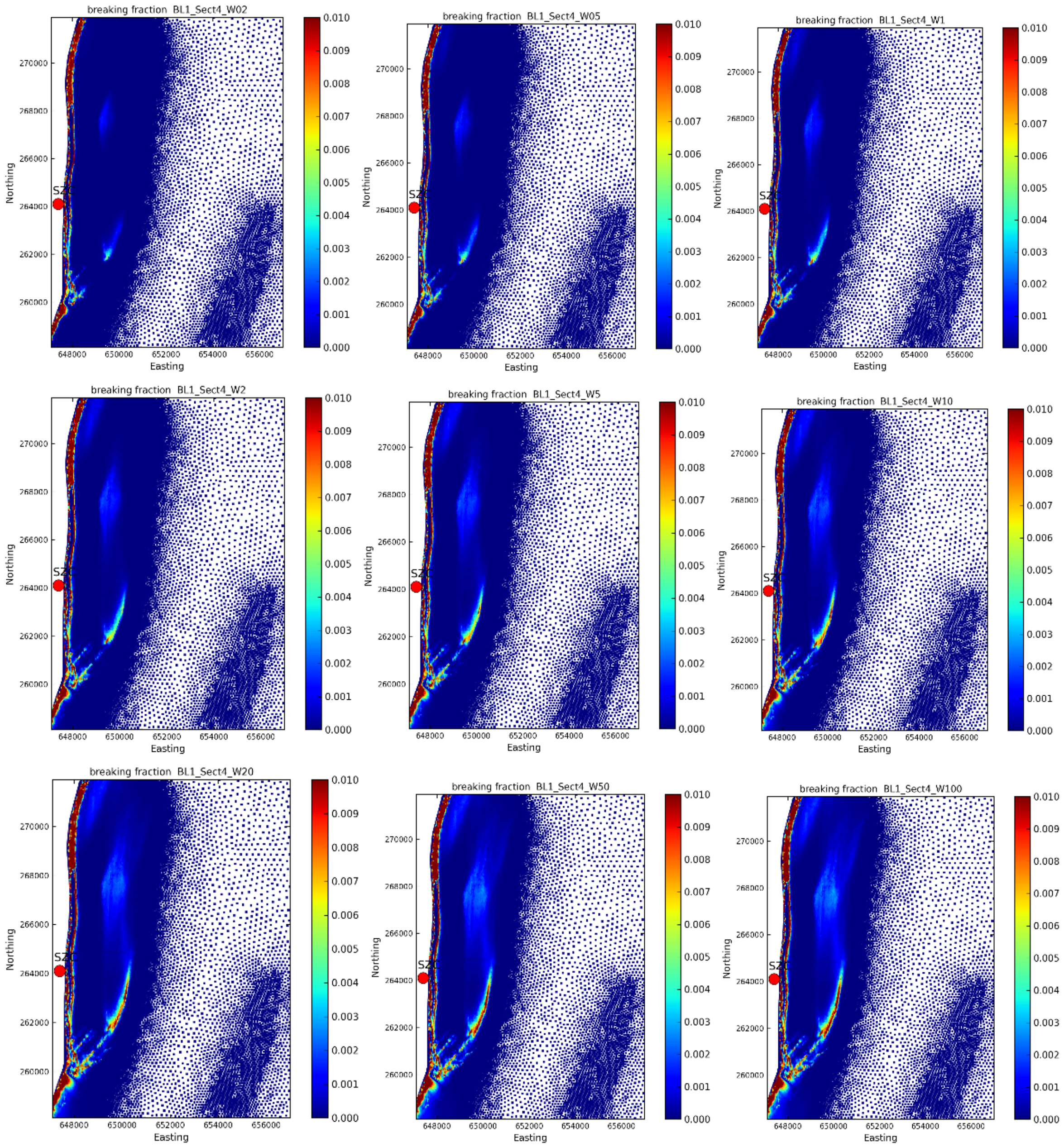


Figure 30. Wave breaking fraction for cases W02-W100 Sector 4 using present bathymetry.

3.2 Simulation of climate change cases (white 0m, green 0.74m, blue 1.01m, purple 1.55m brown 1.81m SLR)

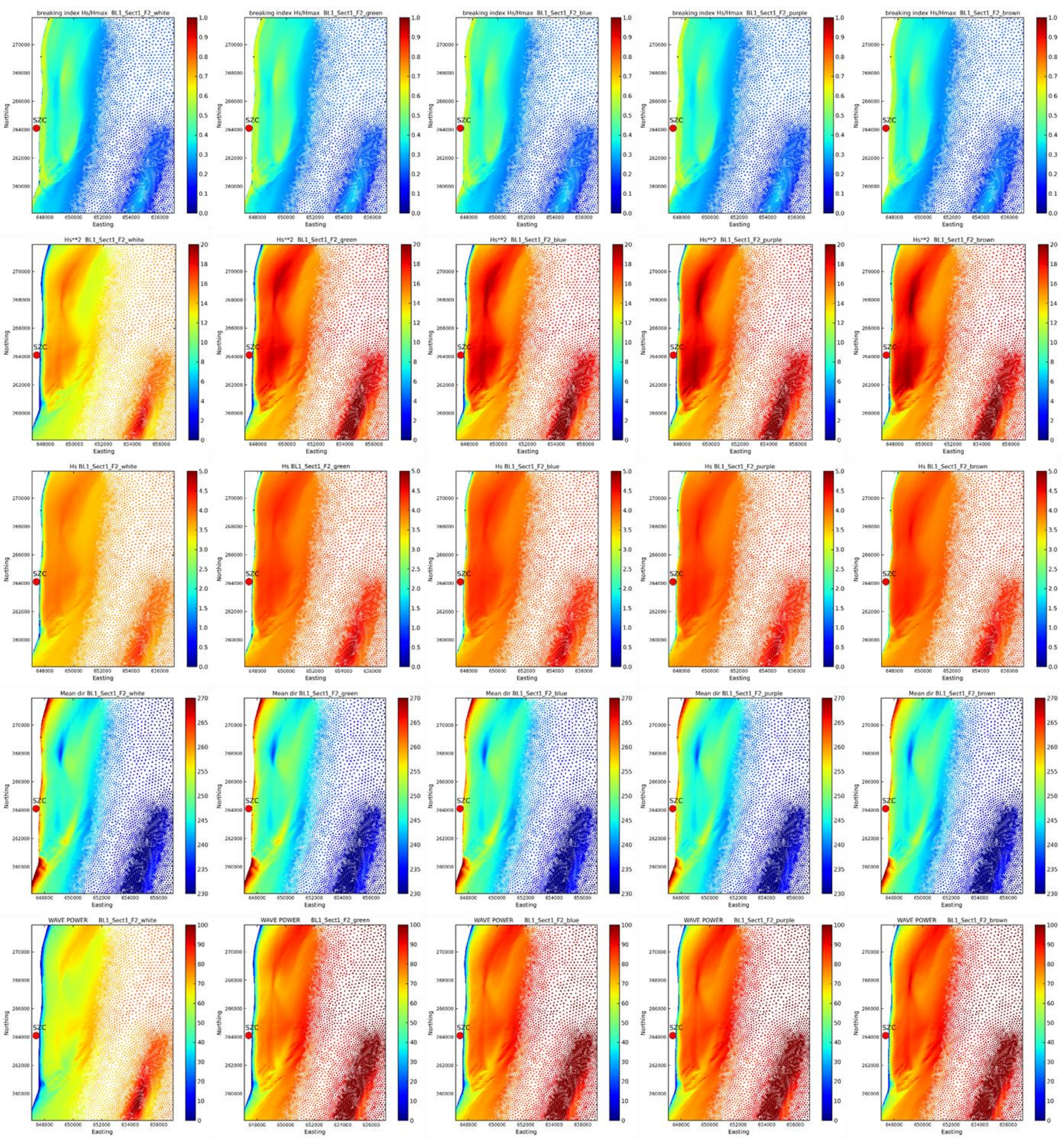


Figure 31 Breaking ratio[3] (index), Square of wave height, wave height, mean direction (too), wave power, condition F2, for climate cases (white, green 0.74m, blue 1.01m, purple 1.55m, brown 1.8m SLR) please zoom to view images.

[3] The breaking ratio is determined as the ratio of the modelled H_s to the potential maximum wave height H_{max}, where H_{max} is 0.73 * local water depth. (Battjes and Stive 1985)

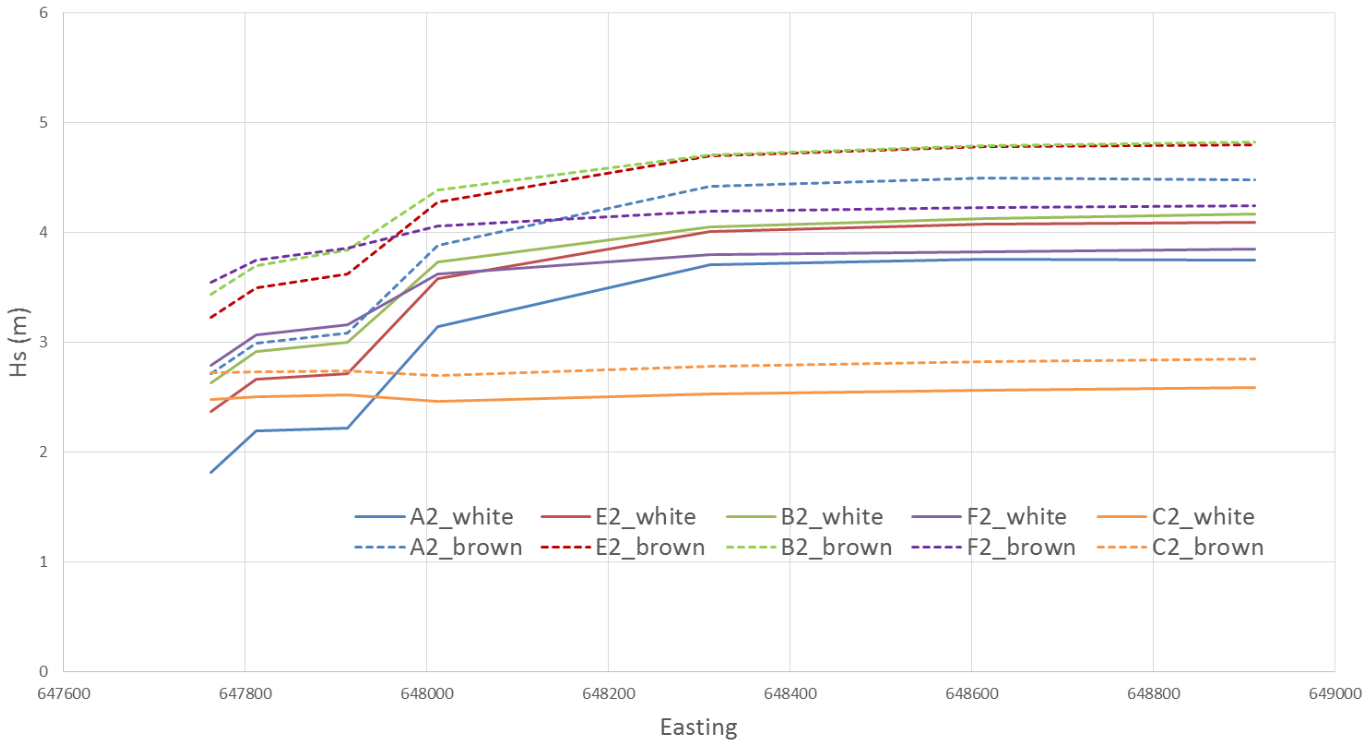


Figure 32 Nearshore (0- 1200m) wave height Hs (m), for Sector 1 simulations at 1:1000 return period, baseline levels and including 1.8m of sea level rise (brown case).

As demonstrated in Figure 27, the F2 condition results in the highest near shore wave heights, these have therefore been considered using climate change scenarios as in Figure 31 which shows the F2 (1:1000) for sea level rise conditions. Evident from the wave breaking ratio (index) for the white case (baseline), in contrast to the lower return conditions, is that much of the breaking fraction is spread out over the entire bank area and inshore towards the near shore bars. This is in contrast to low return cases where breaking occurs on the outside of the bank and on the near shore bars. In relation to the wave height and subsequent plots it should be noted that the offshore wave height boundary conditions are 10% higher for the climate scenarios compared to the baseline, case, hence there is greater wave power in all climate cases compared to the baseline, however there appears to be little difference in near shore wave power between green, purple, blue and brown cases. In relation to potential wave run up which is the primary flood risk concern it is the near shore wave power that is relevant.

To demonstrate the role of increased sea level, Figure 32 (which is similar to Figure 27) shows the closest 1200m inside of the Sizewell Bank complex, for the conditions around the JPA, for the base line and the climate simulation of 1.8m increased water level (Case brown). For the increased water level case the B2 and F2 simulations produce the highest near shore wave heights and these are significantly higher than the corresponding no climate (white) runs.

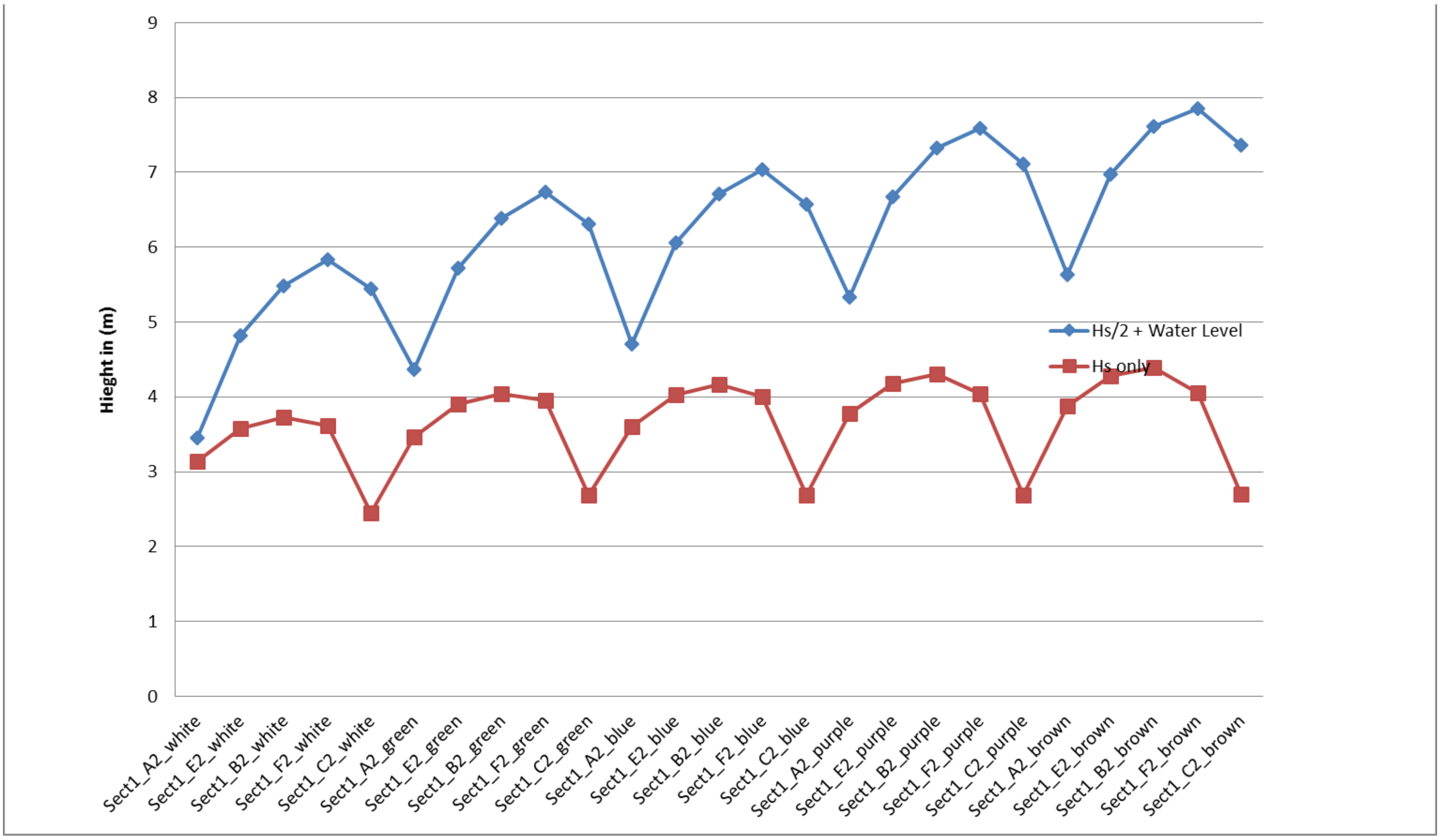


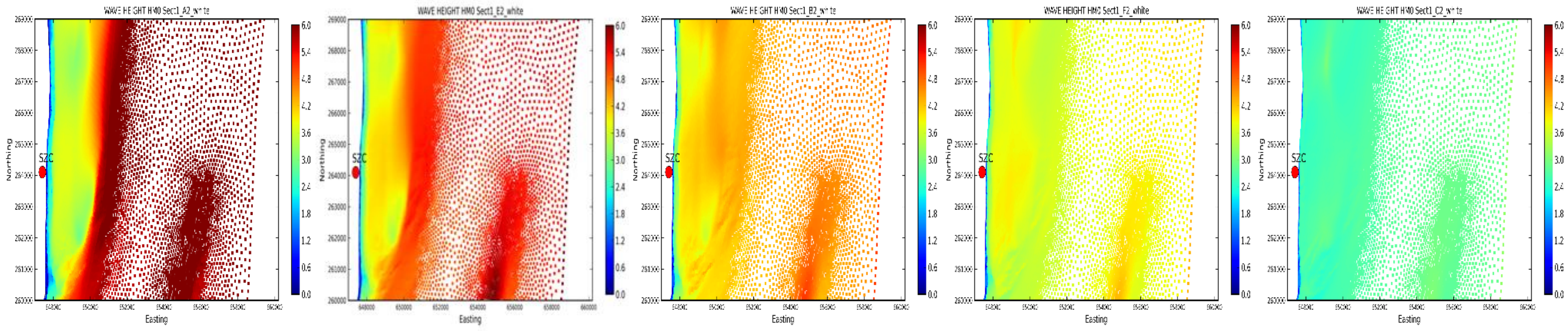
Figure 33 Combined half significant wave height + water level for Sector 1 for six climate cases (white, green, blue, purple and brown from Table 2) at 300m from the coast at 1:1,000 return periods. This is not to indicate wave run up but to give an indication of how the different cases relate to the near shore peak water levels.

Figure 33 shows a summary of predicted extreme water levels for five climate change related SLR cases for the A, E, B, F and C conditions, for 1: 1,000 year events, for Sector 1. Evident from this is that for the white (baseline) and green scenarios (0.74m SLR), maximum water levels are similar between the B, F and C cases. For the more extreme climate scenarios (purple and brown 1.55m and 1.8m SLR respectively) then the F case becomes more dominant.

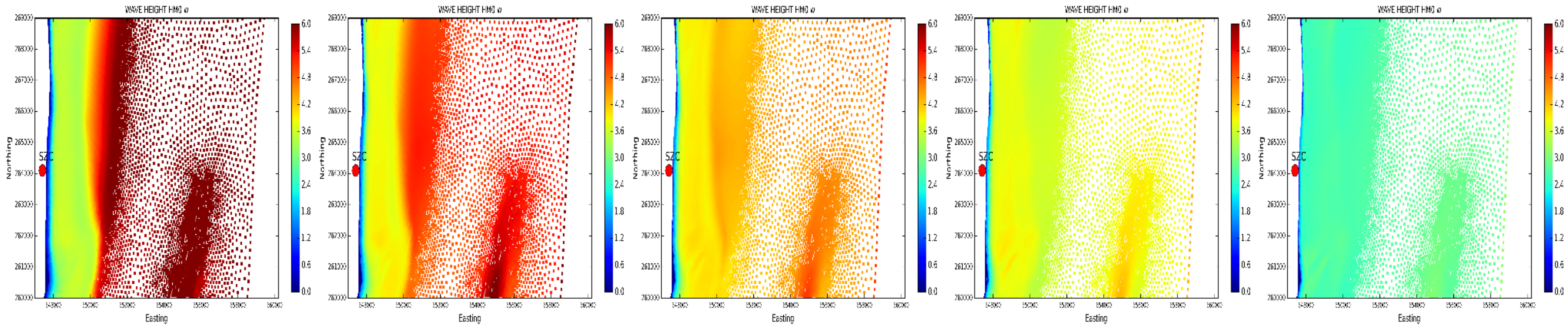
3.3 Simulation of conditions around the JPA curve for different geomorphic scenarios.

Figure 34 shows the results of simulations of the geomorphic scenarios with present sea levels. (Present sea levels have been used as they are most likely to show the effect of the scenario). The response to each geoscenario compared to baseline is slightly different depending on the JPA condition considered. The response at the coast line also varies geographically. The elongated bank scenario results in near shore wave heights which are very similar to the present baseline case. The shallow southern trough scenario generally results in reduced energy into the area south of Sizewell, with slightly higher wave heights in the Minsmere region to the north of the SZC location.

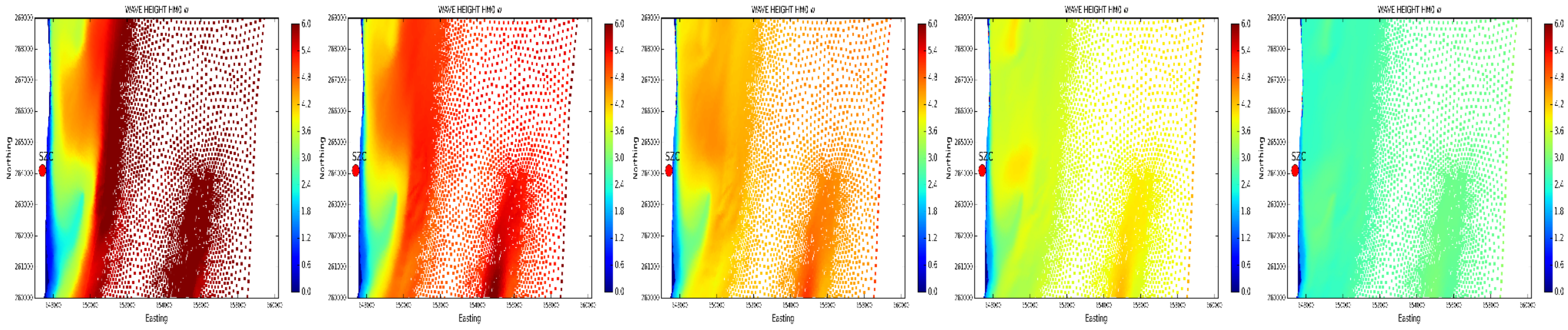
The lowered bank by 5m (which includes removal of sediment) shows the greatest difference from baseline for conditions A, E and B, with higher wave heights inshore. The lowered bank simulation is therefore worthy of further consideration. The lowered bank with infill simulation is similar to the lowered bank simulation but in the vicinity of SZC a little less wave energy reaches the shore line. The migrated bank scenarios are very similar to the baseline, in relation to near shore wave heights (and hence energy),



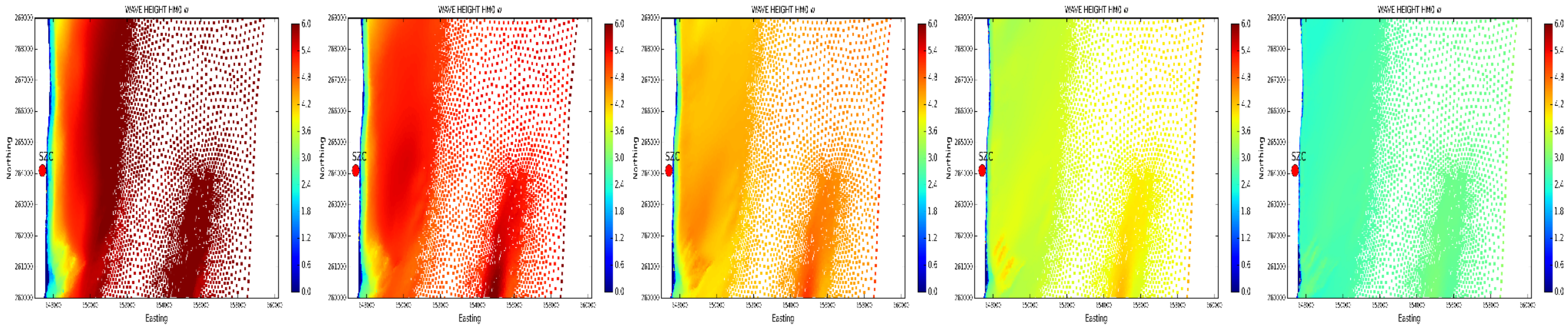
Baseline, present bathymetry.



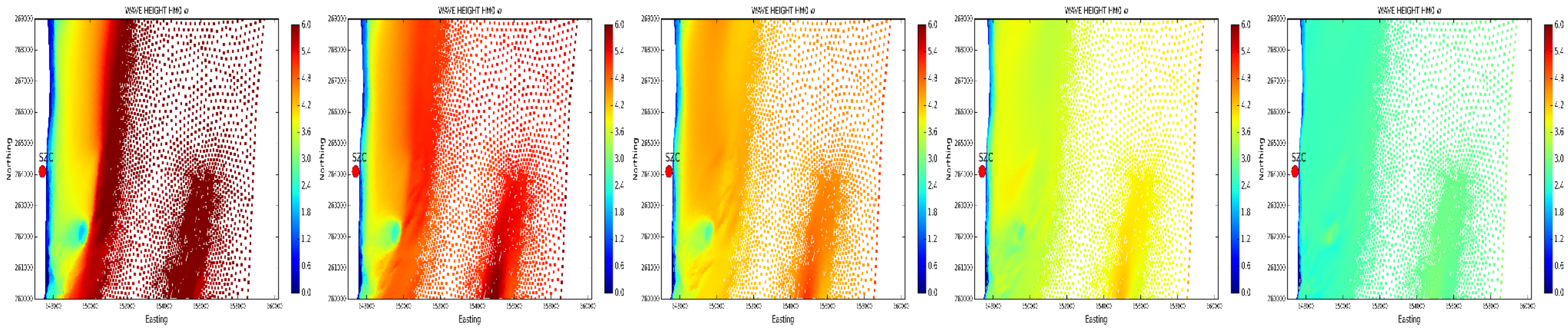
Elongated bank.



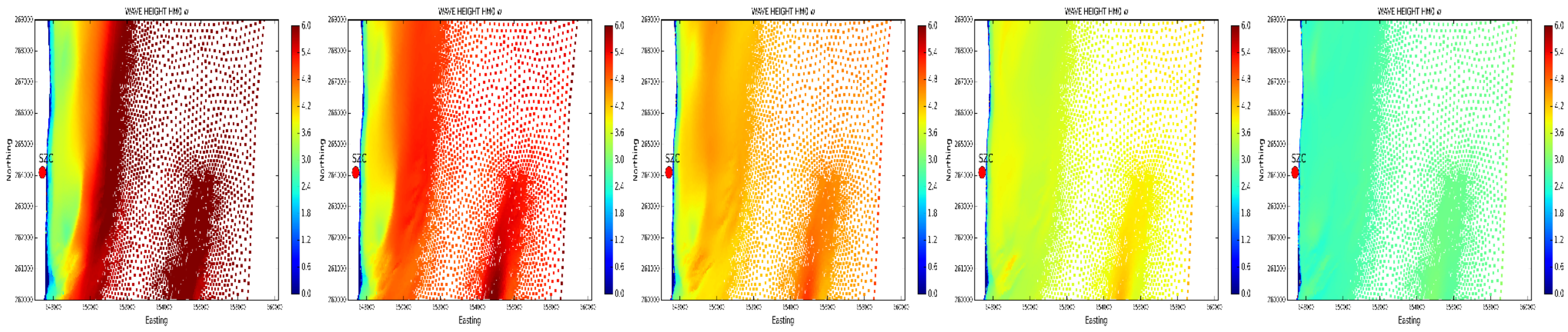
Shallow trough



Lowered bank by 5m.



Lowered bank and infill.



Migrated bank, eastwards by 700m.

Figure 34 Geoscenarios for present sea level (case white) for Conditions A2,E2,B2,F2,C2 (1:1000) around the JPA curve

3.4 Simulations using different water levels (climate change predictions) for baseline and lowered bank scenarios.

It should be noted that all the cases shown in Figure 34 are at the baseline water level (0.13m ODN “white”). Given the different effects observed in the simulations over the range of boundary conditions from Table 7 and noting that extreme events could include, besides extreme waves, a significant surge component, we conducted simulations for several cases with large water levels. These simulations were based on 1 in 1000 years Sector 1 case ‘F2 white’ (Hs=4.47m and WL=4.02m ODN), with consideration given also to future climate changes, namely the ‘blue’ and ‘brown’ scenarios (1.105m and 1.8m increases in water levels), thus resulting in 3 cases with water levels of WL=4.02m, 5.125m and 4.82m ODN, respectively. The results showing the spatial distribution of wave breaking fraction, significant wave heights and wave power along wave-crest for the 3 cases are shown in Figure 35 for the 5m bank lowering geoscenario and difference between the scenario and present baseline Figure 36.

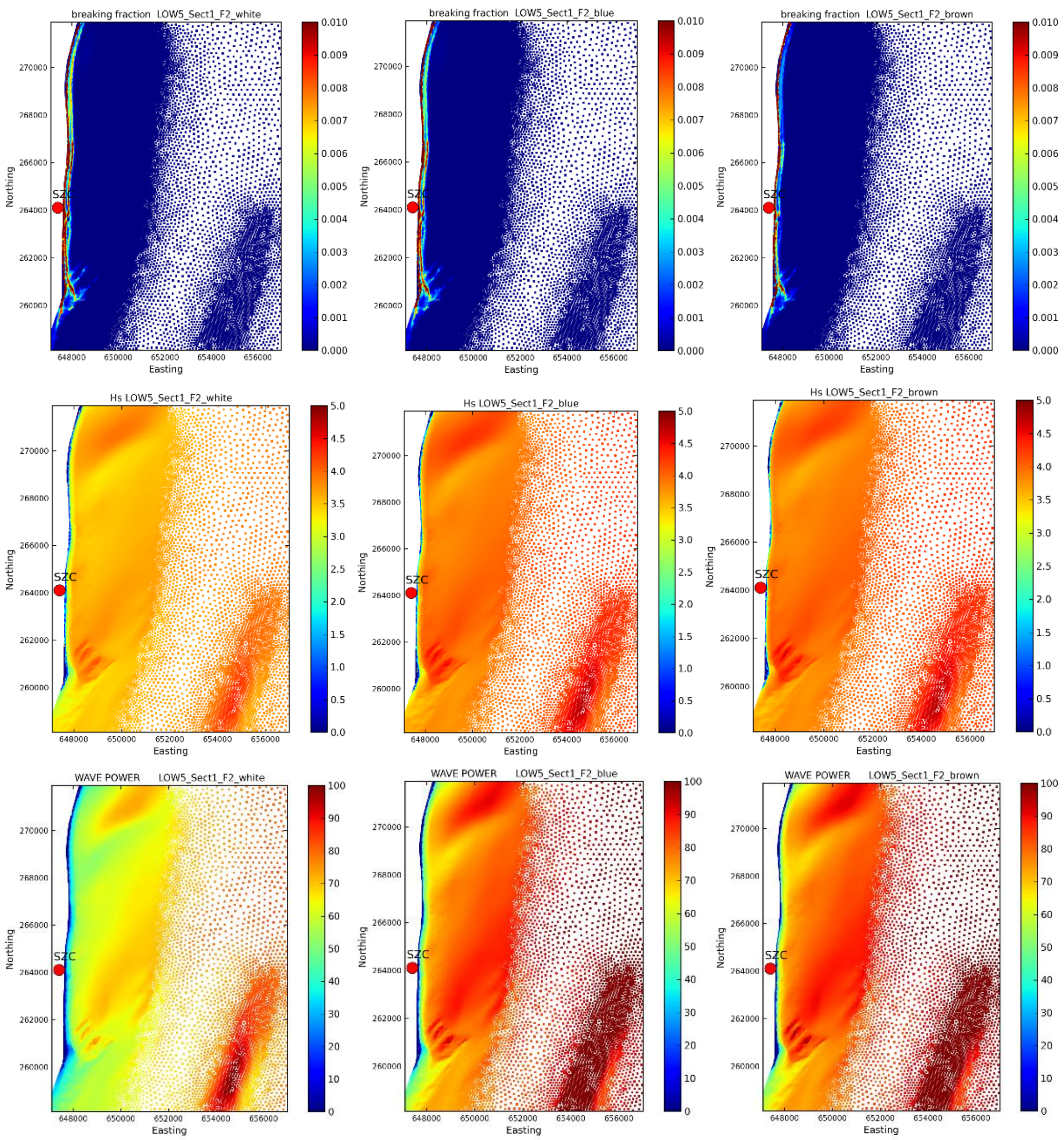


Figure 35. The 5m bank lowering geoscenario breaking fraction (top row), significant height (middle row) and power per unit crest length (bottom row) for Sector 1 cases F2 white, blue and brown (Hs = 4.47m, WL = 4.02m, Hs =4.92, WL=5.125m and Hs= 4.92, WL = 5.82m ODN, respectively).

Figure 35 indicates that for the lowered bank scenario there is some difference between the present case (white) and the blue case, but little change from the blue case to the brown. Figure 36, shows the difference between the Lowered bank and present bathymetry for the three climate change cases as well as a near-shore zoom-in view for the ‘white’ and ‘brown’ cases only in Figure 37.

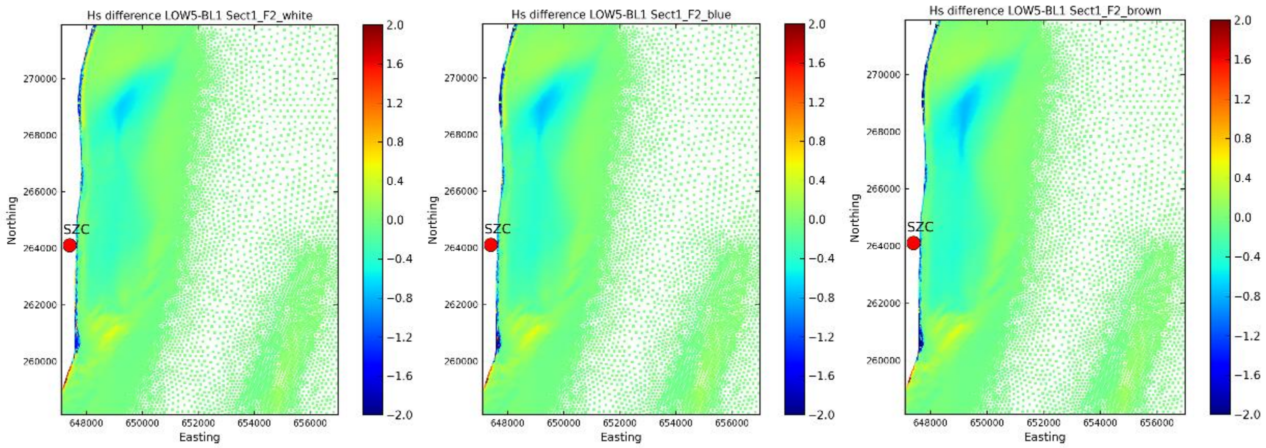


Figure 36. The difference in significant wave height between the 5m bank lowering and present bathymetry geoscenarios for Sector 1 cases F2 white, blue and brown (Hs = 4.47m, WL = 4.02m, Hs = 4.91m, WL = 5.125m, Hs=4.91m, WL= 5.82m, respectively).

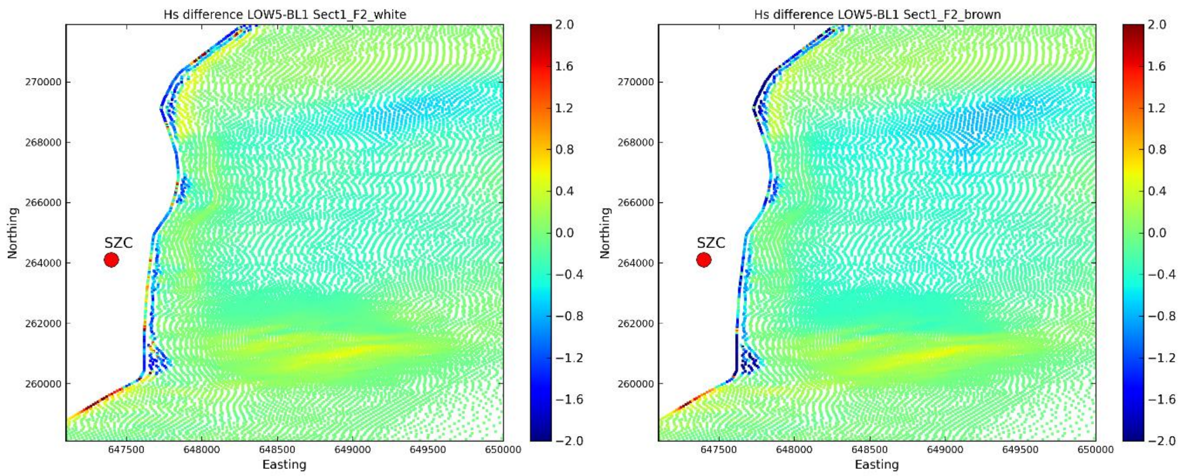


Figure 37. Near shore view of the difference in significant wave height between the 5m bank lowering and present bathymetry geoscenarios for Sector 1 cases F2 white and brown (Hs = 4.47m, WL = 4.02m and Hs = 4.92m, WL= 5.82m, respectively).

The results shown in Figure 36 and Figure 37 confirm the modest effect of the offshore banks in these elevated water level cases simulations. Some limited differences (at most 0.5m or about 10% of the local significant wave height) can be observed over the banks and to the south of the banks area. These differences, mostly negative over the banks and especially in the north (i.e. bank removal reduces wave height) and positive to the south of the banks (i.e. bank removal increases wave height) are due to shoaling over the banks as well as changes in the wave refraction patterns around them. The slightly counter intuitive result that for the extreme events there is little difference between the present bathymetry and future scenarios, drives further investigation into lower return periods. A full analysis is in Appendix B with a subset presented below.

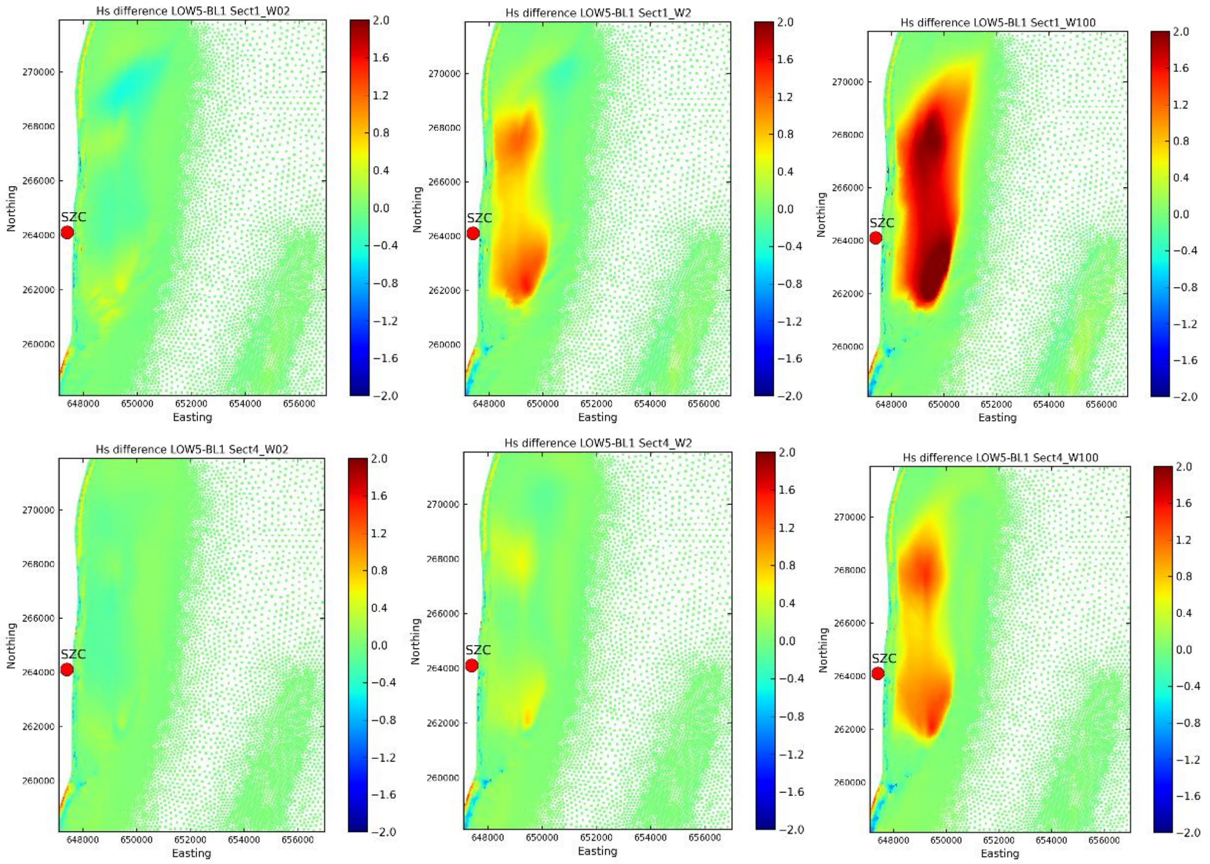


Figure 38. The difference in significant wave height between the 5m bank lowering and present bathymetry geoscenarios for cases W02 (2 per year), W2 and W100, Sector 1 and 4.

Figure 38 shows the difference in significant wave heights between the 5m bank lowering and the present bathymetry scenarios, for the lowest (1 in 0.2 years W02), an intermediate (1 in 2 years W2), and the highest (1 in 100 years W100) boundary waves cases, for both Sector 1 and Sector 4.

In the case of the lowest waves W2 (3.27m for Sector 1 and 3.09m for Sector 4), the difference in wave height is slightly negative over some of the banks area, i.e. the removal of the banks results in a modest decrease of wave heights in this area. This suggests that for the set of boundary conditions at the lowest end of the range we considered here, the effects of the offshore banks on the wave propagation is one of wave shoaling and little or no breaking. For increased boundary wave heights, however, as illustrated by the results in W2 case (4.35m for Sector 1 and 3.83m for Sector 4), and especially in the W100 case (6.11m and 4.97m), the differences are becoming more positive, i.e. the removal of the banks for the system results in significant increase in wave heights over the banks area. This shows that for the sets of boundary conditions at intermediate and upper end of the range we considered (see Table 7), the main effect of the offshore banks on the wave propagation is one of wave breaking. However, even in the case of the highest waves W100, there is very little difference in the very near-shore (~200m) area between the results of the two geoscenarios.

3.5 What happens to wave period across the domain?

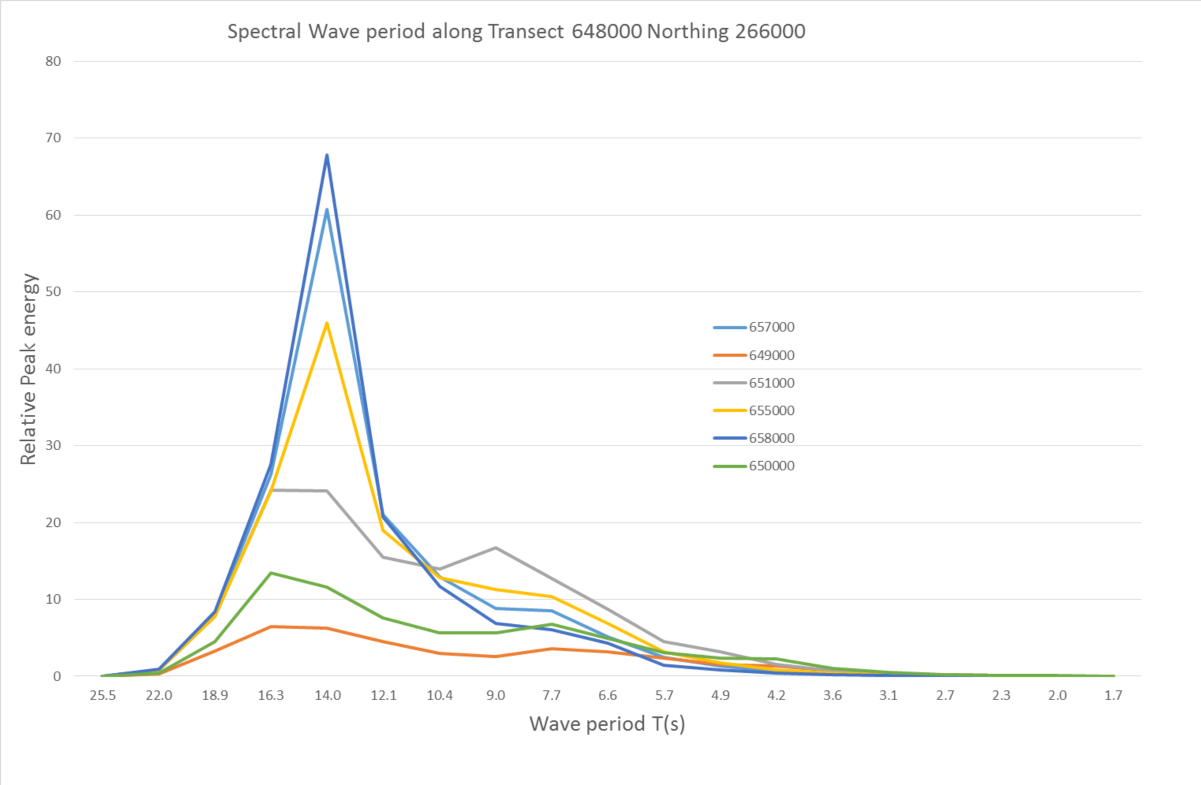


Figure 39 Wave energy spectrum along a transect (Northing 266000) for the A1 White case. Note peak period remains the same, the mean period becomes much shorter with propagation onshore. The legend gives the Easting position of the point analysed. Points are West – East.

One feature of propagation of large waves across the sand bank system and the subsequent propagation across sand bar systems, is that the mean period and peak periods will change. As the waves lose energy from bottom friction, wave-wave interaction and breaking there will be a transfer of energy to shorter periods. Thus, the mean wave period will alter substantially whereas the peak period associated with the most energy will remain approximately constant. Figure 39 shows the distribution of energy with period, for a West – East transect, slightly to the North of the Minsmere sluice; the near shore positions have the widest spectrum.

4 Conclusions

This report shows that for present bathymetry the JPA conditions of B and F result in the highest near shore wave heights, and when considered with water level, the highest combined extreme wave level comes from these conditions. Including the effects of climate change (increased water levels and wave height) gives increased waves at the shore line, with the B and F conditions resulting in greatest combined levels.

The simulations of the geomorphic scenarios show that it is only the lowered bank scenario that results in near shore wave increases in the vicinity of the SZC proposed site. Simulations run at low return periods (2 to 100 years) do show near shore (1000m) increase in wave energy in the lowered bank simulations and by inference the importance of the present bank, although very near shore (<200m) there is little difference. However, for extreme waves (1:1000 returns), when sea levels are also raised there is little difference in the near shore between the geoscenarios and the present bathymetry. Geoscenarios are necessarily artificial (albeit developed from the existing bathymetry), whereas present bathymetry has been accurately surveyed, it would therefore seem logical to focus the majority of subsequent work (e.g. wave run up studies) on the present bathymetry cases.

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Appendix A The Weibull method

Weibull distribution:

$P(H_s)=1-\exp[-\{(H_s-a)/b\}^c]$ (1)

H_s = significant wave height

P=probability less than H_s

Parameters *b* and *c* are found by least squares (linear regression) fitting; parameter *a* is found by minimising RMS difference between data and the linear fit.

Calculation of the H_s for a given return period ($N_{R.P.}$ years)

The probability of the $N_{R.P.}$-year return period event is:

$P(N_{R.P.}$ year event$)= 1- 1/(N_{R.P.} \times n)$ (2)

where *n* is the average number of events per year.

The significant wave height H_s for a given return period $N_{R.P.}$ can then be calculated by substituting relation (2) into (1).

Our data covers 33 years (1980-2012). The number of observations is 56239 in Sector 1 and 56689 in Sector 4, thus giving *n*=1704.21 events/year for Sector 1 and *n*=1717.85 events/year for Sector 4.

The observations were binned, with successive bins separated by 1cm (resulting in approximately 500 bins). An experiment with bins separated by 5cm and 10cm was undertaken, and the results of predicted H_s were different by no more than 1cm from those in the table above.

The method for calculating the 95% confidence limits quoted for each return period was to use the calculated Weibull parameters *a*, *b*, and *c* to generate random distributions of significant wave heights, with the same number of data points as the original (observational) distribution. We have used 100 of these seeded random distributions for both Sector 1 and 4, to calculate a sample of 100 random H_s values for each return period, and the 95% percentile values were calculated from the 100 random values.

Appendix B Further detail for low return periods for baseline and lowered bank scenario.

B.1 Understanding where energy is extracted; results of the wave breaking simulations with geoscenarios.

In order to understand where wave energy is expended in the Sizewell system we undertook an investigation of the spatial distribution of wave breaking and the associated effects on the distribution of wave height and wave power using a series of increasing extreme wave heights with return periods from 0.2 to 100 years. The 9 values used in the modelling for Sectors 1 and 4, as well as the associated wave periods and wind speed are given in Table 7. In all cases, the water levels were taken as 0.13m ODN, which represents the current mean sea level at Sizewell. Only low return periods events have been considered so that a comparison with known patterns of wave breaking can be undertaken.

Table 7. Boundary conditions to run for present mean sea water levels.

Probability				
Sector 1 (from 30deg N)	Name	Hs (m) Wave Height	Mean Period Tm01 (s)	Wind (m/s)
1: 0.2	W02	3.27	7.9	14
1: 0.5	W05	3.70	8.3	15
1: 1	W1	4.02	8.7	16
1: 2	W2	4.35	9.0	17
1: 5	W5	4.76	9.4	18
1: 10	W10	5.08	9.7	19
1: 20	W20	5.39	9.9	20
1: 50	W50	5.80	10.3	21
1: 100	W100	6.11	10.5	22
Sector 4 (from 150deg N)	Name	Hs (m) Wave Height	Mean Period Tm01 (s)	Wind (m/s)
1: 0.2	W02	3.09	5.8	13
1: 0.5	W05	3.39	5.9	14
1: 1	W1	3.61	6.0	15
1: 2	W2	3.83	6.1	15.5
1: 5	W5	4.11	6.3	16.5
1: 10	W10	4.31	6.6	17
1: 20	W20	4.51	6.4	17.5
1: 50	W50	4.78	6.5	18
1: 100	W100	4.97	6.6	18.5

Figure 27 and Figure 28 show the wave breaking fractions for Sector 1 and 4 cases, respectively. While for the lowest waves considered, namely the 1 in 0.2 years W02 cases, only some limited breaking takes place over the offshore banks and most waves break over the longshore bars, the breaking fraction over the banks becomes much more significantly when increasing wave heights are considered.

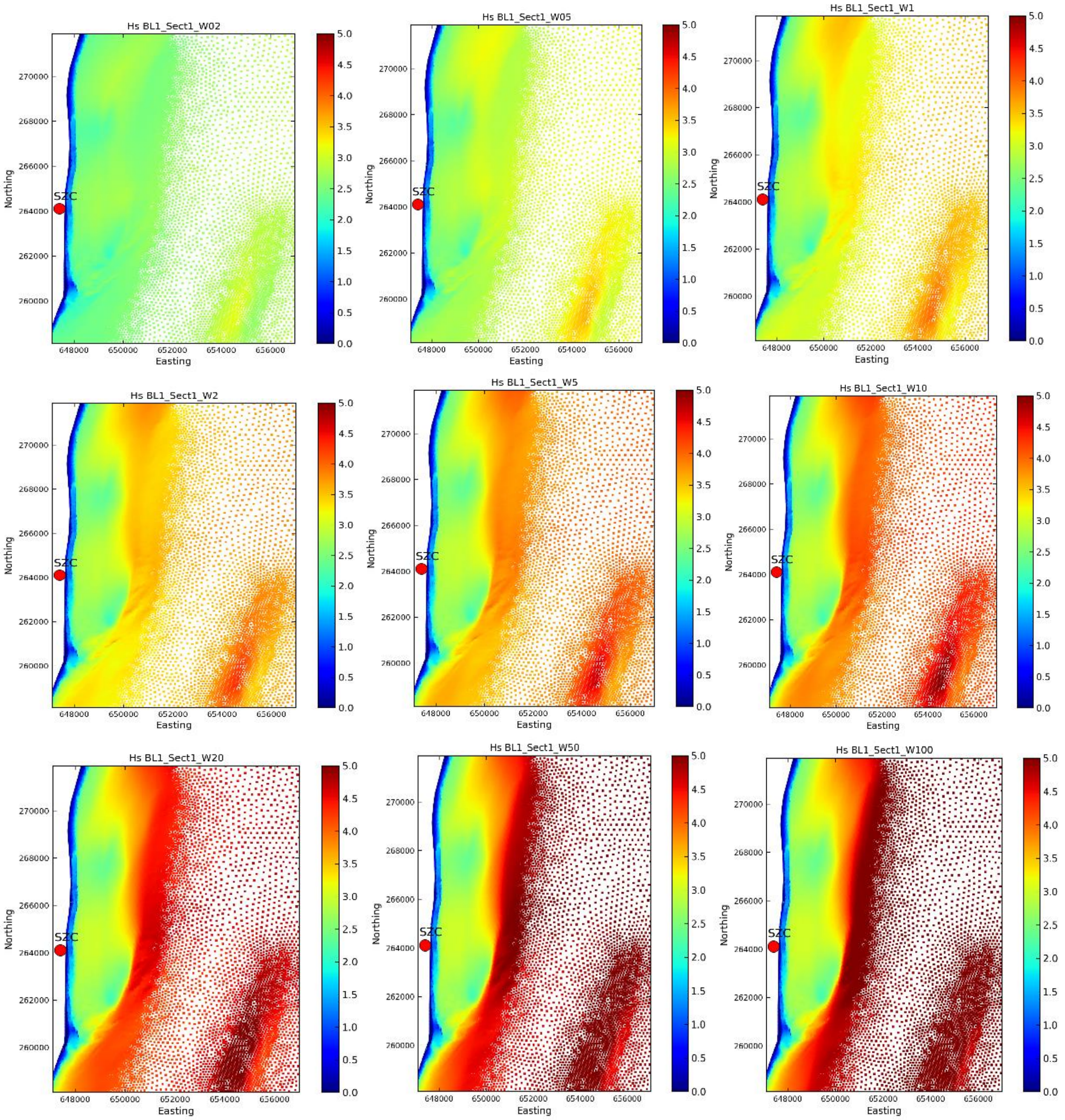

Figure 40 Significant wave heights (Hs) for cases W02-W100 Sector 1, condition A, using present bathymetry

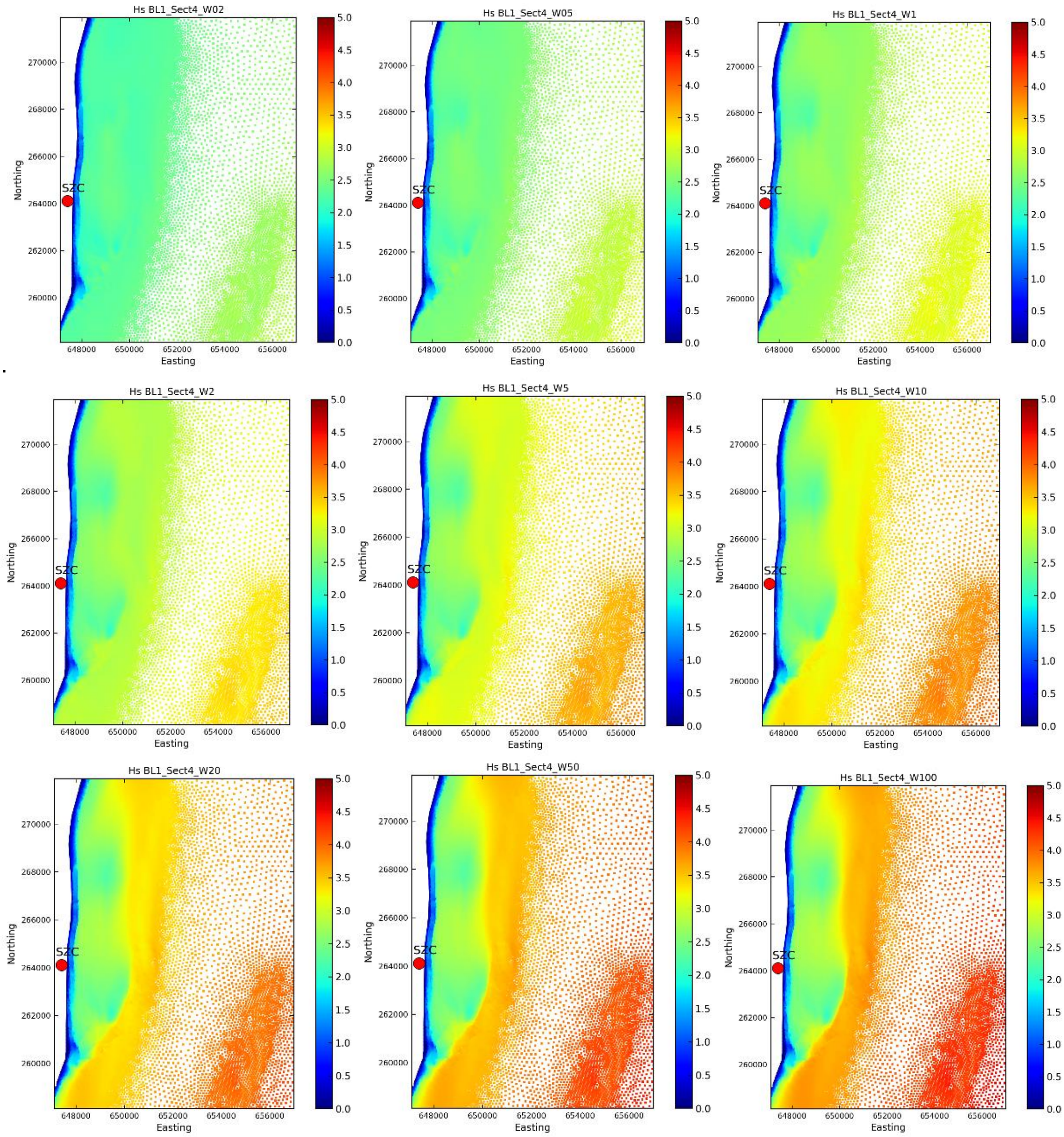

Figure 41. Significant wave heights for cases W02-W100 Sector 4 using present bathymetry.

The effect of wave breaking over the offshore banks on the spatial distributions of the significant wave heights and of the wave power along the wave-crests are shown in Figure 38 and Figure 40 for Sector 1, and in Figure 39 and Figure 43 for Sector 4, respectively. The results show that both the wave heights and the wave power over the offshore banks and near-shore change very little over the range of 9 extreme boundary conditions W02 - W100 from Table 7, while outside these areas both wave heights and wave power scale up with the boundary wave heights.

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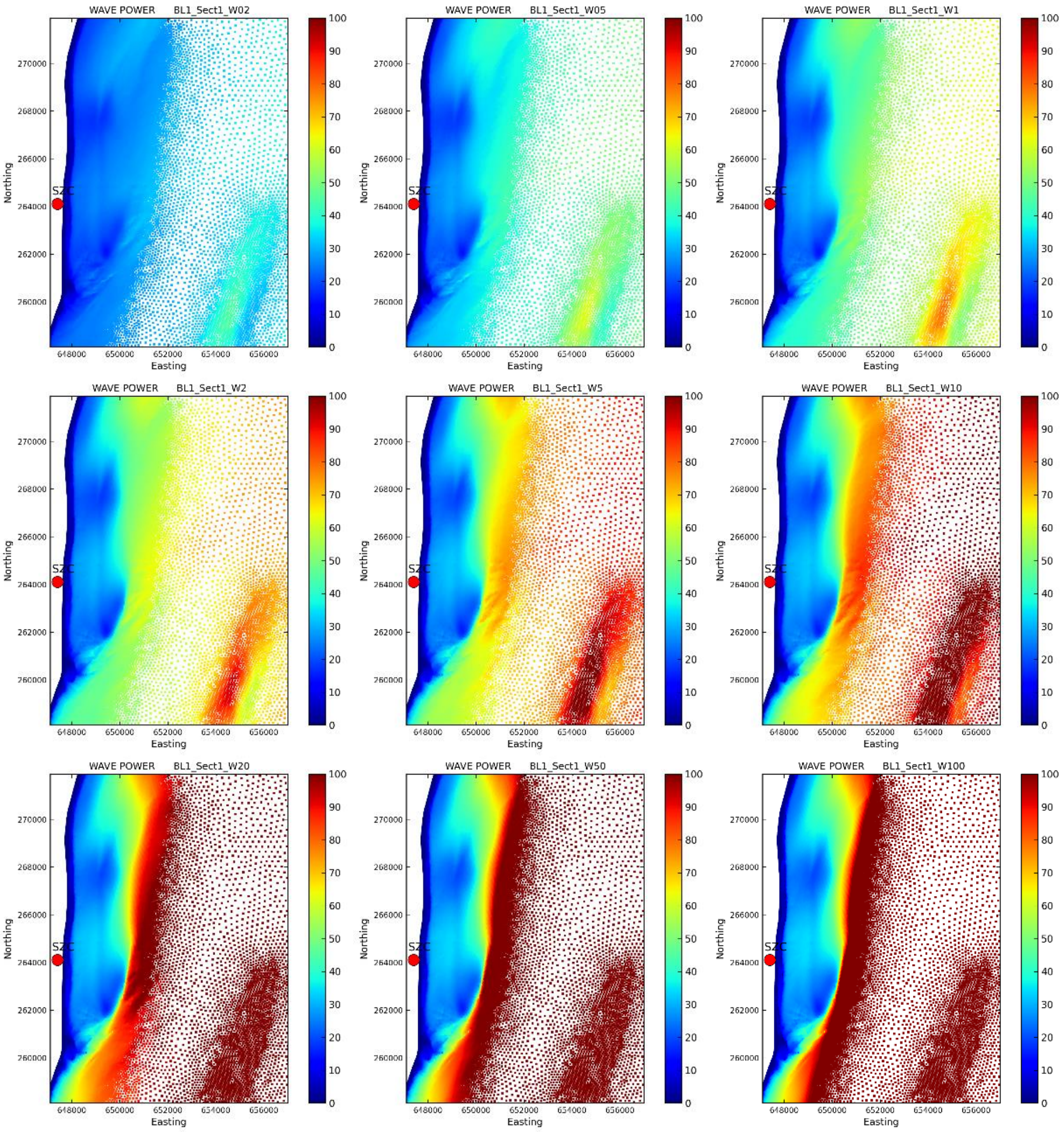

Figure 42. Wave power per unit wave-crest length (in kW/m) for cases W02-W100 Sector 1 using present bathymetry.

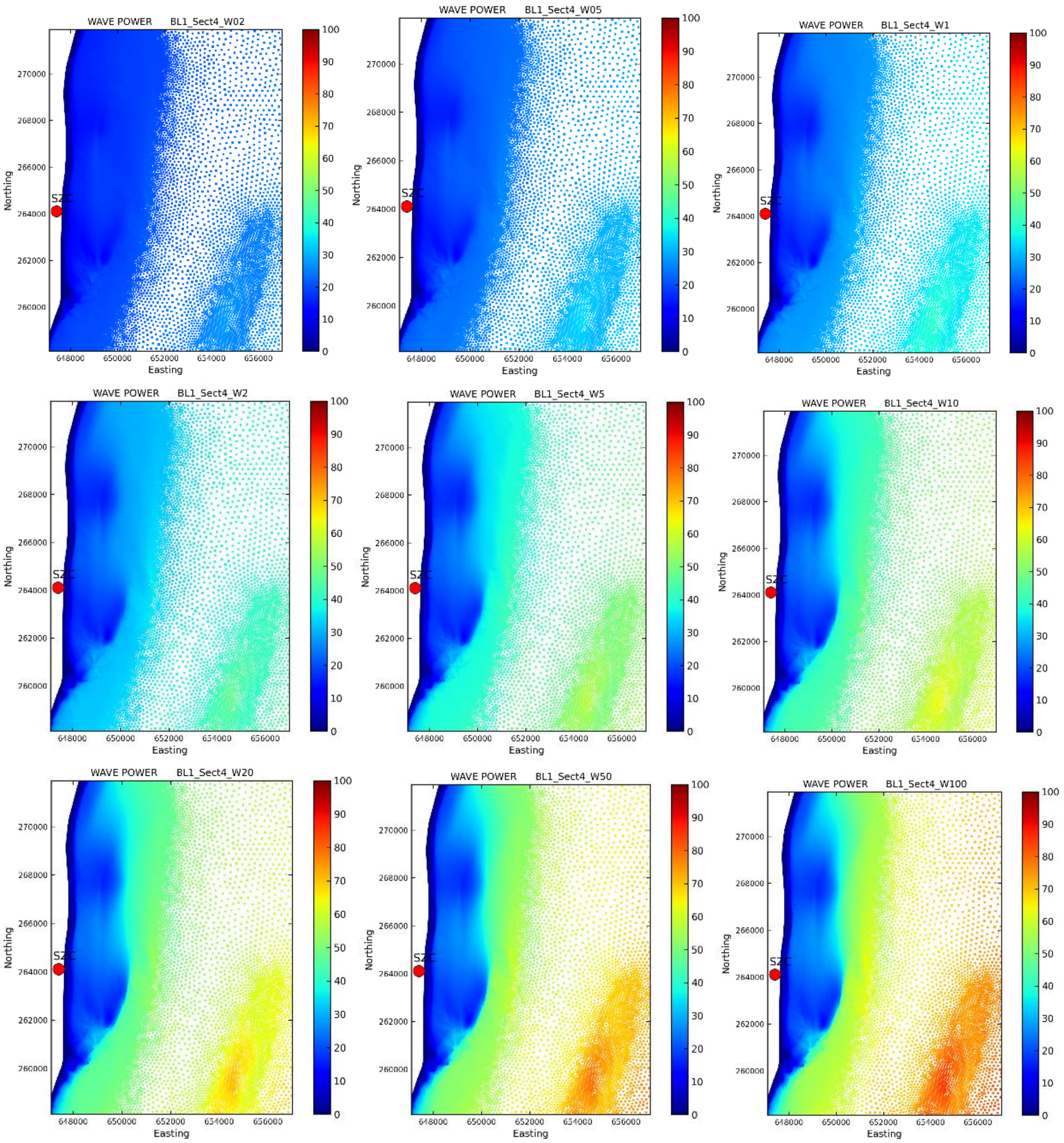

Figure 43. Wave power per unit wave-crest length (in kW/m) for cases W02-W100 Sector 4 using present bathymetry.

In order to investigate further the effects of wave breaking over the offshore banks, we repeated the simulations with the boundary conditions from Table 7 for a different geoscenario, namely the ‘5m bank lowering’ (BEEMS Technical Report TR108), which effectively removes the offshore banks from the system without other changes to bathymetry. The results of these simulations are shown in Figure 44-Figure 49.

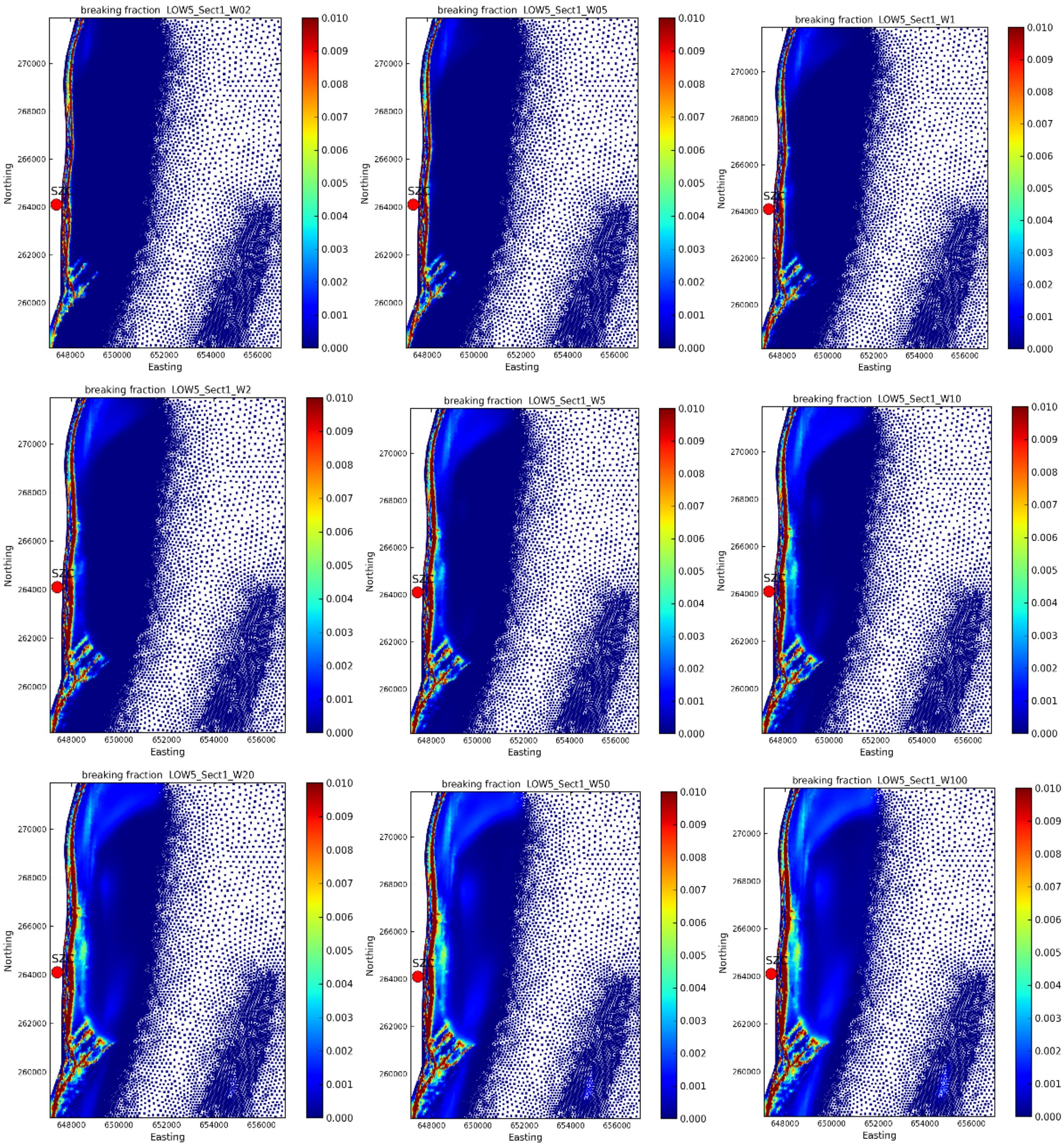

Figure 44. Wave breaking fraction for cases W02-W100 Sector 1 using the 5m banks lowering geoscenario.

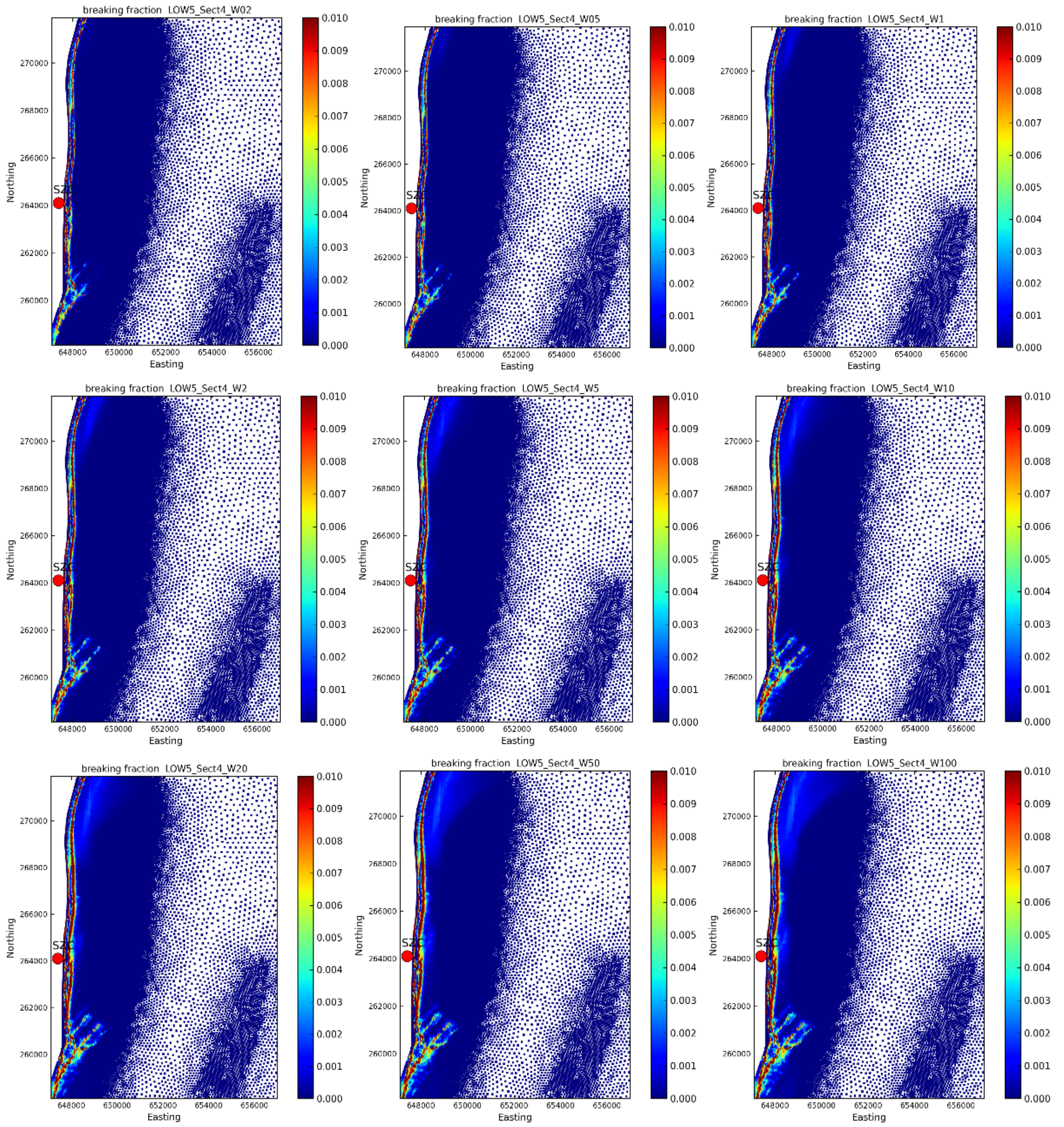

Figure 45. Wave breaking fraction for cases W02-W100 Sector 4 using the 5m banks lowering geoscenario.

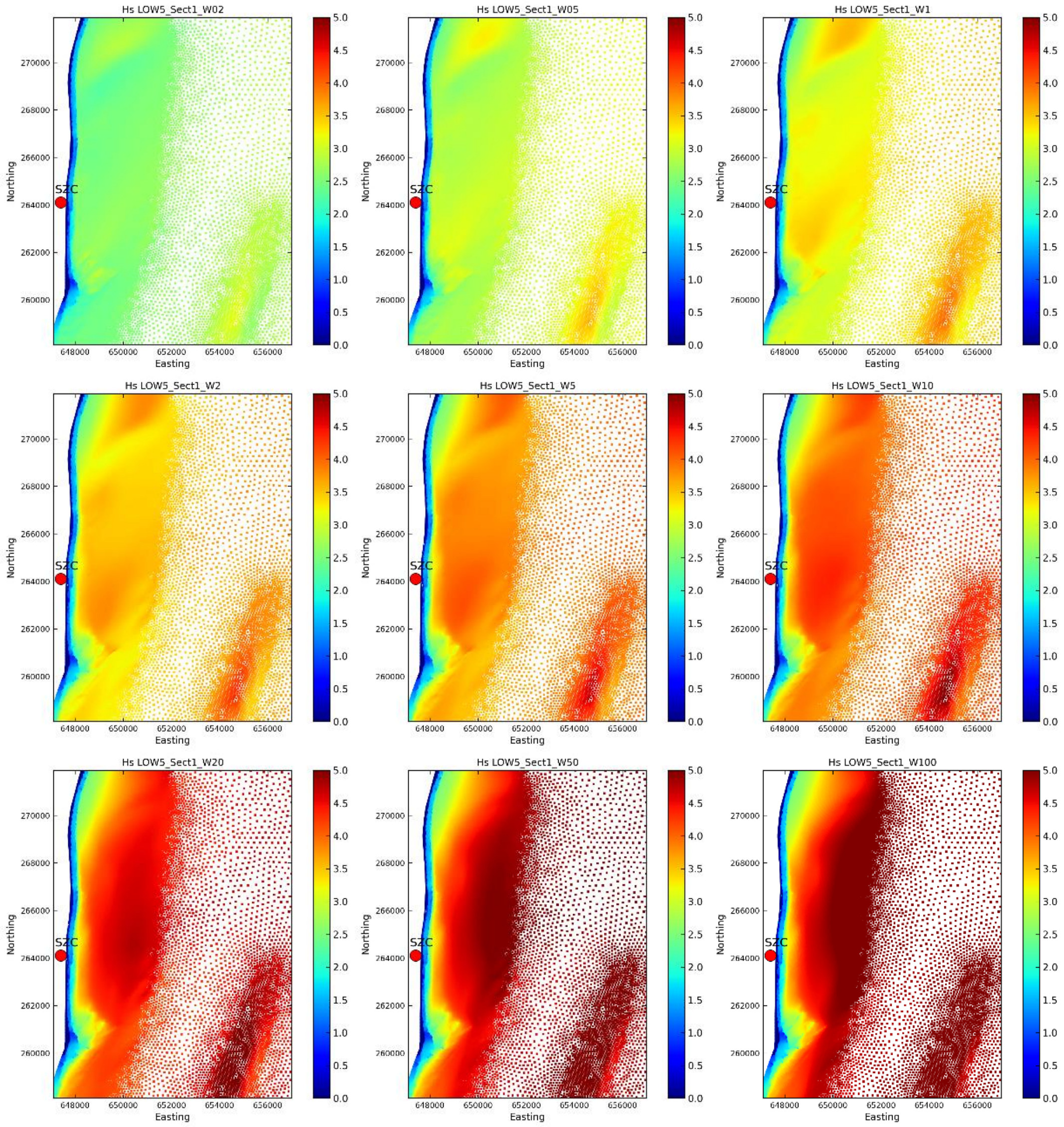

Figure 46. Significant wave height for cases W02-W100 Sector 1 using the 5m banks lowering geoscenario.

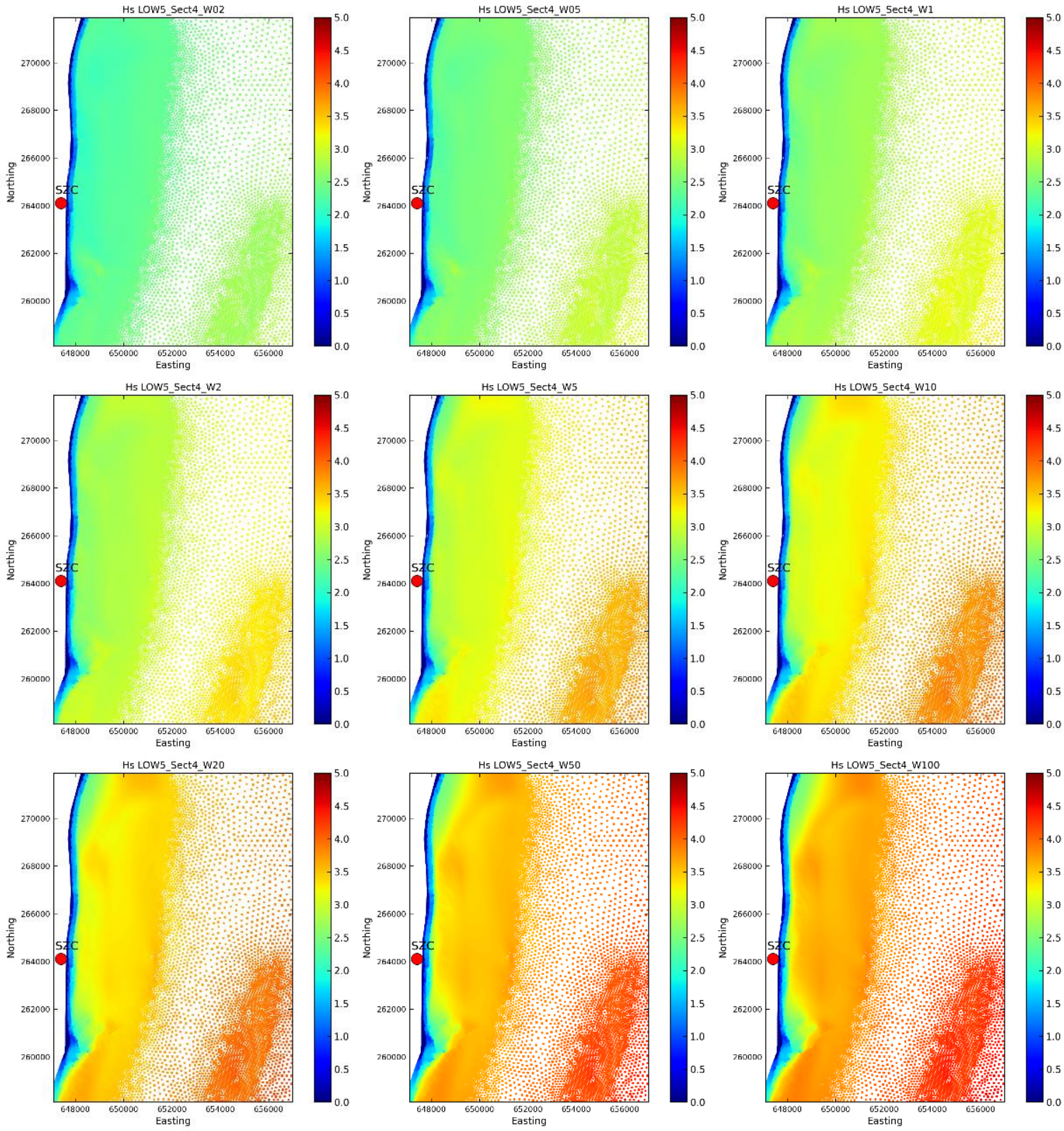

Figure 47. Significant wave height for cases W02-W100 Sector 4 using the 5m banks lowering geoscenario.

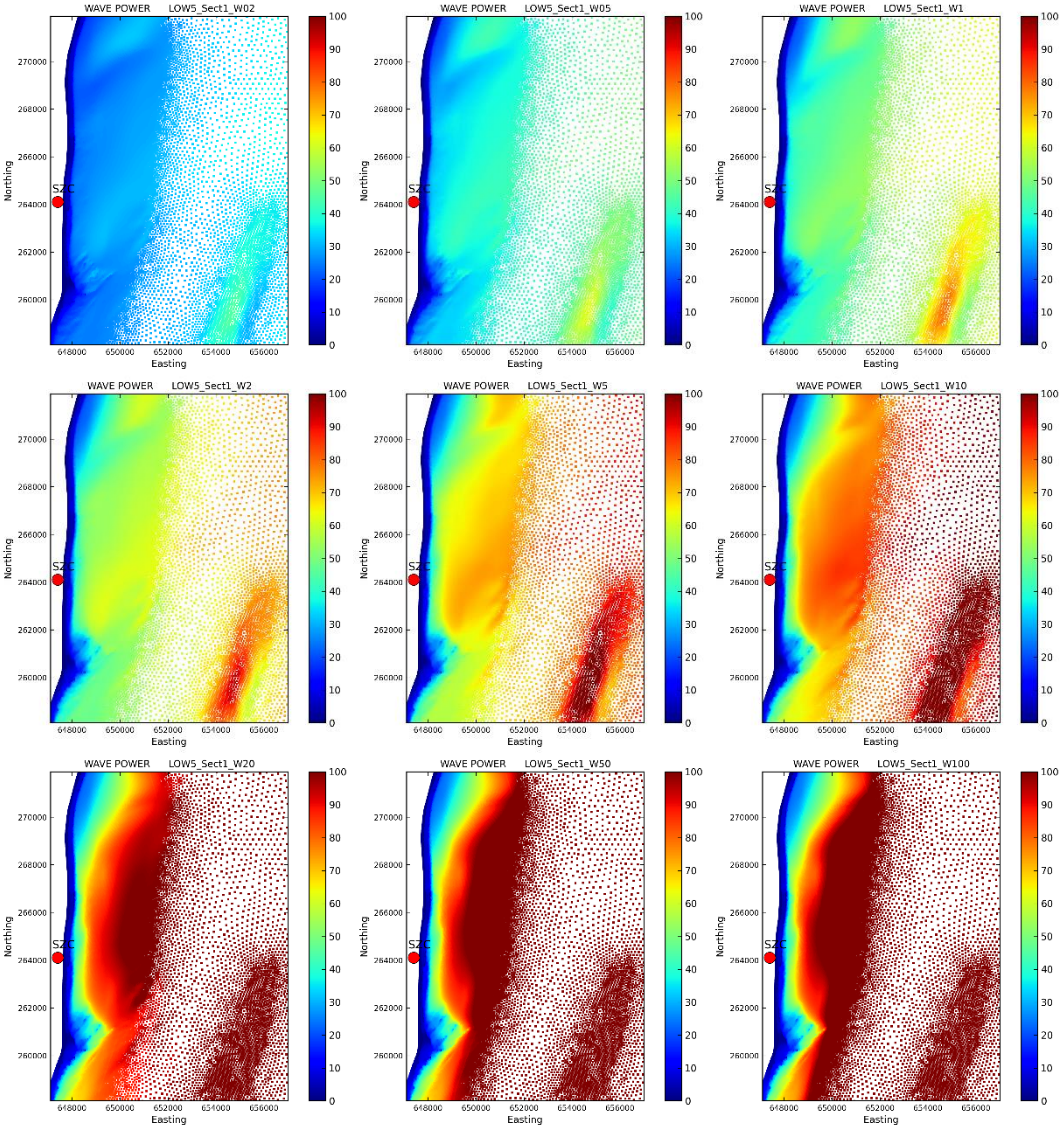

Figure 48. Wave power per unit wave-crest length for cases W02-W100 Sector 1 using the 5m banks lowering geoscenario.

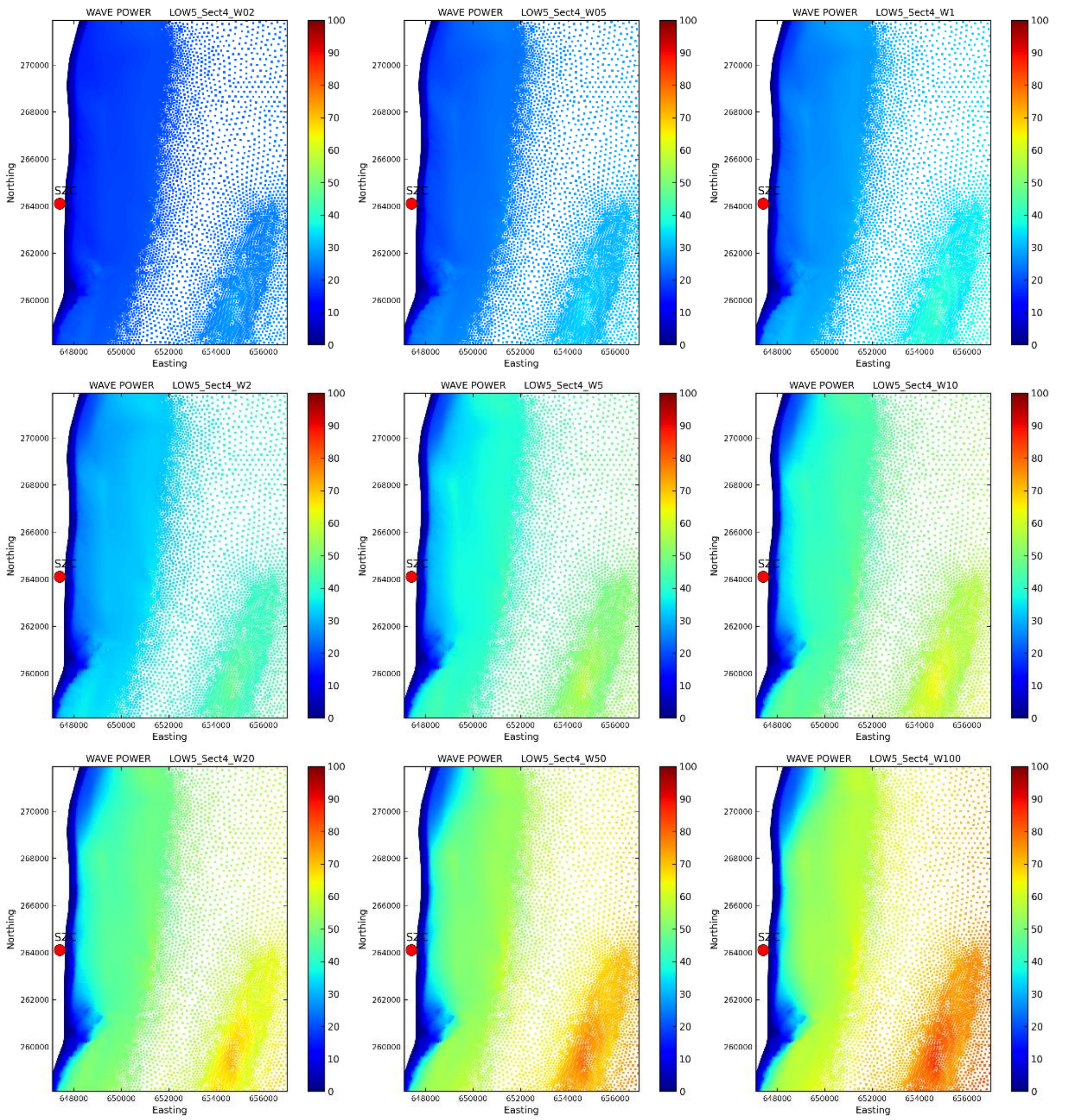

Figure 49. Wave power per unit wave-crest length for cases W02-W100 Sector 4 using the 5m banks lowering geoscenario.

With the offshore banks lowered, there is very little breaking over the banks area, even with the highest waves considered in case W100 (6.11 m for Sector 1 and 4.97m for Sector 4), as seen in Figure 44 and Figure 45. As a consequence, as shown in Figure 46-Figure 49, the wave heights and wave power over the banks area are no longer limited in magnitude, in contrast with the present bathymetry results from Figure 43.

For a more quantitative comparison between the two geoscenarios set of results, Figure 50 shows the difference in significant wave heights between the 5m bank lowering and the present bathymetry scenarios, for the lowest (1 in 0.2 years W02), an intermediate (1 in 2 years W2), and the highest (1 in 100 years W100) boundary waves cases, for both Sector 1 and Sector 4. In the case of the lowest waves W2 (3.27m for Sector 1 and 3.09m for Sector 4), the difference in wave height is slightly negative over some of the banks area, i.e. the removal of the banks results in a modest decrease of wave heights in this area. This suggests that for the set of boundary conditions at the lowest end of the range we considered here, the effects of the offshore banks on the wave propagation is one of wave shoaling and little or no breaking. For increased boundary wave heights, however, as illustrated by the results in W2 case (4.35m for Sector 1 and 3.83m for Sector 4), and especially in the W100 case (6.11m and 4.97m), the differences are becoming negative, i.e. the removal of the banks for the system results in significant increase in wave heights over the banks area. This shows that for the sets of boundary conditions at intermediate and upper end of the range we considered (see Table 7), the main effect of the offshore banks on the wave propagation is one of wave breaking. Remarkably, however, even in the case of the highest waves W100, there is very little difference in the near-shore (~300m) area between the results of the two geoscenarios.

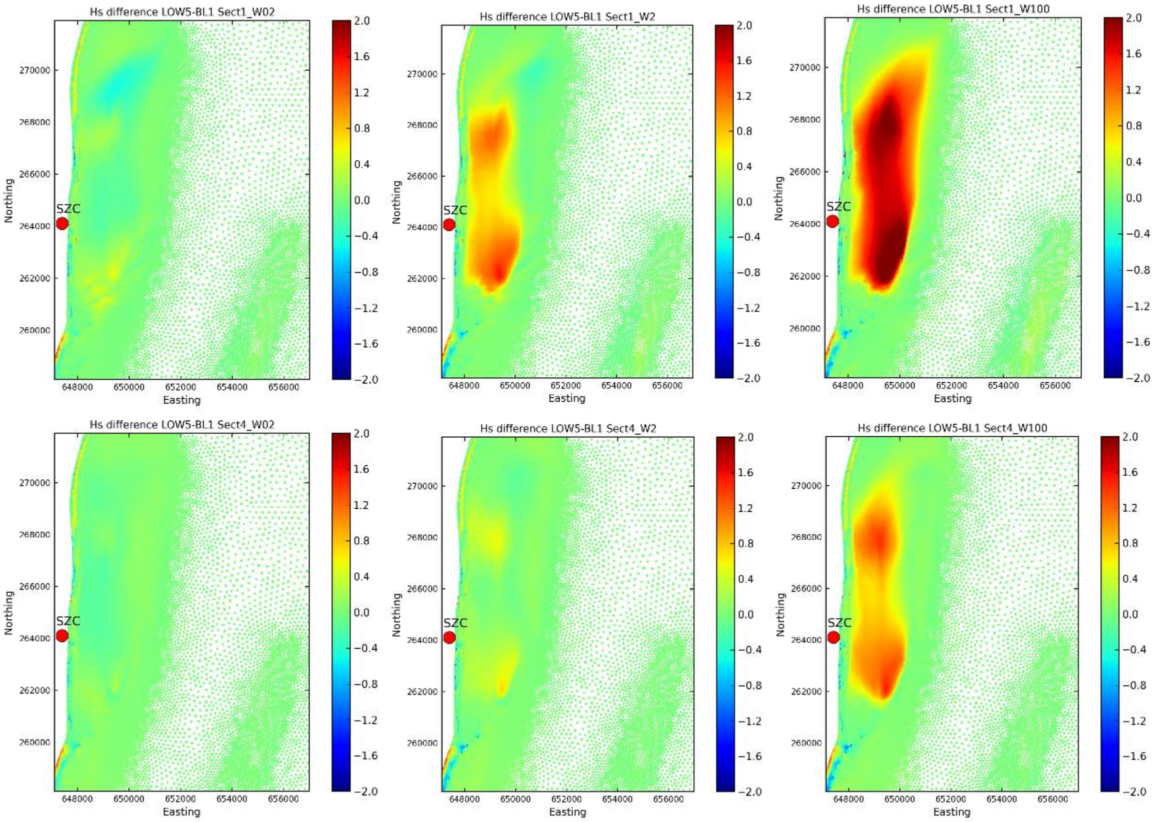

Figure 50. The difference in significant wave height between the 5m bank lowering and present bathymetry geoscenarios for cases W02, W2 and W100, Sector 1 and 4.

Appendix C Results of the alongshore wave energy distribution study. Baseline and lowered bank scenarios.

As well as extreme events, a consideration of the flood risk assessment is the security of the beach frontage in the vicinity of the proposed development. Of particular concern is wave energy on to the beach, which could then directly lower the beach or affect the width of the beach through longshore transport. Beach lowering will be considered in a future BEEMS study using an “X-beach” model. However, as a means to increase understanding of the processes which contribute to along shore dynamics change we undertook an investigation of the alongshore distribution of the wave energy and its temporal variability in the period 1991-2012, and how this is affected by the offshore banks.

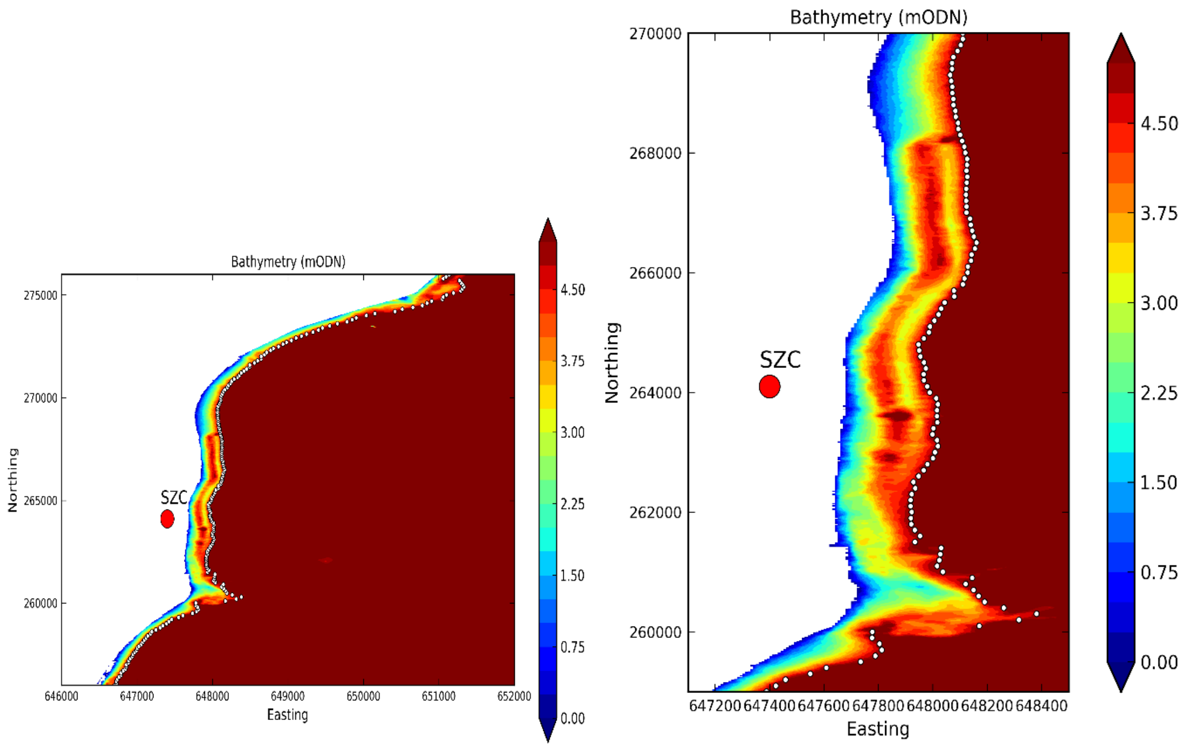

Figure 51. Overall and zoom-in view of the alongshore points where wave powers are calculated. The points are located on the 5m ODN bathymetric depth contour and are spaced at 100m northings intervals.

A 21-year (1992-2012) record of wave data taken from the Met. Office European Wave Model prediction point 1045 was considered as representative of the offshore wave boundary conditions for the Sizewell domain. We used the BEEMS TOMAWAC wave model to translate this offshore record into inshore wave records at 200 points located on the 5m bathymetric depth contour and regularly spaced at 100m northing intervals, as illustrated in Figure 51.

In order to reduce the required computational effort, the offshore record was organised into 3-dimensional bins having a resolution of 0.1m significant wave height Hs, 2s peak wave period Tp and 5° mean wave direction, with a total number of 22500 distinct (Hs, Tp, direction) bins. The TOMAWAC simulations were based on larger bins having a resolution 0.5m Hs, 2s Tp and 22.5° mean direction, resulting in a total number of 520 computational runs for each geoscenario considered. This was then followed by an interpolation procedure in order to match the resolution of the offshore record bins.

The calculated records of wave power along wave-crest at each of the 200 inshore locations was then cumulated over the duration of successive calendar months, in order to produce the cumulative energy per wave-crest for each month from January 1991 to December 2012.

The distribution of monthly cumulative energy per wave-crest along the Sizewell Bay shoreline is shown in Figure 52 for one year, which clearly shows the monthly variation; summer months have less energy and winter months higher energy. Figure 53 (years 1991-2002) and Figure 54 (years 2003-2012), for each calendar month, thereby illustrating both the intra-annual and the inter-annual variability under the present bathymetry. In order to facilitate comparisons within and between years, we calculated also the “average month” distribution for each year, shown with a red line in the plots.

We also undertook a second set runs using the 3m bank lowering geoscenario, but as the corresponding results are visually very similar to the present bathymetry runs, we present only the difference between the lowered bank and present bathymetry results in Figure 55 and Figure 56. These inter-scenario difference results show only a modest intra-annual and inter-annual variability. The alongshore distribution does not show any obvious positive or negative overall difference, but there are some persistent local differences, mostly positive in the south and mostly negative in the north, suggesting that the lowering of the banks leads to some increases in nearshore energy in the south and some decreases in the north. Interestingly, these effects are in agreement with those observed in the case of the 1 in 1000 years Sector 1 F2 simulations and shown in Figure 36-Figure 37. Although using very different boundary conditions, in both cases there is very little wave breaking over the banks area (only a very small fraction of the waves from the 21-year wave record have the necessary height, while the F2 case has elevated water levels), and the main effect of the banks is likely to be one of wave shoaling and refraction with similar patterns in both cases.

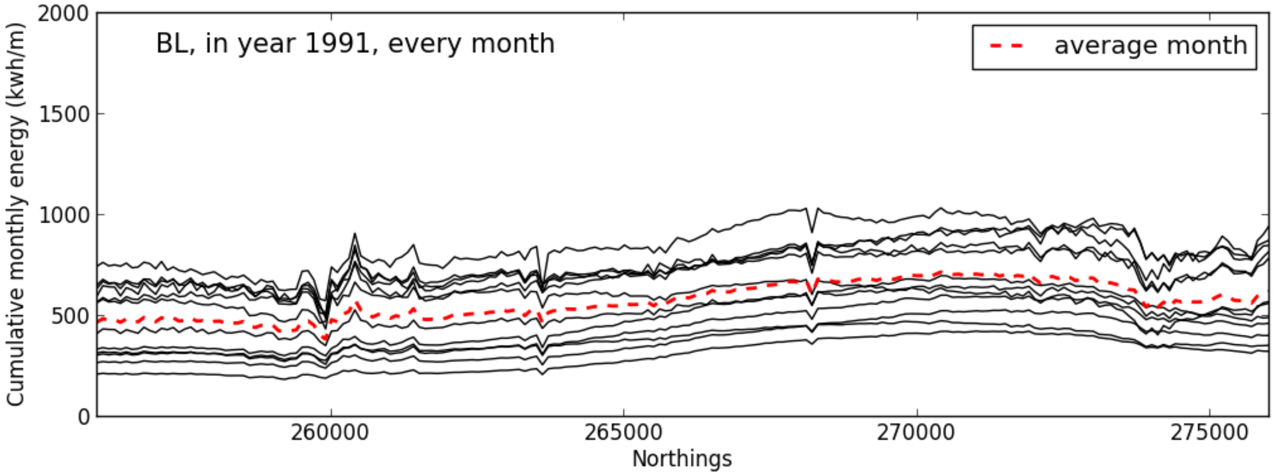

Figure 52 Cumulative monthly wave energy density along the Sizewell Bay coastline for 1991 at monthly intervals. Red line marks the annual average. (Darker lines are merely co-incidence of over lapping grey lines).

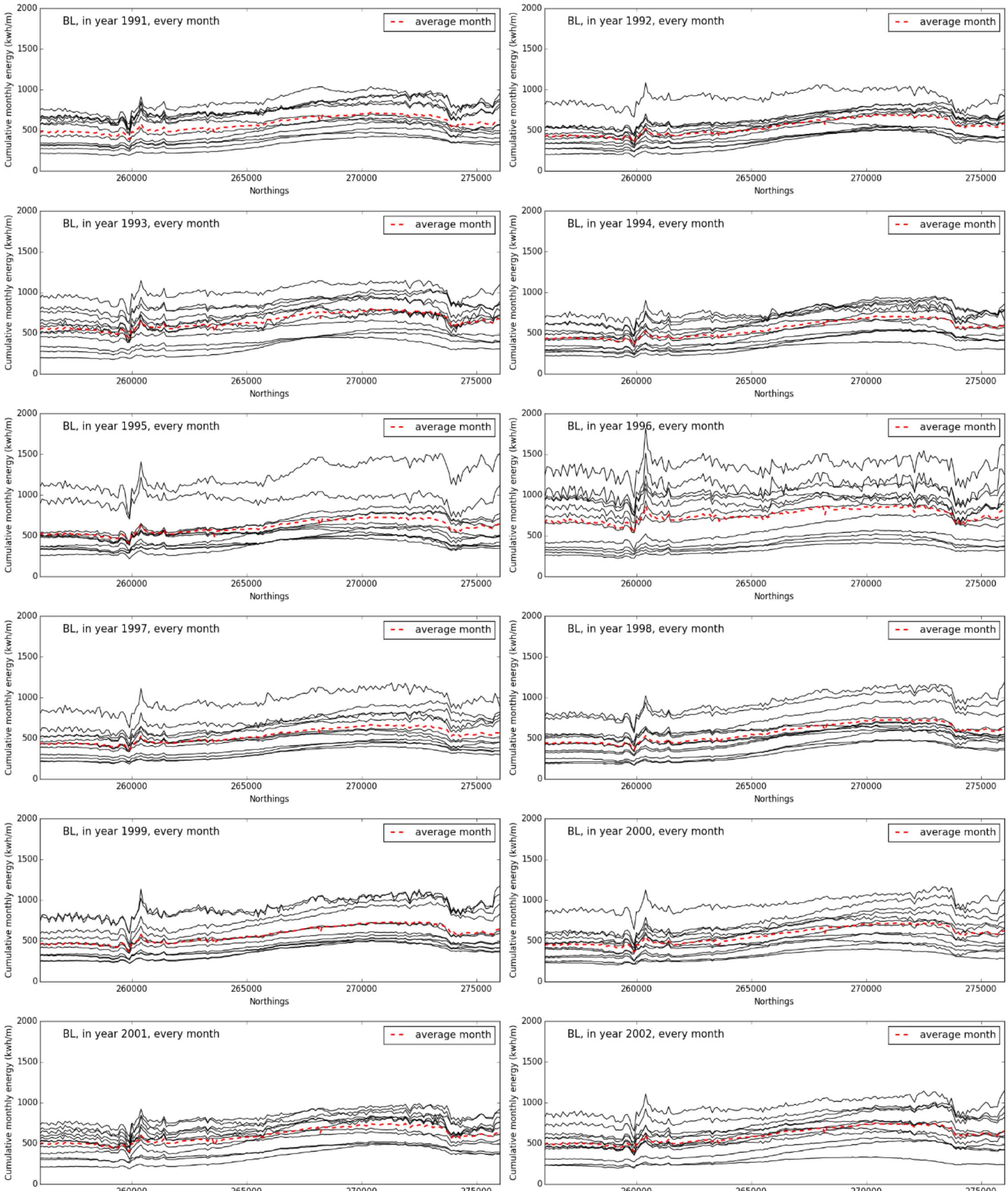

Figure 53. Cumulative monthly energy per unit wave-crest length (in kwh/m) reaching the 5m bathymetric depth contour, for each individual calendar month and the year-averaged month, calculated using present bathymetry, in the years 1991-2002.

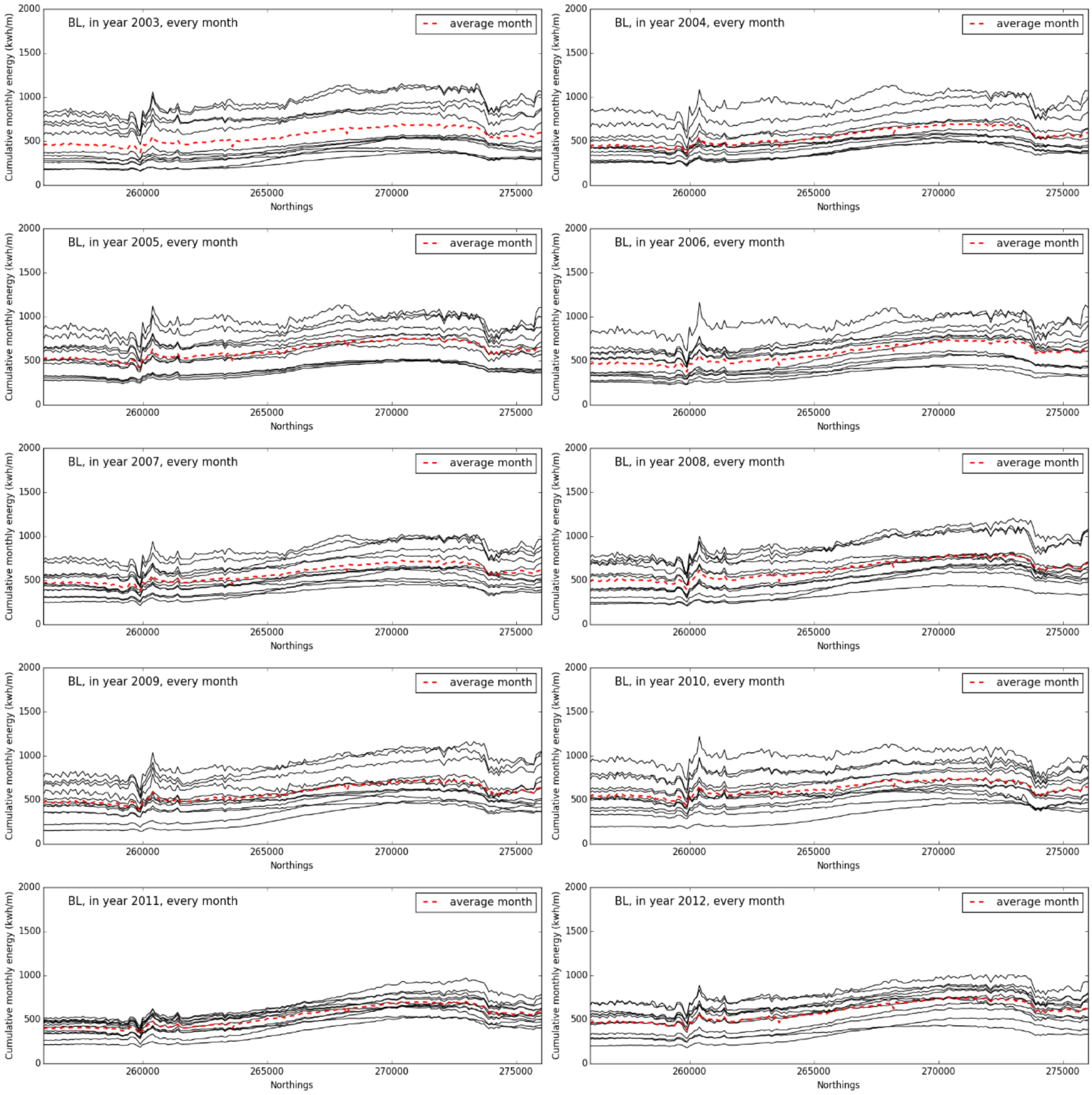

Figure 54. Cumulative monthly energy per unit wave-crest length (in kwh/m) reaching the 5m bathymetric depth contour, for each individual calendar month and the year-averaged month, calculated using present bathymetry, in the years 2003-2012.

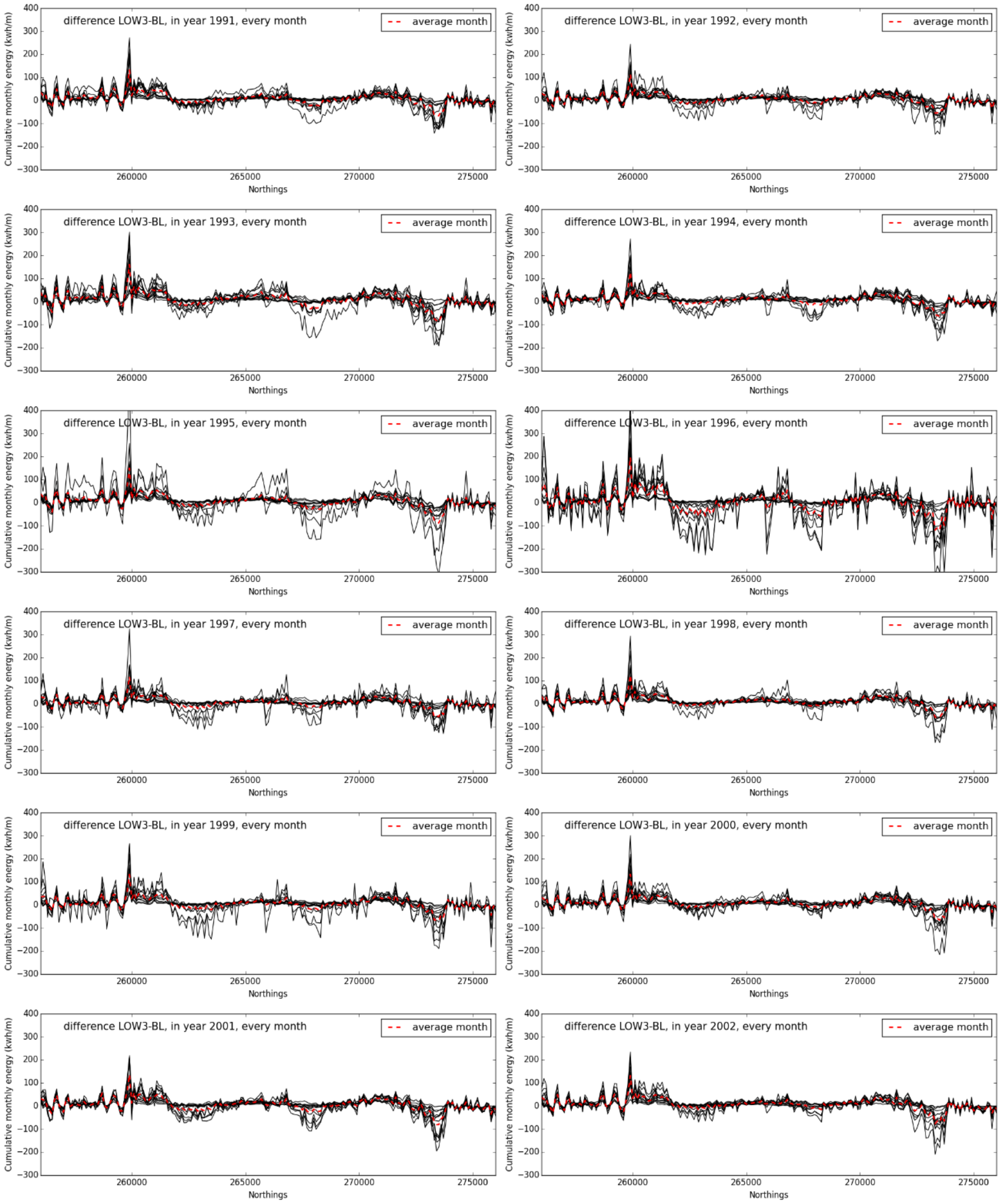

Figure 55. The difference in cumulative monthly energy per unit wave-crest length (in kwh/m) reaching the 5m bathymetric depth contour, calculated between the results obtained using the 3m bank lowering and the present bathymetry geoscenarios, for each individual calendar month and the year-averaged month, in the years 1991-2002.

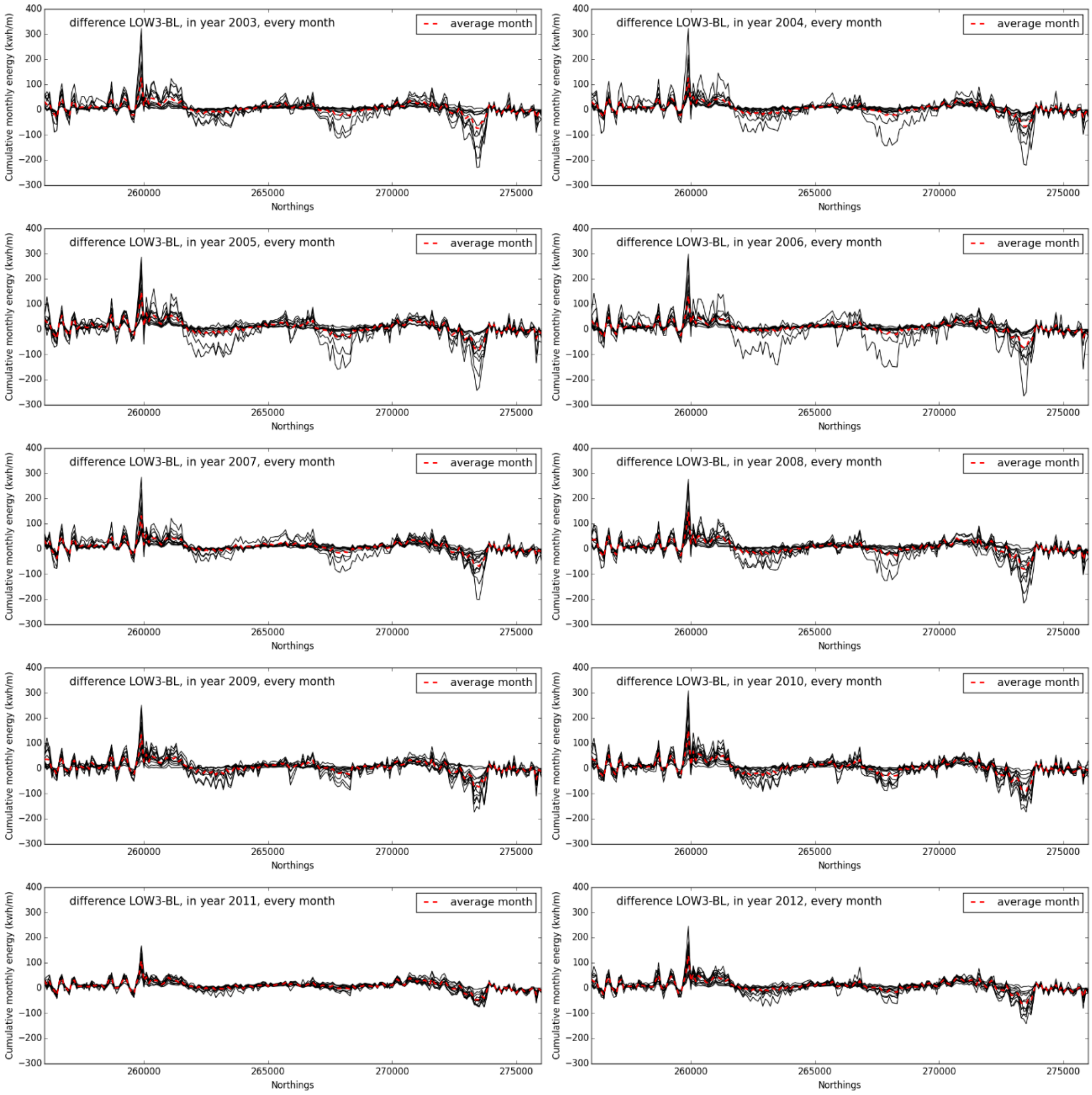

Figure 56. The difference in cumulative monthly energy per unit wave-crest length (in kwh/m) reaching the 5m bathymetric depth contour, calculated between the results obtained using the 3m bank lowering and the present bathymetry geoscenarios, for each individual calendar month and the year-averaged month, in the years 2003-2012.

RHDHV, 2014. SIZEWELL C FLOOD RISK ASSESSMENT - AMAZON SENSITIVITY TESTS

Note

HASKONINGDHV UK LIMITED
RIVERS, DELTAS & COASTS

To	:	[redacted]
From	:	[redacted]
Date	:	8 December 2014
Copy	:	[redacted]
Our reference	:	PB1452/N/303517/Hayw
Subject	**:**	Sizewell C Flood Risk Assessment - Amazon Sensitivity Tests

1. Introduction

Before using Amazon to carry out a first "scan" of the coast at Sizewell to identify scenarios that overtopping is predicted, there are three issues that need to be discussed and agreed. These issues are:

- defining a representative defence/beach profiles for flood risk analysis;
- approach to removal of "sacrificial" berm; and
- the worst combination of water level and wave height of the same joint probability.

This note presents and discusses our approach to defining representative defence/beach profiles, and the results of sensitivity tests on berm removal and various combinations of water levels and waves at Profile S6. This single profile was chosen for these initial tests, and will be followed with analysis at additional profiles to provide the full suite of required assessments.

2. Representative Profile

Figure 1 presents defence/beach profiles at Profile S6 extracted from the latest LiDAR (2010) and ground level surveys (2013-2014). The profiles are split into the "active zone" where beach levels are subject to seasonal changes and "inactive" zone where ground is rarely flooded by overtopped sea water. We found that the three ground level surveys closely match each other within the "inactive" zone. From this we have concluded that the representative profile in "inactive" zone should be based on ground level survey data, rather than LiDAR.

For the "active" zone, for conservative estimation, the representative profile is compiled by picking the lowest ground levels from both ground level survey and LiDAR data.

Figure 2 presents the compiled representative defence/beach profile for S6 using the above explained approach.

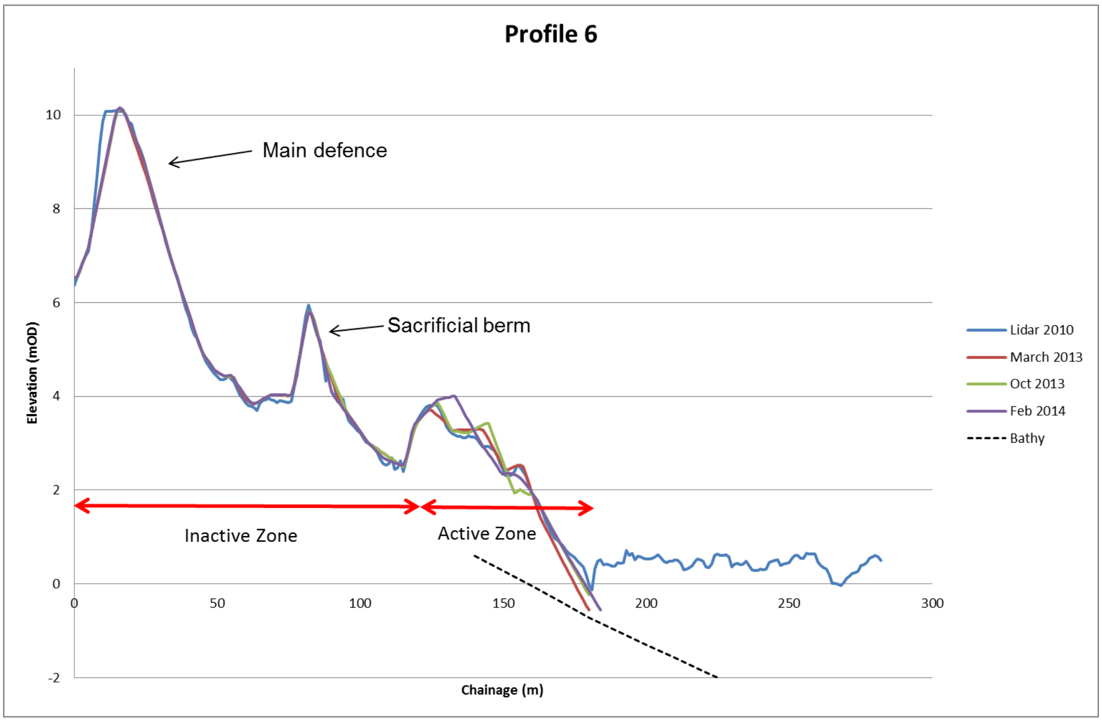

Figure 1: Defence/beach profiles extracted from LiDAR and ground level survey data

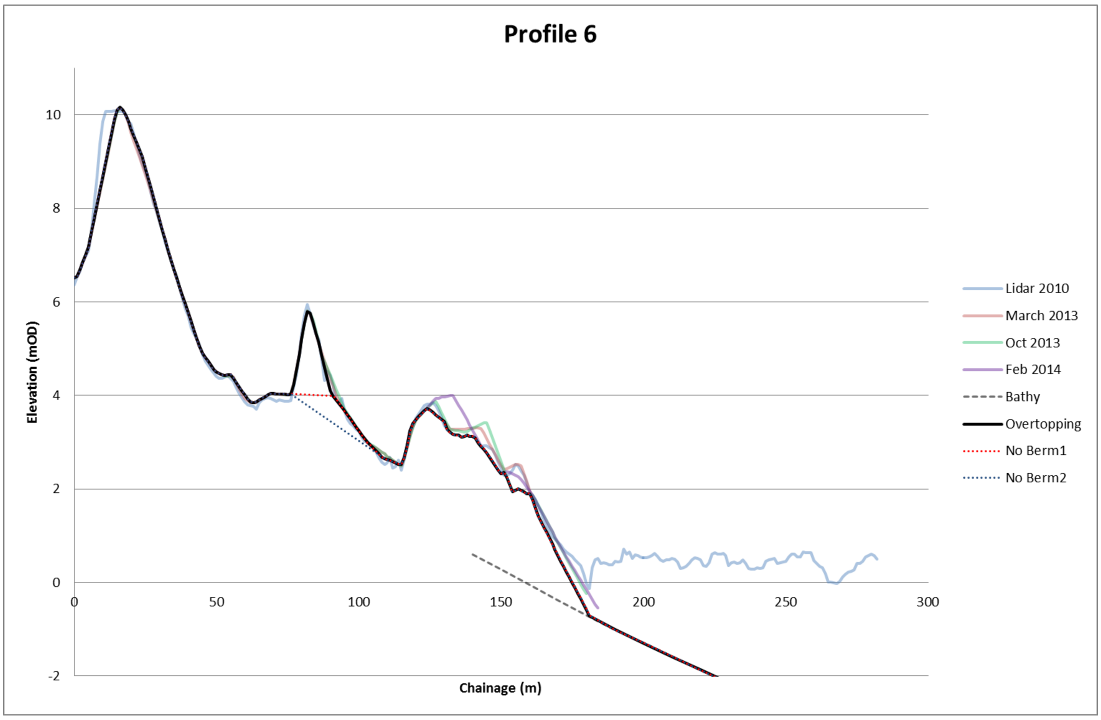

Figure 2: Representative defence/beach profile (black thick line) at S6 for overtopping analysis

3. Removal of "Sacrificial Berm"

At the SZC FRA Technical Sub-Group Meeting on 13th November 2014, the approach to considering potential erosion during an extreme storm was discussed and, specifically, whether the "sacrificial" berm should be removed when undertaking overtopping analysis for this scenario.

Figure 2 presents two options for berm removal. Given that it is difficult to determine how the berm will fail, we have modelled two options to determine which is the worst case scenario in terms of overtopping rates. "No Berm 1" assumes that the sacrificial berm is removed with an approximately horizontal base at the same elevation as the land directly behind the berm. "No Berm 2" assumes a sloping base between the base at the back of the berm and the junction between the active and inactive zones. At this initial stage we have undertaken runs for both berm removal scenarios, to test the sensitivity of overtopping model outputs to this parameter.

4. Combination of Water Level and Wave Conditions

Table 1 presents the combinations of water levels and waves provided by CEFAS which have been adopted in these initial sensitivity tests.

The Amazon model boundary is set to approximately one wave length from the water edge (where mean water level line meets beach), which is approximately at the sacrificial berm.

Table 1: the combinations of water level and nearshore wave conditions

Joint Return Period (year)	Combinat-ion Code[1]	Water Level (m AOD)	Hs (s)	Tp (s)	Wave Length (m)	Amazon Model Extent (meter from Sacrificial Berm)
1:1,000	A2	1.89	2.48	13.55	286	300
1:1,000	E2	3.03	3.18	12.79	255	250
1:1,000	B2	3.62	3.08	11.71	214	200
1:1,000	F2	4.02	2.92	10.90	185	200
1:1,000	C2	4.22	2.60	9.36	137	150
1:200	A3	1.76	2.32	12.88	259	300
1:200	B3	3.18	2.88	11.30	199	200
1:200	C3	3.66	2.53	9.11	129	150

Note: Hs is the nearshore wave height extracted from TOMAWAC model results at one wave length from the sacrificial berm.

5. Results and Discussions

[1] Combination Codes as presented by CEFAS during Coastal Technical Group meeting with regulators on 13th November 2014.

Tables 2 and 3 present predicted mean overtopping rates for the current beach profile (with sacrificial berm remaining in place) for the 1 in 1000 year and 1 in 200 year events. The results show that the worst combination is F2 for the 1 in 1000 year even and B3 for the 1 in 200 year event. The model results also show that the existing flood defence is not overtopped based on “present day” mean sea level.

Table 2: predicted overtopping rates for 1 in 1,000 year RP

Scenarios	Mean overtopping rates (l/s/m)
A2	0.0013
E2	2.15
B2	8.34
F2	16.71
C2	7.57

Note: mean overtopping was calculated at the left red triangle shown in Figure 3

Table 3: predicted overtopping rates for 1 in 200 year RP

Scenarios	Mean overtopping rates (l/s/m)
A3	0.0002
B3	0.97
C3	0.25

Note: mean overtopping was calculated at the left red triangle shown in Figure 3

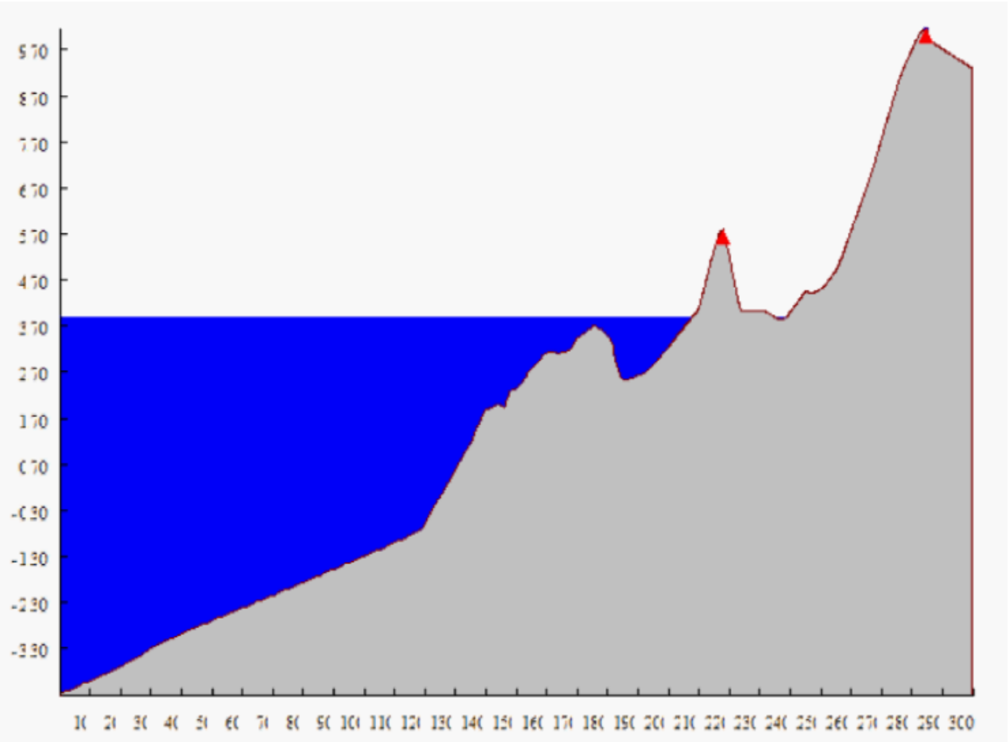

Figure 3: Profile in Amazon model for the representative profile with the sacrificial berm

Table 4 presents the predicted mean overtopping at the location of the sacrificial berm for both berm removal scenarios (the level was at 4m AOD). The results show the volumes of water over this point are similar between two options. It should also be noted that even with berm removal there was no overtopping at the existing flood defence (right hand triangle in Figure 3).

Table 4: predicted overtopping rates for two berm removal option for 1 in 1,000 year RP[2]

Scenarios	Berm removal options	Mean overtopping rates (l/s/m)
F2	No Berm 1	270.9
F2	No Berm 2	245.8

Three animations are attached. It is suggested using the attached Powerpoint slide to play them together for comparison (using Slide Show mode).

6. Conclusions

Based the results discussed above, the following conclusions may be drawn from this sensitivity tests:

- The worse combination is not the combination of highest water level and lowest wave. This means we need to run 3 combinations of joint probability in the first "scan" to ensure the worst combination is captured.
- The existing defence can defend 1 in 1000 year storm with the "present day" mean sea level.
- The difference in the volume of water over the berm location is similar between two berm removal options. However, as a conservative approach, for the berm removal option, Option 1 (partial removal) is recommended.

[2] Only 1 in 1,000 assessed; results from this show no significant difference, therefore 1 in 200 not assessed as difference at 1 in 200 would in any case be less than for 1 in 1,000.

RHDHV, 2015. SIZEWELL C - OVERTOPPING COMPARISON CALCULATION ON DESIGN PROFILE (WITH BEACH EROSION)

Note

HASKONINGDHV UK LIMITED
RIVERS, DELTAS & COASTS

To	:	[redacted]
From	:	Royal HaskoningDHV
Date	:	21 January 2015
Copy	:	
Our reference	:	PB1452/N//Hayw
Subject	**:**	Sizewell C - overtopping comparison calculation on design profile (with beach erosion)

1 Introduction

In the report “Input Parameters for SZC Sea-Defence – Design: Wave Overtopping Study”[1], a design profile and design wave conditions for the assessment of proposed sea defences at Sizewell C were provided. The report also indicated that Jacobs intended to carry out an overtopping analysis using the EurOtop neural network method.

In the report “Sizewell C Sea Protection - Phase 2: Technical Note Overtopping“[2], overtopping calculations were described, using input parameters from the NNB GenCo report, which led to the Conceptual Design Options for Sea Defence.

EDF Energy has asked Royal HaskoningDHV to carry out an overtopping analysis using the Amazon software. This has been carried out for the two erosion scenarios shown in Figure 1 of the NNB GenCo Report, which is reproduced as Figure 1 of this note. These two scenarios are:

1. A ‘worst case’ scenario where the whole beach is eroded back to the toe of the sea-defence structure, and
2. The ‘design basis’ scenario where the 5m bund is eroded, but the area between the 5m bund and the main sea defence is not eroded.

This note presents initial results from the Amazon modelling, which predicted wave overtopping on both of the above erosion scenarios. The note also provides a comparison between Amazon and EurOtop for both scenarios and in particular provides a check against the EurOtop neural network method used by Jacobs to assess scenario 2 (Jacobs have not assessed scenario 1).

2 Defence Profile

The defence tested for this initial assessment has a crest level of 14m AOD and a 1:3 front slope, as shown in Figure 1., which also illustrates the two erosion scenarios described above..

[1] Input Parameters for SZC sea defence design: wave overtopping study, version 0.2, NNB Gen Co Ltd, dated 24 June 2014 (referred to in this note as the NNB GenCo report)
[2] Sizewell C Sea Protection - Phase 2: Technical Note Overtopping, Jacobs UK Ltd., Report Number: 60PO5501/SZC/SP/TN/001 (Rev A), October 2014 (referred to in this note as the Jacobs report).

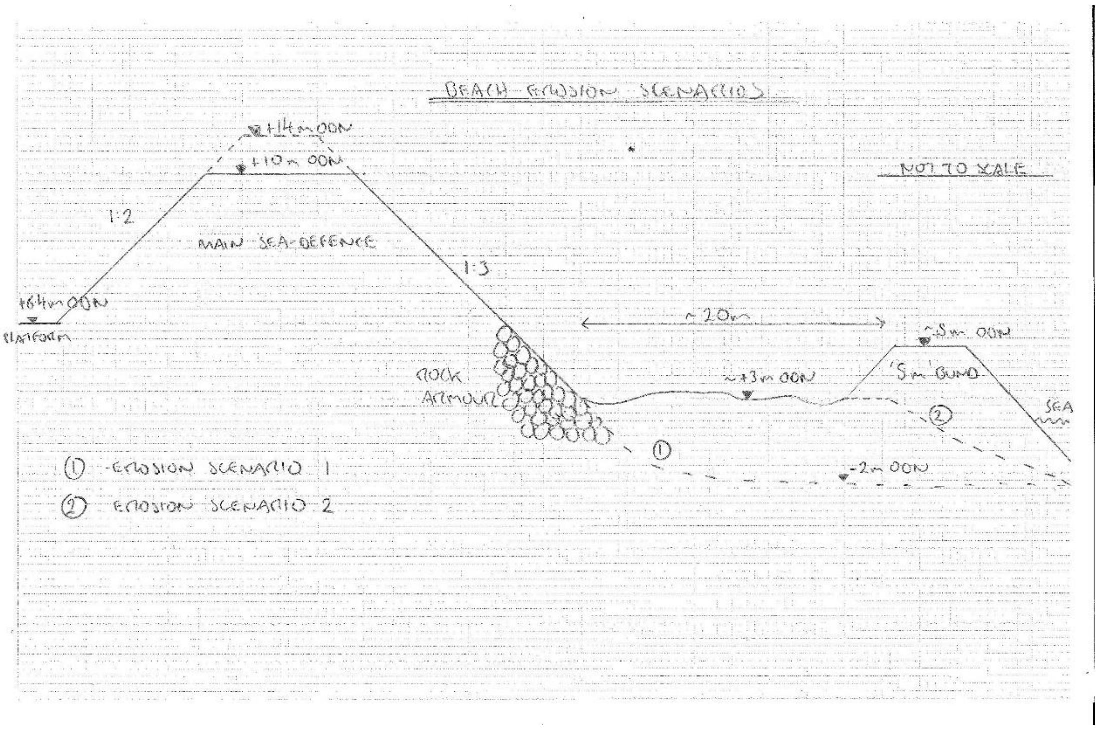

Figure 1: Defence/beach profile

3 Erosion Scenario 1

Table 1 presents the input wave conditions extracted from Table 3 of the NNB GenCo report for Erosion Scenario 1.

Table 1: Input parameters used for Amazon and EurOtop calculations

Climate Change Scenario No.	Climate change scenario (2110)	Wave derivation method	Overtopping Case	Water level (m ODN)	Wave height (m)	Wave period (T_m, s)	Water depth at the toe (m)
I	Reasonably foreseeable (high emission 84%)	Depth-limited y=0.78	1	6.00	6.24	11	8.00
II		Joint probability modelling (adapted from [6])	3	5.65	5.50	11	7.65
III	Credible Maximum (H++ upper limit + vertical land movement)	Depth-limited y=0.78	4	8.19	7.95	11	10.19
IV		Joint probability modelling (adapted from [6])	6	7.84	6.50	11	9.84

Note: the water depth and wave height were referenced to Erosion Scenario 1

3.1 Amazon calculations

Amazon requires a complete defence/beach profile. Figure 2 presents the adopted defence/beach profile, whereby the 1:3 front slope was extended to deep water (-36m AOD). This resembles a typical profile that would be used in physical modelling; the reason for this approach is that the EurOtop methods were built on databases produced by physical modelling tests, and therefore taking this approach within Amazon allows a comparison of outputs.

The Amazon model also requires the input of a wave spectrum. In this study, TMA spectrum (TMA spectrum is based on JONSWAP spectrum but with shallow water adjustment) was adopted, and a ratio of T_p/T_m=1.19 was used to convert T_m to T_p which is required for TMA spectrum.

3.2 EurOtop calculations

For comparison, an overtopping calculation was also carried out using the EurOtop empirical method. Figure 3 shows a snapshot from one of the EurOtop calculations. In the calculation, the probabilistic equations were adopted (the deterministic equations would give higher overtopping rates). Further, a smooth surface (concrete) was chosen for the slope, although our sensitivity tests show that the roughness of slope made only a marginal difference to the results in this case.

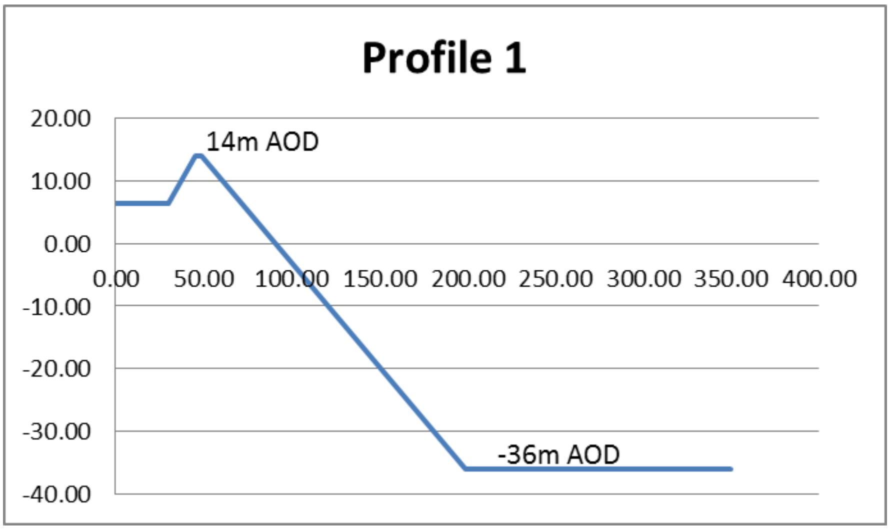

Figure 2: Defence/beach profile represented in Amazon

3.3 Results and Discussions

Table 2 presents the results of Amazon and EurOtop empirical methods.

Table 2: Comparison of the overtopping rates produced by EurOtop empirical and Amazon

	CC Scenario	Wave period (T_m, s)	Wave height (m)	Water level (m AOD)	Mean overtopping rate (l/s/m)
EurOtop	I	11	6.24	6	712
Amazon		11	6.24	6	600
EurOtop	II	11	5.5	5.65	457
Amazon		11	5.5	5.65	390
EurOtop	III	11	7.95	8.19	2,495

Amazon		11	7.95	8.19	1,897
EurOtop	IV	11	6.5	7.84	1,489
Amazon		11	6.5	7.84	1,197

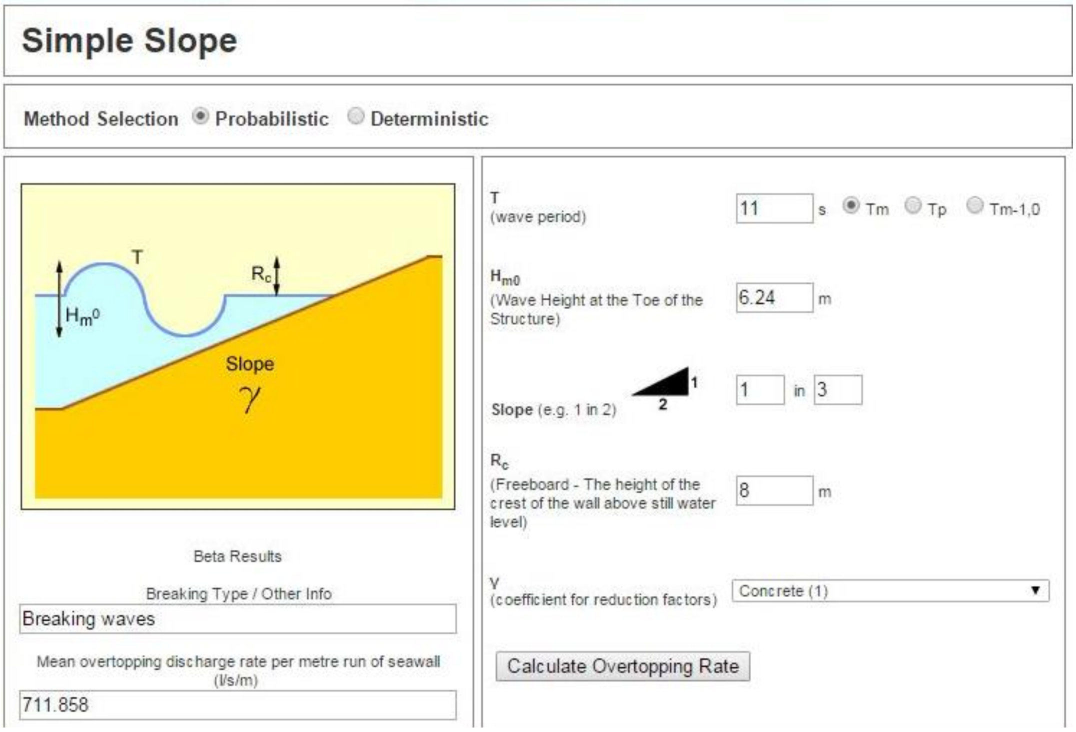

Figure 3: EurOtop empirical method Climate Change Scenario I

The results show that, for Erosion Scenario 1, both methods predicted significant overtopping for all four climate change scenarios, and also that the predicted overtopping rates are comparable between the two methods.

4 Erosion Scenario 2

4.1 Input Data

Table 3 presents the input wave conditions extracted from the NNB GenCo report for Erosion Scenario 2 for the reasonably foreseeable (high emission 84%) climate change scenario only, as this was the scenario assessed by Jacobs.

Table 3: Input parameters used for Amazon and EurOtop calculations

Climate Change Scenario No.	Climate change scenario (2110)	Wave derivation method	Water level (m ODN)	Wave height (m)	Wave period (T_m, s)	Water depth at the toe (m)
I	Reasonably foreseeable (high emission 84%)	Depth-limited y=0.78	6.00	2.34	11	3.00

Note: the water depth and (depth-limited) wave height were referenced to Erosion Scenario 2

We would like to point out that it is inappropriate to use a depth-limited method to estimate wave height at a location less than half wave length to the structure. Within such a short distance (20m in this case), there is insufficient time for the wave to be adjusted to the depth limited wave before it hits the structure. This approach may under-estimate wave overtopping rates.

The EurOtop neural network model was based on laboratory tests in which the input wave height was established by a long foreshore beach (often a flat seabed between the toe of a tested structure and the wave generation paddle).

For accuracy (and safe design), it is recommended the use of a proper wave transformation model (for example, nonlinear wave model) to derive wave heights at the toe of a structure.

Figures 4 to 7 present four defence profiles that Jacobs calcuatled overtopping for using the EurOtop neural network method. For comparison purpose, the seaward boundary was located at the toe (3m AOD). Ideally, an Amazon model boundary is recommended to be located at approximately one wave length from the structure.

It is noted that the wave period in the NNB GenCo report was given as T_m=11s but in the Jacobs 'report that $T_{m-1,0}$ = 12s was used. This means Jacobs used a ratio of $T_m/T_{m-1,0}$=1.09.

Amazon model requires the input of a wave spectrum. In this study, the TMA spectrum was adopted, and a ratio of $T_p/T_{m-1,0}$=1.1 was used to convert $T_{m-1,0}$ to T_p which is required for the TMA spectrum.

4.2 Results and Discussions

Error! Reference source not found. presents the results of the Amazon and EurOtop neural network methods. In 3 cases, Amazon predicted significantly higher mean overtopping rates than the EurOtop neural network model. Only in case 4 were the mean overtopping rates predicted by Amazon similar those from the EurOtop neural network model.

Table 4: Comparison of the overtopping rates produced by EurOtop neural network and Amazon

	CC Scenario	Wave period ($T_{m-1,0}$, s)	Wave height (m)	Water level (m AOD)	Mean overtopping rate (l/s/m)
EurOtop	I	12	2.34	6	1.94
Amazon		12	2.34	6	21.5
EurOtop	II	12	2.34	6	3.09
Amazon		12	2.34	6	27.9
EurOtop	III	12	2.34	6	1.96
Amazon		12	2.34	6	17.9
EurOtop	IV	12	2.34	6	22.8
Amazon		12	2.34	6	17.3

Note: wave period in the NNB GenCo report was given as T_m=11s but the Jacobs report suggests that $T_{m-1,0}$ = 12s was used. This means Jacobs used a ratio of $T_m/T_{m-1,0}$=1.09.

Conclusions

In Erosion Scenario 1, the Amazon model predicted similar overtopping rates to the EurOtop empirical method, and these predicted overtopping rates are substantial

In Erosion Scenario 2, the Amazon model predicted significantly higher overtopping rates than the EurOtop neural network model, and Amazon's predicted overtopping rates for Erosion Scenario 2 are still significant.

In Erosion Scenario 2, we noted that a depth-limited wave height was adopted by the Conceptual Design. We would like to point out that it is inappropriate to use a depth-limited method to estimate wave height at a location less than half wave length to the structure. Within such a short distance (20m in this case), there is insufficient time for the wave to be adjusted to the depth limited value before it hits the structure. This approach may under-estimate wave overtopping rates,

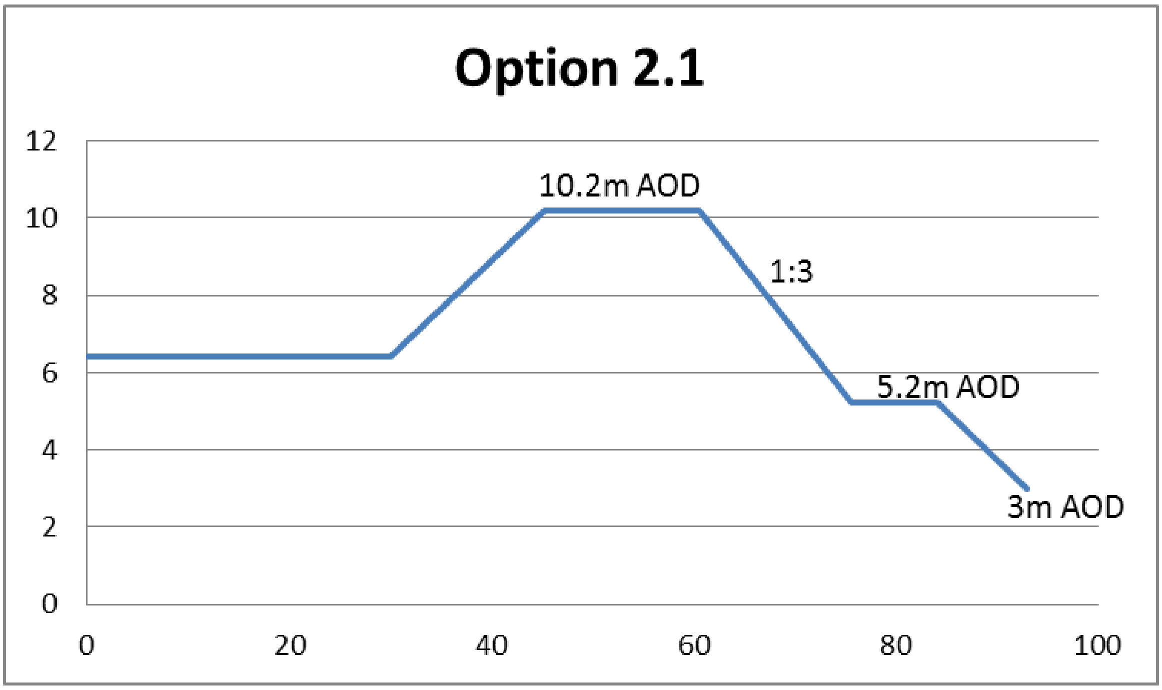

Figure 4: Defence profile of Option 2.1

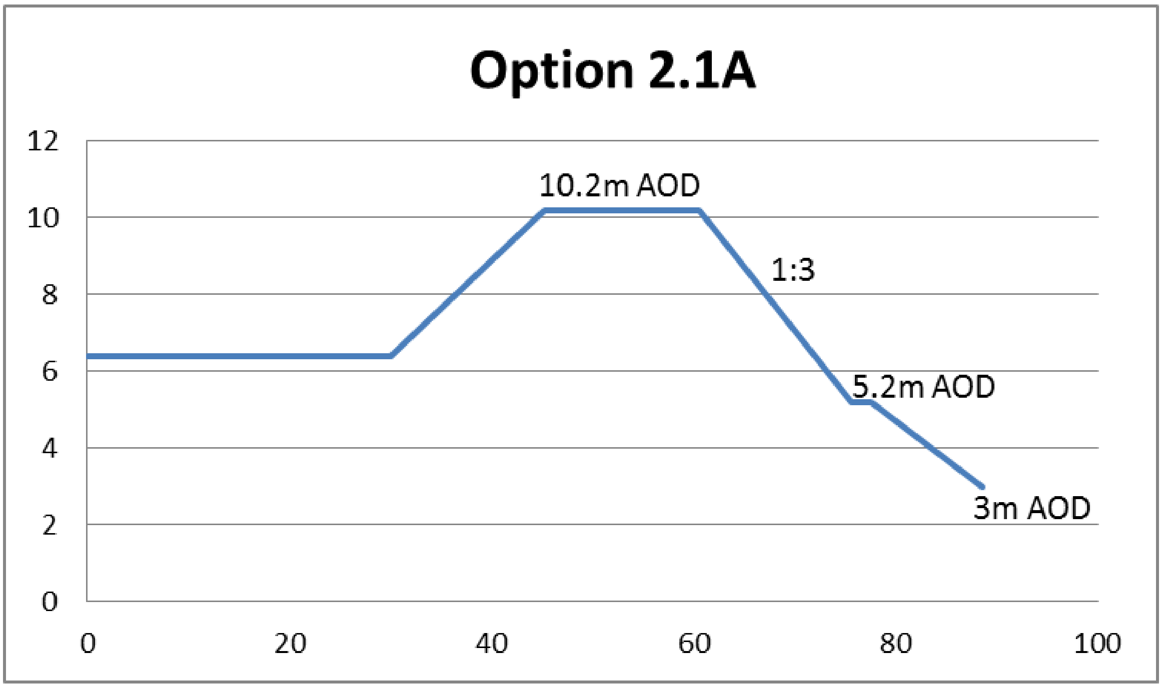

Figure 5: Defence profile of Option 2.1A

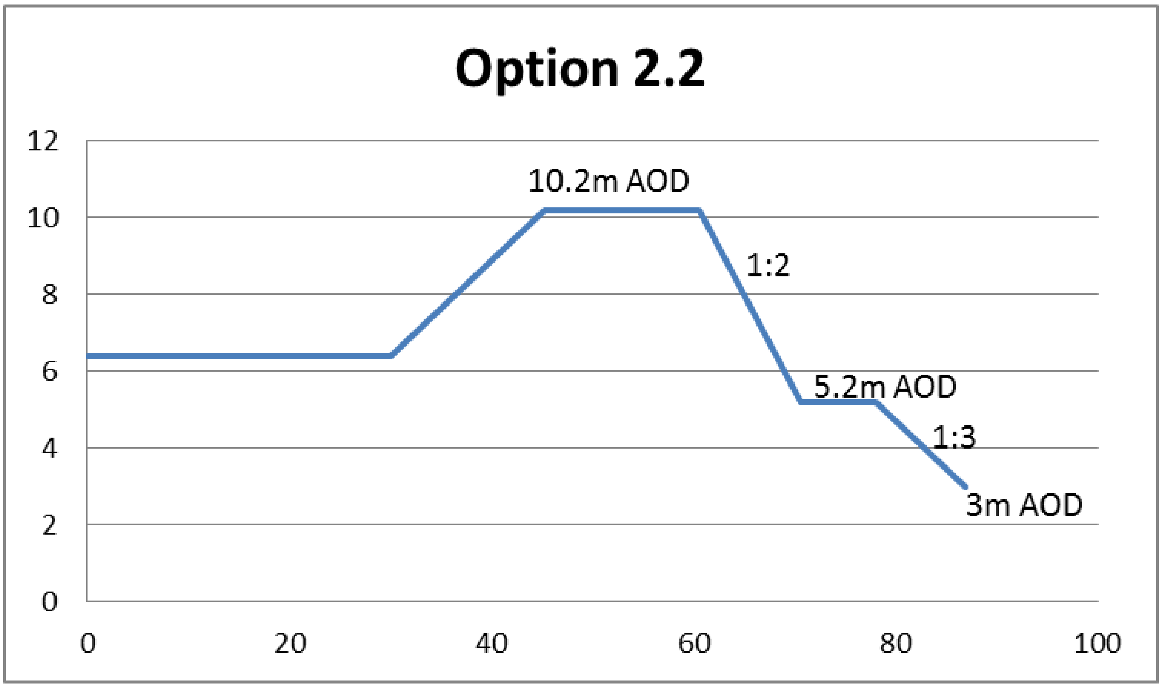

Figure 6: Defence profile of Option 2.2

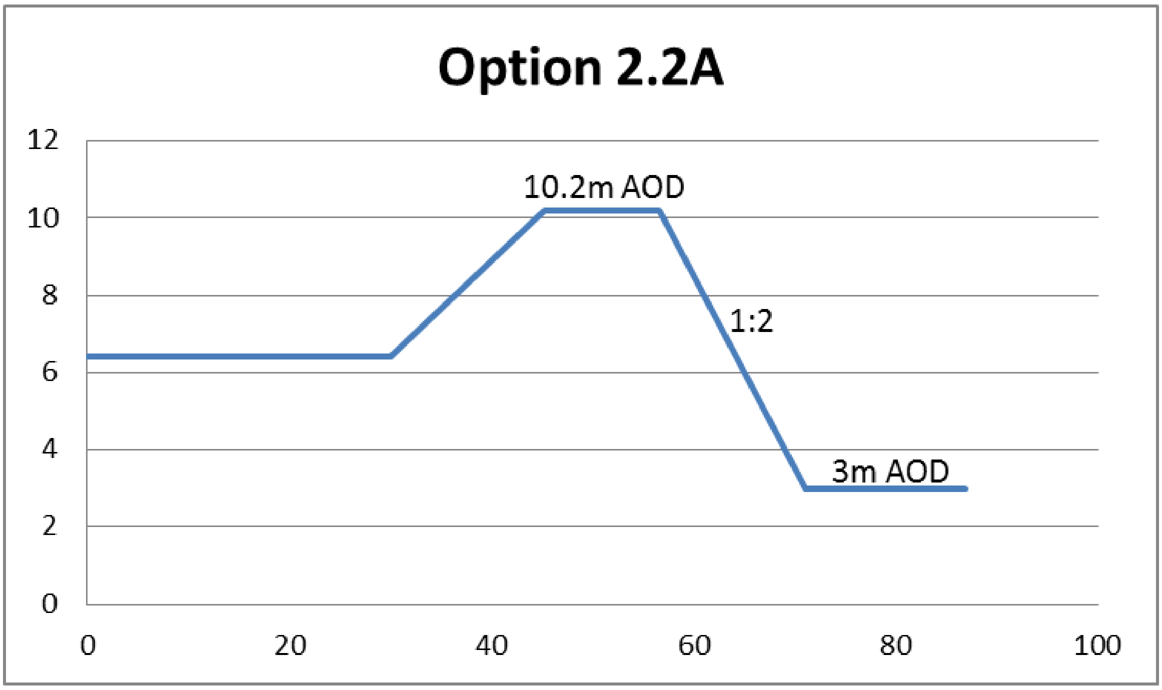

Figure 7: Defence profile of Option 2.2A

RHDHV, 2018. SZC MDS COASTAL OVERTOPPING MODELLING – SUMMARY AND ANTICIPATED DELIVERABLES

Royal HaskoningDHV
Enhancing Society Together

Note / Memo

HaskoningDHV UK Ltd.
Water

To:	[redacted] EDF
From:	[redacted]
Date:	16 August 2018
Copy:	[redacted]
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Classification:	Project related

Subject: **SZC MDS – Coastal Overtopping Modelling – Summary and Anticipated Deliverables**

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1 Introduction

This note relates to coastal modelling work undertaken towards the Flood Risk Assessment for the proposed development of the Sizewell-C (SZC) EDF Nuclear New Build (NNB) power station, Main Development Site (MDS), including the Northern Mound and SSSI crossing.

Section 2 provides a summary of the current status of assessment, including key previous documents. Section 3 then sets out the plan of work for 2018 (in preparation for Stage 3 Consultation) and for 2019 (finalising of the modelling and FRA for the Development Consent Order).

2 Status of Assessment to 2017

This section provides a brief chronology of key historical technical notes issued, key presentations made to EA/ONR, key decisions reached and any more recent unpublished work. These are as follows:

- Technical Development Summary - Coastal: Sizewell C Nuclear New Build FRA Scoping, 2nd draft dated on 18th Jan 2013 (Ref: RHDHV 9X353504 000002).
- FRA Scoping Report: Sizewell C Nuclear New Build, 2nd Final (with minor changes after 1st Final), dated on 24th Jan 2014 (RHDHV 9X353504 000005)
- Sizewell C Flood Risk Assessment – Overtopping Analysis Input Requirements from CEFAS for discussion with CEFAS and EDF, dated on 12th March 2014
- Flood Risk Assessment Sizewell C: AMAZON for overtopping prediction, dated on 17th March 2014 (contents of this note were later incorporated into the note for wave overtopping methodology note: "modelling overtopping of sea defences")
- Sizewell C Flood Risk Assessment and Nuclear Safety Case Recommended Climate Change allowances, 1st version dated on 14th May, and 2nd version dated on 1st July 2014.
- Sizewell C Flood Risk Assessment Recommended Climate Change Allowances, 4th version dated on 14th October 2015.
- Workshop on 13th November 2014 including EA and ONR, discussed offshore extreme waves, extreme water levels, joint probability, wave transformation model and its calibration and wave overtopping modelling approach.
- Workshop on 11th September 2015, focused on wave overtopping modelling approach.
- Sizewell C Flood Risk Assessment Recommended Climate Change Allowances, final version dated on 8th December. 2015
- Sizewell C Flood Risk Assessment - Amazon Sensitivity Tests, dated on 8th December 2014.

- Sizewell C - overtopping comparison calculation on design profile (with beach erosion), dated on 21st Jan 2015.
- Sizewell C Flood Risk Assessment Overtopping modelling scenarios, 1st version dated on 27th Jan 2015
- Sizewell C Flood Risk Assessment Overtopping modelling scenarios, last version dated on 28th July 2015. This note describes the defence profile and climate change scenarios should be considered.
- Sizewell C Flood Risk Assessment - Amazon Sensitivity Tests – Shingle Layer, dated on 20th March 2015.
- Nearshore Wave Data Overview, dated on 13th May 2015.
- Sizewell C Flood Risk Assessment, modelling overtopping of sea defences, issued dated on 11th Jan 2016, 23rd June 2016, and 17th Jan 2017. The purpose of this technical note is to describe the approach that will be taken to modelling overtopping of the sea defences at Sizewell C (SZC). The Jan 2017 version still had some comments attached and it is not clear whether a clean version was sent to EA, or whether any comments were provided from EA to EDF.
- SZC FRA - Amazon model runs, dated on 9th Feb 2016

In summary, the climate change allowance on sea level rise and wave growth has been fully agreed with EA and ONR, based on UKCP09. Refer to section 3.1.4 **Error! Reference source not found.**for discussion on UKCP18.

The wave overtopping methodology has been discussed with EA/ONR twice (two workshops) and is ongoing.

The last note contains Amazon model runs for one profile of the new build platform profiles (initial profile and breached profile) for storm events of 1 in 200 years and 1 in 1,000 years under some climate change scenarios (inshore wave data was not completely available for all climate change scenarios at the time).

No work has been done yet on the construction phase, Northern Mound, or SSSI Crossing Wave Overtopping.

3 Anticipated Work and Deliverables

3.1 Anticipated Work for 2018

It is important that the methodology of wave overtopping modelling is fully agreed with EA and ONR if this has not been done, to avoid potential abortive work if their views or requirements change. RHDHV understand that the responsibility for obtaining this agreement rests with EDF, while RHDHV will provide support/assistance where required and in line with agreed scope for such support.

In support of the Stage 3 consultation, preliminary flood risk modelling is anticipated for:

- Main platform during construction (the profile and offshore Joint Probability conditions that produced the highest overtopping quantities, namely profile 3, and run 1 in 200 and 1 in 1,000 yr scenarios to look at overtopping rates during construction).
- The Northern Mound (this profile was not previously available)
- The SSSI crossing. This road will be needed for access/egress up to at least 1:200y. The profile shape for the SSSI crossing will require merging with a CEFAS conservative 'roll-back' scenario (existing beach profile 1 assumed, but with the shoreline predicted to erode landward).

The remainder of section 3.1 will later be migrated to an updated version of the overtopping modelling report, together with the results.

3.1.1 Profile Derivation

Profiles for wave overtopping modelling require merging of various datasets of near-shore bathymetry, beach profiles (topo surveys and LiDAR) and proposed sea defences. Profiles have previously been extracted at the locations shown in Figure 3-1 below, with LiDAR used to highlight changes in elevations on the right hand image.

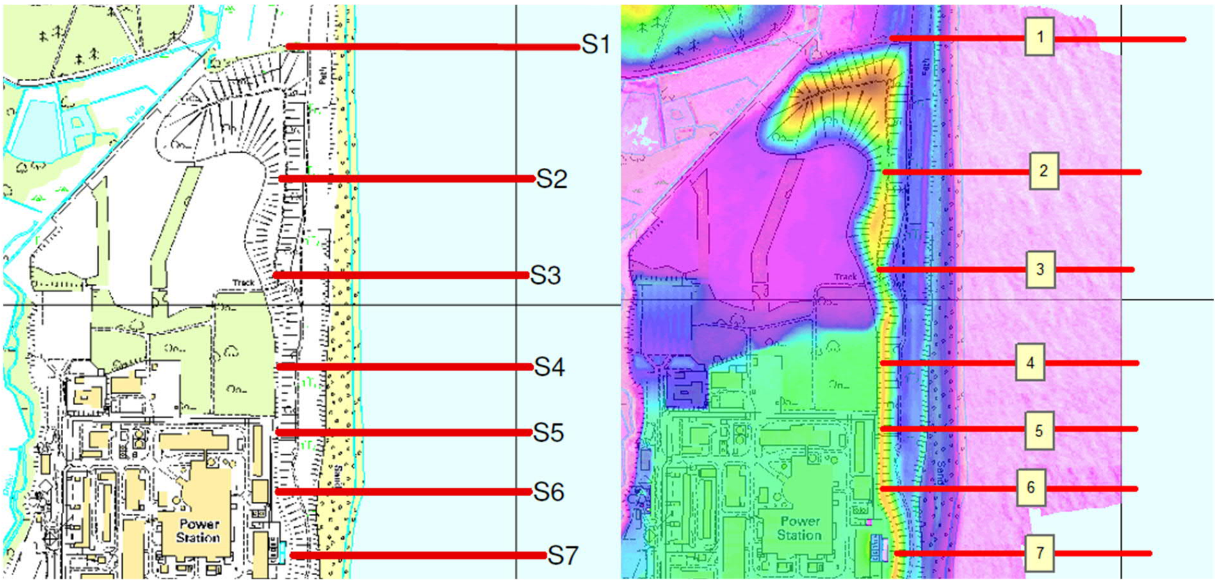

Figure 3-1: Existing profile locations

In support of the Stage 3 consultation, preliminary flood risk modelling is anticipated for:

- Main platform during construction (the profile and offshore Joint Probability conditions that produced the highest overtopping quantities, namely Profile 3, and run 1 in 200 and 1 in 1,000 yr scenarios to look at overtopping rates during construction).
- The Northern Mound (this profile was not previously available). A modified version of Profile 1 is proposed below.
- The SSSI crossing. This road will be needed for access/egress up to at least 1:200y. The profile shape for the SSSI crossing will require merging with a CEFAS conservative 'roll-back' scenario (existing beach profile 1 assumed, but with the shoreline predicted to erode landward).

Profile 3 construction phase profile was derived from the existing profile 3 and drawing SZC-SZ0100-XX-000-DRW-100025 (dated 14/07/2018). The location of the profile relative to the proposed platform is shown in Figure 3-2 below. The profile data is illustrated in Figure 3-3, in which the green dotted line labelled 'Construction - Main Development Site' is proposed for the overtopping modelling.

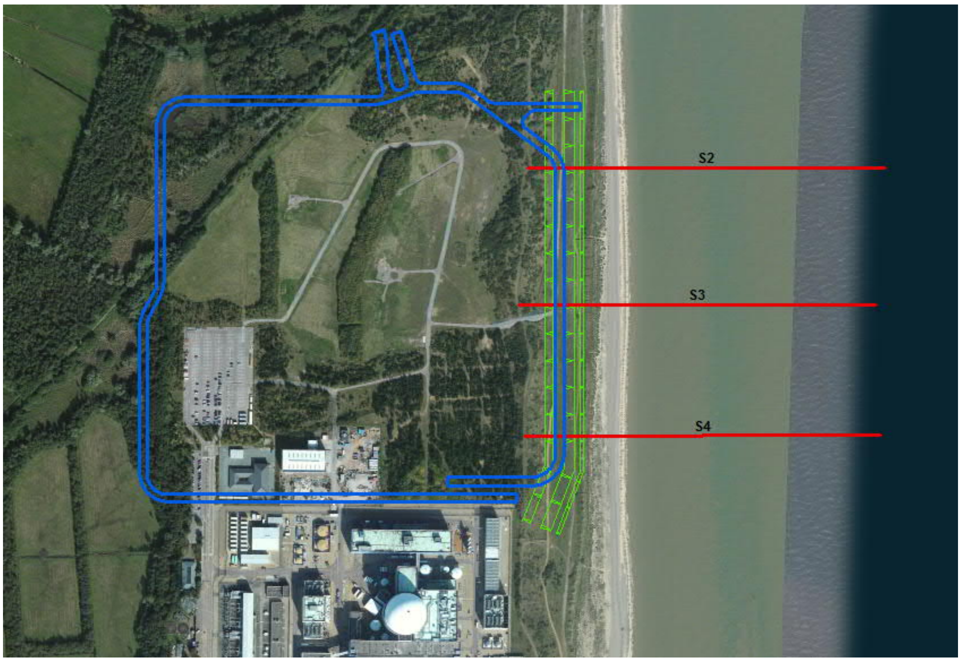

Figure 3-2: Location of profile 3 relative to proposed platform

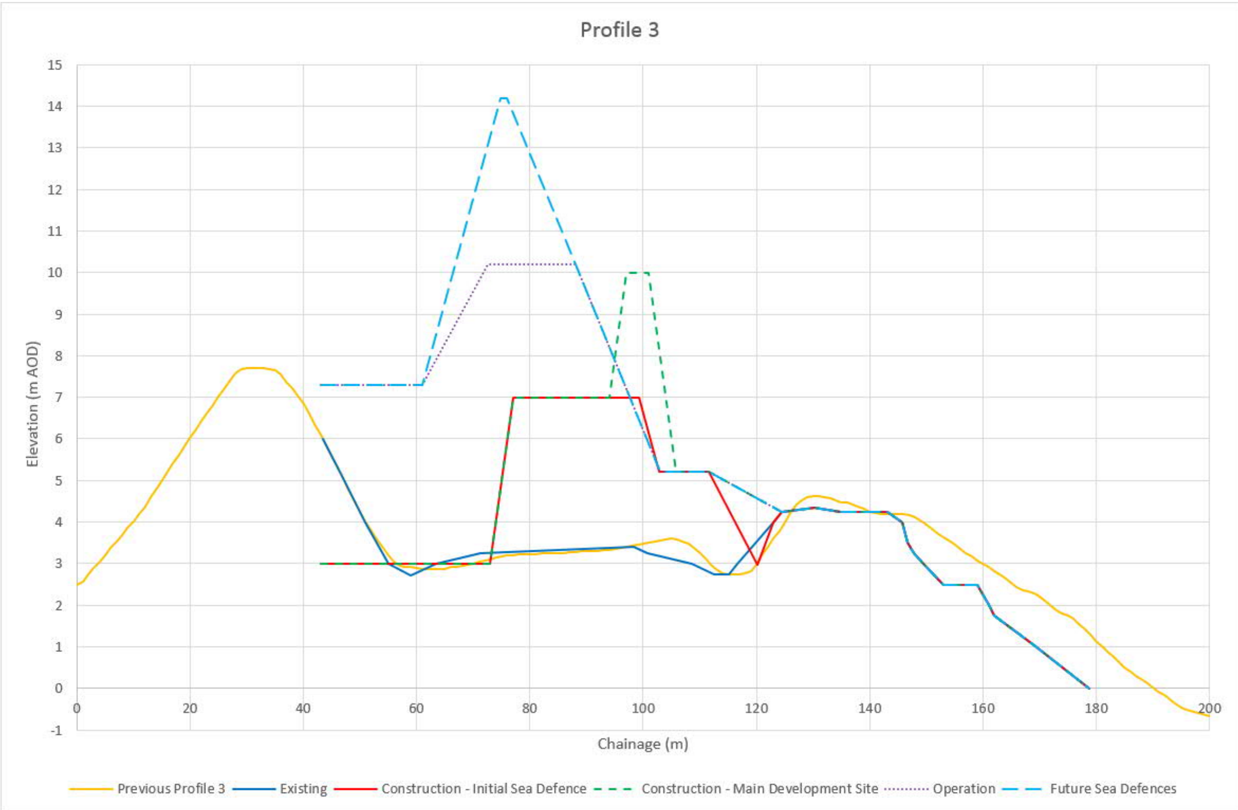

Figure 3-3: Profile 3 merging for overtopping model (construction phase)

It should be noted that the 'Existing' profile in Figure 3-3 (dark blue line) was derived from the provided design drawing (SZC-SZ0100-XX-000-DRW-100025) that included existing ground levels prior to construction. This was understood to be surveyed in 2018. The beach levels of the 'Existing' profile are lower than the 'Previous Profile 3' (which is based on a survey from February 2014).

The Northern Mound overtopping profile was constructed using the latest drawing of sea defences (SZC-SZ0100-XX-000-DRW-100031 dated 29 June 2018, section 2-2, shown in Figure 3-4 below) and combined with the previously developed profile 1. The profile 1 was derived by selecting the worst (lowest) data from the various topographic datasets, with bathymetry data only used for the offshore end of the profile. The proposed sea defence profile required merging at an angle, as shown in Figure 3-5. Since Amazon 1D wave model is proposed, it is assumed that waves will still arrive normal to the derived 1D profile, and so the adopted overtopping profile is more conservative. The location of the proposed sea defence profile is shown below (section 2-2), followed by the profile merging (plan view Figure 3-5 and cross section in Figure 3-6).

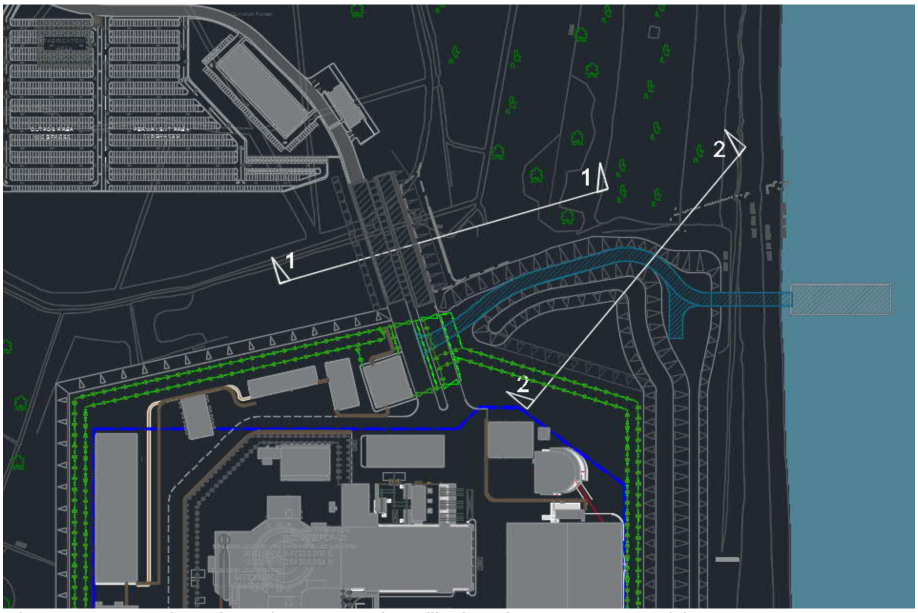

Figure 3-4: Location of Northern Mound profile (section 2-2, extracted from SZC-SZ0100-XX-000-DRW-100031)

Figure 3-5: Plan view of profile datasets prior to merging

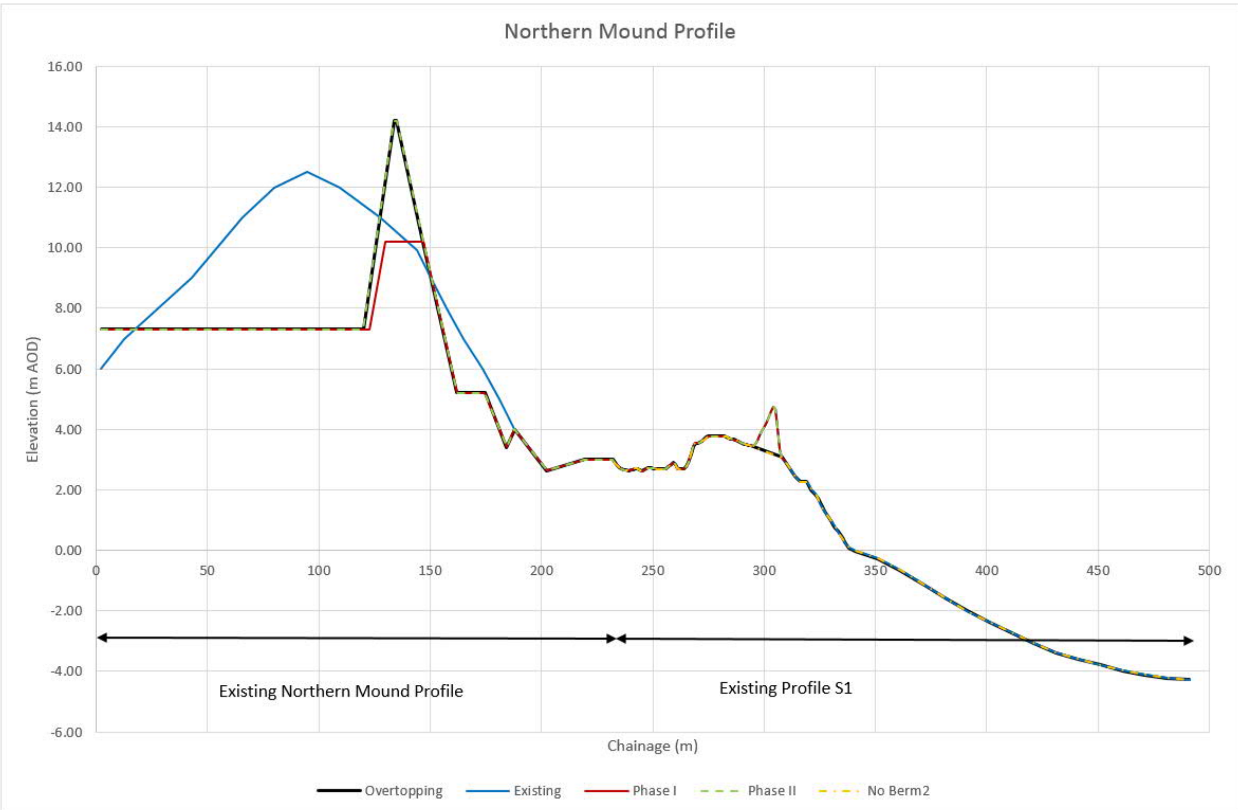

Figure 3-6: Northern Mound profile merging for overtopping

The SSSI crossing is also based on a modification of profile 1, but with the shoreline moved landward to test a future potential 'coastal roll-back' scenario. The position of the coastline relative to the existing was informed by a high level CEFAS study. The proposed SSSI crossing profile was based on the latest drawing of sea defences (SZC-SZ0100-XX-000-DRW-100031, dated 29 June 2018, section 1-1, shown in Figure 3-7 below).

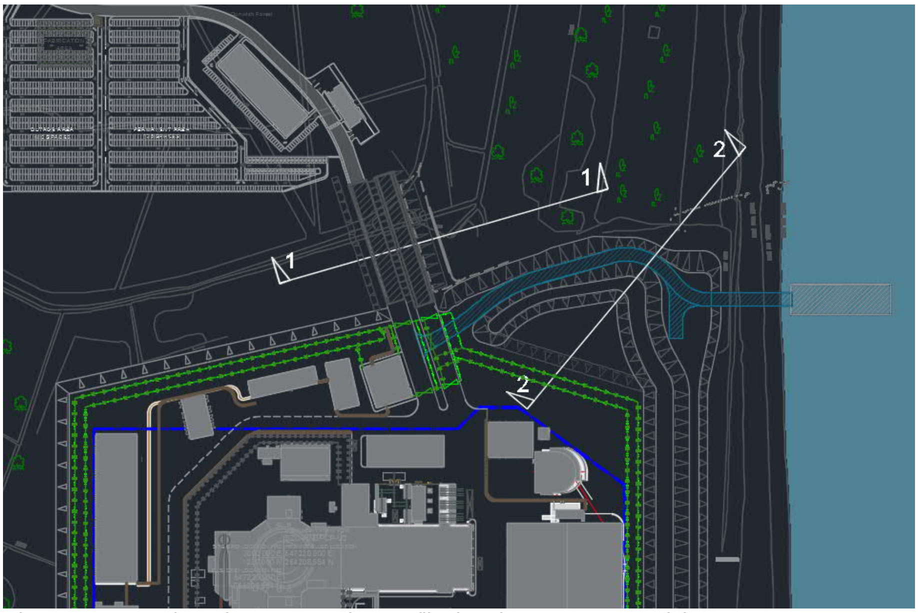

Figure 3-7: Location of SSSI crossing profile (section 1-1, extracted from SZC-SZ0100-XX-000-DRW-100031)

3.1.2 Scenario Selection for 2018 runs

The profiles will be processed for use in Amazon, and run for the return periods and climate change scenarios proposed in Table 1. This is intended to provide a preliminary assessment of the risk in these locations, using a reduced number of scenarios, which will inform the PEIR for Stage 3 consultation and also inform the scale of further investigations required for 2019.

Table 1 Summary of proposed Joint Probability Combinations and Climate Change Scenarios

Situation	Input scenarios available	1:200	1:1000	1:10,000
MDS Profile3 construction phase 2030[1]	2025[1] 95% high emission = 0.113m SLR (Case D)	x	x	
Northern Mound modified Profile1 operational phase 2110	2110 95% med emission = 0.74m SLR (Case 2)	x		
	2110 95% high emission = 0.91m SLR (Case 3)		x	n/a[2]
	2110 Upper End Estimate with land motion and surge = 1.81m SLR (Case 7)			n/a[2]
	2110 BECC Lower = 1.55m SLR (Case 8)			
	2110 H++ with land motion plus surge, same as BECC Upper = 3.2m SLR (Case 10)			x
	2110 95% med emission = 0.74m SLR (Case 2)	x		

SSSI crossing modified Profile1 operational phase 2110	2110 95% high emission = 0.91m SLR (Case 3)		x	n/a[2]
	2110 Upper End Estimate with land motion and surge = 1.81m SLR (Case 7)			n/a[2]
	2110 BECC Lower = 1.55m SLR (Case 8)			
	2110 H++ with land motion plus surge, same as BECC Upper = 3.2m SLR (Case 10)			x

*Note **1**: Construction phase currently estimated to be circa 2030. This model run will use wave conditions from 2025 (previously calculated by CEFAS). The use of high emission Sea Level Rise will mitigate the change from 2025 to 2030. Further runs are likely to be performed in 2019, after UKCP18 becomes available.*
*Note **2**: Inshore wave data is not currently available for some scenarios for 1 in 10,000 years.*

All proposed runs would be carried out for the worst joint probability combination of extreme water level and wave height. CEFAS combination codes for the worst joint probabilities determined in the previous sensitivity are: F1, F2 and C3 for the 1:10,000, 1:1000 and 1:200 return period respectively.

The model results will be interpreted to inform the PEIR for Stage 3 consultation, although these may not be the final results at discussed in the following sections.

3.1.3 Criteria for Flood Risk Assessment

Prior to the execution of final simulations in 2019, it is important to define and agree the desired output in terms of locations to be assessed, output parameters and tolerance of outcomes, including potentially tolerable overtopping rates in different situations, and whether flood spreading modelling might be required to calculate depth and hazard.

3.1.4 Climate Change update UKCP18

Later in 2018, when UKCP18 is released, there is an activity planned that will review the key changes in UKCP18, to inform which tasks may need to be re-done in 2019 using UKCP18 climate predictions. If UKCP18 gives significantly different sea level rise, CEFAS will have to re-run their wave model before RHDHV can run updated wave overtopping modelling.

3.2 Anticipated Work and Deliverables for 2019

Activities anticipated for 2019, possibly influenced by UKCP18, include:

- Review and extract final design defence profiles;
- Obtain "erosion" beach profile from CEFAS (for safety case);
- Obtain final wave climate information from CEFAS (updated if required based on UKCP18), plus case scenario selection (this is expected to cover the majority of scenarios on **Table 1** above, but the case combinations may change due to UKCP18);
- Finalize Amazon model setup;
- Run Amazon models for the agreed return periods (1 in 200 years, 1 in 1,000 years and 1 in 10,000 years) and climate change scenarios.
- Provide model results for external review (confirm who/requirements)
- Interpretation and document results for final FRA.

RHDHV, 2020. EDF ENERGY. UK CLIMATE CHANGE PROJECTIONS 2018 – REVIEW AND PROPOSED RESPONSE

Royal HaskoningDHV
Enhancing Society Together

Note / Memo

HaskoningDHV UK Ltd.
Water

To: EDF SZC Project Team
From: Katarzyna Bozek
Date: 13 March 2019
Copy: Andrew Craig, Ian Dennis, David Brew
Our reference: PB6582WATNT_UKCP18_D01
Classification: Project related

Subject: **UK Climate Change Projections 2018 - Review and Proposed Response**

1 Introduction

The purpose of this technical note is to review recently published UK Climate Projections 2018 (UKCP18), compared with currently adopted allowances, and recommend the climate change parameters to be used for the modelling scenarios as part of the Flood Risk Assessment (FRA) work for the proposed Sizewell C development (SZC).

The note primarily covers climate change allowances related to FRA, required as part of the planning process. Whilst it may also be informative to the nuclear safety case, it does not make any explicit recommendations for that study. Concurrently, EDF R&D are preparing a response document on UKCP18.

The note considers climate change associated with coastal flood risk, i.e. relative sea-level rise, storm surge, wind and waves, as well as pluvial and fluvial flood risk, i.e. rainfall intensity and river flows. Currently adopted climate change allowances (as at 2016) are summarised in Section 2, followed by updates from UKCP18 in Section 3. Section 4 indicates changes in extreme still water levels available from the draft (soon to published) updated UK Coastal Boundary Dataset. Section 5 provides recommendations for climate change allowances to be applied in the SZC FRA study.

2 Currently Adopted Climate Change Allowances (2016)

This section provides summary of climate change allowances for assessment of pluvial, fluvial and coastal flood risk at SZC derived in previous analyses in 2015 and 2016. These were based on latest available guidance at the time and were discussed and agreed with EDF and the Environment Agency (EA).

In the previous assessment, climate change allowances were presented for the proposed timings of each phase of Sizewell C. These timings were agreed at an FRA meeting held on 21st May 2015 with the Environment Agency and are as follows:

- 2017: start of construction;
- 2025: end of construction & start of commissioning (used for assessment of construction phase flood risk);
- 2085: end of operation (60 years predicted operational lifetime);
- 2110: end of decommissioning;
- 2140: interim spent fuel store decommissioned; and
- 2185: theoretical maximum site lifetime (160 years).

It was assumed that 2185, as theoretical maximum site lifetime would be used in the FRA for assessment of potential off-site impacts, whereas on-site risks would only be considered to 2140 as the end of Interim Spent Fuel Store.

As discussed in later sections of this report, these dates will be adjusted for a later start of construction that is now anticipated.

2.1 Rainfall Intensity and River Flows

Initial assessment of climate change allowances for rainfall intensity and river flows was carried out in 2015 in line with the National Planning Policy Framework (NPPF) and associated guidance, Environment Agency climate change guidance (2013) and including a specific study for changes in pluvial events at the Sizewell area, commissioned by EDF from the Met Office[1]. Following this assessment, a technical note on 'Recommended Climate Change allowances; Fluvial, Pluvial and Groundwater' (RHDHV, February 2016) was issued in early February 2016. Also in February 2016, the Environment Agency published updated guidance on Climate Change Allowances for Flood Risk Assessments. In addition, the EA had provided comments on the previously derived (RHDHV, February 2016) climate change allowances. Following the 2016 guidance and comments from the EA, the approach for dealing with climate change for Sizewell C was updated accordingly as described in the note 'Sizewell C – Flood Risk Assessment Climate Change: Response to reflect 2016 Climate Change guidance' (RHDHV, September 2016).

The currently adopted climate change allowances (RHDHV, September 2016) for fluvial flood risk are based on the Anglian River Basin District peak river flow allowances for the Upper End Estimates and H++ Scenario with corresponding allowances for each epoch as presented in **Table 1**.

Table 1. Peak River Flow Allowances for Anglian River Basin.

Climate Change Epoch	Upper End (90th percentile)	H++ Scenario
'2020s' (2015-39)	+25%	+25%
'2050s' (2040-2069)	+35%	+40%
'2080s' (2070-2115)	+65%	+80%

Note: The above allowances were extracted from the guidance on 'Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities', Published on 19 February 2016 by the Environment Agency.

As recommended in the 2016 guidance, the 2080s changes are used for time horizons/epochs beyond 2115.

The 2016 guidance also states that for areas greater that 5km^2, the fluvial climate change allowances should be used for peak rainfall intensity. Since the hydraulic model developed for the SZC FRA study applies a direct rainfall to an area of more than 5km^2, peak flow ranges will be applied to account for climate change in peak rainfall intensity.

Further details on the initial climate change assessment and updates following 2016 guidance can be found in the note: 'Sizewell C – Flood Risk Assessment Climate Change: Response to reflect 2016 Climate Change guidance', (RHDHV, September 2016).

[1] Met Office, 2011. Extreme Precipitation Analysis at Sizewell: Final Report.

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2.2 Sea Level Rise and Storm Surge

Initial assessments of climate change allowances for sea level rise and storm surge considered multiple sources of information and guidance available at the time, including the following reports:

- Atkins (2014). Sizewell C Platform Level and Coastal Flooding: Scoping Report for ALARP Assessment, April 2014.
- BECC (2014). BECC Scoping Paper: How to Define Credible Maximum Sea Level Change Scenarios for the UK Coast [authored by Professor Robert Wilby], January 2014;
- BEEMS (2010). Update on Sea Levels for BE Sites using UKCP09 [authored by Robert Nicholls and Derek Clarke], February 2011;
- BEEMS (2013). Estimation of extreme sea levels at Sizewell. Technical Report TR252 [authored by Kenneth Pye and Simon Blott], November 2013;
- Environment Agency (2011). Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities;
- Environment Agency (2013). Climate Change Allowances for Planners. Guidance to Support the National Planning Policy Framework, September 2013;
- Office for Nuclear Regulation and Environment Agency (2013). Joint Advice Note: Principles for Flood and Coastal Risk Management, Version_3, April 2013; and
- Shennan, I., Milne, G. and Bradley, S. (2012). Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. Journal of Quaternary Science, 27, 64-70.

Environment Agency (2011) guidance recommends using the UKCP09 95%ile estimates of the medium emissions scenarios for reasonably foreseeable climate change and H++ scenario for the credible maximum climate change up to 2110 and beyond.

The initial assessment of climate change allowances appropriate for SZC FRA considered the EA guidance as well as other reports listed above, and a comprehensive study compared rates of change for relative sea level rise and storm surge. Recommended allowances were determined for each epoch, with selected climate change scenarios, as follows:

- the 95%ile of the medium emissions scenario defined by UKCP09 for the reasonably foreseeable sea level rise scenario;
- the upper end of UKCP09 H++ with land motion for up to 2100 and the BECC (2014) upper estimates of sea level rise for beyond 2100;
- no allowance for storm surge for reasonably foreseeable scenario and 1.0m storm surge for epoch beyond 2085 for the credible maximum scenario. The credible maximum estimates of storm surge are at the very top end of the modelled estimates of UKCP09. For the BECC (2014) estimates, surge is already integrated into the values presented.

Summary of derived climate change allowances for sea level rise (including applicable storm surge) for key points in time, relative to 2008 baseline, are presented in **Table 2**.

Table 2. Climate change scenario changes in sea level (in m) relative to a baseline of 2008

Year	UKCP09 / BEEMS (2011)	UKCP09 / BEEMS (2011)	Environment Agency (2011), Shennan et al. (2012)	BECC (2014)	Environment Agency (2011), Shennan et al. (2012)	BECC (2014)
	Medium Emissions 95%ile	High Emissions 95%ile	Upper-End Estimate with Land Motion	BECC Lower	H++ with Land Motion	BECC Upper
2017	0.047	0.058	0.043	-	0.061	-
2025	0.093	0.113	0.082	-	0.116	-
2085	0.522	0.637	0.710	-	1.361	-
2110	*0.744*	*0.908*	1.105	*1.550*	2.206	*3.200*
2140	*1.014*	*1.238*	-	*1.950*	-	*3.920*
2185	*1.419*	*1.733*	-	*2.400*	-	*4.730*

*Note: Italics indicate values that are extrapolated beyond the range stated in guidance (for UKCP09 and BEEMS (2011) values) or interpolated between two bounding values (for BECC (2014) values).

Details on the approach and derived sea level rise and storm surge allowances are set out in Technical Note: Sizewell C Flood Risk Assessment Recommended Climate Change allowances', RHDHV, September 2015. These allowances have been discussed and agreed with the Environment Agency.

2.3 Wind and Wave Climate

Climate change allowances for 'increased storminess' resulting in higher wind speeds and wave heights adopted in the initial study (RHDHV, 2015) were based on Environment Agency's (2013) guidance. The 2013 guidance suggested assuming a precautionary increase in wave height of 5% to 2055 and then 10% from 2055 to 2115, although UKCP09 report stated that seasonal mean and extreme waves are generally expected to experience little change in the North Sea.

Due to the significant uncertainties associated with both the future position of the storm track over the UK and the projections of (wind and) wave climate within UKCP09, the currently recommended increases in wave height at Sizewell C for flood risk assessment are 10% for the reasonably foreseeable scenarios and 15% for the credible maximum scenarios with no change in predominant wave direction.

There will also be a change in wave climate associated with sea level rise, as waves propagate across (slightly) deeper water and therefore break (slightly) closer to shore. BEEMS modelling studies will inherently incorporate this aspect if suitable sea level rise conditions are included in its joint probability assessment and wave transformation models.

Further details on the 2015 assessment of potential changes in wave climate are provided in Technical Note: Sizewell C Flood Risk Assessment Recommended Climate Change allowances', (RHDHV, September 2015).

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3 UKCP18 Climate Change Allowances Updates

UK Climate Projections 2018 (UKCP18) provides an updated set of climate projections out to 2100 in the UK and globally, and tools to access climate data designed to help decision-makers assess their risk exposure to climate. The major innovations in UKCP18 include the use of new observations of weather and climate, inclusion of a more recent generation of climate models from around the world and results from the latest Met Office global and regional climate models used to provide the most up-to date assessment of how the climate of the UK may change over the 21st century and beyond.

In the UKCP18, Representative Concentration Pathways (RCPs) were used, in line with the emissions scenarios specified in the Intergovernmental Panel on Climate Change's latest 5th assessment report. UKCP09 used the SRES (Special Report on Emissions Scenarios) emissions scenarios which were reported on in the IPCC's 4th assessment report. The emissions scenarios are represented by four radiative forcing levels at the top of the atmosphere by 2100 set to: 2.6, 4.5, 6.0 and 8.5 W/m^2. These create four RCPs that are used in UKCP18; namely RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 respectively.

Table 3 presents the global mean temperature increase (best estimate and range between 5th and 95th %iles) associated with each RCP and corresponding most similar SRES emissions scenario from UKCP09.

Table 3. The increase in global mean surface temperature averaged over 2081-2100 compared to the pre-industrial period (average between 1850-1900) for the RCPs (best estimate, 5-95% range) Extracted from UKCP18 Guidance: Representative Concentration Pathways Report (Met Office, 2018)

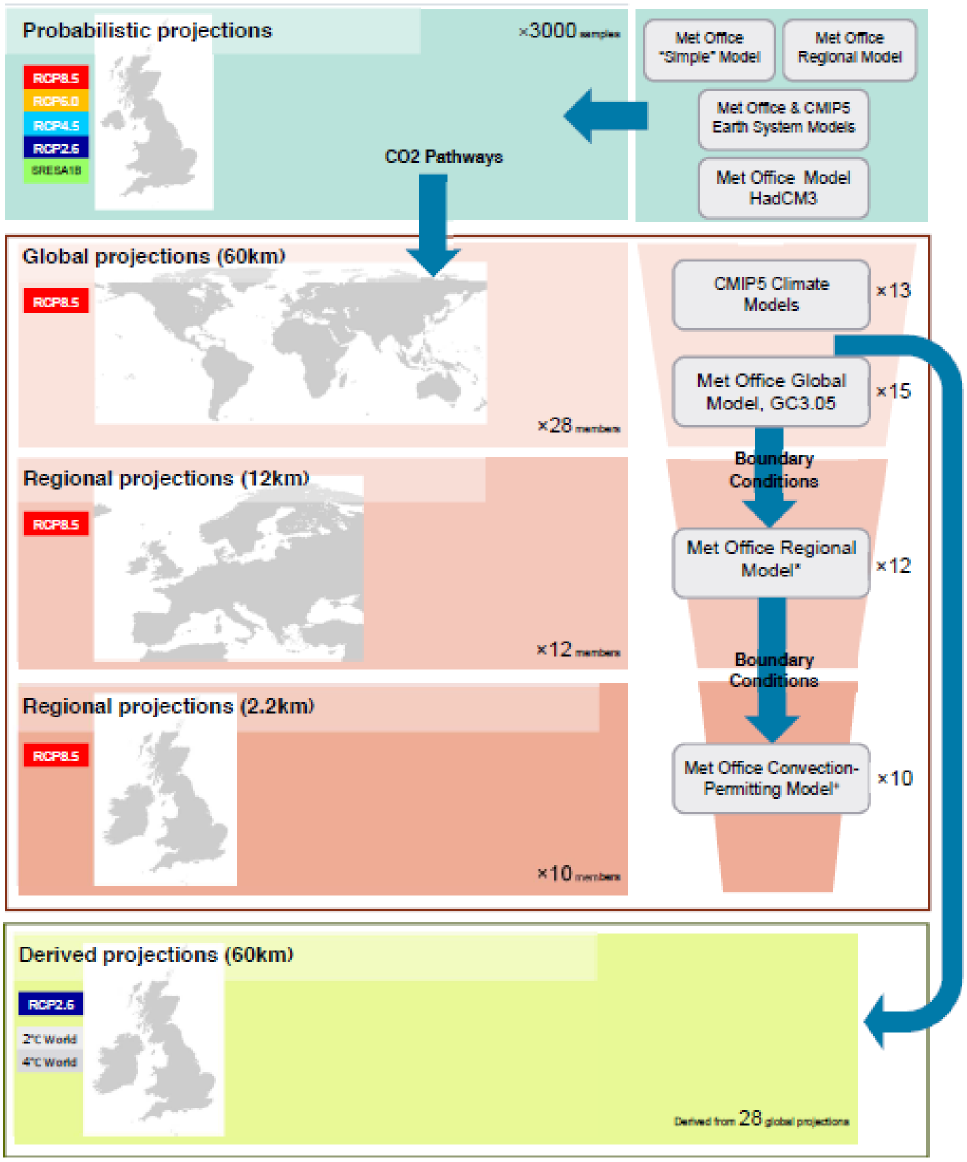
RCP	Increase in global mean surface temperature (°C) by 2081-2100	Most similar SRES scenario (in terms of temperature)
RCP2.6	1.6 (0.9-2.3)	None
RCP4.5	2.4 (1.7-3.2)	SRES B1 (low emissions scenario in UKCP09)
RCP6.0	2.8 (2.0-3.7)	SRES B2 (between the low and medium emission scenarios in UKCP09)
RCP8.5	4.3 (3.2-5.4)	SRES A1F1 (high emissions scenario in UKCP09)

The updated UKCP18 probabilistic projections over land provide a set of high-resolution spatially-coherent future climate projections for the globe at 60km scale and for the UK at 12km regional scale. Updates to the marine projections give new estimates for sea-level rise and storm surge.

This Section provides summary of land and marine projections relating to the SZC FRA study and comparison with currently adopted climate change allowances.

3.1 Land Projections

UKCP18 Land Projections provide climate features, such as anomalies in humidity, precipitation, sea level pressure, radiation wave flux and air temperature for probabilistic, global, regional and derived projections at different scales. **Figure 1** presents schematic showing how the different land projections components are connected, their scale and what climate models have been used to derive them.



*similar to global model but set up for regional simulations (HadREM-GA705) +model name is HadREM-GARA11M

Figure 1. Schematic showing how the different components of the land projections are connected (extracted from 'UKCP18 Guidance: How to use the UKCP18 land projections', Met Office, 2018).

In terms of climate change allowances used for the SZC FRA study, the UKCP18 land projections provide only changes in rainfall patterns. In summary the UKCP18 states that over land the projected general trends of climate changes in the 21st century are similar to UKCP09, with a move towards warmer, wetter winters and hotter, drier summers. Rainfall patterns across the UK are not uniform and vary on seasonal and regional scales and will continue to vary in the future. The projections show a pattern of larger increases in winter precipitation over southern and central England and some coastal regions towards the end of the century. Summer rainfall reductions tend to be largest in the south of England. These key messages refer to total rainfall over a 3-month season and do not infer information about the intensity of individual rainfall events.

Figure 2 below illustrates changes in rainfall intensity across England for the winter season for three epochs relative to 1981-2000 year baseline for the RCP8.5 based on probabilistic projections. The results suggest that for the location of SZC Development (Minsmere River Catchment) precipitation for the winter season is predicted to increase by up to 20% for the 2020-2039 epoch, up to 30% for 2040-2059 and up to 50% for the 2080-2099 epoch.

Table 4 presents a comparison of currently adopted climate change allowances for increases in rainfall intensity with estimates provided by UKCP18. The UKCP18 allowances are based on probabilistic projections for RCP8.5 which is most similar to high emissions scenario from UKCP09.

Table 4. Comparison of climate change allowances for increase in rainfall intensity

Climate Change Epoch	EA Guidance*: Upper End Allowance	EA Guidance*: H++ Scenario	UKCP18**
'2020s' (2015-39)	+25%	+25%	+10%
'2050s' (2040-2069)	+35%	+40%	+35%***
'2080s' (2070-2115)	+65%	+80%	+50%

*% for increase in rainfall intensity are adopted from allowances for peak river flow for Anglian River Basin, as recommended in the guidance for catchments over, say 5km^2.
**Precipitation anomaly for winter season across England based on probabilistic projections for RCP8.5.
***Derived as average % of winter precipitation anomaly in England between 2040-2059 and 2060-2079 time slices (extracted from Met Office Land Projections Maps: Probabilistic Projections (https://www.metoffice.gov.uk/research/collaboration/ukcp/land-projection-maps, accessed on 19th February 2019).

UKCP09 provided a Weather Generator which is a tool for providing long synthetic series of daily climate variables. This was then were used for risk analysis of impacts that depend upon the sequence of weather conditions such as peak river flows. The Weather Generator has not been provided in UKCP18.

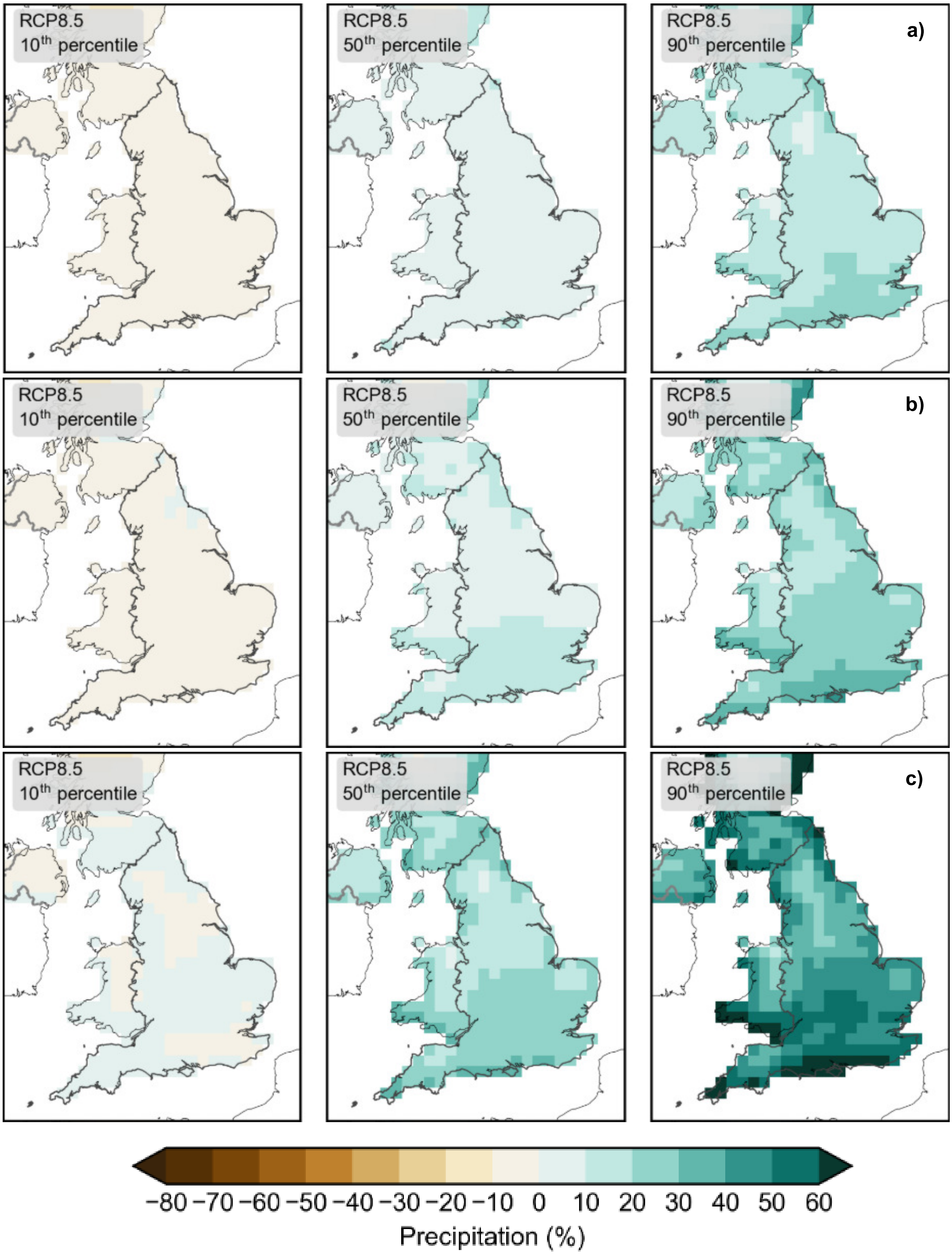


Figure 2. Winter Precipitation anomaly for epochs: a) – 2020-2039, b) – 2040-2059 and c) – 2080-2099, relative to 1981-2000 baseline (extracted from Met Office Land Projections Maps: Probabilistic Projections, accessed on 19th February 2019).

3.2 Marine Projections

The UKCP18 Marine Projections provide estimates of changes in coastal sea level, including extreme water levels that arise from storm surges and surface waves. The time-mean sea level projections of UKCP18 are based on updated scientific methods and climate change scenarios compared to UKCP09, that include ice dynamics in projections of future sea level rise, resulting in systematically larger values than presented in UKCP09.

Key findings from the marine projections of UKCP18 are that the RCP climate change scenarios span a greater range of climate forcing over the 21st century than the SRES scenarios used in UKCP09. UK coastal flood risk is expected to increase over the 21st century and beyond under all RCP scenarios, meaning that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will most likely be dominated by the effects of time-mean sea level rise, rather than changes in atmospheric storminess associated with extreme coastal sea level events. Exploratory time-mean sea level projections to 2300 suggest that UK sea levels will continue to rise over the coming centuries under all RCP climate change scenarios. The 21st century projections of average wave height suggest changes up to 10-20% and a general tendency towards lower wave heights. Changes in extreme waves are also of order 10-20%, but there is no agreement in the sign of change among the model projections. Changes in wave climate over the 21st century on exposed coasts will be dominated by the global response to climate change, and more sheltered coastal regions are likely to remain dominated by local weather variability. The UKCP18 results do not provide any indication on correlation between the extreme sea levels and significant wave height.

The plume of sea level anomalies for marine projections around UK coastline for 21st century projections and extended projections to 2300 were downloaded from the UKCP18 User Interface[2] for the two grid cells closest to the SZC development, as illustrated in Figure 3. It should be noted that at the location of the SZC development there are two grid cells that could be used. Initial assessment of the sea rise anomalies showed that grid cell to the north of the SZC (grid square 52.28^{o}, 1.75^{o} highlighted in **Figure 3** below) gives slightly higher relative sea rise allowances. To adopt conservative approach, this cell was selected for further assessment.

[2] UKCP UI - https://ukclimateprojections-ui.metoffice.gov.uk/ui/home

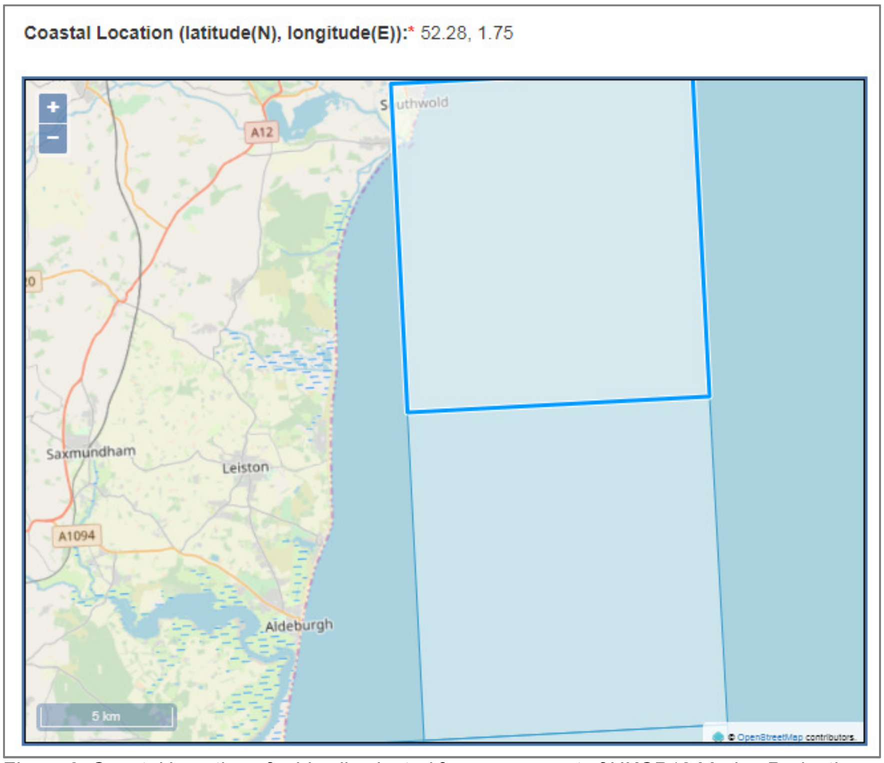


Figure 3. Coastal Location of grid cell selected for assessment of UKCP18 Marine Projections for Sea Level Anomalies (extracted from UKCP UI Products, https://ukclimateprojections-ui.metoffice.gov.uk/products, accessed on 2nd January 2019).

The time-mean sea level anomaly plots for 2007-2100 and 2007-2300 are presented in **Figure 4** and **Figure 5** respectively. These projections represent relative sea level rise using baseline 1981-2000 and scenario RCP8.5.

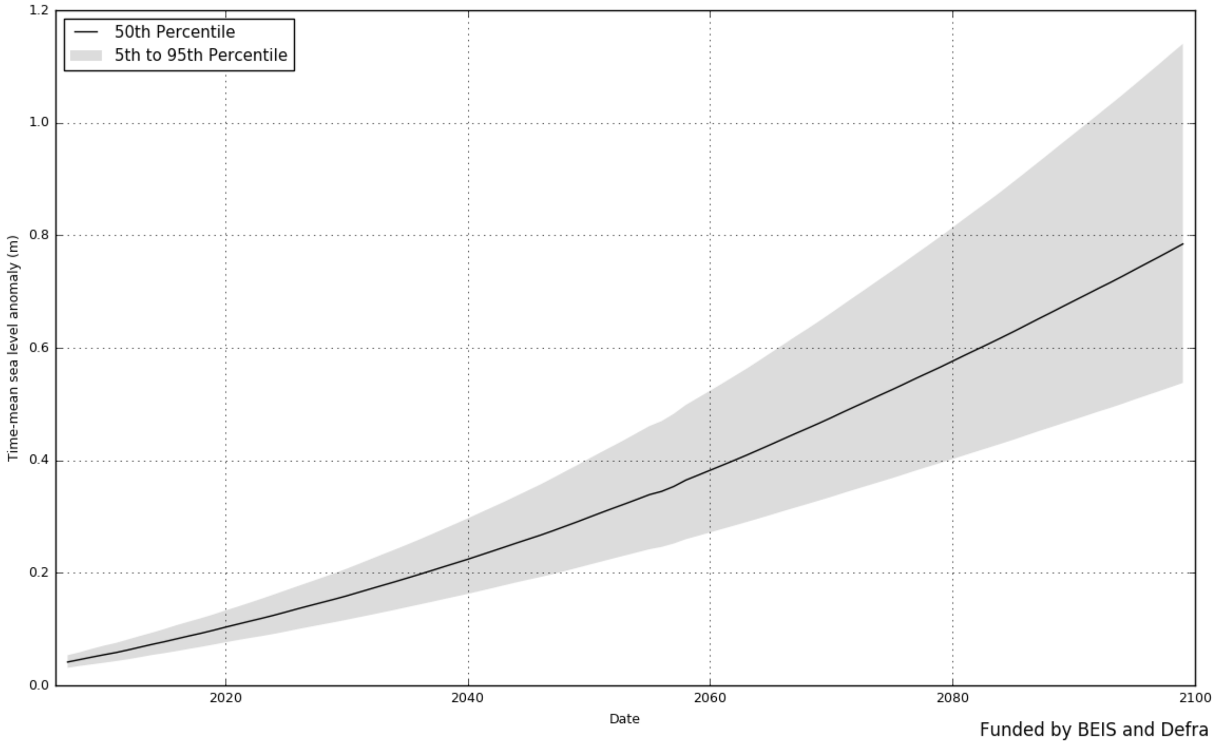


Figure 4. Time-mean Sea Level Anomaly (m) for 2007 to 2100 for grid square 52.28º, 1.75º, using baseline 1981-2000, and scenario RCP8.5 (extracted from UKCP UI Products for 'Plume of sea level anomalies for marine projections around UK coastline, 2007-2100', https://ukclimateprojections-ui.metoffice.gov.uk/products, accessed on 2nd January 2019).

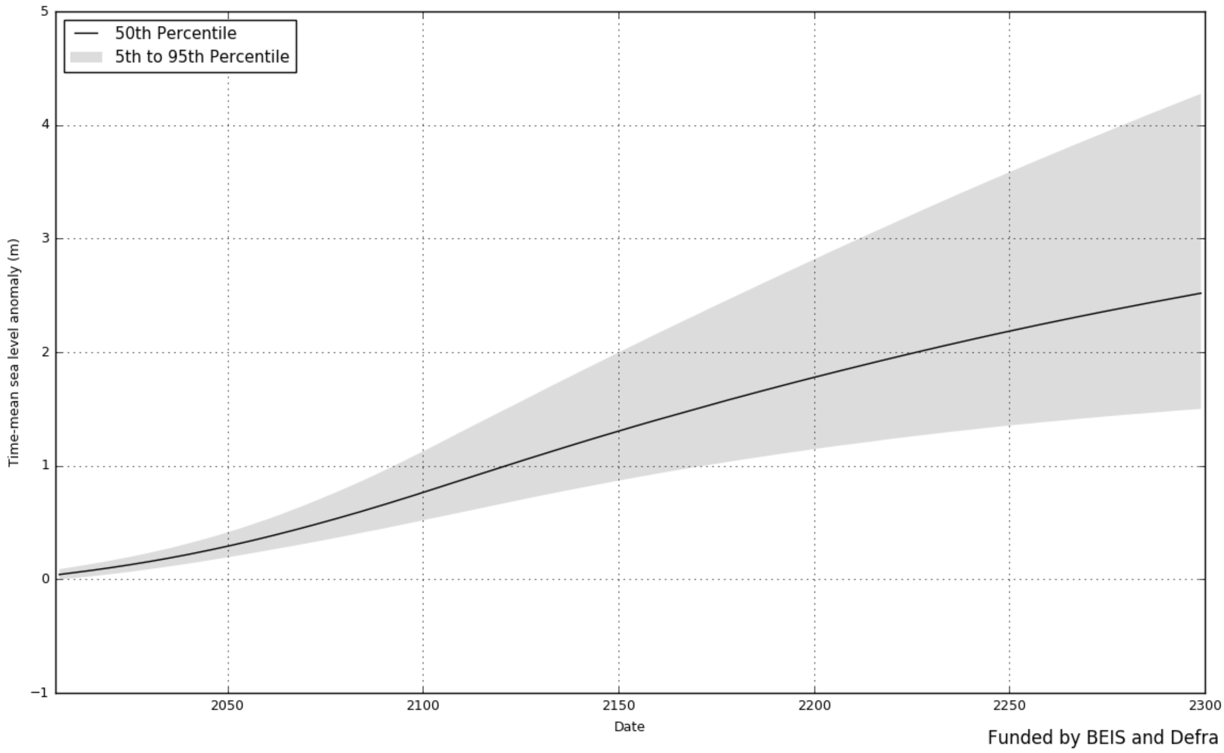


Figure 5. Time-mean Sea Level Anomaly (m) for 2007 to 2300 for grid square 52.28º, 1.75º, using baseline 1981-2000, and scenario RCP8.5 (extracted from UKCP UI Products for 'Plume of sea level anomalies for marine projections around UK coastline using exploratory method, 2007-2300', https://ukclimateprojections-ui.metoffice.gov.uk/products, accessed on 2nd January 2019).

The downloaded time-series of sea level anomalies was used to derive relative sea level rise with baseline of 2008 to compare with the previous assessment (RHDHV, 2015). For this purpose, the 95th percentile of RCP8.5 scenario was used, as the most similar to UKCP09 95th percentile of high emissions scenario. UKCP18 UI does not currently provide marine results for RCP6.0 (between the low and medium emission scenarios in UKCP09).

Figure 6 illustrates the differences between the climate projections of relative sea level rise derived from the previous assessment (RHDHV, 2015) and those derived from UKCP18, with dotted lines indicating values that are extrapolated beyond the range stated in the respective guidance. The results show that the RCP8.5 scenario of UKCP18 gives higher rates of change in sea level over 21st century than the high emissions scenario from UKCP09, with an increase up to 0.9m for 2185.

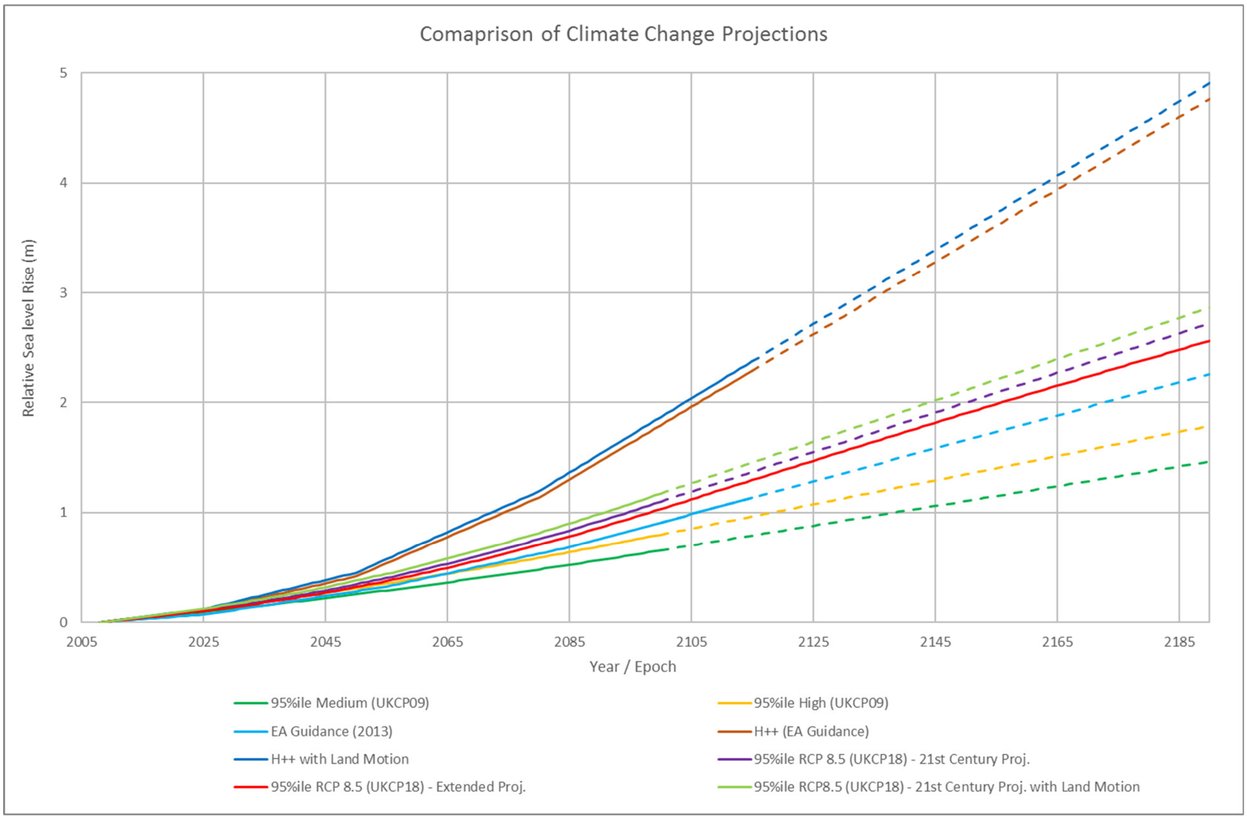


Figure 6. Comparison of UKCP09, EA Guidance and UKCP18 Climate Projections for relative sea level rise, with baseline 2008.

The H++ scenario from UKCP09 provided as plausible high-end scenario was not updated as a part of the UKCP18 projections.

Table 5 presents comparison of relative sea level rise at key points in time (in relation to SZC development) derived from the initial assessment (based on UKCP09 and other guidance/studies) and the UKCP18 projections, all relative to baseline 2008. Please note that values for years over 2100 are extrapolated beyond the range provided in the projections and the EA guidance.

Table 5. Relative Sea Level Rise at key points in time derived from initial climate change assessment (UKCP09, EA Guidance) and UKCP18, grid cell in front of SZC development).

Year	95%ile of Medium Emissions Scenario (UKCP09)	95%ile of High Emissions Scenario (UKCP09)	95%ile RCP8.5 (UKCP18) – 21st century projections*	H++ Scenario with Land Motion and Surge (Environment Agency, 2011)
2025	0.093	0.113	0.110	0.116
2085	0.522	0.637	0.835	1.361
2110	0.744	0.908	1.208	3.206**
2140	1.014	1.238	1.731	4.220**
2185	1.419	1.733	2.561	5.741**

*Note: For epochs beyond 2100 allowances are based on UKCP18 Plume of sea level anomalies for marine projections around UK coastline using exploratory method, 2007-2300 (i.e. extended projections).
** Note H++ beyond 2100 includes 1m surge in line with EA 2011 guidance

As a part of the UKCP18 Marine Projections storm surge modelling has been carried out. Storm surges are defined as short-lived increases in local water level above that of the astronomical tide, mostly driven by atmospheric pressure gradients and winds, typically in shallow seas. The diversity and competition of the processes in the climate system makes projections of the storm track response to climate change less robust than, for example, the global mean temperature response. Therefore, storm surge model simulations were forced by an ensemble of five climate models. The model results suggest a relatively small contribution from storm surge changes and it is not yet known whether storm surges will become more severe, less severe or remain the same.

The UKCP18 also used an ensemble of seven global wave models to explore potential changes in mean and mean annual maximum significant wave height (SWH) under RCP8.5 scenario. Results from these simulations suggest an overall decrease in mean SWH around most of the UK coastline of 10-20% over the 21st century, but the sign of change differs among models and coastal location. In additions, high resolution regional model projections are presented based on a single model under RCP4.5 and RCP8.5 scenarios. showing more consistent changes across the 21st century and RCPs for the more exposed coastline, where remote generation of swell waves dominates SWH.

Figure 7 illustrates change in mean annual maximum significant wave height (absolute change in meters) at the end of 21st century for the RCP8.5 scenario, derived from the regional wave model.

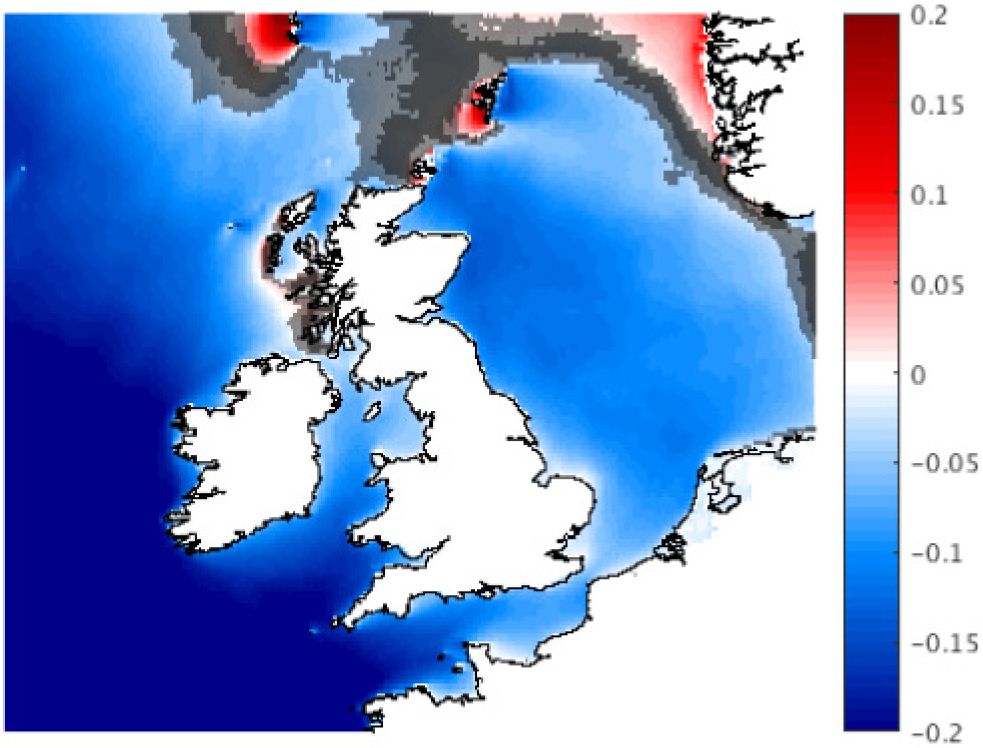


Figure 7. Change in Mean Annual Maximum Significant Wave Height from UKCP18 regional wave model, an absolute change, in metres (extracted from UKCP18 Marine Report, Met Office 2018).

Although projections of changes in wave climate are presented in the overall UKCP18 Science Report and UKCP18 Marine Report, the associated data is not included as a part of UKCP18 deliverables currently available for download. Therefore, it is not possible to investigate wave projections on a local scale relative to the SZC development.

4 Extreme Still Water Levels

A number of studies have been carried out to estimate extreme sea levels at Sizewell, including British Energy Estuarine & Marine Studies (BEEMS) Technical Report TR139, TR252 and TR322 on Sizewell Extremes (2014), HR Wallingford Sizewell Power Station Extreme Sea Level Studies (2010) and UK Coastal Flood Boundary Conditions produced for the Environment Agency in 2011 (Project SC060064/TR4: Practical Guidance Design Sea Levels). The latest extreme water levels derived in the BEEMS study and presented in TR322 Report (BEEMS, 2014) were used in the analysis of joint probability of waves and sea levels, that was then applied in wave transformation modelling and subsequently in analysis of overtopping of sea defences for the coastal flood risk assessment.

Concurrently to the updated UK Climate Projections project (UKCP18), the Environment Agency has been updating the UK Coastal Flood Boundary Conditions (UK CFB) with revised extreme still water levels around the UK coastline, to be published in 2019. Provisional results have been provided from this study in order to assess relative change in the extreme still water levels and advise on potential impacts on the SZC FRA study.

The extreme peak sea levels from the 2011 and the 2018 UK CFB studies were extracted for a series of return periods at chainage point 4192 located within the SZC project boundary (outlined in red), as illustrated in **Figure 8** below. **Table 6** presents the derived extreme still sea levels from both datasets and the relative difference between them.

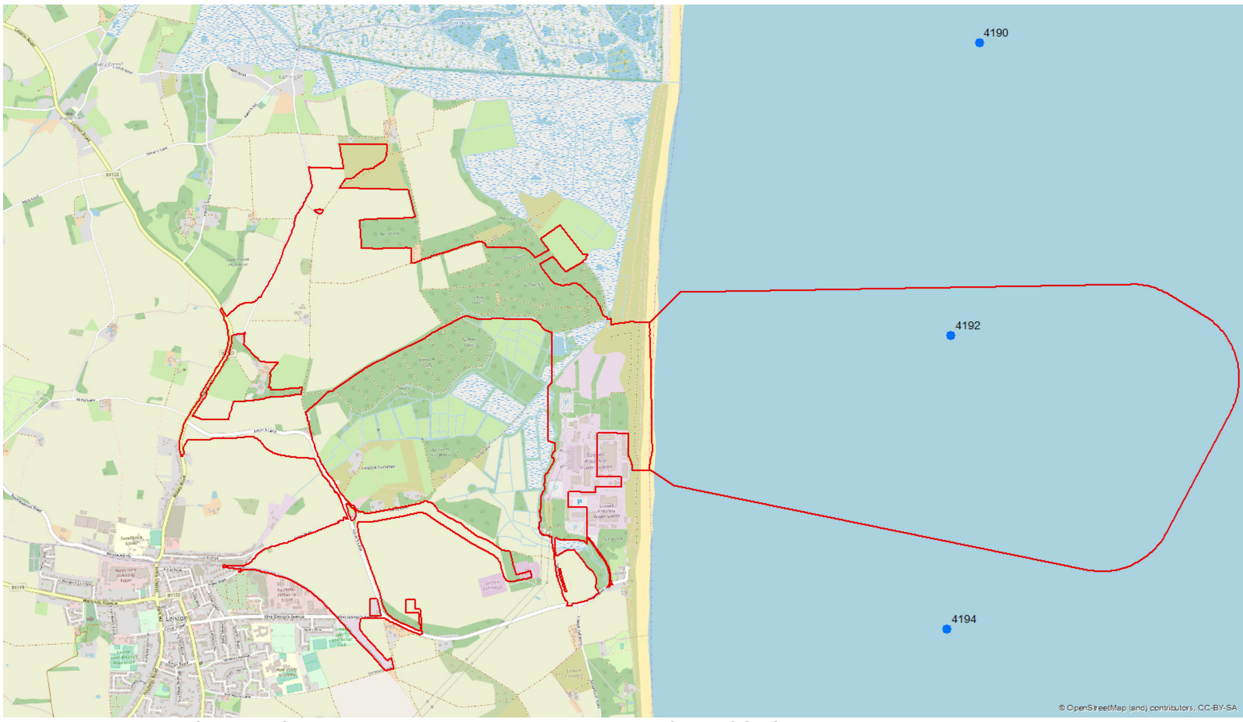


Figure 8. Location of the UK Coastal Flood Boundary Dataset Point in front of SZC development.

Table 6. Extreme Still Water Levels from the 2011 and updated 2018 UK CFBC (Chainage 4192).

Return Period (years)	UK Coastal Boundary Dataset 2011	UK Coastal Boundary Dataset 2018	Difference
T1	1.98	2.00	+0.02
T2	2.12	2.15	+0.03
T5	2.30	2.35	+0.05
T10	2.45	2.51	+0.06
T20	2.60	2.66	+0.06
T25	2.65	2.71	+0.06
T50	2.80	2.84	+0.04
T75	2.90	2.92	+0.02
T100	2.96	2.98	+0.02
T150	3.07	3.06	-0.01
T200	3.13	3.11	-0.02
T250	3.19	3.16	-0.03
T300	3.23	3.20	-0.03
T500	3.36	3.30	-0.06
T1000	3.55	3.43	-0.12
T10000	4.21	3.87	-0.34

The comparison in Table 6 shows that the updated extreme still sea levels are slightly higher for events with higher frequency and for events with lower frequency are slightly lower than those derived in 2011.

In order to assess impact of the updated UK CFB extreme still water levels, a comparison with the water levels derived in the BEEMS study was carried out, as presented in **Table 7**.

Table 7. Comparison of Extreme Still Water Levels for Sizewell derived in BEEMS Study (2014) and UK Coastal Flood Boundary Conditions (2018).

Return Period (years)	Water Level (OD) – BEEMS (2014)	UK Coastal Boundary Dataset 2018	Difference
T1	2.23	2.00	-0.23
T2	2.39	2.15	-0.24
T5	2.61	2.35	-0.26
T10	2.79	2.51	-0.28
T20	2.98	2.66	-0.32
T50	3.24	2.84	-0.40
T100	3.45	2.98	-0.47
T200	3.66	3.11	-0.55
T500	3.96	3.30	-0.60
T1000	4.20	3.43	-0.77
T10000	5.06	3.87	-1.19

Table 7 above suggests that the extreme still water levels derived in the BEEMS study are consistently higher for all return periods and therefore more conservative than those provided in the UK Coastal Flood Boundary Conditions.

5 Recommended Climate Change Allowances

The basis for identifying climate change allowances to be used in the FRA for the Sizewell C are the reasonably foreseeable and the credible maximum climate change scenarios that will be applied at different phases of the development. The Nuclear Safety Case will consider events at a greater magnitude that those considered in the FRA.

In this note, currently proposed timings of each phase of the SZC development are assumed as follows:

- 2025: start of construction;
- 2030: end of construction & start of commissioning (used for assessment of construction phase flood risk);
- 2090: end of operation (60 years predicted operational lifetime);
- 2140: interim spent fuel store decommissioned, stated by EDF (end of assessment to risks on site); and

- 2190: theoretical maximum site lifetime (160 years in line with EA/ONR Joint Advice Note, 2013), used for assessment of impacts or changes in flood risk off site due to the presence of SZC (main platform and SSSI crossing).

It should be noted that the original timings, agreed at an FRA meeting with the EA held on 21st May 2015, were derived based on planned start of construction in 2017. Since the meeting, the project has been postponed, and then re-started in 2018. Therefore, the times for each phase of the development were adjusted by 5 years to account for the delays in the programme. It is also assumed that hydraulic modelling is not required for all phases of the development, but rather for key points in time.

5.1 Pluvial and Fluvial

The initial assessment recommended using the Upper End and H++ Scenario allowances for both rainfall intensity and peak river flows, in line with the EA guidance on 'Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities', 2016. These allowances are based on UKCP09 or research using UKCP09 data undertaken by the EA. Following release of UKCP18 it is anticipated that the guidance provided by the EA will be updated during 2019, as stated on the EA website "*This guidance is being revised in line with the UK Climate Projections 2018. Please contact the Environment Agency for interim guidance if you are preparing a flood risk assessment for a development or local plan affected by tidal flooding"* (https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances).

Considering the EA advice above is directed for FRAs including tidal flooding, it is assumed that for assessing fluvial and pluvial flood risk, currently provided allowances are still valid. That is also supported by the fact that current guidance suggests that UKCP09 provides useful information on change to rainfall across the UK and that this information is most robust for more common events such as changes to the wettest day of a season, whereas typically, for flood management purposes the concern is rarer events such as those that have a 1 in 20 per year chance of occurring or rarer. In addition, for catchments with area above 5km^2 the recommendation is to apply the same increases in rainfall intensity as peak river flows for the corresponding river basin. On the basis that UKCP18 also provides estimates of change in precipitation for various temporal resolutions rather than extreme rainfall events, it is recommended for the SZC FRA study to adopt the approach outlined in the EA 2016 guidance.

Table 8 summarises recommended climate change allowances for rainfall intensity and peak river flows to be applied for all considered return period events in hydraulic modelling, required to assess flood risk at each phase of SZC development.

Table 8. Recommended Climate Change Allowances to use in SZC FRA for assessment of pluvial and fluvial flood risk.

Development Phase	Year	Climate Change Scenario	Climate Change Allowance
End of Construction / Commissioning	2030	Upper End Allowance	+25%
End of Operation	2090	H++ Scenario	+40%
Interim Spent Fuel Store Decommissioned	2140	H++ Scenario	+80%
Theoretical Maximum Site Lifetime	2190	H++ Scenario	+80%

The hydraulic model developed for the SZC FRA study has a downstream boundary at the Minsmere Tidal Sluice and outfall structure, with the sluice controlling ingress of salt water into the fluvial system. It is assumed that focus of fluvial modelling is assessment of flood risk during extreme fluvial and pluvial events and therefore not focussing on extreme coastal events. On that basis, it is considered appropriate to apply sea level rise allowance in line with the NPPF and EA guidance (2016), rather than applying values derived for the assessment of coastal flood risk, that consider much higher rates of change in relative sea level, such as the H++ and BECC Upper scenarios.

Figure 9 presents sea level allowance provided in the EA guidance (2016). Allowances are given for different epochs in millimetres (mm) per year with cumulative sea level rise for each epoch in brackets.

Area of England	1990 to 2025	2026 to 2055	2056 to 2085	2086 to 2115	Cumulative rise 1990 to 2115 / metres (m)
East, east midlands, London, south east	4 (140 mm)	8.5 (255 mm)	12 (360 mm)	15 (450 mm)	1.21 m
South West	3.5 (122.5 mm)	8 (240 mm)	11.5 (345 mm)	14.5 (435 mm)	1.14 m
North west, north east	2.5 (87.5 mm)	7 (210 mm)	10 (300 mm)	13 (390 mm)	0.99 m

Figure 9. Sea level allowance for each epoch in millimetres (mm) per year with cumulative sea level rise for each epoch in brackets (for 1990 baseline).

Following cumulative sea level rise allowances were derived (based on East of England) and are recommended to apply to the tide curve for the three climate change epochs/ key points in time for the SZC development:

- 2030: +0.075m;
- 2090: +0.722m;
- 2115: +1.097m.

These values and associated tide curves were generated prior to the release of UKCP18. The values applied lie between the High scenario (95%ile) of UKCP09, and the RCP8.5 (95%ile) of UKCP18. Since the fluvial model uses MHWS rather than extreme tides, the slight increase to UKCP18 RCP8.5 and re-running of fluvial models is not considered necessary as it would not significantly change the results or outcomes of the fluvial risk assessment.

5.2 Coastal

Climate change allowances for sea level rise (SLR) and storm surges derived in the previous assessment (RHDHV, 2015) were based on multiple studies and scenarios, as summarised in Section 2.2 of this note. From the scenarios considered, only UK Climate Projections have been updated and therefore it is assumed that other guidance and studies are still valid and can be used to inform the SZC FRA where applicable.

Considering that allowances for sea level rise provided in the updated UK Climate Projections (UKCP18) are higher than those derived in the UKCP09, as presented in Table 5 in Section 3.2, it is recommended that those higher values are evaluated in the SZC FRA. Currently available results from UKCP18 do not provide scenario equivalent to 95%ile Medium Emissions scenario from UKCP09 (which was previously agreed as the 'reasonably foreseeable' climate change). In the interim, the more conservative UKCP18 RCP8.5 95%ile will be used as a high 'reasonably foreseeable' scenario. The FRA will discuss the level of conservatism associated with this approach. As part of the Safety Case and ongoing climate monitoring regime, actual and projected climate change will be reviewed every 10 years (including any updated projections available at the time), to inform decisions on when to raise the defences in front of the main SZC platform and SSSI crossing. This will also feed into periodic updates of the Flood Warning and Evacuation Plan.

The summary interpretation of the recent evidence presented in UKCP18 Science Report (Met Office, 2018) is that the H++ scenario of UKCP09 should still be considered as plausible high-end sea level pathway and therefore, the recommendation is that decision makers make use of the projections from UKCP18 alongside multiple strands of evidence, including H++ scenarios, when assessing vulnerabilities to future extreme water levels.

As stated in Section 4, derived climate change allowances were applied to the baseline water level and used in joint probability analysis to determine extreme sea level and nearshore wave conditions for assessment of overtopping of coastal sea defences. These analyses were carried out by Cefas for EDF, prior to the release of UKCP18.

As stated in Section 3.2, UKCP18 results suggest relatively small contribution from storm surge changes to the extreme water levels, and currently there is low confidence in predicting whether storm surges will become more severe, less severe or remain the same. The previous assessment (RHDHV, 2015) suggested applying 1m surge to for climate change epochs beyond 2085 for the credible maximum scenarios only, i.e. H++ scenarios. Since UKCP18 does not provide clear guidance on potential changes to storm surge in the future, is it recommended that the approach adopted in the previous assessment is retained and therefore no surge is applied to the 'reasonably foreseeable' scenario for RCP8.5.

Also, the previous assessment (RHDHV, 2015) recommended using climate change allowances for increase in significant wave heights based on the EA guidance (2013), and not direct results from UKCP09. Therefore, due to the UKCP18 results indicating a general relative reduction in significant wave height, and the lack of clear recommendations or data available to derive appropriate allowances from UKCP18, we propose to retain the conservative wave assumptions from the previous assessments, namely 10% increase for all epochs for reasonably foreseeable scenarios and 15% for credible maximum scenarios.

Based on the above conclusions, it is recommended to use previously derived climate change allowances for changes in storm surges and significant wave heights. For the relative sea level rise allowances, the recommendation is to focus on the 95%ile of the RCP8.5 scenario where applicable (in place of 95%ile of High Emissions or Medium Emissions scenarios from UKCP09), and on the H++/BECC Upper, and where feasible 'match' these allowances to the closest available currently available climate change scenarios considered in Cefas joint probability assessment. Wave overtopping modelling will use the updated still water levels and the nearest available wave conditions.

Table 9 presents derived climate change allowances for sea level rise for two key points in time, i.e. end of construction and interim spent fuel store decommissioned. All values are relative to 2008 baseline year.

Table 9. Derived Climate Change Allowances for selected scenarios and key points in time, relative to 2008 year baseline.

Development Phase	Year	Relative Sea Level Rise Climate Change Allowance for 95%ile of RCP8.5 (UKCP18)** Scenario (m)	Relative Sea Level Rise Climate Change Allowance for BECC Upper (2014)*** Scenario (m)
Start of Construction	2025	0.110	-
End of Construction / Commissioning	2030	**0.148**	-
End of Operation	2090	0.921	-
Interim Spent Fuel Store Decommissioned	2140*	**1.713**	**3.920**
Theoretical Maximum Site Lifetime	2190	2.561	4.820

Note **bold** values indicate particular focus scenarios, although additional scenarios may be run to inform the assessments
*Note: It was stated by EDF that Interim Spent Fuel Store will be decommissioned by 2140, which is therefore adopted as the end of on-site risk assessments. The EA/ONR Joint Advice Note (2013) suggests consideration a whole life of 160 years, for assessment of off-site impacts at the end of site lifetime.
**Note: For epoch beyond 2100 allowances are based on UKCP18 Plume of sea level anomalies for marine projections around UK coastline using exploratory method, 2007-2300 (i.e. extended projections).
***Note: BECC Upper (2014) estimates have surge component already integrated into the values presented, so no further surge adjustment was applied

Table 10 summarises recommended key simulation scenarios to be used in assessment of wave overtopping of the coastal defences, notably the main sea defence and the SSSI Crossing. These include suggested flood event frequencies and climate change allowances for sea level rise (including storm surge where applicable) for the selected epochs for the two key development phases, i.e. end of construction and interim spent fuel store decommissioning. Intermediate epochs may be assessed as required to inform the threshold for raising of the sea defences in line with the climate change adaptation approach. It is worth noting that the timing of end of construction/ commissioning phase has been shifted by 5 years due to project delays and therefore previously derived allowance for sea level rise up to 2025 has been updated to reflect additional 5 years of potential change. For that reason, the closest case from the currently available Cefas joint probability assessment has been identified, that will be used to derive nearshore wave conditions for wave overtopping modelling. The extreme still water levels for the overtopping model will be derived by applying climate change allowances presented in the Table 10 below to the 2008 baseline still water level.

Table 10. Recommended Scenarios for Wave Overtopping Simulations with corresponding Climate Change Allowances, relative to 2008 baseline year.

Year	Climate Change Scenario	Return Period (years)	Main Sea Defence Height	Allowance for Sea Level Rise (m)	Closest Cefas Joint Probability Case
2030	95%ile of RCP8.5 (UKCP18)	200 1000	5.0mOD and 7.0mOD**	0.148	Case D (Dark Grey, 0.113m SLR)
2140	95%ile of RCP8.5 (UKCP18)*	1000 10,000 100,000	7.3mOD*** and 10.2mOD	1.731	Case 7 (Brown, 1.805m SLR)

	BECC Upper (2014)	1000 10,000 100,000	10.2mOD*** and 14.2mOD	3.920	Case 15 (Dark Red, 3.92m SLR)

*Note: For epoch beyond 2100 allowances are based on UKCP18 Plume of sea level anomalies for marine projections around UK coastline using exploratory method, 2007-2300 (i.e. extended projections).
**5.0m assumed most exposed (lowest elevation) of coastal defences during preparation of sea defence foundations, to be confirmed with EDF Engineering team, followed by interim haul road elevation at 7.0m.
***Overtopping Simulation for the SSSI Crossing only.

Tidal breach analysis will also be carried out, to inform a comprehensive assessment of coastal flood risk. These will test both on-site and off-site risk during construction and at the end of site lifetime. For the purpose of this assessment, it is proposed to use the UKCP18 RCP8.5 scenario for all considered epochs.

Table 11 summarises recommended simulation scenarios to be used in assessment of tidal breach of coastal defences, notably the main sea defence and the shingle ridge near the tank traps. These include suggested flood event frequencies and climate change allowances for sea level rise for the selected epochs for three key development phases, namely end of construction (2030) and interim spent fuel store decommissioned (2140) for the main sea defence and end of site lifetime (2190) for the shingle beach near the tank traps.

Table 11. Recommended Scenarios for Tidal Breach Simulations with corresponding Climate Change Allowances, relative to 2008 baseline year.

Year	Climate Change Scenario	Return Period (years)	Sea Defence	Allowance for Sea Level Rise (m)	Closest Cefas Joint Probability Case
2030	95%ile of RCP8.5 (UKCP18)*	200 1000	Main Defence and Shingle Beach	0.148	Case D (Dark Grey, 0.113m SLR)
2140			Main Defence	1.731	Case 7 (Brown, 1.805m SLR)
2190			Shingle Beach	2.561	Case 9 (Yellow, 2.55m SLR)

*Note: For epoch beyond 2100 allowances are based on UKCP18 Plume of sea level anomalies for marine projections around UK coastline using exploratory method, 2007-2300 (i.e. extended projections).

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SZC CO. 2016. ECO-HYDROLOGY CONDITIONS IN SIZEWELL MARSHES SSSI, AN OVERARCHING REVIEW OF FACTORS INFLUENCING VEGETATION COMPOSITION AND DISTRIBUTION

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Authors	Kathryn Skinner, and Mark Lang, Arcadis
Checked by	Mark Lang, Arcadis
Approved by	Jon Davies, Arcadis
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ECO-HYDROLOGICAL CONDITIONS IN SIZEWELL MARSHES SSSI: AN OVERACHING REVIEW OF FACTORS INFLUENCING VEGETATION COMPOSITION AND DISTRIBUTION

VERSION 2 – JULY 2016

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EXECUTIVE SUMMARY

The purpose of this Technical Note is to bring together a suite of work and to provide a technical summary of the detailed analyses that have been undertaken of botanical survey data collected from the fen meadow communities of Sizewell Marshes Site of Special Scientific Interest (SSSI) between 1995 and 2013. Full details of these analyses are included in the four reports appended to this Technical Note. The fen meadow is considered to be sensitive to changes in hydrology (both groundwater and surface water) that could potentially arise from the construction and/or operation of the proposed Sizewell C power station.

Ellenberg values were used to identify the distribution, composition and environmental tolerances, of plant species identified through National Vegetation Classification (NVC) surveys. This analysis was initially undertaken on plant species recorded at the stand level (i.e. an area of relatively homogenous vegetation occupying a field or part of a field). Following requests by consultees, a more detailed analysis was undertaken using Ellenberg values at the quadrat level (i.e. comparing the 2m x 2m quadrats within fen meadow stands) in order to discern any potential trends not obvious at the stand level.

Where the data allowed, statistical analyses were undertaken to identify whether any statistically significant trends in the environmental parameters were present, and whether there had been statistically significant changes in vegetation composition over the survey period as a result.

A peer review of these analyses was undertaken by OHES. OHES was in agreement with the methodology and results from the stand and quadrat level Ellenberg analysis and developed the review of the botanical data further to provide further insight into the factors driving fen meadow composition and distribution. The results of these analyses indicated considerable agreement in the underlying environmental conditions as suggested by the four analyses carried out, however there were also a number of key differences as follows:

- The Ellenberg analysis at the quadrat level found no evidence to support the pattern of areas of higher fertility within the fen meadow, which had been suggested at the stand level analysis.
- The quadrat level review found no evidence to support an inferred trend of underlying saline influence suggested by the stand level and OHES reviews and strongly indicated a lack of underlying saline influence.
- The stand level analysis suggested a mild underlying acidic influence in some locations. This is now thought to be misleading, the presence of acidic indicators being more likely to reflect low fertility indicators.

The OHES review enabled the fen meadow habitats within Sizewell Marshes SSSI to be assigned to one of four grades, indicative of relative richness of key fen species. The most species-rich grades (Grades 1 and 2) were found to show a strong correlation with increased soil wetness, circum-neutral to mildly calcareous reaction and infertile conditions, with the suggestion that areas of Grade 1 fen meadow represented the optimal management and growing conditions. The groundwater regime, in combination with the management regime, was identified as the key factors determining the character and compositions of fen meadow habitat.

This Technical Note pulls together information from four separate reports which are appended to this report. The arrangement of these appendices and their associated figures are set out below in Table 1 for clarity.

Table 1 Arrangement of Technical Note, figures and appendices

Report Reference	Figures included in Report	Figures from other reports referenced in this report
Technical Note (This document) ***S-EX524 – Technical Note - Review of Eco-hydrology conditions at Sizewell Marshes. An overarching review of factors influencing vegetation composition and distribution.***	1. Indicative distribution of fen meadow at varying grades of species richness across Sizewell Marshes SSSI 2. Location of fen meadow compartments 3. 3. Indicative distribution of M22 NVC communities and variants	N/A
Appendices		
S-EX531 – Appendix A – Ellenberg analysis at the stand level of M22 and ditch vegetation.	(Note Figures 9, 11, and 12 are embedded in the text of the report) 1. Distribution of M22b and M22d within Sizewell Marshes 2. Location of fen meadow stands within Sizewell Marshes SSSI 3. Location of ditch communities within Sizewell Marshes SSSI 4. Location of fen meadow stands within Minsmere South Levels 5. Location of ditch stands within Minsmere South Levels 6. Location of fen meadow stands within Sizewell Marshes SSSI indicative of Ellenberg R value variations	N/A

Report Reference	Figures included in Report	Figures from other reports referenced in this report
	7. Location of fen meadow stands within Sizewell Marshes SSSI indicative of Ellenberg S value variations 8. Location of fen meadow stands within Sizewell Marshes SSSI indicative of Ellenberg F value variations 9. Graphs a-e within text – Species frequency across Ellenberg scales for fen meadow stands within Sizewell Marshes SSSI 10. Location of ditch communities within Sizewell Marshes SSSI indicative of Ellenberg R value variations 11. Location of ditch communities within Sizewell Marshes SSSI indicative of Ellenberg S value variations 12. Graphs a-e within text – Species frequency across Ellenberg scales for ditch communities within Sizewell Marshes SSSI 13. Graphs a-e within text – Species frequency across Ellenberg scales for fen meadow stands within Minsmere South Levels	
S-EX532 – Appendix B – Ellenberg analysis at the quadrat level of M22 and ditch vegetation.	1. Location of fen meadow communities across Sizewell Marshes SSSI 2. Location of ditch communities across Sizewell Marshes SSSI 3. Location of fen meadow quadrats recording reaction indicator species across Sizewell Marshes SSSI 4. Location of fen meadow quadrats recording nitrogen indicator species across Sizewell Marshes SSSI	Report - ***S-EX531 – Appendix A – Ellenberg analysis at the stand level***, figures from this report reference: 6. Location of fen meadow stands within Sizewell Marshes SSSI indicative of Ellenberg R value variations 7. Location of fen meadow stands within Sizewell Marshes SSSI

Report Reference	Figures included in Report	Figures from other reports referenced in this report
	5. Location of fen meadow quadrats recording moisture indicator species across Sizewell Marshes SSSI 6. Location of ditch quadrats recording reaction indicator species across Sizewell Marshes SSSI 7. Location of ditch quadrats recording nitrogen indicator species across Sizewell Marshes SSSI 8. Location of ditch quadrats recording moisture indicator species across Sizewell Marshes SSSI	indicative of Ellenberg S value variations 8. Location of fen meadow stands within Sizewell Marshes SSSI indicative of Ellenberg F value variations 10. Location of ditch communities within Sizewell Marshes SSSI indicative of Ellenberg R value variations 11. Location of ditch communities within Sizewell Marshes SSSI indicative of Ellenberg S value variations
S-EX523 – Appendix C – Biocensus – Trends in plant occurrence and Ellenberg indicators at Sizewell	1. Location of Suffolk Wildlife Trust monitoring plots within Sizewell Marshes SSSI 2. Graph embedded in text – Trends in Mean weighted F Ellenberg values at plot G39 at Sizewell 3. Graph embedded in text – Trends in Mean weighted R Ellenberg values at plot M7 at Sizewell 4. Graphs embedded in text – Trends at Mean weighted N Ellenberg values at plots G34, G50 and M7 at Sizewell 5. Graphs embedded in text – Trends in Mean weighted S Ellenberg values at plots G19, G34, G37 and M7 at Sizewell	N/A
S-EX533 – Appendix D – OHES Trends in the Composition of Fen Meadow in Sizewell Marshes: A supplementary report. Independent review of botanical data by OHES.	1. Indicative distribution of fen meadow at varying grades of species richness across Sizewell Marshes SSSI 2. Location of fen meadow compartments	N/A

Report Reference	Figures included in Report	Figures from other reports referenced in this report
	3. Indicative distribution of M22 NVC community and variants	

1.0 INTRODUCTION

1.1 Purpose of report

1.1.1 The purpose of this Technical Note is to bring together a suite of work and to provide a technical summary of the detailed analyses that have been undertaken of botanical survey data collected from the Sizewell Marshes Site of Special Scientific Interest (SSSI) and a small area within Minsmere South Levels, part of the adjacent Minsmere to Walberswick Heaths & Marshes SSSI. Full details of these analyses are included in the four reports appended to this Technical Note.

1.1.2 The aim of these analyses has been to identify any obvious patterns in the distribution and composition of the vegetation communities present, and to use this to infer any trends in the underlying eco-hydrological conditions. The analyses have focussed on fen meadow and ditch communities, as these are considered to be the most sensitive to changes in the hydrological regime. The results of ditch community assessments have not, however; been included in this Technical Note which is focused on the M22 fen meadow community. Details of the ditch analysis are outlined in the reports appended in Appendix A (Hyder, 2015) and B (Arcadis, 2016).

1.1.3 A hydrological Conceptual Site Model (CSM) has been developed (by Atkins 2015) for Sizewell Marshes SSSI to describe the hydrological conditions underpinning an ecologically diverse area which may be impacted by the proposed Sizewell C development. The aim is to facilitate assessment of the likely impact of the development upon groundwater and surface water conditions and the ecological features that they support, as well as to identify appropriate mitigation measures and opportunities for ecological enhancement within Sizewell Marshes, and to identify, if required, mitigation requirements. The review of botanical data outlined in this Technical Note was a key element in the development of the CSM.

1.1.4 This Technical Note considers the following information:

- Section 1.2 summarises the botanical survey data that has been considered during these analyses.
- Section 2 summarises the analysis methodologies and the results of these analyses.
- Section 3 compares the results of the different analyses and provides details of the overarching trends and/or patterns in the vegetation communities identified, suggesting what this tells us about the underlying eco-hydrological conditions.

1.2 Survey data

1.2.1 Numerous, detailed, botanical surveys have been undertaken across Sizewell Marshes SSSI in recent years. Survey data considered during these analyses has focused on national vegetation classification (NVC) surveys undertaken in 2007 and 2008 by Amec Foster Wheeler (previously Entec, and hereafter referred to as Amec) (Entec 2007, 2008), and botanical surveys undertaken by Ecology, Land and People (ELP) and subsequently OHES between 1995 and 2013, on behalf of Suffolk Wildlife Trust (SWT). Note that OHES, who undertook a review of the analyses to date (see Section 2.4) also undertook both the NVC work for Amec and the majority of the monitoring work for SWT. The senior ecologist who carried out the majority of SWT's annual botanical surveys since 1995, as well as Amec's NVC surveys in 2007 and 2008, now works for OHES Environmental (OHES) and has been engaged by Arcadis Consulting (UK) Ltd to peer review its works and provide specialist advice.

1.2.2 Amec's NVC surveys of the fen meadow followed the standard NVC methodology, with samples taken from standard 2m x 2m quadrats. The fen meadow vegetation was divided into 17 vegetation stands (a stand being an area of relatively homogenous vegetation), with each stand given the prefix FM (for fen meadow). Each FM stand was then assigned to the appropriate NVC community.

1.2.3 Botanical surveys of areas of fen meadow and other habitats by ELP/OHES on behalf of SWT were undertaken across 12 no 10m x 10m monitoring plots. Surveys were undertaken primarily to determine the effects that management regimes within Sizewell Marshes SSSI have had on the botanical composition of the fen meadow plant communities. Six of the plots have been assessed in odd years since 1995, while the remaining six plots have been assessed in even years since 1996. As part of the vegetation monitoring programme, each plant species identified was also assessed in relation to their frequency of occurrence within the monitoring plot.

1.2.4 Fen meadow communities are attributable to the NVC community 'M22', the Blunt-flowered Rush (*Juncus subnodulosus*) – Marsh Thistle (*Cirsium palustre*) mire community, of which four sub-communities are recognised (Rodwell, 1991). Amec surveys in 2007 and 2008 (Entec 2007, 2008) identified the presence of two M22 sub-communities within Sizewell Marshes SSSI, namely M22b (*Briza media – Trifolium spp.*) and M22d (*Iris pseudacorus*).

Although M22 is the dominant vegetation community, with all of the FM stands being assigned to one or other of the M22 sub communities, survey work has established that there was significant variation within the M22 communities present, with affinities to other vegetation communities identified, including MG8 *Cynosurus-Caltha* grassland and MG12 *Festuca arundinacea* grassland.

Figure 3 presents an indicative simplified distribution of the M22 communities across Sizewell Marshes.

2.0 ECO-HYDROLOGICAL ANALYSES

2.1 Introduction

2.1.1 The following section summarises the methodologies and results of the analyses that have been undertaken on the botanical survey data detailed in Section 1.2 above. Full details of these analyses are provided in the reports referenced in each sub-section below, and which are appended to this technical note.

2.2 Ellenberg values – Stand Level

a) Methodology

2.2.1 Initial analyses focused on the fen meadow stand plant community lists (i.e. the plants present within stands of homogenous vegetation) generated from botanical surveys conducted by both Amec and ELP. The relevant Ellenberg values (Ellenberg 1979, 1988 and Ellenberg *et al.* 1991) for the following environmental variables were assigned to each plant species recorded: light, moisture, reaction, nitrogen and salt.

2.2.2 Ellenberg values, although based on an arbitrary scale, provide an indication of the ‘realised ecological niche’ of a species (i.e. the range of environmental conditions within which each plant species is often found growing). The frequency of species with each value within an environmental variable was plotted to enable the identification of patterns (if any) within and between Amec stands and SWT plots.

2.2.3 A revised version of the Ellenberg values (ECOFACT, 1999) tailored to more accurately represent the typical values present in the UK was used for this analysis. The frequency of plant occurrence present in survey data collected by ELP was plotted against time in order to identify any long-term trends in the data.

2.2.4 It should be noted that because Ellenberg values attempt to place individual plant species in a series of “boxes” for each environmental variable, some professional judgement is required when considering the results. For example, plant species regarded as being indicative of acid soil (the Reaction variable) conditions also grow very well in soils with a low nutrient status, so their presence may indicate low fertility rather than an acidic influence per se. Likewise the Ellenberg scale for Salt is a scale of how tolerant individual plant species are to saline conditions, which the majority of plants are to a greater or lesser degree. Therefore the presence of a salt tolerant species may simply reflect the presence of a plant species with some tolerance to saline conditions, not necessarily that a saline influence is present. Throughout this Technical Note professional judgement has been exercised when considering the results.

2.2.5 As Ellenberg analysis can be slightly misleading, a number of different analyses where undertaken with the suite of botanical data available to ensure a robust analysis of the data.

2.2.6 A short survey narrative was provided with both the Amec and ELP data. This narrative was based on the identified species, NVC community and the professional judgement of the surveyors. Key messages (where present) within these narratives were extracted and compared against the results of Ellenberg analyses to determine whether there was any correlation.

2.2.7 Full details of Ellenberg values and the methodologies used are provided in Hyder (2015), presented in Appendix A.

b) Results

2.2.8 This stand level analyses was undertaken in 2015 and the level of understanding of the marshes and the underlying eco-hydrological conditions has increased as the work has progressed. Therefore the conclusions presented below differ slightly from the report forming Appendix A.

2.2.9 Analyses indicated that, overall, the majority of fen plant species present within Sizewell Marshes SSSI had no clear preference and/or tolerance related to particular environmental conditions. Fen meadow communities were considered to primarily support plant species typical of circum-neutral to slightly basic conditions, wet ground conditions, intermediate to moderate levels of fertility and high levels of light. This is not unexpected, Sizewell Marshes SSSI being a wetland site supporting calcareous fen vegetation.

2.2.10 However, a number of trends contrary to this general theme were also identified:

- A minor west to east salinity gradient within fen meadow stands with increased salinity in the east;
- A south west to north east moisture gradient within fen meadow stands, with increased moisture in the north east of the marshes;
- An area of slightly increased base influence (set against the overall calcareous nature of the fen meadow) within fen meadow stands in the east; and
- Isolated areas of increased fertility suggested in western and central areas. It is considered that grouping plant species at the stand level may have over emphasised the importance of the nitrogen rich indicator species giving a misleading impression of overall fertility.

2.2.11 A comparison of these trends with those identified through the other analyses undertaken is provided in in Section 3 below. Full details of the results of stand level analyses are provided in Hyder (2015) in Appendix A.

2.3 Ellenberg values – Quadrat Level

c) Methodology

2.3.1 Following the above analysis at the stand level, it was requested by consultees that more detailed analysis be undertaken at the quadrat level. The aim was to compare the individual 2m x 2m quadrats within the fen meadow stands of Sizewell

Marshes SSSI, in order to consider whether a more detailed resolution of vegetation composition and distribution could be identified.

2.3.2 The analysis at the quadrat level was undertaken through the consideration of those plant species which have Ellenberg values at the extremities of the considered environmental variables (salt, light, reaction etc.) and which were recorded to occupy at least 30% of a particular quadrat, as determined through the application of the DOMIN scale (see Appendix B) . This decision was taken in order to ensure highlighted trends were not based on a plant species that was present in very low abundance, perhaps just a single stem, thereby ensuring that any trends or patterns were more likely to be representative of actual conditions on the ground.

2.3.3 It should be noted that because Ellenberg values attempt to place individual plant species in a series of “boxes” for each environmental variable, some professional judgement is exercised when considering the results, see Section 2.2.4.

2.3.4 Following the stand level analyses, it was determined that no further assessment at the quadrat level would be undertaken for the light scale due to the apparent absence of any pattern or trend in this variable (initial results showing that all plant species had a strong positive association with light).

2.3.5 Due to variations in the survey methodologies and the data collected between the Amec and ELP surveys, quadrat level analyses were undertaken only on those data collected by Amec.

2.3.6 Full details of the methodologies employed in the quadrat level analysis are provided in Arcadis (2016) in Appendix B.

d) Results

2.3.7 Analyses of Ellenberg variables at the quadrat level provided some confirmation and support for the trends originally identified through the Ellenberg analyses at the stand level.

2.3.8 Trends at the quadrat level were largely consistent with those at the stand level for the reaction, salt and moisture Ellenberg variables within fen meadow communities. Overall both the stand and quadrat level analysis point to underlying circum-neutral to basic reaction. It is considered that the minor acidic trend identified is because plant species indicative of acid conditions also tolerate low fertility (see below) rather than there being an actual specific acidic influence. Finally there is no real evidence for an underlying saline influence, although plant species that can tolerate a degree of salinity are present in low abundance.

2.3.9 The nitrogen Ellenberg variable within fen meadow communities was largely inconsistent between those identified at the stand and quadrat level, with quadrat level analyses suggesting no evidence of high fertility, unlike the isolated areas of higher fertility levels suggested at the stand level, see section 2.2.10. Overall the trend at the quadrat level is strongly for plant species indicative of low fertility conditions being widespread across the fen meadow.

2.3.10 These trends are summarised in in Section 3, below, and are compared to those trends identified through other the analyses. Full details of the results of quadrat level analysis are provided in Arcadis (2016) in Appendix B.

2.4 Ellenberg values – Statistical Analyses

e) Methodology

2.4.1 Long-term botanical data collected by ELP across Sizewell Marshes on behalf of SWT was investigated to determine whether there are significant temporal trends, and to quantify levels of variability in plant species composition and distribution as a means of considering the stability of vegetation communities surveyed at different locations over time.

2.4.2 Ellenberg values (for reaction, moisture, light, nitrogen and salt), and the frequency of occurrence, were used to calculate a weighted mean value for each plot in each year, a commonly-used analysis method for this type of data, and these survey aims (Robbins and Mathew, 2014 and Pitcairn *et al*., 2002).

2.4.3 Linear regression analyses were conducted for each plot and each Ellenberg variable, with statistical significance considered against the standard p-value of <0.05 and a reduced p-value of 0.008, which was calculated to take account of the repeated nature of the data.

2.4.4 Plots were ranked by their standard deviations in order to highlight which plots were most variable, with regard to their mean-weighted Ellenberg values, across the period studied.

2.4.5 Full details of the methodologies used during statistical analyses of Ellenberg values are provided in Biocensus (2016) in Appendix C.

f) Results

2.4.6 Consideration of temporal trends identified light, moisture and reaction Ellenberg values to be increasing at the majority of plots surveyed over time, while nitrogen and salt decreasing at most surveyed plots. The majority of plots showed a trend towards increasing base influence, with one plot showing a minor increase in acid conditions over time. The increase in base conditions is unexpected but could potentially be explained by an increase in plant species diversity (some of which will be indicators for basic conditions) due to ongoing conservation management. As mentioned elsewhere within this report, the indication on an acid influence is thought to be potentially misleading, as many of the plant species indicative of acidic conditions are also commonly found in low fertility conditions.

2.4.7 These trends were found to be statistically significant on nine occasions at a p-value of <0.05. However, while these may represent real trends, the strength and significance was not sufficient to be confident that they are not the product of random fluctuations. At the reduced p-value of 0.008 (i.e. greater statistical significance) only one relationship, indicating a reduction in saline influence at G34, was significant. This reduction in saline influence is also borne out the additional analysis conducted by OHES (Section 2.4) and the Ellenberg analysis at the quadrat level, which has not showed a strong underlying saline influence.

2.4.8 Ranked standard deviations identified plot M7 as the most variable plot overall, as well as being the most variable plot for three of the five Ellenberg variables considered. Plots Y (outside of Sizewell Marshes SSSI at the southern end of the Minsmere South Levels) and G37 were also found to be notably variable. Plots G50 and M9 were identified as the least variable. Note that plot M7 is actually located in an area of the marshes that has been allowed to develop into reedbed, so its apparent variability may be in relation to the management decision to allow reedbed to develop here and the successional change this compartment is undergoing.

2.4.9 It is suggested that an overall trend in increasing light, moisture and reaction (basic) may reflect the influence of positive conservation management which, over time, is improving the ecological condition of the Sizewell Marshes SSSI.

2.4.10 A summary of the trends identified is provided in Section 3, and a comparison with the trends identified through other analyses undertaken. Full details of the results of statistical analyses of Ellenberg values is provided in Biocensus (2016) in Appendix C.

2.5 OHES – Fen Meadow Botanical Review

g) Methodology

2.5.1 The review carried out by OHES comprised two elements:

- A review of the Ellenberg analysis work (at both the vegetation stand and quadrat level) carried out by Arcadis; and
- An independent review of the survey data and the literature to develop further the review of the botanical data, to identify whether there are any obvious additional differences in the composition and distribution of the fen meadow vegetation but highlighted by the Ellenberg analysis.

2.5.2 OHES were in agreement with the methodology by which the Ellenberg analysis had been carried out and the conclusions that had been reached.

2.5.3 The botanical review carried out by OHES considered a number of factors in relation to the vegetation composition and associated sensitivities within the fen meadow communities of Sizewell Marshes SSSI. The primary review considered the characteristics of rich-fen vegetation and the general conditions in which these characteristic species are typically found.

2.5.4 Further consideration of Principal Rich-Fen indicator Species (PRFS), see Wheeler (1988), was undertaken, identifying the range of fen meadow species that typically constitute a fen meadow assemblage. The number of Wheeler's PRFS was summed for each plot, the average number of species per plot then being considered as a measure of the relative richness. Relative richness was assessed on an arbitrary scale from Grade 1 to 4, with Grade 1 indicative of the richest areas and Grade 4 the least species-rich presented below.

2.5.5 Note that it is recognised that Sizewell Marshes is in favourable condition (according to the last condition assessment carried out in 2009 by Natural England) and that all of the fen meadow habitat present forms part of the cited SSSI interest feature (regarded to be of national importance), although some areas of fen meadow are clearly more species-rich than others.

Table 2. The four grades of M22 (fen meadow) identified by OHES

Grade of M22	Rational
Grade 1	Good quality fen meadow supporting relatively high numbers of Principal Rich-Fen Species and other mire species, including a suite of 'low fertility' indicators.
Grade 2	Good quality fen meadow supporting and a suite of Principal Rich-Fen Species and other mire species, including a suite of 'low fertility' indicators.
Grade 3	Fair quality fen meadow, support some Principal Rich-Fen Species and other mire species, with few 'low fertility' indicators.
Grade 4	Drier fen meadow grading to rush pasture and dry grassland, supporting few Principal Rich-Fen Species and other mire species, with very few 'low fertility' indicators.

2.5.6 The distribution of the grades of fen meadow is indicated on **Figure 2**.

2.5.7 Further consideration of Ellenberg values was undertaken, using tabulations by Hill *et al*. (2004, 2007) to provide non-weighted sums per plot of those attributes selected to represent the relative differences of the recorded vegetation across environmental gradients of moisture, reaction and nitrogen.

2.5.8 A review was also undertaken of the observations and survey narratives recorded across the survey period, considering vegetation management, seasonal variability and the potential for hydrological impacts.

2.5.9 Full details of the methodologies implemented during the botanical review of fen meadow data are provided in OHES (2016) in Appendix D.

h) Results

2.5.10 An overview of the vegetation types recorded identified the central area of Sizewell Marshes SSSI as an area of particular species-richness, with compartments G37, G38, G39 (all south-eastern Sizewell Marshes SSSI) and M12 (central Sizewell Marshes SSSI) supporting a number of species not found elsewhere within the SSSI (see **Figure 1** for management compartment locations).

2.5.11 Fen meadow stands at the eastern extent of Sizewell Marshes SSSI were noted to contain a greater proportion of plant species suggestive of a brackish influence.

Meanwhile, stands at the western end of Sizewell Marshes SSSI were considered to indicate a transition to drier peat.

2.5.12 As discussed in Section 1.2.5, the use of Wheeler's (1988) list of PRFS enabled areas of 'good-quality' fen meadow to be located and categorised on a Grade 1 (richest) to Grade 4 (poorest) scale.

2.5.13 The most species-rich stands (Grade 1) were identified away from valley margins and Sizewell Drain. These stands included a number of species noted to be intolerant of fluctuating water tables. It is considered that these areas may indicate the coming together of optimal management and growing conditions. Areas of Grade 2 fen meadow, while containing many of the species recorded in Grade 1 areas, were also noted to include a number of (less sensitive) species that were suggestive of a greater degree of fluctuations in the water table.

2.5.14 These areas of 'good-quality' fen meadow (Grades 1 and 2) were found to have a strong correlation with high soil wetness, circum-neutral to mildly calcareous reaction, and infertile conditions, as corroborated by the Ellenberg analysis. Unlike the stand-level Ellenberg analysis, however, little correlation was identified between the quality of fen meadow and the presence of species typically found in dry, acidic or high fertility conditions, again this is bourne out by the Ellenberg analysis at the quadrat level, showing a strong relationship between plant species indicative of low fertility conditions. With regard to plant species indicative of acidic conditions, the majority of indicator plants growing within Sizewell Marshes SSSI are also very common in low fertility situations. Therefore, the presence of acid indicator plant species (as indicated by the Ellenberg reaction values) is likely to be more a reflection of the low fertility status of the marshes as a whole, rather than any specific acidic influence, in what is a largely calcareous wetland system.

2.5.15 Consideration of the narratives provided alongside this survey data, in association with the conclusions drawn from analyses of the survey data, suggested that within a number of plots a gradual decline and/or disappearance in saline influence is occurring (as reflected in the decrease in the frequency and number of brackish tolerant species recorded). This was also a conclusion drawn by the statistical analysis and the Ellenberg analysis.

2.5.16 Sporadic new plant species records, to a plot comprising low-fertility indicator species, were restricted to compartments considered to represent Grade 1 fen meadow. This was considered to provide additional support for the suggestion that areas of Grade 1 fen meadow are representative of optimal management and growing conditions. In other words, new plant species not previously recorded arise most often in the Grade 1 fen meadow.

2.5.17 Consideration of the survey narratives, data and initial NVC mapping of Sizewell Marshes SSSI in 1993 suggests a trend of increasing habitat quality, with rush pasture transitioning to fen meadow over time. This is considered to be due, in part at least, to the sustained period of management that has been undertaken by SWT, whereby grazing and topping of the vegetation have reduced the rush cover (and thus the shade cast by the rush), allowing more sensitive plant species to establish.

2.5.18 A summary of the results of the botanical review are provided in in Section 3, below. Full details of the review undertaken are provided in OHES (2016) in Appendix D.

3.0 CONCLUSION

3.1.1 A summary of the eco-hydrological conditions identified across Sizewell Marshes SSSI is provided below.

3.1.2 As a result of the various analysis undertaken and knowledge of the Eco-hydrological conditions improved, a number of key differences have emerged in particular between the stand level and quadrat level Ellenberg analysis. These key differences are as follows:

- The Ellenberg analysis at the quadrat level found no evidence to support the pattern of areas of higher fertility within the fen meadow, which had been suggested at the stand level analysis. The quadrat level analysis strongly indicated low fertility across the fen meadow as a whole, supported by the OHES review.
- The quadrat level review found no evidence to support an inferred trend of underlying saline influence and strongly indicated a lack of underlying saline influence.
- The stand level analysis suggested a mild underlying acidic influence in some locations, this is thought to be misleading.

3.1.3 The key differences outlined above are discussed in more detail below. Based on the detailed analyses undertaken, it is considered that the following, overarching trends are present:

- Vegetation assemblages, survey results and professional judgement enabled the identification of four 'Grades' of fen meadow quality (see Table 2, for details of these Grades and the caveat that is applied to these definitions).
- Areas of 'good quality' fen meadow (i.e. those identified as Grade 1 or Grade 2) show a strong correlation with increased soil wetness, circum-neutral to mildly calcareous reaction, and infertile conditions. These conclusions are supported by both the Ellenberg and statistical analysis.
- The quality of fen meadow noted within areas designated as Grade 1 is considered to suggest the convergence of an optimal management regime and ideal growing conditions; these are the most species-rich areas.
- The brackish influence that has been inferred from the Ellenberg stand level analysis, the survey narrative from the NVC survey carried out by AMEC, and the OHES review is considered to be misleading and likely to simply represent the presence of a low number and abundance of plant species able to tolerate saline conditions, rather than suggesting a saline influence.
- Any potential underlying acidic influence is thought to be due to the fact that many plant species indicative of acidic conditions are also characteristic of low fertility conditions. The low fertility status of the marshes having been

corroborated by both the OHES review and the quadrat level Ellenberg analysis.

- Since initial mapping of the NVC communities in 1993, an improvement in the quality of the habitats present in Sizewell Marshes SSSI seems to have occurred, with vegetation communities transitioning from rush pasture to species-rich fen meadow.
- The beneficial groundwater regime, in terms of an appropriate depth and stability of the water table, combined with effective conservation management, are considered to be key drivers in the determination of the character and composition of the fen meadow habitat.

Table 3. Summary of trends identified through analysis of botanical data from Sizewell Marshes SSSI

Ellenberg Variable	Stand	Quadrat	Statistical Analysis	Botanical Review	Overview
Fen meadow					
General	A central area in which there is water mixing was suggested, this was due to the presence of a number of west to east gradients and an apparently greater variability between stands in the central region of Sizewell Marshes SSSI.	N/A	Plot M7 was identified as the most variable location across Sizewell Marshes SSSI, while plots M9 and G50 were identified as the least variable (and therefore the most stable locations) over the course of the survey period. M7 has been allowed to progress and develop as reedbed, which may explain the variability.	The separation of fen meadow into one of four grades of species richness (grade 1 being the most species-rich and grade 4 the least) indicates that the richest areas of fen meadow – considered to be ‘good-quality’ fen meadow – are located away from the valley edge and the Sizewell Drain, primarily occurring through the central region of Sizewell Marshes SSSI. Areas of the lowest quality fen meadow (grade 4) were identified primarily at the western extreme, while areas of grade 3 fen meadow included the edges of Sizewell Marshes SSSI and the northern extent.	Following the extensive reviews undertaken, it is considered that the mixing suggested from initial stand-level consideration of Ellenberg values is not actually present but a reflection of low fertility indicator species being present amongst a suite of basic indicator species. This area falls within the grade 1 and 2 fen meadow.
Reaction	Reaction conditions were considered to be largely consistent across Sizewell Marshes SSSI, although minor variations were noted that suggested that eastern areas may	Reaction indicator species indicate the presence of a circum-neutral to basic influence throughout Sizewell Marshes SSSI, while localised areas of potential	Plot G42 was identified as the most variable, with plot M9 the least variable, within an area of Grade 2 fen meadow. 71% of plots had a positive trend in	Consideration of areas of ‘good-quality’ fen meadow and indicator values for reaction conditions produced a strong correlation. This indicated that most of	The analyses undertaken consistently suggest the absence of overt extremes in reaction conditions across Sizewell Marshes SSSI with circum-

Ellenberg Variable	Stand	Quadrat	Statistical Analysis	Botanical Review	Overview
	receive a greater basic influence, while more circum-neutral to mildly acidic conditions may be present to the south.	acidic influence are present in the extreme south and north.	reaction, indicating a trend towards basic conditions over time. However, M7 was the only SWT plot showing statistical significance (at <0.05), and instead indicated a plant community increasingly adapting to acidic conditions (although this was not significant at the lower p-value and could therefore potentially be due to chance). As M7 has been allowed to develop into reedbed, this may explain the variation.	the 'good-quality' stands were composed of species indicating circum-neutral conditions grading to mildly calcareous.	neutral and mildly calcareous reaction predominating. While some areas appear to indicate a potential acidic influence, it should be noted that species indicative of an acidic influence are also often found in areas of low nitrogen (i.e. infertile conditions). It is therefore considered, that areas of apparent acidic influence are more likely to reflect the presence of species indicative of infertile conditions.
Salt	Saline conditions were considered to be largely consistent across Sizewell Marshes SSSI, with minor variations suggesting an increased brackish influence in eastern areas. The extremely low saline conditions noted in central, northern and western areas suggests the presence of a west to east salinity gradient.	Saline influence at the quadrat level was extremely limited, with only a single quadrat recording a species at the required frequency level (at the eastern extent of Sizewell Marshes SSSI). At decreased levels of frequency, saline influence was recorded comparatively more widely, suggesting a greater saline influence in south-eastern areas. However, this trend is	Plot M7 was identified as the most variable, and plot G38 the least variable. As M7 has been allowed to develop into reedbed, this may explain the variation. 64% of plots had a negative trend in salt, indicating a decrease in salinity over time. Statistically significant trends in decreasing salinity were recorded at plots G37 and M7, and a trend in increasing salinity at plot G19 (all at a p-value of 0.05).	A slight brackish influence is suggested on the coastal end of the valley. This corresponds to the gradual decline and disappearance of a group of brackish-tolerant species from compartments to the east, as noted within survey narratives. Those areas recording the highest scores in the Principal Rich-Fen Species (PRFS) assessment (corresponding to areas of 'good quality'	The stand level Ellenberg analysis and the OHES review suggest a slight underlying saline influence, albeit one that is declining. This was not however backed up by the Ellenberg analysis at the quadrat level. Which showed no indication of an underlying saline influence. Overall the trend is towards a lack of strong underlying saline influence and may simply reflect the

Ellenberg Variable	Stand	Quadrat	Statistical Analysis	Botanical Review	Overview
		based on a highly limited number of quadrats and is therefore considered to indicate only a very weak trend. Overall the trend at the quadrat level is for no underlying saline influence.	However, none of these were significant at the reduced p-value of 0.008, and these trends may therefore be due to chance (owing to the large number of samples involved). A statistically significant trend at a p-value of 0.008, for decreasing saline conditions, was noted at plot G34 in central Sizewell Marshes SSSI.	fen meadow - Grades 1 and 2) were noted to lack any evidence of a brackish influence.	presence of a low number and abundance of plant species tolerant of saline conditions, but with no actual underlying saline influence, apart from potentially a minor influx along the Leiston Drain from the Minsmere Sluice.
Moisture	No species at the extremes (extreme dry or permanent submersion) were recorded. However, the variations in moisture indicator species suggests the presence of a south-west to north-east moisture gradient with increased wetness in the north-east.	As expected of a site supporting wetland habitat, no dry site indicator species were identified. Wet site indicator species were recorded throughout Sizewell Marshes SSSI; however, the presence of more than one wet site indicator species in quadrats located in eastern and southern areas, and a comparatively reduced number of these species in western and northern areas, suggests the presence of a south-west to north-east	Plot G37 was identified as the most variable, and plot G42 the least variable, both located within Grade 1 fen meadow. 79% of plots had a positive trend in moisture, indicating increases over time. A statistically significant trend in increasingly wet conditions was identified at plot G39 within Grade 1 fen meadow; however, this was not found to be significant at the reduced p-value, and it is therefore possible that this trend was due to chance.	Areas of 'good-quality' fen meadow were found to have a strong correlation with areas of increased soil wetness, with the richest stands (FM1d in compartments G34 and G35) being of the wet form of the M22b *Briza-Trifolium* sub-community. However, there were a number of exceptions, including FM3c and FM1a, which demonstrate that it cannot be equivocally stated that wetter stands support more rich-fen species.	Moisture conditions were notably skewed to the wetter end of the scale, as would be expected from a wetland habitat. However, a south-west to north-east moisture gradient was indicated by the analyses. This was supported by the correlation between areas of 'good-quality' fen and increased soil wetness, with areas of Grade 1 and 2 fen meadow located in central, eastern and southern areas of the site. The statistical analysis highlighting a

Ellenberg Variable	Stand	Quadrat	Statistical Analysis	Botanical Review	Overview
		moisture gradient.			positive trend in moisture could reflect the reduction in abstraction, but note it was not significant at the reduced p-value.
Light	No notable trends identified	Not analysed	Plot M7 was identified as the most variable and plot G38 the least variable. No statistically significant trends at either p-value were identified. It was considered that this indicated the absence of a consistent directional change in the light variable over the study period.	It was noted from the survey narratives over the study period that where levels of light have increased as subsequent increase in low-growing herbs and shorter sedges and/or grasses have been recorded, thus causing an increase in species-richness. However, this was not identified as a variable with a strong correlation with areas of 'good-quality' fen.	No notable trends could be identified from consideration of light as an environmental variable, although it was noted that good conservation management reducing the height of rush etc. could potentially have increased light availability resulting in an increase in overall species richness. This was not significant however so could also be due to chance.

4.0 REFERENCES

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Arcadis (July 2016) – Eco-hydrology: Analysis of Ellenberg values for National Vegetation Classification quadrat data in Sizewell Marshes SSSI and Minsmere South Levels.

Biocensus (July 2016) – Trends in plant occurrence and Ellenberg indicators at Sizewell.

OHES (July 2016) – Trends in the Composition of Fen Meadow in Sizewell Marshes: A Supplementary Report.

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APPENDICES

Appendix A – Arcadis – Sizewell C Project Ellenburg Stand Level Review of M22 and Ditch Vegetation Communities Within Sizewell Marshes and Minsmere South Levels.

Appendix B – Arcadis – Eco-hydrology: Analysis of Ellenberg values for National Vegetation Classification quadrat data in Sizewell Marshes SSSI and Minsmere South Levels.

Appendix C – Biocensus – Trends in plant occurrence and Ellenberg indicators at Sizewell.

Appendix D – OHES – Trends in the Composition of Fen Meadow in Sizewell Marshes: A Supplementary Report.

FIGURES

Figures

Figure 1 – Location of Fen Meadow Compartments.
Figure 2 – Distribution of fen meadow at varying grades of species richness across Sizewell Marshes SSSI.
Figure 3 – Simplified distribution of M22 NVC community across Sizewell Marshes SSSI.

SZC CO. 2016. THE M22 VEGETATION COMMUNITY, HYDROLOGICAL TOLERANCES AND SENSITIVITIES: A PROPOSED APPROACH FOR ASSESSING HYDROLOGICAL IMPACTS.

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THE M22 VEGETATION COMMUNITY: HYDROLOGICAL TOLERANCES AND SENSITIVITIES. A PROPOSED APPROACH FOR ASSESSING HYDROLOGICAL IMPACTS

VERSION 5 – SEPTEMBER 2016

CONTENTS

EXECUTIVE SUMMARY

This report presents a detailed review of the scientific literature relating to the hydrological sensitivities and tolerances of the M22 Fen Meadow community. It also presents a methodology outlining how the FEFLOW model will be used to assess the potential changes to the underlying hydrological regime of the M22 community resulting from the construction of Sizewell C.

A fully illustrated worked example is presented, showing the assessment of potential effects of a construction scenario using FEFLOW. The construction scenario modelled includes the reduced infiltration associated with the Temporary Construction Area, the cut-off wall and active dewatering. This scenario was selected as it represents the period with the greatest potential for changing water levels within the Sizewell Marshes.

A review of recent literature confirms that Fen Meadows develop as groundwater-dependent peatland vegetation typically maintained by grazing and/or mowing, though it is the extent of capillary rise, rather than the location of the water table, that determines the influence of groundwater within Fen Meadow stands.

The dependence of Fen Meadow vegetation on the influence of groundwater has been shown to vary between the constituent species, as do the physiological adaptations to changes in the hydrological regime.

Two species assemblages within the vegetation at Sizewell Marshes are particularly vulnerable to changes in the annual hydroperiod, these being:

- groups of low-growing ground-dwelling species; and
- species associated with low fertility and/or high lime content.

These species assemblages are largely restricted to good quality areas of Fen Meadow (Grades 1 and 2).

A large-scale field experiment in base-rich Fen (described in the report) has concluded that over-wetting or drying-out for up to approximately two weeks were not damaging to the peatland. This indicates that fen vegetation has some resilience to over-wetting and drying for short periods.

The review has also emphasised that Fen species may be more sensitive to light availability than water table depth in some situations. This may be reflected by the distribution of the low-growing assemblage of sensitive species at Sizewell Marshes, and suggests that effective conservation management is also important for maintaining a species-rich sward.

It is concluded that whilst the published information relating to M22 is useful, it is too broad-brush to provide site-specific thresholds for hydrological change against which to assess potential impacts arising from the Sizewell C development upon the M22 stands located within Sizewell Marshes SSSI. Instead, the approach that will be adopted (which is consistent with the Environment Agency's 'Ecohydrological guidelines for lowland wetland plant communities') will be to use the FEFLOW model to establish site-specific baseline envelopes for the M22 communities at Sizewell for use in the assessment of any impact arising from the construction and operational scenarios.

Using the FEFLOW model, a baseline for each grade of Fen Meadow has been derived that effectively envelopes the range of hydrological conditions underlying each grade.

The worked example, using the construction scenario described above, has shown that there will be no change in the extent of summer drawdown or surface inundation for Fen Meadow Grades 1 and 2, with the predicted changes being within the baseline envelope; i.e. the existing status quo is maintained and no significant effect is therefore envisaged.

A minor change was predicted for Grades 3 and 4, with the level of summer drawdown being slightly lower, outside the baseline envelope. Modelling showed that additional mitigation measures, in the form of a control structure, effectively mitigated this effect. Again, no significant effect is envisaged subject to mitigation.

1.0 INTRODUCTION

1.1.1 Detailed consultation has been undertaken with the Environment Agency and Natural England in relation to assessing the potential hydrological effects of the proposed Sizewell C development on habitats within Sizewell Marshes, in particular the M22 fen meadow community.

1.1.2 A detailed review of the fen meadow vegetation, and factors influencing the distribution and species composition of the fen meadow, has been produced as a companion to this report (Arcadis 2016). The purpose of this review was to bring together a suite of work and to provide a technical summary of the detailed analyses that have been undertaken of botanical survey data collected from Sizewell Marshes to evaluate baseline conditions.

1.1.3 In addition, a supplementary technical note (Atkins, 2016a) provides further detail on the FEFLOW model and clarifies the causes of residual uncertainty, inherent in all numerical models, where real world conditions cannot be fully represented in the model.

1.1.4 This report presents a detailed review of the scientific literature relating to the hydrological sensitivities and tolerances of the M22 Fen Meadow community. It also presents a methodology outlining how the FEFLOW model will be used to assess the potential changes to the underlying hydrological regime of the M22 community resulting from the proposed Sizewell C development.

1.1.5 An illustrated worked example is presented, showing the assessment of potential effects of a construction scenario using FEFLOW. The construction scenario modelled includes the reduced infiltration associated with the Temporary Construction Area, the cut-off wall, and active dewatering. This scenario was selected as it represents the period with the greatest potential for changing water levels within the Sizewell Marshes. It is emphasised that this is a preliminary model run and represents but one of a number of assessment scenarios that will be carried out under different climatic regimes.

1.1.6 The remainder of this report is set out as follows:

- Section 2 presents the results of the literature review.
- Section 3 sets the hydrological context with actual observations.
- Section 4 provides further detail in the use of the FEFLOW model.
- Section 5 presents the proposed assessment methodology.
- Finally, section 6 presents a worked example using FEFLOW to assess potential changes in the hydrological regime of the M22 fen meadow.

2.0 LITERATURE REVIEW

2.1 General overview

2.1.1 This section provides a summary of the review of the literature that has been undertaken. The aim of the literature review has been to collate information relating to the hydrological preferences and functioning of Fen Meadow and similar habitat types in order to inform what the site-specific hydrological preferences and tolerances of the M22 Fen Meadow communities at Sizewell Marshes may be.

2.2 Broad hydrological tolerances of M22 Fen Meadow

2.2.1 M22 is a species-rich Fen Meadow community and a detailed account of the plant composition and distribution, together with the underlying drivers that account for this floristic diversity is given in the companion report to this document (Arcadis 2016).

2.2.2 Wheeler *et al.* (2009) has produced a useful summary of the broad hydrological tolerances of the M22 community (as summarised in the Environment Agency's Fens and Mires update of the 'Ecohydrological guidelines for lowland wetland plant communities'). Note that the account has been drawn from a wide number of samples and therefore represents broad hydrological tolerances for the M22 community across the UK as a whole, and is not site-specific. This document therefore develops the evidence base for impact assessment taking account of site-specific data in accordance with the above guidelines.

2.2.3 The broad hydrological preferences for the M22 community are summarised below:

a) Sensitivity

2.2.4 Due to the wide range of water table conditions in which M22 can occur it is difficult to comment on sensitivities in relation to changes in the underlying hydrological regime. Some drying of M22 may lead to a change in floristic composition, but the magnitude of any change will depend upon the 'wetness' of the starting point before drying began to occur. The fact that many of the species that distinguish M22 from other vegetation are wet meadow species means that some drying may have little impact on species diversity per se and may actually lead to an overall net increase in plant species diversity. The importance of focusing on the plant species more indicative of wet meadow and Fen, rather than overall species diversity, is explored in the companion report to this document (Arcadis, 2016).

b) Water regime

2.2.5 Mean values for annual rainfall and potential evaporation for the M22 sites examined by Wheeler *et al.* (2009) are shown in Table 1.

Table 1. Mean rainfall and potential evaporation for stands of M22

	Mean	Minimum	Maximum
Rainfall (mm per annum)	651	539	1,050
Potential evaporation (mm per annum)	601	435	638
Mean summer water table (cm above and below ground level)	-10.8	-175	+12

2.2.6 As shown in Table 1, water conditions associated with M22 are variable, and typically water conditions range from being rather dry to water levels being just above the surface. Much of the variation in species composition can be attributed to differences in the kind and degree of waterlogging (Rodwell, 1991b).

2.2.7 The following broad comments regarding optimal and sub-optimal water levels for the M22 community are set out in Wheeler *et al.* (2009) :

Optimal water levels

- Most examples of M22 are characterised by summer water tables that are below the surface (5 to 18 cm below the ground level).
- The M22 stands with the highest summer water tables are mostly those with the strongest groundwater inputs.
- The most species-rich stands are found at summer (growing season) water levels of between about 5 and 20 cm below ground level.

Sub-optimal or damaging water levels

- Very wet sites (summer water table usually above-surface between tussocks) tend to be less species-rich. Even relatively short periods of inundation in the growing season can be damaging, both because of direct effects on plant communities (e.g. on seed germination) and indirect effects resulting from impacts on vegetation management.
- Moderate reduction in water levels may actually increase species richness (Shaw and Wheeler, 1991), but a long-term reduction of the summer water table beneath high quality stands of M22 can be expected to result in some loss of botanical interest. The impact of relatively modest reductions in the water table on species richness will be moderated to some degree by the action of the capillary fringe.

2.2.8 From the above information it is clear that both summer drawdown and surface water inundation in the summer could potentially have a negative effect on the M22 community, depending on the extent and duration of such events.

2.3 Significance of water level in controlling Fen habitat condition

2.3.1 Fen Meadows develop as groundwater-dependent peatland vegetation typically maintained by grazing and/or mowing (Wheeler *et al.*, 2009). The water level is usually accepted as a master environmental factor controlling the habitat conditions (e.g. Okruszko (1995)). Kotowski *et al.* (2001) distinguish between the direct influence of the water level in controlling the availability of water to the vegetation and the significance of water table depth below the ground surface in mediating the hydro-chemical environment supporting the vegetation. In fact, they argue that water level is not directly significant in functioning Fen Meadows as the high capillary rise evident in peat soils typically supplies water to the root zone.

2.3.2 The level of groundwater in Fen peatlands is believed to act mostly in an indirect way (Kotowski *et al.* 2001). Firstly, it controls nutrient availability by affecting the peat mineralisation rate (Godshalk & Wetzel 1978; Swift *et al.* 1979; Okruszko 1995). Following a fall in groundwater level the decomposition becomes largely accelerated (Grootjans 1985) and large amounts of nutrients are released (Verhoeven 1986). Secondly, high groundwater level creates anaerobic conditions and thus changes soil redox potential (Gambrell & Patrick 1978; De Mars & Wassen 1999). The response to such conditions differs among species (Armstrong 1978); for example, many *Carex* species are known for their ability to oxidise the root zone, which makes them less sensitive to anaerobic conditions (Moog 1998; Moog & Brugemann 1998).

2.3.3 The effect of water regime on environmental conditions in wetlands is usually accompanied by the influence of the chemical composition of water, in particular the effect of pH on nutrient availability. For example, the availability of phosphorous is reduced under alkaline conditions, while nitrogen occurs in different forms at different pH levels (Verhoeven 1986; Koerselman *et al.* 1993; De Graaf *et al.* 1998). In Fens, these factors are related to the source of water, which may have a high or low content of minerals, depending on their abundance in the subsoil and on the importance of rainwater feeding (Van Wirdum 1993; Van Diggelen *et al.* 1996).

2.4 Factors affecting the annual hydroperiod and soil moisture content of peats in East Anglian Fen sites

2.4.1 The nearest public weather station to Sizewell Marshes is at Levington, some 25 miles to the south, which recorded mean annual rainfall of 561 mm[1] (Minimum 461 mm; Maximum 780) over the period 1981-2010. This is 86 per of the mean rainfall reported for stands of M22 Fen Meadow (Wheeler *et al.*, 2009). With Growing Degree Days and Growing Season Length near or above the average for England[2], the Fen Meadow vegetation would be more likely to experience soil moisture stress in wetlands where the influence of groundwater was not sustained during the growing season.

2.4.2 Wheeler and Shaw (1992) reviewed the sensitivities of East Anglian Fens to dehydration, and noted that there was a tendency for the mean water tables associated with specific community types – including M22 Fen Meadows - to be somewhat lower (i.e. drier) in Eastern England valley Fens compared to those elsewhere.

2.4.3 Gowing and Spoor (1998) found that differences in soil hydrophysical properties can be important in some situations in determining the relationship between water tables and soil water conditions in the main rooting zone. In lowland peats, for example, the ability

[1] Source: Accessed 25/08/16 http://www.metoffice.gov.uk/public/weather/climate/u1315b791#?tab=climateMaps

[2] Source: Accessed 25/08/16 http://www.metoffice.gov.uk/public/weather/climate

of the substrate to retain available water following drawdown of the water table may vary significantly depending upon the type and degree of decomposition of the peat (Burton and Hodgson, 1987) and intermittent rewetting of the surface by rainfall.

2.4.4 Wheeler and Shaw (1992) report that 85% of the examples of M22 found in their survey of England and Wales were located in Spring Fen/Valley Fen. In undisturbed peats, capillary water may be drawn several decimetres above the height of the water table, though the extent of capillarity may vary markedly at different soil moisture contents (AMEC 2013) and with differing intensities of evapotranspiration.

2.4.5 Some authors (e.g. Londo, 1988) consider that reliance on the groundwater table as a measure for the eco-hydrological conditions in the rooting zone of Fen vegetation should be replaced by floristic indicators of groundwater influence. The use of 'phreatophytes' to assess groundwater dependence of the Fen Meadow vegetation is considered below.

2.5 Variation in M22 within Sizewell Marshes

2.5.1 The Fen Meadow vegetation on Sizewell Marshes is variable in species composition, the number of rich-Fen and other mire species it supports, and also on the dependence of its flora on groundwater supply. The vegetation is also composed of a number of species assemblages with distinct eco-hydrological characters, which provide a subtle range of sensitivities to variations in moisture content at the ground surface.

2.5.2 Appendix A is a tabular summary of the species attributes referred to in this section. The attributes are drawn from the literature and from expert knowledge of the Fen Meadow vegetation.

2.6 National Vegetation Community types

2.6.1 In the companion report to this one (Arcadis, 2016) it was highlighted (on the basis of work carried out by OHES Environmental) that the Fen Meadow stands within Sizewell Marshes SSSI were grouped into 17 distinct vegetation stands with M22 *Juncus subnodulosus-Cirsium palustre* Fen-Meadow community being the dominant vegetation community. However, it was noted that there was significant variation within the M22 communities present, with affinities to other vegetation communities, including MG8 *Cynosurus-Caltha* grassland and MG12 *Festuca arundinacea* grassland, identified. Much of the variation in species composition can be attributed to differences in the kind and degree of waterlogging (Rodwell, 1991).

2.7 Grading the floristic richness of the Fen Meadow vegetation

2.7.1 OHES Environmental (as summarised in Arcadis, 2016) employed Wheeler's (1988) concept of Principal Fen Species to group the Fen Meadows within Sizewell Marshes into four grades according to the number of Principal Fen Species - and other species frequently found in groundwater-dependent mires – that they support. This classification (see Table 2, below) was used to distinguish 'good-quality' Fen Meadows (Grades 1 and 2) from other vegetation types on the Marshes that support Fen species (Grades 3 and 4). Using the Environmental Indicator Value system (Hill *et al.*, 2004; Hill *et al.*, 2007), the 'good-quality' Fen Meadows at Sizewell Marshes are shown to have a strong correlation with high soil wetness, circum-neutral to mildly calcareous reaction and infertile conditions.

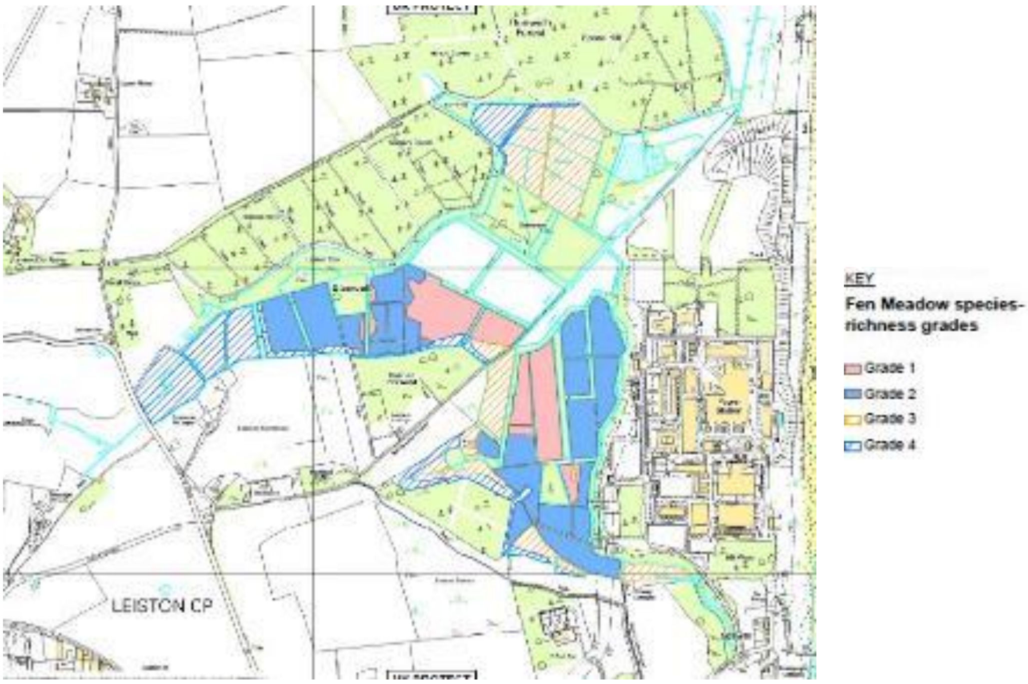
2.7.2 Note that it is recognised that all of the Fen Meadow present is currently in favourable condition, and that it all forms part of the cited SSSI habitat interest feature (in contrast, the wading bird element of the SSSI breeding bird assemblage is now absent). However, analysis of the floristics does enable a grading of the Fen Meadow, which indicates that some areas contain sensitive or scarce species not present in the other grades, and, using professional judgement, can be regarded as being of greater ecological significance than other areas. This grading is based on real differences in the floristics of the M22.

Table 2. Grades of M22 within Sizewell Marshes

Grade	Rationale
Grade 1	Good quality Fen Meadow supporting relatively high numbers of Principal Rich-Fen species and other mire species, including a suite of 'low fertility' indicators.
Grade 2	Good quality Fen Meadow supporting a suite of Principal Rich-Fen species and other mire species, including a suite of 'low fertility' indicators.
Grade 3	Fair quality Fen Meadow, supporting some Principal Rich-Fen species and other mire species, with few 'low fertility' indicators.
Grade 4	Drier Fen Meadow grading to rush pasture and dry grassland, supporting few Principal Rich-Fen species and other mire species, with very few 'low fertility' indicators.

2.7.3 The indicative distribution and extent of the four grades of M22 is presented on Figure 1 below.

Figure 1. Distribution of grades of Fen Meadow



2.8 Floristic evidence for groundwater dependence on Sizewell Marshes

2.8.1 The degree of groundwater dependence suggested by each grade of Fen Meadow has been described using Londo's definitions of the relationship between the constituent species and the influence of groundwater. Londo (1988) defined 9 categories describing this relationship, based on his concept of 'phreatophytes' – plant species that occur exclusively in or are largely limited to the sphere of influence of the water table. Definitions of this classification are given in Table 3.

Table 3. Definitions of species groundwater-dependence (Londo, 1988)

Class	Category	Definition
Hydrophyte	H	Species with vegetative parts submerged or floating on the water surface.
Obligate phreatophytes	W	Species requiring a water table at the soil surface (in years with a normal water table) or higher during part of the year or permanently for good development and completion of their life-cycle, e.g. germination.
	F	Species growing only within the sphere of influence of the water table, which is generally below the soil surface.
Non-obligate phreatophytes	V	Species growing mainly or almost exclusively within the sphere of influence of the water table, which is generally below the soil surface.
	K	Lime phreatophytes - species growing within the sphere of influence of the water table (which is generally below the soil surface), but occurring above this sphere of influence on soils rich in lime.
	P	Local phreatophytes - species that grow above the sphere of influence of the water table in much of their area of distribution (outside the limestone area), but depend on this sphere of influence in certain areas or places.
	D	Dune phreatophytes - species that are not limited to the sphere of influence of the water table (where they are aphreatophytes), but grow exclusively or mainly within this sphere of influence in dunes or other sand areas.
Aphreatophytes	A	Species that are not bound to the sphere of influence of the water table. However, many of these species can be found, often abundantly, within the sphere of influence of the groundwater.
Halophytes	Z	Species that grow only in salt habitats. When they also occur (sometimes incidentally) in environments with fresh groundwater, they are classified in one of the other categories.
Hydrophyte	H	Species with vegetative parts submerged or floating on the water surface.

2.8.2 Table 4 (below) confirms that, when summed, species classed as phreatophytes make up on average 71.5% of all Fen plots, with the proportion only declining in the group of Grade 4 meadows. The species composition of all 4 grades of Fen Meadow is therefore largely composed of groundwater-dependent species according to Londo's (1988) classification. However, it should be borne in mind that the frequency of occurrence of these species varies between grades, and Grades 1 and 2 typically support much higher populations of many of these species.

Table 4. Proportion of groundwater-dependent species recorded from each grade of Fen Meadow.

Class	Category	All plots (%)	Grade 1 (%)	Grade 2 (%)	Grade 3 (%)	Grade 4 (%)
Hydrophytes	H	2.6	1.4	1.1	2.7	0.0
Obligate Phreatophytes	W	24.1	26.1	27.2	23.3	14.0
	F	8.6	10.1	9.7	5.5	6.0
Non-obligate Phreatophytes	V, K, P, D	38.8	37.6	35.8	42.5	40.0
Aphreatophytes	A	24.1	21.7	23.9	24.7	40.0
Halophytes	Z	1.7	2.9	2.2	1.4	0.0
Total Phreatophytes (%)		71.5	73.8	72.7	71.3	60.0

2.9 Species assemblages and their sensitivity to changes in groundwater influence

2.9.1 Following Londo (1988), a group of species assemblages can be recognised at a finer level of definition than the NVC survey, in terms of their dependence on the influence of groundwater, and by their physiognomy as part of the Fen Meadow swards. Not all assemblages have a significant presence on Sizewell Marshes, but some are particularly sensitive to the presence of groundwater.

2.9.2 As shown in Table 5, below, a suite of general Fen Meadow species, usually intermixed with generalist species, scramblers and plants also frequent in wet grassland, form the matrix defining the vegetation as encompassed within the *Juncus-Cirsium* community. Wheeler (1980, p777) comments on the occurrence in some types of Fen Meadows of extensive populations of species typical of the wet grasslands of nutrient-rich Calthion pastures. He speculates that their occurrence may be related to the absence of strongly reducing conditions perhaps caused partly by the extensive sub-surface rhizomes of the dominant rushes helping to aerate the substratum, but also, and probably more importantly, by the movement of seepage water through the Fens (see Armstrong & Boardman, 1967).

Table 5. Species assemblages occurring on Sizewell Marshes, in terms of frequency and groundwater-dependence.

Londo's categories are: H = Hydrophyte; O – Obligate phreatophyte; N = Non-obligate phreatophyte; A = Aphreatophyte; S = Halophytes. Species allocated to each assemblage are indicated in Appendix A.

Assemblage	Categories					Description	Frequency
	H	O	N	A	S		
General Fen Meadow species			✓			This group of species are generalists and tend to be common in Fen Meadows and wet grasslands, usually within the influence of groundwater (*Juncus inflexus*, *J. articulatus*) or at least partially rain-fed (*Cirsium palustre, Angelica sylvestris, Juncus effusus*).	Abundant
Generalists				✓		Aphreatophytes independent of the sphere of influence of groundwater. This does not mean that these species avoid groundwater: no indications of any avoidance behaviour have been found: the initial 'a-' of aphreatophyte means here 'indifferent'. These species can be found, often abundantly, within the sphere of influence of the groundwater.	Abundant
Scramblers		✓	✓			A common niche in Fen Meadows is adopted by species that can scramble onto rush tussocks, lifteing their leafy stems into higher light situations.	Frequent
Wet grassland species		✓	✓			This group of species require high light conditions but require moist conditions to be maintained throughout the growing season, especially those species occupying shallow hollows.	Frequent
Swamp species		✓				A larger group of species that are tolerant of periods of inundation during the growing season, and are commonly associated with shallow depressions in the ground surface on the marshes, or within compartments which frequently experience inundation.	Locally frequent
Low-nutrient species			✓			This group is often associated with low-nutrient and/or lime-rich situations favouring short swards, usually on slightly raised ground.	Locally frequent
Shade-tolerant species		✓	✓			These species are rather more tolerant of water table fluctuations, and are also typical of reed-Fen or taller wet grasslands.	Occasional
Ground-dwelling species		✓				This group is composed of low-growing species reliant on groundwater influence reaching the soil surface, with relatively	Occasional

Assemblage	Categories					Description	Frequency
	H	O	N	A	S		
						short periods of flooding or drawdown. Periods of drawdown that lead to nutrient flushes and the growth of a shading canopy are not tolerated.	
Halophytes					✓	Species normally found in saline habitats. Like hydrophytes, they are scarcely present in the NVC plots and are only represented by *Juncus gerardii* and *Oenathe lachenalii*. Both species live in swampy conditions of upper salt-marsh, and are restricted to hollows on Sizewell Marshes.	Rare
Marginal species		✓				A small group of 'stream-edge' species that are scattered in some parts of the Marshes; these are most likely to occur near ditch margins, where groundwater-rich drainage waters are temporarily ponded.	Rare
Floating mats		✓				The only species able to form floating mats of vegetation is Bogbean *Menyanthes trifoliata*. Although tolerant of periods of water table drawdown during the growing season, it is adapted to float during periods of inundation. It occurs intermixed with ground-dwelling species.	Rare
Hydrophytes	✓					True 'aquatic' plants are at most only a very infrequent associate of the Fen Meadow vegetation. These species are indicative of very prolonged or even permanent inundation, where the ground surface would be only infrequently exposed.	Rare

2.9.3 Collectively, these assemblages place many of the types of swards on the Sizewell meadows into a rather grassy form of the community typical of sites with some drainage. The sward structure is also rather typical of sites where the naturally fertile swards promote strong rush growth, but are neither dry enough for grassland plants to replace the rushes in managed situations, nor wet enough for swamp and shade-tolerant reed-Fen species to achieve dominance, though both situations are present in the drier and wetter areas of the Marshes.

2.9.4 Sward height and canopy thickness both have a moderating effect on the ability of under-canopy and ground-dwelling and low-nutrient species to survive, and both groups occur either as isolated patches in full sunlight, or as scattered fragments almost entirely within the 'good quality' Fen Meadows (Grades 1 and 2). As indicated in Table 3, these two species assemblages are obligate phreatophytes that are particularly sensitive to sustained groundwater influence, though their distribution may also be affected by light availability (Kotowski *et al.*, 2001; also discussed below).

2.9.5 Numerical estimates of species/water regime relationships can assist in the assessment of desirable, or acceptable, regimes for the maintenance of specific plant communities and species. At the level of the plant community, Wheeler *et al.* (2009), however, note that floristic variation within a community type may often reflect environmental variation, and that peripheral members of the community unit may be associated with rather different environmental conditions (such as water levels) than core members. On Sizewell Marshes, all four grades of Fen Meadow (but especially Grades 1 and 2) may support more than one species assemblage, and species from different categories of the Londo (1988) classification may occur in close proximity, rendering absolute water-level targets difficult to apply.

2.9.6 Similarly, they caution that any attempt to specify the habitat range of a community depends critically upon the precise compass of the unit and the range of samples that are considered to be appropriate members of it. This is borne out on the Sizewell Marshes where micro-topographical variations create an uneven ground surface (of the order of 5-20 cm) allowing the low-nutrient or ground-dwelling assemblages to occupy micro-sites within a sampling plot, though favourable hydrological conditions may be confounded by an over-shading rush canopy. Similarly, the swamp assemblage may co-exist amongst general Fen-Meadow species by occupying the shallow hollows that grade out onto slightly raised ground frequented by grassier vegetation.

2.9.7 Several authors provide mean summer water levels for individual plant species, collating data collected from different sites at different times, and presenting the mean value as a central point along a spectrum between recorded upper and lower limits of tolerance (e.g. Newbold & Mountford, 1997; Wheeler & Shaw, 1992). Values from Newbold & Mountford (1997) are from stands of vegetation across the UK, whilst those of Wheeler & Shaw (1992) are from wetland sites within East Anglia. Appendix B provides a direct comparison between the individual plant species tolerances cited by Newbold & Mountford (1997) and Wheeler & Shaw (1992) for plant species present within Sizewell Marshes.

2.9.8 The results of this comparison show that there is wide variation between the preferred hydrological regimes for individual plant species; for example, Bog Pimpernel (*Anagallis tenella*) has a preferred range of 1cm below to 3cm above ground level, whilst Marsh Bedstraw (*Galium palustre*) has a preferred range of 20cm below to just at ground level. A simple assessment was carried out by summing the values across species and presenting the mean values, and this is presented in Table 6, below.

Table 6. Mean hydrological preferences for wetland plant species.

Newbold and Mountford (1997) Hydrological regime (cm above or below ground level)			Wheeler and Shaw (1992) Hydrological regime (cm above or below ground level)		
Extreme dry	**Preferred**	**Extreme wet**	**Summer water level**	**Minimum**	**Maximum**
-42	-7	18	-9	6	-22

2.9.9 This suggests that the individual component plant species of wetland communities such as M22 have a preference for a summer water table close to the surface (7-9 cm below ground level) but can tolerate drawdown (22-42 cm below ground level) as well as coping with some inundation. The results are, of course, not specific to the M22 community itself, being for plant species across a range of wetland habitats, but do provide a broad indication of water level requirements. The majority of individual plant species tolerances also fall within the broad tolerances for the M22 community across the UK as a whole, characterised by summer water tables that are below the ground surface (5 to 18 cm below the ground level; see Section 2.2).

2.9.10 Some caution needs to be exercised when using these hydrological tolerances for individual plant species, as they have collated data collected from different sites at different times, and presented the mean value as a central point along a spectrum between recorded upper and lower limits of tolerance (e.g. Newbold & Mountford, 1997; Wheeler & Shaw, 1992). These provide general guidance for average summer water levels at the species level, and have limited utility for proscribing the water level requirements of species assemblages.

2.9.11 At the level of species, Wheeler (1999) asserts that it can be surprisingly difficult to relate plant species distributions to the height of the water table in between-site comparisons, as individual species may occupy different positions along a strong gradient of surface wetness at different sites (Spence, 1964). He comments that even within a single wetland site, the temporal variation of water table at any one point is often equal to, or greater than, the point-to-point variation at any one time.

2.9.12 Notwithstanding this, the national guidelines developed in Wheeler *et al.* (2009; summarised in the Environment Agency's Fens and Mires update March 2010 of Ecohydrological guidelines for lowland wetland plant communities) provide a sensible first approximation for a summer water table target of 5 to 18 cm below the general ground level. This clearly emphasises the requirement for more species-rich sites – especially those, like Sizewell Marshes, which support assemblages of ground-dwelling and low-nutrient species assemblages – to sustain groundwater influence throughout the growing season.

2.9.13 However, the Grade 1 and Grade 2 groups of Fen Meadow on Sizewell Marshes already support both assemblages (i.e. ground-dwelling and low-nutrient species) which have been tracked through the Suffolk Wildlife Trust (SWT) Fen Meadow Monitoring Programme since 1995 (Parmenter (1997-2001) and Stone (2003-15)). These assemblages have occupied similar areas of the Marshes over this period, and were recorded in the SWT NVC Survey in 1993. It is therefore very likely that the groundwater regime has been favorable over this period, and site-specific hydrological data relating to the groundwater regime should be considered for adoption within the FEFLOW model (Section 3), as recommended in the Ecohydrological Guidelines 2010.

2.10 Hydroperiod thresholds

2.10.1 Wheeler (1999) reviewed evidence that, in different situations, species composition and community limits of wetland vegetation can be influenced by occasional extreme water level minima and maxima, by average minima and maxima, by average water levels, by the frequency and duration of fluctuations, and by the timing of these events.

2.10.2 For sites where the annual hydroperiod means that the soils are typically saturated, and for vegetation and species that are not constrained by high water tables, Wheeler (1999) notes that it is possible to identify a 'normal' water table minimum for the growing period that can be considered to form a 'safety threshold' (a threshold appropriate for the maintenance of a species or community in normal circumstances – but which may well be higher than the actual minimum that can be tolerated). It is likely to be considerably easier to specify such a threshold than to determine actual species and community limits with respect to water regimes.

2.10.3 One key characteristic of the threshold is the recognition that the cumulative period of time for which a particular water level is exceeded can provide a sensitive characterisation of hydrological regimes with regard to vegetation composition. This concept takes into account both the magnitude and duration of water level fluctuation. Gowing and Spoor (1998) have derived 'sum exceedance values' which quantify the depth–duration the water table is above or below a specified threshold value. SEVs have been developed in a way that can be related meaningfully to species distributions and abundance (Gowing and Spoor, 1998; Silvertown *et al.* 1999; Adams, Gilman and Williams, 1994).

2.10.4 The concept is based on two terms: a 'dryness SEV' (in metre weeks), which is the period of time for which the water table is lower than a specified threshold with a soil surface matric potential of 0.5 m; and an 'waterlogging SEV', which is the time period for which the water table is above a specified threshold associated with 10 per cent air-filled soil porosity at 10 cm depth. Gowing *et al.* (2002) provide SEV plots for 99 wet grassland species - including many of the less sensitive species occurring at Sizewell Marshes – which demonstrate the wide range of tolerances to periods of wetting and drying displayed in that habitat. The plots indicate that many species are relatively immune to short periods of waterlogging or droughting (two weeks), but that more prolonged periods may lead to catastrophic declines in affected populations.

2.10.5 As with all depth–time water table summations, identification of target water table values from SEVs is not straightforward, and Wheeler *et al.* (2009) caution that it is often inappropriate to use single target depths as a guide for management. Rather, as should be the case for Sizewell Marshes, the concept provides a tool to identify the potential for 'normal' hydroperiod thresholds to be exceeded during periods of drought or flooding.

2.10.6 Cusell *et al.* (2015) provide one of the very few examples of large-scale field experiments in base-rich Fens to investigate the physical and biogeochemical impacts of short term (two week) droughts and inundations in species-rich Fens during summer and winter. Their conclusions were dependent upon the physical cohesiveness of surface peats and the character of the root mats binding the surface.

2.10.7 Drawdown below threshold limits led to a water table drop of 10–15 cm in non-floating Fens, and led to a strong increase of Eh (from -200 to +500 mV) upon water level draw-down in the upper 5 cm of rich-Fen soils, indicating oxygen intrusion into these soils. This short-term intrusion of oxygen did not lead to acidification or eutrophication, but it is well known that longer episodes of drought can stimulate net mineralization rates and acidification by aerobic oxidation processes (Grootjans *et al.*, 1986; Mettrop *et al.*, 2014).

2.10.8 Summer and winter inundations over a two-week period were found to be dependent upon soil moisture levels at the time, and varied markedly between years. Hydrochemical changes were similarly dependent upon rates of evapotranspiration and the extent to which they facilitated the infiltration of base-rich inundation water. In rich-Fens, infiltration of inundation water led to an increase of alkalinities and Ca-concentrations in soil pore waters. This acts to delay anaerobic hydrochemical changes during brief inundations, though the progress of redox reactions is well known to require physiological adaptations from flood-tolerant species (e.g. Braendle and Crawford, 1987), and Wheeler *et al.* (2009) note that very wet sites (summer water table usually above-surface between tussocks) tend to be less species-rich. At Sizewell Marshes, increased inundation is likely to promote species losses, including from the ground-dwelling and low-nutrient species assemblages.

2.11 Direct and indirect effects of changes in the hydrological regime

2.11.1 Wassen *et al.* (1990), investigating the Biebrza Marshes in Poland, concluded that their hydrodynamics determined vegetation composition primarily by regulating nutrient dynamics. Indeed, many authors use the hydrological conditions that control the nutrient availability in wetlands to explain vegetation zonation (e.g., Pałczyñski (1984); Wassen *et al.* (1990); Van Diggelen *et al.* (1991a)).

2.11.2 Such data are used also for predictive modelling in nature management and restoration ecology (Van Diggelen *et al.* 1991b; Barendregt *et al.* 1993). However, when descriptive data on species' responses to hydrological conditions are being compared between distinct areas, differences are found (Kotowski *et al.* 1995). One of the key variables that confounds species-water regime comparison is the difficulty in presenting actual water table depths for species occupying a small part of a patch with micro-topographical variation, where the ground surface may display a depth range of several decimetres over the sample plot.

2.11.3 Another relationship between water levels and plant responses is of direct significance to the ground-dwelling and low-nutrient species assemblages. It has been long recognised that differences in light availability directly influence plant growth (e.g., Boardman (1977); Stitt & Schulze (1994)). Other studies proved that light availability varies greatly between different communities (Fliervoet 1984) as well as vertically within a vegetation stand (Fliervoet 1984; Hirose & Werger 1995; Anten & Hirose 1999). Dependence of species distribution patterns on light availability has been shown by, amongst others, Kooiman (1993) for the Fen bryophyte *Scorpidium scorpioides*.

2.11.4 Kotowski *et al.* (2001) compared the effect of light intensity with the effect of water level depth on the growth of low-competitive Fen species, including Marsh Pennywort *Hydrocotyle vulgaris*. They found that this group of species had no preference for a particular water regime but that their distribution was strongly correlated to sites with high light availability, which they found to have a major effect on species establishment. They concluded that:

- Low-competitive Fen species tend to be restricted to stands with stable high groundwater levels, thus in nutrient-poor conditions.
- This assemblage of Fen plant species is excluded from nutrient-rich wetlands due to the competition for light.

2.11.5 This study has particular significance for relating water levels and vegetation management to meeting conservation targets for the Fen Meadows. Kotowski *et al.*

(2001) stress that the relationship between the occurrence of Fen species and the existing hydrological conditions may be an indirect one. They propose that three separate mechanisms can be discerned:

- (1) the influence of hydrological (and hydro-chemical) conditions on nutrient availability;
- (2) the negative relationship between site fertility and the amount of light under the vegetation canopy; and
- (3) the relationship between the occurrence of Fen species and light conditions.

2.11.6 Where a fall in water table promotes tall growth and an increase in shade, a higher stocking density and duration of grazing on the firmer ground conditions may promote high light levels and increase the area with suitable micro-sites to support these sensitive species assemblages.

2.11.7 The most sensitive period of year for Fen Meadow is the growing period and the period when conservation management would occur (April to September), but also potentially the late winter and early spring periods, as wet ground conditions at this time of year will to some extent dictate what conditions are like during the growing season and when conservation management would occur. If conditions are too wet, this could be impeded.

2.11.8 This serves to emphasize that conservation management, as well as maintenance of water table are both important in maintaining the conservation status of Fen Meadow communities.

2.12 Summary and conclusions

2.12.1 A review of recent literature confirms that Fen Meadows develop as groundwater-dependent peatland vegetation typically maintained by grazing and/or mowing (e.g. Wheeler *et al.*, 2009).

2.12.2 The water level is usually accepted as a master environmental factor controlling the habitat conditions, though it is the extent of capillary rise, rather than the location of the water table, that determines the influence of groundwater within Fen Meadow stands (Kotowski *et al.*, 2001).

2.12.3 The dependence of Fen Meadow vegetation on the influence of groundwater has been shown by Londo (1988) to vary between the constituent species, as do the physiological adaptations to changes in the hydrological regime (e.g. Armstrong, 1978).

2.12.4 Two species assemblages within the vegetation at Sizewell Marshes are particularly vulnerable to changes in the annual hydroperiod, these being:

- groups of low-growing ground-dwelling species; and
- species associated with low-nutrient and/or high lime content.

2.12.5 These (generally more sensitive) species assemblages are largely restricted to good quality areas of Fen Meadow (Grades 1 and 2), and have thrived in these areas since being recorded by the SWT NVC Survey in 1993, either as patches or scattered fragments amongst general Fen Meadow vegetation.

2.12.6 The literature on water level requirements of these species confirms that both assemblages are reliant on groundwater influence throughout the growing season. Published results of spot water table heights collated from across Britain (Wheeler and Shaw, 1992; Newbold and Mountford, 1997) provide an indicative range and mean values of summer water table depth where these species occur. However, Wheeler and Shaw (1992) found that mean summer water tables associated with Fen Meadows in East Anglia were typically lower than in other areas.

2.12.7 The national guidance for the optimum mean summer water table (for all Fen Meadows falling within the M22 community) of summer (growing season) water levels of between about 5 and 20 cm below ground level (Wheeler *et al.*, 2009; Environment Agency, 2010) are likely to be broadly representative of hydrological conditions at the best fen meadow sites but should not be taken literally as actual site conditions may vary. The properties of the substrates, in particular their ability to maintain high soil moisture levels in the rooting zone in the summer due to capillary fringe effects, are likely to be important.

2.12.8 In a large-scale field experiment in base-rich Fen, Cusell *et al.* (2015) concluded that short periods of over-wetting or drying out (two weeks) were not damaging to the peatland; this is borne out by the work of Gowing *et al.* (2002) on a large group of plants largely occurring in non-sensitive species assemblages. This study indicates that base rich fen vegetation has some resilience to short periods of water stress, both wetting and drying.

2.12.9 Kotowski *et al.* (2001) has emphasised that Fen species may be more sensitive to light availability than water table depth in some situations. This suggests that effective conservation management is also be a pre-requisite to maintaining a species-rich sward.

2.12.10 It was felt that the published information relating to M22 is useful, but is too broad-brush to provide site-specific thresholds for hydrological change against which to assess potential impacts arising from the Sizewell C development upon the M22 stands located within Sizewell Marshes SSSI. Instead, the approach that will be adopted (which is consistent with the Environment Agency's 'Ecohydrological guidelines for lowland wetland plant communities') will be to use the FEFLOW model to establish site-specific baseline envelopes for the M22 communities at Sizewell for use in the assessment of any impact arising from the construction and operational scenarios.

3.0 SETTING THE CONTEXT WITH ACTUAL OBSERVATIONS

3.1 Observed groundwater levels

3.1.1 As discussed in Section 2, the information about the hydrological tolerances and sensitivities of the M22 Fen Meadow community, in particular the optimal hydrological regime over the course of a typical growing season, need to be treated with some caution. Specifically, they need to be set into context, as factors such as seasonal and yearly variation in groundwater levels, and the effectiveness of conservation management, are also important in influencing the distribution and composition of the community. Understanding the real world hydrological regime is a complicated task, and involves more than just adopting a prescriptive water level value derived from the literature.

3.1.2 Hydrographs showing the observed hydrological regime (from boreholes), and the baseline as per the output from FEFLOW, for each of the four grades of Fen Meadow are presented in Appendix E. The hydrographs for each of the four grades of Fen Meadow show a broadly similar hydrological regime; however, there are subtle differences between monitoring points in each of the four grades of Fen Meadow, as follows:

- Observed groundwater levels in Grade 1 Fen Meadow have an annual range of approximately 0.3 m, with limited shallow surface inundation;
- Observed groundwater levels in Grade 2 Fen Meadow have an annual range of approximately 0.4 m, with periods of deeper surface inundation;
- Observed groundwater levels in Grade 3 Fen Meadow have an annual range of approximately 0.4 m, with spatially limited surface inundation. Overall average depth to water is greater over the year than in Grade 1 and Grade 2; and
- Observed groundwater levels in Grade 4 Fen Meadow have an annual range of 0.4 m, with no surface inundation. Overall average depth to water is greater over the year than the other three grades.

3.1.3 These subtle differences in groundwater levels, along with site management practices, appear to influence the extent and species composition of the better quality, more species-rich grades of Fen Meadow.

3.1.4 The observed hydrographs taken from different monitoring points (shown on Figure 2, below) for Grade 1 Fen Meadow, the highest quality composition, are presented in Figure 3. This will be used as a case study for this report.

Figure 2. Fen Meadow Grades and Peat groundwater monitoring network

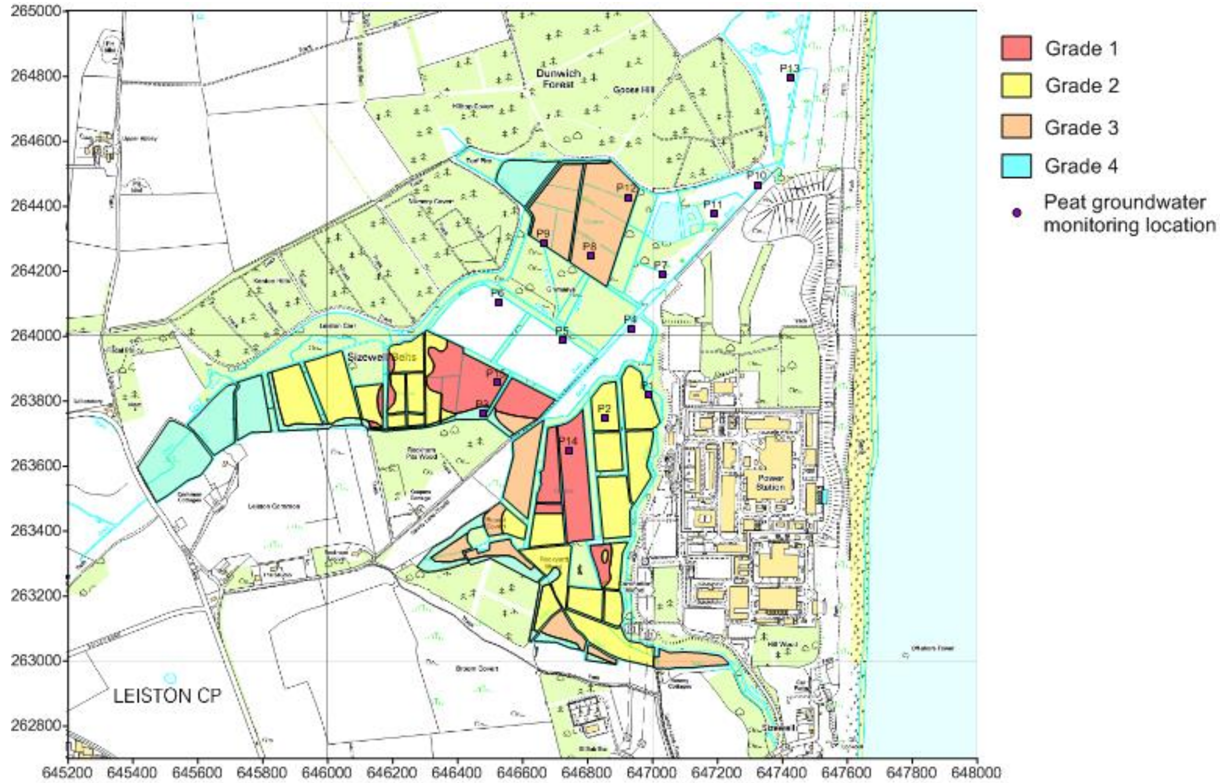
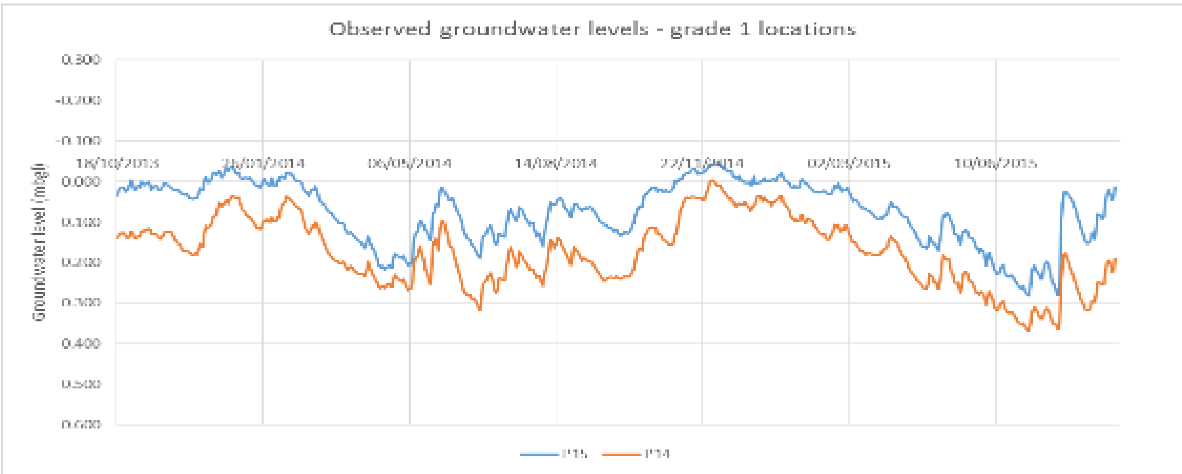


Figure 3. Observed hydrographs for Grade 1 Fen Meadow



3.1.5 From Figure 3 (which shows the observed groundwater levels at two different piezometer locations, P14 and P15, see Figure 2), it is clear that the Grade 1 Fen Meadow experiences quite marked seasonal and yearly variation in groundwater levels. During the winter period, actual observed groundwater levels can be above the ground surface for short periods, whilst during the summer months the groundwater drops below the ground surface, on average by 10-15cm, but up to 30 or 40cm for short periods. Similar seasonal patterns are also shown in the observed data for the other grades of Fen Meadow; however, there are subtle differences. There is greater surface inundation in Grade 2, and Grades 2, 3 and 4 all display a progressive increase in depth to the summer water table.

3.1.6 Clearly there is a difference between an optimal hydrological path, as defined by the literature review (which suggests that some of the most sensitive plant species have a preference for water levels to be within 5cm of ground level during the summer) and the actual observed hydrological regime as described above. This difference can be explained by the hydraulic properties of peat, which allow a strong capillary draw to be applied, provided it has not undergone drying (which damages the internal structure).

3.1.7 The water table is not a sharp change between wholly saturated and wholly unsaturated conditions. The water table simply demarks the upper boundary of fully saturated conditions, above which is a partially-saturated zone. This partially-saturated zone comes about as a result of surface tension, with pores in the soil acting as capillaries. When evaporation takes place at the ground surface, a "pull" is exerted on moisture in the ground, resulting in capillary rise. Capillary moisture is in hydraulic continuity with the water table, and the degree of saturation decreases with increased distance above the water table.

3.1.8 The degree to which the rise of water can be supported in the capillary fringe depends on the material properties of the substrate, with finer-grained soils demonstrating greater potential for this phenomenon. The height of the capillary fringe for a given soil is determined when the surface tension forces (pull up) and gravity (pull down) are in equilibrium. Where shallow water tables exist in soils with potential for high capillary rise, moisture is constantly pulled to the surface by evaporative loss, meaning that the soil profile above the water table is in the zone of capillary saturation. This means that water is available to plants with shallower rooting depths (above the water table) when water levels fall.

3.1.9 It is postulated that the best quality Fen Meadows (Grades 1 and 2) are located where the hydrological regime is more favourable. It is also possible that the peat substrate in these areas has a higher capillary potential, enabling sensitive plant species (that require water to be readily available near the ground surface) to thrive. The lower grades (3 and 4) may constitute areas where seasonal variations in water levels, although only subtly different, are less favourable. The peat in these areas may have been disturbed or suffered a drying event such that it no longer has the same capillary potential. This means that the more sensitive plant species find it harder to establish.

3.1.10 It is also noted that the ability of peat to sustain a capillary fringe relies on the internal structure. Should peat have undergone extended periods of drying, or the internal structure been otherwise damaged, then the potential for capillary rise is more limited.

3.1.11 The observed water levels demonstrate that there is a fairly narrow range of hydrological conditions within which each of the four Fen Meadow grades exist. A reduction in water levels beyond that currently experienced may result in less water being available by capillary action. The assessment will compare the predicted change in water levels against existing baseline conditions to determine whether any reduction in water levels is outside the range currently experienced by each grade.

3.1.12 As discussed in both Section 2 and 3, as well as low groundwater levels the other aspect of hydrology that is important with regards M22 is the avoidance of excessive periods of spring/summer inundation, with water lying above the ground surface. The assessment will consider the potential for construction-related impacts and the presence of the operational power station to extend such periods of inundation (either spatially or in duration) beyond current conditions. Should the scenario modelling show that changes in inundation patterns are anticipated, either in spatial extent or duration, professional judgement will be applied to assess the likely effect on ecological receptors. This will take account of direct effects on receptors as well as indirect effects via management.

3.1.13 The observed monitoring record (2013 to 2016) covers a period of relative climatic stability, with no extreme events, such as a prolonged drought or extreme rainfall, recorded. It is intended to use the FEFLOW model to produce a synthetic dataset representing a range of conditions (i.e. drought year, wet year, extended period of typical conditions) to extend the observed record. These synthetic datasets will be used, as set out in Section 5, to define the assessment thresholds.

4.0 FURTHER CONSIDERATIONS IN USE OF THE NUMERICAL GROUNDWATER MODEL

4.1.1 A transient numerical groundwater flow model has been constructed using the FEFLOW code. The model is coupled with a local surface water model, developed using the MIKE11 code, in the area of the Sizewell Marshes SSSI, to allow groundwater and surface water interaction to be represented. The development of the coupled numerical model (hereafter referred to as the FEFLOW model) is detailed in a separate report (Atkins, 2016).

4.1.2 The FEFLOW model is a good numerical representation of the conceptual understanding of groundwater flow in Sizewell C and the surrounding area, and the behaviour of the FEFLOW model, including response to changes of input parameters, is in line with anticipated hydrogeological behaviour.

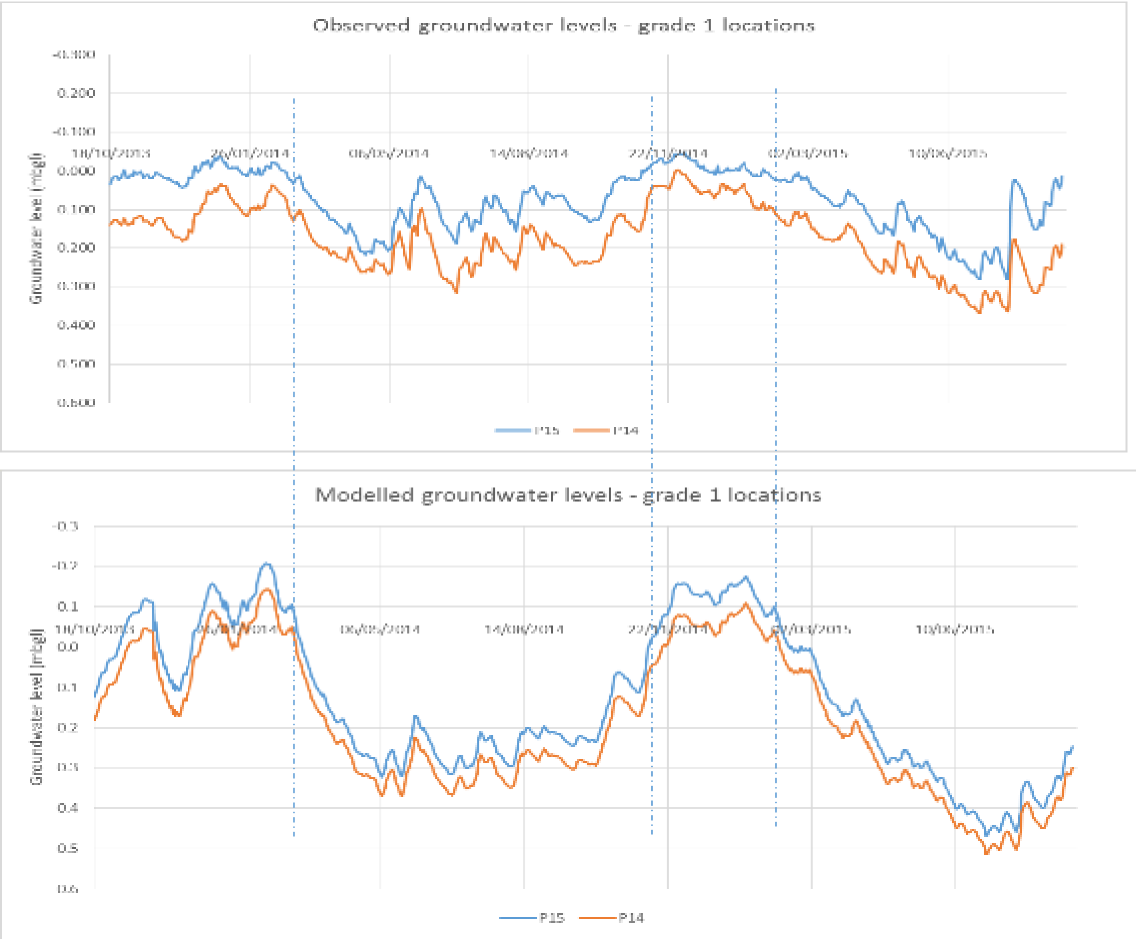
4.1.3 The FEFLOW model is well calibrated and suitable for use in the assessment of development scenarios. Seasonal fluctuations in modelled Peat water levels are well matched with monitoring data (particularly in the eastern monitoring locations closest to the development site), and the timing of seasonal highs and lows and overall trends in Peat and Crag groundwater levels are well simulated by the model.

4.1.4 A supplementary technical note (Atkins, 2016a) provides further detail on the FEFLOW model and clarifies the causes of residual uncertainty, inherent in all numerical models, where real world conditions cannot be fully represented in the model.

4.1.5 The FEFLOW model calculates water levels as elevations above a set datum (Ordnance Datum), rather than as depths below ground level. This means that the reported model results need converting to depths below ground level for use in the ecological assessment. It is possible to carry out this conversion at monitoring points as the boreholes have been surveyed in. The modelled water level elevation is subtracted from the surveyed borehole elevation to give a depth below ground level. However, in the intervening areas of the Sizewell Marshes no topographical survey data exists. The approach to dealing with water depths in the intervening areas, where no topographic survey data exists, is discussed in Section 5.

4.1.6 It is recognised that while the FEFLOW model is a good representation of real world conditions, there is a tendency to overestimate the seasonal variation in water levels. This can be seen when comparing the time series plot of modelled water levels with observed data. The cause of this overestimation is discussed in the supplementary technical note. Figure 4, below, shows the disparity between modelled and observed data for monitoring locations in Grade 1 Fen Meadow.

Figure 4. Observed and modelled hydrographs for Grade 1 Fen Meadow.



4.1.7 The modelled hydrograph shows comparable seasonal timing to the observed data, although the change in water levels is overestimated in the model. This means that during winter months a higher water level is predicted. However, the onset, and critically the end, of the inundation period (which will be used in the assessment) coincides with the observed data.

4.1.8 The fall in summer water table levels is greater in the FEFLOW model than in the observed data, meaning that a direct comparison with observed conditions would overestimate the impact of any predicted changes. In order to undertake a meaningful assessment of the potential changes resulting from development, the results of model scenarios, representing construction and operational phases, will be compared with a synthetic baseline derived from the FEFLOW model to take into account this behaviour.

4.1.9 The above relates to the assessment of unmitigated scenarios. It is recognised that mitigation may be required to prevent potentially detrimental changes outside the baseline range occurring in the Sizewell Marshes. It is possible to assess the efficacy of potential mitigation measures, such as any control structure(s) in the downstream end of the realigned Sizewell Drain, using the FEFLOW model, as such features can be represented and their efficacy tested in the model.

5.0 PROPOSED ASSESSMENT METHODOLOGY

5.1.1 The analysis outlined within this report has provided an understanding of the optimal hydrological regime for the Fen Meadow vegetation present within Sizewell Marshes SSSI. Further, an understanding has been developed of the existence of a fairly narrow range of hydrological conditions within which each of the four Fen Meadow grades exist.

5.1.2 Recognising that the available monitoring data covers a period of relative climatic stability, and taking into account that real world conditions cannot be directly compared with the FEFLOW model due to the overestimation of seasonality, it is proposed to establish a synthetic baseline for use in assessing potential change. This will be achieved by producing contours, and time-series plots from a number of locations in the baseline FEFLOW model, to demonstrate the range of hydrological conditions encountered by each grade of Fen Meadow in existing conditions.

5.1.3 From the literature review it is clear that the main issues that could potentially affect the hydrological regime of Fen Meadow at Sizewell are as follows:

- Changes in summer drawdown levels (an increase could be negative, whilst a reduction may be positive, at least in the short-term).
- Changes in summer inundation (prolonged inundation would be damaging, whilst a reduction in duration, or cessation of inundation, may constitute a positive effect).
- Any changes to hydrological regime in the late winter/early spring that influences the two points above.

5.1.4 In order to ensure the full range of existing baseline conditions are represented, a series of observation points will be set around the perimeter of each grade to produce a record of modelled water levels. The upper and lower ends of the recorded range will be used to produce a baseline time-series envelope for each grade of Fen Meadow. This envelope will represent an upper and lower threshold against which any hydrological change arising from the development can be measured.

5.1.5 As noted in Section 3, topographic data are held for the observation boreholes in the Sizewell Marshes; however, there is not a comprehensive topographic dataset available to allow the conversion from water-level elevations to depths below ground level, which is used in the assessment. Although LIDAR data are held for the area of the Sizewell Marshes, the vertical resolution is too poor to allow it to be used for this purpose, as a result of the nature of the vegetation cover. In the first instance, the assessment will be undertaken using interpolated topography between observation points. If necessary, additional topographic survey data can be collected in a targeted fashion to allow a refined assessment, taking into account actual topography.

5.1.6 Models will be run for each of the construction and operation scenarios, and the outputs used to see whether change resulting from the development falls outside the baseline envelope.

5.1.7 To assess changes in summer drawdown, observation points set in areas where there is a change in water levels will be compared with the baseline envelope for the appropriate Fen Meadow grade. If the change resulting from the development lies within the baseline envelope, then it will be considered that there is no impact, as the water levels are within the existing range encountered by that Fen Meadow grade.

5.1.8 Contour plots will be produced over the late spring/early summer period for comparison with baseline conditions. Contour plots will be produced to show the change in inundation at different dates, allowing any increase in the spatial extent to be identified, as well as any extension in the duration that inundation is occurring. If there is an increase in inundation, either spatially or temporally, this will be considered to be potentially detrimental.

5.1.9 A range of climatic events, such as extremely wet conditions in the lead up to spring and summer (the critical time period to facilitate management), will be modelled without development to allow the incremental change (e.g. extended period of inundation) to be assessed in the construction and operational scenario modelling.

5.1.10 If the results of the scenario modelling show change in summer drawdown outside the baseline envelope, or an increase in inundation, it will be necessary to explore further mitigation measures. Mitigation features, such as any water control structures on the diverted Sizewell Drain, would then be modelled to determine their efficacy.

5.1.11 Following completion of the assessment outlined above, water level monitoring will continue to allow ongoing assessment of real world conditions prior to and during construction and operation of Sizewell C. Should the ongoing monitoring yield information which alters the understanding of the hydrological regime prior to construction, the assessment will be reviewed, and updated if necessary.

5.1.12 Should the reassurance monitoring undertaken during construction and operation show changes that are outside the range predicted by the FEFLOW model, then further mitigation measures will be considered and the efficacy of such measures modelled by the FEFLOW model. It is also important to note that there is also an existing set of control structures within the Sizewell Marshes SSSI that is currently used to manage water levels. The use of this infrastructure to fine-tune the flow and level of surface water within the Sizewell Marshes SSSI is not directly represented in the FEFLOW model, but it does offer additional opportunity for mitigation of changes in water level through management practice.

5.1.13 A worked example is presented below to demonstrate how the ecological assessment will be undertaken with supporting information from the FEFLOW model.

6.0 WORKED EXAMPLE

6.1 Introduction

6.1.1 This section presents a worked example showing how the FEFLOW model will be used to assess the potential changes to hydrological regime resulting from the construction of Sizewell C.

6.1.2 The overall aim of the assessment is to maintain the existing hydrological regime for each grade of Fen Meadow, to maintain the status quo.

6.1.3 As indicated in the main report, the FEFLOW model will be used to generate a synthetic baseline for each grade of Fen Meadow against which the potential effects of each construction scenario can be modelled and assessed. The model will be used to consider a range of climatic conditions, as well as construction and operational scenarios, in the assessment.

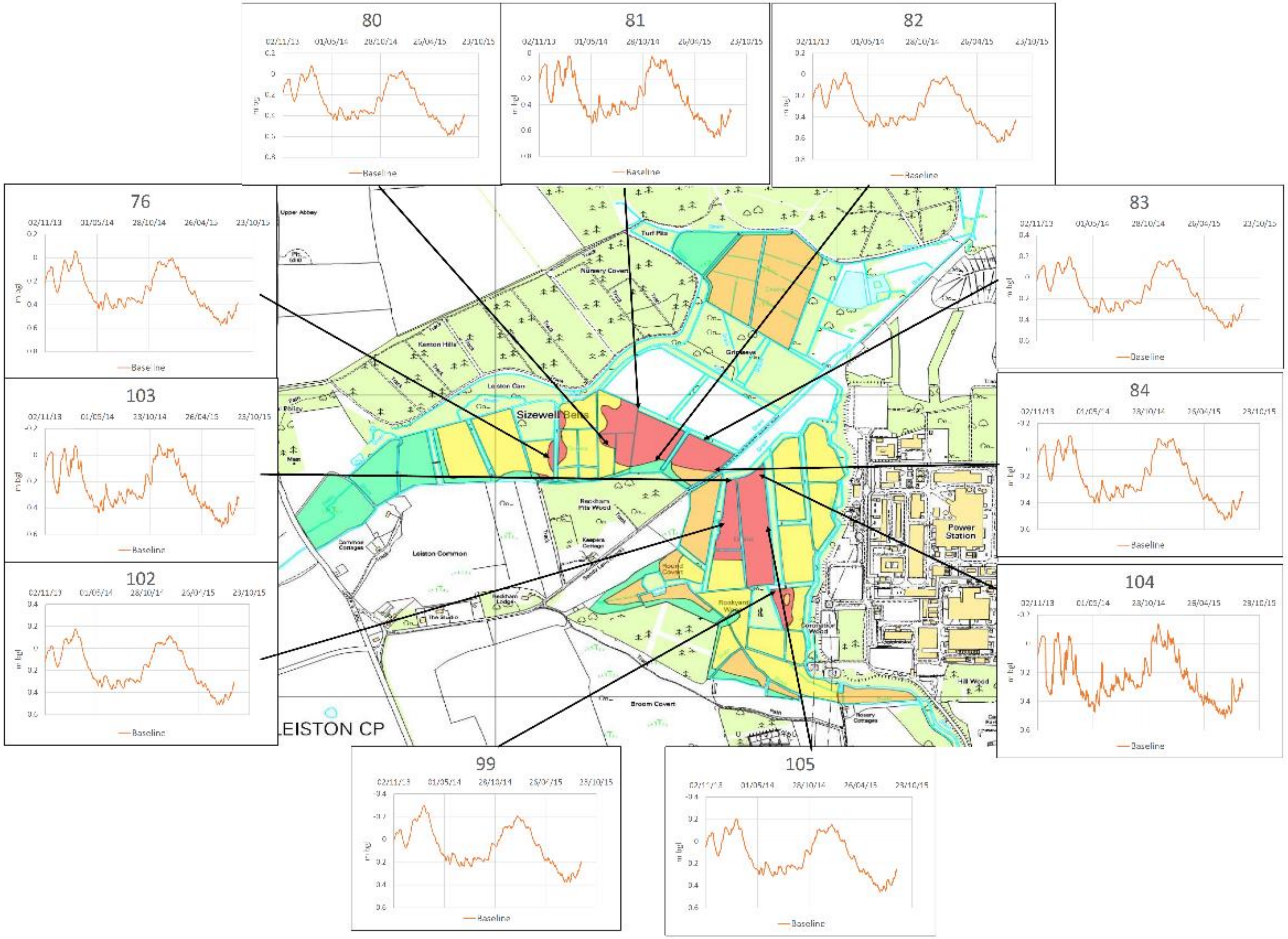
6.1.4 For the purposes of the worked example a preliminary construction scenario has been used. The worked example uses climatic data from the last five years, representing recent conditions. The findings of the worked example, while informative, are not based on the final scenario inputs, so do not constitute the final assessment of potential impact.

6.2 Methodology

6.2.1 For the purposes of this worked example, an enveloped baseline has been generated for typical climatic conditions. Enveloped baselines have been generated for all four grades of Fen Meadow, with Grade 1 being used here for illustrative purposes. The enveloped baselines for the other three grades of Fen Meadow are presented in Appendix B. The charts included in the appendix for Grades 2 to 4 follow the same conventions as those for Grade 1, although they have not been processed to the same level as those presented in the main body of the report.

6.2.2 Time-series plots for observation points selected to produce the baseline envelope for Grade 1 Fen Meadow are shown in Figure 5, below:

Figure 5. Time-series plots for observation points used to establish Grade 1 envelope baseline.



6.2.3 The enveloped baseline for Grade 1 Fen Meadow is shown below, on Figure 6, with observation point 99 giving the upper (i.e. wetter) boundary of the envelope and observation point 81 the lower (i.e. drier) boundary. Time-series plots for the other observation points around the perimeter of Grade 1 Fen Meadow all fall between the time-series plots of these two observation points.

6.2.4 The synthetic baseline produced from the FEFLOW model typically has a range of 20 cm between the upper and lower bound, with a maximum summer drawdown to 0.6 m bgl (below ground level).

6.2.5 Figure 7 (below Figure 6, overleaf) shows a series of contour plots produced to illustrate inundation under baseline conditions. Where water is above ground level, the contours have been filled to help visually represent the extent of inundation. Darker shading indicates greater inundation depth. For the purposes of the worked example, monthly plots have been used to ascertain the duration and extent of the inundation: November, when water levels are high and inundation starts to occur; February and March, in the lead up to spring; and April, which is the start of the management and growing season. For the actual assessment, the time step for the contour plots can be altered and be weekly, or even daily, if required.

6.2.6 For the worked example, the contour plots cover the Sizewell Marshes SSSI, focussed on the central and northern areas, as this is the area where the greatest change is anticipated in this scenario. Additional observation points can be added during the assessment to increase the area covered by the contours, should change be shown to extend further (e.g. into the Minsmere South Levels). When reporting the actual assessment, the different grades of Fen Meadow will also be indicated on the plots to aid interpretation.

6.2.7 It can be seen on the baseline contour plots that the inundation doesn't occur in the central part of the Sizewell Marshes, where the Grade 1 Fen Meadow is present. The extent of inundation reduces through the spring period and into the growing and management season in April.

Figure 6. Envelope baseline Grade 1 Fen Meadow.

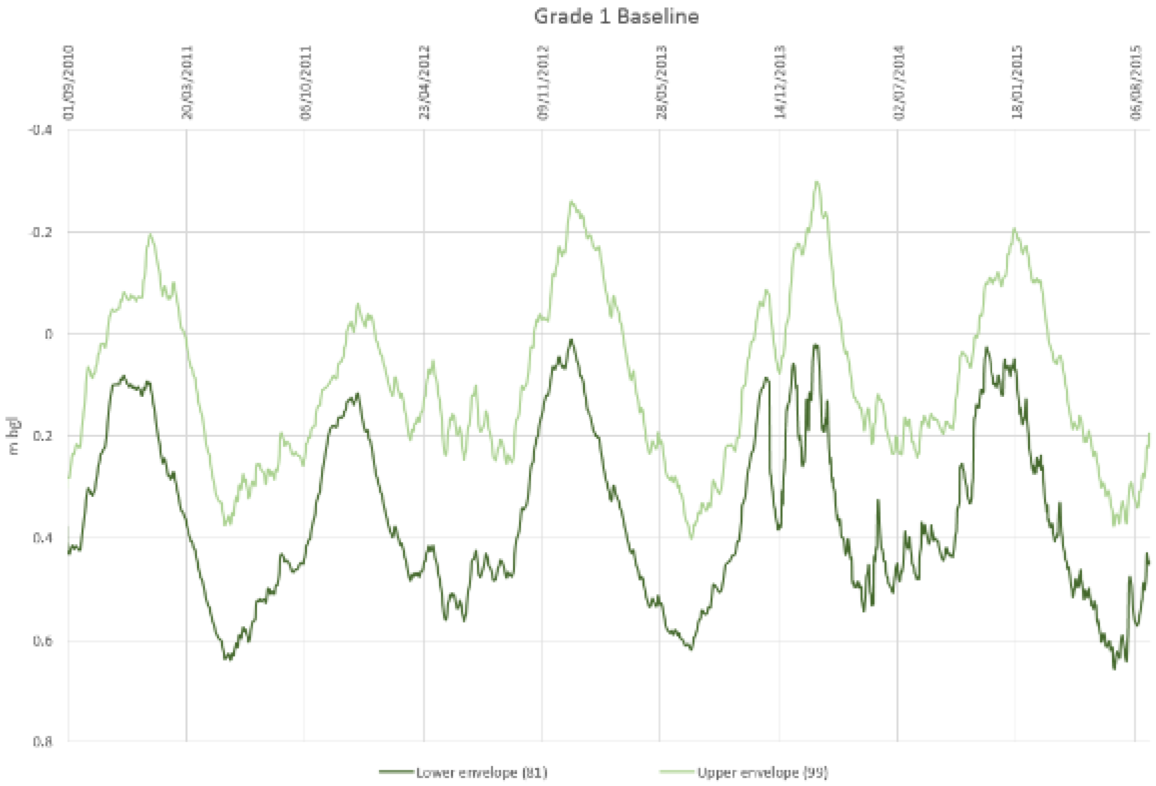
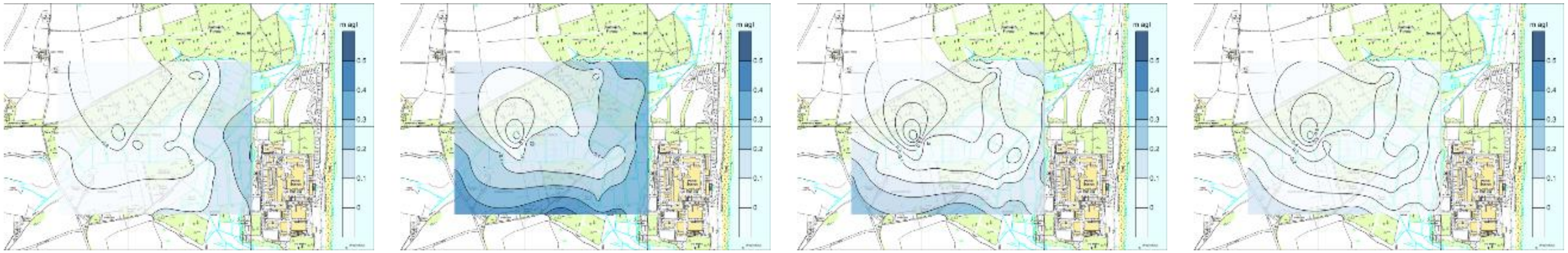


Figure 7. Contour plots showing inundation baseline (m above ground level (agl)).



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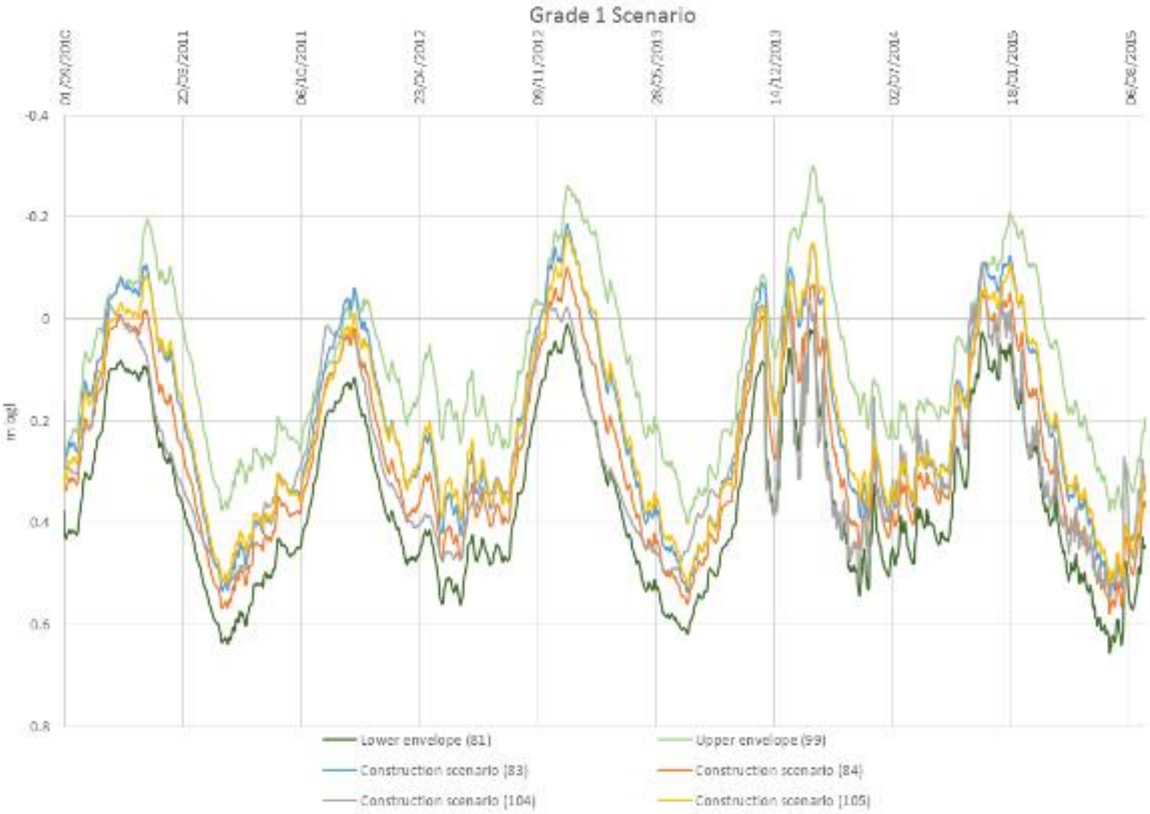
6.2.8 The preliminary scenario that has been chosen for the purposes of the worked example is during the construction phase, and includes the reduced infiltration associated with the Temporary Construction Area, the cut-off wall and active dewatering. This scenario was selected as it represents the period with the greatest potential for changing water levels within the Sizewell Marshes.

6.2.9 In order to ensure that there is no significant detrimental effect to any of the Grades of Fen Meadow arising as a result a change in underlying hydrological regime caused by the Sizewell C Construction, the overall aim has been to try and ensure that any effects on each of the observation points stay within the baseline envelope. The effects of the construction scenario on the Grade 1 Fen Meadow observation points is shown below in Figure 8:

Figure 8. Effects of construction scenario on Grade 1 Fen Meadow.



6.2.10 As can be seen from Figure 8, the construction scenario does not significantly alter the status quo, and only causes a minor effect across the Grade 1 Fen Meadow, perhaps causing a very slight drying effect. As the hydrological changes caused by the construction scenario across each of the observation points lie within the enveloped baseline, it is considered that the range of hydrological conditions currently experienced by Grade 1 Fen Meadow will be maintained, and therefore the full suite of conditions required by the component plant species will continue to be represented.

6.2.11 Time-series hydrographs showing the effects of the construction scenario on the other Grades of Fen Meadow (Grades 2-4) are presented in Appendix D.

6.2.12 Figure 9 (overleaf) shows the effects of the construction scenario on surface water inundation (9A), with the baseline contour plots for comparison (9B).

6.2.13 During the winter months, the baseline predicts that there is some surface inundation which dries gradually during the spring so that by April, at the start of the plant growing season, there is very little inundation. The effect of the construction scenario is to reduce the level of inundation very slightly. This is likely to be due to the effects of realigning the Sizewell Drain reducing any surface water rebound. It is recognised that as the model over-predicts seasonality, the inundation indicated on the contour plots is not representative of real world conditions, as observed data for Grade 1 show no inundation. For the purposes of the assessment, however, a comparative assessment is being made between modelled water levels. This means that if the modelled water level in the scenario is within the baseline model water level envelope there is considered to be no impact.

6.2.14 The modelled scenario has therefore not increased the level of surface water inundation, and no significant effects upon the Fen Meadow are envisaged. In addition, reduced inundation leading into the summer months may facilitate access for site management.

Figure 9A Contour plots during construction scenario (m agl) – areas experiencing inundation are shown in blue

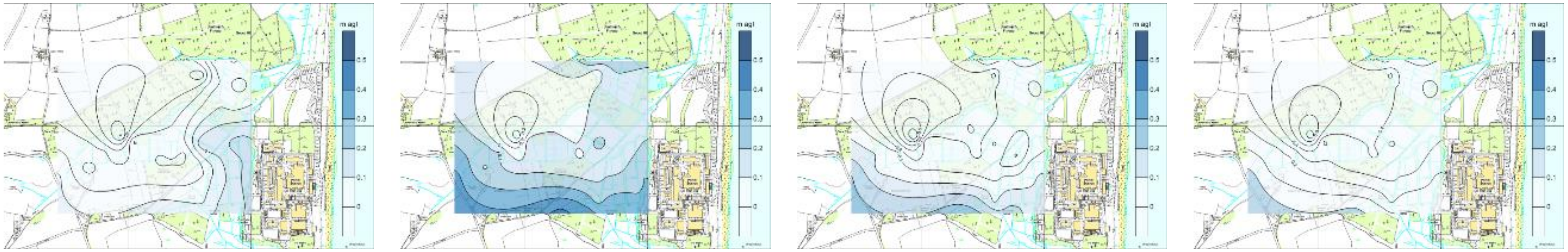


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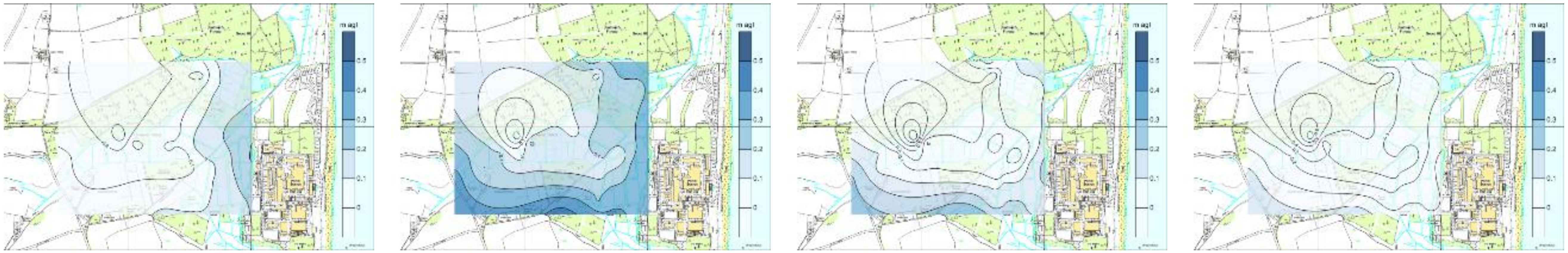
Figure 9B Baseline Contour plots (m agl) – areas experiencing inundation are shown in blue



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6.2.15 For the worked example of Grade 1 Fen Meadow, it is not necessary to consider further mitigation measures, as the change in levels in the scenario is within the baseline envelope. Should the assessment find a case where the predicted change is outside the baseline envelope, the model can be used to assess the degree of this change, and to explore potential mitigation measures. Potential further mitigation measures include the installation of a new control structure at the downstream end of the realigned Sizewell Drain to help maintain surface water levels within the drains, and thereby maintain groundwater levels in the surrounding peat.

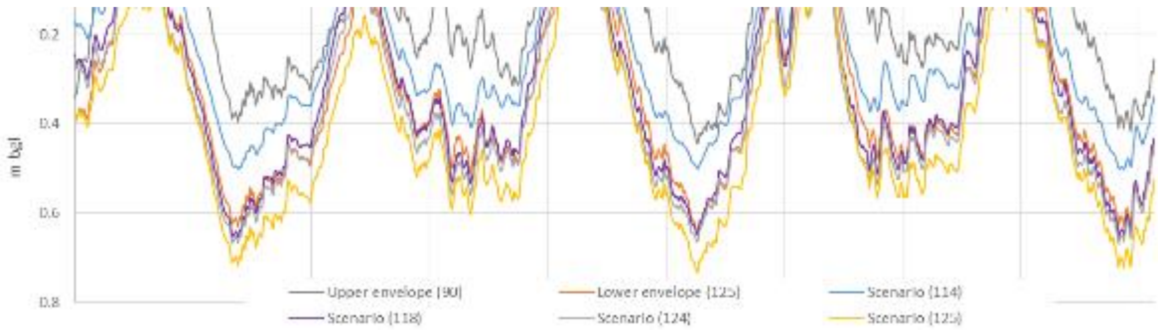
6.2.16 The use of Water Management Zones (WMZs) will act to mitigate the impact of the construction on the groundwater environment. The design of the WMZs is yet to be finalised but it is anticipated that, if necessary, the design of the WMZs could be adjusted to mitigate impacts on the areas of Fen Meadow closest to the Temporary Works Areas.

6.2.17 The worked example has focused only on the Grade 1 Fen Meadow. However, an assessment of the effects of the scenario under typical climatic conditions on the remaining grades of Fen Meadow has also been undertaken. The results are presented in Appendix D.

6.2.18 The hydrographs presented in Appendix D show that no predicted effects are envisaged to arise that will affect the Grade 2 Fen Meadow. Changes to all observation points lie within the enveloped baseline, i.e. baseline conditions are being maintained.

6.2.19 However, changes to the observation points for Grades 3 and 4 show that the construction scenario causes a slight drawdown of water levels below the lower threshold, i.e. the predicted change is outside of the enveloped baseline. A magnified cut-out of the modelled construction scenario on the Grade 3 Fen Meadow is presented below in Figure 10. The full plot is included in Appendix D.

Figure 10. Magnified plot of modelled groundwater levels in Grade 3 Fen Meadow for construction scenario (m bgl).

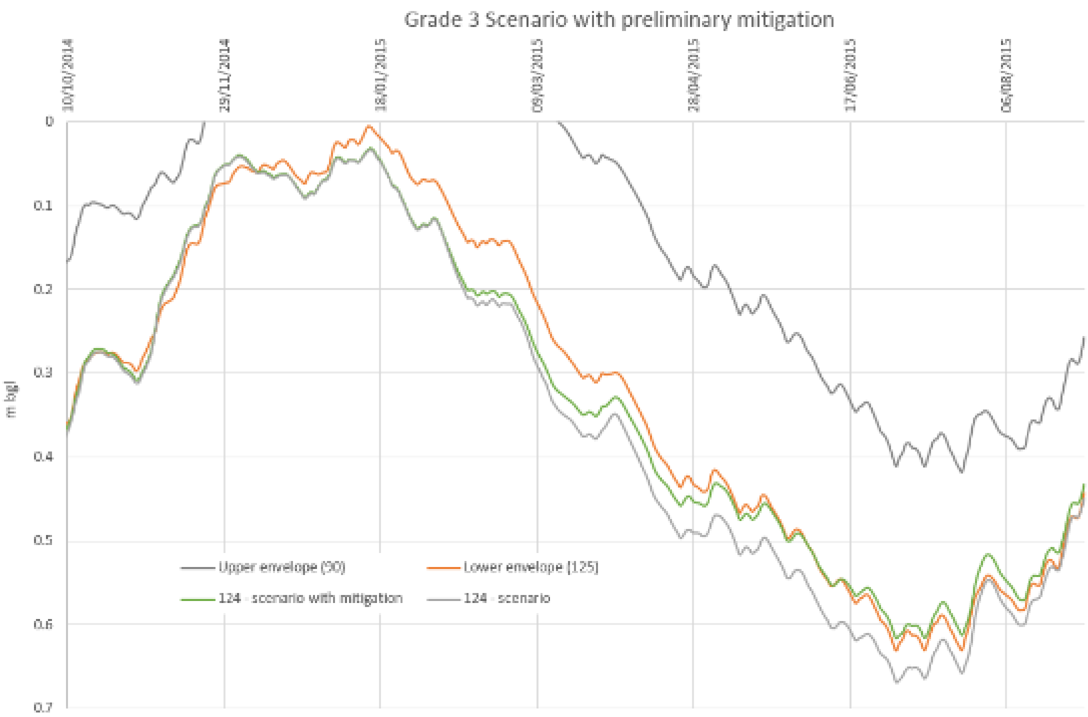


6.2.20 The drop below the enveloped baseline is minimal, and measures can be employed to reduce and mitigate for this effect, such as the installation of a control structure in the Sizewell Drain in this area.

6.2.21 A preliminary model run has been carried out which includes a control structure (a thin-plate weir) installed in the realigned Sizewell Drain, close to the confluence with the Leiston Drain (NGR: 647005 264401). The weir prevents water levels dropping below the elevation of the weir plate during the summer months. The preliminary model run demonstrated that the addition of a control structure does reduce the drop in water levels within the Grade 3 and Grade 4 areas, particularly close to the drain.

6.2.22 Figure 11 shows a magnified cut-out of the modelled water levels at location 124 from this preliminary run, alongside the water levels for the construction scenario without mitigation measures. The full plot is included in Appendix D. The addition of the new control structure brings the water level during construction back in line with the enveloped baseline.

Figure 11. Magnified plot of modelled groundwater levels in Grade 3 Fen Meadow during the construction scenario with and without mitigation measures (m bgl).



6.2.23 During the assessment the location of the weir and elevation of the weir plate can be adjusted in the model to determine the optimum location and elevation required to mitigate the drop in water levels in the areas of Grade 3 and 4 Fen Meadow.

6.2.24 Figure 12 (overleaf) shows the effects of introducing the additional control structure on inundation during the scenario. The figure shows that the control structure makes a negligible difference to the area of Fen Meadow that experiences inundation compared to a scenario without mitigation measures.

Figure 12A Contour plots during construction scenario with additional control structure in Sizewell Drain (m agl) – areas experiencing inundation are shown in blue

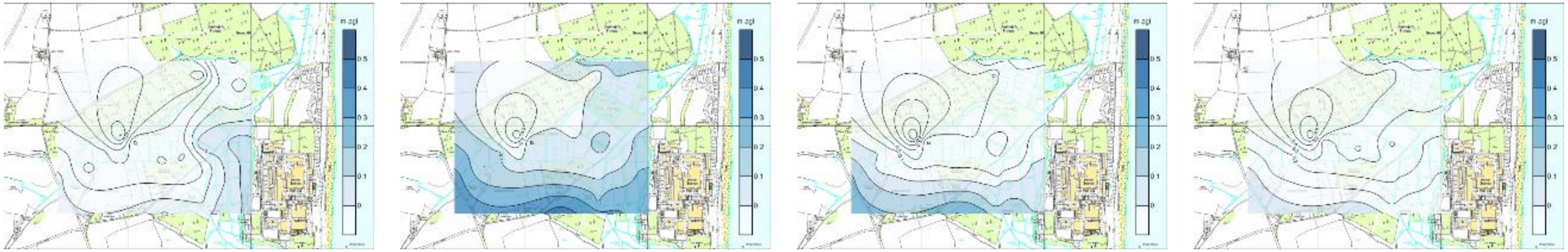


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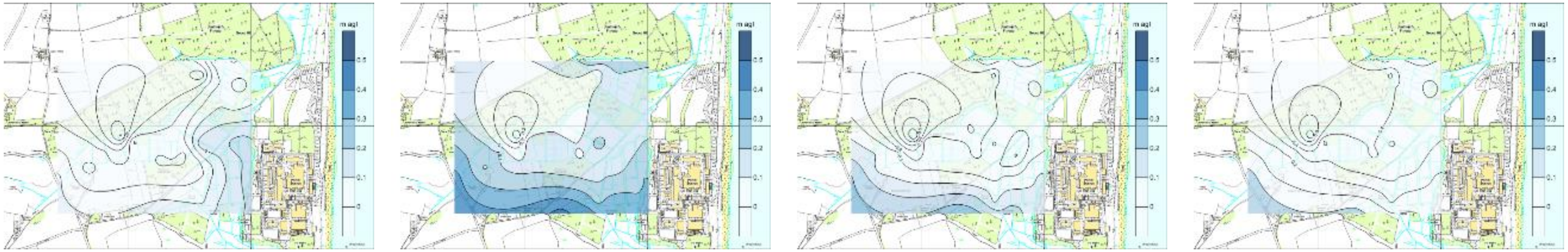
Figure 12B Contour plots during construction scenario (m agl) – areas experiencing inundation are shown in blue



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APPENDIX A: SUMMARY OF SPECIES ATTRIBUTES FROM VARIOUS LITERATURE SOURCES AND EXPERT KNOWLEDGE

The table given overleaf provides a summary of the species attributes referred to in the report. The codes used in the table are explained below, which provides a summary of each attribute.

A. Fen Meadow vegetation grade

Following Wheeler (1988), each type of Fen Meadow identified by the Entec NVC survey is allocated to one of four grades by averaging the number of Principal Rich-Fen species (PFS) and other mire species (MIR) recorded in each sample plot.

B. Floristic evidence for groundwater dependence

Each species has been allocated to a category of phreatophyte by Londo (1988) and is used to calculate the proportion of the floral composition of each grade of Fen Meadow designated to each category. Codes are defined in Table 1.

N.B. Bryophytes were not categorized by Londo (1988).

C. Species assemblages

Using expert knowledge of the general niche occupied by the constituent species recorded by the Entec NVC survey, each species has been assigned to a species assemblage:

FEN	General Fen Meadow	FLT	Floating Fen
GEN	Generalist	GND	Ground-dwelling*
HAL	Halophyte	HYD	Hydrophyte
LOW	Low-nutrient Fen*	MGL	Marginal species
SCR	Scrambler	SWP	Swamp species
WGL	Wet grassland		

* Recognised as the most sensitive species assemblages to changes in groundwater regime

D. Species with SEV plots

Using Gowing *et al.* (2002), species are listed where a Sum Exceedance Values plot has been published. Each plot is indicative of the 'favoured' water regime of each species, in terms of waterlogging and soil drying.

M22 Vegetation Community – Hydrological sensitivities and tolerances

	A. Grade		B. Category of phreatophyte										C. Species assemblages	D. SEV plots
	PFS	Mire	H	W	F	V	K	P	D	A	Z	B		
Agrostis canina		o				o							LOW	
Agrostis capillaris										o			GEN	o
Agrostis stolonifera								o					GEN	o
Alnus glutinosa sapling	o						o						FEN	
Alopecurus geniculatus						o							WGL	o
Alopecurus pratensis						o							WGL	o
Amblystegium riparium												x	WGL	
Anagallis tenella	o			o									GND	
Angelica sylvestris	o					o							FEN	
Anthoxanthum odoratum		o								o			GEN	o
Arrhenatherum elatius										o			GEN	o
Bellis perennis									o				GEN	o
Betula pubescens seedling		o						o					FEN	
Brachythecium rutabulum												x	GEN	o
Briza media									o				LOW	o
Bromus hordeaceus agg.										o			GEN	o
Bryum pseudotriquetrum		o										x	LOW	
Calliergonella cuspidatum	o											x	FEN	o
Caltha palustris	o			o									FEN	o
Calystegia sepium								o					FEN	
Cardamine pratensis		o				o							WGL	o
Carex acutiformis	o			o									SWP	o
Carex disticha	o			o									SWP	o
Carex echinata	o			o									GND	
Carex flacca							o						LOW	o
Carex hirta										o			GEN	o
Carex lepidocarpa	o			o									GND	
Carex nigra	o				o								LOW	o
Carex otrubae					o								WGL	
Carex ovalis		o						o					FEN	
Carex panicea	o					o							LOW	o

M22 Vegetation Community – Hydrological sensitivities and tolerances

	A. Grade		B. Category of phreatophyte										C. Species assemblages	D. SEV plots
	PFS	Mire	H	W	F	V	K	P	D	A	Z	B		
Carex pulicaris	o				o								LOW	
Carex riparia	o			o									SWP	o
Centaurea nigra										o			GEN	o
Cerastium fontanum										o			GEN	o
Cirriphyllum piliferum												x	GEN	
Cirsium arvense										o			GEN	
Cirsium dissectum	o			o									GND	
Cirsium palustre		o				o							FEN	o
Climacium dendroides	o											x	WGL	
Cratoneuron filicinum												x	GND	
Cynosurus cristatus										o			GEN	o
Dactylis glomerata										o			GEN	o
Dactylorhiza fuchsii		o					o						LOW	
Dactylorhiza praetermissa	o					o							LOW	
Danthonia decumbens		o							o				LOW	
Deschampsia cespitosa						o							WGL	o
Eleocharis palustris	o			o									SWP	o
Eleocharis uniglumis		o		o									GND	
Epilobium palustre	o			o									FEN	
Epilobium parviflorum	o						o						FEN	
Equisetum arvense									o				GEN	
Equisetum fluviatile	o			o									SWP	
Equisetum palustre		o		o									FEN	o
Eriophorum angustifolium	o			o									SWP	
Eurhynchium praelongum												x	GEN	o
Festuca rubra										o			GEN	o
Festulolium loliaceum								o					WGL	
Fraxinus excelsior seedling							o						FEN	
Galium palustre	o			o									SCR	o
Galium uliginosum	o			o									SCR	
Glyceria fluitans				o									MGL	o
Glyceria notata					o								WGL	
Hippurus vulgaris			o										HYD	
Holcus lanatus		o						o					GEN	o

M22 Vegetation Community – Hydrological sensitivities and tolerances

	A. Grade		B. Category of phreatophyte										C. Species assemblages	D. SEV plots
	PFS	Mire	H	W	F	V	K	P	D	A	Z	B		
Hydrocotyle vulgaris	o				o								GND	
Hypericum tetrapterum	o			o									FEN	
Iris pseudacorus	o			o									SWP	
Isolepis setacea	o		o										HYD	
Juncus articulatus	o					o							FEN	o
Juncus bufonius		o				o							WGL	
Juncus conglomeratus		o				o							WGL	
Juncus effusus		o				o							FEN	o
Juncus gerardii											o		HAL	
Juncus inflexus		o				o							FEN	o
Juncus subnodulosus	o			o									SWP	
Lathyrus pratensis		o								o			SCR	o
Lemna minor			o										HYD	
Lolium perenne										o			GEN	o
Lotus pedunculatus	o					o							FEN	o
Lychnis flos-cuculi	o				o								WGL	o
Lysimachia vulgaris	o					o							FEN	
Lythrum salicaria	o				o								FEN	
Mentha aquatica		o			o								FEN	
Menyanthes trifoliata	o			o									FLT	
Myosotis laxa caespitosa	o			o									MGL	o
Oenanthe lachenalii	o										o		HAL	
Ophioglossum vulgatum		o			o								WGL	o
Pedicularis palustris		o		o									GND	
Persicaria amphibia						o							WGL	o
Phalaris arundinacea	o					o							FEN	o
Phleum bertolonii										o			GEN	
Phleum pratense										o			GEN	o
Phragmites australis	o			o									SWP	
Plantago lanceolata										o			GEN	o
Plantago major								o					GEN	
Poa pratensis										o			GEN	o
Poa trivialis										o			GEN	o
Polytrichum formosum												x	LOW	

M22 Vegetation Community – Hydrological sensitivities and tolerances

	A. Grade		B. Category of phreatophyte										C. Species assemblages	D. SEV plots
	PFS	Mire	H	W	F	V	K	P	D	A	Z	B		
Potentilla anserina								o					WGL	o
Potentilla erecta		o						o					LOW	
Prunella vulgaris									o				GEN	o
Quercus robur seedling										o			GEN	
Ranunculus acris		o							o				GEN	o
Ranunculus flammula	o			o									SWP	o
Ranunculus repens								o					WGL	o
Rhinanthus minor								o					WGL	o
Rhytidiadelphus squarrosus												x	GEN	
Rumex acetosa										o			GEN	o
Rumex conglomeratus								o					WGL	
Rumex crispus										o			GEN	o
Schedonorus arundinaceus						o							WGL	o
Schedonorus pratensis										o			GEN	o
Schoenoplectus tabernaemontani				o									SWP	
Scleropodium purum												x	GEN	
Scorpidium cossonii	o											x	LOW	
Stellaria graminea		o								o			GEN	o
Stellaria palustris	o					o							FEN	
Succisa pratensis		o					o						LOW	o
Taraxacum officinale agg								o					WGL	o
Trifolium pratense										o			GEN	o
Trifolium repens										o			GEN	o
Triglochin palustris	o			o									GND	
Urtica dioica										o			GEN	
Valeriana dioica	o				o								GND	
Veronica beccabunga				o									MGL	
Vicia cracca		o								o			SCR	o
Vicia hirsuta										o			SCR	

APPENDIX B: HYDROLOGICAL REQUIREMENTS OF PLANT SPECIES RECORDED IN M22 STANDS AT SIZEWELL

Plant Species	Newbold and Mountford (1997) Hydrological regime (cm above or below ground level)			Wheeler and Shaw (1992) Hydrological regime (cm above or below ground level)		
	Extreme Dry	Preferred Hydrological Regime	Extreme Wet	Summer water level	Minimum	Maximum (cm a/bgl)
Anagallis tenella	Not given	-1 to +3	Not given	-9.25	-0.2	-36.5
Angelica sylvestris	-100	Not given	+5	-11.33	Not given	Not given
Caltha palustris	-35	Not given	+15	-6.90	+15.2	-50
Cardamine pratensis	-20	-5 to +5	+10	-6.44	+8	-21.10
Carex acutiformis	-40	0	+50	-3.71	+7	-18
Carex disticha	-65	Not given	Not given	-9.92	Not given	Not given
Carex echinata	-20	-10 to +10	+20	-9.72	+10.8	-31.6
Carex flacca	Not given	-5	0	-14.09	+6	-48.4
Carex nigra	-65	-15 to 0	0	-30.5	+15.2	-59
Carex panicea	-65	Not given	+5	-5.6	+7	-22
Carex pulicaris	-100	-30 to -10	0	-14.63	+8	-48.4
Dactylorhiza fuchsii	-30	-20 to -5	0	-11.05	Not given	Not given
Dactylorhiza praetermissa	-30	-20 to - 10	0	10.89	Not given	Not given

M22 Vegetation Community – Hydrological sensitivities and tolerances

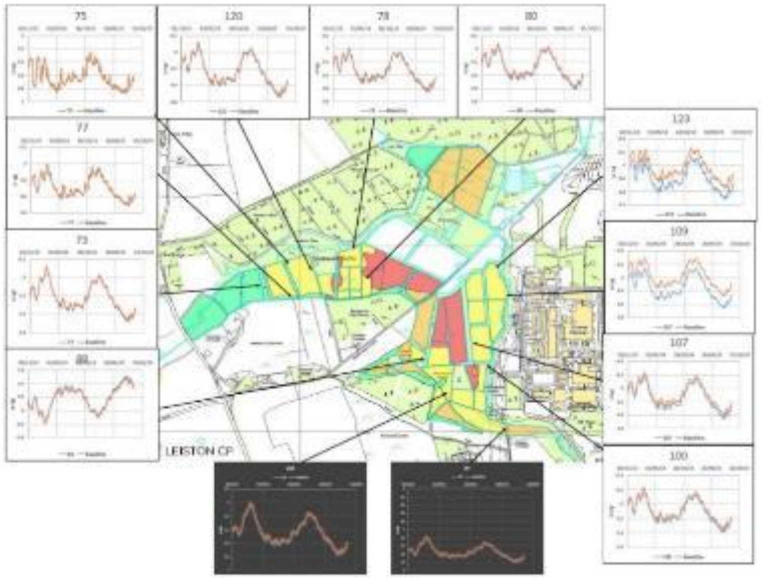
Plant Species	Newbold and Mountford (1997) Hydrological regime (cm above or below ground level)			Wheeler and Shaw (1992) Hydrological regime (cm above or below ground level)		
	Extreme Dry	Preferred Hydrological Regime	Extreme Wet	Summer water level	Minimum	Maximum (cm a/bgl)
Eleocharis palustris	-50	-5 to +5	+10	+4.40	+4.4	+4.4
Epilobium palustre	+40	-20 to 0	+10	-3.95	+15.2	-50
Equisetum arvense	-200	-10	Not given	-6.4	-2.2	+16.4
Equisetum fluviatile	-30 to -10	+60	+100	-4.1	+16	-50
Equisetum palustre	-30	-20 to +20	+30	-3.95	+8	-16.4
Eriophorum angustifolium	-50	-30 to 0	+10	-9.26	+16	-59
Galium palustre	-40	-20 to 0	+20	-2.64	+8	-18
Galium uliginosum	-25	-20 to -5	+20	-11.66		
Hydrocotyle vulgaris	-20	-4 to +2	+4	-11.29	+16	-50
Hypericum tetrapterum	-100	Not given	+4	-10.52	Not given	Not given
Iris pseudacorus	+60	-10 to +10	+60	-1.38	+15.52	-38
Juncus articulatus	-60	-30 to 0	+ 10	-10.28	+14.6	-32.4
Juncus bufonius	Dry to -10	Not given	Not given			
Juncus conglomeratus	-100	-5	0	-48.4	+15.2	-48.4
Juncus effusus	-55	Not given	+30	-39.5	+15.2	-59
Juncus subnodulosus	-40	Not given	+30	-9.73	Not given	Not given
Lotus pedunculatus	-40	-10	Not given	-13.32	Not given	Not given
Lychnis flos-cuculi	-40	-20 to +5	Not given	-14.03	Not given	Not given

M22 Vegetation Community – Hydrological sensitivities and tolerances

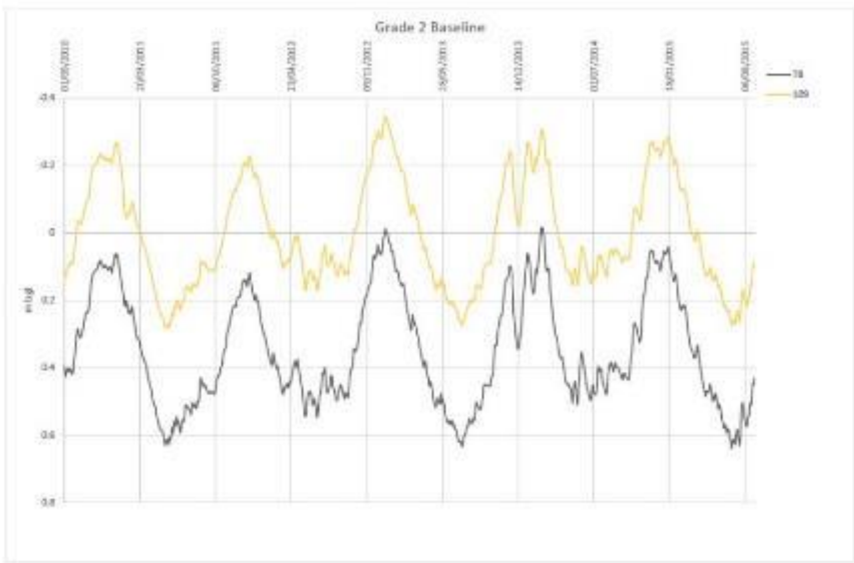
Plant Species	Newbold and Mountford (1997) Hydrological regime (cm above or below ground level)			Wheeler and Shaw (1992) Hydrological regime (cm above or below ground level)		
	Extreme Dry	Preferred Hydrological Regime	Extreme Wet	Summer water level	Minimum	Maximum (cm a/bgl)
Lysimachia vulgaris	-50	-25 to 0	+10	-9.6	Not given	Not given
Lythrum salicaria	-40	-10 to +10	+10	-19.04	Not given	Not given
Mentha aquatica	-60	-10 to +10	+10	-7.88	+15.2	-50
Menyanthes trifoliata	-10	+10 to +75	+100	-6.67	+8	-59
Myosotis laxa caespitosa	-30	-5 to 0	+10	-3.4	+9.2	-50
Oenanthe lachenalii	-50	0	Not given	-6.8	Not given	Not given
Persicaria amphibia	-100	+30 to +100	+125	-9.2	-9.2	-9.2
Phalaris arundinacea	-60	-40 to 0	+30	+1.6	+5.4	-3
Phragmites australis	-100	-20 to 0	+50	-11.7	+24.6	-100
Ranunculus flammula	-30	-5 to +5	+30	-2.1	+8	-8.2
Triglochin palustris		-20	-10	-5.2	+15.2	-20.75
Valeriana dioica	-45	-5	Not given	-12.76	Not given	Not given
Veronica beccabunga	-25	0	+40	-3.4	-1	-5

APPENDIX C ENVELOPED BASELINE FOR FEN MEADOW GRADES 2-4

The observation points chosen for the construction of the enveloped baseline for Fen Meadow Grades 2-4 are presented below, together with the enveloped baseline produced.

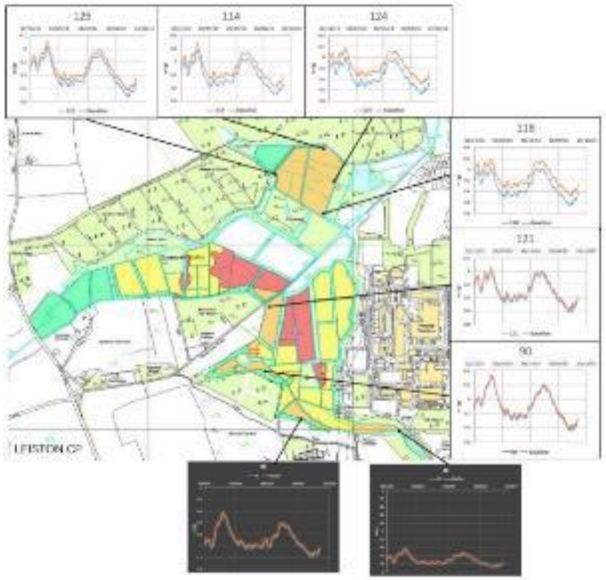


Grade 2 Observation locations

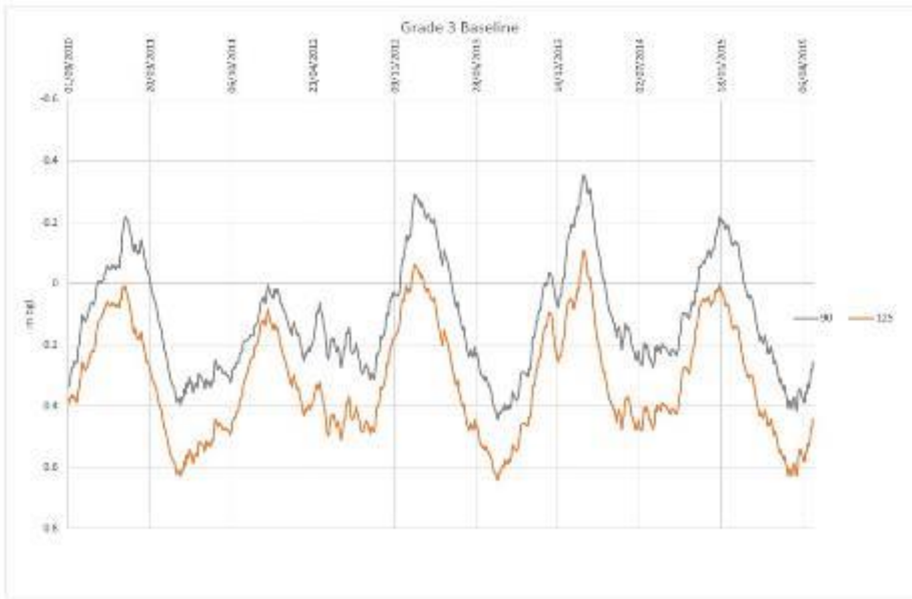


Grade 2 Enveloped baseline

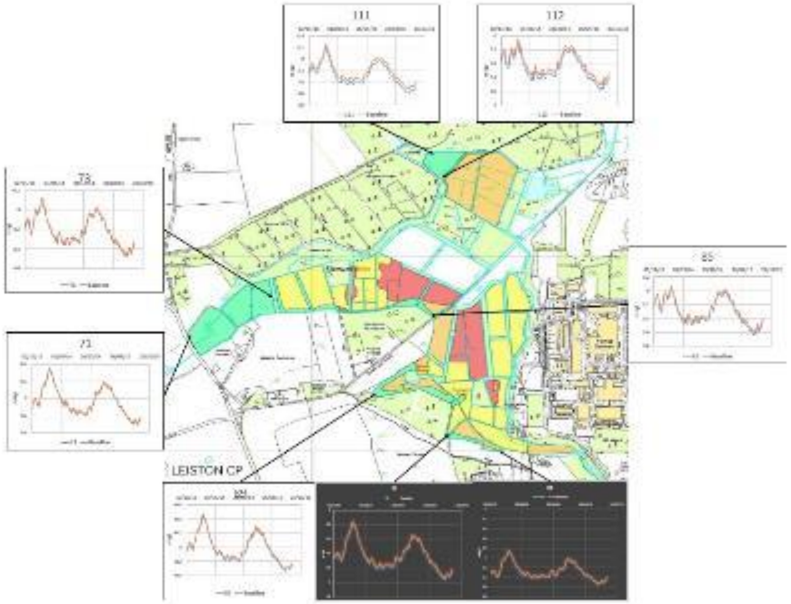
M22 Vegetation Community – Hydrological sensitivities and tolerances



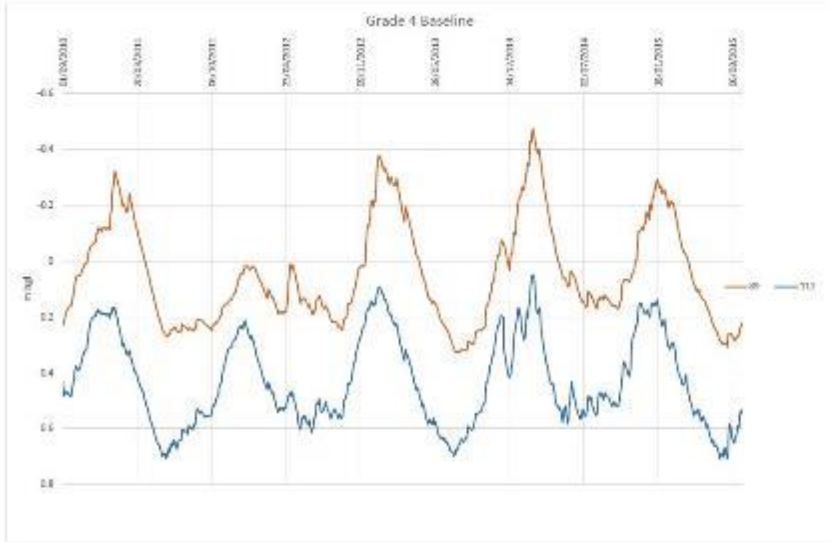
Grade 3 Observation locations



Grade 3 Enveloped baseline



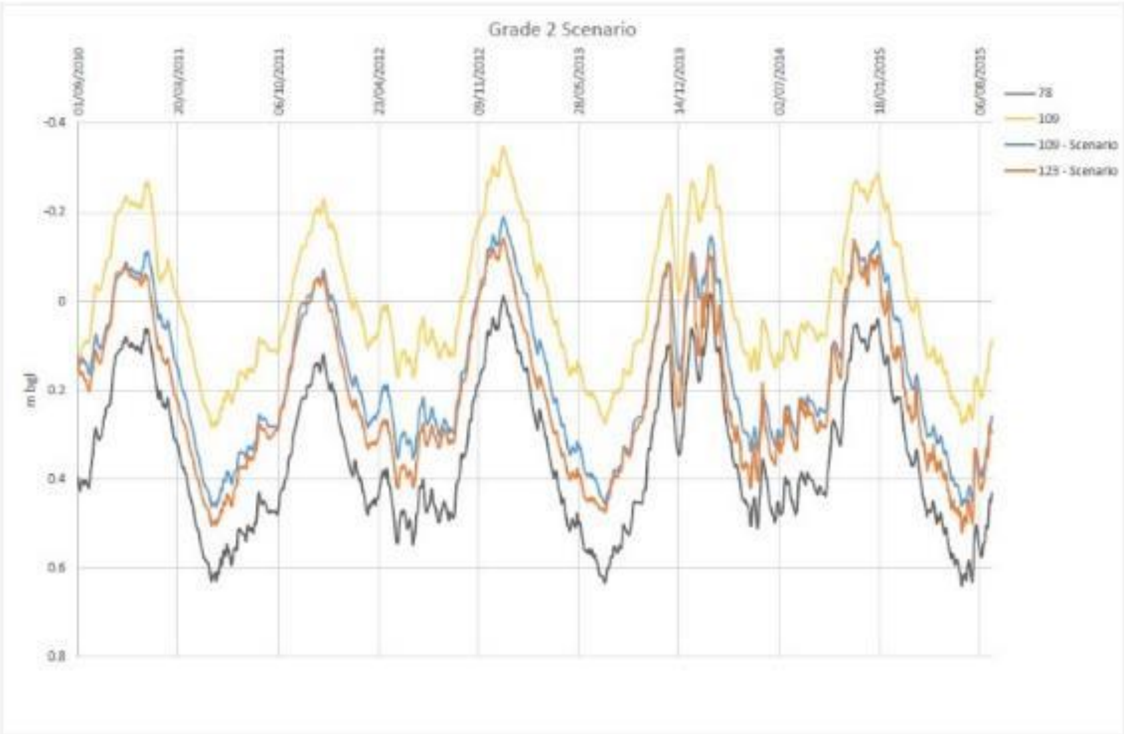
Grade 4 Observation locations

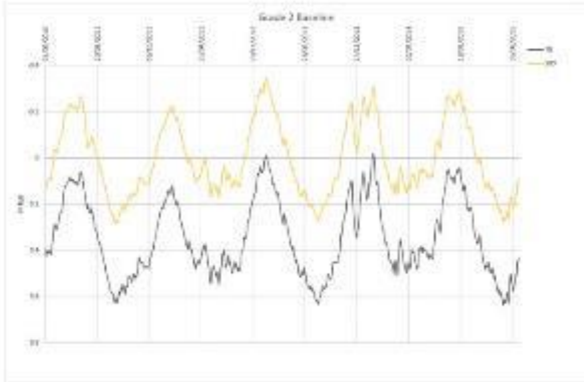


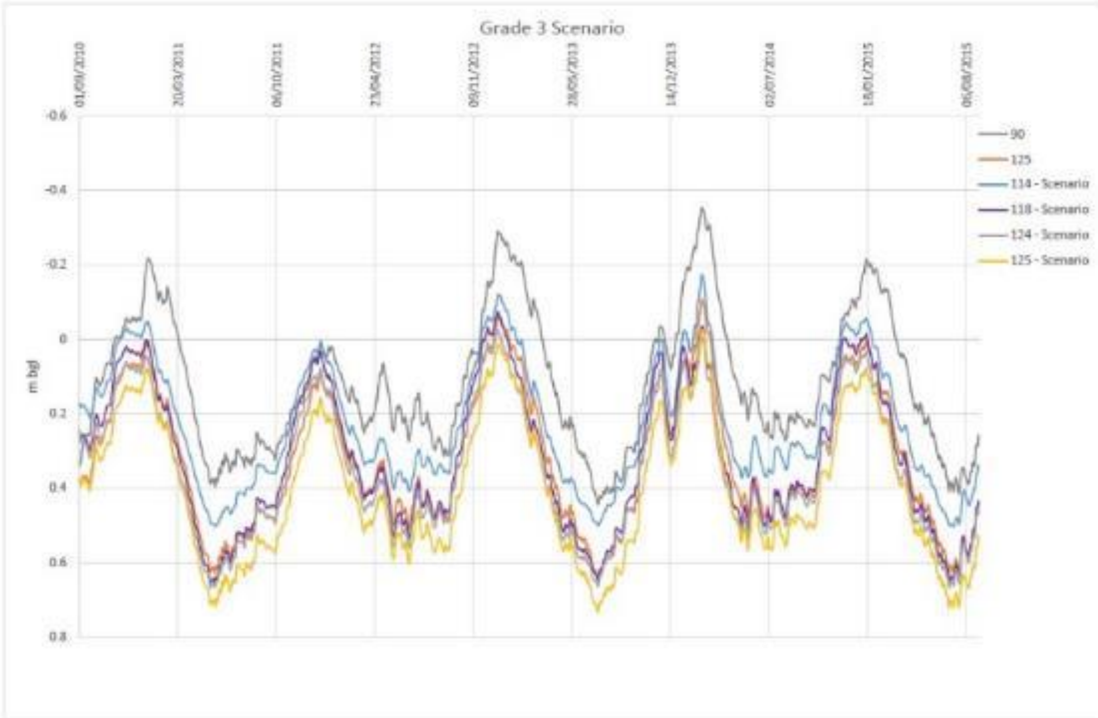
Grade 4 Enveloped baseline

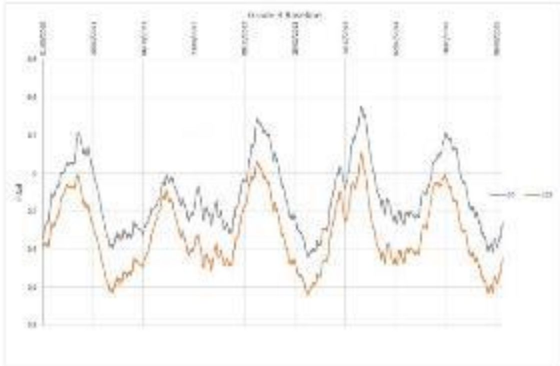
APPENDIX D MODELLED CONSTRUCTION SCENARIOS - FEN MEADOW GRADES 2-4

Modelled construction scenarios for Fen Meadow Grades 2-4 are presented below, together with the enveloped baseline produced.

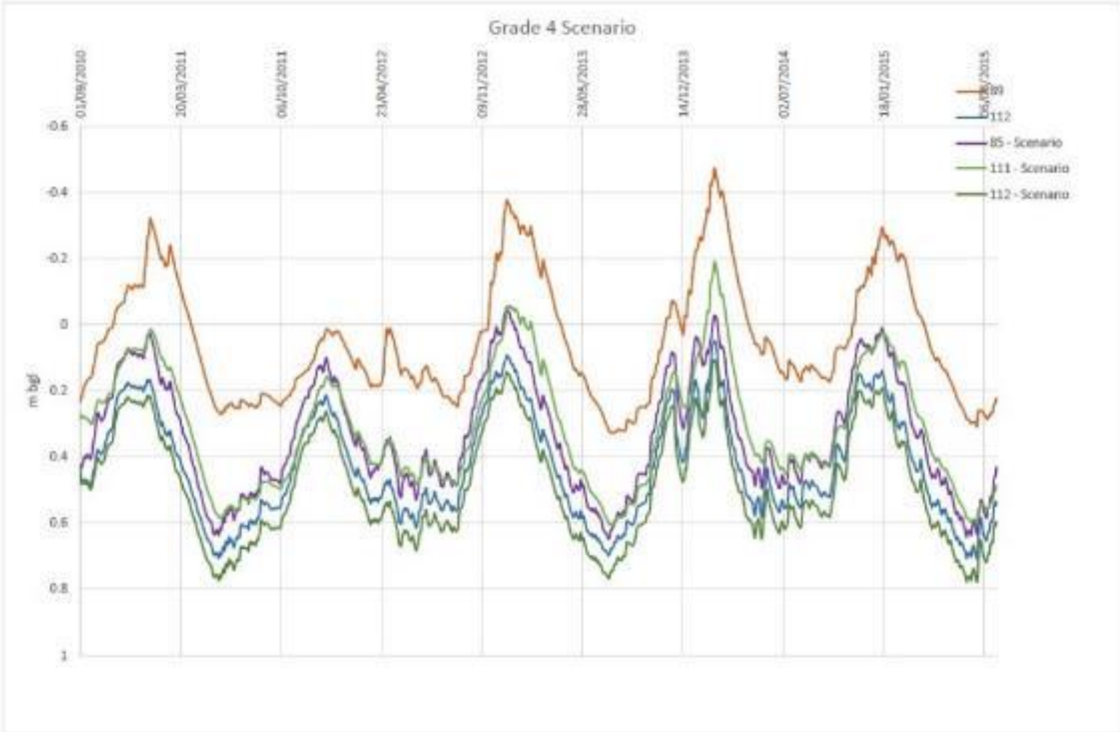


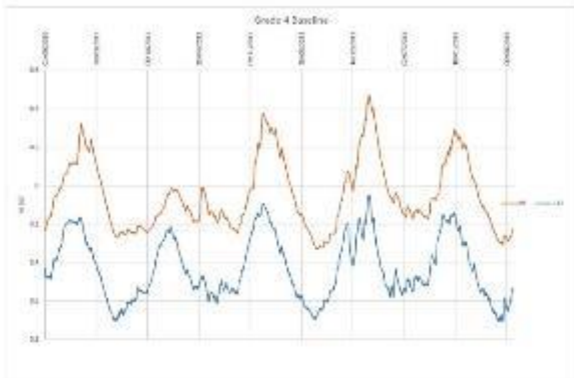


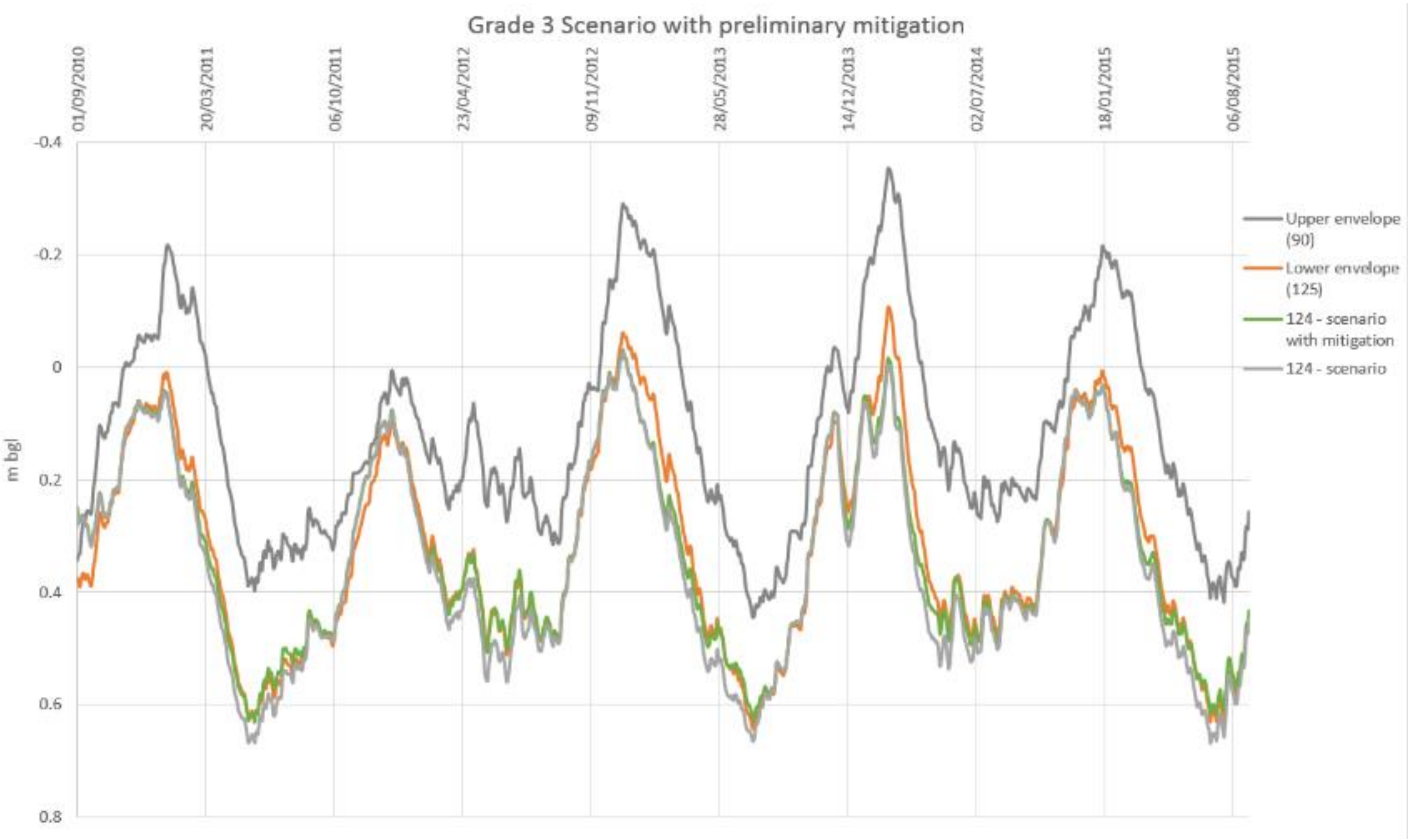

Grade 3 Scenario
01/09/2010
20/03/2011
06/10/2011
23/04/2012
09/11/2012
28/05/2013
14/12/2013
02/07/2014
18/01/2015
06/08/2015
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
m bgl
90
125
114 - Scenario
118 - Scenario
124 - Scenario
125 - Scenario



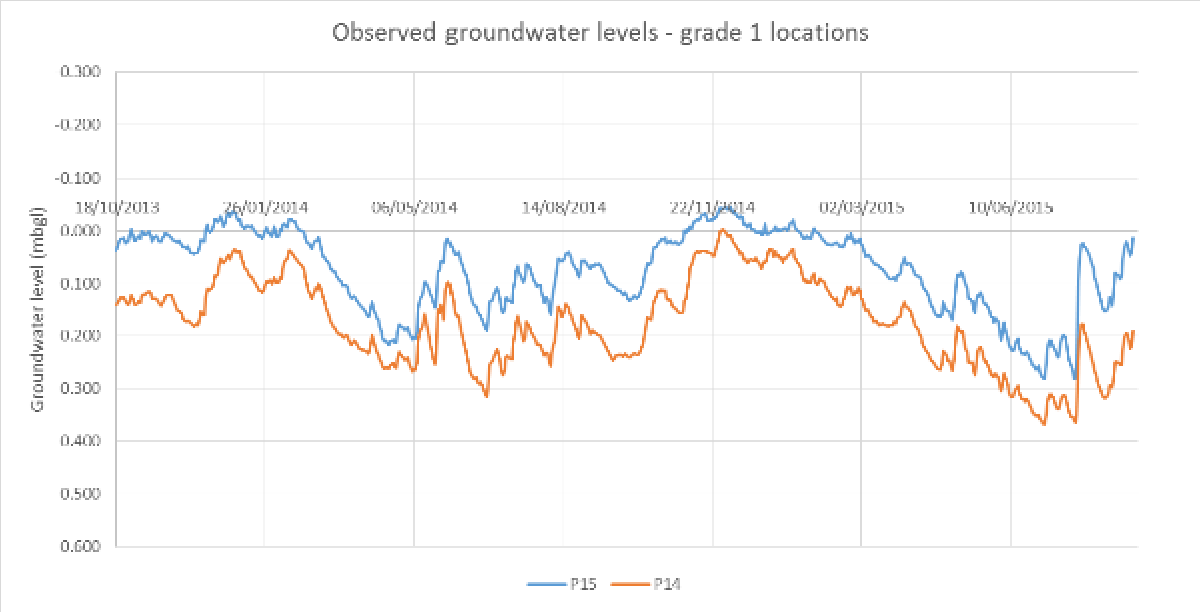
M22 Vegetation Community – Hydrological sensitivities and tolerances

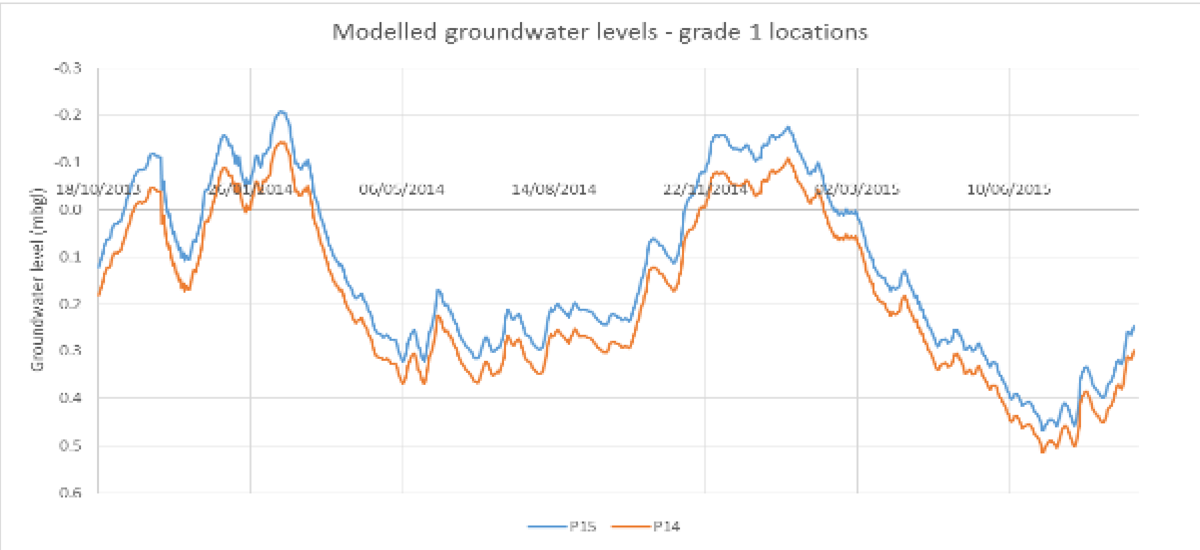


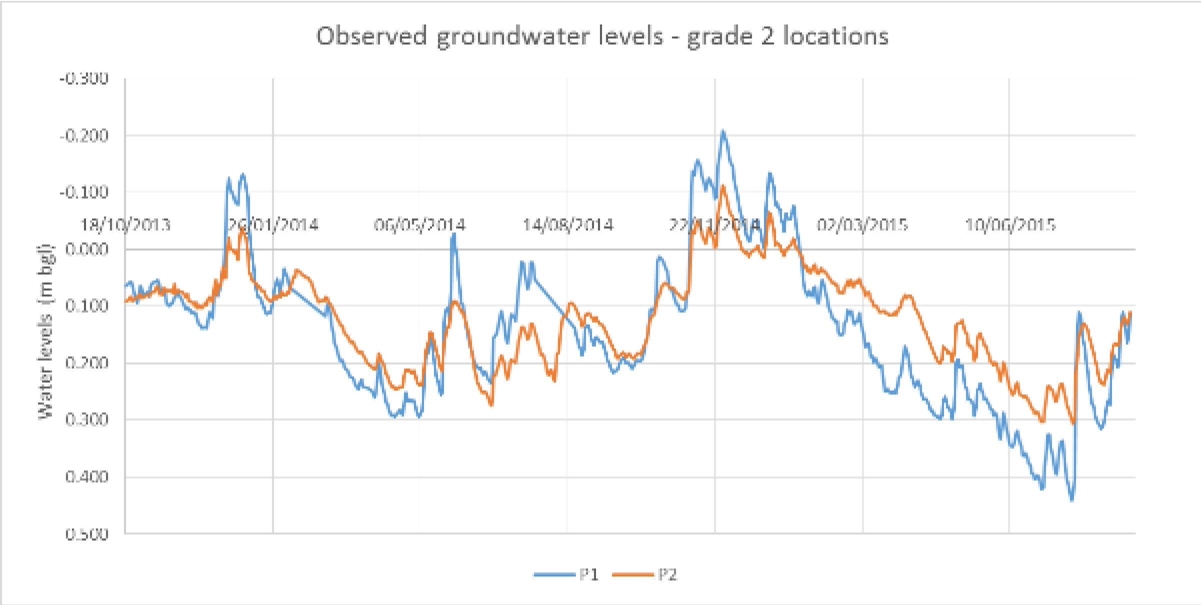


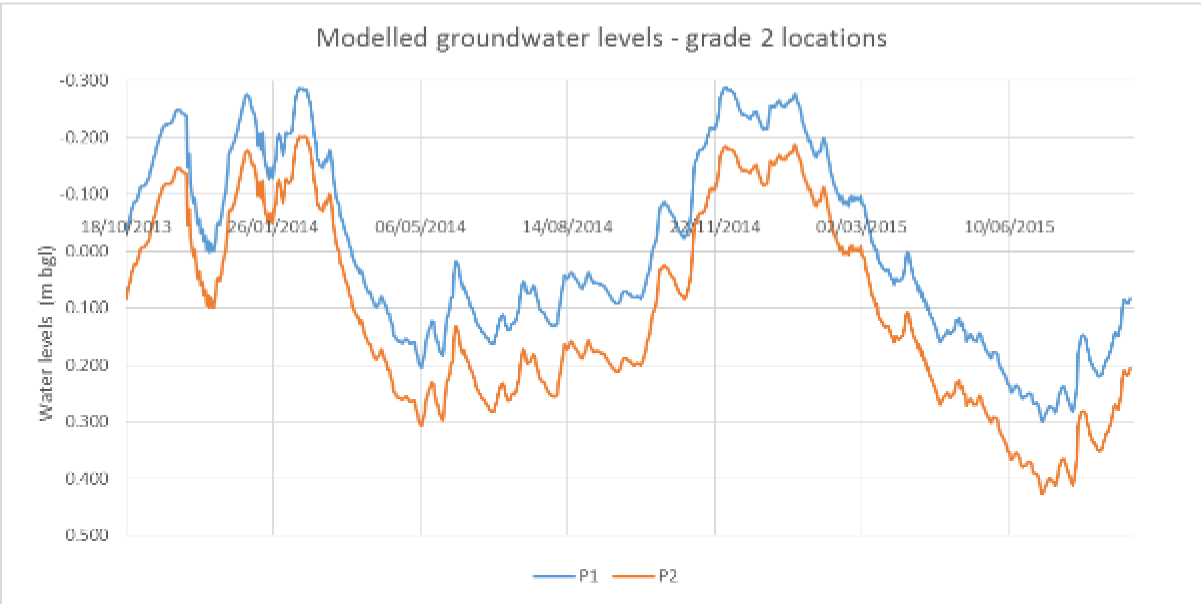

Grade 3 Scenario with preliminary mitigation
01/09/2010
20/03/2011
06/10/2011
23/04/2012
09/11/2012
28/05/2013
14/12/2013
02/07/2014
18/01/2015
06/08/2015
-0.4
-0.2
0
0.2
0.4
0.6
0.8
m bgl
Upper envelope (90)
Lower envelope (125)
124 - scenario with mitigation
124 - scenario

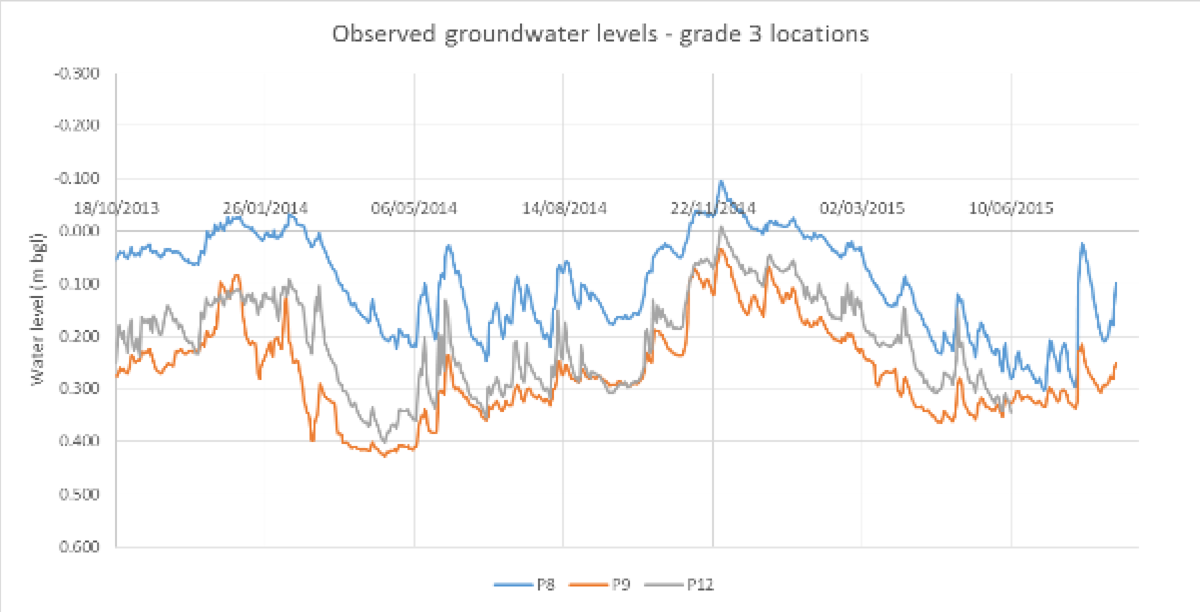
APPENDIX E OBSERVED AND MODELLED HYDROGRAPHS FOR FEN MEADOW GRADES 1-4

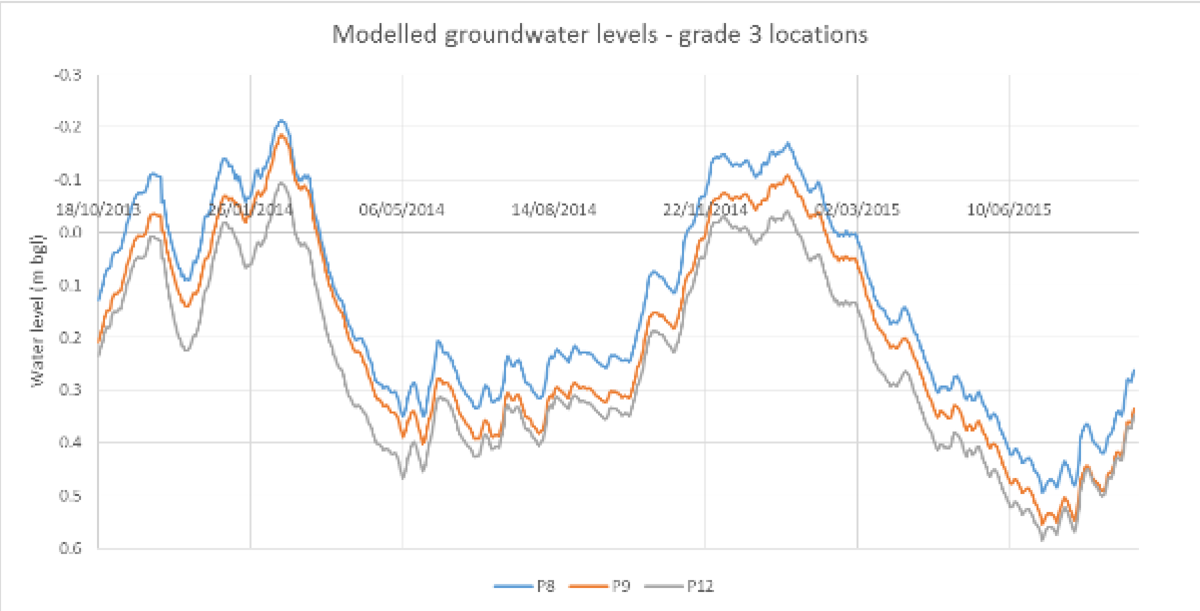





Observed groundwater levels - grade 2 locations
Water levels (m bgl)
-0.300
-0.200
-0.100
0.000
0.100
0.200
0.300
0.400
0.500
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
P1
P2


Modelled groundwater levels - grade 2 locations
Water levels (m bgl)
-0.300
-0.200
-0.100
0.000
0.100
0.200
0.300
0.400
0.500
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
P1
P2


Observed groundwater levels - grade 3 locations
Water level (m bgl)
-0.300
-0.200
-0.100
0.000
0.100
0.200
0.300
0.400
0.500
0.600
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
P8
P9
P12


Modelled groundwater levels - grade 3 locations
Water level (m bgl)
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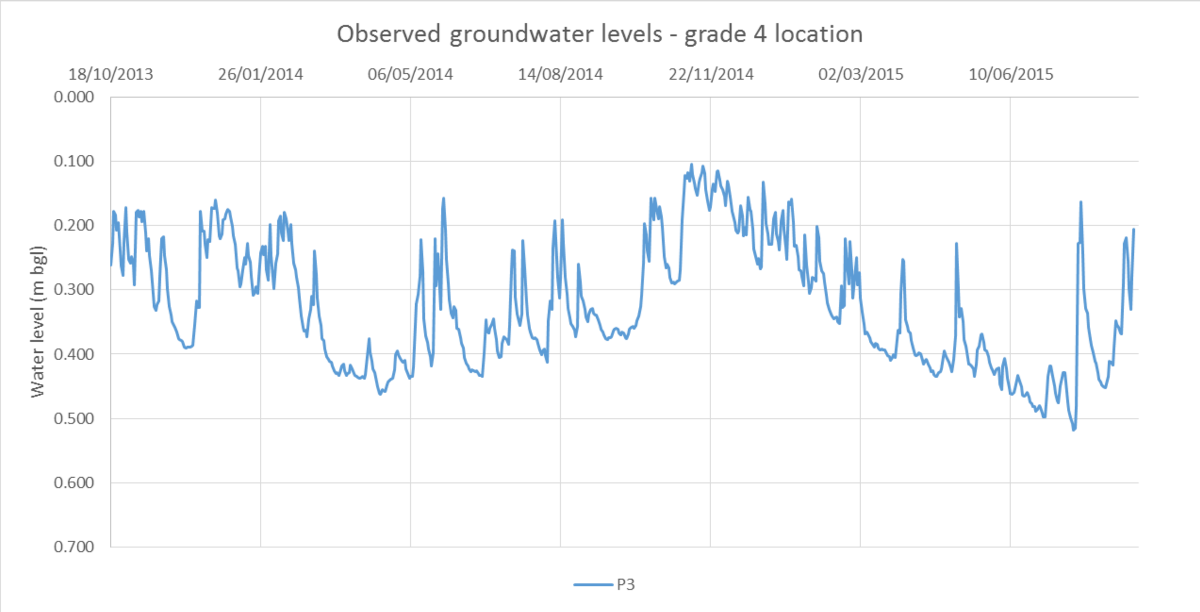
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
P8
P9
P12



Observed groundwater levels - grade 4 location
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
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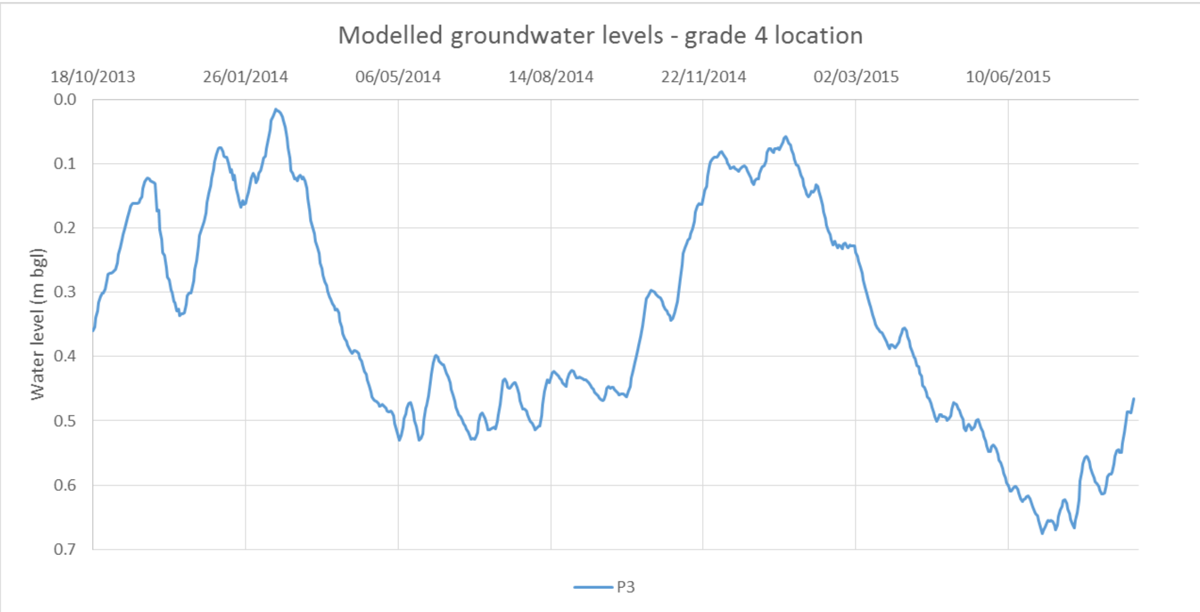
0.100
0.200
0.300
0.400
0.500
0.600
0.700
Water level (m bgl)
P3



Modelled groundwater levels - grade 4 location
18/10/2013
26/01/2014
06/05/2014
14/08/2014
22/11/2014
02/03/2015
10/06/2015
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Water level (m bgl)
P3

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27/3/17	3	Final	Revised Assessment Approach for M22 Vegetation

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CONTENTS

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1. INTRODUCTION

1.1 Purpose of this report

1.1.1 The construction and operation of the proposed Sizewell C Power Station (hereafter referred to as Sizewell C) has the potential to alter the hydrological regime underlying sensitive M22 fen meadow vegetation, which could potentially alter the floristic composition of the vegetation.

1.1.2 A comprehensive literature review, and an initial proposed impact assessment approach and methodology, together with a worked example, was presented in a previous document EDF Energy/NNB GenCo (hereafter referred to as EDF Energy) (2016) *The M22 Vegetation Community: Hydrological Tolerances and Sensitivities: A proposed approach for assessing Hydrological Impacts. Version 5 September 2016.*

1.1.3 Stakeholders were content with the literature review, which is not repeated here. However, concerns were expressed about some aspects of the proposed assessment method. In particular, it was felt that the size of the proposed threshold envelope for acceptable impacts for each grade of fen meadow was too broad and might mask changes that could be significant (see **Section 3** for further details on this and other comments).

1.1.4 The purpose of this report is to present a revised methodology which EDF Energy intends to use in the Environmental Impact Assessment (EIA) for Sizewell C, taking account of stakeholder feedback on the original proposal. A new worked example has been provided for clarity.

1.1.5 M22 fen meadow is one of the designated features of Sizewell Marshes Site of Special Scientific Interest (SSSI) and is considered to be the plant community most likely to be sensitive to changes in hydrological regime. It is intended that the assessment approach developed for M22 is adapted for other wetland habitat types, if required, for example the floodplain grassland within the Minsmere to Walberswick Heaths and Marshes SSSI.

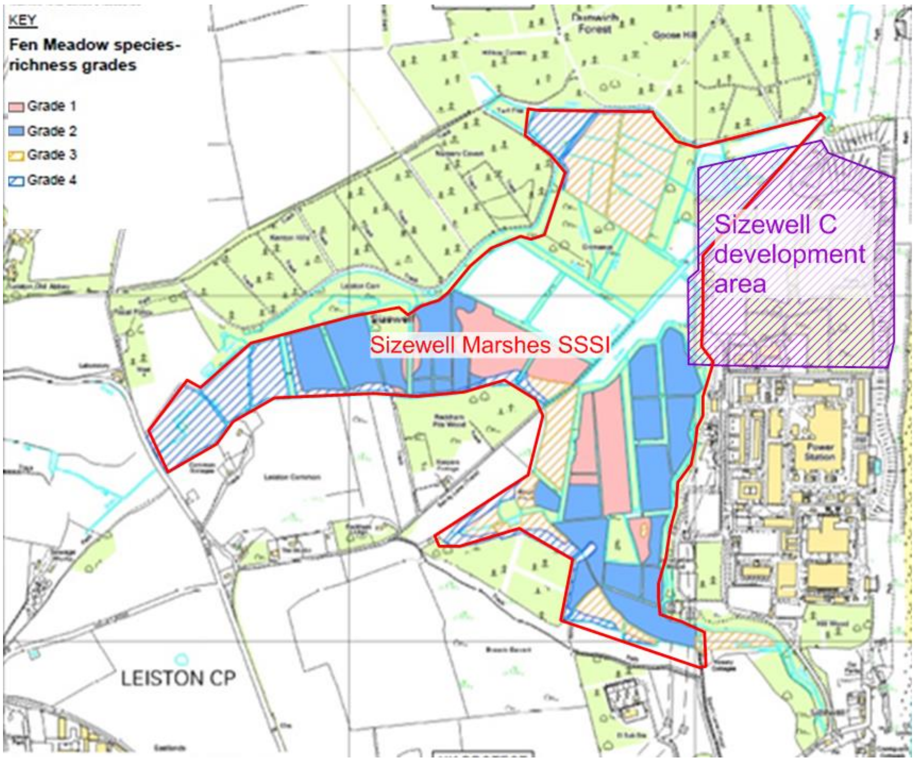
2. OVERVIEW OF PREVIOUS ASSESSMENT APPROACH

2.1.1 The previous assessment (EDF Energy, 2016) presented sufficient information to enable the delineation of the M22 fen meadow vegetation into four distinctive grades. The rationale and distribution of the four grades are shown on **Table 1** and **Figure 1** below:

Table 1. Grades of M22 fen meadow within Sizewell Marshes SSSI

Grade	Rationale
Grade 1	Good quality fen meadow supporting relatively high numbers of Principal Rich-Fen species and other mire species, including a suite of ‘low fertility’ indicators.
Grade 2	Good quality fen meadow supporting a suite of Principal Rich-Fen species and other mire species, including a suite of ‘low fertility’ indicators.
Grade 3	Fair quality fen meadow, supporting some Principal Rich-Fen species and other mire species, with few ‘low fertility’ indicators.
Grade 4	Drier fen meadow grading to rush pasture and dry grassland, supporting few Principal Rich-Fen species and other mire species, with very few ‘low fertility’ indicators.

Figure 1. Distribution of fen meadow grades within Sizewell Marshes SSSI



From the literature review, the main issues that could potentially affect the hydrological regime of M22 fen meadow at Sizewell C are as follows:

- Changes in summer drawdown levels (a decrease in absolute water levels could be negative, whilst an increase in absolute water levels may be positive, at least in the short-term).
- Changes in summer inundation (prolonged inundation could be damaging, whilst a reduction in duration, or cessation of inundation, may constitute a positive effect).

2.1.2 The literature review provided very little information about the hydrological regime of the M22 fen meadow community during the winter months, in particular what would constitute an optimal regime, or what changes to the winter hydrological regime would be regarded as damaging. It was considered that an element of professional judgement would therefore need to be used to determine this.

2.1.3 The available monitoring data covers a period of approximately two years, which will not encompass the full range of natural climatic conditions that should be considered by the assessment. Additionally, real-world conditions cannot be directly compared with the FEFLOW model due to the recognised overestimation of seasonality in the model (see Atkins, 2016a). Recognising these factors, it was proposed to establish a synthetic baseline for use in assessing potential change. The baseline model runs would be used to produce contours, and time-series plots from several locations in the FEFLOW model to represent the range of hydrological conditions likely to be encountered by each grade of fen meadow under existing pre-development conditions i.e. reflecting wet years, dry years etc.

2.1.4 To ensure the full range of existing baseline conditions were represented in the assessment, it was proposed to set a series of observation points around the perimeter of the full extent of each grade within the SSSI. The up-hydraulic gradient and down-hydraulic gradient ends of the recorded range in distribution of each grade within would then be used to produce a baseline time-series envelope for that grade within the SSSI. This envelope would represent an upper and lower threshold against which any modelled hydrological change arising from the development could be measured (taking into account any mitigation that is required to limit potential impacts that would otherwise fall outside of the baseline range). This was judged to be an appropriate method since it allowed impact assessment and consideration of mitigation need and efficacy to be carried out taking account of the actual range of hydrological conditions currently experienced by each grade of fen meadow within the SSSI, rather than placing reliance on published tolerance ranges, which may not reflect actual site conditions.

2.1.5 Topographic data are held for the observation boreholes in the Sizewell Marshes SSSI; however, there is not a comprehensive topographic dataset available to allow the conversion from water-level elevations to depths below ground level, which is used in the assessment. Although LIDAR data are held for the area of the Sizewell Marshes SSSI, the vertical resolution is too poor to allow it to be used for this purpose, as a result of the nature of the vegetation cover. Therefore, it was proposed in the first instance, the assessment would be undertaken using interpolated topography between observation points. Where required for the assessment, additional topographic survey data could be collected in a targeted fashion to allow a refined assessment, taking into account actual topography.

2.1.6 It was proposed that models would be run for each of the construction and operation scenarios, and the outputs used to see whether change resulting from the development falls outside the baseline envelope for each grade.

2.1.7 To assess changes in spring and summer drawdown, time-series hydrographs for the construction and operation scenarios would be compared with the baseline envelope for the appropriate fen meadow grade. If the change resulting from the development lies within the baseline envelope for each grade, then it was considered that this would suggest that significant adverse effects from the development on the vegetation, for example significant changes in the amount or quality of the sward, are unlikely, as water levels would be within the existing baseline range encountered by that particular fen meadow grade, which are thus tolerable.

2.1.8 To assess changes in inundation, contour plots would be produced over the late spring and early summer period for comparison with baseline conditions. Contour plots would be produced to show the change in inundation at different dates, allowing any increase in the spatial extent to be identified, as well as any extension in the duration that inundation is occurring. If there was an increase in inundation, either spatially or temporally, then it was proposed that this would be regarded as being potentially detrimental.

2.1.9 It was proposed that a range of climatic events, such as extremely wet conditions in the lead up to spring and summer (the critical time period to facilitate management), would be modelled without development to allow the incremental change (e.g. extended period of inundation) to be assessed in the construction and operational model scenarios.

2.1.10 If the results of the scenario modelling showed a change in spring and summer drawdown outside the baseline envelope for one or more grades, or an increase in inundation, it would be necessary to explore further mitigation measures. Mitigation features, such as a water control structure on the diverted Sizewell Drain, would then be modelled to determine their efficacy.

2.1.11 Following the completion of the assessment outlined above, water level monitoring would continue to allow ongoing assessment of real world conditions prior to and during construction and operation of Sizewell C. Should the ongoing monitoring yield information which altered the conceptual understanding of the hydrological regime prior to construction, the assessment would be reviewed, and updated if necessary.

2.1.12 Reassurance monitoring would be undertaken during the construction and operation of SZC. Recorded water levels would be compared against a framework of trigger and action levels, to be defined in construction and operational phase monitoring plans. These monitoring plans will be developed prior to construction and operation respectively and be informed by the results of the FEFLOW scenario modelling. Boreholes in the existing monitoring network would be used to record water levels and regularly reviewed to ensure compliance with trigger and action levels during both construction and operation.

2.1.13 Should the reassurance monitoring undertaken during construction and operation show changes that are outside the range predicted by the FEFLOW model, then further mitigation measures would be considered and the efficacy of such measures modelled by the FEFLOW model. It is also important to note that there is also an existing set of control structures within the Sizewell Marshes SSSI that is currently used to manage water levels. The use of this infrastructure to fine-tune the flow and level of surface water within the Sizewell Marshes SSSI is not directly represented in the FEFLOW model, but it does offer additional opportunity for mitigation of changes in water level through changes in management practice.

2.1.14 A worked example of the proposed methodology was presented showing how the assessment methodology would work in practice.

3. STAKEHOLDER FEEDBACK

3.1.1 Comments on the proposed methodology were received from both the Environment Agency (EA) and Natural England (NE).

3.1.2 Both organisations confirmed that the detailed literature review and ecohydrology analysis of the botanical survey data was detailed and suitable for use in the assessment process with no further requirement.

3.1.3 In addition, both organisations supported the principle of using the FEFLOW groundwater model to establish baseline time series hydrographs for a range of climatic conditions against which to model the potential effects of the Sizewell C scheme through a number of construction and operational scenarios. However, both organisations expressed concern that the envelope thresholds per grade of fen meadow were too broad and could mask localised changes that could be of ecological significance and provided a number of other detailed comments on the proposed method.

3.1.4 A summary of stakeholder comments is provided below in **Table 2**.

Table 2. Comments received from EA and NE

Comment	EDF Response
EA Comments	
• The size of the threshold envelope for acceptable impacts for each of the four grades of fen meadow is too broad and might mask localised changes.	• The revised approach considers a field by field approach with three observation points per field to enhance resolution.
• What the risk assessment will look like if modelled impacts fall outside of the envelopes. How will the risks to ecology be considered and the acceptability of these impacts?	• The revised approach sets out how risk assessment will be undertaken in Section 4.3.
• How do you propose to mitigate impacts and test the credibility of any mitigation?	• Mitigation approach is set out in the methodology in Section 4.3. The worked example includes embedded mitigation in the form of a control structure with the FEFLOW model used to demonstrate its effectiveness in Section 5.4.
• We consider additional observation points internal to the compartments are needed, which may require some new topographical surveys.	• The revised approach in Section 4.3 considers a field by field approach with at least one internal observation point per field to enhance resolution.
• The current use of interpolated topography needs to be addressed.	• This is discussed in the revised approach in Section 4.3.
• No criteria for winter conditions are given. The Habitats Directive Review of Consents process does include the criterion for soil moisture to return to	• The criteria for acceptable winter conditions are given within the revised approach in Section 4.3 and are

Comment	EDF Response
saturation during the winter months, should something similar be considered here?	summarised in Table 3.
NE Comments	
• We consider the use of envelopes around the grades of fen meadow as inappropriate, as with development water levels could change by up to 30cm and would be considered to have no significant effect. Also, all the observation points are cited around the edges of the grades of fen meadow, conditions will also be variable across the fields, so we question if the observation points are in the best locations.	• The revised approach considers a field by field approach with at least 3 observation points per field to enhance resolution.
• Care is needed in the interpretation of changes to summer and winter drawdown and inundation as short term sub-optimal conditions may not be detrimental and the acceptability of change may depend on objectives for an area and its starting point.	• The revised approach has presented acceptable levels of change for spring and summer and winter drawdown and spring and summer inundation in Section 4.3, which are summarised in Table 3.
• We advise that a more straightforward and simple comparison of changes to water levels, with and without development should be made on a point by point spatial and temporal (extent and duration) basis, presenting the results as both hydrographs and contour maps. • The results could then be used to determine whether development would be detrimental to the vegetation in a particular location and what mitigation is required.	• The revised approach considers a field by field approach with three observation points per field to enhance resolution. • If required detailed assessment will include review of vegetation composition in the area to be affected as set out in Section 4.3.
• We advise that the observed water table regime should be taken as the basis for determining adverse effect and following this initial study further studies should be carried out to ascertain if the water level regime in the lower grades of fen meadow could be manipulated to enhance vegetation condition.	• This has not been carried forward into the revised assessment methodology. The rationale behind using synthetic baselines for assessing modelled change has been set out in the previous methodology report, and discussed at length during stakeholder workshops. Using the modelled baseline allows a broader range of climatic conditions to be explored in the scenario modelling, which would not be possible using observed data alone.
• Care is needed in the interpretation of the contour plots depending on the degree of correlation between modelled ground surface and the actual ground surface. Further monitoring may be	• The existing topographic data will be used with conservative consideration of the inherent error, as discussed in Section 4.3. If areas are identified as at risk of significant effect, additional topographic survey data may be

Comment	EDF Response
required to evaluate this relationship.	collected locally to constrain the initial assessment.
• No criteria for winter conditions are given. The Habitats Directive Review of Consents process does include the criterion for soil moisture to return to saturation during the winter months, should something similar be considered here.	• The criteria for acceptable winter conditions are given within the revised approach in Section 4.3 and summarised in Table 3.

3.1.5 As indicated in the above table, this stakeholder feedback has largely been taken into account in the revised assessment approach (see Section 4).

3.1.6 Feedback pertaining to the use of the observed water table regime as the basis for determining adverse impact has not been carried forward into the revised assessment methodology. The rationale behind using synthetic baselines for assessing modelled change has been set out in the previous methodology report, and discussed at length during stakeholder workshops. In order to allow a range of climatic conditions to be represented in the scenario modelling the observed water level record is not appropriate as it doesn't include more extreme climatic conditions such as an extended drought. It is not practicable to collect monitoring data for all climatic conditions that may be encountered during the construction and operation phases so synthetic baselines are used to allow the incremental change resulting from the development in these conditions to be assessed. However, empirical data groundwater monitoring records for the site may assist in assessing the significance of any modelled changes in water levels.

3.1.7 Both NE and the EA make reference to the Habitats Directive Review of Consents process, used to determine if permitted abstraction is likely to damage sites afforded a statutory designation under the European Habitats Directive. This level of assessment (known as a Habitats Regulation Assessment (HRA)) needs to be able to demonstrate "beyond reasonable scientific doubt" the absence of any potential adverse effect upon integrity.

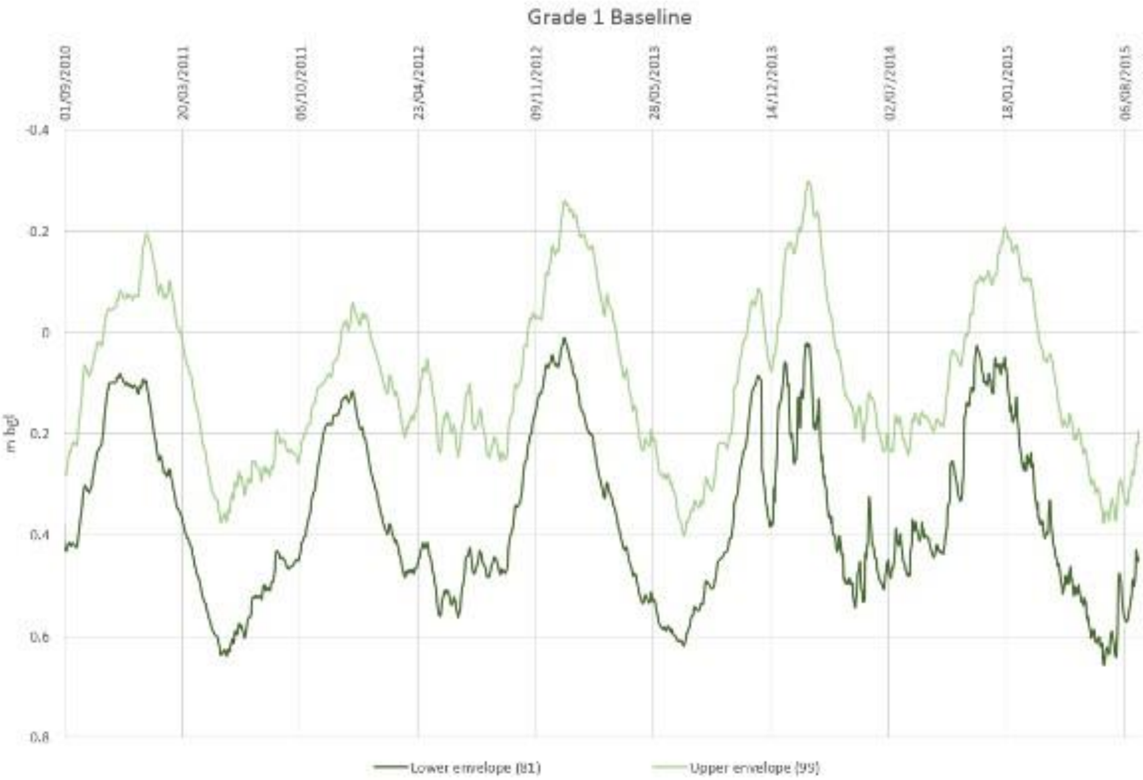
3.1.8 Whilst this is a helpful suggestion, and we think there is some learning that can be applied here, for example using representative assessment points and providing greater resolution to the baseline hydrological assessments, the fen meadow within Sizewell Marshes SSSI is not of European value, so we need to be careful to avoid drawing too much comparison. Our focus in the context of Environmental Impact Assessment (as opposed to HRA) is to assess likely significant effects, for which a lower burden of proof applies.

4. REVISED ASSESSMENT APPROACH

4.1 Introduction

4.1.1 The previous assessment approach produced a ‘Threshold Envelope’, for each of the four grades of fen meadow (see **Table 1**). This envelope gave the upper and lower hydrological regime that each grade of fen meadow currently experiences. The envelope was developed by identifying upgradient and downgradient monitoring points to demonstrate the range of water levels experienced by each grade across the whole of Sizewell Marshes SSSI. This, therefore, reflects the local hydrological conditions underlying Sizewell Marshes SSSI and is considerably more accurate than the broad hydrological tolerances of M22 fen meadow as derived from the literature. As Sizewell Marshes SSSI is currently in favourable ecological condition it is envisaged that the existing hydrological regime underlying each grade of fen meadow is also likely to be optimal or close to optimal. An example of the envelope for the grade 1 fen meadow is shown below in **Figure 2**:

Figure 2 Envelope baseline for grade 1 fen meadow



4.1.2 The stakeholder observations outlined in **Section 3** have been taken on board and, where considered appropriate, have been addressed within the revised assessment methodology. This includes the refining of the baseline range to be on a field by field basis. The revised assessment approach is illustrated via a new worked example in **Section 5**.

4.1.3 Preliminary scenario modelling (Atkins, 2016c) indicated that some embedded mitigation may be required to mitigate the potential changes to groundwater levels in the Sizewell Marshes SSSI, particularly in the areas adjacent to the cut-off wall during the construction scenario when dewatering is occurring. As such, an example control structure (a thin-plate weir) has been included as an embedded mitigation measure in the model runs for the worked example discussed in **Section 5**, and such embedded mitigation is referred to in this section.

4.1.4 This initial control structure has been included only as an example of the type of embedded mitigation that could be included in the final assessment. During the assessment, the type of weir, its location and the elevation of the weir plate can be adjusted in the model to determine the optimum location and elevation required to mitigate the change in water levels most effectively.

4.2 Establishing acceptable levels of change

4.2.1 The overall aim of the assessment approach is to maintain the status quo i.e. to maintain the existing hydrological regime that underlies the M22 fen meadow vegetation, despite the presence of the proposed Sizewell C development. Initial modelling results indicate that, in the absence of any mitigation measures, there will be some alterations to the underlying hydrological regime resulting from the proposed development, albeit considered to be minor. To determine whether any modelled change in groundwater levels is acceptable, agreed acceptable levels of change in groundwater levels must be established.

4.2.2 In the previous assessment baseline envelopes were established for each grade of fen meadow, calculated based on the range of modelled baseline time series across the site within each grade. These site-wide baseline envelopes for each grade are shown in **Figure 3**. To increase resolution, the updated assessment establishes a baseline envelope time series of groundwater levels for each individual field. Where the modelled scenario groundwater levels remain within this envelope the change can be considered to be acceptable as no change outside the naturally experienced variation for vegetation for that field will have occurred.

4.2.3 It is important to recognise that the M22 fen meadow communities are long-established in the Sizewell Marshes. Inherently they will have survived periods of drought and flooding, and would tolerate conditions outside of this baseline range. The broad tolerances for the M22 fen meadow community across the UK are characterised by summer water tables that are below the ground surface. The national guidelines developed in Wheeler et al. (2009) - summarised in the Environment Agency's Fens and Mires Update March 2010 of Ecohydrological Guidelines for Lowland Wetland Plant Communities - provide a first approximation for a spring and summer water table target of

5 cm to 18 cm bgl. Literature presented in the previous report (EDF, 2016) suggests that although the individual component plant species of wetland communities such as M22 fen meadow have a preference for a summer water table close to the surface (7 to 9 cm below ground level (bgl)) they can tolerate drawdown of tens of centimetres (down to 22-42 cm bgl) and cope with some inundation.

4.2.4 The FEFLOW transient groundwater model was calibrated to a target of being within 10 cm of observed groundwater levels. This calibration target was agreed with stakeholders based on their understanding of plant species tolerances. Recognising this, and the literature values for drawdown tolerances that plant species within the M22 fen meadow can withstand discussed above, a change in groundwater levels of up to 5 cm outside of the field baseline envelope would be also considered acceptable. This change lies well within the tolerance range of the plants species within the M22 fen meadow community. Therefore, a 5cm envelope has been added below the lower field baseline values in the revised assessment. The use of this envelope is discussed in more detail in subsequent paragraphs.

4.2.5 Determining if an increase in inundation, either spatially or temporally, would be potentially detrimental is not a straightforward task and would depend on numerous factors including seasonality, area, and duration. It also needs to be considered that spring and summer inundation is a naturally occurring event and the M22 fen meadow vegetation is to a certain extent adapted to events of this nature. For this assessment, any increase in the area or depth of inundation for periods longer than two weeks are considered to have a potentially significant effect, and require further assessment. Two weeks of inundation, above the inundation already tolerated as demonstrated by the baseline scenario, has been used as a threshold as this would likely cause die-off underlying vegetation.

4.3 Revised assessment approach

4.3.1 The revised assessment methodology is similar to that presented previously; the overall intention is to maintain the status quo so that there will be no significant change to the existing hydrological regime. As the M22 fen meadow is currently in favourable ecological condition, then maintenance of the existing hydrological regime, coupled with on-going conservation management, will likely continue to maintain the ecological status of the fen meadow.

4.3.2 Recognising that the available monitoring data covers a period of relative climatic stability, and considering that real world conditions cannot be directly compared with the FEFLOW model due to the overestimation of seasonality, it is still proposed to establish a synthetic baseline for use in assessing potential change.

4.3.3 A number of scenario runs have previously been proposed in order to explore the impacts of the development under normal climatic conditions and during periods of climatic extremes (e.g. extreme high and low rainfall).

In order to allow direct comparison with a relevant synthetic baseline, baseline runs for the various climatic conditions will also be carried out. This allows cumulative effects to be assessed of extreme climatic conditions in addition to the effects of the development. Further details of the planned scenario runs are given in Atkins (2016a) and the relevant section is included as **Annex A** of this report.

4.3.4 The proposed assessment approach involves several discrete elements for each scenario as presented below:

- a) initial scenario model run to establish the Zone of Influence (ZoI) by comparison with the baseline model run;
- b) establish observation points within each field within the ZoI, and re-run scenario and baseline models with these included;
- c) compare modelled time series for scenario observation points (with embedded mitigation in place and without) against baseline envelope for each field, and, dependent on the outcomes of this comparison, assess potential impacts at critical periods of the growing season;
- d) undertake detailed assessment of potential impacts, where necessary determine appropriate additional mitigation measures, and re-run model with additional measures included to assess their impact; and
- e) consider the impact of any residual effects, following mitigation, on the M22 fen meadow.

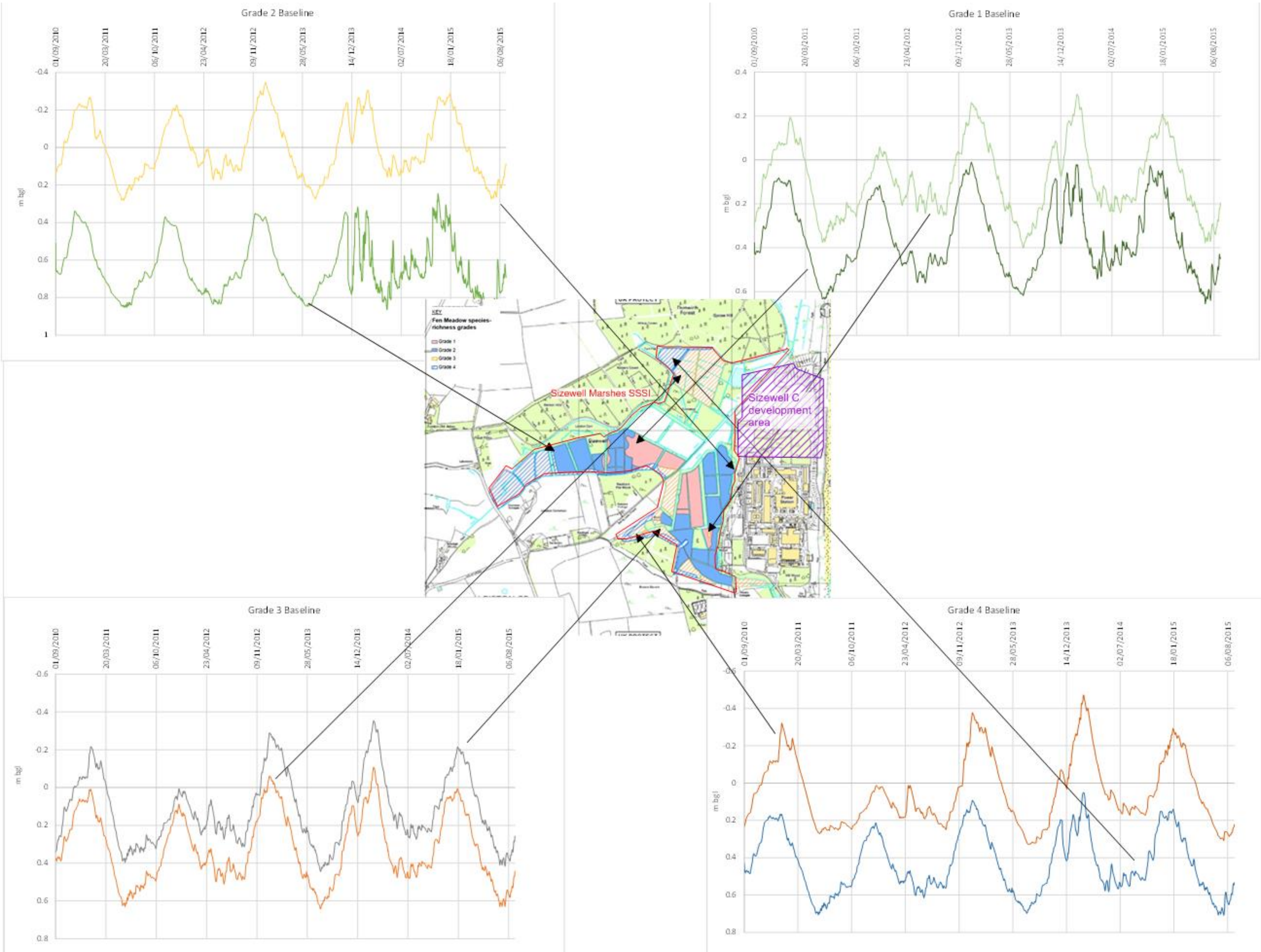
Further detail on each of these stages is presented in the following sections.

a) Establishing the Zone of Influence

4.3.5 An initial run of each scenario model will be undertaken to identify which fields within Sizewell Marshes SSSI are likely to be directly affected by the construction and operation of the proposed Sizewell C. The outputs would be compared to the relevant baseline model to identify the fields where the water levels are projected to change as a result of the development, and therefore highlight the precise area of habitat that will require detailed assessment for each scenario.

4.3.6 The focus of the assessment will be on those fields closest to the development footprint that are most likely to be at risk of being directly affected. If potential changes to the hydrological regime of the affected fields are within acceptable thresholds of change then it is envisaged that fields further outside the ZoI are highly unlikely to be affected. If mitigation is required, an appraisal of the ZoI with mitigation included will be undertaken to ensure there are no unintended changes beyond the original ZoI. Establishing the ZoI at the start of the assessment identifies those areas of fen meadow most at risk of being affected by the development, and prevents unnecessary assessment of fields unlikely to be affected.

Figure 3 Site-wide baseline envelope for different grades of fen meadow



b) Establishing observation points and re-running models

4.3.7 Three observations points will be established in each field within the ZoI as follows:

- Observation Point A - up-gradient edge of the field;
- Observation Point B - the middle of the field; and
- Observation Point C - down-gradient edge of the field.

4.3.8 The up-gradient and down-gradient observation points will be chosen based on the groundwater contours generated by an initial run of the baseline model. The groundwater level time series from the baseline model for Observation Points A and C will define the upper and lower limits of the baseline envelope for that field. The baseline envelope defines the range of hydrological conditions encountered in that field under normal baseline conditions.

4.3.9 Observation Point B will be used to generate the groundwater level time series from the scenario model output for each field, which will be compared to the baseline envelope to assess the impact of the development on the hydrological regime in that field. An observation point from the centre of the field is proposed as this will be most representative of water levels across the field.

4.3.10 Once the observation points are established, the relevant baseline model and scenario model will be re-run with the observation points in place for each field within the ZoI to allow time-series to be generated at these locations.

c) Comparison of scenario outputs and baseline envelope

4.3.11 The scenario time series for Observation Point B will be compared with the derived baseline envelope for each field, to see whether the change resulting from the development closely matches, or falls outside the baseline envelope for that field.

4.3.12 The following aspects of the hydrological regime underlying the M22 fen meadow vegetation will be considered:

- spring and summer (growing season) drawdown;
- spring and summer (growing season) inundation; and
- winter regime.

4.3.13 Each of these aspects of the hydrological regime will be assessed independently, as change outside the defined acceptable limits could potentially be sufficient to cause a change in the underlying M22 fen meadow vegetation. Assessment thresholds have been established for each aspect, following the discussion in **Section 4.2**. The thresholds are presented in **Table 3** and described in more detail in the following paragraphs.

4.3.14 Generating observation points for each individual field provides a much greater resolution for the assessment than previously proposed, which is helpful to better understand impacts and assess efficacy of mitigation measures. However, it is still relevant to also consider how any predicted change in water level compares to the natural variation in baseline water levels that exist for each grade of fen meadow across the SSSI as a whole, and these have been included as outer thresholds in **Table 3**. Where changes in groundwater levels lie outside the established thresholds for that field, consideration will be given in the assessment as to whether the changes lie within the site-wide baseline envelopes shown in **Figure 3**.

4.3.15 For each aspect of the regime the assessment will take a structured approach. The scenario outputs will initially be compared to the synthetic baseline, and assessed against the thresholds summarised in **Table 3** to define a particular outcome for the assessment of that aspect of the regime. Depending on the outcome, further more detailed assessment may be required, as described below.

4.3.16 As discussed in **Section 4.1**, embedded mitigation in the form of a control structure (weir) on the Leiston Drain would be included in the scenario runs (see **Figure 4**). The effects of the scenario will be considered with the embedded mitigation in place.

Figure 4 Location of additional control structure

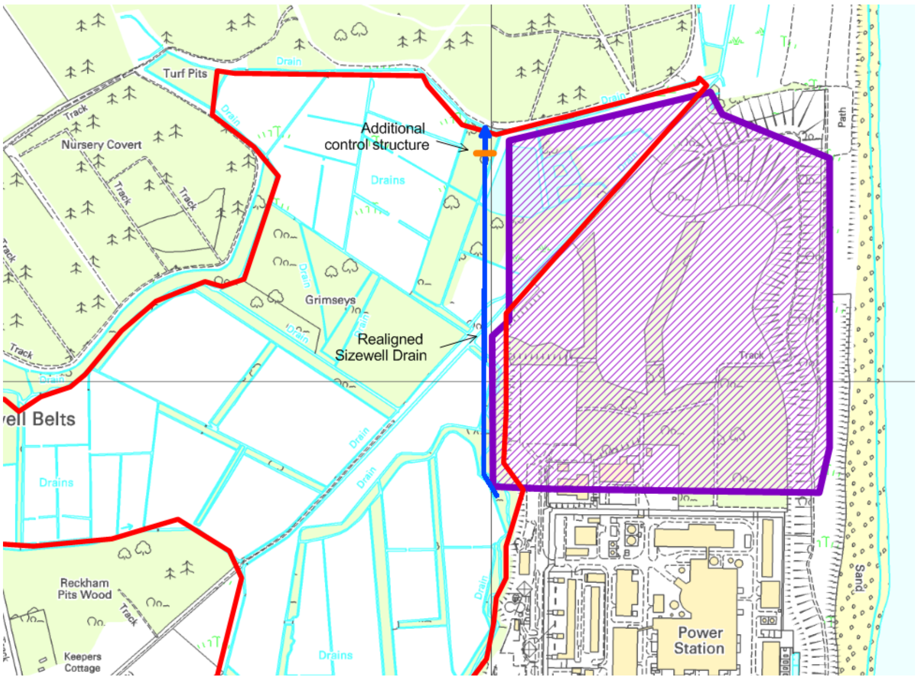


Table 3. Thresholds for acceptable change

Spring-summer drawdown	The development scenario falls within the baseline for the individual field being considered, or within 5 cm of the baseline.	The development scenario is more than 5cm outside the baseline for the individual field being considered, but is within the enveloped baseline for the grade of fen meadow in which the field lies.	The development scenario is more than 5cm outside the baseline for the individual field being considered, and outside the enveloped baseline for the grade of fen meadow in which the field lies.
Spring and summer inundation	No increase in the area and depth affected by inundation. Inundation is not prolonged above that seen in the baseline by more than two weeks.	The depth of inundation, or the spatial extent is increased. Inundation is prolonged above that seen in the baseline by more than two weeks.	N/A
Winter regime	The winter regime for the development scenario falls within the winter baseline for the individual field being considered, or within 5 cm of the baseline.	The winter regime for the development scenario is greater than 5cm below the winter baseline for the individual field, but is within the enveloped winter baseline for the grade of fen meadow in which the field lies.	The winter regime for the development scenario is greater than 5cm outside the winter baseline for the individual field, and lies outside the enveloped winter baseline for the grade of fen meadow in which the field lies.
	Outcome 1	**Outcome 2**	**Outcome 3**

ii. Spring-summer drawdown

4.3.17 The assessment of any changes to spring and summer drawdown and to the winter regime follow the same process. For both, the assessment will take a structured approach. First the scenario time series for Observation Point B from each field will be compared with the baseline envelope for that field, allowing the scenario time series to be assessed against the criteria outlined in **Table 3**. Depending on the outcome of this assessment, further work may be required, e.g. to refine any embedded mitigation measures.

4.3.18 For spring and summer drawdown, the three possible outcomes of the preliminary assessment shown in **Table 3** will determine what is required next in the assessment as follows:

- Outcome 1 – With the embedded mitigation in place, the development scenario is within 5cm of the baseline for the individual field being considered. Therefore, the embedded mitigation is fully effective, and there is no likely significant effect. No further assessment required.
- Outcome 2 - With the embedded mitigation in place, the development scenario is more than 5cm outside the baseline for the individual field

being considered, but is still within the enveloped baseline for the grade of fen meadow in which the field lies. Therefore, the embedded mitigation is partially effective, but as the residual change is greater than 5cm there is a potential for a significant effect. There should be consideration to optimising mitigation such as raising the weir plate or incorporating additional mitigation measures. Further detailed assessment is required (see **section d**).

- Outcome 3 - With the embedded mitigation in place, the development scenario is more than 5cm outside the baseline for the individual field being considered, and is also outside the enveloped baseline for the grade of fen meadow in which the field lies. Therefore, the embedded mitigation is not effective and there is a likely significant effect. A detailed assessment would be required and it may not be possible to fully mitigate the predicted effect. Further detailed assessment is required (see **section d**).

iii. Winter regime

4.3.19 As mentioned in **paragraph 3.1.5** there is little information available as to what constitutes an acceptable winter hydrological regime for the M22 fen meadow vegetation community. Winter is a less sensitive time of year than the growing season, but as mentioned in **Table 2**, the review of the consents process does have the criterion that winter water levels must be sufficient to allow re-saturation of the soils underlying M22 fen meadow, therefore prolonged drawdown in the winter months could potentially cause a significant effect.

4.3.20 Observations during ecological surveys at Sizewell Marshes SSSI indicate that during the winter months the M22 fen meadow community is generally wet underfoot, sometimes impassable with areas of surface flooding. The existing groundwater monitoring network has recorded groundwater levels above ground level at half of the monitoring locations in the Sizewell Mashes SSSI during the winter season. Groundwater is typically recorded above ground level at monitoring locations in the centre and east of the Sizewell Marshes SSSI, including in areas of fen meadow, between November and January. However, the observed groundwater level data does show variations in the winter months of up to 40 cm, which suggests that vegetation within the fen meadow can tolerate significant fluctuations in groundwater level during the winter. Even within areas of grade 1 fen meadow, variations in groundwater level of up to 30 cm are observed in the monitoring data record. This indicates that a wide range of conditions are currently experienced by each grade of fen meadow during the winter period.

4.3.21 It is envisaged that the embedded control structure would not be designed primarily to mitigate against any observed drawdown caused by the development scenario during the winter months, as water levels in the Sizewell Drain and the surrounding groundwater are likely to be higher than the elevation of the weir plate at this time of year.

4.3.22 If the water levels within the Sizewell Drain are above the level of the weir plate, and groundwater is within the baseline envelope for the respective fen meadow grades, for the majority of the winter period, it is considered that there will be sufficient recharge to the soils beneath the M22 fen meadow community, and no significant effect.

4.3.23 Again, the initial comparison of development scenario against baseline will be undertaken with more detailed assessment occurring depending on the outcomes. The outcomes for the winter regime are as follows:

- Outcome 1 – The winter regime for the development scenario is less than 5cm outside the winter baseline for the individual field being considered, and is within the enveloped winter baseline for the grade of fen meadow in which the field lies. There is no likely significant effect, therefore no further assessment is required.
- Outcome 2 – The winter regime for the development scenario is more than 5cm below the winter baseline for the individual field being considered, but is still within the enveloped winter baseline for the grade of fen meadow in which the field lies. Therefore, there is no likely significant effect. It is envisaged that as the winter level is within the enveloped baseline for the grade of fen meadow in which the field lies then water levels will be sufficient for recharge.
- Outcome 3 – The winter regime for the development scenario is more than 5cm below the winter baseline for the individual field being considered, and is also below the enveloped winter baseline for the grade of fen meadow in which the field lies for more than 50% of the winter period. Therefore, there is the potential for a likely significant effect, further detailed assessment required (see section d).

iv. Spring and summer inundation

4.3.24 Determining if an increase in inundation, either spatially or temporally, would be potentially detrimental is not a straightforward task and would depend on numerous factors including seasonality, area, and duration. It also needs to be considered that spring and summer inundation is a naturally occurring event and the M22 fen meadow vegetation is to a certain extent adapted to events of this nature. As summarised in **Table 3**, additional inundation caused by the development scenario lasting more than two weeks duration during the growing season, beyond the extent of any inundation already seen in the baseline, would be considered to be potentially detrimental. This would likely cause die-off underlying vegetation.

4.3.25 A similar approach to that advocated for spring and summer drawdown will be implemented, with an initial comparison occurring first followed by a more detailed assessment if necessary.

4.3.26 To assess changes in spring and summer inundation, contour plots of inundation depths on specific days over the late spring and early summer period will be generated for baseline conditions, and for the scenario run. The baseline and scenario inundation contours will be subtracted from one another to generate a difference contour plot to identify any areas where inundation has been prolonged, or the depth or spatial area of inundation has increased.

4.3.27 The outcomes for assessing spring and summer inundation are as follows:

- Outcome 1 – The spatial extent of the area affected by inundation and the depth is unchanged; inundation does not occur for greater than two weeks beyond that already experienced in the baseline during the growing season. There is no likely significant effect. No further assessment required.
- Outcome 2 – The spatial extent of the area affected by inundation or the depth is increased; inundation occurs for greater than two weeks on top of the existing inundation seen in the baseline model. Therefore, there is the potential for a likely significant effect, further detailed assessment required (see **section d**).

4.3.28 It is important to note that initial scenario model runs do not indicate any increase in the extent of inundation.

d) Detailed assessment

4.3.29 If the outcomes from the comparison process above shows a potential for a significant effect within an individual field, despite the presence of the embedded mitigation, then a detailed assessment would be undertaken. This assessment may require additional data to be collected, and could include some or all of the following:

- Comparison of the predicted change against the empirical evidence from observed groundwater modelling relating to the grade of fen meadow within which the individual field lies.
- Review existing survey data for the affected field, or if required, carry out surveys of the vegetation within the affected field, to determine the nature and floristic composition of the affected area and undertake a review of the sensitivity of the plant species present to changes in hydrological regime, making reference back to the eco-hydrological guidelines and published tolerances for individual plant species.
- Carry out local topographical survey to improve the resolution of predicted outcomes.

4.3.30 Additional topographical data may be required because to estimate the impact of any residual effects, the modelled time series data will need to be converted from water level elevations relative to Ordnance Datum to water levels expressed as metres below ground level (m bgl). As noted in the previous methodology report (EDF, 2016), topographic data are held for the observation boreholes in the Sizewell Marshes SSSI; however, this dataset does not include data points in all the fields within the Sizewell Marshes SSSI. Although LIDAR data are held for the area of the Sizewell Marshes SSSI, the vertical resolution is too poor to allow it to be used for this purpose, because of the nature of the vegetation cover. In the first instance, the assessment will be undertaken using interpolated topography based on the existing topographical dataset. If necessary, additional topographic survey data can be collected in a targeted fashion to allow a refined assessment, taking into account actual topography.

4.3.31 Where interpolated topography is used to convert the water level elevations to depths below ground, the potential error in the topographical interpolation will be included in the conversion. For example, if water levels were calculated to be at 0.1 m bgl using interpolated topographic data with an error of 0.15 m, the estimated water levels used for the assessment would be 0.25 m bgl. This approach would give a conservative estimate of water levels in metres below ground.

4.3.32 Where a significant effect is considered likely, the additional data will be considered using professional judgement to assess the significance of the change and its magnitude. This will include reference to the broad hydrological requirements of the M22 fen meadow community as derived from the literature and will consider additional measures, such as modification to the conservation management of the field in question to reduce the magnitude of effect. Where necessary, additional mitigation measures will be considered.

e) Mitigation measures and residual effects

4.3.33 As described above, the comparison of the development scenario against the baseline will follow a structured approach. It will only consider additional mitigation measures (over and above the embedded control structure) if the outcomes of the scenario modelling show changes considered likely to have a significant effect, and only then after a detailed assessment of the likely significance of the effects has been carried out. Any additional mitigation, such as additional control structures, would be modelled to determine their efficacy.

4.3.34 Reassurance monitoring would be undertaken during the construction and operational periods to allow comparison of observed water level variation during construction and operational activities with predicted levels. Additionally, feedback would be sought from the site managers (Suffolk Wildlife Trust). Recorded water levels would be compared against a framework of trigger and action levels, to be defined in construction and operational phase monitoring plans. Should the reassurance monitoring show changes that are outside the range predicted by the FEFLOW model, and outside the established baseline for the grade of fen meadow concerned, then additional measures would be considered such as raising the weir plate (embedded mitigation), alteration of the siphons present in other parts of the Sizewell Marshes SSSI, or modifying the conservation management plan.

4.3.35 In addition to the monitoring of water levels, vegetation monitoring will also be carried out (continuing the detailed condition assessment work already carried out). If the composition of the M22 fen meadow community is seen to be changing and these changes are attributable to changes in the underlying hydrological regime, as opposed to changes in conservation management, then this would also be a trigger for corrective action.

4.3.36 All monitoring requirements will be set out in a monitoring action plan that will also include a set of triggers for corrective action.

4.4 Changes to groundwater quality

4.4.1 Long-term changes to water quality as a result of the development may have a detrimental impact on the M22 fen meadow. The proposed approach to modelling changes in water chemistry in the assessment has been set out previously (Atkins, 2016b). Instead of directly representing hydrochemistry in the model, any potential changes in water chemistry will be identified by comparing the relative magnitude of the various components of the water balance of the Sizewell Marshes SSSI area in the baseline model with each scenario. The key components of the water balance that would be considered are: upflow from underlying Crag groundwater, recharge from rainfall, and interaction with surface water in the drainage ditch system. Each component has a hydrochemical signature, which combine to provide favourable conditions for the M22 fen meadow habitat.

4.4.2 The assessment would compare the various components of the water balance in the baseline model, and the scenario model to determine whether any significant changes are predicted, which could impact the hydrochemistry within the Sizewell Marshes. A full worked example of this methodology is presented in Atkins (2016b).

5. ASSESSMENT – WORKED EXAMPLE

5.1 Introduction

5.1.1 A worked example is presented in this section to demonstrate how the ecological assessment will be undertaken with supporting information from the FEFLOW model. This worked example comprises a single field of grade 2 fen meadow located in close proximity to the proposed development within the area most likely to experience change. The construction scenario has been used for this worked example. This includes the temporary works compounds, cut-off wall and the internal dewatering system. The construction scenario is likely to have the greatest impact on the Sizewell Marshes SSSI in terms of changes to water levels, so the initial outputs presented here are indicative of the likely worst-case effects from the development.

5.1.2 It should be noted that this worked example represents a first pass of the modelling to indicate how the assessment will work in practice. Some aspects of the modelling output will be further refined when the actual assessment is undertaken e.g. design of control structure.

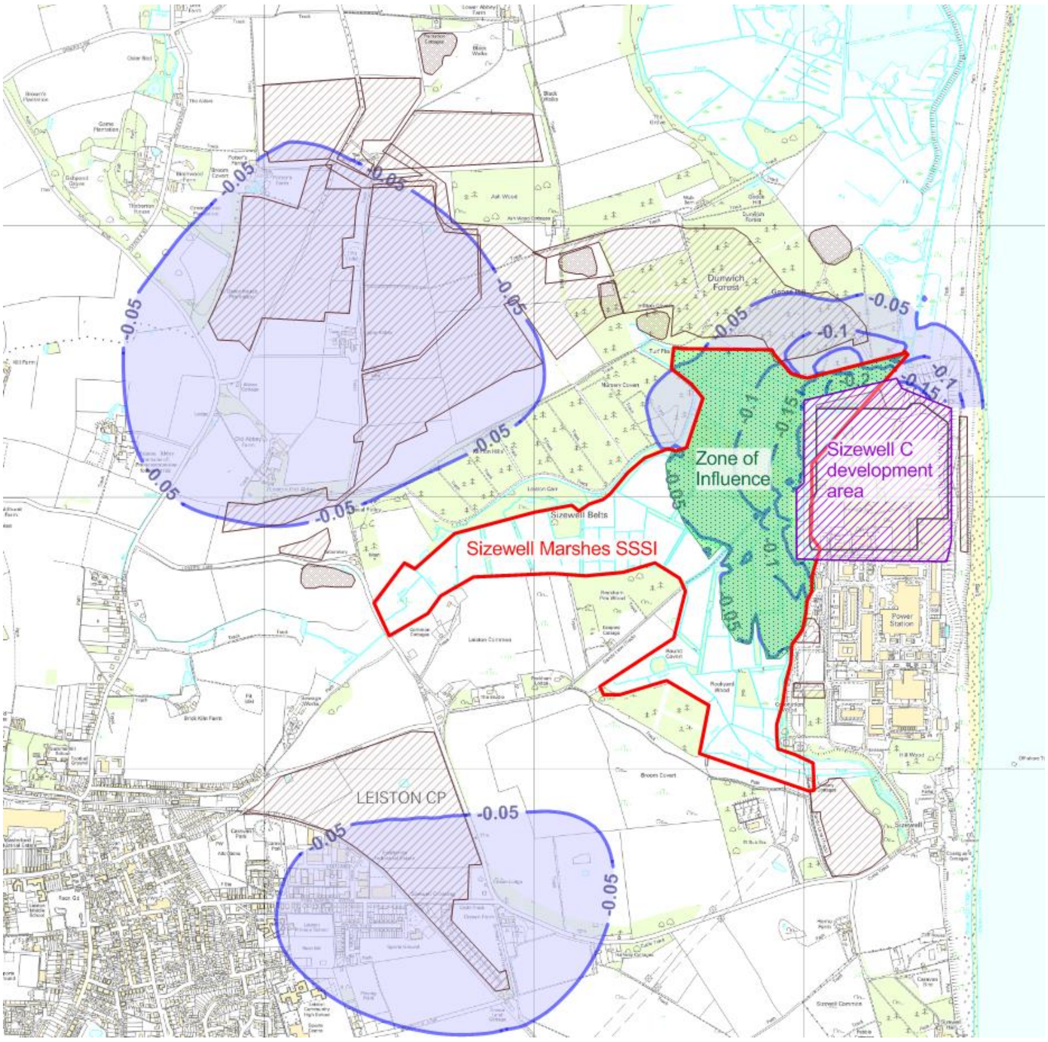
5.2 Establishing the Zone of Influence

5.2.1 The ZoI has been defined by considering the change in groundwater levels across the Sizewell Marshes SSSI between the baseline model run and the scenario run. The difference in groundwater levels has been considered in the spring and summer and winter based on model output from the day in each season which shows the greatest difference in groundwater levels. The ZoI will be defined by the fields of fen meadow where the groundwater levels change by more than 5 cm in the scenario run compared to the baseline. This threshold represents half of the stated target model calibration with respect to groundwater levels in the Sizewell Marshes SSSI, which was based on the recognised tolerances of the fen meadow species (see **Paragraph 4.2.28**).

5.2.2 **Figures 5** and **6** show the defined ZoI based on the differences in groundwater levels in spring and summer and winter between the baseline and scenario model for the worked example. The ZoI in winter is larger, and as such all the fields within this area would be carried forward for assessment, even if they lie outside the spring and summer ZoI. It should be noted that the grade 1 fen meadow largely lies outside the spring and summer ZoI.

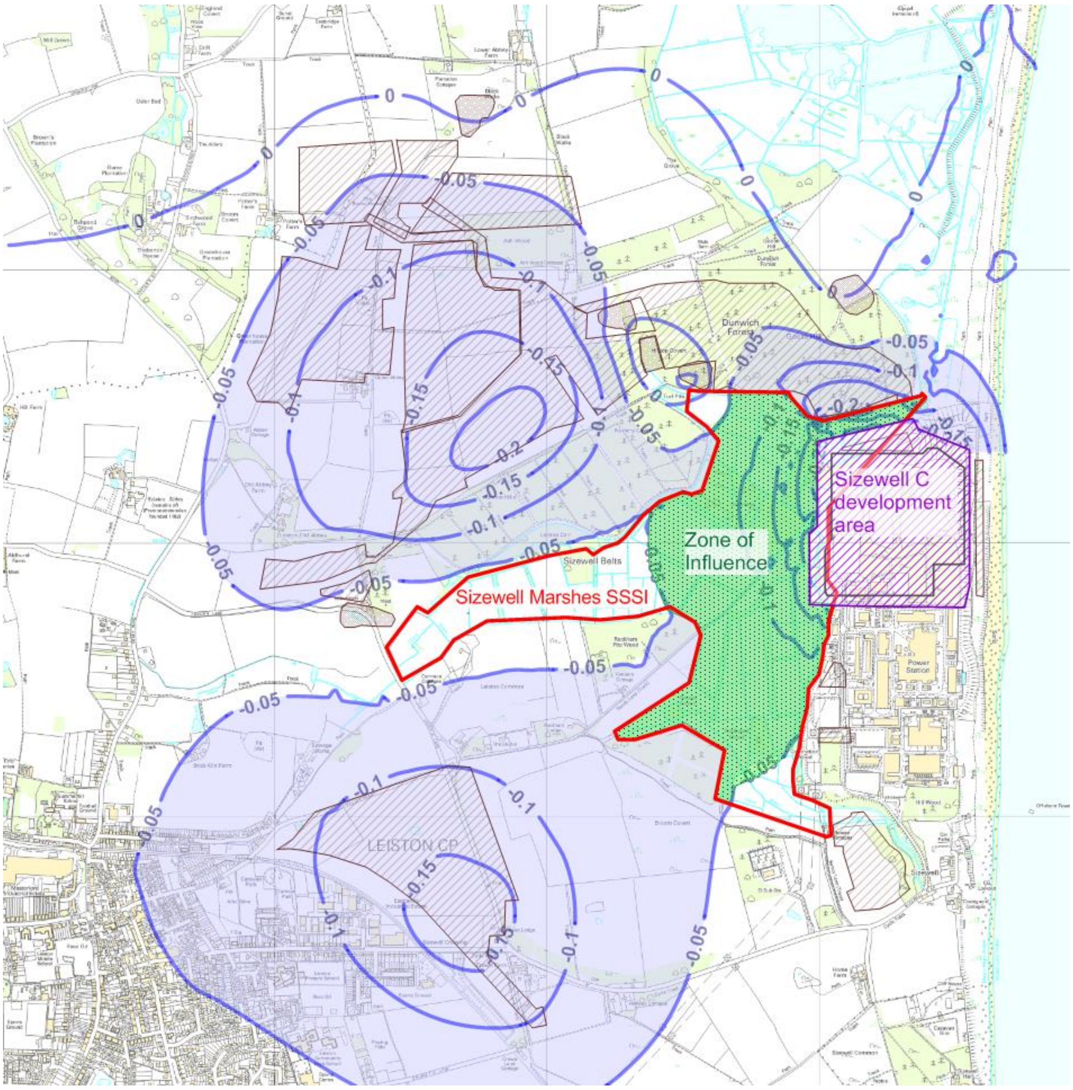
5.2.3 Both figures show areas of change in groundwater levels greater than 5cm outside of the Sizewell Marshes SSSI as a result of reduced infiltration underneath the temporary works areas. There areas are not fen meadow habitat (both are mainly arable farmland) so would not be considered for assessment. It should be noted that Minsmere South Levels lies outside the ZoI in both seasons.

Figure 5. ZoI based on spring and summer water level difference contours.



Notes: Areas where water levels have decreased by greater than 5cm in the scenario run compared to the baseline are shown in blue. Contours lines are shown in 0.05m intervals. Defined ZoI is shown in green.

Figure 6. ZoI based on winter water level difference contours.

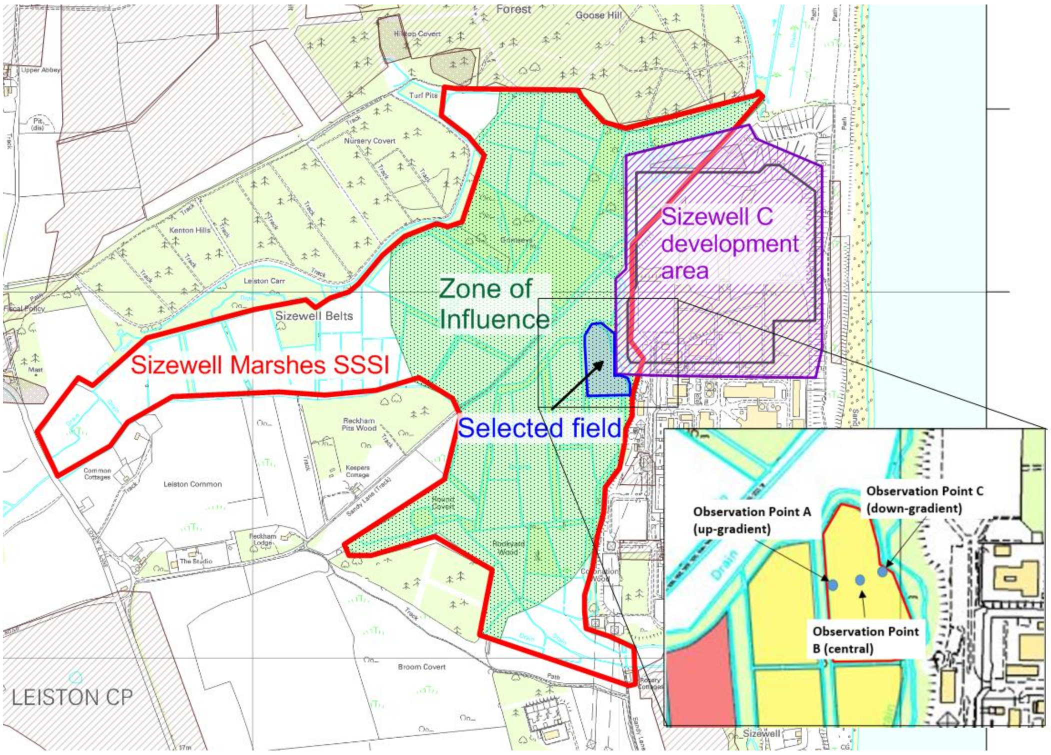


Notes: Areas where water levels have decreased by greater than 5cm in the scenario run compared to the baseline are shown in blue. Contours lines are shown in 0.05m intervals. Defined ZoI is shown in green.

5.3 Observation points

5.3.1 For the purposes of this worked example, a single field of grade 2 fen meadow within the ZoI adjacent to the cut off wall has been selected, as shown in **Figure 7**, below. Three observation points were added to this field in the models according to the criteria described in **paragraph 4.3.7**.

Figure 7. Selected field and observation points



5.4 Embedded mitigation

5.4.1 As discussed in **Section 4.1**, embedded mitigation in the form of a control structure (weir) on the Leiston Drain would be included in the scenario runs, and has been included in this example so that the effects of the scenario will be demonstrated with and without the embedded mitigation measures in place. The location of the weir is shown in **Figure 4**.

5.4.2 This initial control structure has been selected to demonstrate the type of mitigation measure that can be included. During the assessment, the location of the weir and elevation of the weir plate can be adjusted in the model to determine the optimum location and elevation required to mitigate the change in water levels most effectively. Although the control structure in this worked example does not return water levels completely within the defined baseline (see **Section 5.2**), it does demonstrate the mitigating impact that can be achieved. The control structure would be suitably designed to facilitate eel passage.

5.5 Comparison of scenario model outputs and baseline envelope

5.5.1 The baseline envelope of water levels for this field is shown in orange in **Figure 8** (below), based on the outputs from the baseline model run for Observation Points A and C. The time series from the scenario model for Observation Point B, in the centre of the field, is shown in grey. **Figure 8** also shows the upper and lower enveloped baseline thresholds for the grade 2 fen meadow in which the field lies.

The scenario model results in a reduction in groundwater levels throughout the year in this field which takes the groundwater levels outside of the field specific baseline envelope by approximately 20 cm.

a) Spring and summer drawdown

5.5.2 The time series output from Observation Point B demonstrates that the control structure acts to reduce the drop in water levels (drawdown) during the spring and summer months. With the control structure in place, water levels during spring are largely kept to within 5cm of the baseline envelope for the field in question. From mid-May onwards in 2014, and mid-July in 2015, the residual difference increases, up to 15 cm below the field baseline. The residual change still lies well within the previously established envelope baseline for grade 2 fen meadow, shown in green dotted line on **Figure 8**.

5.5.3 This would be Outcome 2 as set out in **Section 4.3**. With the embedded mitigation in place, the development scenario is more than 5cm outside the baseline for the individual field being considered, but is still within the enveloped baseline for the grade of fen meadow in which the field lies. The embedded mitigation is therefore partially effective, but as the residual change is greater than 5cm there is a potential for a significant effect. It would be appropriate to consider optimising the mitigation, such as raising the weir plate. As discussed in **section 5.4**, the embedded mitigation here is a preliminary example, and in the actual assessment the height of the weir plate, and its location would be adjusted to achieve the maximum mitigation effect possible.

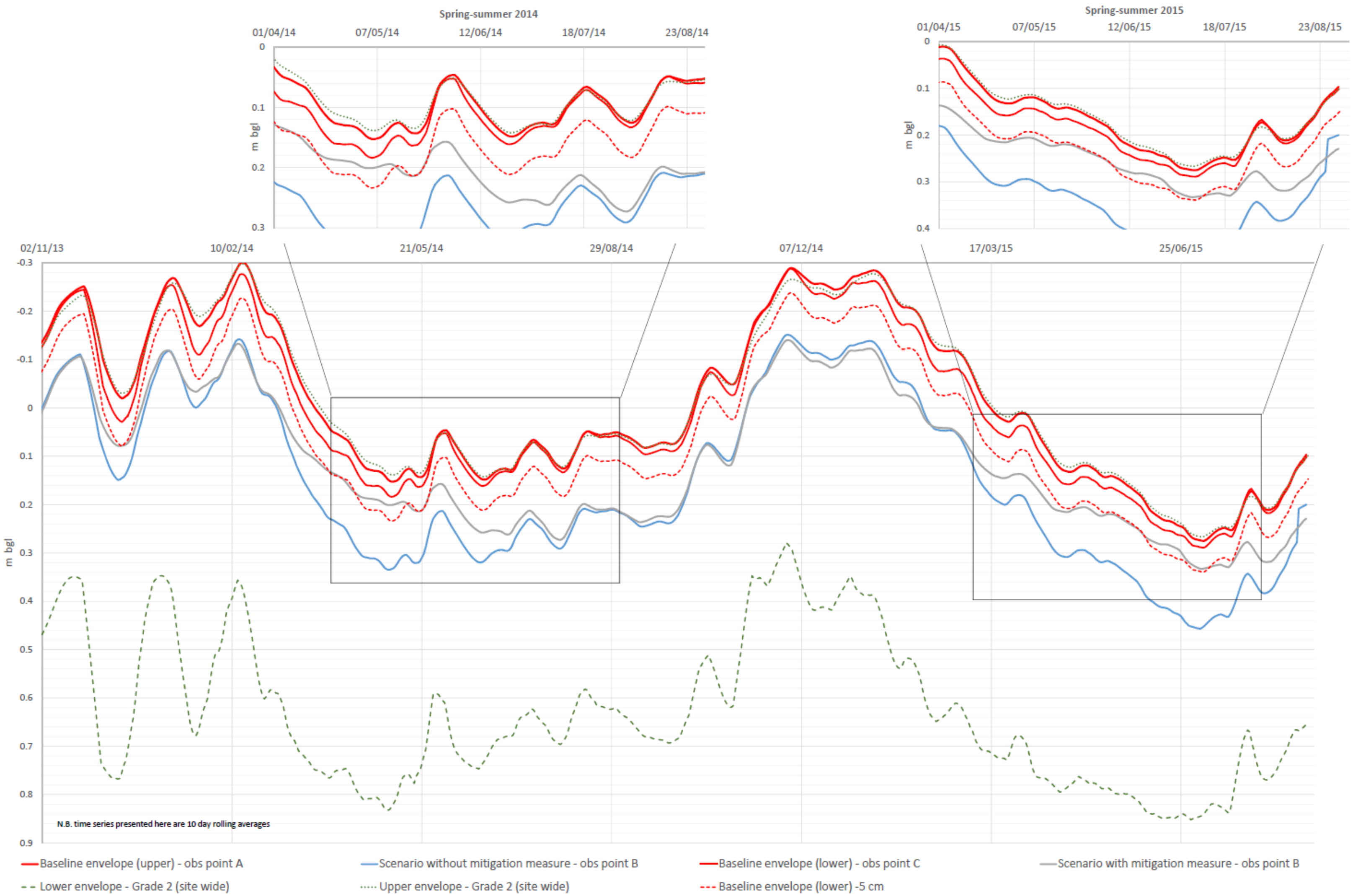
b) winter regime

5.5.4 The time series output from Observation Point B from this model run demonstrates that the control structure does not mitigate against the additional drawdown seen during the winter months, as levels in the Sizewell Drain and the surrounding groundwater are higher than the elevation of the weir plate at this time of year. See **paragraph 4.3.21** for a detailed discussion of this point.

5.5.5 With the embedded mitigation in place, the water levels are kept to within 15 cm of the baseline envelope for the field in question but remain with the previously derived tolerances for grade 2 fen meadow. This would be Outcome 2 (see **Section 4.3**). The winter regime for the development scenario is more than 5cm below the winter baseline for the individual field being considered, but is still within the enveloped winter baseline for the grade of fen meadow in which the field lies. Therefore, there is no likely significant effect.

5.5.6 For reference, **Figure 8**, and the time series plots for each of the Observation Points within the assessed field are included in large format in **Annex B**.

Figure 8. Comparison of scenario output with baseline envelope for a single field of grade 2 fen meadow, and the site-wide envelope.



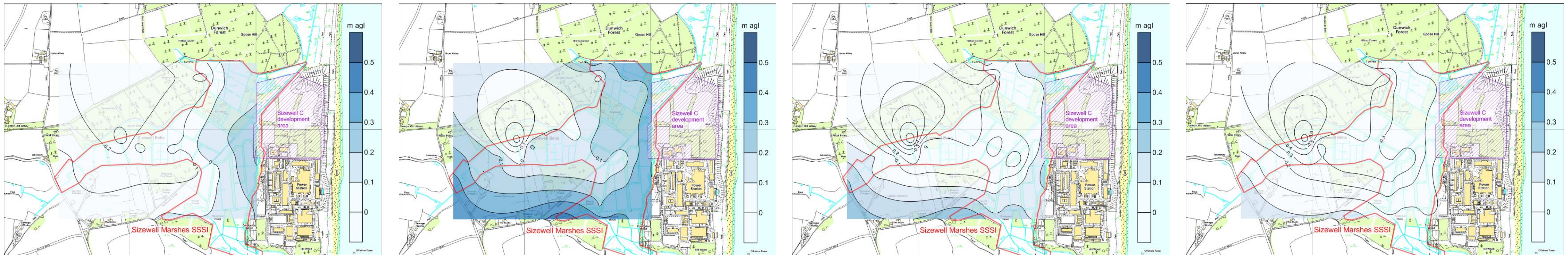
c) spring and summer inundation

5.5.7 **Figure 8** (above) also indicates that there would likely be a change to the late spring and early summer inundation within the ZoI. As discussed in **paragraph 0**, changes to the inundation would be assessed using spatial contour plots of the inundation depth. For the final assessment, a series of difference contour plots would be generated to quantitatively assess the changes in inundation depth and extent between the baseline and scenario runs over time. For demonstration purposes in this document, the inundation contours for the baseline and scenario have been compared visually as there is no increase in the scenario. **Figure 9A** and **9B** (below) show the degree of surface water inundation during the scenario run, compared to that in the baseline model.

5.5.8 During the winter months, the baseline model (**Figure 9A**) predicts that there is some surface inundation which dries gradually during the spring so that by April, at the start of the plant growing season, there is very little inundation. The contours for the construction scenario (**Figure 9B**) show that the depth, and the area of inundation is reduced slightly compared to the baseline. This is likely to be due to the effects of realigning the Sizewell Drain, reducing any surface water rebound. It is recognised that as the model overpredicts seasonality the inundation indicated on the contour plots is not representative of real world conditions. For the purposes of the assessment, however, a comparative assessment is being made between modelled water levels.

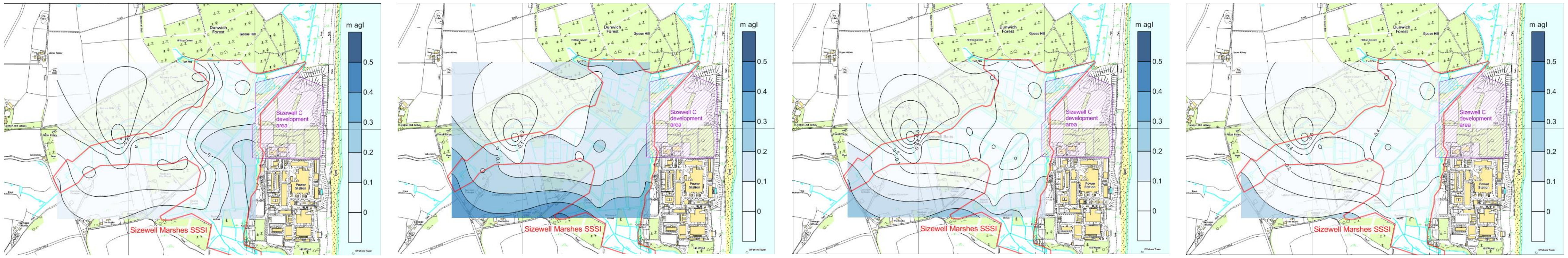
5.5.9 The modelled scenario does not increase the depth or area of surface water inundation when compared to the modelled baseline, or prolong the duration of inundation by greater than two weeks' duration during the growing season. Indeed, the development scenario does not predict any inundation beyond the early part of April. Therefore, no significant effects upon the M22 fen meadow are predicted.

Figure 9A. Baseline contour plots (m agl) – areas experiencing inundation are shown in blue



November 2013 February 2014 March 2014 April 2014

Figure 9B. Contour plots during construction scenario (m agl) – areas experiencing inundation are shown in blue



November 2013 February 2014 March 2014 April 2014

6. CONCLUSIONS

6.1.1 The revised approach presented in this report, taking into account stakeholder feedback, represents a structured and robust approach for assessing the potential impacts of the Sizewell C development on the hydrological regime underlying the sensitive M22 fen meadow vegetation in the Sizewell Marshes SSSI, considered to be the plant community most likely to be sensitive to changes in hydrological regime. The assessment methodology uses the numerical model to define “synthetic” baseline hydrological conditions, establish thresholds, quantify potential changes caused by development and test the efficacy of mitigation.The assessment approach considered for M22 could also be adapted, if required, for other wetland habitat types, for example floodplain grassland within the Minsmere to Walberswick Heaths and Marshes SSSI.

6.1.2 A worked example, in the area of anticipated greatest change, has been presented to demonstrate how the methodology will be applied during the assessment stage. Despite the worked example not being based on final design information key aspects have been included, such as the cut-off wall, internal dewatering system and temporary works compounds. The embedded mitigation in the worked example had limited refinement, as the model scenario is not an actual assessment scenario, however some positive outcomes are already apparent:

- Using a worst-case development scenario with the greatest potential to cause change in the hydrological regime has defined a ZoI showing potential effects are likely to be localised to the fields close to the development footprint.
- Increased resolution has been achieved using observation points on a field by field basis, allowing a more constrained assessment of potential impacts of change.
- Initial modelling outcomes suggest that the development is unlikely to significantly affect summer inundation or the winter hydrological regime.
- The efficacy of mitigation measures such as the embedded control structure can be modelled.

7. REFERENCES

Wheeler, B.D., Shaw, S.C., Brooks, A, & Whiteman, M. (2010). Ecohydrological guidelines for lowland wetland plant communities - fens and mires update March 2010.

Atkins (2016a). Sizewell Site C – Transient Groundwater Flow Model Report [Ref: 5129919/TR/033].

Atkins (2016b). Technical note: Sizewell Site C - follow up works from transient model workshop.

Atkins (2016c). Technical note: Sizewell C Groundwater Model – Scenario Modelling (DRAFT).

EDF (2016). The M22 Vegetation community: Hydrological tolerances and sensitivities A proposed approach for assessing hydrological impacts.

Environment Agency (October 2016). Comments on The M22 Vegetation Community: Hydrological tolerances and sensitivities. A proposed approach for assessing hydrological impacts' (Version 5, September 2016).

Natural England (October 2015). Comments on The M22 Vegetation Community: Hydrological tolerances and sensitivities. A proposed approach for assessing hydrological impacts' (Version 5, September 2016).

ANNEXES

Annex A Proposed scenario runs

Annex B High resolution plots for the time series plots at each of the Observation Points within the assessed field for the worked example, and Figure 6

Annex A Proposed scenario runs

7. Future scenario modelling

The calibrated transient model will be used to assess a range of design scenarios representing discrete phases of the development comprising the enabling phase, construction phase and operational phase, summarised in Table 6-1 below.

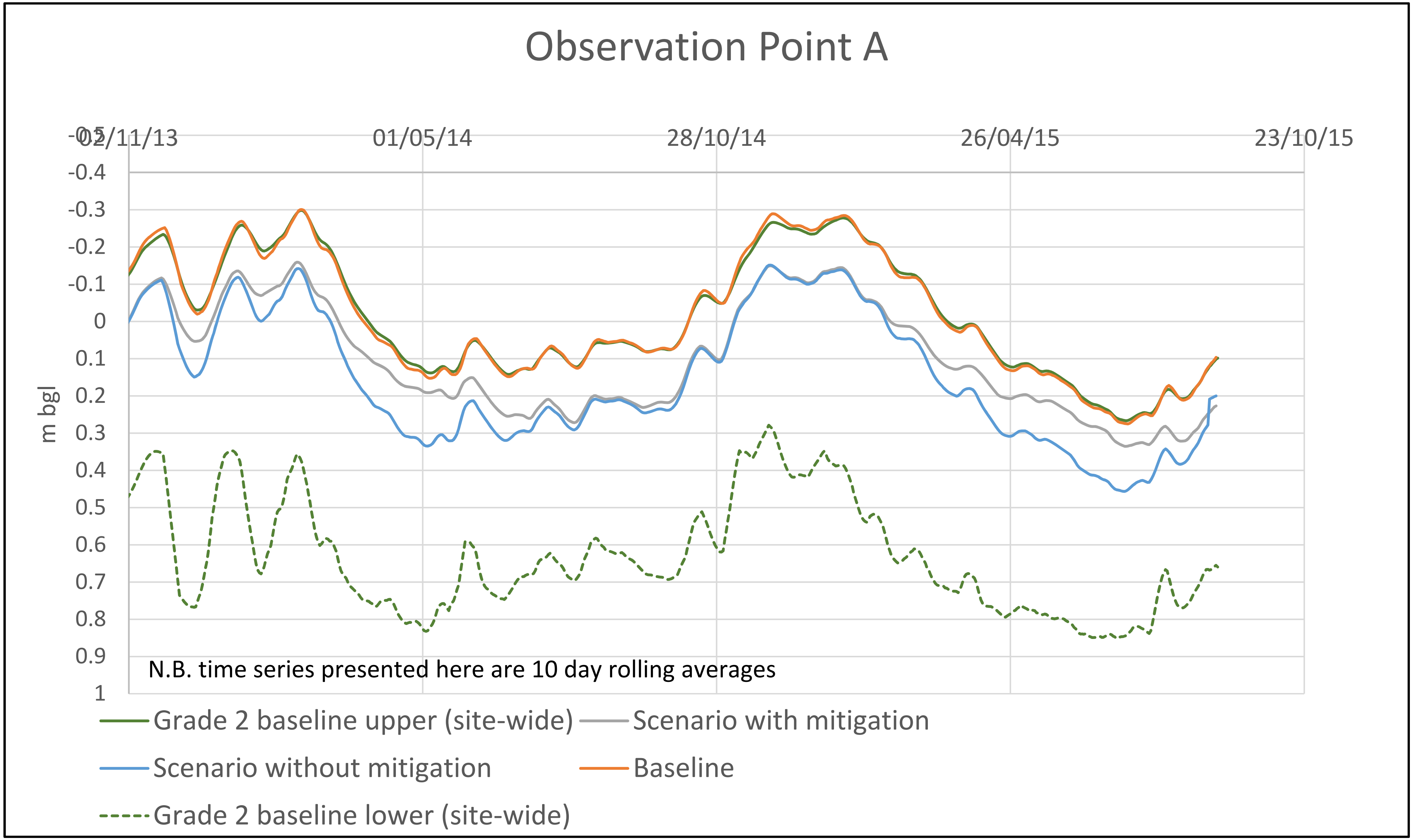
Table 7-1 Summary model scenarios

Scenario	Development aspects		Climatic conditions
	Permanent	Temporary*	
Baseline	None	None	• Present day "normal" • Driest likely • Driest possible • Wettest likely • Sea level rise and climate change
Site establishment	• Realignment of surface watercourses to the west and north of the platform. • Presence of the Aldhurst Farm Habitat Compensation Scheme. • Presence of a SSSI crossing between the main development site and the TCA. • Presence of a deep cut-off wall around the main platform. • Presence of sheet pile walls along the western and northern sides of the platform toe.	• Presence of fully excavated Borrow Pits. • Clearance and relevelling of TCA. • Presence of elevated platform in main development site (height in m OD to be determined).	• Present day "normal" • Driest likely • Driest possible • Wettest likely
Main construction	• Realigned surface watercourses to the west and north of the platform. • Presence of the Aldhurst Farm Habitat Creation Scheme. • Presence of a SSSI crossing between the main development site and the TCA.	• Construction dewatering within the cut-off wall. • Presence of the TCA, including the campus. • Presence of Water Management Zones. • Presence of the TCA, including the campus.	• Present day "normal" • Driest likely • Driest possible • Wettest likely

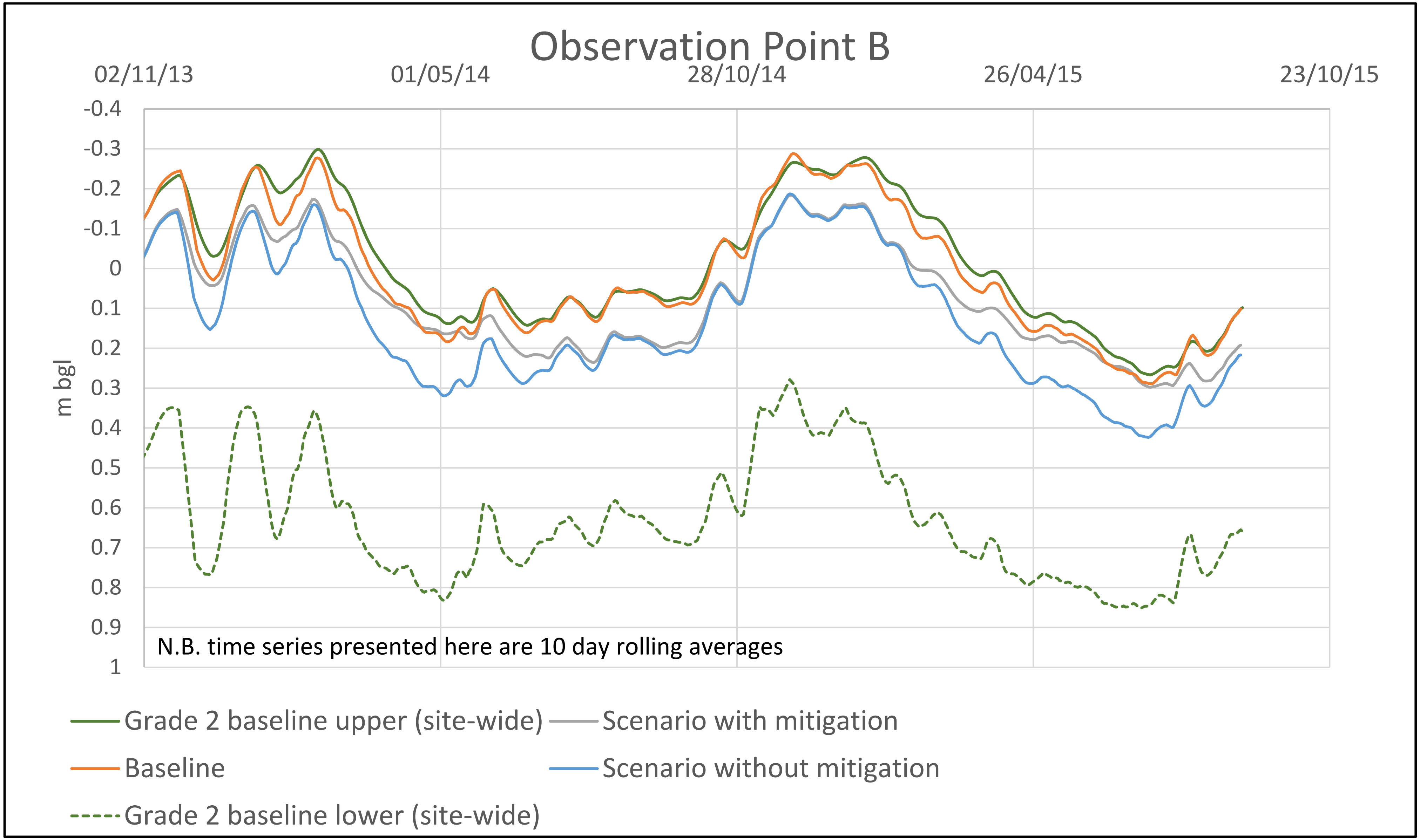
<table>
<tr><th rowspan="2">Scenario</th><th colspan="2">Development aspects</th><th rowspan="2">Climatic conditions</th></tr>
<tr><th>Permanent</th><th>Temporary*</th></tr>
<tr><td></td><td>Presence of a deep cut-off wall around the main platform.
Presence of sheet pile walls along the western and northern sides of the platform toe.
Construction of site platform to final level.
Presence of fully backfilled and restored Borrow Pits with allowance for settlement (elevation in m OD to be determined).</td><td>Stockpiling of material over backfilled borrow pit (details to be determined).</td><td></td></tr>
<tr><td>Operation</td><td>Realigned surface watercourses to the west and north of the platform.
Presence of the Aldhurst Farm Habitat Creation Scheme.
Presence of a SSSI crossing between the main development site and the TCA.
Presence of a deep cut-off wall around the main platform.
Presence of sheet pile walls along the western and northern sides of the platform toe.
Presence of raised platform at main development site.
Backfilled Borrow Pits
Potential breach of the cut-off wall;
Presence of low permeability ground cover at main development site.
Reinstatement of Water Management Zones.
Reversion of TCA to pre-development conditions.</td><td>None</td><td>Present day “normal”
Driest likely
Driest possible
Wettest likely
Sea level rise and climate change</td></tr>
</table>

*Condition may apply for duration of scenario but with varying properties e.g. dewatering to differing levels during construction.

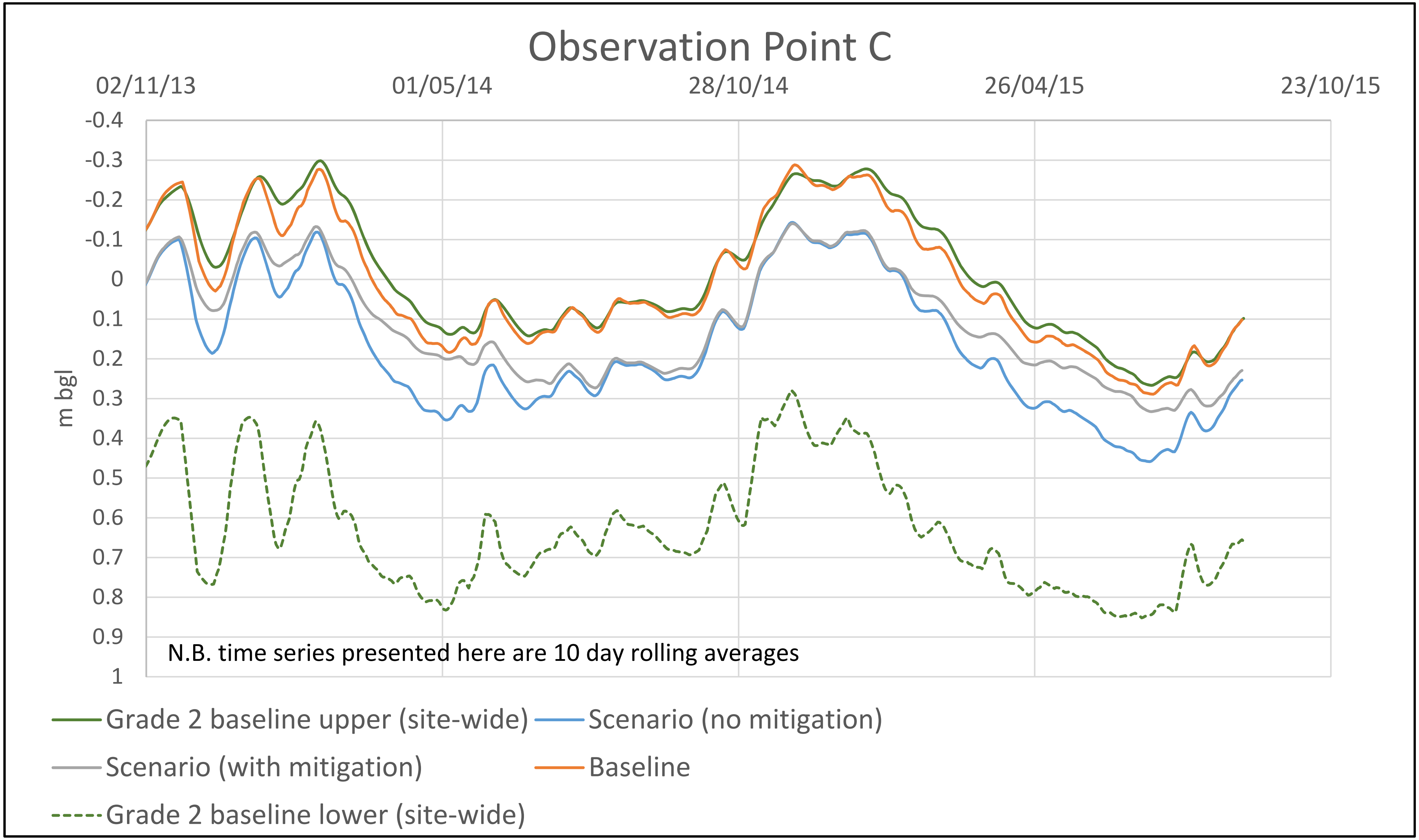
Annex B High resolution plots for the time series plots at each of the Observation Points within the assessed field for the worked example, and Figure 8



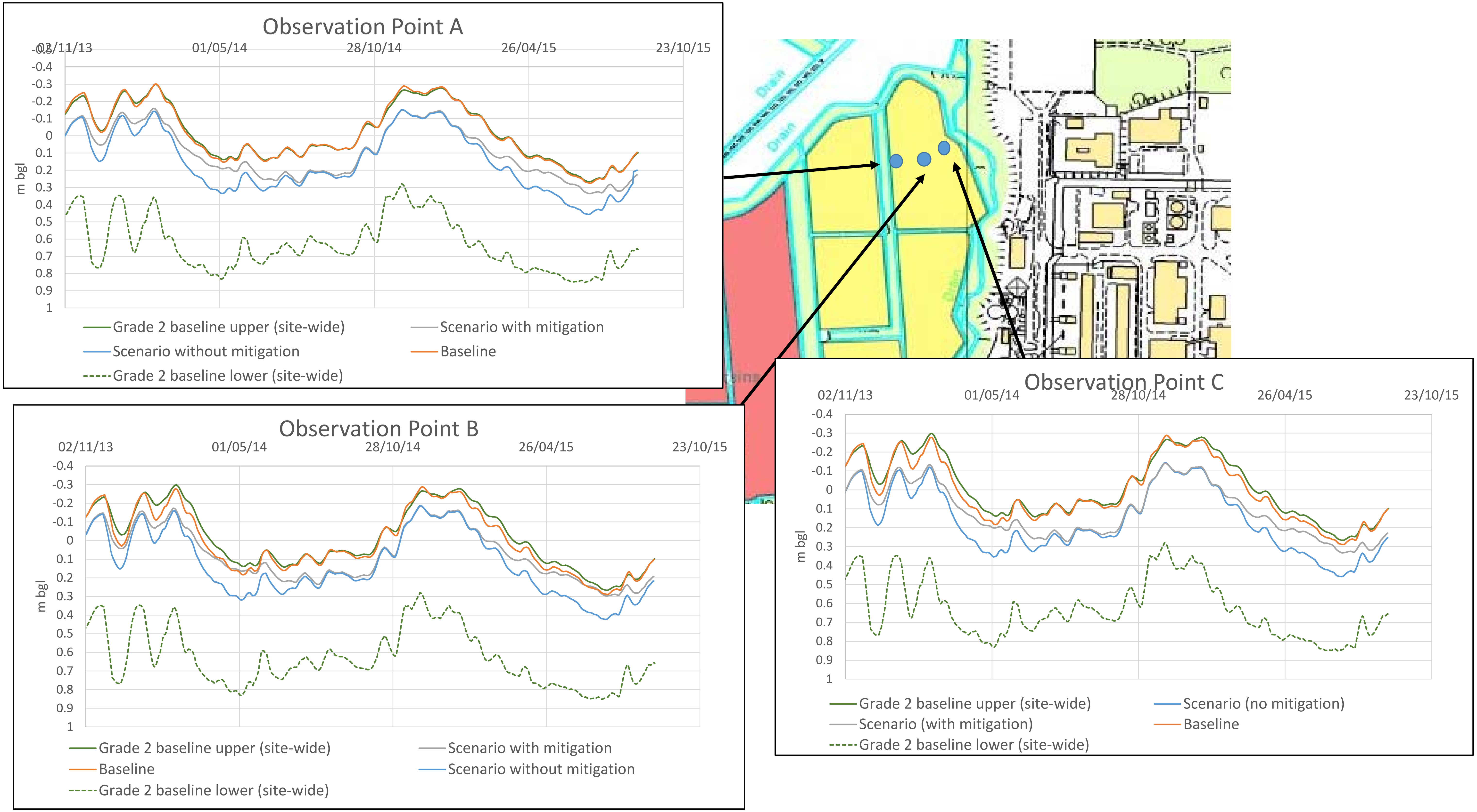
Observation Point A
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m bgl
02/11/13
01/05/14
28/10/14
26/04/15
23/10/15
N.B. time series presented here are 10 day rolling averages
Grade 2 baseline upper (site-wide)
Scenario with mitigation
Scenario without mitigation
Baseline
Grade 2 baseline lower (site-wide)



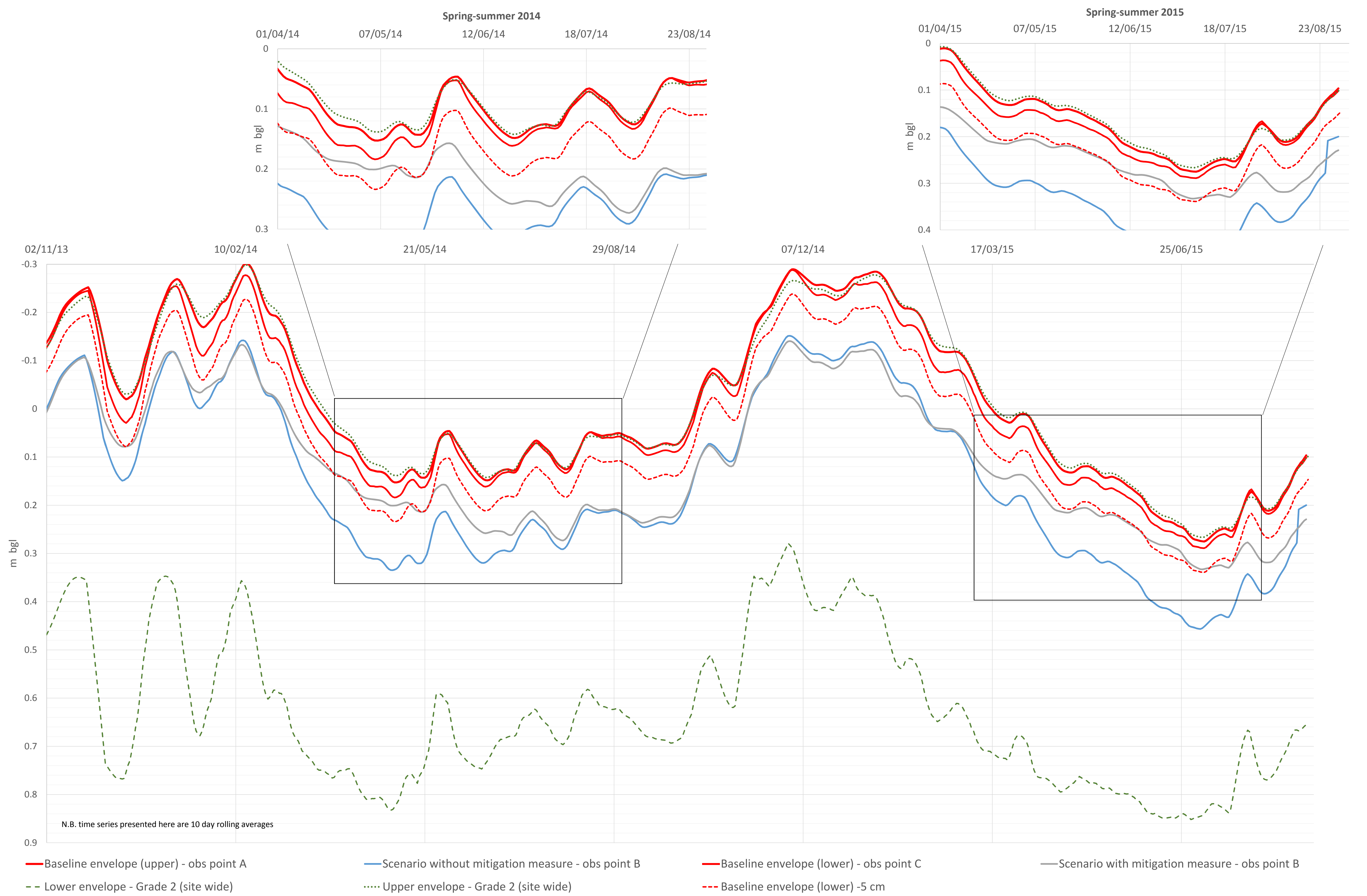
Observation Point B
02/11/13
01/05/14
28/10/14
26/04/15
23/10/15
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m bgl
N.B. time series presented here are 10 day rolling averages
Grade 2 baseline upper (site-wide)
Scenario with mitigation
Baseline
Scenario without mitigation
Grade 2 baseline lower (site-wide)



Observation Point C
02/11/13
01/05/14
28/10/14
26/04/15
23/10/15
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m bgl
N.B. time series presented here are 10 day rolling averages
Grade 2 baseline upper (site-wide)
Scenario (no mitigation)
Scenario (with mitigation)
Baseline
Grade 2 baseline lower (site-wide)



N.B. time series presented here are 10 day rolling averages



Spring-summer 2014
01/04/14
07/05/14
12/06/14
18/07/14
23/08/14
Spring-summer 2015
01/04/15
07/05/15
12/06/15
18/07/15
23/08/15
02/11/13
10/02/14
21/05/14
29/08/14
07/12/14
17/03/15
25/06/15
m bgl
N.B. time series presented here are 10 day rolling averages
Baseline envelope (upper) - obs point A
Scenario without mitigation measure - obs point B
Baseline envelope (lower) - obs point C
Scenario with mitigation measure - obs point B
Lower envelope - Grade 2 (site wide)
Upper envelope - Grade 2 (site wide)
Baseline envelope (lower) -5 cm