RIVER MEDWAY (FLOOD RELIEF) ACT 1976

Inquiry into the Environment Agency's Revised Scheme for the Leigh Flood Storage Area, Kent

Proof of Evidence by Ben Gibson of Jeremy Benn Associates Limited, on behalf of the Environment Agency

31 March 2021

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Personal details and introduction

1. My name is Ben Gibson. I have a BSc (Hons) in Geography, an MSc in Integrated Environmental Studies, and I am a Chartered Water and Environmental Manager with the Chartered Institution of Water and Environmental Management.

2. I have worked for Jeremy Benn Associates Limited for 11 years, and have worked on projects involving flood modelling and flood data for the duration of this time.

3. My current role is "Principal Analyst". My principal experience is focused on non-real time flood modelling and mapping as is used, among other things, to support understanding of strategic flood risk management activities. Non-real time flood risk modelling differs from real-time flood modelling used to support flood forecasting and other flood incident activities such as issuing flood warnings.

4. My role includes being a technical lead on flood modelling projects, as well being project manager for flood modelling projects and undertaking technical reviews of flood risk models. I am Jeremy Benn Associates Limited's modelling lead for Good Practice & Quality Assurance.

5. I was Jeremy Benn Associates lead modeller for the preparation of the fluvial (river) flood risk mapping modelling which is available for the River Medway and which forms the baseline modelling against which the Revised Scheme is compared.

6. I was Jeremy Benn Associates lead modeller for the preparation of the Revised Scheme modelling that has supported the application and also led of the preparation of the associated Flood Risk Assessment (FRA), which is inquiry core document "CD3.1d".

7. My evidence covers the technical details of the flood modelling and how flood modelling has been used to assess how the Revised Scheme affects the existing and predicted future flood risk. Where relevant, supporting information has been presented in Appendices.

8. The evidence which I have prepared and provide for this appeal reference DPI/H2265/20/13 in this proof of evidence is true and I confirm that the opinions expressed are my true and professional opinions.

Glossary of flood modelling terms

9. Flood modelling uses a lot of terminology, some of which will be referred to throughout this Proof of Evidence. Many of the terms used are generic to all modelling studies. Therefore, for clarity I have provided specific definitions for these terms in paragraphs 9.1 to 9.43. The terms are not presented in alphabetical order, which is intentional as the definition of one term often leads directly onto the next term. Additionally, I have set out a list of acronyms used within the Proof of Evidence within paragraph 10. In places within the Proof of Evidence an italicised '*X*' is used in place of a specific number when explaining a quantity or value. This approach is used to help communicate and explain the point being described, for which many different quantities or values for '*X*' could apply.

9.1. Flood risk: A combination of the statistical probability of a flood event occurring and the scale of the consequences if it does. So high risk can include circumstances that might not occur very frequently but have very substantial consequences, such as a dam failing and also circumstances that occur relatively frequently and have more moderate consequences, causing relatively frequent but less severe harm.

9.2. Probability of flooding: The likelihood of a flood event happening is usually expressed in terms of its predicted frequency. This is most often communicated in terms of a percentage. For example, a flood event may be referred to as having a 1% probability of being equalled or exceeded in any one year, also referred to as an Annual Exceedance Probability (AEP). This chance of the event occurring is present each and every year.
The probability of flooding can sometimes be expressed in terms "return period", which is the inverse of the AEP e.g. a 1 in *X*-year return period flood (e.g. if *X*-years is 100-years, this is equivalent to a 1% AEP event). The use of return period as the descriptor tends to lead the reader to conclude that a flood of this magnitude will be recorded only once in every *X*-years. However, this is not the correct interpretation and probability of occurrence is better considered as an event with a percentage chance of being equalled or exceeded in a single year, as described above. It is possible to have two or more 1 in X-year flood events at the same location within the same year – the statistics simply tell us that this type of scenario is very unlikely to occur.

9.3. A flood event: A term used to refer to a period of time where river flows and/or water levels have exceeded their normal range. During a flood event, impacts to communities will not necessarily be felt; they will be dependent on the local flood risk and possibly the standard of protection afforded by any measures that might be in place to reduce the flood risk.

9.4. A design event: A flood event which is used (for example in modelling) to set the conditions to be designed for. Design events are often not observed “actual” events, but are prescribed design conditions prepared using hydrological estimation methods. Often several design events are prepared/assessed which have flow rates with differing probabilities of flooding to understand the effects over a range of circumstances with different chances being experienced.

9.5. Hydrology: The study of water in the environment. For the purpose of this case it is used to refer to the estimation of river flood flows at points of interest. Design flows estimated using hydrological analyses are a key input to a hydraulic model.

9.6. Flood Estimation Handbook: This is a set of five printed volumes (published by the Centre for Ecology & Hydrology) which provides guidance on estimating rainfall and river flood frequency in the UK and outlines methods for assessing the rarity of notable rainfalls or floods.

9.7. Continuous simulation: A hydrological estimation method. This is a rainfall-runoff hydrological method that simulates a long time-series of rainfall and flow events, rather than using a single design event of specified probability. From this long time-series of events, individual design events can be selected. The approach is often considered on catchments where there are complex combinations of factors that affect the magnitude of flood flows and flood water levels.

9.8. Time-series: A term to describe how a variable (e.g. flow or water levels during flood) varies over time.

9.9. Hydrograph: A term used to describe how a river responds to rainfall. This is often presented as a time-series of flow or water levels during an event.

9.10. Rising limb: The trace of the hydrograph before the peak of a flood event has occurred.

9.11. Falling limb: The trace of the hydrograph after the peak of a flood event has occurred.

9.12. Peak flow rate: The maximum rate of flow over a given period of time (often the duration of a flood hydrograph). The peak flow rate can change at any given point along a river system, for instance due to attenuation of flood flows (e.g. due to storage effects), or additional flow inputs e.g. tributaries

9.13. Peak water level (also often referred to as the peak flood level): The maximum level that the water surface reaches over a given period of time (often the duration of a flood hydrograph). The peak water level is likely to change at any given point in a catchment, among other things due to change the ground level.

9.14. Flood propagation: A general term used to describe the change in flood conditions (e.g. change in flow rates and water levels) during a flood event. This may be influenced by factors including the rate of rainfall, catchment conditions and natural or man-made controls on the catchment condition (e.g. flood water storage).

9.15. River bed: The base/bottom level of a channel.

9.16. Probability Distributed Model (PDM): These are a type of hydrological model which use rainfall-runoff methods to estimate flows for the catchment the model represents. Probability Distributed Models seek to replicate hydrological responses to input rainfall by accounting for parameters associated with soil moisture, soil drainage, baseflow (sub-surface flow) and fast runoff (overland flow).

9.17. Rainfall-runoff methods: A hydrological method for estimating flows in a catchment by considering the relationship between storm rainfall and the corresponding stream flow response. While the specification of the analysis prepared relates to the scale (both spatial and temporal) of interest, the methods will often include a.) a volumetric loss to account for hydrological processes such as evaporation, groundwater recharge, interception losses and soil moisture storage and b.) a time distribution model to represent the catchment response.

9.18. Stochastic rainfall series: In the context of the hydrology assessment prepared to provide inputs to the flood risk mapping modelling for the River Medway: artificial rainfall generated with statistical characteristics that are intended to be similar to real rainfall.

9.19. Hydraulic model: A tool to simulate the real world in a repeatable and controllable manner. In this case, the term refers to numerical modelling (which uses computational methods and software to solve the mathematical scientific equations that govern the behaviour of the flow of water) contrasted with another approach, physical modelling, which involves the construction of physical scale models and testing these using actual flowing water in a hydraulic laboratory.

9.20. Flood risk mapping model: A hydraulic model used to prepare mapping of risk during observed or design flood event conditions. One or more design events is often simulated through a flood risk mapping model, and the resulting calculations are presented graphically e.g. as data tables or visualisations of the flooding (e.g. maximum flood extents, flood depths, flood water levels). In this case, the flood risk mapping model provides the definitive results in terms of flood mapping output predictions.

9.21. Flood routing model: A hydraulic model used to determine the change in shape of a flow hydrograph as it moves along a channel and/or floodplain. Flood routing models are not necessarily concerned with calculating water levels. In the context of the River Medway flood modelling, flood routing models were used in the hydrological assessment to assess which flood events within the continuous simulation series provide the required flood event probabilities at different locations across the catchment. The flood routing model is not used to provide definitive flood mapping outputs.

9.22. Boundary conditions: These are conditions that must be included into the model such as the hydrological flows, the ground topography and the channel shape. Some boundary conditions reflect inputs to models (e.g. hydrology inputs such as flow or rainfall), conditions of the system at the downstream extent of/where water leaves models (e.g. water levels at a lake, reservoir or the sea), or can be associated with locations within the model where conditions are known the apply (e.g. known areas where water levels are regulated, or flow vs water level relationships apply).

9.23. Hydraulic roughness: The resistance that water will experience when passing over land or channel features. This is a function of the materials of the surface (the surface can include: the river bed, banks or floodplain), including the extent, density and type of vegetation growth. Flood water will flow more easily over smooth surfaces (such as short grass or concrete) than is the case for rough surfaces (such as hedges, thickets, woodland). Hydraulic roughness is often expressed as the coefficient Manning's *n*, described below.

9.24. Manning's *n*: This is a roughness coefficient first introduced by Irish Engineer Robert Manning in 1889, which represents the roughness or friction affecting the flow of water by the surface (e.g. channel) over which the water flows. The rougher the surface the greater the effect of friction on the flow.

9.25. Reservoir Unit: An input specific to Flood Modeller software hydraulic models (other hydraulic software packages may have similar inputs, but named differently), in which an elevation vs area relationship is established for a region of land, and applied in the model to represent where storage of water is possible (the elevation vs area relationship enables volumes of storage to be derived).

9.26. Digital Terrain Model (DTM): A mathematical representation of the ground surface with all vegetation and buildings removed ('filtered out') to provide a bare earth representation of the ground surface. A DTM is most often in the form of a regular grid, in which an elevation value is assigned to each grid square. In flood studies they are usually developed from LIDAR surveying and the surveyed surface is often referred to as a Digital Elevation Model (DEM).

9.27. LIDAR, an acronym (Light Detection and Ranging): Sometimes called 3D laser scanning. LIDAR is a remote surveying technique that uses a laser scanner, usually mounted to a light aircraft, to measure the shape and elevation of the ground surface. The approach produces highly detailed elevation maps of the ground surface.

9.28. Metres Above Ordnance Datum (mAOD): An ordnance datum is a vertical datum used for deriving altitudes/elevations. A point location or feature may be expressed as have a distance above ordnance datum (AOD). In this instance, the Ordnance Datum refers to the datum at Newlyn. Inputs to hydraulic models are often applied in mAOD, and outputs are often exported in this format too e.g. water levels at different points along a river system.

9.29. Baseline model: A descriptive term applied to a model that represents the current conditions of an area. In this case, the baseline model represents Leigh FSA as operated in accordance with the River Medway (Flood Relief) Act 1976, with a maximum operating water level of 28.05mAOD.

9.30. Revised Scheme model (sometimes referred to as a “Scenario model”): A model that incorporates changes to the baseline model to represent proposed changes associated with a scheme/scenario. The effects of a proposed scheme or scenario in terms of flood levels or extents can be investigated by comparing the results against a Baseline model. For the Leigh FSA, the Revised Scheme model reflects the scenario where the Normal Maximum Operating Water Level (NMOWL – see below) is increased to 28.60mAOD.

9.31. Normal Maximum Operating Water Level (NMOWL): The maximum water level, measured on the upstream side of the Leigh FSA permitted under the Scheme. This is currently 28.05mAOD. The Revised Scheme seeks to increase this level to 28.60mAOD.

9.32. Model parameter: A variable in a model that is used to represent an environmental condition / physical property from the real world. These can exactly match the real world or be approximations, typically based on accepted practice or empirical research. A model parameter can also refer to a value that is specified to inform the way in which the numerical calculations are solved by a computer for the simulation e.g. the model timestep.

9.33. Model schematisation: A general term referring to the configuration of the model with regards to its various components e.g. representation of channels, floodplain, structures, flood flow inputs etc.

9.34. Timestep: A model parameter which describes the frequency at which the mathematical calculations used to predict the flow of water are computed. Model timesteps are often in the order of seconds e.g. flows/levels within the model are calculated at every location every *X*-seconds.

9.35. Model proving: A descriptive term reflecting the process of investigating and providing model results that show the model appropriately represents the characteristics of the actual system being simulated. The outcome of this exercise provides information that informs the level of confidence that users can place in the predictions. The activities that can be completed as part of model proving are often linked with availability and quality of observed data. Model proving activities may include model calibration, verification and sensitivity testing. It may also include ‘sensibility checks’ on the predictions, which are less quantitative in nature, but reflect on people’s understanding of the effects that are experienced at area of interest. For instance, this could involve the understanding of flooding mechanisms from persons that knowledgeable of the area of interest being compared against the model’s predicted flooding.

9.36. Model calibration: The process of adjusting aspects of the model e.g. its schematisation, input of parameters, to improve the quality in the model predictions in representing previously observed conditions (typically, measured flows and levels and flood extents). The process demonstrates that the model can reliably represent past events (within the agreed tolerance levels) to give confidence that it is an appropriate tool for investigating flood risk.

9.37. Model verification: The process of taking a model that has been calibrated and testing its ability to recreate previously observed conditions for an independent set of historical data, not used in the calibration process. A model is said to be verified when the outputs of this process produces results that match the conditions seen during the historic data set (with in the tolerance set for the modelling exercise).

9.38. Model sensitivity testing: the process of adjusting parameters within the hydraulic model and assessing the change in predictions when these assumptions are changed. Consideration is often given to whether adjustment of parameters is needed to try and improve the fit between modelled and observed conditions and to understand the sensitivity of model results to the assumptions made by the modeller.

9.39. Model uncertainty: Aspects of the hydraulic modelling which are difficult to know, or are known but precisely not quantified. Aspects of model uncertainty could influence the ability of the model to produce representative and/or robust predictions of flooding. Uncertainty with a model is often linked with the confidence that can be placed in its outputs.

9.40. Freeboard: An allowance that takes account of adverse uncertainty in the prediction of physical processes that affect a defence level and physical processes which affect the defence level, which have not been allowed for in the design water level. This definition is taken from Environment Agency Report SC120014, titled “Accounting for residual uncertainty: updating the freeboard guide”.

9.41. Backwater effect: This is where conditions downstream of the point or area of interest, influence the flows/flooding at the area of interest.

9.42. Residual risk: Environment Agency Report SC120014, titled "Accounting for residual uncertainty: updating the freeboard guide", defines residual risk as "The risk which remains after all risk avoidance, reduction and mitigation measures have been implemented". The concept presented within the Flood risk and coastal change section of the Planning Practice Guidance (Reference ID: 7-041-20140306) provides a useful set of examples of what residual risk can include. These examples are under three categories 1) failure of flood management infrastructure, 2) failure of a reservoir and 3) a severe flood event that exceeds a flood management design standard. Residual risks are common in flood risk management schemes, as every possibility eventuality cannot be designed for.

9.43. Flood Risk Assessment (FRA): This is a document that assesses the flood risk to and from a proposed development or scheme. Where necessary, Flood Risk Assessments are prepared to accompany a planning application submitted to the local planning authority. An FRA reviews a proposed development or scheme against the risk of flooding from all relevant sources (e.g. river (fluvial), surface water (pluvial), groundwater etc) and understands any changes in flood risk to or from the development compared with the current (baseline) position.

10. Acronyms used within the Proof of Evidence are listed below. For completeness, where acronyms have been stated within the Glossary of Terms, they have been repeated here:

1D: One-dimensional
2D: Two-dimensional
AEP: Annual Exceedance Probability
AMAX: Annual Maxima
DEM: Digital Elevation Model
DTM: Digital Terrain Model
FRA: Flood Risk Assessment
FSA: Flood Storage Area
GIS: Geographic Information System
LEHES: Leigh Expansion and Hildenborough Embankment Scheme
LIDAR: Light Detection and Ranging
mAOD: Metres Above Ordnance Datum
MIOS: Measures in the Interest Of Safety
NMOWL: Normal Maximum Operating Water Level
NPPF: National Planning Policy Framework
OBC: Outline Business Case
PDM: Probability Distributed Model
PPG: Planning Practice Guidance
RMMMP: River Medway Catchment Mapping and Modelling Project

11. In places within the Proof of Evidence the use of 'elevation' and 'level' may be used interchangeably when describing the height of an object, water surface or value above Ordnance Datum.

12. In places within the Proof of Evidence the use of 'flood depth' and 'flood water level' may be used interchangeably when describing changes in flooding. At any given location, an increase in flood depth of *X* will correspond with an increase in flood water level of *X* at the same location. This premise is presented in Figure 1. The inclusion of a tree within the graphic is illustrative only. Changes in water depths/levels are often compared against receptors to understand the change in flooding.

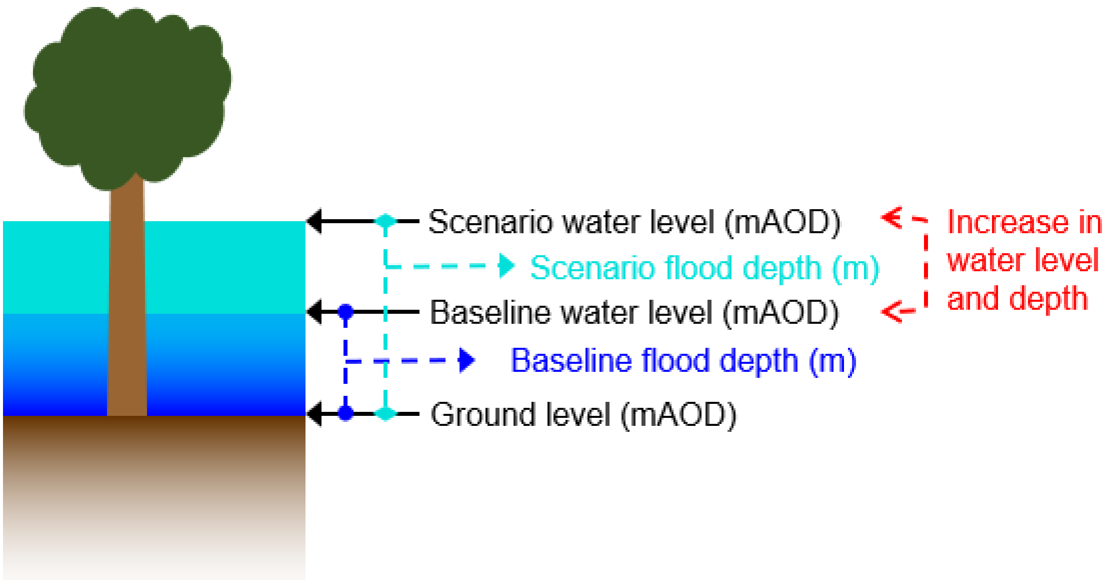

Figure 1: Conceptualisation of how flood depth and flood level are related

13. The flood risk mapping models prepared for the River Medway catchment were simulated for 140 hours of flooding, within which the peak of the flood event occurs. Therefore, graphs and time-series of data presented within this proof of evidence will have time-series that reflect this duration of time: 0-140 hours.

Why flood modelling and mapping work is prepared to assess flood risk

14. As the modelling provides the results that are the basis for the conclusions in the FRA, I consider that it is helpful to clarify what flood modelling is used for, and its potential limitations.

15. The Environment Agency commissions flood modelling to help support their requirement to take a risk-based approach to managing flood risk from rivers and the sea. Large scale flood models are not generally developed in-house by the Environment Agency. Typically, external consultants are employed to use the Environment Agency data and work jointly to produce these flood models on the Environment Agency's behalf. Ownership of the model and its results rests with the Environment Agency.

16. A useful way to visualise the results of a flood modelling exercise is to present the expected maximum extent of flooding on a mapped background. This makes it easy to visualise areas prone to flood risk for flood events with different probabilities of occurrence. Additionally, other information that is often presented from flood modelling is the maximum depths of water that are predicted at locations across an area of interest (e.g. metres above ground level), as well as the maximum water levels (in metres Above Ordnance Datum, mAOD). Refer to paragraph 39 for further details of visualising flood modelling outputs.

Understanding flood risk

17. For the purposes of applying the National Planning Policy Framework (NPPF) and the accompanying Planning Practice Guidance (PPG), "flood risk" is defined as a combination of the probability and the potential consequences of flooding from all sources. With respect to fluvial flooding on the rivers Eden and Medway the NPPF requires that an assessment of flood risk involves consideration of the both the probability and consequences of flooding. Accordingly, the evidence presented in this Proof not only focuses on explaining the hydrological and modelling methods used to analyse the flood probability and the results obtained, but also considers the consequences of the changes to the flood probability resulting from the implementation of the Revised Scheme.

Probability of flooding

18. In accordance with the Table 1 of the PPG, the Flood Zones describe how consideration should be given to the probability of flooding. The probabilities of a given flow rate occurring at any particular point in a river system can vary between virtually zero and near certainty. When considering flood risk, the probability is often referenced in terms the annual probability (likelihood) of flooding. Whether or not these flow rates can lead to flooding depends on local factors. Typically, as the probability of a location being flooded reduces, the consequences of a flood event (linked in part to the magnitude of the flood event) typically increases. For instance, a flood event with a lower probability of occurrence will often have a larger flood extent (and so flood depths and water levels) compared with a flood event with a higher probability of occurrence.

19. Even where long records of river levels and flows are available, we cannot be sure that the full range of potential floods has been experienced. There is always a chance that a more severe flood than previously observed may occur in the future. A method is therefore required for estimating a more complete range of possible scale of floods at a given location.

20. A series of reference events known as "design events" are therefore commonly used. These are theoretical events, the magnitude of which is often informed by statistical analysis of flood behaviour at the site in question to help determine what the size of these reference events should be. A range of design events within different probabilities are often prepared, typically including flood events that are considered to occur relatively frequently e.g. 20% AEP (1 in 5 chance

of being equalled or exceeded in a single year), to those that are occur very infrequently e.g. 0.1% AEP (1 in 1000 chance of being equalled or exceeded in a single year).

21. In flood risk studies, preparation of the flows used to assess design events takes place as part of a hydrology assessment. A hydrology assessment, among other things, determines what flood estimation approaches are appropriate for the watercourse and catchment being considered, investigates the data available to inform analysis (e.g. data at rainfall or river gauges), considers historic flood events in the catchment, and prepares flood estimates following the preferred flood estimation method(s). The assessment is then typically recorded in a hydrology report (often referred to as a flood estimation report).

22. The design event flows prepared as part of the hydrology assessment are then typically used in the hydraulic model (using a computational model) to provide predictions of flooding for each design event.

Consequences of flooding

23. With respect to an FRA the PPG states "The assessment should demonstrate to the decision-maker how flood risk will be managed now and over the development's lifetime, taking climate change into account, with regard to the vulnerability of its users (see Table 2 – Flood Risk Vulnerability)". Table 2 of the PPG contains information on the "Flood risk vulnerability classification" and identifies the following categories to be considered:
    - Essential infrastructure
    - Highly vulnerable
    - More vulnerable
    - Less vulnerable
    - Water-compatible

    In addition to Table 2, the PPG also contains information in Table 3 setting out how consideration should be given to flood risk vulnerability and Flood Zone compatibility.

    Table 3 is reproduced as follows:

Vulnerability Classification		Essential Infrastructure	Water-Compatible	Highly Vulnerable	More Vulnerable	Less Vulnerable
Flood Zone	Zone 1	✔	✔	✔	✔	✔
	Zone 2	✔	✔	Exception Test	✔	✔
	Zone 3a	Exception Test	✔	✖	Exception Test	✔
	Zone 3b	Exception Test	✔	✖	✖	✖

✔ *Development is appropriate*

✖ *Development should not be permitted*

24. The Revised Scheme is designated as water-compatible according to Table 2 of the PPG. Table 3 also illustrates how the flood risk vulnerability of uses should be taken into account in an FRA. Water-compatible development is shown as being appropriate in all Flood Zones, providing evidence that for water-compatible development it is possible to assume there is no increase in risk in circumstances where the probability of flooding increases or decreases (the logic being that if there was an increase in flood risk then there would be a "x" in one of the boxes). This is logical since for water-compatible development the effect of a flood is not material, as compared to more vulnerable development that is damaged or affected by a flood occurring.

What is a hydraulic model?

25. "Hydraulic modelling" in the context of this case refers to the use of specialist computer software (computational modelling) that use numerical methods to solve the arithmetic equations that scientifically represent the behaviour of flood flow, water level and velocity (as well as other metrics) in different physical settings.

26. The "models" prepared (flood risk mapping models and flood routing models) are a simplified representation of reality. However, influential physical components of the river system and catchment hydrology are represented by numbers and water level predictions made by solving the fundamental equations of fluid motion (which are largely dictated by gravity effects, as water flows downhill and involves the transfer of potential energy [height] to kinetic energy [movement]). Therefore, the "model" itself is a combination of appropriate inputs (boundary conditions e.g. flood flows), physical representation of the river channels and floodplains (e.g. geometry, hydraulic roughness) and an approximation of how water moves (the numerical model).

27. A key decision in the process of developing a hydraulic model is the "schematisation" of a river or catchment system, as this defines the conceptual approach to simplifying complex topography and river flow components so they can logically represent the observed characteristics of the actual system.

28. A model will be created for a specific stretch of river by collecting detailed measurements using a combination of ground based and remote surveying to understand the dimensions (size) of the channels and floodplains and the resistance that water will experience when passing over or through these land and channel features (known as roughness).

29. Information to inform river dimensions will include cross-sections of the channel along its length, the size of hydraulically significant bridges, culverts and weirs, and the shape and elevation of the floodplain. Decisions on the hydraulic roughness values to assign for the channel and floodplain will often involve consideration of photos or satellite imagery to help understand the land cover (e.g. hardstanding, grassland, trees), obstructions and other information. All this information is compiled in the computational model to build an appropriate representation of the river system.

30. The model will use the inputs (the design events) calculated in the hydrology assessment and simulate how water will flow through the model due to the controlling influence of gravity and resistance to flow. A key component of the resistance to flow is a parameter that represents the hydraulic roughness of the channel and floodplain, which introduce friction which will inhibit the flow. The balance between gravity and resistance to flow is key to determining what the flood level and extents will be at a given location.

31. Different software (these are commercially available products) use different numerical methods to provide solutions to the governing hydraulic equations, so the choice of software is a factor in the characteristics of the results that can be obtained. A number of software packages specifically designed for hydraulic modelling of rivers are available. The Environment Agency does not specify that a particular package should be used. However, the modelling software must be capable of producing the required output. Independent benchmarking using standard datasets has been carried out to allow the capabilities and suitability of different software packages to be demonstrated and compared to other similar packages.

32. Hydraulic modelling is often the most appropriate method to simulate the flow of water through river channels and across floodplains to assess the influence of a proposed development/scheme compared with a baseline.

33. For the purpose of assessing the effects of proposed schemes it is conventional to assemble a “Baseline model” that includes numeric representation of the situation that exists prior to the implementation of a scheme. By making adjustments to the numeric data within the Baseline model it is possible to create a model that represents the characteristics of a proposed scheme (e.g. the Revised Scheme at Leigh FSA). By running the two models that have been created it is then possible to compare the difference in the predicted results to understand the extent of effects arising from the implementation of a scheme.

Use of dimensions in flood modelling and model schematisation

34. Hydraulic models can be classified according to the number of dimensions that they use to represent the system being analysed. For flood risk modelling work in the UK common practice is to analyse systems as being one, and/or two dimensions. In certain applications modelling that solves systems in three dimensions can also be used. In some applications a combination of dimensions is represented in the flood risk model (e.g. 1D and 2D).

35. One dimensional (1D) hydraulic models solve the equations of flow assuming that flow and water level vary only in the longitudinal direction along the watercourse channel and floodplain (e.g. typically from upstream to downstream along the centreline of the watercourse). A typical approach is to represent the performance of the 1D channel system as a series of discrete cross-sections (in the context of the modelling software considered in this case, these are often referred to as “River Sections”) each of which have distance and elevation

pairings along a transect (a line across the channel and/or floodplain) which describe its geometry (each representing the geometry of the channel/floodplain at that location). Other aspects of 1D hydraulic modelling are discussed in the sub-sections below.

35.1. The model can represent flood water flows from one River Section to the next, but can also represent the flow of flood water via other pathways or interact with other features if included within the modelling.

35.2. Where features such as bridges, radial/sluice gates or weirs are present within the channel, 1D modelling software includes specific 'units' which represent the hydraulic performance of specific features e.g. by applying relevant equations to solve the predictions relating to flow, velocity and/or water level. At these structures, flow that would not pass 'through' them, but instead over or around them can be described by additional numerical 'units' e.g. parallel River Sections or other features which typically represent the flow route as if it were flow over a weir (which can be of varied geometry).

35.3. In addition to representing the geometry of the floodplain with cross-sections, it is also possible to define elevation vs area relationships for regions of floodplain and apply these within the model, effectively forming area of a defined volume that varies with height (in the context of the modelling software considered in this case, these are often referred to as "Reservoir Units"). Figure 2 conceptualises a 1D model schematisation.

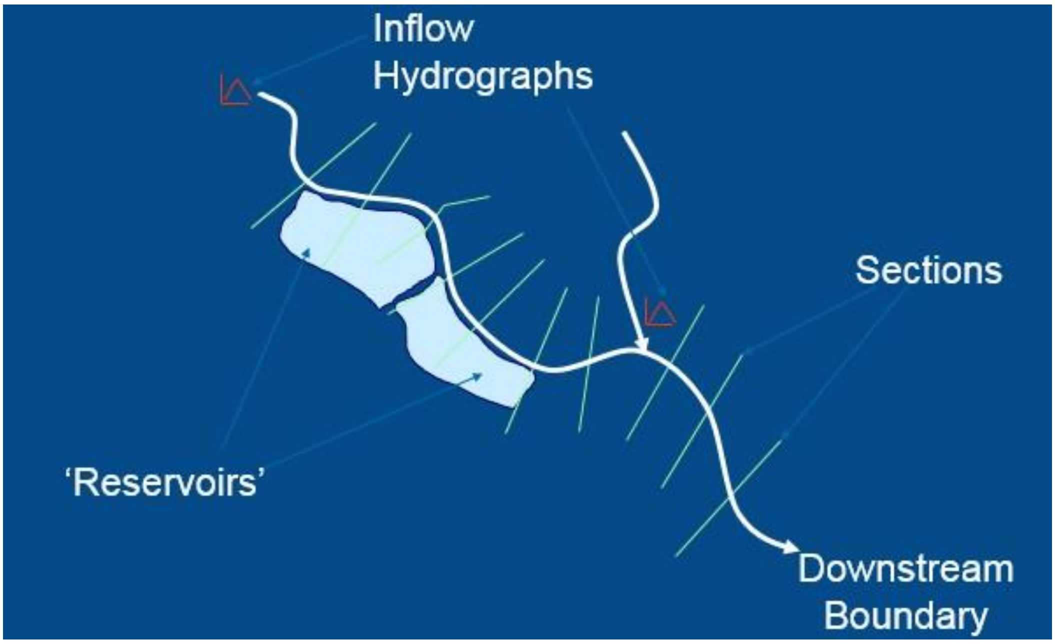

Figure 2: Conceptualisation of an example 1D modelling schematisation

36. One dimensional hydraulic modelling is more computationally efficient, meaning the time taken to simulate a period of time associated with a flood is less (compared with a more computationally involved approach). This can enable notably longer simulation times to be assessed or a greater number of simulations to be completed compared with what is feasible with Two-dimensional (2D) modelling approaches (which are computationally more involved and require solution of the basic equations many more times for each timestep of the computational analysis).

37. Hydraulic modelling prepared using 1D techniques produces a single flow rate, water level and average velocity value at each cross-section, structure, reservoir unit etc within the model at each timestep. The range of features within a model are often referred to as “nodes” as they often appear within the software as point features (e.g. where the cross-section intersects the channel). The models are often referred to as “lumped parameter” models as all of the characteristics of the system are represented at a series of discrete nodes. Intermediate water levels not calculated at a node can only be determined by interpolation, so the spacing and location of nodes can be influential. The interpolation process involves averaging the water level between the upstream and downstream node, with a weighting applied to the average based on the intermediate location position between the two nodes. For example, if the intermediate location is two-thirds of the distance away from the upstream node, the averaging applied to water levels is two-thirds to the downstream node and one-third to the upstream node.

38. By the nature of how 1D hydraulic models solve the mathematical equations, in that modelled units are only linked to the immediate upstream and downstream units, there is no inherent 2D geographical component to the modelling.

39. The water levels predicted by the 1D hydraulic modelling at nodes can then be processed in other geographic software packages (typically Geographic Information System (GIS) software) to compare the predicted water levels obtained from the model results against recorded ground levels, to extract the extent, depth and water level of the flood water. Typically, a water level surface is prepared from each cross-section by linearly interpolating water levels between each cross-section (in simple terms this could be explained as drawing a straight line of the water level at one node to the water level at the next node and so on). This water level surface is then compared with the elevations of the channel and floodplain in a Digital Terrain Model (DTM), to produce the flood extent, depth and level information. Figure 3 presents images supporting the understanding of this process.

40. Two-dimensional hydraulic models calculate water depth and depth-averaged velocity on a fixed grid or irregular mesh. For river systems this is usually for the floodplain on either side of the watercourse channel. The grid (or mesh) divides up the river floodplain into a number of cells (or elements) often of the same, or similar, size. Two-dimensional models solve equations of flow for both the x and y directions (for rectangular grid models the flows are perpendicular to one another). Therefore, whereas 1D models assume that flow and water level vary only in the longitudinal direction, 2D models enable this to vary in a lateral direction to. For fixed grid models y is perpendicular to x. Figure 4 conceptualises a 2D model schematisation. Cell (element) size is a key consideration of the spatial resolution of the model, and will be determined for a model by factors such as the intended application of the modelling, data availability, the size of the river being modelled and available computing power.

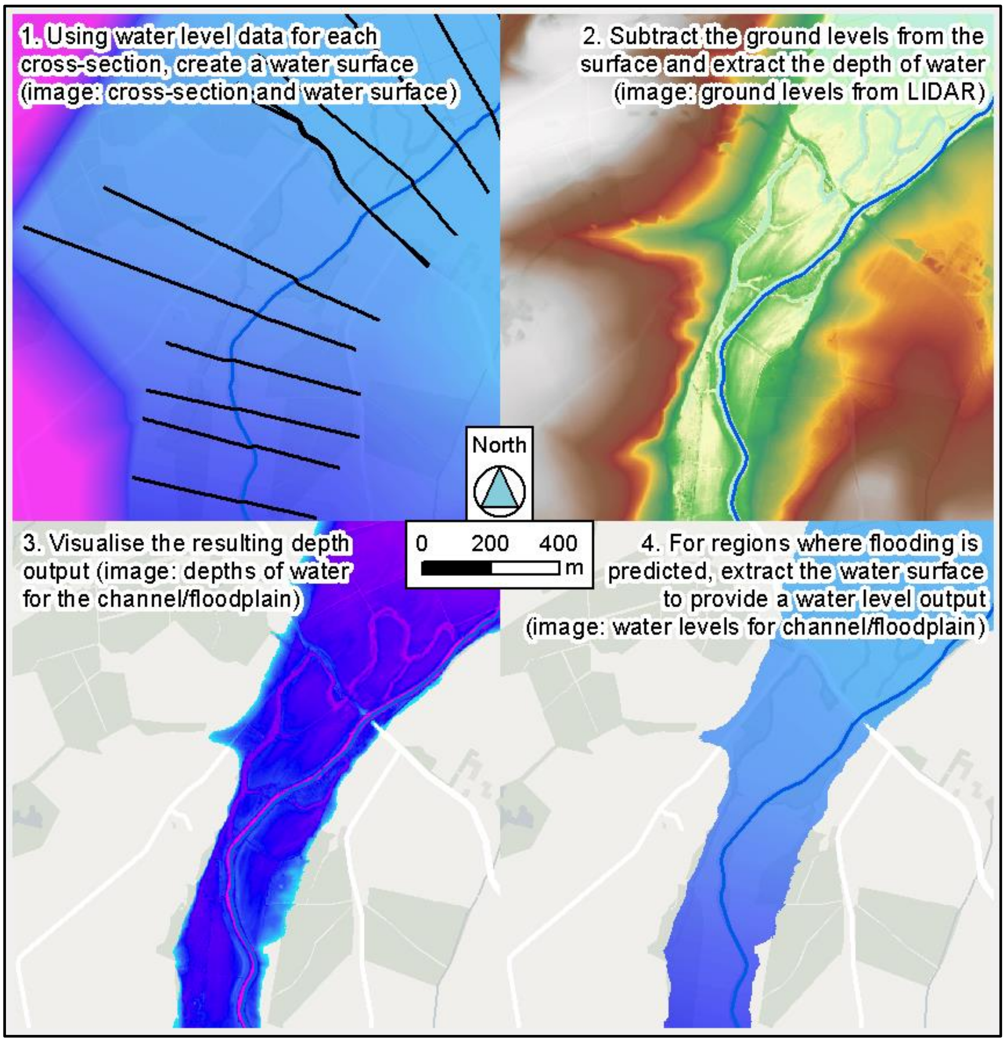

Figure 3: Stages of a 1D model flood mapping process

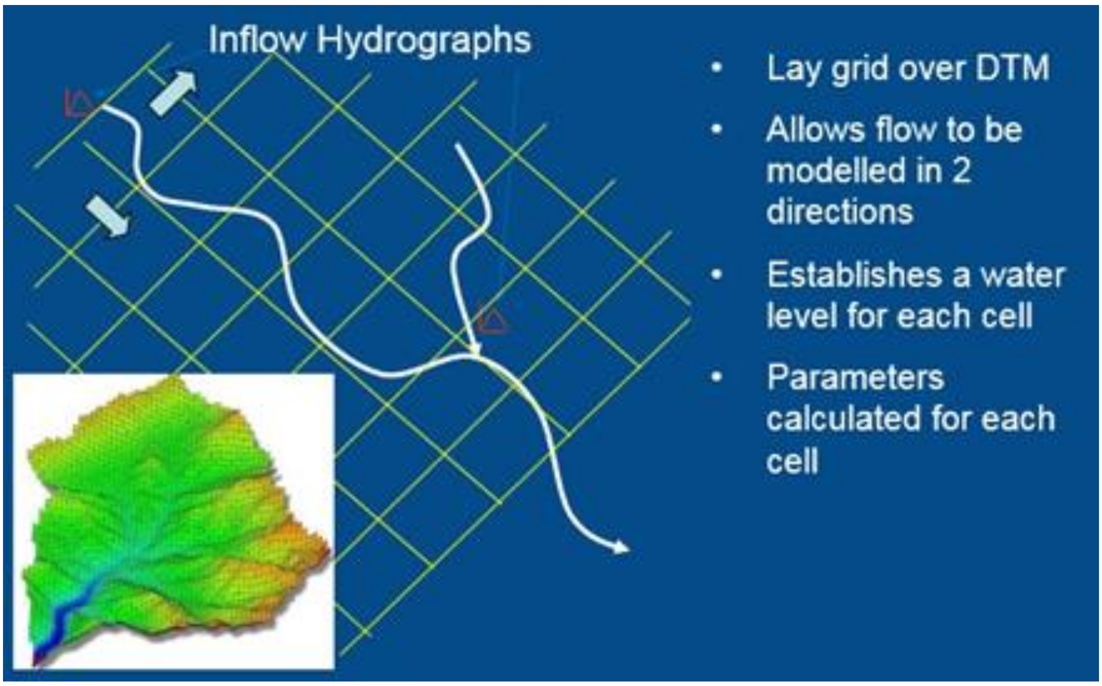

Figure 4: Conceptualisation of an example 2D modelling schematisation

41. Two-dimensional hydraulic modelling approaches use a Digital Elevation Model (DEM) to represent ground levels on the floodplain and other features (e.g. raised railways, roads etc). The topography, slope and surface characteristics (e.g. hydraulic roughness) are used in the calculation of how water will flow and spread across a whole surface (often referred to as the model “domain”). The modelling approach allows for multiple flow paths to be simulated in a number of directions, in response to changing water levels on the DEM surface. This approach often requires less input by the modeller to define flow routes on the floodplain.

42. In fixed grid models, the size of the cells is typically fixed for a given model domain, but a model can contain multiple domains each of which has its own cell size. The computational speed of 2D models is greatly influenced by the size (and therefore number) of the cells/elements within the 2D simulation domain. Mesh size will depend upon the specific project requirements for that area, as discussed in paragraph 40.

43. Two-dimensional modelling approaches have an inherent geographical element to the model, given that ground elevations contained in the DEM are positioned in real-world coordinates. At each grid cell (or mesh element) within the flood risk model, information relating to the flood flows (e.g. depth, water level, flow, velocity) is computed and recorded and can be exported from the model. Often this is exported directly into outputs that can be viewed by GIS software packages.

44. It is possible, and often the case in England, that a river and floodplain system is represented by a combined 1D and 2D schematisation, to realise the benefits of both approaches (and use each to their merits). A combined 1D-2D model typically simulates the river channels and structures in a 1D domain (using 1D methods) and then links this to a 2D representation of the floodplains. A dynamic linkage between the 1D and 2D elements allows water to move freely between channel and floodplain as dictated by the water levels. Figure 5 conceptualises a 2D model schematisation.

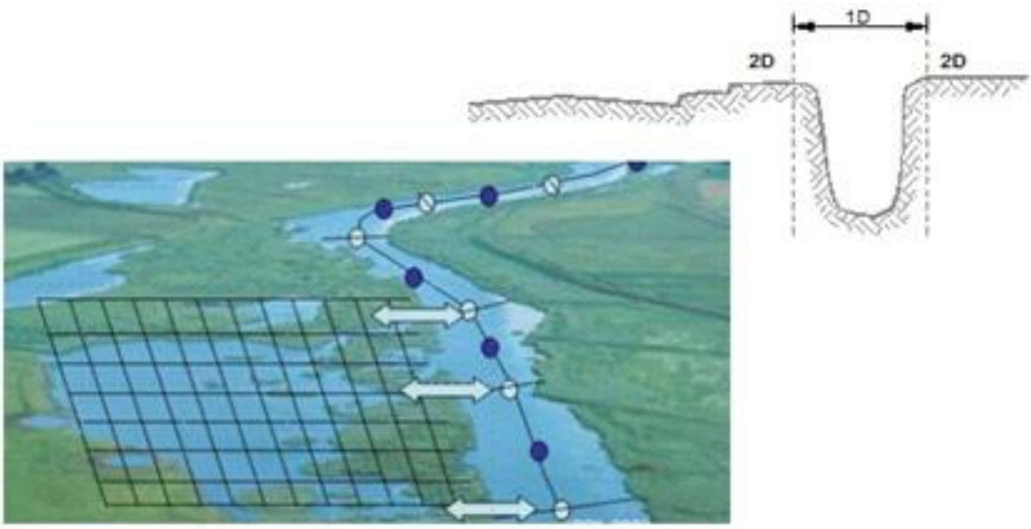

Figure 5: Conceptualisation of an example 1D-2D linked modelling schematisation

45. Decision on an appropriate model schematisation is typically made with knowledge of the source of flooding being considered. Different modelling approaches have different merits, so understanding the source of flooding considered, pathways for flooding, and likely receptors is important.

46. All objects in a river channel or floodplain have an effect on the water flowing past them. Some of the effects are very small and/or localised while others can be very large and widespread. When developing flood models, consideration is given to including objects that produce effects that are significant to the scale of the question being addressed. A decision is often taken not to include objects that produce effects that are insignificant, given that this will be likely to increase the complexity of the model, which could increase the risk of encountering issues that do not provide any further certainty with respect to the results (whether it be with the model itself e.g. stability issues, or associated with the delivery of the project e.g. delivery to programme, size of data produced etc).

Flood model confidence and uncertainty

47. All environmental models involve a simplification of the complexity of the real world. It is not possible or necessary to fully represent the infinite complexity of natural environments. Modelling software includes parameters that can be included to account for this complexity and replicate how it influences the flow of water, while not seeking to define each complex element in its own right. An example of such a parameter is hydraulic roughness.

48. Often, the confidence that can be placed in predictions from a model is considered through a model proving exercise. Model proving activities may include model calibration, verification and sensitivity testing. Establishing, and if possible, improving the confidence in a model also typically results in a reduction in the uncertainty associated with a model and its predictions.

49. For model calibration/verification, an activity completed during development of the model, by comparing model predictions of flooding when simulating historic flood events with actual data recorded during the flood events, it is possible to understand how closely the model replicates reality.
It is usually assessed in terms of one or more the following measures:
- Difference between observed and modelled peak water levels
- Difference between observed and modelled water levels throughout the event
- Difference between observed and modelled timing of peak flow magnitudes
- Difference between observed and modelled flood extents: have areas of observed flooding been predicted by the model, and vice versa have areas observed not to have flooded been predicted by the model.

50. During model calibration, decisions can be taken on whether adjustments should be made to adjust any of the model schematisation, model inputs or model parameters to improve the flood model predictions. The concept here is that the closer the model can replicate observations from historic events the greater the confidence that is held in the model. However, any adjustments made to the model need to be justifiable and physically based. For instance, it is not

acceptable to force-fit the predictions of a model to more closely replicate reality if the adjustments (e.g. to parameters) are beyond what is deemed realistic. An example of an unrealistic adjustment would be increasing the hydraulic roughness of a channel to represent a condition in which vegetation fully occupies the channel, when we know the channel had much smaller quantities of vegetation during the flood event.

51. The calibration process is sometimes followed by independent verification using a different set of data to that used in the calibration (e.g. one or more additional historic flood events are tested). No further changes are made to the model at this point, and the exercise serves to confirm whether the model can replicate the observed flooding (usually to within defined intervals e.g. ±*X*m on water levels) across a range of different event conditions.

52. If the modelled predictions are able to reproduce, within an appropriate limit, important observations from the historic flooding information, then it supports that the model is appropriate for its intended application. That is to say it is an appropriate physical representation of the river system and it can appropriately represent flooding in the area to the level of detail for its intended application.

53. For model sensitivity testing, adjustments are made to model parameters (or sometimes to the model inputs or model schematisation) and the changes in flood predictions assessed. Model sensitivity testing may take place alongside model calibration (to help inform whether proposed adjustments are appropriate and will assist in improving performance), or may be conducted separately.

54. When an adjustment is made to the model as part of a sensitivity test, the change is often compared against the relevant baseline (e.g. the parameter as it was before adjustment) to determine changes in flood predictions. This change may be assessed in absolute terms (e.g. change in water level in metres) or expressed as a percentage change (e.g. change in water depths compared with the baseline). The latter approach can help inform decision-making with respect to how sensitive the model is the adjustment made e.g. while an absolute change in water level at a location considered by some to be relatively ‘large’, if the flood depths in the baseline are also ‘large’, then the percentage change in depth may be relatively ‘small’ (and so the model is less sensitive to the change).

55. Conducting sensitivity testing can help us understand changes in predictions for a single scenario, and thereby be used to reduce the uncertainty in the model and increase confidence. However, when assessing a Baseline scenario against a Revised scenario in flood models, it is important to assess the relative magnitude of change in predictions between the scenarios and understand whether the change in the value of a selected parameter (e.g. hydraulic roughness) in both scenarios affects the overall conclusion. It would not be appropriate to apply the sensitivity adjustment to only one scenario, as this would introduce an additional variable in the model making it harder to determine whether any change in the model predictions is due to the scenario intervention or the parameter adjustment. What this analysis should be looking to understand is whether, when comparing models on a like-for-like basis (with the exception of whatever the scenario intervention is) whether the same conclusions remain.

Flood risk mapping and model projects used to assess the effects of the Revised Scheme

56. Flood risk modelling, mapping and analysis that has helped inform the Baseline and Revised Scheme scenarios has been completed during delivery of several projects. The sections I have presented below describe these projects and the aspects of these that are relevant to the inquiry.

The Environment Agency River Medway Catchment Mapping and Modelling Project (RMMMP) models (2015)

57. In November 2013, the Environment Agency commissioned a project to prepare updated fluvial (river) flood modelling and mapping for the River Medway catchment extending from the upstream of the main river systems on the River Eden and River Medway watercourses, to Allington Lock, Maidstone. The final digital deliverables for the project were agreed in December 2015. The project is here-in shortened to the RMMMP (2015).

58. The main project report for the RMMMP (2015) forms inquiry core document "CD1.18". The modelling project prepared several documents that formed part of the digital deliverables package, which form appendices to the RMMMP (2015) main project report and are provided as other core documents to the inquiry. In addition, a suite of digital deliverables and tools were prepared and accompany the reporting. These include outputs such as predictions of flooding from the model e.g. tabulated water levels, GIS outputs of flooding, as well as the model input and output files themselves. Where necessary, reference is made to documents and/or files from this deliverables package, with reference to specific sections/datasets of interest, where possible.

59. An objective of the RMMMP (2015) modelling was to prepare flood mapping for the catchment area described in paragraph 57 for a range of flood event probabilities, ranging from 20% AEP to 0.1% AEP for scenarios in which current defence infrastructure (e.g. Leigh FSA) is in place, referred to as 'defended case' models, and for scenarios in which current defence infrastructure is not in place, referred to as 'undefended case' models. Modelling and mapping was also prepared for 10% AEP and 1% AEP events with increases to flows of 20% applied, reflecting the guidance at the time for considering predicted future changes to flood flows due to the influence of climate change. The guidance document stating the relevant climate change flood flows applicable at the time of preparing the RMMMP (2015) modelling was the National Planning Policy Framework (2012) and its associated technical guidance document (refer to Table 5) within the document.

Flood risk modelling

60. The approach to preparing updated flood mapping models was agreed via the preparation of a model strategy document, reviewed by and agreed with the Environment Agency project team. The modelling strategy was informed by aspects including review of existing models and consideration of available data.

61. In addition to preparing updated hydraulic models covering the area of interest, updated flood flow hydrology inputs were prepared for required flood event probabilities.

62. The flood risk mapping models for the River Medway catchment were prepared with consideration to the Environment Agency's Operational Instruction 379_05; "Computational modelling to assess flood and coastal risk", provided in Appendix 1 of this Proof of Evidence.

63. Four flood risk mapping models were prepared for the River Medway catchment and referred to as Models 1, 2, 3 and 4. These models were used to simulate predicted flooding in different areas of the catchment. Each model used "ISIS" (later versions are now referred to as "Flood Modeller") and "TUFLOW" computational modelling software packages to calculate the flood predictions. These software packages are some of those that are typically used within the UK to prepare flood modelling predictions, having passed Environment Agency benchmarking tests and being approved for this purpose. A brief summary of each model is presented below, and Figure 5-1 within the RMMMP (2015) main project report, which forms inquiry core document "CD1.18", displays the spatial extent of each model. Appendix B (Model Operation Manuals) of the RMMMP (2015) of the main project report contains more details of the flood models. These are inquiry core document references "CD1.18-2-1" to "CD1.18-2-4".

63.1. Model 1: The spatial extent of the model is the catchment upstream of and including Leigh FSA, with the downstream extent of the model being the embankment at Leigh FSA. The full length of the River Medway main river, including Leigh FSA, and the River Eden main river downstream of the railway line at the east of Church Street, Edenbridge (grid reference: Easting:545015m/Northing:146075m) is represented using 1D modelling techniques. Upstream of the area stated above, 1D-2D modelling techniques are used. For areas that are modelled with 1D modelling techniques, the geometry of the channel and floodplain is primarily described by series of cross-sections positioned at intervals along the watercourse. The geometry of the channels is informed by topographic survey, while the geometry of the floodplains is extracted from LIDAR DTM data. Two exceptions to the cross-section approach to representing floodplains in the 1D area are Hever Lake (located immediately east of Hever Castle) and Haysden Water (located within the footprint of the FSA, to the south of the River Medway and west of the FSA embankment). These locations are represented by reservoir units (elevation vs area relationships) which are connected to the watercourses via structures which discharge into/from the lakes, or 'spill units' representing elevations of the banks along the river. Reasons for selecting a 1D and 1D-2D modelling approaches for Model 1 are discussed in paragraph 100.

63.2. Model 2: The spatial extent of the model extends from immediately downstream of Leigh FSA to downstream of Tonbridge (Hartlake Road). A 1D-2D modelling approach is used for the full extent of the model. The main channels and their structures are represented in a 1D model and the floodplain and is represented in a 2D model. Three domains are present within the 2D model. Two domains (covering the model area from Leigh FSA to the railway line upstream of Tonbridge, and from downstream of the A26 at the eastern extent of Tonbridge to Hartlake Road) have cell sizes of 20m, while the area between these two domains has a cell size of 5m. Reasons for selecting a 1D-2D modelling approach for Model 2 (in addition to Models 3 and 4) are discussed in paragraph 100.

63.3. Model 3: The spatial extent of the model extends from downstream of Tonbridge (A26) to East Farleigh gauging station, including Coult Stream, River Teise and River Beult. A 1D-2D modelling approach is used for the full extent of the model. The main channels and their structures are represented in a 1D model and the floodplain and is represented in a 2D model. Four domains are present within the 2D model. Two domains focused on the floodplain at and around the settlements of East Peckham and Yalding have cell sizes of 6m, while the other two domains, covering more rural areas have cell sizes of 20m. Note that for the 1% AEP and 0.1% AEP undefended case events (which inform Flood Zones 3a and 2 presented on the Environment Agency's Flood Map for Planning), the cell size for the latter two domains was reduced from 20m to 10m.

63.4. Model 4: The spatial extent of the model extends from downstream of Teston gauging station to Allington Lock, including part of the River Len as it discharges into the River Medway. A 1D-2D modelling approach is used for the full extent of the model. The main channels and their structures are represented in a 1D model and the floodplain and is represented in a 2D model, with a single domain that has a cell size of 6m.

Flood hydrology inputs

64. As part of the hydrology assessment, the continuous simulation approach to preparing flood hydrology inputs was adopted for the RMMMP (2015). Justification for this is provided within Appendix A (Hydrology report) of the RMMMP (2015) main project report, and also within paragraphs 97 to 99 of this document. The core document reference for Appendix A (Hydrology report) is "CD1.18-1". Continuous simulation hydrological methods are a form of rainfall-runoff approach identified with the Environment Agency's Flood Estimation Guidelines (Operational Instruction 197_08). Operational Instruction 197_08 is provided in Appendix 2 of this Proof of Evidence.

65. Continuous simulation is a rigorous method for estimating design flows for complex hydrological problems like those present in the River Medway catchment (e.g. the presence of multiple relatively large watercourses and the influence of the operation of Leigh FSA). It involves applying a very long synthetic rainfall series to a model of the catchment, thereby simulating flows over a very long time period (see paragraph 66). The approach enables results

at locations throughout the catchment to be analysed to understand the peak flow for a given magnitude flood event. The benefit is that it allows for the modelling of the whole river system for a wide range of different permutations and combinations of storm event, and by analysing the results to understand the probability of a particular flood. In different locations of the catchment, different rainfall conditions (and therefore flood response) may give rise to a particular magnitude flood event. However, it is also possible that events with similar magnitudes (in terms of peak flow rate) may have different durations and shapes to their hydrographs (the flow rate vs time).

66. For the River Medway hydrology, a simple summary of the approach is as follows:
    - A 5,000-year long spatially-varying stochastic rainfall series was prepared for the catchment. The term stochastic refers to the rainfall model generating artificial rainfall data with statistical characteristics that are intended to be similar to real rainfall.
    - For largest Annual Maxima (AMAX) flood events within the 5,000-year long rainfall record (AMAX events are those with the largest flow rate recorded each year), corresponding flow rates for sub-catchments were prepared by applying the rainfall within Probability Distributed Moisture (PDM) rainfall runoff models that calculate the flow response for the catchment.
    - For these flood events, flow rates were applied to flood routing models of the River Medway, which routes flows through the channel/floodplain. These routing models are numerical models that are more simplified than the flood risk mapping models. For the climate change conditions in which flow rates are increased, an alternative set of simulations were applied to the flood routing models reflecting this increase in flows.
    - Three flood routing models were prepared:
        - 1) ‘Upper Medway’ which extends from the upstream limit of the main river for the River Eden and River Medway catchments to a short distance downstream of Leigh FSA;
        - 2) ‘Middle Medway’ which extends from downstream of Leigh FSA to East Farleigh gauging station (the model also includes reaches of the River Bourne, River Beult (from Stilebridge gauging station) and River Teise (from Stonebridge gauging station), and
        - 3) ‘Beult’ which extends along the River Beult from Smarden to Stilebridge gauging station.
    - Individual events were selected from inspection of the flood routing modelling outputs (flow rates at points throughout the catchment) which represented the required flood event probabilities to be tested. The applicable events changed spatially (e.g. due to the presence of a large tributary watercourse entering the River Medway, and upstream/downstream of Leigh FSA), meaning that multiple events needed to be selected to provide the relevant event magnitude outputs model-wide.
    - The selected events were then simulated through the mapping models described above to provide definitive predictions of flooding for each magnitude flood event.
    - Where multiple events needed to be selected and tested within a model, the model extent was divided up into sub-areas (referred to as ‘output zones’) within which different event predictions were applicable and so were used to inform the resulting flood mapping that was prepared. Output zones were

required in Model 1 and Model 3, and Figure 7-1 and Figure 7-2 within the RMMMP (2015) main project report, which forms inquiry core document “CD1.18”, display their spatial extent for the two models, respectively. The output zone applicable to flood predictions at Leigh FSA is number 8.

Operation of Leigh FSA within the flood routing modelling

67. The radial gates at Leigh FSA can be operated in flood events to actively manage the storage of water in the FSA, and therefore the flow rates that are released from the FSA to the downstream catchment. It was necessary to incorporate an appropriate representation of the operation of the radial gates in the RMMMP (2015) hydrology and modelling analysis, so that predictions of water levels in the FSA and flow rates passing downstream are representative.

68. The operation of Leigh FSA radial gates within the Upper Medway flood routing model is based on a computer programme (set of rules used in the modelling) written to represent how operators choose to adjust the flow rates released from the FSA on the basis of flow forecasts. Further context to the actual operation of the radial gates at the FSA is provided by Mr Andrew Irvine. During delivery of the RMMMP (2015), for a sub-set of continuous simulation hydrology events the computer programme was checked against the choices on operation of the FSA radial gates made by real operators when they were presented with the same flood flows. Refer to paragraph 96 for the outcome of these comparisons.

69. The 1D model structures representing the radial gates were taken forward from the Upper Medway forecasting model with some amendments made to enable the required activities of the mapping project to be delivered (as summarised within section 3.5.3 of the Hydrology report, which forms Appendix A to the main project report for the RMMMP (2015). The core document reference for Appendix A to the RMMMP (2015) is “CD1.18-1”. The flood forecasting model, used by the Environment Agency to assess potential flood conditions using predicted and/or observed rainfall, provided a sensible starting point for representing the radial gates within the flood routing model, as it was already being used operationally by the Environment Agency. In the forecasting model, the gates were operated according to logical rules, with the effect to allow a flow of roughly 75m^3/s to be released from the structure. If the reservoir level reaches 28.05mAOD at the upstream of the radial gates, the gates change operation to release the inflow (as far as they are able) to prevent 28.05mAOD being exceeded.

70. In order to represent the operation of the radial gates in the model, the approach described below was taken. Sections 3.5.4 and 3.5.5 of the RMMMP (2015) Hydrology report, which forms core document reference “CD1.18-1” provide detail of the practicalities of preparing modelling for these scenarios. Key aspects of the approach are as follows:
    - A decision to change the operation of the FSA is made 24 hours before releases have to exceed the normal target outflow. No subsequent revision of this decision is made for the remainder of the model run.
    - An optimum flow released from the FSA is selected (to the nearest 10m^3/s) that gives the lowest outflow without exceeding 28.05mAOD water level at the

upstream of the FSA radial gates. If no scenario is less than that level, the one that gives the lowest water level at the upstream of the radial gates is chosen.

- Figure 3-8 within the RMMMP (2015) Hydrology report, which forms inquiry core document “CD1.18-1”, displays for one continuous simulation event, the varying time-series of outflows from the FSA (left image) and corresponding water-level time-series at the upstream of the radial gates (right image) for various 10m^3/s outflow scenarios.

71. The water-level time-series from the Upper Medway flood routing model at the upstream of the radial gates was extracted from each of the continuous simulation events, and for events taken forward for simulation in the flood risk mapping model, this water-level time-series forms the downstream boundary condition.

72. The continuous simulation time-series outflows from the Upper Medway flood routing modelling were extracted for all events considered within the 5,000-year long event series. These formed the flow inputs to the Middle Medway flood routing model that is used to inform the selection of flood events with the required probabilities along the River Medway to Allington Lock.

The Environment Agency Medway Scenario Modelling project (2016)

73. In December 2015, the Environment Agency commissioned a project to conduct a range of modelling and analysis activities associated with the River Medway and River Beult. This project is referred to as the Medway Scenario Modelling project (2016). Much of this work involved making use of the flood models prepared as part of the RMMMP (2015). The two workstreams within that are relevant to the inquiry are:
    73.1. Updated flood modelling and mapping for the Model 2 flood risk mapping model: Revised flood modelling and mapping was prepared for this model to reflect some refinements to flood inflows for Hawden Stream and Hilden Brook (small tributaries of the River Medway) prepared as part of a different project and to represent updated topographic data for the Cannon Bridge development and Avebury Avenue flood wall in Tonbridge.
    73.2. Updated climate change modelling: Flood modelling and mapping for Models 1-4 (using the updated version of Model 2 prepared in this project) to prepare defended case and undefended case predictions for the 1% AEP event with increases to flow (often referred to as flow allowances) of +35% and +70%.

74. The updated modelling and mapping prepared for the Model 2 flood risk mapping model replaced the modelling and mapping deliverables prepared for the RMMMP (2015), and the climate change modelling and mapping outputs reflected two of several flow allowance scenarios that formed part of updated guidance on assessing climate change in the River Medway catchment (reference: Flood risk assessments: climate change allowances. Available: https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances). This guidance replaced the guidance applicable at the time of preparing the RMMMP (2015) modelling (refer to paragraph 59).

The Environment Agency River Medway Flood Storage Areas Options Modelling project (2016)

75. In August 2015, the Environment Agency commissioned a project to prepare flood modelling and mapping for a range of scenarios associated with assessing the viability of flood management options within the River Medway catchment. The project was concluded in 2016 and is referred to as the Medway Flood Storage Areas Options Modelling project (2016).

76. One workstream delivered as part of this project which is relevant to the inquiry was the preparation of modelling and mapping for a scenario in which the Normal Maximum Operating Water Level (NMOWL) for Leigh FSA was increased to 28.85mAOD. The revised NMOWL tested in this project is not the same level as the Revised Scheme which is the consideration for the inquiry. However, the approach to adjusting the operation of the Leigh FSA radial gates in the Upper Medway flood routing model used for this project is the same as used for the Revised Scheme modelling.

77. Revisions were made to the Leigh FSA operational approach within the Upper Medway flood routing model used in the continuous simulation analysis. The additional storage provided under this scenario reduces peak flow rates downstream for many flood events. Therefore, the flood risk mapping models downstream of Leigh FSA were re-run to incorporate these changes in outflows for required event probabilities and produce updated flood depth maps for comparison with the baseline scenario.

78. This project sought to understand the impacts on outflows from Leigh FSA, and the resulting change in flood predictions for the revised NMOWL scenario. It did not prepare updated flood mapping for the catchment upstream of the FSA, but the approach taken to representing this adjusted NMOWL is the same approach taken for the Revised Scheme which is the focus of this inquiry (a NMOWL of 28.60mAOD).

The Environment Agency Leigh Expansion and Hildenborough Embankment Scheme (LEHES) Outline Business Case Options Modelling project (2019)

79. In December 2017, the Environment Agency commissioned a project to prepare flood modelling and mapping for a range of scenarios to inform the preparation of an Outline Business Case (OBC) for the Leigh Expansion and Hildenborough Embankment Scheme. The project was concluded in 2019 and is referred to as the LEHES OBC Options Modelling project (2019).

80. Following the same approach taken for the Medway Flood Storage Areas Options Modelling project (2016), three alternative Normal Maximum Operation Water Level scenarios were assessed in this project: 28.60mAOD, 28.85mAOD and 29.00mAOD.

81. From the revised continuous simulation hydrology modelling, revised boundary conditions were extracted for inclusion within the mapping models. Flood modelling was produced for each of the NMOWL scenarios for each of the four flood risk mapping models (Model 1, 2, 3 and 4) for the River Medway. Therefore, unlike the Medway Flood Storage Areas Options Modelling project (2016), flood predictions were mapped within and upstream of Leigh FSA.

82. For the River Medway Model 1, the downstream boundary water level at immediately upstream of the radial gates at Leigh FSA can influence the flow of flood water upstream. Therefore, comparison of outputs from the NMOWL scenario modelling with those from the Baseline modelling (28.05mAOD NMOWL) allows any predicted change in flooding due to the NMOWL scenarios to assessed.

83. The 28.60mAOD NMOWL scenario was the preferred option carried forward from the LEHES OBC Options Modelling project (2019) and is the focus of proposed revision to the Leigh Barrier which is the focus of this inquiry. This is discussed further in the evidence presented by Mr Tim Connell.

The Environment Agency Leigh Expansion and Hildenborough Embankment Appraisal and Design project

84. In July 2019, the Environment Agency commissioned a project to prepare the Appraisal and Detailed Design for the Leigh Expansion and Hildenborough Expansion Scheme. This project is referred to as the LEHES Appraisal and Design project.

85. This project continued on from the preferred scheme details prepared as part of the LEHES OBC Options Modelling project (2019). Relevant to the flood modelling and mapping prepared at Leigh FSA, the Revised Scheme involves a change in the agreed operating regime to permit water levels at the upstream of the radial gates to be stored to a maximum of 28.60mAOD. The project also considered the construction of flood defences in Hildenborough, which the Revised Scheme at Leigh FSA will enable. This modelling prepared for the Hildenborough flood defences does not influence the predictions from the flood risk mapping modelling in Leigh FSA.

86. The LEHES Appraisal and Design project included preparation of the Flood Risk Assessment report that was submitted as part of the Environment Agency's application for planning permission submitted to Sevenoaks District Council (reference: 20/02463/FUL). The FRA forms inquiry core document "CD3.1d".

87. Additional modelling and mapping was prepared for the Model 1 flood risk mapping model to support the Flood Risk Assessment report. Flood modelling and mapping was prepared for both the 28.05mAOD and 28.60mAOD NMOWL scenarios for alternative flood events with probabilities of 1.33% AEP, 1% AEP and the 1% AEP event with flows increased by 20%.

88. Flood modelling and mapping for these alternative events was prepared because the characteristics of the original design events with these probabilities from the RMMMP (2015) had flood volumes, when assessed in terms of their probability of occurrence, that notably exceeded those of the flow probability used for the purpose of assessing proposed schemes. To provide some context to this, both of the original design events exhibited double-peaked events (those with elevated flows prior to the main peak of the flood event) and the probability of occurrence of flood volumes associated with flow rates above $75m^3/s$ exceeded the magnitude of target design event. For the 1.33% AEP event the probability of occurrence associated with the flood volume was 0.55% AEP, while for the 1% AEP event the probability of occurrence associated with the flood volume was 0.2% AEP. This information was derived from the continuous simulation hydrological outputs prepared and delivered during the RMMMP (2015). Given that the, these are considered as residual risk events.

89. The original design events, with probabilities of occurrence for flood volumes that exceed the peak flow magnitude AEP being assessed, are considered a residual risk in the context of the Revised Scheme, as discussed within section 5.3.1 of the FRA (inquiry core document "CD3.1d"). Figure 6 displays for the 1% AEP event, the original double-peaked and alternative/revised single-

peaked flood flow model time-series extracted at the confluence of the River Eden and River Medway upstream of Penshurst. For the double-peaked event, the second peak is the event with the peak flow rates that equates to the 1% AEP event. It can be seen that while the peak flow rates are similar (the peak flow rate dictates the relevant annual exceedance probability of the event) the event shapes (and corresponding flood volumes) are different, with the double-peak event having two peaks at or very close to the 1% AEP magnitude within a 40-hour period.

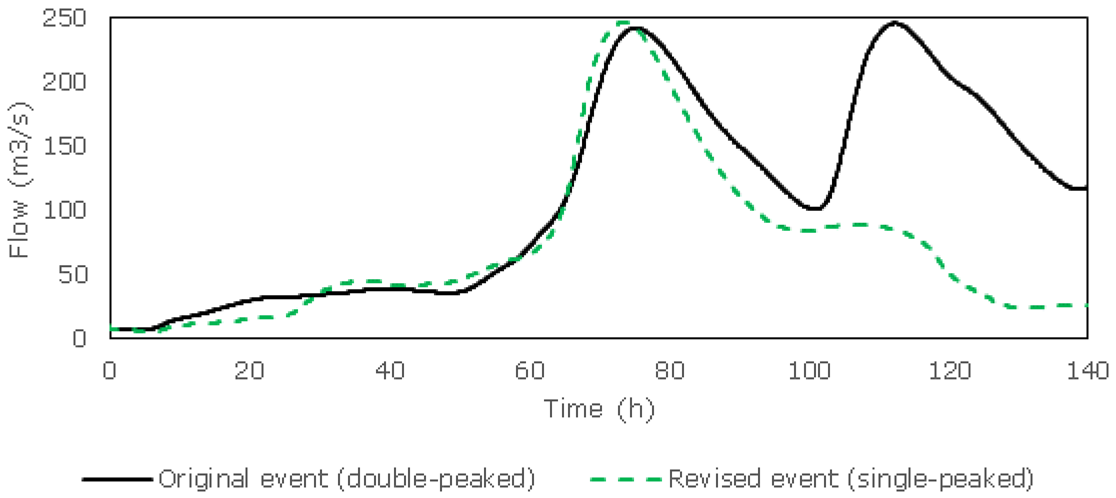

Figure 6: Time-series of model flows at the confluence of the River Medway and River Eden from the original double-peaked and revised single-peaked design events used to inform the 1% AEP flood event within the FSA

90. I should note that the flood risk modelling used to inform the mapping presented in Appendices A and B of the Flood Risk Assessment report (core document reference “CD3.1d” was shared with consultants WSP who are working for and on behalf of Penshurst Place Estates with respect to technical matters associated with the flood risk mapping evidence submitted by the Environment Agency.

91. In addition to modelling and mapping of alternative events as described above, remodelling of previously simulated events at a NMOWL of 28.05mAOD (the Baseline) was prepared prior to submission of the FRA. This re-modelling was prepared as it was noted that the downstream boundary condition (water level at the upstream of the radial gates) applied to the Model 1 flood risk mapping model in the RMMMP (2015) had not applied the water levels in the FSA associated with the optimum storage scenario. Instead, it had selected water level time-series for the scenario in which the FSA aims to regulate downstream flows to circa 75m^3/s, which for many larger flood events is not the optimum scenario. Therefore, in the original Baseline modelling from the RMMMP (2015) the water-level time-series reflected a situation where excessive water was being stored within the FSA. This led to water levels being held at the NMOWL for longer periods of time than the optimum operation scenario. While this affected the Baseline mapping prepared for Model 1 in the FSA, it did not affect the modelling and mapping for the Models 2, 3 and 4 given that simulations for these models correctly used the flow time-series for the optimum storage event.

Applicability of the Baseline flood risk mapping model to inform the flood predictions for the current operation at and within Leigh FSA

92. The Baseline flood risk mapping model represents Leigh FSA as operated in accordance with the River Medway (Flood Relief) Act 1976, with a maximum operating water level of 28.05mAOD. It is this model which is adjusted to form the Revised Scheme model, and against which the Revised Scheme model predictions are compared to understand the changes in flooding that result from the Revised Scheme. Therefore, it is important that the Baseline flood risk model is able to appropriately predicted flood risk within the Flood Storage Area, allowing meaningful comparisons to be made. This section presents information relating to the Baseline flood model and explains why it is considered appropriate for predicting flood risk within the FSA.

93. The 1D model schematisation within Leigh FSA is appropriate for computing flood predictions within Leigh FSA. The channel and floodplain within the FSA consist of a well-defined 'corridor' along which flood water flows, with ground levels rising above the flood level at either side of the floodplain. While parts of the channel have banks that are raised above the level of the floodplain, water levels in times of flood are elevated above the level of the banks meaning the channel and floodplain are well connected. The average distance between River Sections within the FSA is 170m, which is appropriate given that the curvature of the water surface profile is not extreme. Use of a Reservoir Unit to represent the floodplain south of the river at Haysden Water is sensible given that the floodplain expands notably here, and it is 'offline' (i.e. it is a discrete body of water without inflow or outflow) from the river where water levels would be expected to be more consistent. A 1D extended cross-section approach enables the model to replicate the dominant direction of flow (upstream to downstream), produce representative water surface profiles and enables the backwater effects produced by operation of the radial gates when storing water in the FSA to be calculated.

94. The geometry of channel sections and structures within the model are informed by topographic survey data. The geometry of the floodplain is informed by filtered LIDAR data, with elevation points along the floodplain extracted at typically 5m intervals. This provides fine detail of the shape of the floodplain, which combined with the spacing of cross-sections replicates the available volume of the FSA along its length.

95. Structures located within the FSA through which the River Medway flows through or over, which may be considered most relevant are discussed below. The location of these structures is displayed in Figure 7, which is presented later in this document. Additionally, maps are also presented later in this document (Figure 11 and Figure 12) displaying the extent of flooding for the various design events in the Baseline scenario.

    95.1. <u>Rogues Hill bridge/road.</u> Rogues Hill road is raised up to circa 2.2m above the elevation of the River Medway floodplain, resulting in constriction to the area of floodplain through which water can flow. Between the upstream and downstream sides of Rogues Hill bridge, peak water levels in the

Baseline scenario differ by circa 0.45m in the 20% AEP event, increasing to circa 0.9m in the 1% AEP plus climate change event. Differences in water levels between the upstream and downstream side of Rogues Hill is evident visually in photos provided by objection statements made relating to the application. These objections are presented in inquiry core document "CD3.1b". For instance, two photos in the objection from Mr and Mrs Storey and one from Mr and Mrs Thompson display flood water flowing across Rogues Hill to a lower level on the downstream (eastern) side of the road.

95.2. Although the presence of the flow constriction caused by the structure results in the water level differences described above, the flow rates upstream and downstream of the bridge are consistent, indicating that the bridge and road do not result in attenuation of the flood flow. This means that predictions made by the model at the Leigh FSA radial gates, based on flow and level are not influenced by any attenuation at the Rogues Hill bridge/road structure. Additionally, the difference in water levels upstream and downstream of the structure during times of flood supports the premise that any backwater impacts from the storage of water at the FSA downstream would not propagate upstream beyond Rogues Hill road.

95.3. Ensfield Road bridge/road. At the bridge crossing the River Medway, Ensfield Road is raised up to circa 2.2m above the elevation of the River Medway floodplain, but circa 100m northwest of the bridge, Ensfield Road is only raised up by only circa 0.2-0.3m above the elevation of the River Medway floodplain. Between the upstream and downstream sides of Ensfield Road bridge, peak water levels in the Baseline scenario differ by circa 0.15m in the 20% AEP event, decreasing to less than 0.05m in the 5% AEP event and those with higher flow rates. Although the presence of the flow constriction caused by the structure results in the water level differences described above, the flow rates upstream and downstream of the bridge are consistent, indicating that the bridge and road do not result in attenuation of the flood flow. This means that predictions made by the model at the Leigh FSA radial gates, based on flow and level are not influenced by any attenuation at the Ensfield Road bridge/road structure. Additionally, the small difference in water levels upstream and downstream of the structure during times of flood supports the premise that the representation of the bridge does not detract from the ability of the model to simulate any potential backwater impacts from the storage of water at the FSA.

96. While it is acknowledged that the computer programme used within the flood routing model to represent the operation of the radial gates at Leigh FSA is a simplification of reality, checking of the model operation completed during the RMMMP (2015), as described below, meant that the model operation was appropriate. Therefore, given that the way in which the FSA is operated will remain, the model operational approach is considered appropriate to inform decisions relating to changes in flooding resulting from the Revised Scheme. A sub-set of flood events from the continuous simulation hydrological assessment were tested through the flood routing model computer programme and these were checked against the choices made by Leigh FSA operators when

confronted with the continuously simulated flows. After three iterations, the flood routing model results agreed well enough with the operators' choices for the method to be signed off.

97. The Hydrology Report which forms Appendix A to the main report of RMMMP (2015) concludes that flow frequency curves prepared for the project (which reflect the flow rate vs event probability) match well at most of the gauging stations. The core document reference for Appendix A to the RMMMP (2015) is "CD1.18-1". In the context of Leigh FSA, it is noted for Vexour Bridge gauging station that the data available for the extreme 1968 event introduces discrepancies when comparing the continuous simulation hydrology flow frequency curves against another method (the FEH Statistical Single Site method), but the conclusion drawn is that the continuous simulation hydrology is considered to be more representative.

98. The hydrological methods used for the RMMMP (2015) were quality assured by two Environment Agency technical specialists during the course of the project prior to accepting the methods and outputs.

99. I consider the strengths of the hydrological methods adopted for the RMMMP (2015), which help understanding of flood risk within the River Medway catchment, and also assessment for the Revised Scheme are the following:

99.1. <u>Continuous simulation approach (generally):</u> As noted within section 3.5 of OI 197_08, the continuous simulation approach is advantageous for the River Medway given that there are multiple influences affecting flood predictions (e.g. multiple tributaries, presence/operation of Leigh FSA, floodplains influencing attenuation). Its use provides increased confidence in the resulting hydrology estimates by reducing assumptions, and it enables a more coherent, multivariate (influence of multiple variables) and probabilistic (considering a very large range of possible scenarios) view of the flood hazard in comparison to using conventional hydrological frequency analysis methods. There was appropriate data to enable calibration of the continuous rainfall-runoff modelling and a stochastic rainfall modelling. The variety of flood type prepared by and considered within the hydrological modelling allows robust decisions to be made with regards to the design events selected to inform event probabilities across the catchment.

99.2. <u>Operation of Leigh FSA radial gates:</u> Described in paragraphs 67 to 72, the operation of the Leigh FSA radial gates included with the flood routing modelling provides a robust representation of the operation of the FSA for each of the design events simulated through the flood risk mapping model, and indeed the numerous other continuous simulation events that were considered during the hydrology modelling. The prediction of water levels within the FSA, and therefore the calculation of backwater impacts, allow meaningful conclusions to be drawn from the modelling predictions, including potential changes in flooding upstream. Additionally, an important requirement is for the changes in downstream flood flows due to operation of the radial gates at Leigh FSA to be assessed. The determination of an optimum outflow for each of the flood events considered during the hydrology assessment allowed the extraction of relevant design event probability outflows from the FSA, rather than for instance assuming that the 1% AEP event informing flows into the FSA is also the event that results in a 1% AEP event outflow from the FSA, which may not be the case.

99.3. Spatial varying rainfall: Spatial variability of rainfall is another positive aspect of continuous simulation hydrological methods raised in section 4.4 of OI 197_08. Spatially varying rainfall was prepared that was calibrated using observed data and produces growth curves that are consistent with the Flood Estimation Handbook depth duration and frequency model. Rainfall growth curves relate to how the rainfall depths change with the magnitude of the rainfall event and the duration of the rainfall. This rainfall, prepared at hourly intervals, enables the variable response of rainfall throughout the catchment to be modelled, which is more realistic than assuming that a consistent rainfall profile (rainfall vs time) is applicable catchment-wide upstream the area of interest. Accordingly, the flow response on watercourses is also more representative of likely responses in real flood events, rather than the potential for their peaks to be combined if a single rainfall profile was used.

99.4. PDM rainfall-runoff modelling: Use of PDM models for the hydrology assessment followed a distributed approach, which OI 197_08 indicates is a natural choice for large or varied catchments, and for those with floodplain or reservoir storage. These are key reasons that the approach was used for the River Medway catchment, and enable the variable response of contributing catchments to be appropriately represented.

99.5. Flood routing modelling for design event selection: The use of the flood routing models as part of the hydrology assessment, enabled the continuous simulation event that represents the required event probabilities to be extracted at various points (for Models 1 and 3 – at the output zones) in the models. As mentioned in paragraph 99.1, this enables the influence of multiple tributaries and floodplain attenuation, among other factors, to be taken into account, and so when extracting an event with a specific probability for an area of interest, the influential mechanisms which influence the development of a flood, and therefore the peak flow rate at a given point in the catchment, have been taken into account.

99.6. Large event dataset with different flood characteristics: An advantage of continuous simulation modelling, as stated within OI 197_08 is that the process produces a rich variety of flood types, including those with high peaks, high volumes, multiple peaks and sequences of events. This variety reduces uncertainty in the design events selected for simulation through the flood risk mapping models at locations throughout the catchment. For instance, for flood risk mapping Model 2, the continuous simulation events that are chosen to provide the required probability of flooding are based on the peak outflow from the Leigh FSA, meaning that the characteristics of a flood which influence operations of the FSA (e.g. peak flow rate, flood volume, hydrograph shape), and therefore the outflow are explicitly taken into account.

100. I consider the strengths of the hydraulic modelling methods adopted for the RMMMP (2015), which help understanding of flood risk with the River Medway catchment, and also assessment for the Revised Scheme are the following:

100.1. <u>One-dimensional schematisation within Leigh FSA:</u> The 1D modelling approach adopted for Leigh FSA is beneficial as it enables the model to run in a stable manner (e.g. with numerical oscillations which can add 'noise' to the predictions of flows, water levels etc, or model failure), relatively quickly (e.g. less than a day, rather than multiple days as with other models) and with modest data storage resources, which benefits the simulation of the numerous simulations that were required for the RMMMP (2015) modelling and the assessment of Revised Scheme modelling for comparable events. Given that the flow of water in the Leigh FSA is upstream to downstream along the River Medway and its floodplain, the 1D approach appropriately resolves the flow routes and influence of any backwater impacts from storage of flood water at the Leigh FSA.

100.2. <u>Two-dimensional schematisation on areas of floodplain downstream of Leigh FSA:</u> Areas of the floodplain downstream of Leigh FSA have more complex flow routes (e.g. various channels within Tonbridge, propagation of water in a north-westerly direction into Hildenborough) and have areas where the elevations of the river bank and/or flood defences are more influential. For these reasons, a 2D modelling schematisation was benefits these models was used.

100.3. <u>Calibration and verification of the flood risk mapping models:</u> These activities, described in paragraphs 102 to 105, tested the models' ability to replicate observed flooding. The acceptance of calibration performance by the Environment Agency project team, which was completed for three events as recommended by OI 379_05, and the predicted flooding presented during the verification process supports the view that the predictions from the flood modelling can reasonably be relied upon to inform estimates of predicted flooding in the Baseline model, and changes in predicted flooding expected in scenario testing that is developed from it.

100.4. <u>Sensitivity testing completed using the flood risk mapping models:</u> The sensitivity testing prepared using the Baseline modelling, described in paragraphs 106 to 108, suggests that the modelling is relatively insensitive to changes in hydraulic roughness and flow rates (two parameters that OI 379_05 recommends are adjusted during sensitivity testing), particularly in the context of the depths of flood water within Leigh FSA during times of flood. The insensitivity of the predictions to these factors is a strength of the modelling, and supports the robust nature of the predictions derived from it. It also suggests that these factors are unlikely to be influential to the overall outcome of scenario testing if the same adjustment (e.g. increasing hydraulic roughness) was completed in Baseline and Scenario model configurations.

101. The flood risk mapping models prepared for the study were quality assured during the course of the project by an Environment Agency Flood and Coastal Risk Management Modelling and Hydrology Technical Advisor prior to accepting them for use to prepare the flood mapping outputs. Additionally, confidence in the modelling is enhanced by calibration, verification and sensitivity testing activities that were completed.

102. Calibration of the Model 1 flood risk mapping model completed by Jeremy Benn Associates Limited during the delivery of the RMMMP (2015) (as well as for the other Models 2-4) used three historic events: November 2000, February 2009 and December 2013. Verification of the model outputs was completed by Environment Agency personnel with knowledge of the catchment and historic flood conditions, who inspected the outputs for these three historic events, plus the 20%, 5% and 1% AEP defended case events. To facilitate this process, a mapping workshop was held, during which predictions from the modelling were inspected. Section 6.1 of the RMMMP (2015) main report (inquiry core document "CD1.18") documents this process, and Appendix C to the report presents the data/outputs of the calibration events. The core documents with references "CD1.18-3-1" to "CD1.18-3-4" form the contents to the Appendix C and contain the data/outputs of the calibration events.

103. In addition to schematisation and parameterisation of the hydraulic models being influential in assessing calibration, the overall performance is also dependent on the performance on the continuous simulation hydrology and the reliability of the observed rainfall during each event, which combined to produce flow inputs into the flood risk mapping model. Section 6.1.2 of the RMMMP (2015) main report notes that whilst both are considered satisfactory for the purposes of the project, the performance of the PDM models should be viewed alongside the flood risk mapping model calibration information.

104. Data to inform the calibration and verification process was not available within Leigh FSA. However, consideration was given to model predictions versus historic data recorded at gauge sites was made throughout the catchment. Across the full extent of Model 1, for each event and gauging site, the average difference in peak water levels was -0.07m (modelled predictions are 0.07m lower than the observed data).

105. In the context of Leigh FSA, Colliers Land Bridge and Penshurst gauging stations provide the closest sites for calibration on the River Medway and River Eden, respectively. Calibration of the model was deemed satisfactory by the Environment Agency project team, with average differences in modelled peak water levels across these sites of -0.05m, compared with the observed data. The criteria used in Environment Agency modelling assessments for acceptance of differences between modelled and observed water levels can vary according to a number of influential factors (including the purpose of the project, nature of the watercourse and data availability). The differences in modelled vs observed levels are within the ±0.15m criteria typically applicable to the preparation of flood risk mapping models such as the River Medway. This supports the premise that both the flood risk mapping model schematisation

and its parameterisation are appropriate, and also that the continuous simulation hydrology methods are appropriate. The calibration reporting noted that differences in modelled water levels vs observed at these sites are influenced by the raised banks along this reach. These raised banks present a limitation of the extended 1D cross-section modelling approach at the gauging sites, with the modelling predicting relatively larger flow rates via the floodplain before the river channel and bank are fully connected, thereby suppressing the in-channel water levels at the gauge site. This aspect of the modelling is less of a concern within the FSA as flood levels are substantially above the bank levels and so the 1D extended cross-section approach is appropriate for replicating water levels from historic events in this area (as there is good continuity of flow in the channel and the adjacent floodplain).

106. Sensitivity testing for each of the four models was completed using the 1% AEP defended case design event. Sensitivity testing was completed for the scenarios listed below. Changes to model predictions were assessed in terms of changes in peak water levels throughout the model, in terms of both absolute change (in metres) and percentage change in flood depth. Section 6.2 of the RMMMP (2015) main report (inquiry core document “CD1.18”) documents this process, and Appendix C to the report presents the data/outputs of the calibration events. The core documents with references “CD1.18-3-1” to “CD1.18-3-4” form the contents to the Appendix C and contain the data/outputs of the calibration events. Sensitivity scenarios tested were:

- Hydraulic roughness: ±20% change to Manning’s *n* roughness parameter for all River Sections in separate simulations
- Flood flows: ±20% change to hydrology inputs (flood flows) in separate simulations

107. For the modelled reaches between Colliers Land Bridge and Vexour Bridge to the Leigh FSA radial gates, peak flood water levels were found to be relatively insensitive to changes in the hydraulic roughness of River Sections. Peak water levels changed by +0.11m (+2% change in depth) and -0.33m (-1% change in depth) on average for the increased and decreased hydraulic roughness scenarios, respectively.

108. For the modelled reaches between Colliers Land Bridge and Vexour Bridge to the Leigh FSA radial gates, peak flood water levels were found to be relatively insensitive to increases in the flow rates. Peak water levels changed by +0.06m (+1% change in depth) for the increased hydraulic roughness scenario, in part reflecting the regulation of the FSA not exceeding the permitted top water level of 28.05mAOD. Changes in peak flood water levels were found to be more sensitive for decreases in flow rates, which is anticipated, in part given that with lower flows, the FSA need not regulate to the maximum permitted water level.

109. Understanding the confidence and uncertainty associated with a flood risk mapping model is important given that decisions are often made using the outputs. Information regarding confidence and uncertainty with a model allows consideration of whether it is appropriate to use for an intended purpose (e.g. assessing a flood management scheme) and appropriate for decision-making.

110. The confidence a person has in flood risk modelling and mapping can be influenced by many factors. Reducing the uncertainty associated with modelling should improve the confidence held in a model. It is not possible to eliminate uncertainty entirely, and so there is a balance to strike in the effort taken (e.g. cost, quality, time) to reduce uncertainty, considering only the level of detail needed to be satisfied that conclusions drawn from the model, according to its intended application, are appropriate. Examples of uncertainties with flood risk mapping modelling include:

- the model schematisation;
- data informing the construction of the model and its inputs;
- confidence intervals relating to hydrology estimates;
- how the model is able to replicate historic observations of flooding, and
- how sensitive the model's predictions are to changes made to these.

111. Environment Agency guidance on residual uncertainties includes some helpful context to uncertainties within flood risk modelling projects. It does not present a definitive account of all possible uncertainties, but introduces many, and the possible influence they have on decision-making. Aspects of the guidance are discussed below, and commentary is provided against the points raised in the context of the River Medway flood risk mapping modelling. The reference for the guidance is report SC120014, Accounting for residual uncertainty: updating the freeboard guide, which is provided in Appendix 3.

112. The guidance on residual uncertainties is targeted at activities associated with a.) planning and approval of development on the floodplain, b.) appraising and designing flood risk management options and c.) managing existing flood defences. The guidance can be used to assess suggested freeboard allowances for flood risk management schemes and defences. It does not appear to relate to freeboard guidance for other non-flood risk management infrastructure (e.g. roads), but it is acknowledged that the guidance may provide useful information for non-flood management parties such as local community and regulatory bodies.

112.1. The guidance acknowledges that there are many aspects of uncertainty, each of which may have different levels of confidence and magnitudes of impacts on overall predictions (e.g. a water level predicted by a model).

112.2. The guidance states that response to managing residual uncertainties should be risk-based, proportionate to the cost of a scheme and the impact on receptors such as people, infrastructure, the environment and the economy.

112.3. The guidance presents a series of uncertainties associated with data and models in Table B1 (page 52). The table presents uncertainties according to sources, pathways and receptors of flooding. Key uncertainties with each that relate to the River Medway flood risk modelling are: 1) Sources (hydrology aspects: flows, joint probability, rainfall), 2) Pathways (topography e.g. river and floodplain, asset operation) and 3) Receptor (ground levels, property thresholds).

113. Sources, pathway and receptor aspects of uncertainty are discussed below. I consider that the RMMMP (2015) modelling is appropriate for the intended application, given the detailed analyses prepared to inform inputs to the model (sources of flooding), the consideration given the flood pathways (and the information prepared and agreed with the Environment Agency to evidence its performance) and assessment given to predictions at receptors.

113.1. <u>In terms of uncertainty relating to sources</u>, the continuous simulation hydrological approach used for the River Medway flood risk mapping reduces the magnitude of these uncertainties. The spatially varying stochastic rainfall modelling, distributed rainfall-runoff approach via PDMs and use of flood routing models inherently includes consideration of joint probabilities, influential mechanisms that influence the flooding. It is acknowledged that uncertainty with hydrological inputs will remain, but the detailed hydrological analysis prepared for the RMMMP (2015) is considered to provide the best estimate of flood event magnitudes for the catchment. The presence of gauging stations relatively close to Leigh FSA (Colliers Land Bridge and Penshurst/Vexour Bridge) support the assessment and increase confidence in the estimates. The Flood Estimation Guideline (197_08) notes that when considering confidence intervals for hydrology estimates, it is important to realise that a wide confidence interval does not necessarily mean that the best estimate is wrong. It is much more likely to be correct in comparison to the values at the upper and lower confidence limits.

113.2. <u>In terms of uncertainty relating to pathways</u>, the topography applied to the model, both in terms of channel and floodplain geometry is the best available information and the format of data underpinning these model inputs is the type that is typically used for flood risk modelling and mapping projects. The schematisation of models has been justified above, and so too have the outcomes of model proving activities. Asset operation i.e. movement of the radial gates within the model was checked by operators during the RMMMP (2015) and considered appropriate.

113.3. <u>In terms of uncertainty relating to receptors</u>, this consideration for the inquiry is more concerned with changes due to the Revised Scheme. However, the Baseline model configuration allows flood predictions e.g. water levels, to be compared between the Baseline and Revised Scheme to understand any changes in flooding. This, supported by additional data related to the receptors e.g. ground levels, threshold levels of properties etc, allows informed decisions to be made about potential impacts of the Revised Scheme.

Applicability of the revisions to the Baseline flood model to inform the flood predictions for the Revised Scheme at and within Leigh FSA

114. In Paragraph 92 I have described the importance of having an appropriate Baseline flood risk mapping model from which the Revised Scheme model can be prepared and against which the Revised Scheme model predictions can be compared. This section considers the changes that have been made to the Baseline model to represent the Revised Scheme and explains why the changes are considered appropriate for predicting flood risk associated with the Revised Scheme.

115. With the exception of changes to the operation of the radial gates at Leigh FSA (reflecting the difference in permitted maximum water level at the upstream of Leigh FSA radial gates), the schematisation of the flood risk mapping model remains consistent between the Baseline and Revised Scheme scenarios, allowing direct comparisons to be drawn with respect to the influence of the Revised Scheme.

116. The simplicity of the scenario configuration i.e. consistency with all aspects of the model except for adjusting the operational rules describing movement of the radial gates at Leigh FSA, is beneficial for assessing the outcomes of the Revised Scheme. The approach enables a comparative assessment of predictions. This reduces uncertainty, and increasing the certainty and confidence that any changes due to the Revised Scheme are representative of the likely outcome, and not due to other adjustments within the model which might contribute towards differences in predictions. It also reduces the likelihood of alternative outcomes (e.g. where no impacts of the design event modelling are predicted) if any changes were made to data inputs or parameters describing the catchment.

117. Comparison of predicted flooding between the Revised Scheme modelling and that of the Baseline modelling is possible by:
    - Comparison of time-series for outputs from the model e.g. flood water level comparison either directly in the computational software, or by exporting the data to a format that enables comparison in spreadsheets, and
    - Comparison of mapped outputs of flood predictions e.g. peak flood water levels. This process typically involves converting the predictions into GIS format data and subtracting the Baseline modelling outputs from the Revised Scheme outputs, so the change comparative to the Baseline modelling is what is presented.

118. Section 2.1.3 of the FRA conceptualises key aspects of the operation of the FSA and its influence on the changes in water levels upstream of the FSA and change in outflows downstream of the FSA. The FRA report is inquiry core document "CD3.1d". Section 5 of the FRA describes the changes in flood extents and flood depths upstream and downstream of the FSA, and also the change to duration of impoundment above the Baseline NMOWL at the radial gates resulting from the Revised Scheme. The sections below provide further information relating to changes in flooding due to the Revised Scheme upstream of the FSA at particular areas of interest. This is made possible by

the direct comparison of the Baseline and Revised Scheme modelling, given that the only adjustment being made is the operation of the radial gates.

Assessing changes in flooding due to the Revised Scheme

119. There are a number of changes associated with the Revised Scheme which I have presented within the paragraphs below. The main emphasis on changes in flooding due to Revised Scheme is for areas upstream of Leigh FSA, as this is where objections have been raised. However, context to the reduction in flooding downstream afforded by the implementation of the Revised Scheme is also stated.

120. Assessment of changes in flooding due to the Revised Scheme has involved a comparison of the flood risk modelling predictions between the Revised Scheme and Baseline model simulations for comparable flood event probabilities (e.g. 1% AEP for both). Changes in peak flood extents and flood water levels (equivalent to changes in peak flood water depths) have been considered, in addition to changes in water level time-series plots (which provide detail of any changes during a flood event that are below the peak water level). The 1% AEP event has been selected so that the changes in different areas can be more easily contrasted. The conclusions drawn from the information presented are consistent when other design events (e.g. 1.33% AEP and 1% AEP + climate change) are considered.

Changes in flooding predicted downstream of Leigh FSA radial gates

121. I have presented information relating to changes in flooding downstream of Leigh FSA in the paragraphs within this section. While the emphasis of objections raised relate to flooding upstream of the Leigh FSA radial gates, it is important to acknowledge the changes in flooding downstream in order to appreciate the benefits of the Revised Scheme. The information presented below supports the premise of a relatively small increase in flood risk predicted upstream of the FSA radial gates compared with the larger reduction in flood risk predicted downstream of the FSA radial gates.

122. Relatively small increases in flood risk are predicted upstream of the FSA radial gates in the Revised Scheme scenario due to the small change in consequences, influenced by existing flooding in the Baseline scenario, but also relatively few receptors and most of the FSA area being open space. The larger reduction in flood risk predicted downstream of the FSA radial gates in the Revised Scheme scenario results from the reduction in peak flood flows that the Revised Scheme enables, but also due to the notable number of receptors that are located downstream (e.g. within Tonbridge), whose consequences are reduced because of the reduced peak flood flows.

123. Consideration is given below to the change in peak flow rates released from the Leigh FSA between the Baseline and Revised Scheme modelling (expressed in terms of total flow and percentage change). The additional storage volume for flood water associated with the Revised Scheme enables peak flood flow rates to be reduced for many events, reducing the flood risk downstream. These

changes in peak flow rates for design events are presented in the bullet points within paragraph 123.3. Appendices C and D of the FRA (inquiry core document "CD3.1d") present in map form the changes in flood extents and depths in Tonbridge for the Revised Scheme compared with the Baseline scenario for the 5% AEP, 1% AEP and 1% AEP plus climate change events. The discussion I have presented below also includes the 2% AEP and 1.33% AEP events to help emphasise the change in flows released from the FSA for different event probabilities.

123.1. For flood events with a magnitude larger than the probability where there is no change in peak flow rates released from the FSA (approximately the 5% AEP event), the percentage reduction in peak flows is most marked for smaller magnitude events, which is expected as the peak flow rates and total volume of these events will be smaller.

123.2. The benefits of the Revised Scheme realised downstream of the FSA are apparent across a range of flood event probabilities, and the benefit at higher probability (more frequent) events indicates that the benefits of the Revised Scheme will be realised more frequently.

123.3. The change in peak flow rates released from Leigh FSA between the Baseline and Revised Scheme modelling are as follows:

- 5% AEP event: Baseline and Revised Scheme = 81m^3/s (meaning there is less than 1m^3/s change in flow rate)
- 2% AEP event: Baseline = 122m^3/s, Revised Scheme = 102m^3/s, which is a 16% reduction in peak flow rate
- 1.33% AEP event: Baseline = 143m^3/s, Revised Scheme = 123m^3/s, which is a 14% reduction in peak flow rate
- 1% AEP event: Baseline = 173m^3/s, Revised Scheme = 153m^3/s, which is a 12% reduction in peak flow rate
- 1% AEP plus climate change event: Baseline = 213m^3/s, Revised Scheme = 193m^3/s, which is a 10% reduction in peak flow rate

124. Consideration is given below to the change in peak flood depths in Tonbridge between the Baseline and Revised Scheme modelling. Assessing the change in flood depths provides context to the change in consequences of flooding (which are largely influenced by the depth of flood water). The change in peak flood depths (expressed in terms of total depth and percentage change) are presented at a reference point in Tonbridge within paragraph 124.2. The reference point in Tonbridge is at the south-western side of Sovereign Way, located on the opposite side to Botany car park (Easting: 559140m/ Northing: 146260m). This location was selected because it is the first location that is predicted by the modelling to be flooded in the centre of Tonbridge and therefore allows comparisons to be drawn against the greatest number of events. Appendices C and D of the FRA (inquiry core document "CD3.1d") present in map form the changes in flood extents and depths in Tonbridge for the Revised Scheme compared with the Baseline scenario for the 5% AEP, 1% AEP and 1% AEP plus climate change events. The discussion I have presented below includes these events, drawing out more detailed values presented in the maps. However, the discussion also includes the 2% AEP and 1.33% AEP events to help emphasise the change in flooding for different event probabilities. I consider that the change in flood depths presented are generally

representative of the trends in flood depths within Tonbridge, albeit the FRA mapping indicates that there is spatial variability in the change in flood depths. Refer to the mapping presented within the FRA for further details.

124.1. The percentage reduction in peak flood depths is most marked for smaller magnitude events, albeit the 1% AEP plus climate change event also displays a more marked reduction is flood depths compared with the 1% AEP event. This supports the premise that while benefits are predicted for larger magnitude flood events with a lower probability of occurrence, it is the smaller magnitude events with a higher probability of occurrence (more frequent) where the benefits may be greatest.

124.2. The change in peak flood depths between the Baseline and Revised Scheme modelling are as follows:

- 5% AEP event: Baseline = 0.15m, Revised Scheme = 0.08m, which is a 47% reduction in depth
- 2% AEP event: Baseline = 0.53m, Revised Scheme = 0.42m, which is a 21% reduction in depth
- 1.33% AEP event: Baseline = 0.75m, Revised Scheme = 0.69m, which is an 8% reduction in depth
- 1% AEP event: Baseline = 0.87m, Revised Scheme = 0.82m, which is a 6% reduction in depth
- 1% AEP plus climate change event: Baseline = 1.15m, Revised Scheme = 1.02m, which is an 11% reduction in depth

Changes in flooding predicted upstream of Leigh FSA radial gates

125. Before presenting the change in flooding resulting from the implementation of the Revised Scheme, it is firstly helpful to consider the context of the Baseline scenario (current scheme) versus a scenario in which Leigh FSA is not present (an ‘undefended’ scenario where the embankment and radial gates are not present). This comparison confirms that while the changes in flooding close to the location of the FSA embankment are relatively large, changes in flooding further upstream, e.g. within Penshurst, are relatively small. Flood extent comparisons for these two scenarios for the 1% AEP event are displayed in Appendix 3 to this proof , where it is seen that the change in flood extents lessens with distance upstream. For context, the 0.55m increase in maximum permitted water level at the radial gates associated with the Revised Scheme is contrasted with a circa 3.6m increase in peak water levels at the radial gates between the undefended and baseline (current scheme) scenarios for the 1% AEP event. The relatively small change in the permitted water level for the Revised Scheme helps understand why the changes in flood depths are less notable and are predicted to extend for a shorter distance upstream.

126. In the paragraphs below I have compared model predictions of water levels and extents between the Revised Scheme and Baseline for various locations upstream of, and within, Leigh FSA, as shown in Figure 7. The FRA report (inquiry core document “CD3.1d”) presented in map form, the changes in peak flood depths for the area of the FSA for the 1.33%, 1% AEP and 1% AEP plus climate change events. Changes in peak flood depths between the Revised Scheme and Baseline scenario show consistent trends for the 2% AEP event when compared with the Appendix B maps presented in the FRA (inquiry core

document “CD3.1d”), while no change in flood depths are predicted for the 5% AEP event, as storage of flood water to the current maximum operation level of 28.05mAOD is not required to manage flood flows downstream.

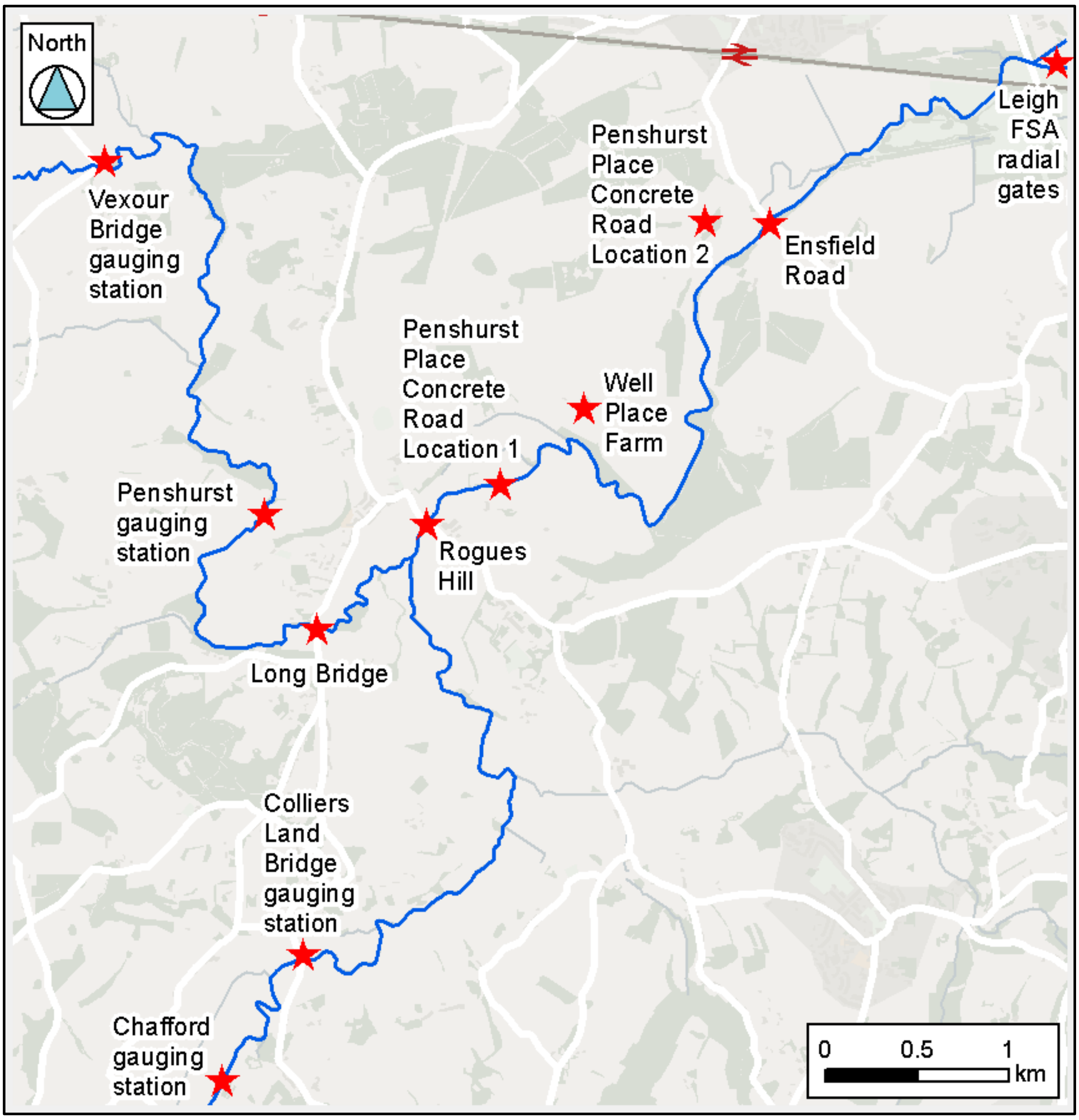

Figure 7: Locations that model predictions of peak water levels and extent are compared between the Revised Scheme and Baseline

127. Given that objectors have raised points that relate to areas upstream of the FSA e.g. Long Bridge and gauging stations, I have also presented information for these locations using data extracted from the modelling, both at the peak of flooding, but also for the duration of flood events. Where relevant, for each location an example graph is presented from the 1% AEP event to help evidence changes in flood depths/water levels. This event has been selected so that there is consistency in the graphs between locations and also given that the 1% AEP event is a key event focused on within the FRA report. The 1% AEP event has been used within the graphs, rather than the 1% AEP plus climate change event, due to the change in peak flood depths being greater in this event between. Refer to the depth change maps presented in Appendix

B.2 and B.3 of the FRA report (inquiry core document “CD3.1d”) to visualise the differences between these events. The change in water levels (e.g. magnitude and duration) is likely to change on an event-by-event basis. However, inspection of the design events modelled to inform Revised Scheme show consistent trends and so I consider use of the 1% AEP event to be representative of the typical changes expected.

128. **Changes in flooding at Chafford gauging station:** Chafford Bridge gauging station is located on the River Medway between Chafford Lane and Spring Hill (B2188) and upstream of Colliers Land Bridge gauging station. The gauging station is located circa 11km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 7m across this length. The Chafford Bridge gauging station is used to record flood levels and flows along the River Medway.

128.1. Comparison of outputs from the Baseline and Revised Scheme modelling indicates that no changes in predicted flooding at Chafford gauging station are anticipated due to the Revised Scheme.

129. **Changes in flooding at Colliers Land Bridge gauging station:** Colliers Land Bridge gauging station is located on the River Medway upstream (west) of Spring Hill (B2188). The gauging station is located circa 10km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 6m across this length. The gauging station is used to record flood levels and flows along the River Medway.

129.1. Comparison of outputs from the Baseline and Revised Scheme modelling indicates that no changes in predicted flooding at Colliers Land Bridge gauging station are anticipated due to the Revised Scheme.

130. **Changes in flooding at Vexour Bridge gauging station:** Vexour Bridge gauging station is located on the River Eden downstream (east) of a road connecting Chiddingstone Road and the B2027 road of Spring Hill. The gauging station is located circa 12km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 7m across this length. The gauging station is used to record flood levels and flows along the River Eden.

130.1. Comparison of outputs from the Baseline and Revised Scheme modelling indicates that no changes in predicted flooding at Vexour Bridge gauging station are anticipated due to the Revised Scheme.

131. **Changes in flooding at Penshurst gauging station:** Penshurst gauging station is located on the River Eden downstream south of a public bridleway and circa 2.5km upstream of the confluence of the River Eden with the River Medway. The gauging station is located circa 9km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 5m across this length. The gauging station is used to record flood levels and flows along the River Eden.

131.1. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that no changes in flooding at the peak of flood events are anticipated at Penshurst gauging station due to the Revised Scheme.

131.2. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in flood water levels up to 0.10m are predicted on the falling limb of the flood hydrograph for the Revised Scheme after the flood peak. This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 8 presents an example of this difference in water level vs time at the upstream of Penshurst gauging station weir for the 1% AEP event.

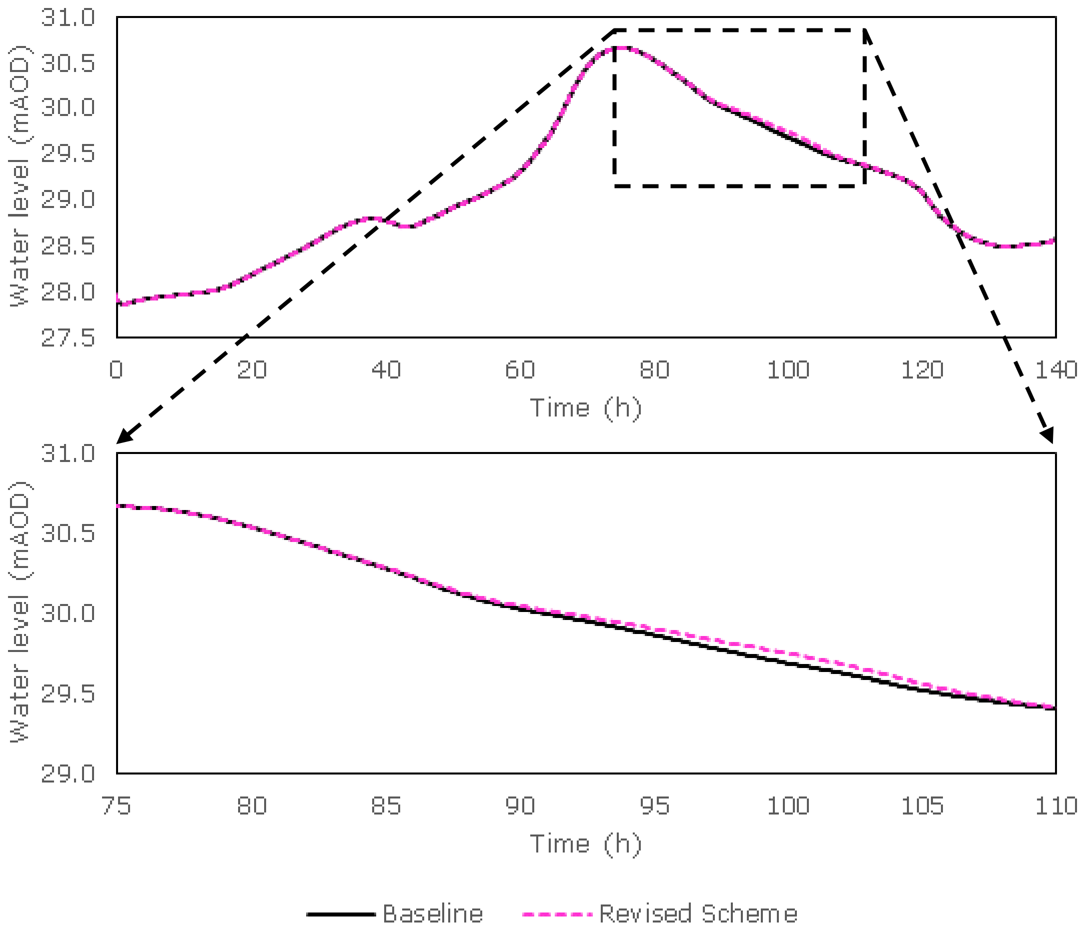

Figure 8: Time-series of modelled water levels for the 1% AEP event at the upstream of the weir at Penshurst gauging station for the Baseline and Revised Scheme. While no change in peak water levels are predicted, water levels for a portion of the falling limb of the hydrograph in the Revised Scheme will be elevated above the level at a corresponding time in the Baseline.

132. **Changes in flooding at Long Bridge:** Long Bridge is located on the River Eden circa 1km upstream of the confluence of the River Eden with the River Medway. The bridge carries to B2188 road over the River Eden. The bridge is located circa 7km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 2.5m across this length.

132.1. Within the Baseline modelling, flood water is predicted on the floodplain upstream and downstream of the bridge in the 20% AEP event (the smallest event considered in the RMMMP (2015)) and flood water is predicted to flow across the road in the 5% AEP event.

132.2. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that no changes in flooding at the peak of flood events are anticipated at Long Bridge due to the Revised Scheme.

132.3. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in flood water levels up to 0.20m are predicted on the falling limb of the flood hydrograph for the Revised Scheme after the flood peak. This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 9 presents this difference in water level vs time at the upstream of Long Bridge for the 1% AEP event.

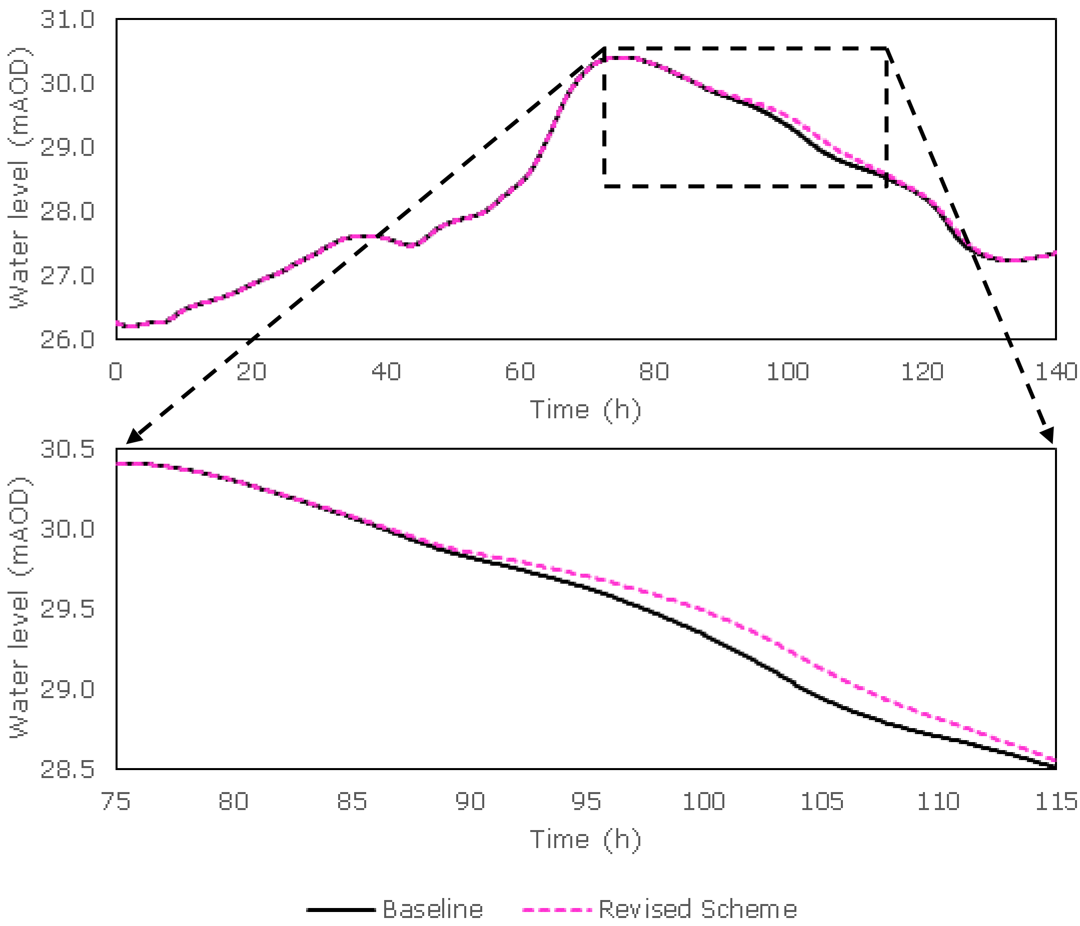

Figure 9: Time-series of modelled water levels for the 1% AEP event at the upstream of Long Bridge for the Baseline and Revised Scheme. While no change in peak water levels are predicted, water levels for a portion of the falling limb of the hydrograph in the Revised Scheme will be elevated above the level at a corresponding time in the Baseline.

133. **Changes in flooding at the upstream side of Rogues Hill:** Rogues Hill, the B2176, is located on the River Medway circa 200m downstream of the confluence of the River Eden with the River Medway. A bridge carries Rogues Hill road over the River Medway. The bridge is located circa 6km upstream of Leigh FSA radial gates and the elevation of the river bed drops by circa 2m across this length. Bridge House is located on the southern side of the River Medway, immediately upstream of Rogues Hill.

133.1. Within the Baseline modelling, flood water is predicted on the floodplain upstream of the road in the 20% AEP event and flood water is predicted to flow across the road in the 5% AEP event. Within the 1.33%, 1% AEP and 1% AEP plus climate change events, depths of up to circa 3.0m, 3.1m and 3.3m, respectively, are predicted on the floodplain immediately upstream of Rogues Hill.

133.2. The lowest threshold level at the main building at Bridge House is 29.05mAOD, as identified in the topographic survey collected by J.C.White Geomatics Limited in July 2018, which forms two attachments to the joint Statement of Case presented by Mr and Mrs Storey (Bridge House), Mr and Mrs Thompson (The Yews), and Mr Burraston and Ms Pallen (Colquhouns Cottage). The attachments provided in the joint Statement of Case are inquiry core documents “RM-002-SOC-02” and “RM-002-SOC-03”. The level of other buildings located to the west of the main building are recorded to be at a lower level than this. The Baseline model indicates that the threshold level of the main building is predicted to be exceeded in a 5% AEP event, which has predicted flood level of circa 29.5mAOD. The peak flood level for the 20% AEP event is circa 28.9mAOD. This indicates that the main building, and other buildings within the property boundary will be flooded in relatively frequent flood events.

133.3. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that no changes in flooding at the peak of flood events are anticipated at the upstream side of Rogues Hill due to the Revised Scheme.

133.4. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in flood water levels up to 0.35m are predicted on the falling limb of the flood hydrograph for the Revised Scheme after the flood peak. This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 10 presents an example of this difference in water level vs time at the upstream side of Rogues Hill for the 1% AEP event.

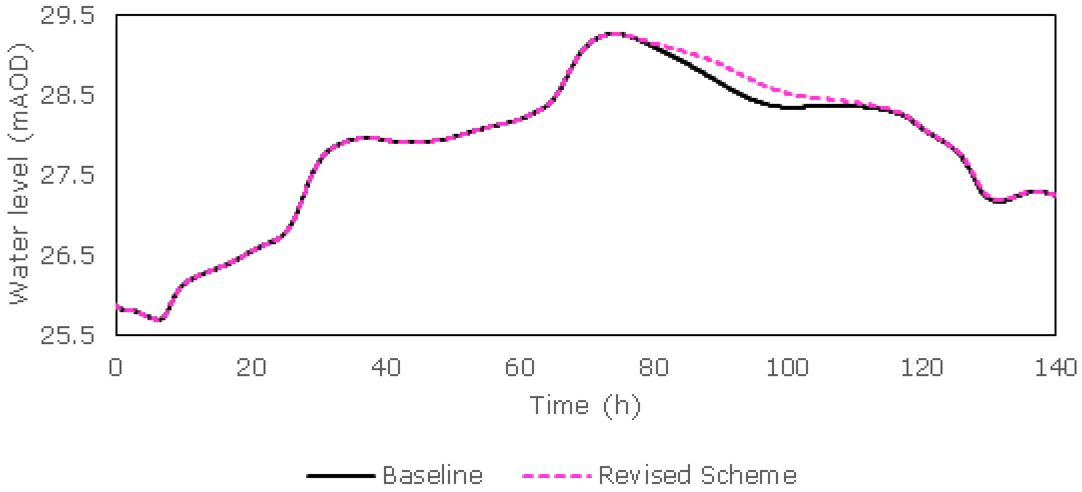

Figure 10: Time-series of modelled water levels for the 1% AEP event at the upstream of Rogues Hill for the Baseline and Revised Scheme. While no change in peak water levels are predicted, water levels for a portion of the falling limb of the hydrograph in the Revised Scheme will be elevated above the level at a corresponding time in the Baseline.

134. **Changes in flooding at Penshurst Place Concrete Road - Overview:** Penshurst Place Concrete Road extends from the B2176 at Penshurst to Ensfield Road located to the northeast. Flooding onto the road is predicted to occur in both the Baseline and Revised Scheme modelling at two locations:

- Penshurst Place Concrete Road Location 1: From circa 300m east of Rogues Hill extending for a length of circa 170m north-eastwards in the 1% AEP plus climate change event. Flood risk mapping for both the Baseline and Revised Scheme modelling indicates the first occurrence of flooding onto the road in the 2% AEP event, with the length of road flooded increasing as the event magnitude increases. Figure 11 presents the extent of Penshurst Place Concrete Road Location 1 referred to in this document, and displays the extent of flooding for the 2% AEP, 1% AEP and 1% AEP plus climate change design events.
- Penshurst Place Concrete Road Location 2: From Ensfield Road for up to circa 400m in a south-westerly direction in the 1% AEP plus climate change event. Flood risk mapping for both the Baseline and Revised Scheme modelling indicates that the road is predicted to flood in an event with a probability of 20% AEP, for which the length of road that is flooded is circa 200m. Figure 12 presents the extent of Penshurst Place Concrete Road Location 2 referred to in this document, and displays the extent of flooding for the 20% AEP, 5% AEP, 1% AEP and 1% AEP plus climate change design events.

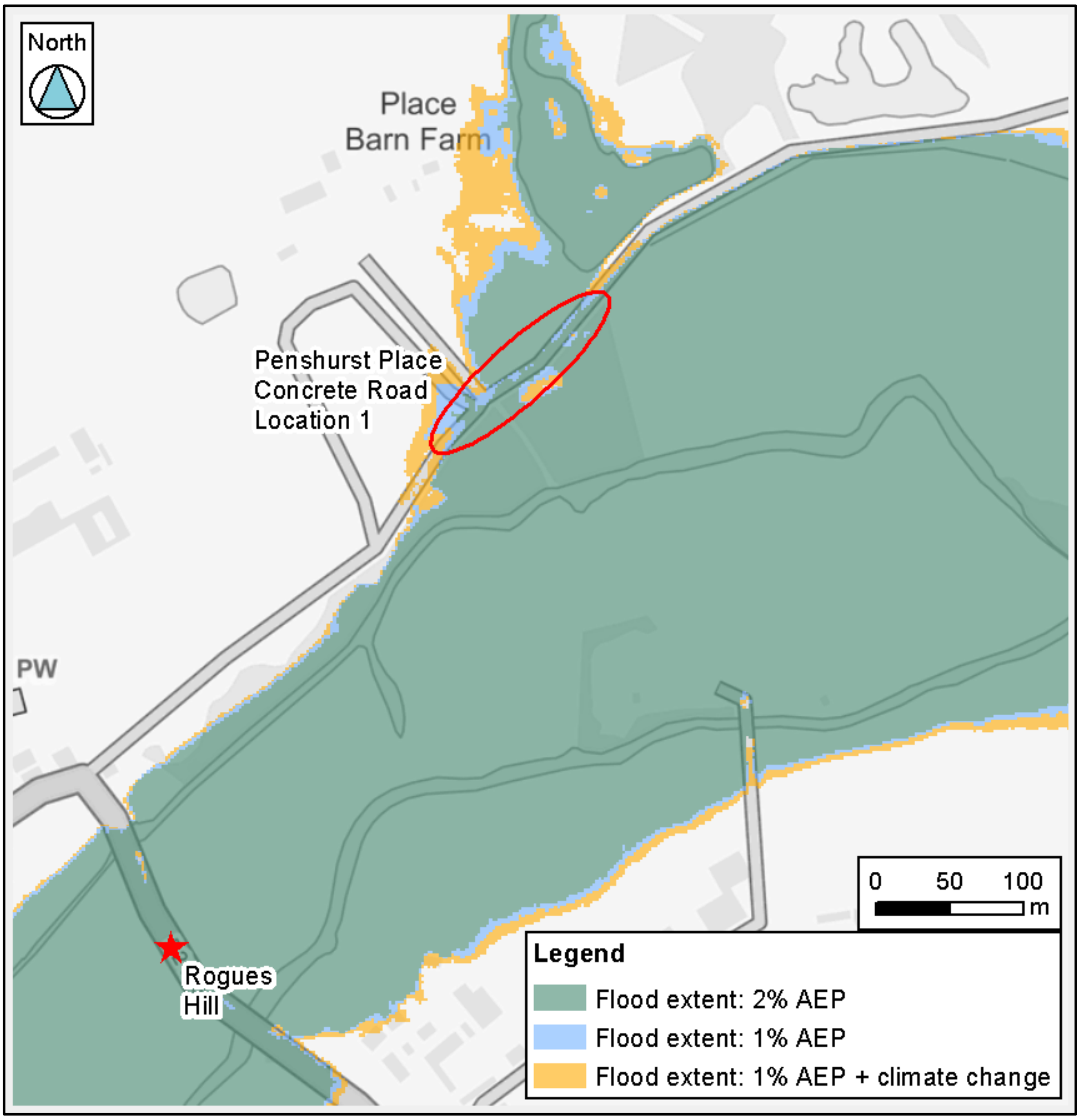

Figure 11: Location of Penshurst Place Concrete Road Location 1, and flood extents for the 2% AEP, 1% AEP and 1% AEP plus climate change design events

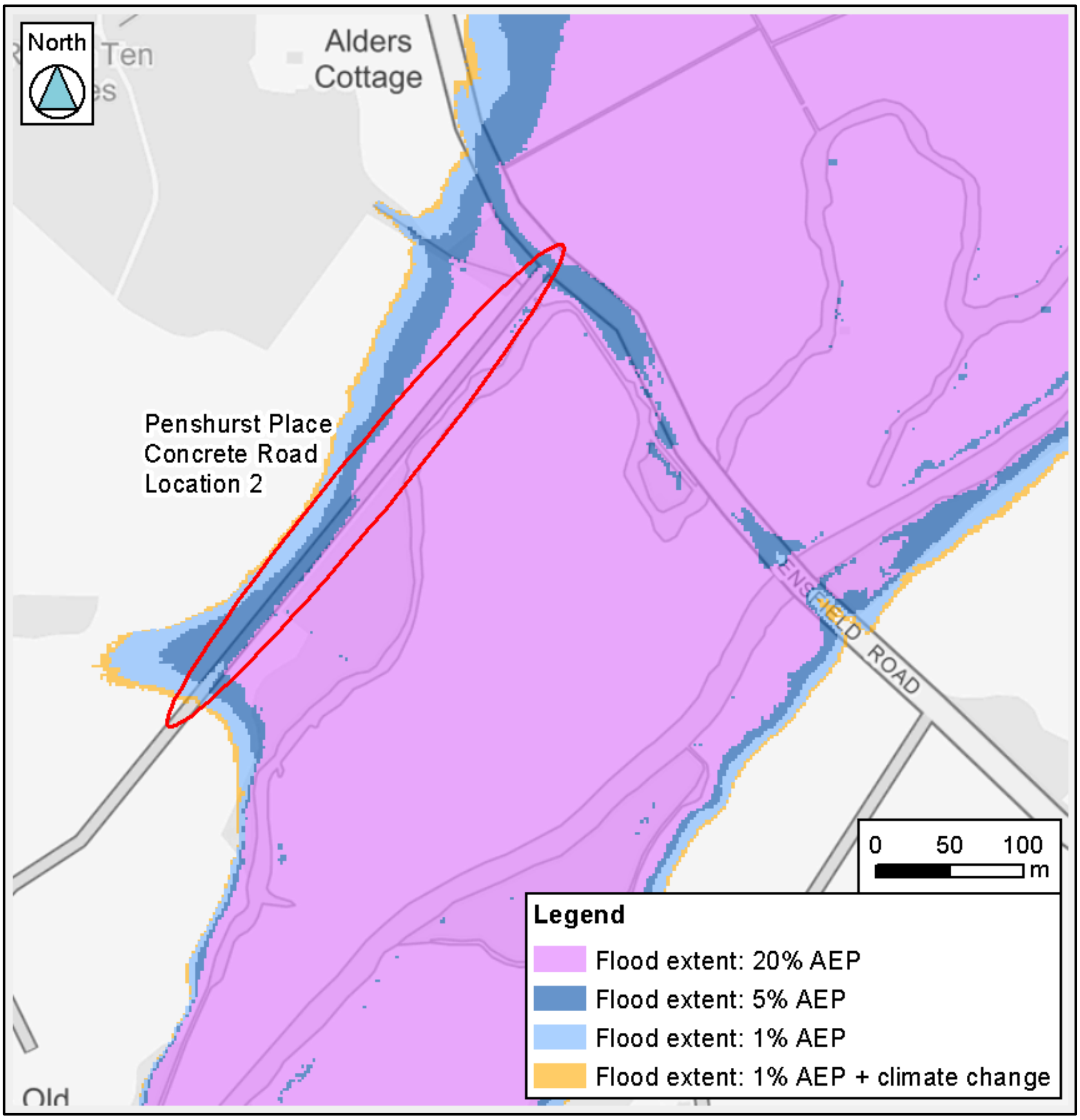

Figure 12: Location of Penshurst Place Concrete Road Location 2, and flood extents for the 20% AEP, 5%, AEP, 1% AEP and 1% AEP plus climate change design events

135. **Changes in flooding for design events at the downstream side of Rogues Hill and Penshurst Place Concrete Road Location 1:** I have combined discussion regarding these two sites given their proximity and because conclusions drawn are similar. Refer to Figure 11 for an overview of the location and extents of flooding in the Baseline.

135.1. Within the Baseline modelling, flood water is predicted on the floodplain downstream of Rogues Hill in the 20% AEP event. Within the 1.33%, 1% AEP and 1% AEP plus climate change events depths of up to circa 1.8m 1.9m and 2.1m, respectively, are predicted on the floodplain immediately downstream of Rogues Hill.

135.2. Flood water is predicted to flow onto Penshurst Concrete Road Location 1 in a 2% AEP event (depth of water up to circa 0.2m). Within the 1.33% AEP, 1% AEP and 1% AEP plus climate change events the length of road flooded increases and depths of up to circa 0.3m, 0.4m and 0.6m are predicted, respectively.

135.3. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that no changes in flooding at the peak of flood events are anticipated at the downstream side of Rogues Hill or at Penshurst Place Concrete road Location 1 due to the Revised Scheme in the modelled design events.

135.4. Comparison of outputs from the Baseline and Revised Scheme modelling indicates that increases in flood water levels up to 0.5m are predicted on the falling limb of the flood hydrograph (after the flood peak). This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 13 presents an example of this difference in water level vs time at the Penshurst Place Concrete Road Location 1 for the 1% AEP event.

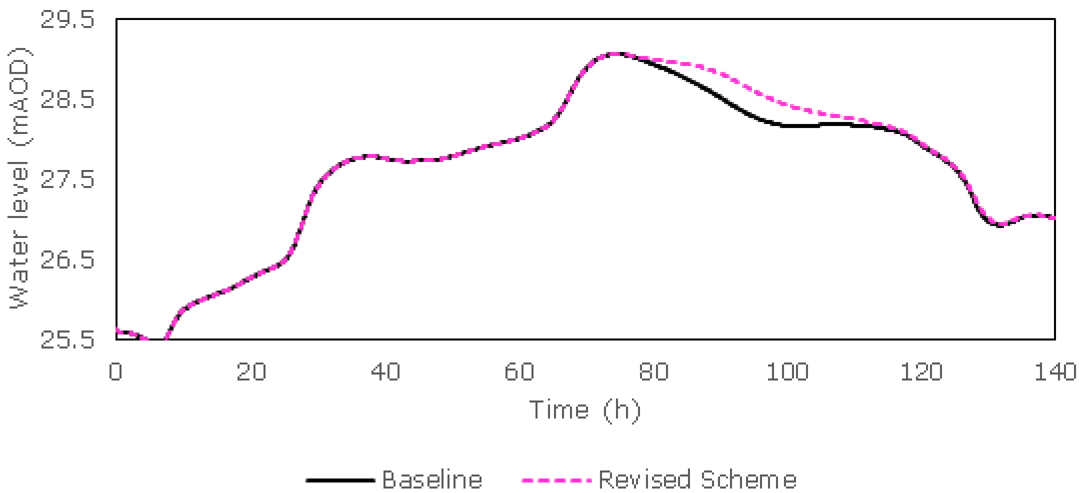

Figure 13: Time-series of modelled water levels for the 1% AEP event at Penshurst Place Concrete Road Location 1 for the Baseline and Revised Scheme. While no change in peak water levels are predicted, water levels for a portion of the falling limb of the hydrograph in the Revised Scheme will be elevated above the level at a corresponding time in the Baseline.

136. **Residual risk of flooding at the downstream side of Rogues Hill and Penshurst Place Concrete Road Location 1:** Some events may have characteristics that differ from the design event modelling, such as those that have multiple flood peaks in relatively quick succession or relatively large flood volumes. It is appropriate that these events be considered as residual risk events, so the potential consequences can be understood and taken into account as appropriate. Section 5.3.1 of the FRA report (inquiry core document "CD3.1d") identifies for these events that it is possible that some of the storage volume within the FSA may be utilised either through flood water flowing onto the floodplain naturally or through operation of the FSA prior to the main peak of a flood event arriving.

136.1. For the Revised Scheme, mitigating actions relating to residual risks are the operating procedures and the other actions taken by the Environment Agency e.g. through the provision of alerts regarding impoundment and flood warnings.

136.2. In the residual risk events, modelling indicates that changes to peak flood water levels could extend to the downstream side of Rogues Hill, but not upstream of it. In this area of the floodplain, between the downstream side of Rogues Hill and circa 1km to the east (the floodplain south of Well Place Farm), the extent of floodplain that experiences changes in water levels and the actual changes in water levels will vary on an event-by-event basis, given that each event has different characteristics associated with the flood e.g. different flow rates during the event, different volumes etc.

136.3. For areas identified to be at residual risk of flooding, the changes in risk are considered to be relatively small for the following reasons:

- the general areas at residual risk are those that are already affected by flooding in the Baseline;
- residual risks are identified for events that have a relatively low probability of occurrence meaning that the magnitude of flooding will already be relatively high;
- no effects are identified whereby an entirely new area of flooding is predicted, where existing flood depths/extents suddenly increase notably, or where the onset of flooding would be very quick, and
- existing impoundment and flood warning arrangements are in place during times of flood.

136.4. For the two residual risk events simulated in the model, with flood probabilities of 1.33% and 1% AEP, peak water levels increased in the Revised Scheme modelling by 0.04m and 0m at the downstream side of Rogues Hill and 0.09m and 0.02m at Penshurst Place Concrete Road Location 1, respectively. These changes in flood depths equate to percentage changes in the 1.33% and 1% AEP events of 2% and 0%, respectively, on the floodplain immediately downstream of Rogues Hill road and 30% and 5%, respectively at Penshurst Place Concrete Road Location 1. Figure 15 presents the changes in peak water levels in the FSA for the 1.33% AEP residual risk event, plotted against floodplain elevations to provide context to the changes in depth.

136.5. Changes in flood extents between the downstream side of Rogues Hill and Well Place Farm to the east are relatively small. Refer to Figure 14. Most areas of the floodplain show changes in the extent of flooding of less than 2m (the flood mapping was prepared to a resolution of 2m), although some areas of change up to 10m are predicted. These larger changes are located at the pond north of the Concrete Road. Figure 14 presents the difference in flood extents between the Baseline and Revised Scheme modelling for the 1.33% AEP residual risk event described above. In addition to the Concrete Road, the boundary of The Yews property, located on the southern side of the River Medway downstream of Rogues Hill is within the area that increased flood depth could occur during residual risk events.

136.6. The J.C.White topographic survey collected in July 2018 identifies that the threshold level of the main (westernmost) building of The Yews ranges between circa 30.1mAOD to 31.2mAOD, while the building connected to the northeast (understood to be a workshop) has a threshold level of circa 29.2mAOD. Other smaller buildings further to the northeast are at lower levels. The July 2018 topographic survey forms two attachments to the joint Statement of Case presented by Mr and Mrs Storey (Bridge House), Mr and Mrs Thompson (The Yews), and Mr Burraston and Ms Pallen (Colquhouns Cottage). The attachments provided in the joint Statement of Case are inquiry core documents “RM-002-SOC-02” and “RM-002-SOC-03”. For the 1.33% AEP, 1% AEP and 1% AEP plus climate change events, the main building threshold level is circa 0.9m, 0.8m and 0.6m above the peak flood levels, respectively so is not considered to be at risk in residual risk scenarios described above. The threshold level of the workshop building is very close to the peak water levels for the 1.33% and 1% AEP events, so it is plausible that flooding at the workshop, and the smaller buildings located to the northeast could be affected by increased flood depths in residual risk scenarios.

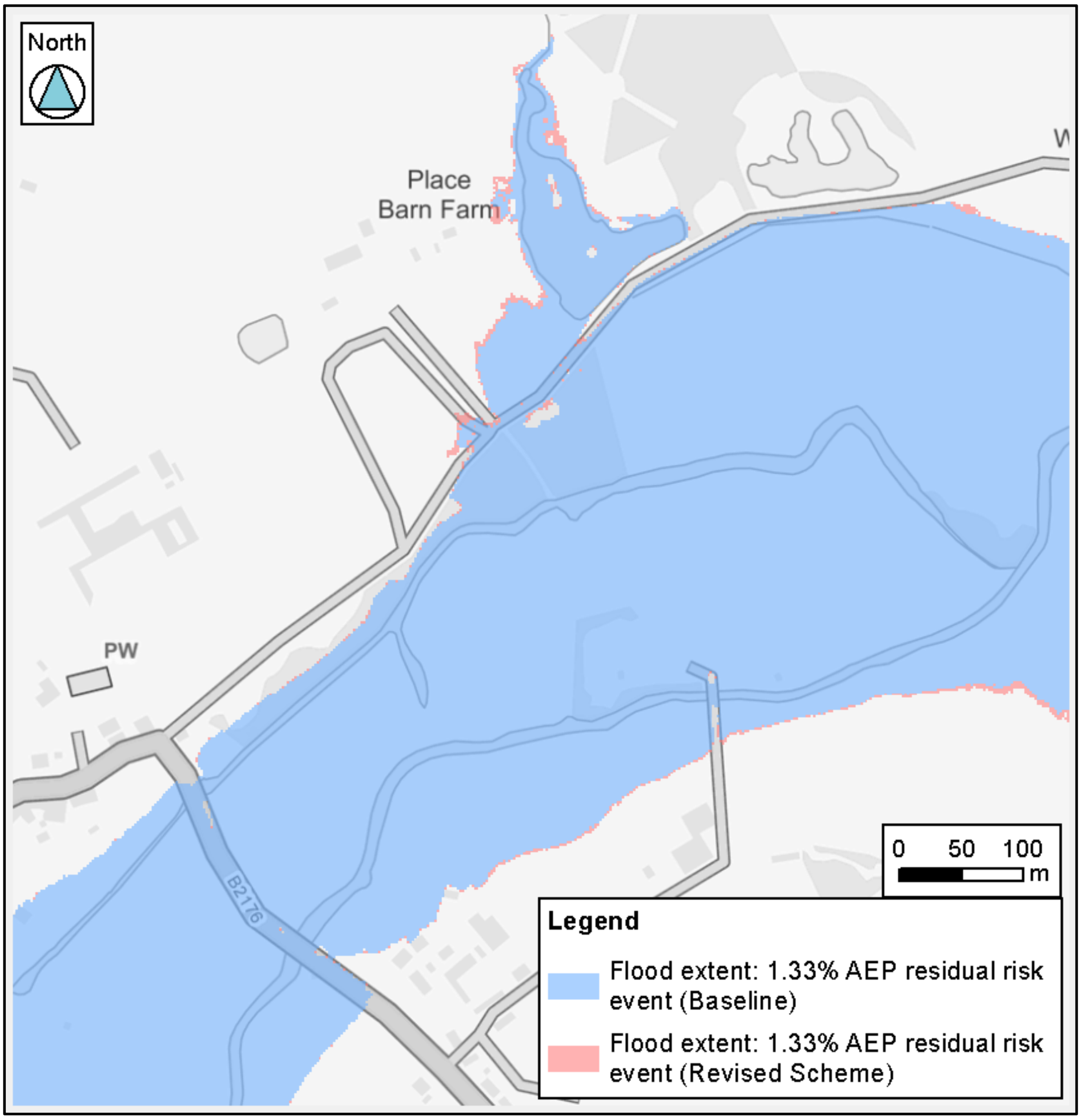

Figure 14: Flood extents from the Baseline and Revised Scheme modelling for the 1.33% AEP residual risk event

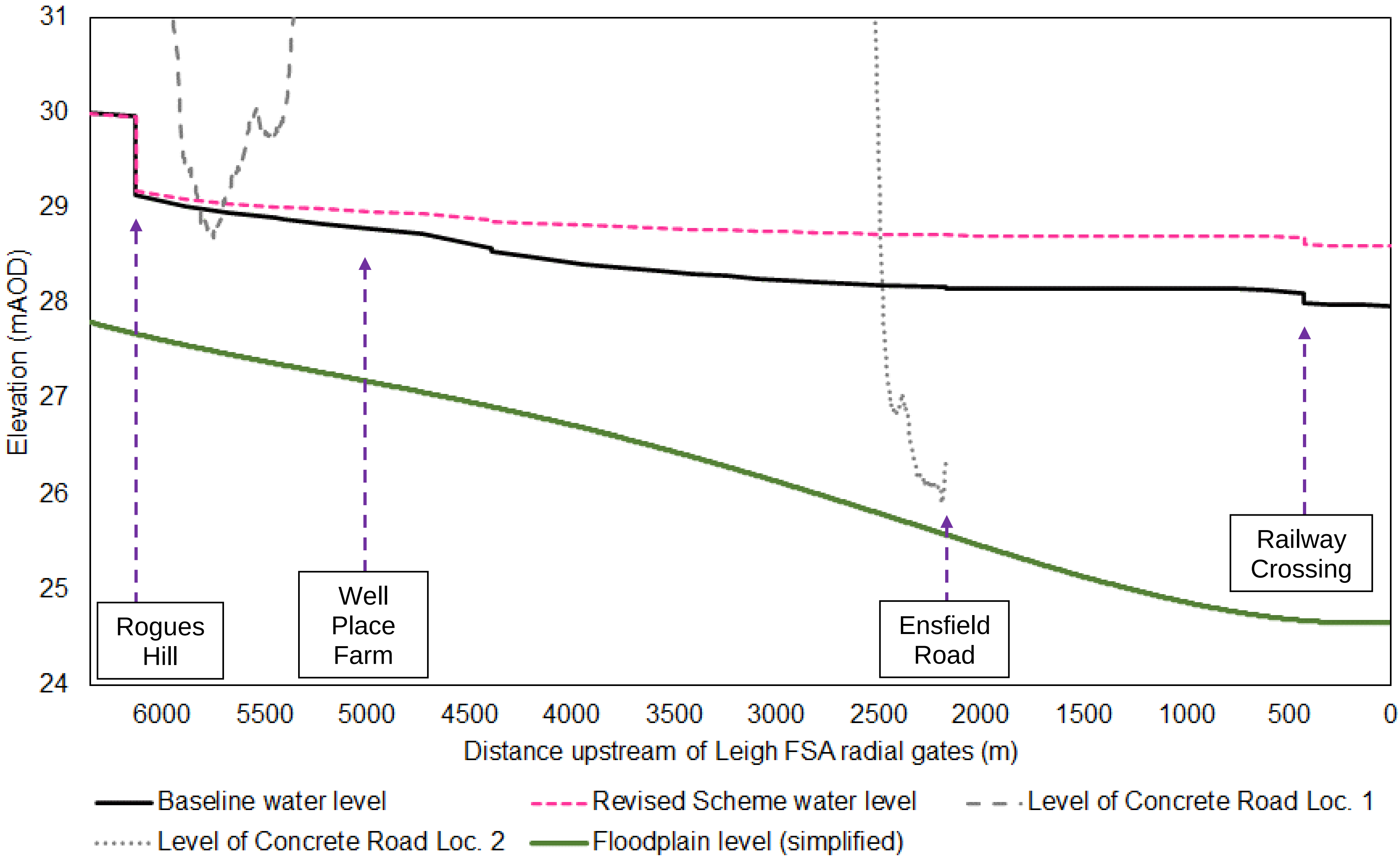

Figure 15: Long-section of peak water levels (Baseline and Revised Scheme scenarios) and floodplain levels for the 1.33% AEP residual risk event

137. **Changes in flooding at Penshurst Place Concrete Road Location 2:** Penshurst Place Concrete Road Location 2 is located circa 2km upstream of Leigh FSA radial gates and the elevation of the river bed nearby is relatively similar to that at the upstream of the Leigh FSA radial gates. The junction of Penshurst Place Concrete Road with Ensfield Road is located circa 250m to the northwest of the river. Refer to Figure 12 for an overview of the location and extents of flooding in the Baseline.

137.1. Within the Baseline modelling, flood water is predicted to flow across Penshurst Place Concrete Road Location 2 in the 20% AEP event, with circa 350m length of the road predicted to be flooded in the 5% AEP event. Flood depths increase considerably for larger magnitude flood events.

137.2. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that Penshurst Place Concrete Road Location 2 is located within an area of the FSA where increases in peak flood water levels of up to 0.55m could occur (reflecting the increase in permitted level for storage of water). Most areas of floodplain in this area show changes in the flood extent of circa 10m. Other than the two roads, no other receptors are affected within this area.

137.3. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in flood water levels up to 1.3m are predicted on the falling limb of the flood hydrograph (after the flood peak). This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 16 presents an example of this difference in water level vs time from the channel at the upstream side of Ensfield Road for the 1% AEP event.

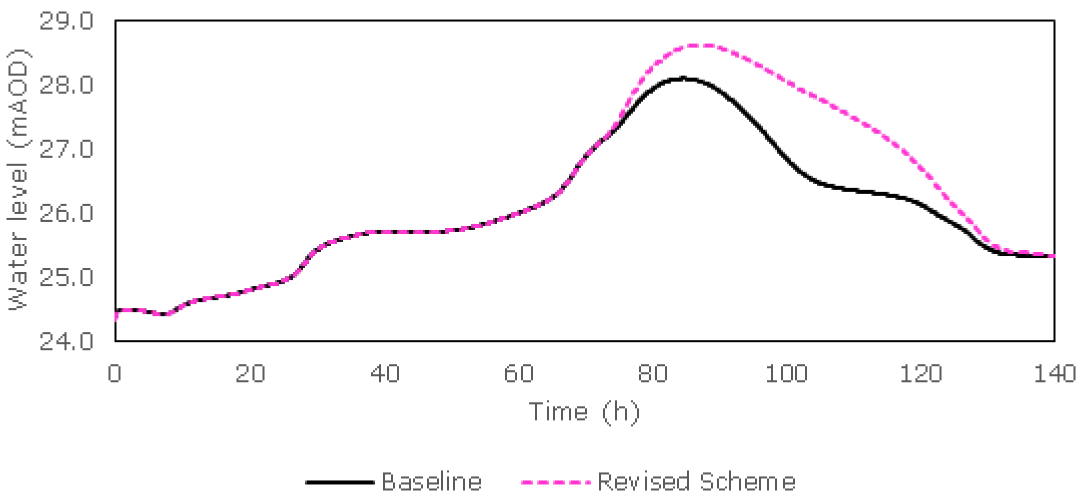

Figure 16: Time-series of modelled water levels for the 1% AEP event at the Penshurst Place Concrete Road Location 2 for the Baseline and Revised Scheme

138. Changes in flooding immediately upstream of the Leigh FSA radial gates:

138.1. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in peak flood water levels of up to 0.55m could occur (reflecting the increase in permitted level for storage of water). The northern extent of the floodplain in this area has predicted changes in the extent of flooding of up to circa 10m, while the southern extent of the floodplain in this area has predicted changes in the extent of flooding of up to circa 60m. Other than Ensfield Road itself, no other receptors are identified as being affected within this area.

138.2. Comparison of outputs from the Baseline and Revised Scheme modelling indicate that increases in flood water levels up to 2m are predicted on the falling limb of the flood hydrograph (after the flood peak). This means that for the Revised Scheme, water within a given range, will be on the floodplain for a longer duration of time, and so areas of the floodplain will take longer to drain away. Figure 17 presents an example of this difference in water level vs time at the upstream of the Leigh FSA radial gates for the 1% AEP event.

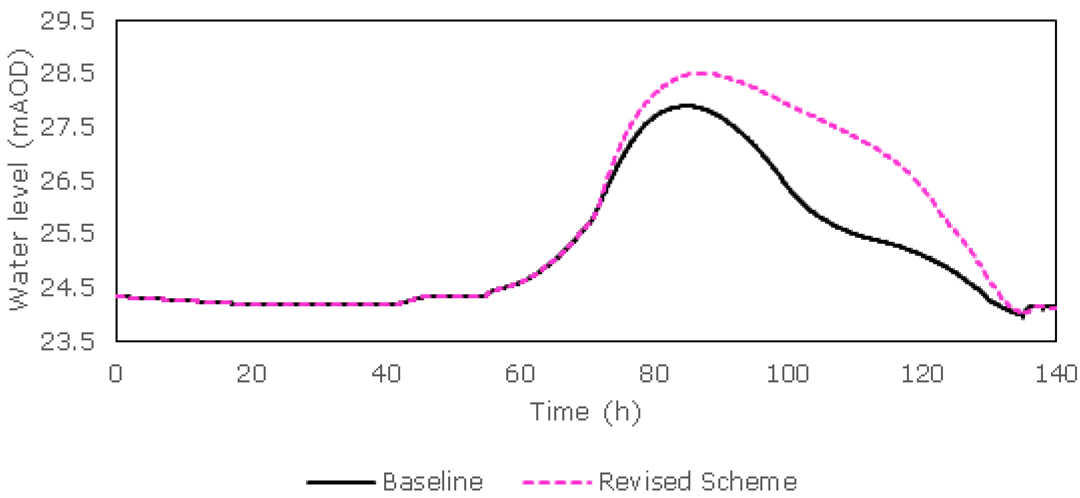

Figure 17: Time-series of modelled water levels for the 1% AEP event at the upstream of Leigh FSA radial gates for the Baseline and Revised Scheme

Timing of flood propagation from sites of interest to the FSA

139. Considering how flood flows and water levels change through time during an event (referred to a flood propagation) is important to help understand the factors that influence the flooding. In the context of the FSA the main factors are the flow rates originating from the catchment upstream and the operation of the radial gates at the FSA, which alters the water levels stored. With an understanding of the flood propagation, it is then more straightforward to appreciate the effects of the Revised Scheme compared with the Baseline.

140. Model results indicate that the time taken for the peak flow rates from Colliers Land Bridge gauging station and Vexour Bridge gauging station to reach the confluence of the River Eden and River Medway is between 3-5 hours.

141. Model results indicate that the peak water level at Rogues Hill coincides with the peak flow rates originating from the catchment upstream. This peak water level typically occurs 10-15 hours prior to the maximum water level at the radial gates being reached. This supports the premise that the peak of flooding at Rogues Hill results primarily from the natural flood response from the catchment upstream, rather than from operation of the FSA. This explains why the peak flood levels presented through figures within paragraphs 131 to 135, are not influenced by the change of operation associated with the Revised Scheme, but the water levels on the falling limb of the hydrograph are. It should be remembered for the Baseline scenario, namely the current operation of the FSA, this may increase flood depths, and this can be by up to 0.1m at Rogues Hill.

142. Figure 18 displays time-series of flows at Rogues Hill and water levels at Rogues Hill and upstream of the Leigh FSA radial gates for the 1% AEP Baseline. The difference in time between the peak water levels at Rogues Hill and upstream of Leigh FSA radial gates is evident. Additionally, it can be seen that a flow of circa 40m^3/s, which occurs circa 50hrs before the peak water level upstream of the radial occurs, results in a water level of circa 28mAOD being predicted, at a time when the water level at the radial gates is 24.2mAOD and the gates are not operating to actively store flood water. The same conclusions are reached when inspecting the results for the Revised Scheme modelling. Figure 19 displays time-series of flows at Rogues Hill and water levels at Rogues Hill and upstream of the Leigh FSA radial gates for the 1% AEP Revised Scheme scenario (28.60mAOD NMOWL).

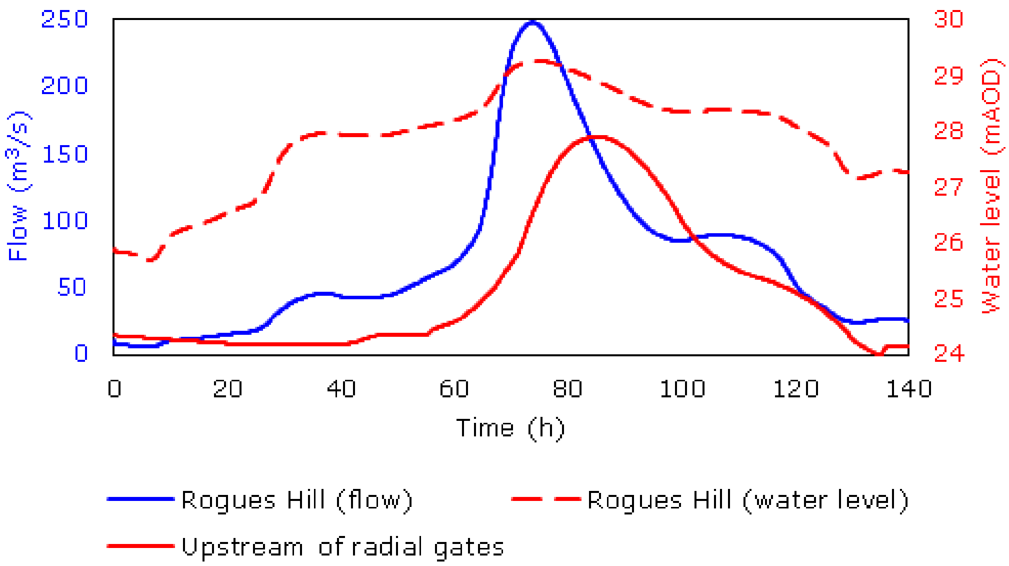

Figure 18: Time-series of modelled flows at Rogues Hill and water levels at Rogues Hill and upstream of the FSA radial gates for the 1% AEP event, for the Baseline event

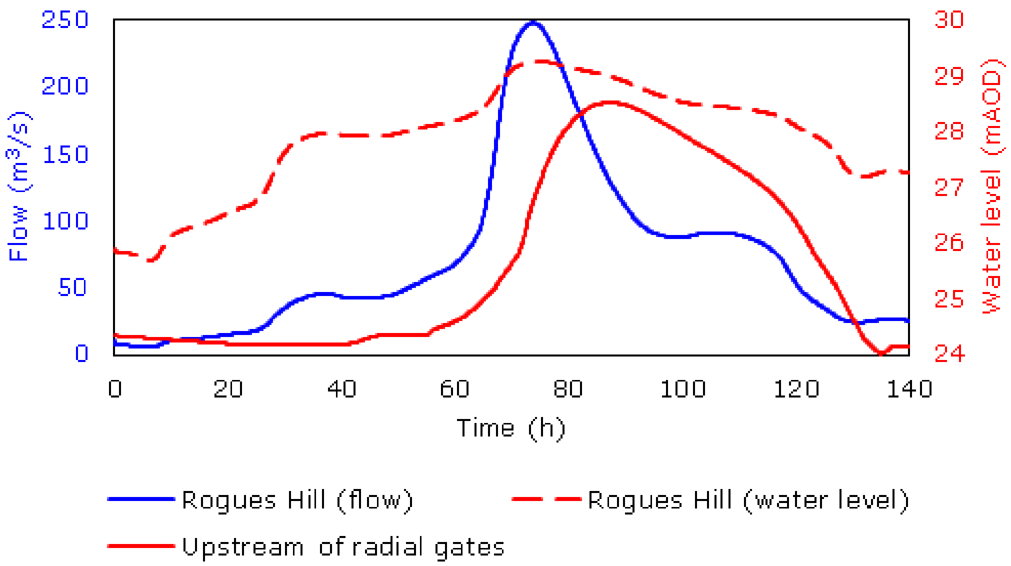

Figure 19: Time-series of modelled flows at Rogues Hill and water levels at Rogues Hill and upstream of the FSA radial gates for the 1% AEP event, for the Revised Scheme event

143. The findings presented in paragraphs 141 and 142 relating to the timing of flood flows and water level from the flood risk mapping modelling are supported by observations from past flood events. This is evidenced in photos presented in other documents associated with the inquiry, as described below.

144. December 2013 event: Appendix B of the Objection to the application raised by Mr and Mrs Storey in July 2020 (inquiry core document reference "CD3.1b") presents photos of internal flooding to the property on 24 December 2013 at 09:52, with photos taken earlier on the same day displaying notable flooding within and around the property boundary. A photo is also provided on 25 December indicating that flooding has reduced at the property.

- It is noted that the photo of Rogues Hill provided at the front of Mr and Mrs Storey's objection states that the photo was "Taken after the Environment Agency operated the Leigh Barrier impounding the existing Flood Storage Area to its maximum depth of 28.05 metres AOD". Appendix B to the Objection identifies that this photo was taken at 09:09 on 24 December 2013. It should be noted that, as presented in Mr Andrew Irvine's Proof of Evidence, the peak water level at the FSA radial gates was not reached until 11 hours later at 22:00 on 24 December 2013.
- At 08:14 on 24 December 2013 when a photo of flooding at the front (east of the property) was taken, the water level at the FSA radial gates indicates that the FSA was only 25% full, yet the peak flow entering the FSA was circa 250m^3/s and approaching the peak flow. This supports the conclusions from the modelling presented in paragraphs 141 and 142 that peak flooding at Penshurst originates from the upstream catchment flows and not due to change in water levels associated with operation of the FSA.
- At 09:52 on 24 December 2013 (when internal flooding of the property is evidenced), the peak flow rate of circa 270m^3/s entering the FSA has been reached, yet the FSA is at less than 50% capacity. This supports the conclusions from the modelling presented in paragraphs 141 and 142 that

peak flooding at Penshurst originates from the upstream catchment flows and not due to change in water levels associated with operation of the FSA.

- The 12-hour difference in timing between the peak inflow (10:00 on 24 December 2013) and the peak water level at the FSA radial gates (22:00 on 24 December 2013) is consistent with the timings evidenced in the design event modelling stated in paragraph 141.

145. December 2019 event: The peak water level recorded at Penshurst gauging station (21:00 on 20 December 2019) occurred 12 hours prior to the peak water level at the FSA radial gates (circa 09:00 on 21 December 2019), which is consistent with the timings evidenced in the design event modelling stated in paragraph 141.

    145.1. February 2020 event: The peak water level recorded at Penshurst GS (01:00 on 17 February 2020) occurred 13 hours prior to the peak water level at the FSA radial gates (14:00 on 17 February 2020), which is consistent with the timings evidenced in the design event modelling stated in paragraph 141.

Changes in the duration of flooding due to the Revised Scheme

146. Within paragraphs 131 to 138 I have presented graphs displaying the changes in the time-series of water levels between the Baseline and Revised Scheme modelling at various locations. These have evidenced that for the Revised Scheme, flood water at a given level may be on the floodplain for a longer duration of time, and so areas of the floodplain may take longer to drain away. This means that backwater effects due to the storage of flood water may prolong the reduction in water levels on the falling limb of the hydrograph. Below, I have presented further information to support the understanding of changes in the duration of flooding due to the Revised Scheme

147. For the 1% AEP event, Figure 16 and Figure 17 present durations of increased flood levels for the Revised Scheme above the maximum flood level in the Baseline scenario. These closely reflect the average duration of impoundment above the Baseline scenario (19 hours) stated in section 5.1.3 of the FRA report (inquiry core document “CD3.1d”). These durations are representative of flood conditions close to the FSA radial gates, where changes in flood levels are greatest. However, the values presented will not be representative of the duration of water levels above the maximum Baseline level further upstream in the FSA. For example, closer to the Well Place Farm as presented in Figure 20, the duration of time water levels are above the maximum level in the Baseline simulation is less. This means that not only is the magnitude of change smaller at this location, but so too is the duration of changes, meaning that consequences in the Revised Scheme are minimised.

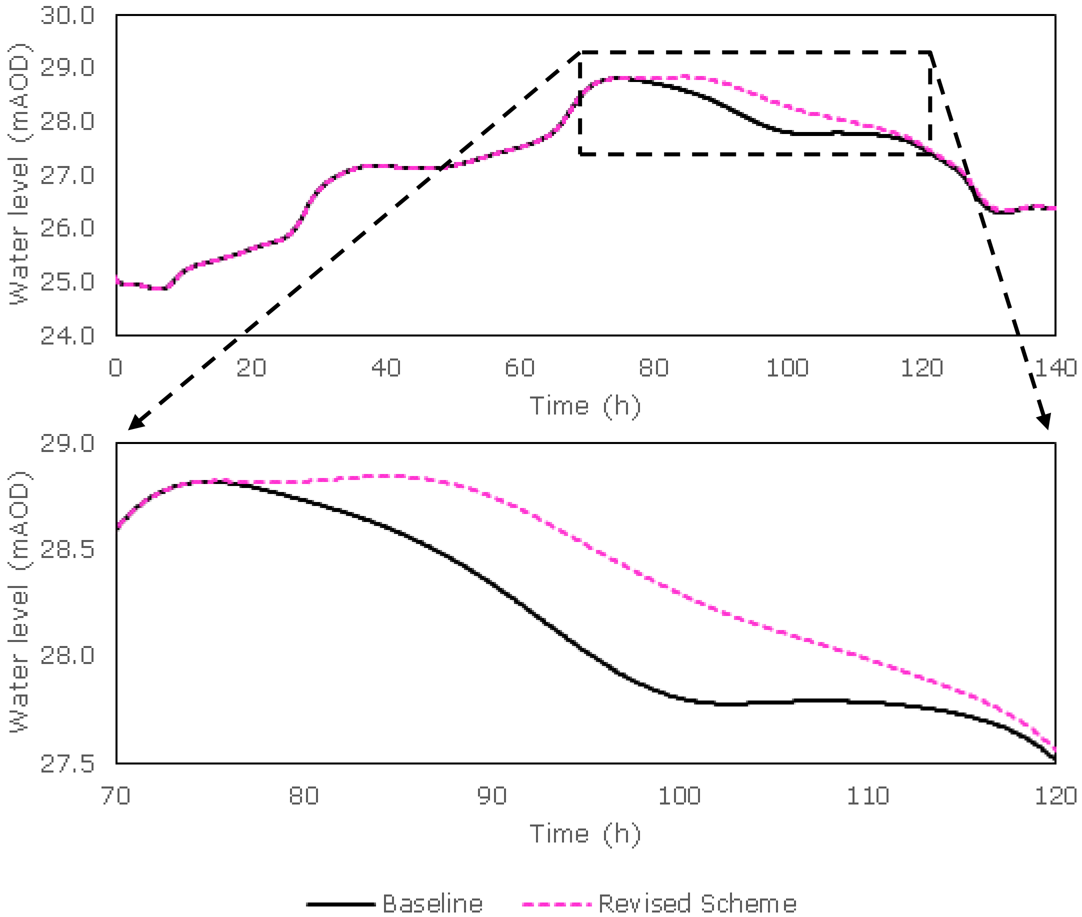

Figure 20: Time-series of modelled water levels for the 1% AEP event south of Well Place Farm for the Baseline and Revised Scheme

148. For the two residual risk events discussed in paragraph 136, in the floodplain between Rogues Hill and Well Place Farm the duration of time that the water levels in the Revised Scheme scenario are above the maximum water level in the Baseline are considerably shorter than at the FSA radial gates. For the 1.33% AEP event at Penshurst Place Concrete Road Location 1 the duration of time that water levels are above the maximum level in the Baseline is 14hrs, while for the 1% AEP event this is 9hrs. Given that these are residual risk events, which have relatively small changes in flood depths (increases of 0.09m and 0.02m at the Concrete Road location 1 for the 1.33% and 1% AEP residual risk events) and there is a relatively short duration of time that this additional flood depth is predicted, the change in risk resulting from this change (an outcome of probability and consequence) is considered relatively low.

149. The water-level time-series presented in the paragraphs above for regions of the floodplain between Penshurst gauging station and Leigh FSA radial gates) indicate that the duration of time that flood water is predicted in the Revised Scheme scenario to be above the level it would otherwise have been at the same point in time for the Baseline scenario is expected to be longer. This change will vary on an event-by-event basis, given that various factors are involved (e.g. magnitude, shape and volume of the hydrograph, operation of the radial gates at Leigh FSA). During this period of time, water levels are still receding (modelling does not indicate that there a single fixed water levels is

retained for a longer duration of time) and the premise described above is apparent - that with distance upstream away from the FSA the duration of time water levels are elevated reduces.

150. Prolonged flooding within the FSA and for areas identified further upstream (for instance as described in paragraphs 130 and 133) will impact relatively few receptors, which are already flooded in the Baseline scenario. These receptors largely comprise open land, road crossings and a small number of properties, so the increase in flood risk is considered relatively low. This is contrasted with the reductions in flooding (both in terms of frequency and depths) downstream of Leigh FSA enabled the Revised Scheme, as discussed in paragraph 124 and the FRA, which will result in a reduction in flood risk that is proportionally larger.

Response to objections to the Revised Scheme focused on flood risk modelling

151. The objections raised relating to the Revised Scheme (inquiry core document "CD3.1b") were responded to by the Environment Agency, as presented within inquiry core documents "CD3.1c" and "CD3.1c-1". Some of these objections raised concerns over the flood risk modelling that has been prepared to inform the understanding of flood risk and the changes resulting from the Revised Scheme. Within the objections raised relating to the Revised Scheme no specific elements of the flood risk modelling have been referred to, but rather more general points made around concerns.

152. Within the following sections I have directed readers to relevant information presented in this Proof of Evidence which relates to the concerns raised by objectors. These sections do not replicate responses already provided to the objectors by the Environment Agency, and do not replicate information already presented in this Proof of Evidence. Instead, the concerns raised by objectors have been grouped into themes and relevant paragraphs of this Proof of Evidence have been referred to.

153. <u>Concerns related to the change in the duration of flooding</u>.

153.1. From my proof I refer the reader to the following paragraphs for details of predicted changes in maximum flood depths and extent, and the water level time-series at specific locations:

- Chafford gauging station, close to Chafford Lane/Chafford Bridge: Paragraph 128
- Colliers Land Bridge gauging station, located at the upstream of Colliers Land Bridge: Paragraph 129
- Vexour Bridge gauging station, located at the downstream of Vexour Bridge: Paragraph 130
- Penshurst gauging station: Paragraph 131
- Long Bridge (B2188): Paragraph 132
- Rogues Hill (B2176), upstream side including Bridge House: Paragraph 133
- Rogues Hill (B2176), downstream side, including The Yews property and Penshurst Place Concrete Road Location 1: Paragraphs 134 to 136

- Penshurst Place Concrete Road Location 2: Paragraph 137
- Upstream of the FSA radial gates: Paragraph 138

153.2. Refer to paragraphs 146 to 150 for further details of the changes in duration of flooding due to the Revised Scheme.

154. Concerns related to the timing of flooding within the River catchment, in relation to operation of the FSA and 'natural flooding' resulting from upstream flows.

154.1. From my proof I refer the reader to paragraphs 139 to 145.1 for details of the timing of flooding associated with the catchment response upstream and storage of flood water in the FSA.

155. Concerns related to the inputs (flood flows) to the flood modelling.

155.1. From my proof I refer the reader to paragraphs 64 to 66 for details of how the flood flow hydrology estimates used within the flood risk mapping model were prepared.

155.2. From my response I refer the reader to paragraphs 97 to 99 for explanation of why the flood flow hydrology estimates used within the flood risk modelling are appropriate.

156. Concerns related to the use of flood modelling, and its ability to replicate historic events.

156.1. From my proof I refer the reader to paragraphs 67 to 72 for details of the operation of the FSA configured within the flood risk mapping model and its representation of FSA operator judgements

156.2. From my response I refer the reader to paragraphs 100 and 101 for discussion on the strengths and checking of the flood risk mapping model

156.3. From my response I refer the reader to paragraphs 102 to 108 for details of the calibration, verification and sensitivity testing analyses prepared for the flood risk mapping model.

156.4. From my proof I refer the reader to paragraphs 109 to 112 for details of confidence and uncertainty with flood risk modelling and the modelling upstream of Leigh FSA embankment.

156.5. From my proof I refer the reader to paragraphs 114 to 118 for why the configuration of the Revised Scheme within the Baseline model is appropriate.

157. Concerns relating to uncertainty with flood modelling.

157.1. From my proof I refer the reader to paragraphs 109 to 112 for details of confidence and uncertainty with flood risk modelling and the modelling upstream of Leigh FSA embankment.

Name:

Ben Gibson BSc MSc MCIWEM C.WEM

Signature: