PHASE 1 REPORT

Definition of Baseline

Prepared for

Network Rail

September 2016

Burderop Park
Wroughton
SN4 0QD

Exeter to Newton Abbot Geo-Environmental Resilience Study

Phase I: Definition of the Baseline

September 2016

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Document History

Version	Date	Description	Created by	Verified by	Approved by
1.0	April 2015	Draft for Network Rail comment	Project Team	DF	PB
2.0	July 2015	Following Network Rail's comments	Project Team	DF	PB
3.0	June 2016	Interim re-issue as per NR Request	Project Team	JRR/RM/DP	PB
4.0	July 2016	Final	Project Team	JRR/RM/DP	PB
5.0	September 2016	Final (Figure 1-1 updated)	Project Team	OR	PB

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Acronyms and Abbreviations

AIMS	Asset Information Management System
AR5	Fifth Assessment Report
BCR	Benefit Cost Ratio
BGS	British Geological Society
CBU	Cliff Behaviour Unit
CMIP5	Coupled Model Inter-comparison Project Phase 5
CO_2	Carbon Dioxide
Defra	Department for the Environment, Food and Rural Affairs
DfT	Department for Transport
EA	Environment Agency
GCM	Global Climate Model
HRA	Habitats Regulations Assessment
IPCC	Intergovernmental Panel on Climate Change
NMR	National Monuments Record
NPV	Net Present Value
NR	Network Rail
PVB	Present Value Benefit
PVC	Present Value Cost
RCP	Representative Concentration Pathways
SAC	Special Area of Conservation
SCOPAC	Standing Conference on Problems Associated with the Coastline
SEA	Strategic Environmental Assessment
SPA	Special Protection Area
SRES	Special Report on Emissions Scenarios
SRS	Strategic Route Sections
SSSI	Site of Special Scientific Interest
WebTAG	Web-based Transport Appraisal Guidance
WFD	Water Framework Directive
WLC	Whole Life Cost

Introduction

1.1 Background

This resilience study focuses upon 32 kilometres of the Western Route extending between the train stations of Exeter St David's and Newton Abbot (Figure 1-1). This iconic stretch of railway follows that of Brunel's coastal route established in 1846 and includes both the Exe and Teign estuaries as well as the exposed coastal section between Dawlish Warren and Teignmouth.

This section of the Western Route carries long-distance train services between stations in Devon and Cornwall to London, Bristol, Wales, the Midlands, Northern England and Scotland. It also accommodates freight services and local services; the key local stations are highlighted on Figure 1-1.

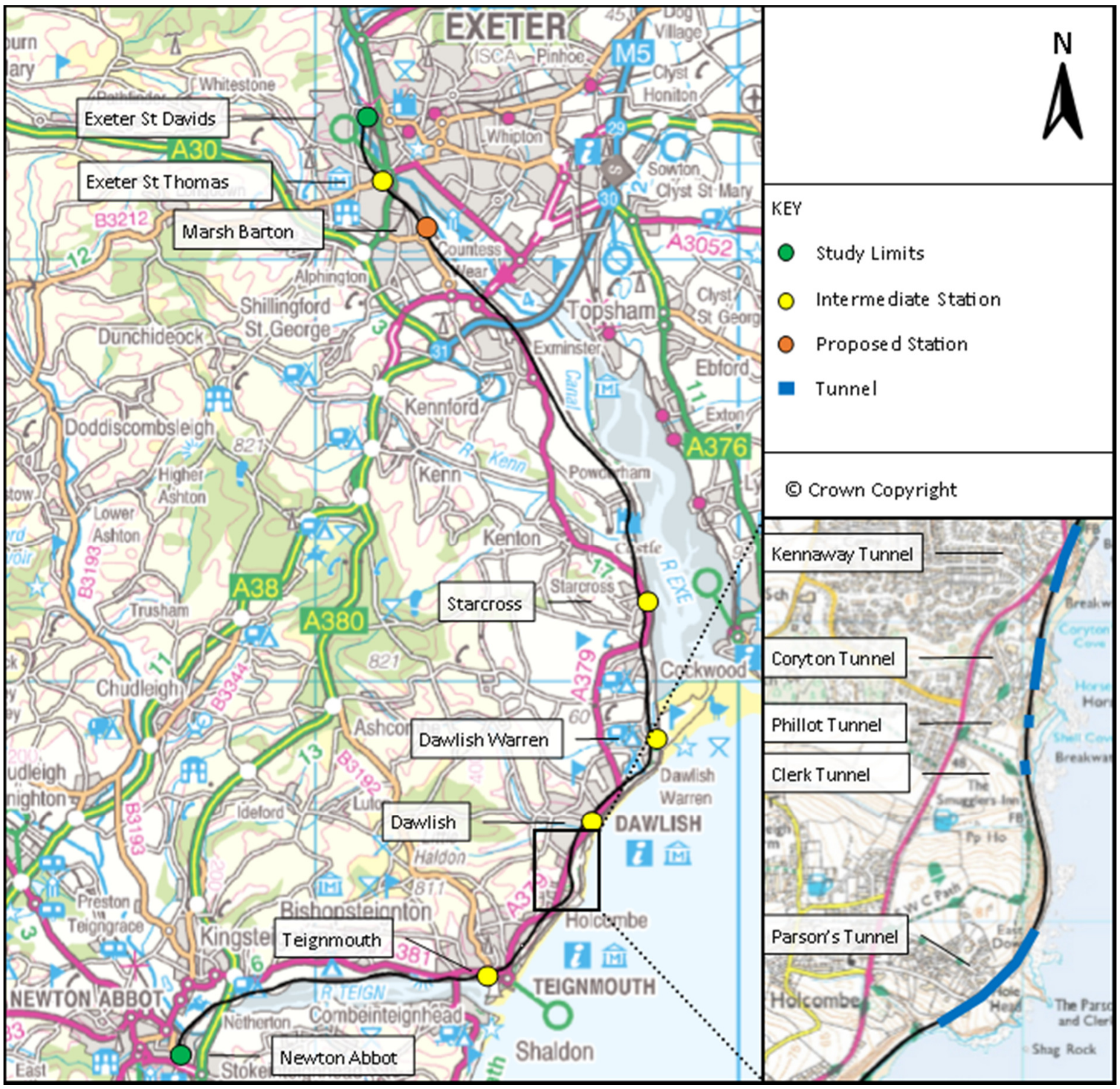

Figure 1-1: Study area with key locations

The environmental challenges faced along this stretch of railway have been well documented in recent years and it is vulnerable to marine erosion and wave overtopping, estuarine and river flooding and cliff instability issues.

Since the railway first opened, the sea wall has often been damaged by marine erosion and overtopping, the coastal track has been flooded and the line obstructed by cliff collapses. As there is no alternative rail route, damage to the railway is likely to result in the suspension of passenger and freight train services to and from the south west peninsula.

On the night of the 4th February 2014, a section of sea wall at Dawlish was destroyed by storms causing a significant stretch of the Western Route to collapse into the sea (Figure 1-2). This was the most high-profile of a number of severe weather-related disruptions to the national rail network in the winter of 2013/14 and was subject to intense media coverage and Government interest. The damage severed a major transport link between Cornwall, Devon and the rest of Great Britain, with rail services unable to operate beyond Exeter for a period of two months.

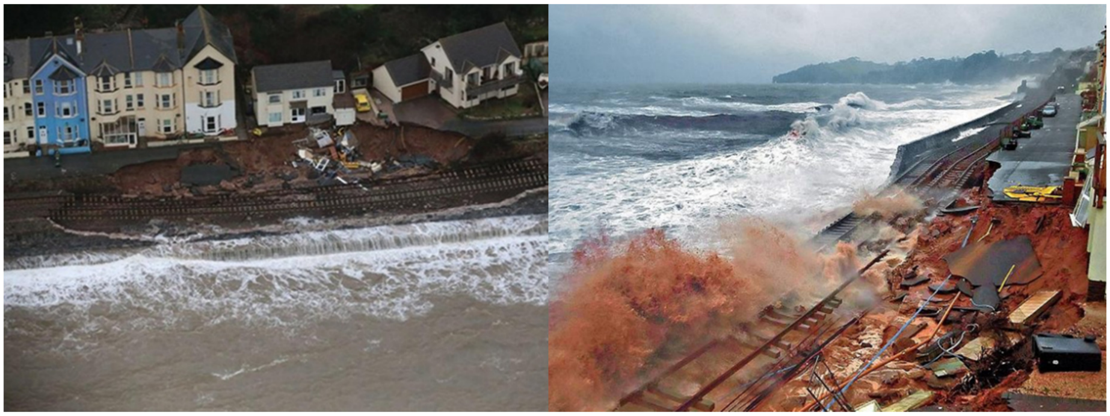

Figure 1-1: Images from 2014 storm damage at Dawlish

Despite Network Rail's widely acknowledged success in repairing the catastrophic infrastructure damage and restoring services, the weather resilience of the railway in Devon and Cornwall remains a significant issue for Government, local stakeholders, for rail operating companies and for Network Rail (NR) as Britain's rail infrastructure owner.

1.2 Objectives

In December 2014 CH2M was commissioned by NR Infrastructure Limited to undertake the Exeter to Newton Abbot Geo-Environmental Resilience Study. The primary objective of this commission is to develop a Resilience Strategy that identifies a holistic long-term asset management plan for the railway line that:

- gives a minimum 50 year view for engineering solutions;
- gives a Best Whole Life Cost / Social, Economic & Environmental solution;
- is based on a 100 year climate change view;
- gives operational resilience in terms of safety and performance;
- gives mean times between service affecting asset failures;
- gives sufficient capacity to accommodate the long term strategic requirements;

The study has been split into the following three phases, with key deliverables associated with each:

- Phase 1: Definition of the Baseline
- Phase 2: Option Assessment
- Phase 3: Resilience Strategy

1.3 Report purpose

This report covers Phase 1 only and describes the work carried out to define the baseline conditions against which all subsequent strategic options will be assessed.

The document is structured as follows:

Section 1: setting the purpose and context of this baseline definition work stage.

Section 2: review of the historical challenges faced along this stretch of railway.

Section 3: assessment of future climate change and recommended scenarios.

Section 4: assessment of processes and metocean conditions.

Section 5 - 7: assessment of the main assets including cliffs and defence structures.

Section 8: looks at resilience and future operational requirements.

Section 9: describes the way in which the economics of options are to be considered.

Section 10: presents the environmental baseline.

Section 11: summarises any outstanding issues and gaps for each discipline.

Section 12: contains the bibliography

1.4 Description of study area

To account for the distinct changes in both engineering features and associated environmental risks the study area has been divided into five sections (Figure 1-3). A short description of each of these five sections is presented below:

Exeter to Dawlish Warren (referred to herein as Section 1): The railway runs for approximately 16.8 kilometres alongside the Exe Estuary, passing adjacent to the villages of Exminster, Powderham, Starcross and Cockwood. The principal environmental exposure along this section is to estuarine and river flooding.

Dawlish Warren to Kennaway Tunnel (referred to herein as Section 2): The railway runs for approximately 3 kilometres alongside the Dawlish sea wall between Dawlish Warren in the north east and Kennaway Tunnel in the south west. The line runs at the base of high sandstone cliffs as far as the steep sided valley at Dawlish, from where it is again backed by high cliff lines to Kennaway Tunnel. The principal environmental exposures along this section are to beach erosion, wave overtopping and cliff instability.

Kennaway Tunnel to Parson's Tunnel (referred to herein as Section 3): The railway line runs for approximately 1.5 kilometres through several tunnels and where exposed to the sea is protected by a masonry sea wall. On the landward side of the tracks are high vertical sandstone cliffs. The predominant defence structures form a continuation of Section 2 with the principal environmental exposures again being to beach erosion, wave overtopping and rock falls.

Parson's Tunnel to Teignmouth (referred to herein as Section 4): The railway line runs for approximately 2.2 kilometres between Parson's Tunnel and Teignmouth Station and represents a continuation of the arrangement described in Section 3. The seaward side of the railway is protected by a sea wall. On the landward side is a high cliff line formed from highly variable, soft bedrock. The principal environmental exposures along this section are to beach erosion, cliff failure and landslides.

Teignmouth to Newton Abbot (referred to herein as Section 5): The railway runs for approximately 8.2 kilometres alongside the north bank of the River Teign Estuary. The principal environmental exposure along this section is to estuarine and river flooding.

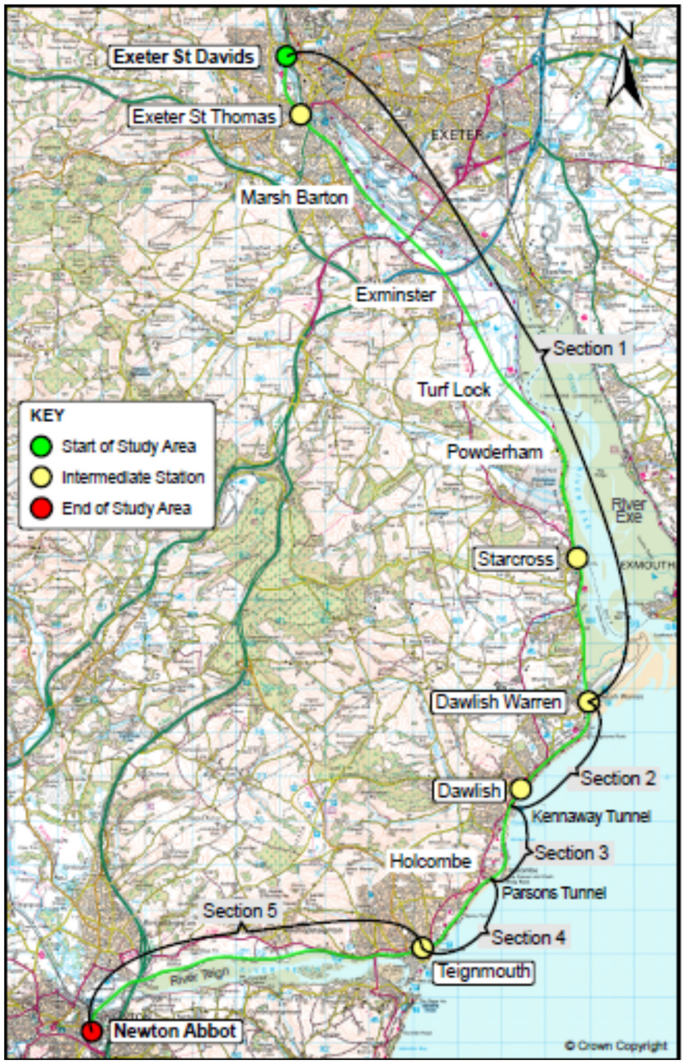

Figure 1-3: Study sections

1.5 Review of records

A large quantity of data has been provided by NR to supplement existing data sources and assist with the development of this baseline report. This transfer of data has been recorded within a data register with the latest version being included within Appendix A of this baseline report.

Historical events catalogue

Since the Western Route was first opened, there has been a long history of breaches in the coastal defences and many occurrences of cliff falls causing adverse impacts on the rail track and services. Throughout its operation, in order to keep the line in service and the public safe, significant effort and investment has been expended on remedial work and engineering improvements.

The locations of key historical cliff and coastal events are presented within Sections 2.2 and 2.3 respectively. Further details of each event, including date and description are provided within Appendix B of this baseline report.

2.1 Cliff stability events

The locations of the identified historical cliff stability events are indicated on Figure 2-1; further detail on these events including year of occurrence and descriptions of the events are available in Appendix B, Table B-1.

Figure 2-1: Cliff stability events

2.2 Coastal defence events

The recorded coastal events are presented on Figure 2-2. These include the locations where storm damage has occurred, repair of the defences and construction of new defences over the life of the railway. The year of occurrence, chainage and a description of the damage sustained and the works carried out can be seen in Appendix B, Table B-1.

Figure 2-2: Coastal defence events

Climate change

3.1 Climate change parameter review

Climate change projections from modelling centres around the world indicate that the climate will change significantly in the 21st century (and beyond). Climate change and adaptation is now recognised as a major issue across all sectors of society, with the potential to impact the human and natural systems upon which the world relies.

A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events. Some climate extremes (e.g. droughts) may be the result of an accumulation of weather or climate events that are not extreme when considered independently. Many extreme weather and climate events continue to be the result of natural climate variability (source: Intergovernmental Panel on Climate Change [IPCC] http://ipcc.ch/). The impact of these changes varies depending on exposure to the climate change variable and the vulnerability of the assets, economy or environment that is exposed.

In order to assess the impact of the projected changes in climate, and to account for these impacts in planning for sustainable infrastructure, it is vital that the potential future changes are explicitly captured in the decision making processes and analyses. When considering an infrastructure system such as that on the Exeter to Newton Abbot line, there is potential for a wide range of important environmental conditions to be affected by climate change.

The complexity of the physical setting means that the line is exposed to, and affected by, a wide range of environmental factors that could be modified in the future, due to climate change, and consequently has the potential to impact upon the performance of the railway. Table 3-1 below presents an overview of the key environmental conditions that could be modified by such change, together with notes on how they could impact the Exeter to Newton Abbot line.

Table 3-1: Key potential climate change impacts on the Exeter to Newton Abbot line

Climate Change Variable	Potential implications
Higher temperatures	Warping of track during extreme high temperatures events. Extreme temperature events exceeding operating range of the assets.
Precipitation changes	Greater extreme rainfall intensity causing flash flooding on track. Greater autumn/winter rainfall leading to increased landslides. Reduced summer rainfall leading to geotechnical instability.
Sea level rise	Increased seawater propagation onto track during coastal storm surges (service disruption, plus corrosion of assets). Increased erosion at sea walls/beaches, increasing potential for structural failure, undermining track infrastructure.
Increased storminess	Increased frequency and intensity of storm surges causing spray and inundation of track. Increased frequency of coastal erosion events. Increased wind loading on fixed and moving assets.

Combinations of the climate change variables outlined in Table 3-1 could also affect other conditions such as changes in snowfall patterns, frequency of fog and changes to low temperature extremes. However, these have lower confidence in terms of climate science and are considered to be of lower priority for planning on this line as they are unlikely to directly impact rail design or operations.

The following section presents a discussion about and recommendations for the values to be used in planning to account for the climate variables identified in Table 3-1.

3.2 Future climate change scenarios

The climate change scenarios and the related variables are discussed in greater detail in Appendix C.

3.2.1 Uncertainty in climate projections

When considering potential future climate change in the planning and delivery of infrastructure it is important to understand and account for the uncertainties inherent in climate projections. Climate science is continually evolving, increasing confidence in the scientific basis upon which future climate conditions are modelled. However, as with any forecast, there is uncertainty in the projected outcomes, even when observed phenomena are being considered. With climate change, the science is considering potential interactions and feedbacks between natural systems that have not previously been observed (for example the rapid melt of polar ice due to increased global atmospheric and sea temperatures) and this therefore reduces the certainty of future projections. Further, global climate models (GCMs) are driven by projections of future atmospheric greenhouse gas emissions which themselves are dependent on global development and technology patterns which are again highly uncertain.

These uncertainties are addressed in GCMs in a number of ways. Firstly, the scientific uncertainty related to the physics of the future global climate and interactions between physical systems, is reflected in the large number of GCMs used to develop climate projections. No one GCM provides the future projections, rather a large number of modelling centres around the world (including the UK Met Office) have developed and run their own GCMs each of which treat the future climate in slightly different ways. There are over 40 GCMs, the results of which are jointly analysed to give 'ensemble' results, with ranges of projections for all climate variables.

Secondly, the uncertainties in future global emissions are captured through the use of a standard set of 'Representative Concentration Pathways' (RCPs), which are four greenhouse gas concentration (not emissions) trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) for its Fifth Assessment Report (AR5; IPCC, 2013). The four RCPs, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 (of 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively). Table 3-2 below presents a summary of the four RCPs, including a cross-reference to the Special Report on Emissions Scenarios (SRES; IPCC, 2000) emissions scenarios used prior to the IPCC AR5 work.

Table 3-2: Description of RCP scenarios

	Description	CO_2 Equivalent	SRES Equivalent
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	1370	A1FI
RCP6.0	Stabilisation without overshoot pathway to 6 W/m^2 at 2100	850	B2
RCP4.5	Stabilisation without overshoot pathway to 4.5 W/m^2 2100	650	B1
RCP2.6	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline	490	None

Through the Coupled Model Inter-comparison Project Phase 5 (CMIP5) the global scientific community contributed the RCPs' simulation results of their GCMs for use through the IPCC AR5 outputs. This data has been extracted here to provide a summary of the range of projected change applicable along the route of the Exeter to Newton Abbot railway.

In the UK, available global climate model data has been refined and developed into scenarios by the UK Climate Programme (UKCP09) and further refined for flood and coastal erosion risk management applications by EA (2011 & 2016). These values are provided in the following sections with appropriate values selected for analysis in this project. The values are presented in the context of the most recent GCM projections, from CMIP5 as used for the 2013 IPCC AR5 climate reporting, to provide a check that these existing UK values remain within the range of the latest science.

3.2.2 Summary of scenarios to be appraised

Based on the discussion presented in the preceding section and Appendix C, Table 3-3 summarises the values to be used in the planning and design of future stages of the Exeter to Newton Abbot Resilience project. Each of these variables will be used as an adjustment to the baseline value for that 'climate metric' either as an absolute uplift or as a percentage change.

Table 3-3: Climate scenarios to be appraised for planning and design

Climate Metric	Change Factors					
	2065			2115		
	Low	Med	High	Low	Med	High
Summer Daily Extreme Temperature	+3.5°C	+4.0°C	+8.2 °C	+4.3°C	+6.5 °C	+15.2 °C
Sea Level Rise	+26cm	+30cm	+55cm	+49cm	+57cm	+107cm
0.5% Probability storm Surge	n/a	n/a	+47cm	n/a	n/a	+105cm
Winter Rainfall	+11%	+15%	+43%	+15%	+19%	+77%
Summer Rainfall	-28%	-36%	-64%	-34%	-45%	-89%
Rainfall Intensity	+7%	+13%	+27%	+15%	+30%	+60%
River Flows	+2%	+23%	+52%	+10%	+40%	+110%

It is recommended that through the planning and analysis for this study, the medium scenario values be used as a 'target' climate condition against which all infrastructure should be appropriately resilient, and that the high scenario values be reviewed as a 'sensitivity' test and considered to ensure plans/designs could be adapted to withstand this condition if such were to transpire. The low scenario provides a baseline 'future without project' condition, to principally be utilised in for investment planning purposes.

Metocean assessment and modelling

4.1 Introduction and methodology

The study area is situated within a dynamic and challenging marine environment and as such the suitability, sustainability and resilience of any future management options for the assets along the Exeter to Newton Abbot line will need to strongly consider how they will be impacted upon and influenced by the prevailing coastal and estuarine processes of the area.

This section describes the work that has been undertaken to inform the Phases 2 and 3 of the project:

- Coastal and estuarine processes for the whole study area (Section 4.2)
- Numerical Modelling and Overtopping Analysis (Section 4.3)
- Flood Modelling (Section 4.4)
- Shoreline Response (Section 4.5)

4.2 Coastal and estuarine processes

4.2.1 Introduction

This stretch of coastline has been subject to a significant amount of study in recent years, with the most relevant studies including:

Futurecoast (Halcrow, 2002)

Futurecoast was a major study looking at 6000 km of the coastline of England and Wales to assess current shoreline evolution and to predict future changes. This analysis considered an "unconstrained" scenario which assumed no defences and allowed coastal process to develop naturally. The study area is fully managed and therefore the Futurecoast predictions "with present management" are of relevance to this understanding of baseline coastal processes.

Sediment Transport Study (SCOPAC, 2004)

Building upon an earlier study published in 1991, and the Futurecoast project above, this brings together the results of subsequent studies and analyses of sediment movements on a sediment cell/sub-cell basis for all of England's Channel coastline and tidal estuaries between Start Point in the West and Beachy Head in the East.

Exe Estuary Coastal Management Study (Halcrow, 2008)

This study identified preferred options to provide a long-term sustainable management strategy for coastal defences at Dawlish Warren and Exmouth seafront.

Dawlish to Teignmouth Sea Wall Feasibility Study (Halcrow, 2009)

This feasibility study investigated the reconstruction and strengthening of the Dawlish to Teignmouth sea walls on behalf of NR, including outline proposals with estimated costs for the works.

South Devon and Dorset Shoreline Management Plan (Halcrow, 2010)

This study was a high-level appraisal assessing the risks associated with coastal processes. This document helps inform the direction of public funding for managing these risks.

Exe Estuary Flood and Coastal Erosion Risk Management Strategy (Halcrow/Atkins, 2013)

This study looked at how the flood and coastal erosion risks in and around the Exe Estuary could be managed over the next 100 years and proposed continued defence of most of the developed coastline.

Teign Estuary Coastal Management Study (Halcrow, 2014)

This study involved the development of a beach management plan to inform, guide and assist the responsible authorities and organisations in managing the beach and associated hard coastal defences, and to ensure that the risk of coastal flooding and erosion to properties and other assets along the Teignmouth and Shaldon frontages continues to be managed sustainably.

The assessments considered both large-scale and local-scale processes. Large-scale and long-term understanding is necessary to assess the sustainability of management options and to take into account any long-term trends or drivers of coastal change. Shorter-term and smaller-scale understanding is important because it identifies local detail and variations from the larger-scale.

Details of the large-scale and smaller-scale processes are contained in Appendix D. Extracts from this Appendix are provided below.

4.2.2 Section 1 - Exe Estuary

The full extent of the Exe Estuary is shown in Figure 4-1. The outer estuary includes the spits of Dawlish Warren and Exmouth (between Langstone Rock and Orcombe Rocks, situated to the west of Exmouth), as well as the ebb (Pole Sands) and flood (Bull Hill Bank) sandbanks.

Figure 4-1: Exe Estuary

4.2.2.1 Movement

The movement of the shoreline in this area is greatly affected by the complex sediment circulation caused by the presence of Pole Sands at the mouth of the Exe Estuary. Along the Exmouth frontage there is a westward transport of sediment due to the clockwise circulation, with material transported towards the estuary from Orcombe Rocks. The longshore transport at Dawlish Warren is from south-west to north-east, also moving sediment towards the estuary.

There has been no recorded retreat in position of the backshore at Exmouth, due to the presence of defences that prevent the natural adjustment of the beaches to storm events. However, beach volumes here have reduced over the recent past (Halcrow, 2007). In contrast, the Dawlish Warren spit has been able to retreat and re-align over the decades and is presently about 400m behind the line of the cliffs where the spit once extended linearly from Langstone Rock. There have also been changes in the plan form of the spit.

The consensus of opinion is that the coastlines either side of the spits both act as an input of sediment to the outer estuary.

Previous studies, notably SCOPAC (2004) and Halcrow (2008), have described the conceptual understanding of sediment transport around Dawlish Warren, Pole Sands, the estuary mouth, Bull Hill Bank and Exmouth. It is considered (SCOPAC, 2004; Posford Duviver, 1998; Halcrow, 2008) that there are two main systems of sediment transport. The first is wave net onshore (and longshore) movement from Pole Sands to Dawlish Warren, and the second is dominant ebb tidal transport south-east along the estuary mouth to sandbanks flanking the Maer channel. It is also suggested (SCOPAC, 2004) that sediment can be transported from the distal end of Dawlish Warren to Bull Hill Bank under flood tides, and then passed back to Pole Sands on ebb tides.

For sands and gravel the inner estuary is considered a temporary store (SCOPAC, 2004), whereas for muddy sediment it is considered a sink, supported by qualitative observations that the Exe Estuary mudflats have accreted slowly over time. SCOPAC (2004) states that the River Exe is the main source of fluvial sediment into the inner estuary. This is estimated as 1,900m^3/yr of fine sediment, which is stored in the inner estuary intertidal area. The Rivers Kenn and Clyst are also noted as potential smaller sources of sediment, but these inputs are not quantified. Erosion of the estuary banks, although also not quantified, is presumably negligible as an input due to the presence of the railway line and flood defences. In contrast to this, it is suggested (SCOPAC, 2004) that 1,000m^3/yr (predominantly sand) is moved from the outer estuary (specifically Bull Hill Bank) to the inner estuary. Whilst this represents a net continuous gain to the inner estuary, it is also noted that non-storm tidal input to the inner estuary is in balance i.e. any net gain comes from storm events. If the net gain is considered to spread across the inner estuary planform, this would on average represent 0.2mm/yr of vertical accretion; if continued over the next 100 years this would amount to 20mm. However, it is recognised that particular locations, such as Bull Hill Bank, are a focus for accretionary processes, rather than the general estuary.

4.2.2.2 Existing predictions of shoreline evolution

The Futurecoast (Halcrow, 2002) prediction for a 'with present management' scenario is for there to be continued erosion and narrowing of the spit and beaches of this section of coast. The impoundment of Exmouth spit would also prevent the shoreline from adjusting to future sea level rise and storm events, leading to an increased likelihood that the defences along the Exmouth frontage would fail and breach in the future.

At Dawlish Warren it is probable that a breach towards the distal end of the spit would occur, exposing the Exe Estuary behind to increased wave attack. The continued defence of the proximal end could limit the degree of such exposure by helping to retain part of the spit.

The Exe Estuary Strategy (Halcrow/Atkins, 2013) reiterated that the future evolution of Dawlish Warren is a key issue for the wider estuary, as there is evidence it controls flood risk (i.e. extreme waves and water levels) in the inner estuary (HR Wallingford, 1965, and anecdotal records from storms in December 1945). Exmouth spit is now inactive and built-up, whilst Dawlish Warren is held in place by defences, except along its distal end, where defences are now buried by sand. The future evolution of Dawlish Warren is dependent on future changes in hydrodynamic climate, sediment supply and management of the existing defences between Langstone Rock and the distal end. Previous work by Halcrow (2008) stated that in the short term (to 2030), extreme events could cause a temporary breach in Dawlish Warren (most likely at the neck or where other breach events occurred such as in 1962), and that continuation of historical trends would result in the coastal frontage of Dawlish Warren rotating anti-clockwise (in-estuary at the distal end). In recognition of this, works to reduce the risk of a breach are being implemented. These are understood to involve positioning a new defence along the rear face of the dunes across the neck of the spit, this constructed using sand filled geotextile bags. Although the existing timber groynes along the seaward face are to be replaced, and the entire beachfront re-nourished (dredged from the adjacent Pole Sands), a more natural evolution of the dunes fronting the Warren is to be encouraged through the removal of the existing lines of gabions that currently define the dune edge at the back of the beach. In order to ensure the longer term integrity of the beach, some periodic recycling and further re-nourishment is anticipated.

Over the last 40 years, sea levels on the UK south coast have risen on average by around 2mm/yr (UK Permanent Service for Mean Sea Level). Current understanding of the estuarine system suggests that marginal accretion of the inner estuary is occurring and would potentially continue into the future.

4.2.3 Section 2 - Langstone Rock to Holcombe

Covering the area between the isolated cliff headland at Langstone Rock and The Parson and Clerk headland at Holcombe, this section of coast consists of cliffs fronted by shingle beaches (refer to Figure 4-2). From Langstone Rock to Dawlish there is one continuous mixed sand-shingle beach, after which the shoreline is interrupted by the presence of a number of small headlands which contain small pocket beaches between them.

The key features are shown in Figure 4-2:

Figure 4-2: Langstone Rock to Holcombe

4.2.3.1 Movement

The open coast between Holcombe and Langstone Rock has been heavily influenced by anthropogenic activities. The mainline railway, constructed in 1846, removed the impact of wave erosion for the majority of the coastline.

The sea wall that protects the railway line prevents erosion of the cliff and has impounded the upper beach sediments upon which it was constructed. The presence of the defences associated with the railway, has resulted in the gradual narrowing of the beach in front of the sea wall due to the effects of beach scouring by wave action. This narrowing occurs along the long section of beach between Langstone Rock and Dawlish. The small pocket beaches between the minor headlands from Dawlish to Holcombe are more stable.

Cliff erosion only occurs where the railway line runs through tunnels cut through the headlands (i.e. where there are no cliff defences).

Although the construction of the railway line has prevented the erosion of the cliffs by the effects of wave action at the cliff toe, these cliffs are not completely stable and are subject to landsliding caused by weathering and high groundwater levels.

4.2.3.2 Existing predictions of shoreline evolution

The Futurecoast (Halcrow, 2002) prediction for a 'with present management' scenario is for there to be a continued reduction in the beach fronting the sea wall and other defences along this section of coast, gradually increasing the risk of the defences failing in the future. There would also be a continued risk of landslides caused by sub-aerial processes as occurs at present.

The Exe Estuary Strategy (Halcrow/Atkins, 2013) noted that future potential change is very dependent on future management of the railway and of Langstone Groyne. Beach erosion will continue, and the difference in drift potential and available sediment would suggest that if Langstone Groyne was damaged or removed, significantly accelerated beach erosion could occur. Sea level rise and increased storminess is likely to result in either unnaturally steepened beach slopes, or beach lowering, particularly in the medium to long term.

4.2.4 Holcombe to Teignmouth

4.2.4.1 Interactions

This section of coast extends from the headland at Holcombe to the northern end of Den Spit at Teignmouth. It consists of cliffs that have been stabilised by the construction of the railway line and associated defences, and is fronted by several stretches of shingle beach. The extent of the section is shown in Figure 4-3.

Figure 4-3: Holcombe to Teignmouth

4.2.4.2 Movement

The stabilisation of the cliff by the construction of the sea wall and railway along the cliff toe has resulted in very little if any cliff recession since the mid-19th century. Despite the stabilisation of the cliffs by the reduction of wave action at the toe, the cliffs are still susceptible to landsliding due to weathering and high groundwater levels.

The presence of the sea wall has led to the gradual narrowing of the beach width as sediment is not replaced along the shoreline by the erosion of the cliffs as would have occurred historically.

4.2.4.3 Existing predictions of shoreline evolution

The Futurecoast (Halcrow, 2002) prediction for a 'with present management' scenario is for there to be a continued reduction in the beach fronting the sea wall and other defences along this section of coast, gradually increasing the risk of the defences failing in the future. There would also be a continued risk of landslides caused by sub-aerial processes as occurs at present.

4.2.5 Teign Estuary

4.2.5.1 Interactions

This section of coast extends from the northern end of Den Spit at Teignmouth, across the mouth of the Teign Estuary where the River Teign discharges to the sea, to The Ness headland at Shaldon on the south side of the Teign Estuary mouth. Also present on the south side of the entrance is Shaldon Beach. This section is shown in Figure 4-4.

Figure 4-4: Teign Estuary

4.2.5.2 Movement

The stabilisation of the cliff to the north of Den Spit by the construction of the sea wall and railway along the cliff toe has resulted in very little if any cliff recession since the mid-19th century. Despite the stabilisation of the cliffs by the reduction of wave action at the toe, the cliffs are still susceptible to landsliding due to weathering and high groundwater levels.

Limited analysis carried out by ABPmer (2007) suggests that Shaldon Beach on the south side of the entrance to the Teign estuary has remained relatively stable between 1998 and 2006, although erosion was observed between 2005 and 2006.

At the mouth of the Teign Estuary (seaward), it is well documented that a cyclical sediment transport relationship occurs between the nearshore sand bars and the beach to the north of the mouth up to Sprey Point.

4.2.5.3 Existing predictions of shoreline evolution

The Futurecoast (Halcrow, 2002) prediction for a 'with present management' scenario is for the continued presence of the defences along the seaward coast of Teignmouth. The management would lead to the gradual narrowing of the beach and foreshore as a result of future sea level rise and in turn increase the risk of failure of these defences over time.

4.2.6 Impacts on NR infrastructure and operation

4.2.6.1 Exe Estuary

The banks of the Exe Estuary are highly managed and natural evolution of the western bank's alignment is not anticipated. Changes in the shape and size of the spit at Dawlish Warren could impact on the rail embankment from Powderham Banks to Dawlish Warren. In particular, if the Warren decreases in size, larger waves could be generated within the estuary and larger waves from beyond the open coast could travel upstream into the estuary.

4.2.6.2 Langstone Rock to Holcombe

This section of the frontage is likely to be subject to continued beach narrowing and eventual scour at the toe of the sea wall. The cliffs around each headland, which are unprotected, will continue to be eroded by wave action. As beach levels lower, the water depth at the toe of the sea wall will increase and the volume of water overtopping the defences in storm events will rise. Coryton's Cove and Shell Cove are considerably more sheltered than the Dawlish frontage and are likely to be less affected by these trends.

4.2.6.3 Holcombe to Teignmouth

This section of the frontage is likely to be subject to continued beach narrowing and eventual scour at the toe of the sea wall. The cliffs around each headland, which are again unprotected, will continue to be eroded by wave action. As beach levels lower, the water depth at the toe of the sea wall will increase and the volume of water overtopping the defences in storm events will rise.

4.2.6.4 Teign Estuary

The coastal processes at the mouth of the Teign Estuary are unlikely to have a direct impact on NR assets. The inner estuary is well sheltered from prevailing storm directions.

4.3 Wave modelling and overtopping analysis

4.3.1 Introduction

HR Wallingford has been commissioned to utilise their expertise in undertaking both the open coast and estuary analysis, with the main deliverables being:

- Joint probability analysis, wave transformation, defence reliability and flood hazard analysis for the present day situation (**Phase 1 – Definition of Baseline**).
- Distributions of return period overtopping rates for each defence within the study area (**Phase 1 – Definition of Baseline**).
- Development of climate change scenarios and support in the identification of mitigation options (**Phase 2 - Option Assessment**).

Further details of the analysis is presented within Section 4.3.2 and Appendix E; performance results are included within Section 5.

4.3.2 Coastal analysis

To derive the present day and future climate change coastal boundary conditions, the methodology adopted by HR Wallingford for EA's State of the Nation flood risk analysis has been applied. The EA has called the approach a "step change in coastal flood risk modelling", in recognition of the major advancement in techniques used.

The methodology is captured Figure 4-5 and includes:

- Stage 1: Offshore multivariate extreme value analysis (Section 4.3.3);
- Stage 2: Wave transformation modelling (Section 4.3.4);

- Stage 3: Analysis of wave overtopping rate and structural failure (Section 4.3.5).

Further description of these stages is contained in Appendix E.

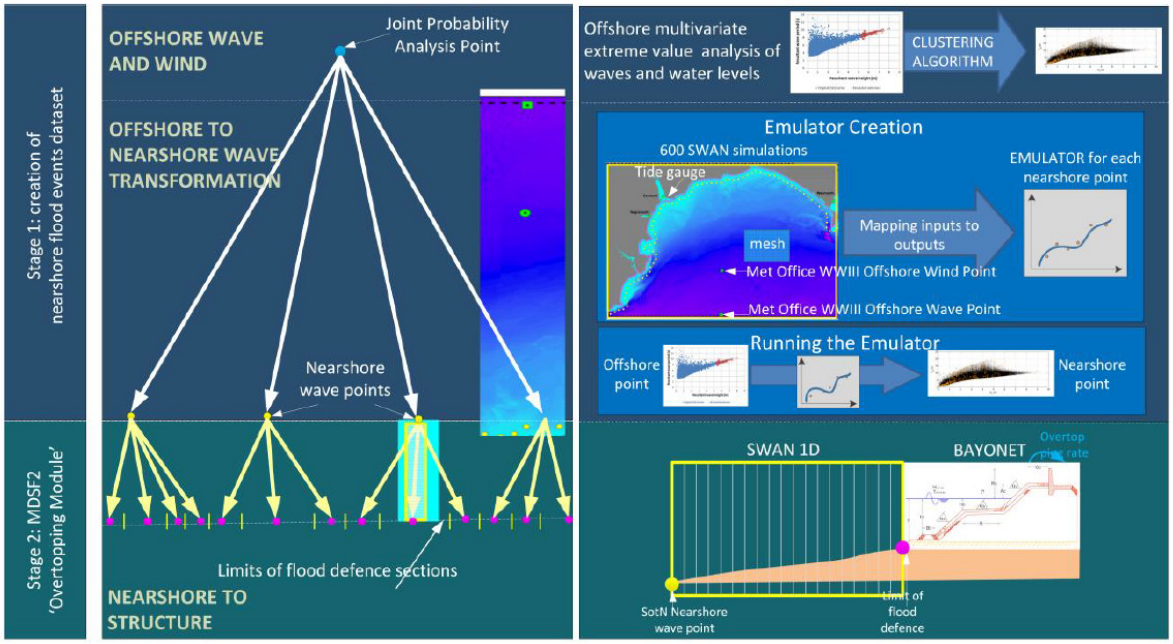

Figure 4-5: Stages in the coastal analysis methodology

4.3.3 Beach profiles

Beach profile analysis was undertaken to characterise the beach levels at the toe of the defences and to inform the coastal modelling work described in Appendix E.

The beach profile data sourced from the Channel Coastal Observatory forms part of a national programme of beach surveying. The profiles in this region are generally located at approximately 100-metre intervals with some profiles surveyed seasonally, others annually and some less frequently. Some survey locations only have two or three survey dates whereas others have 10 or more.

The beach levels at the toe of the coastal defences vary both spatially and temporally along the open coast sections. This variation is partially due to seasonal changes but also in response to particular events. The levels at the toe of a structure influence the structure's response to wave loading and wave overtopping and it is therefore important to capture this to help inform the performance assessment.

The work undertaken analysed the available beach profile data in order to identify any common trends, both in the upper and lower reach of the beach, and has consisted of the following stages:

- Each beach profile was assigned to a relevant defence;
- All beach profiles associated with a defence were considered together to see how the beach varies along the defence;
- Each profile location was assessed separately to determine a mean profile;
- All the mean profiles for each defence were then plotted graphically to generate an upper, mean and lower profile for each defence.

An example of the output is presented in Figures 4-6 and 4-7:

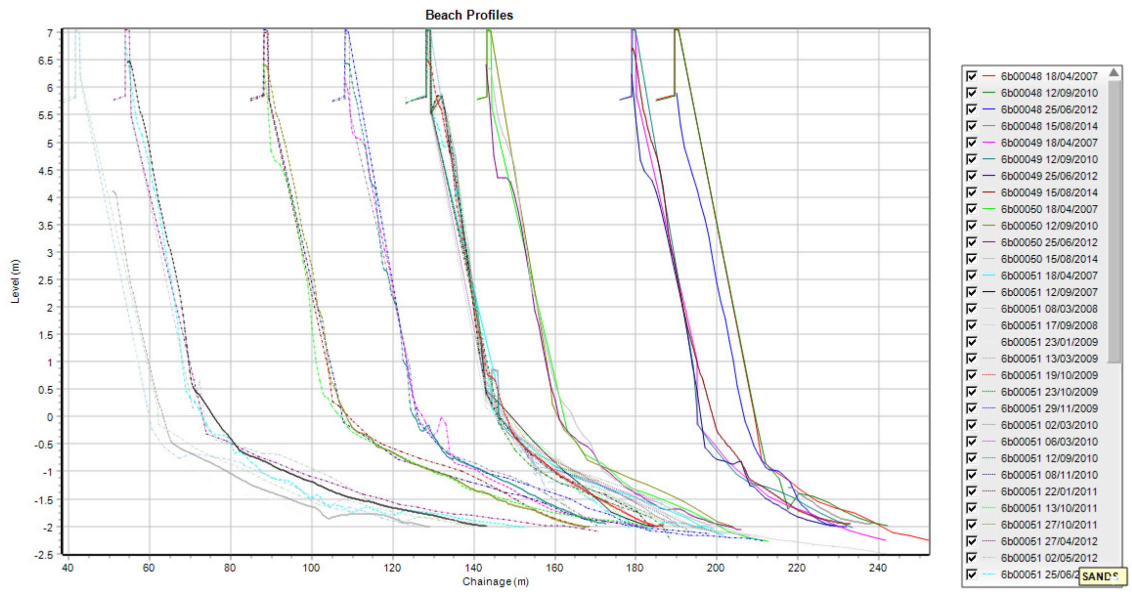

Figure 4-6: Example of beach profiles plotted in SANDS, showing spatial variation along asset 113FAS3351015C01

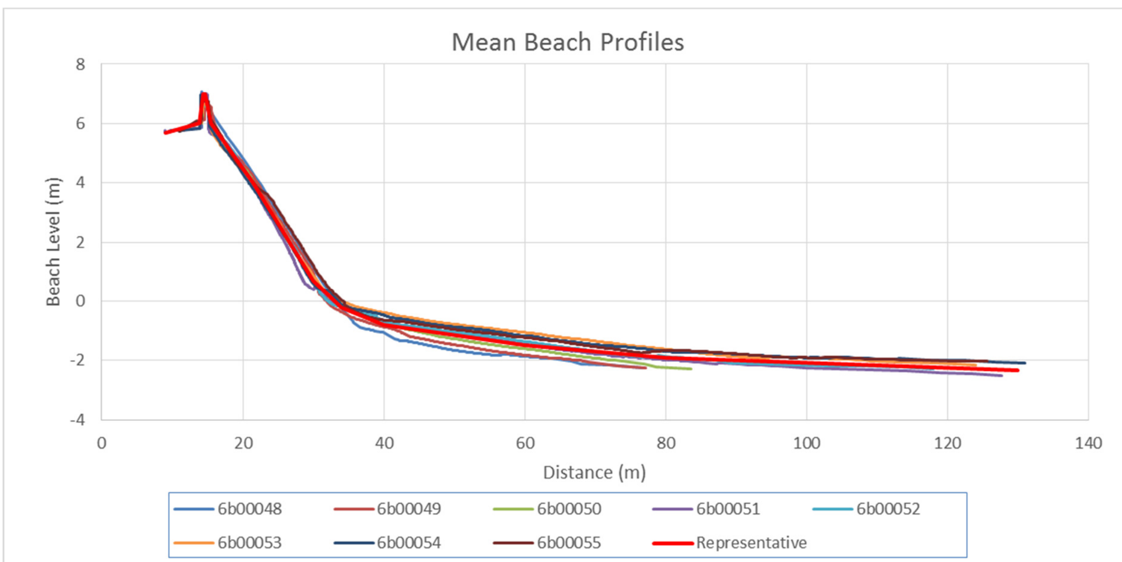

Figure 4-7: Standardised mean beach profiles showing selected representative beach profile for performance analysis

4.4 Flood modelling

In the more sheltered estuary sections of the route, wave overtopping is less of a flood driver. Therefore these areas are more at risk from flooding under extreme water levels and the modelling approach is different to the coastal analysis. The models used are introduced below and described in further detail in Appendix E.

4.4.1 Exe Estuary

The EA's ISIS-TUFLOW numerical model of the Exe Estuary (Mott MacDonald, 2012) has been reviewed and adopted for this study. The model uses a 10-metre resolution grid; an extract for the area around Powderham can be seen in Figure 4-8.

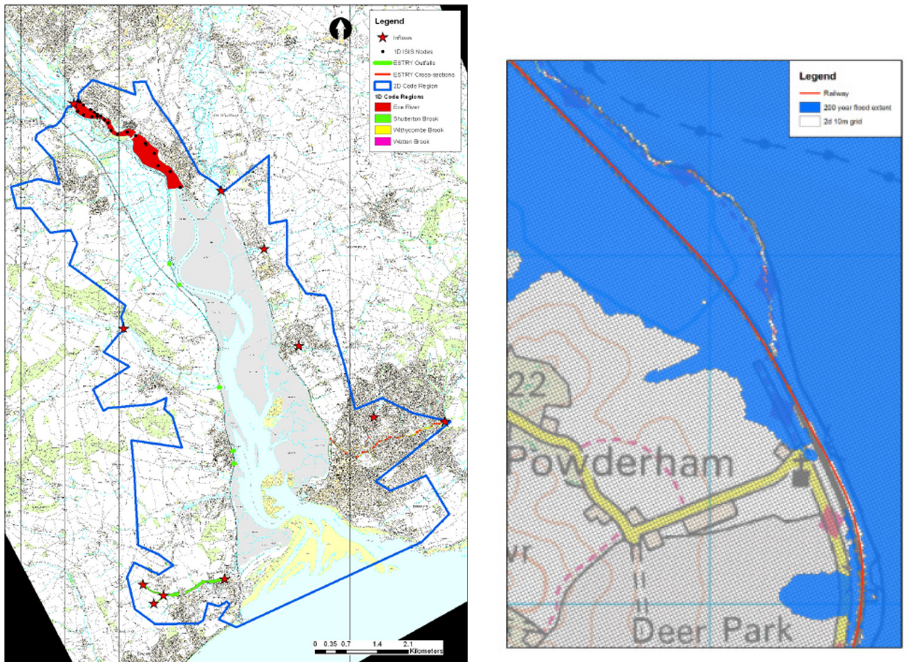

Figure 4-8: Area covered by existing model (extracted from Mott MacDonald, 2012), left, and detail of resolution grid (right)

4.4.2 Teign Estuary

A model of the Teign Estuary was set up with Infoworks 1D-2D. LIDAR data was used to define the geometry of the model. Information from EA's Asset Information Management System (AIMS) database, currently used for State of the Nation, was used to update levels of identified vertical walls.

The set-up of the model is shown in Figure 4-9 below:

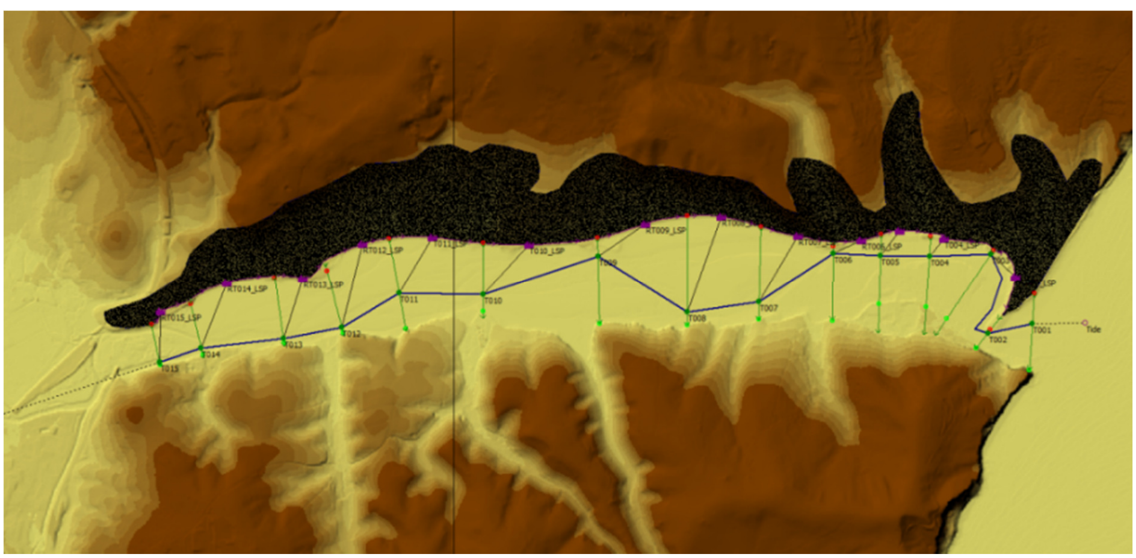

Figure 4-9: Model of the Teign Estuary represented by cross-sections in the estuary channel (1D approach) and with a dense grid on the floodable area of the left bank (2D approach)

4.5 Shoreline response

As well as assessing the potential cross-shore response of the existing and any potential future recharged beach, it is also important to understand the potential for beach material to move along the shoreline as a result of littoral drift processes under the various climate scenarios.

A shoreline modelling exercise was undertaken as part of this study using DHI's LITDRIFT and LITLINE models. The LITDRIFT model simulates the distribution of wave height, set-up and longshore current across a beach to determine how the sediment transport rates along the beach distribute across the beach profile. LITLINE models the shoreline evolution in time.

Two separate LITDRIFT model spaces were used to simulate the Dawlish and Teignmouth beaches (from Langstone Rock to Kennaway Tunnel and Parson's Tunnel to Teignmouth, respectively). Sediment transport rates for both beaches were estimated using 20 years of wave data. Transport rates at Dawlish Beach were predicted to vary from 8,600 m^3/year to 18,600 m^3/year in the direction of Langstone Rock. At Teignmouth Beach, transport rates varied from 14,100 m^3/year northward to 13,100 m^3/year southward.

THE LITLINE model simulation was run for two scenarios: a baseline scenario and one including climate change in 2065. Both of these simulations were run for a time period of 50 years to investigate long-term shoreline evolution of the beaches at Dawlish and Teignmouth. The position of the existing shoreline is taken as the high water mark. In many locations along the study area this is the position of the sea wall.

The results for Dawlish predict that the area in front of the station and towards Kennaway Tunnel will continue to erode and this will only be exacerbated by climate change. The beach from Langstone Rock to approximately 205m 35ch will continue to accrete although the rate is expected to slow down with climate change. The results for Teignmouth show that after 50 years (with or without sea level rise), the shoreline can be expected to be at the sea wall and that there will be no beach at high water. This is in agreement with the findings of Futurecoast (2002) as discussed in Sections 4.2.3.2 and 4.2.4.2 above.

Further detail on the modelling methodology and results can be found in Annex D-1, at the end of Appendix D.

Coastal defence appraisal

5.1 Asset data

This Section outlines the data sources that have been used to obtain defence asset information along the study frontage.

5.1.1 Management of Sea Wall & Estuary Defences

Preliminary asset information was extracted from Tables 3.1, 3.2 and 3.3 of NR's Western Territory procedure report (NR, 2007). Extracts from these tables have been included within Appendix F of this baseline report, with a summary presented in Table 5-1. This asset information is further supplemented by data recorded within NR's structures dashboard which shows a good correlation with the Western Territory dataset.

Table 5-1: Summary of assets owned by NR

Table Ref	Title	Equivalent Study Section	Start Ref	End Ref	Asset No.
3.1	MLN Exe Estuary	1	200m 51.25ch (Powderham)	204m 30ch (Dawlish Warren)	14
3.2	MLN Sea Wall	2-4	204m 16ch (Langstone)	208m 55ch (Teignmouth)	25
3.3	Teign Estuary	5	209m 41ch (Teignmouth Harbour)	212m 62ch (Passage House)	8
				NR Asset No	**47**

5.1.2 Asset Information Management System

Historically, the collation of fluvial and coastal defence information within this area has been undertaken by EA; this data is now held within its AIMS database. This database standardises the classification of all the flood risk assets in England and Wales and generally includes a description of the defence, its condition grade and other survey information pertaining to the defence.

As part of the EA's 'State of the Nation' project, a Rapid Visual Asset Inspection Programme was also undertaken during 2013/14 to assess the condition of all flood risk assets across England.

5.1.3 Asset inventory

Due to the presence of additional asset data including topographic levels and condition grades within the AIMS data has led to this dataset being the primary source for developing this study's asset inventory.

Further information on the content of AIMS is included within Section 5.3 of this report. The information presented within AIMS can be easily extracted into GIS software which allows the defence information to be viewed spatially.

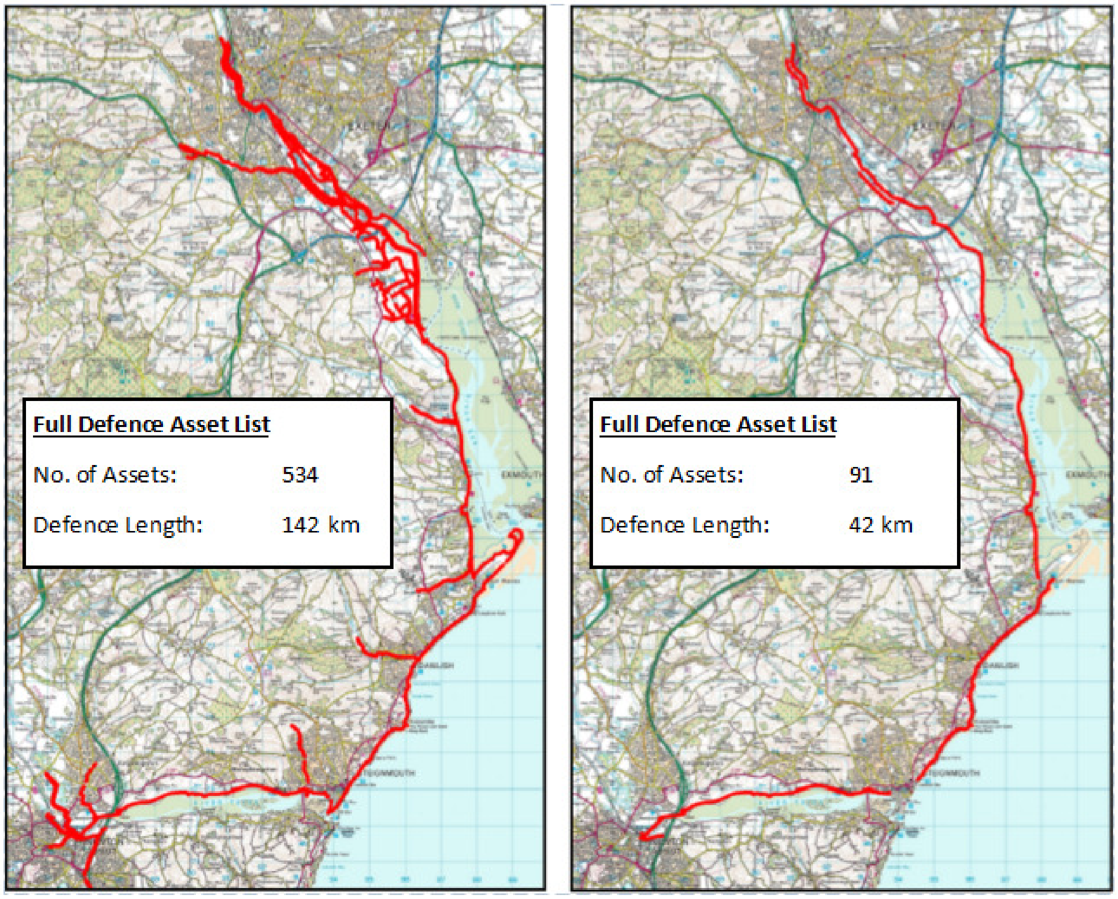

Figure 5-1: Screen shot from SANDS database highlighting the rationalisation of AIMS asset numbers

The data has been refined to include only the defence assets which are deemed to provide primary protection to the railway line. The results of this process are shown graphically in Figure 5-1, with the approximate miles and chainage points of each EA asset ID approximated to enable future comparisons with the Western Territory report to be made.

The full asset inventory is included within Appendix F of this baseline report with a summary presented in Table 5-2.

Table 5-2: Comparison of NR and EA asset classification

Section	Start Ref	End Ref	NR Asset (No.)	EA Asset IDs (No.)
1	Exeter St Davids	Dawlish Warren	14	43
2	Dawlish Warren	Kennaway Tunnel	12	9
3	Kennaway Tunnel	Parson's Tunnel	8	7
4	Parson's Tunnel	Teignmouth Station	5	4
5	Teignmouth Station	Newton Abbot Station	8	28
		Total No. of Assets	**47**	**91**

The substantial increase in recorded EA asset IDs in Sections 1 and 5 is generally related to the additional defence assets located north of Powderham and many short defence lengths around Newton Abbot. These assets are not owned by NR and are therefore not considered as defence assets in the Western Territory document. However these assets, owned by a combination of the EA, local authorities or private parties, are located within the study area and do provide flood defence and/or scour protection to NR assets.

Along the open coast (Sections 2-4), there are several additional breakwater assets owned and maintained by NR. As standalone structures these do not provide flood defence and are therefore not included in the EA's dataset.

5.2 Asset inventory supporting data

5.2.1 Western Territory Procedure

The quality of the performance analysis results is influenced by the availability of up to date topographic levels along and across the defence assets.

The Western Territory document (NR, 2007) described in Section 5.1.1, presents details of typical cross sections between 200m 51.25ch and 212m 63.5ch and includes foreshore, crest and track levels.

5.2.2 LiDAR

Accessibility to LiDAR is particularly important to the quality of the flood modelling work required for both estuaries, as described in Section 4.4, as this dataset provides an indication of the low-lying areas that will be susceptible to flooding. Point data can also be extracted from the LiDAR data to supplement defence cross-sectional data, however due to the spatial resolution of the data care needs to be taken as narrow-crested structures may not display correctly in the grid.

LiDAR data has been obtained from a number of different sources including NR, EA and existing fluvial models.

5.2.3 Site walkover

A site walkover was undertaken in May 2015 and covered the frontage extending between Powderham (mid-way along Section 1) and Teignmouth (Section 4). The purpose of the walkover was to visually verify both the asset data as documented within AIMS, primarily condition grades, as well as the cross- sectional information included within the Western Territory document (NR, 2007).

5.3 Site appraisal methodology

This section outlines the key stages that have been implemented to determine the stand of protection currently afforded by the defence assets.

5.3.1 Condition grade

The Rapid Visual Asset Inspection Programme, described in Section 5.1.2, was carried out in accordance with the EA's Condition Assessment Manual (EA, 2006) which provides a set of visual indicators to assess the integrity and performance of a structure. These indicators enable a condition grade to be determined, which range from 'very good' to 'very poor', as per the description shown in Table 5-3.

Table 5-3: General condition grades for structures in accordance with the EA's Condition Assessment Manual (EA, 2006)

Grade	Rating	Description
1	Very Good	Cosmetic defects that will have no effect on performance
2	Good	Minor defects that will not reduce the overall performance of the asset
3	Fair	Defects that could reduce the performance of the asset

4	Poor	Defects that would significantly reduce the performance of the asset. Further investigation needed
5	Very Poor	Severe defects resulting in complete performance failure

The 2013/14 Rapid Visual Asset Inspection Programme only looked at assets owned by the EA and therefore in some instances the assigned condition grade has been based upon information collated in 2008 as part of the National Flood and Coastal Defence Database update (system precedes AIMS).

It is also important to appreciate that the assigned condition grades only represent a snap shot in time and do not consider any ongoing maintenance regimes that may be in place.

5.3.2 Residual life

The assessment of residual life is important in assisting with the prioritisation of capital works as it provides an indication as to how long an asset will take to either reach structural failure, or a selected condition grade. The assessment takes into account the asset type, whether or not the asset is maintained regularly, and how aggressive the environment is (fluvial, coastal, strong currents etc.) around the asset.

Residual life is determined by comparing the asset's current condition grade to the desired worst case condition grade, where the asset would no longer be structurally sufficient to provide defence against flooding or storm damage This process uses a set of deterioration curves as described in the EA's "Guidance on determining asset deterioration and the use of condition grade deterioration curves" (EA, 2009).

The curves were developed based on previous work (Performance Based Asset Management System), interviews with operations delivery and asset management staff from the EA and expert opinion.

A sample deterioration curve for a vertical concrete sea wall is given in Figure 5-2 and presents a best, slowest and fastest estimate of the deterioration of the asset. Engineering judgement and local experience are applied to select which estimate is the most appropriate or whether interpolation between estimates is needed. Based on the historic nature of the defence, the fastest estimate was considered to be too pessimistic; the slowest estimate was excluded due to the criticality of the assets and therefore the **best estimate** was deemed most appropriate to be taken forward.

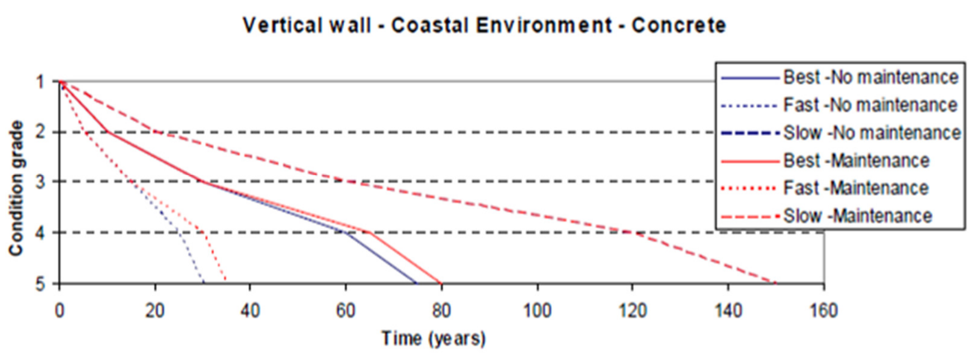

Figure 5-2: Sample deterioration curve for a vertical concrete wall in a coastal setting (EA, 2009)

The assessment of residual life was not undertaken as part of the 2013/14 Rapid Visual Asset Inspection Programme and has therefore been undertaken for this study using the recommended guidance and the following assumptions:

- Maintenance of key assets is carried out regularly (proactive approach);
- Loading is considered to be standard (in line with original design conditions);
- Environmental conditions are generally good but certain coastal assets may deteriorate faster.

The asset is not to deteriorate beyond condition grade 4 as this would be undesirable from an NR operational perspective as condition grade 5 represents “Severe defects resulting in complete performance failure”.

5.3.3 Performance analysis

The performance analysis determines the standard of protection each defence asset provides against flooding and wave overtopping. Different approaches are used for the estuaries and open coast due to the different circumstances that cause service disruption.

5.3.3.1 Performance analysis on the open coast

The performance assessment for sections 2, 3 and 4 (Dawlish Warren to Teignmouth) is primarily based on wave overtopping. Overtopping discharges are calculated using combinations of extreme water levels and wave heights for a range of storm events. The approach for generating overtopping results is presented in Section 4.3 and involves the application of the EurOtop empirical equations (EA/ENW/KFKI, 2007). Overtopping discharges were calculated for 40 return periods, ranging from an annual event (1 in 1 year return period) to an event occurring on average once every 1000 years.

The performance analysis then compares the overtopping discharges for these events against both public safety and damage thresholds. The choice of overtopping threshold is dependent on the defence type and the activities likely to take place in the hinterland. The performance, or standard of protection, is expressed as the highest return period event that does not exceed these damage thresholds. For example, a defence with a 1 in 50 year return period standard of protection will exceed the desired threshold for any events of greater than a 1 in 50 year magnitude.

The threshold for structural integrity is typically set at 200 l/s/m for sea walls; however, given the age of the sea walls between Dawlish and Teignmouth and the mode of failure (damage to the ballast), the lower structural limit of 50 l/s/m has been applied. This is often applied for lightly grassed areas behind a sea wall which are more easily disturbed than a paved or asphalted area would be.

With the majority of the Dawlish Warren to Teignmouth section fronted by a public promenade it is also useful to analyse these defences for pedestrian safety at a low return period (usually a 1 in 1 year return period or 100% annual exceedance probability).

The performance analysis results have been evaluated alongside the residual life assessment to allow the reliability of each defence to be evaluated. In terms of the options development in Phase 2, the solutions intended to provide long-term resilience also need to consider short-term thresholds associated with service disruptions.

The thresholds used in this analysis are extracted from EurOtop (EA/ENW/KFKI, 2007) and are reproduced in Figure 5-3.

5.3.3.2 Performance analysis in the Exe and Teign Estuaries

The primary drivers of flooding in the Exe and Teign estuaries are the high water levels resulting from estuarine and fluvial events. During storm events, a storm surge generated by low atmospheric pressure can be propagated into the estuary from the open coast leading to high water levels upstream. Fluvial events develop after prolonged periods of heavy rainfall and the effect of tide-locking can cause the water levels in the estuary to rise.

Therefore the performance analysis of defences within the estuary is based on extreme water levels and increased fluvial flows. The analysis of the Exe Estuary used an existing ISIS-TUFLOW fluvial model (Mott Macdonald, 2012) which is widely acknowledged as being the most up-to-date model for the area. There is not currently a similar model for the Teign Estuary and therefore a simple model has been constructed in Infoworks 1D-2D using LiDAR to define the geometry of the model. The modelling process is described in further detail in Appendix E.

Table 3.2: Limits for overtopping for pedestrians

Hazard type and reason	Mean discharge q (l/s/m)	Max volume[(1)] V_{max} (l/m)
Trained staff, well shod and protected, expecting to get wet, overtopping flows at lower levels only, no falling jet, low danger of fall from walkway	1 – 10	500 at low level
Aware pedestrian, clear view of the sea, not easily upset or frightened, able to tolerate getting wet, wider walkway[(2)].	0.1	20 – 50 at high level or velocity

[(1)] Note: These limits relate to overtopping velocities well below $v_c \approx 10$ m/s. Lower volumes may be required if the overtopping process is violent and/or overtopping velocities are higher.
[(2)] Note: Not all of these conditions are required, nor should failure of one condition on its own require the use of a more severe limit

Table 3.5: Limits for overtopping for damage to the defence crest or rear slope

Hazard type and reason	Mean discharge q (l/s/m)
Embankment seawalls / sea dikes	
No damage if crest and rear slope are well protected	50-200
No damage to crest and rear face of grass covered embankment of clay	1-10
No damage to crest and rear face of embankment if not protected	0.1
Promenade or revetment seawalls	
Damage to paved or armoured promenade behind seawall	200
Damage to grassed or lightly protected promenade or reclamation cover	50

Figure 5-3: Overtopping thresholds for sea walls (EA/ENW/KFKI, 2007; Section 3)

5.4 Exeter to Dawlish Warren (Section 1)

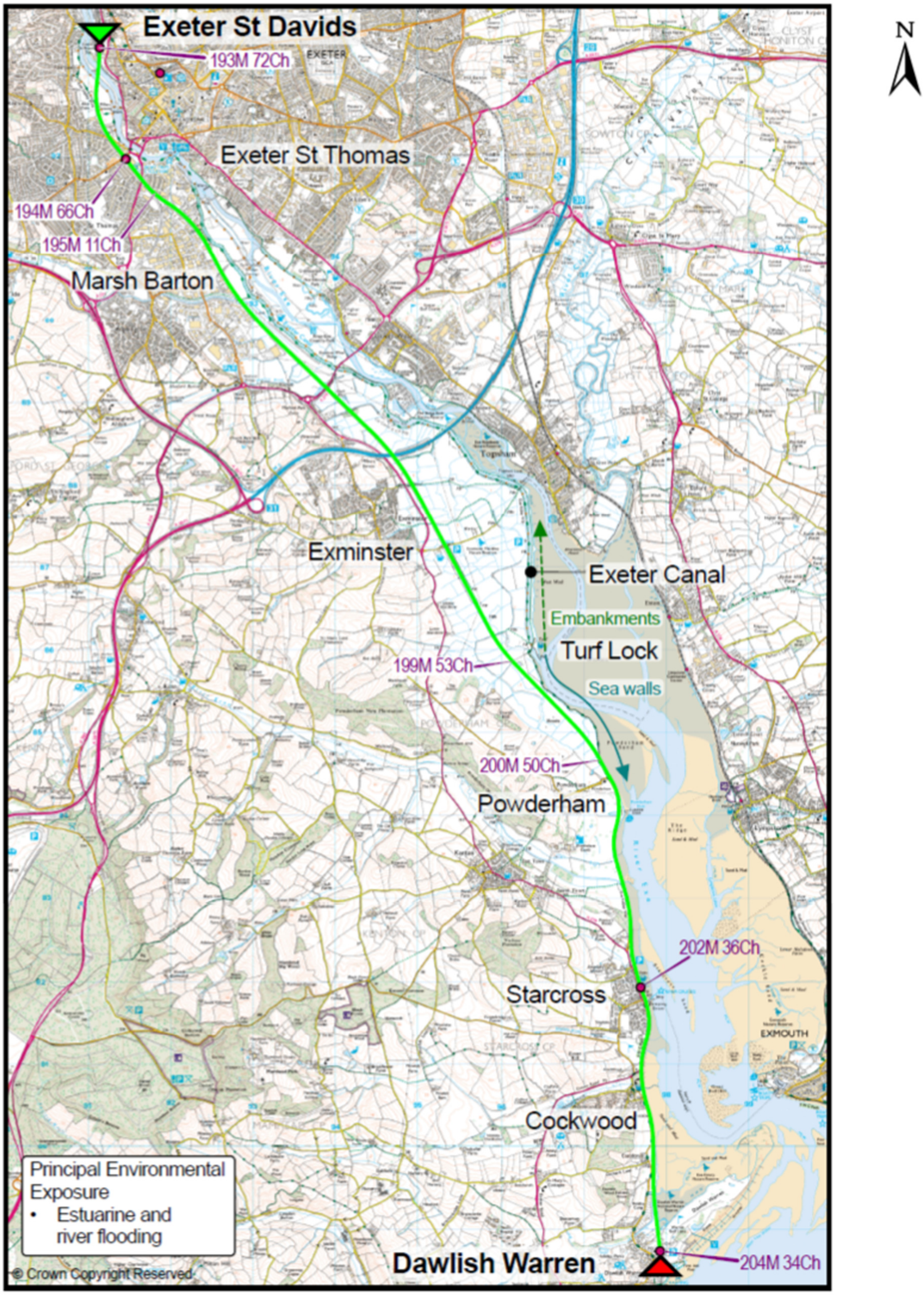

Figure 5-4: Defence overview (Section 1)

5.4.1 Asset inventory

Section 1 (194m 00ch to 204m 34 ch) runs for approximately 16.8 kilometres alongside the Exe Estuary, passing adjacent to the villages of Exminster, Powderham, Starcross and Cockwood.

Refinement of the EA's AIMS database has resulted in the identification of 44 key asset IDs along this frontage. The breakdown of defence type against percentage length is presented in Table 5-4:

Table 5-4: Asset summary (Section 1)

Asset Type	No. Asset IDs	Percentage Length of Frontage
Sea wall	14	36%
Embankment	15	47%
High Ground	12	17%
Bridge Abutment	3	1%
Total	**44 ***	

* There are 43 EA assets in this Section (as presented in Table 5-2); an additional NR asset is included here at Cockwood Harbour as this is the railway embankment across the harbour entrance.

As can be seen from Table 5-4, Section 1 comprises predominantly of embankments and sea walls with a distinct change in defence type occurring at Powderham Banks where the track deviates away from the estuary and behind the Exeter Canal (refer to Figure 5-4 above).

EA flood defences, consisting of embankments, are located seawards of the railway between Exeter and Powderham. South of Powderham, the railway abuts the sea wall through Starcross and Cockwood to Dawlish Warren. These main defence types are shown in Figure 5-5.

Figure 5-5: Typical defences in Section 1; embankments (northern extent) and buttressed vertical wall (southern extent)

5.4.2 Condition assessment and residual life

The embankments are generally recorded as being fair (Condition Grade 3) or better with a corresponding residual life best estimate of between 40 and 115 years.

The sea walls are generally recorded as being fair (Condition Grade 3) or better with a corresponding residual life best estimate of between 50 and 100 years.

5.4.3 Performance analysis

The results of the flood modelling analysis for the Exe Estuary are shown in Figure 5-6 to 5-9 below.

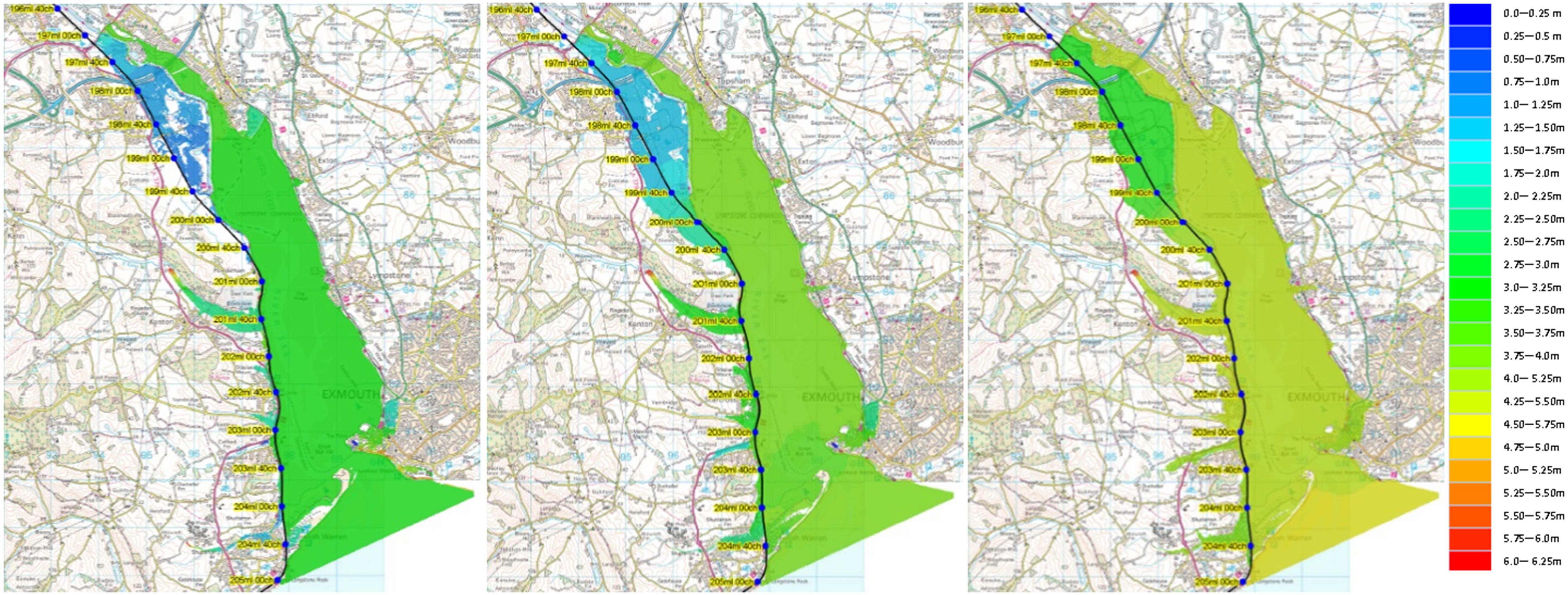

Figure 5-6: Flood extent and flood levels for a 1 in 10 return period event in 2015, 2065 and 2115

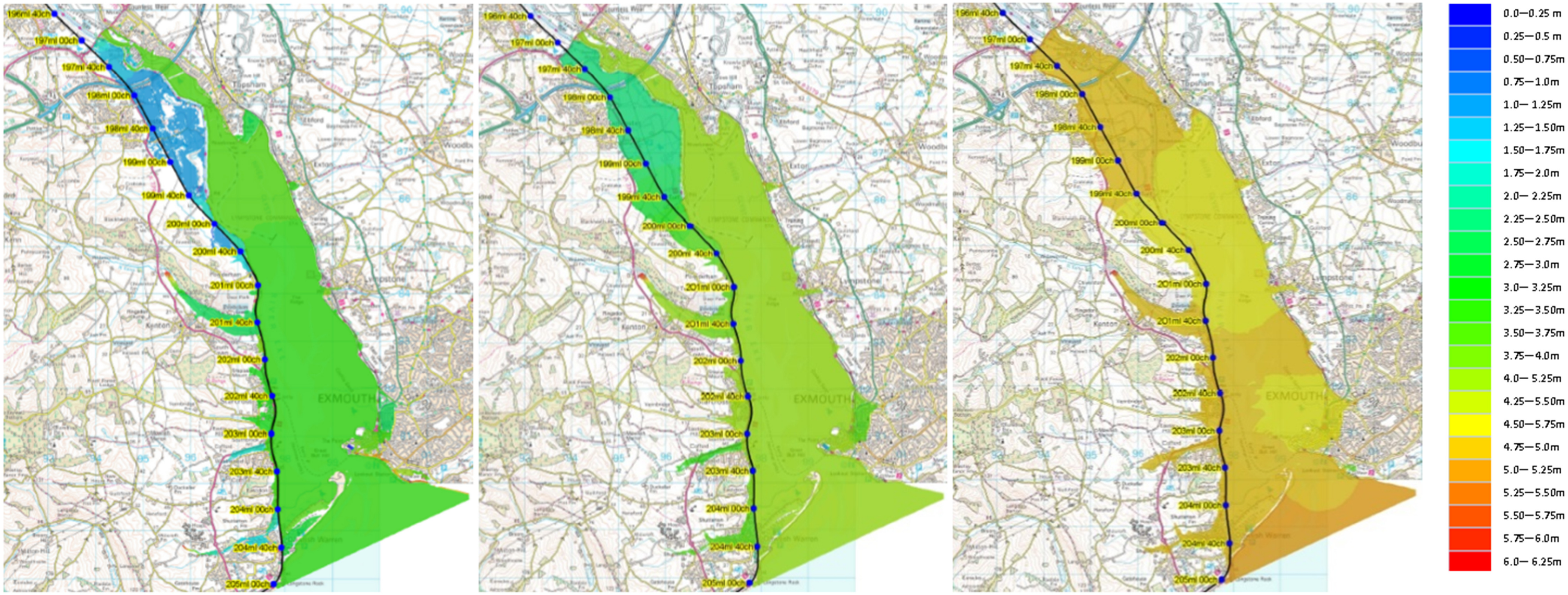

Figure 5-7: Flood extent and flood levels for a 1 in 75 return period event in 2015, 2065 and 2115

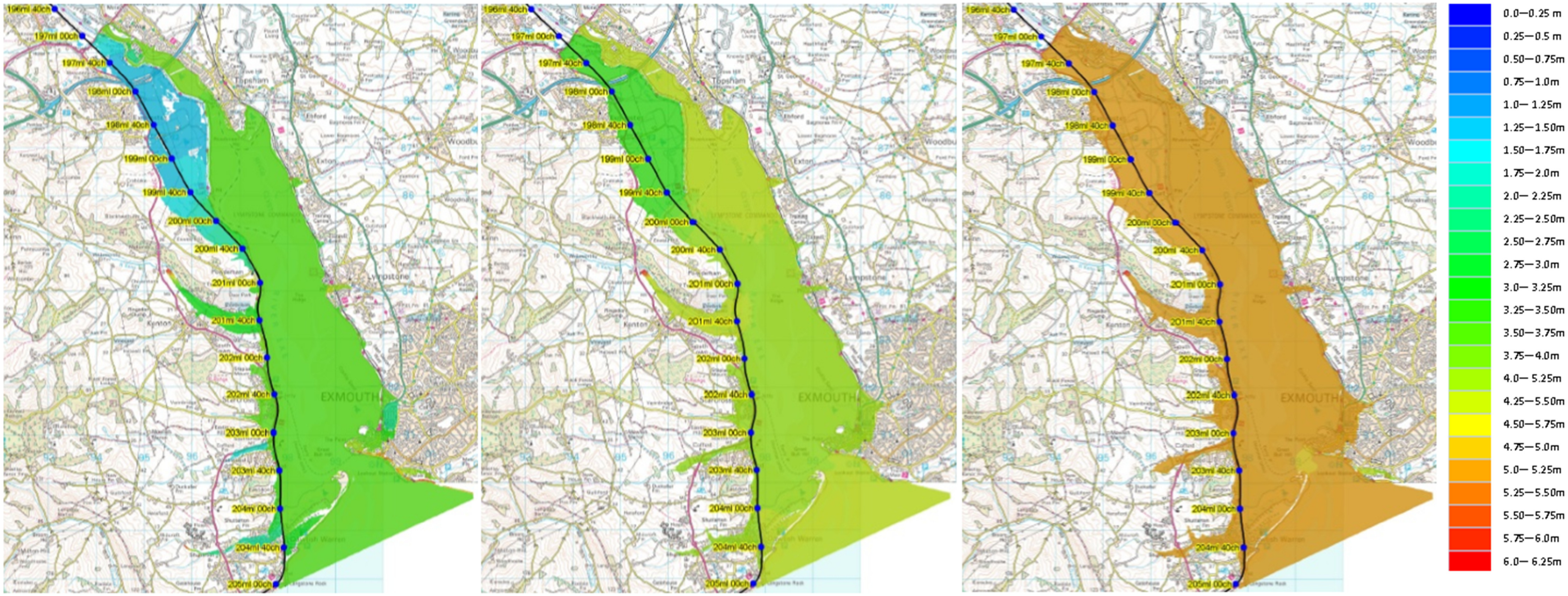

Figure 5-8: Flood extent and flood levels for a 1 in 200 return period event in 2015, 2065 and 2115

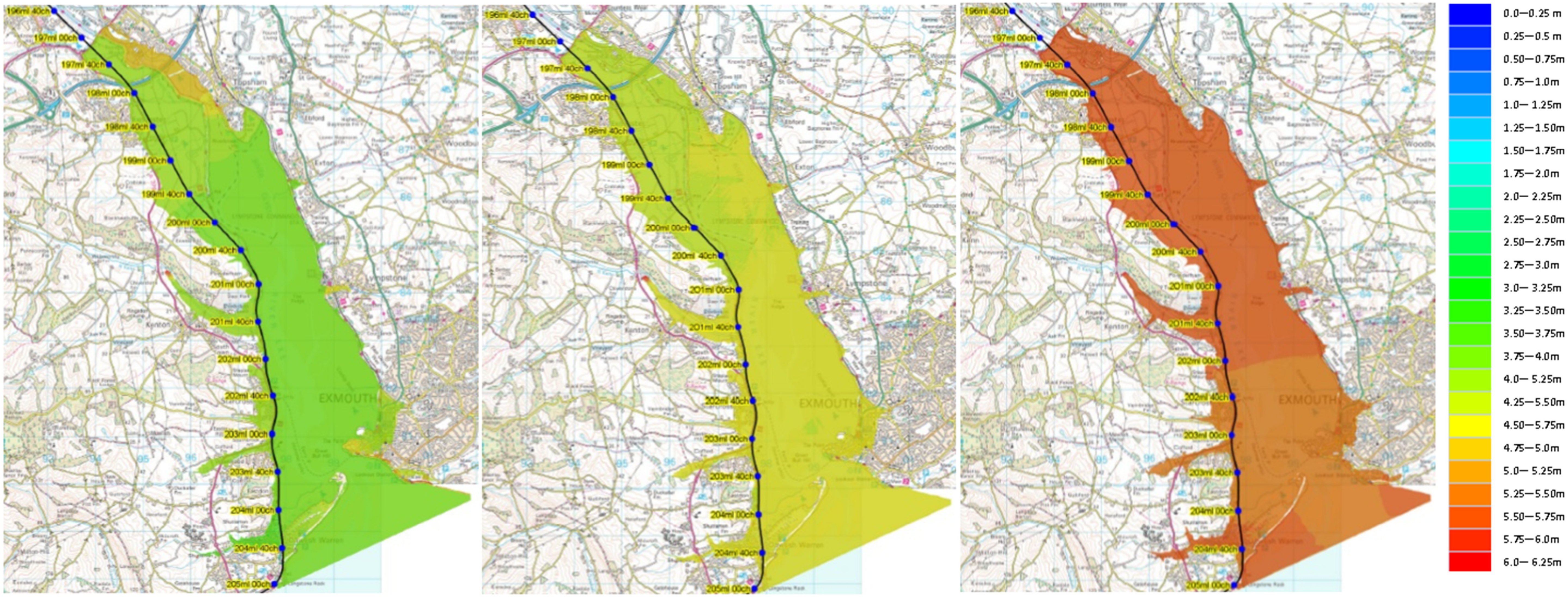

Figure 5-9: Flood extent and flood levels for a 1 in 1000 return period event in 2015, 2065 and 2115

From Figures 5-6 to 5-9 above, it can be seen that protection to the railway north of Powderham Banks is maintained up to a 1 in 200 return period event in 2015 by the EA embankments and the Exeter Canal. The water depths surrounding the railway embankment are lower than the railway embankment itself. However, the levels of these embankments are not sufficient to maintain protection to 2065 and beyond. Therefore, the railway embankment is likely to be affected by flooding under a 1 in 75 return period event by 2065. By 2115, the railway embankment is likely to be affected at least once every 10 years.

5.4.4 Summary

The defence assets in Section 1 are generally in good or fair condition with a reasonable residual life (40+ years). The standard of protection in the present day is between 1 in 75 and 1 in 200 return period, decreasing to between a 1 in 10 and 1 in 75 return period by 2065. By 2115 the standard of protection is predicted to be less than 1 in 10.

A full asset inventory for Section 1 is included within Appendix F of this baseline report and summarises the topographic levels, condition grades, residual life and standard of protection provided by each individual asset.

5.5 Dawlish Warren to Kennaway Tunnel (Section 2)

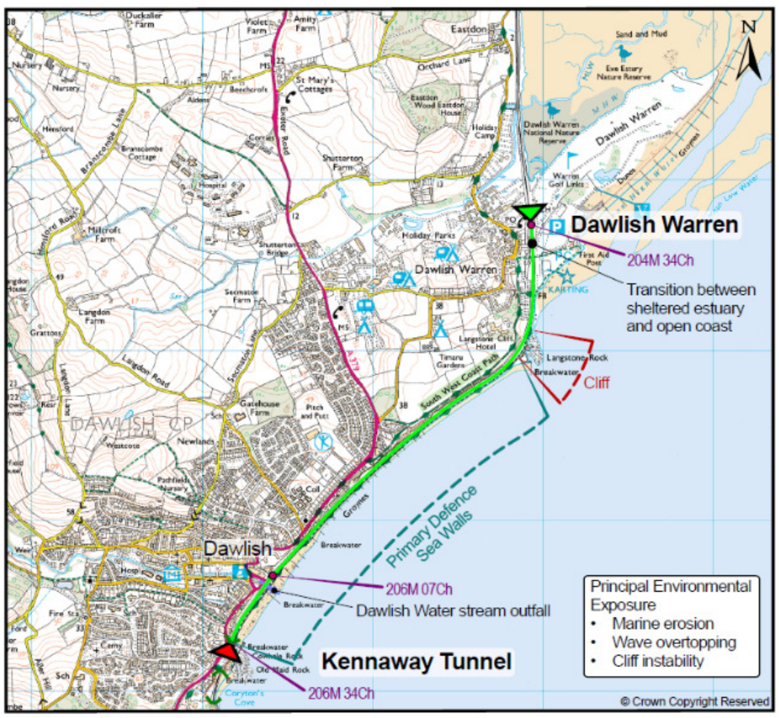

Figure 5-6: Defence overview (Section 2)

5.5.1 Asset inventory

Section 2 runs from Dawlish Warren Station to the north portal of Kennaway Tunnel (204m 30ch to 206m 34ch). The proximal end of Dawlish Warren spit passed through by the railway represents the transition in conditions between the sheltered estuary and open coast frontages. The railway runs for approximately 3 kilometres along the Dawlish sea wall between Dawlish Warren in the east and Kennaway Tunnel in the west. Due to the protection afforded by Dawlish Warren, the “hard” structural defences on this have been included and therefore the total defence length of the frontage is 3.6 kilometres.

Refinement of the AIMS database has resulted in the identification of 9 key assets. The breakdown of defence type against percentage length is presented in Table 5-5.

Table 5-5: Asset summary (Section 2)

Asset Type	No. Asset IDs	Percentage Length of Frontage
Sea wall	7	88%
Embankment	1	9%
Cliff	1	3%
Total	**9**	

From Table 5.5 it can be seen that the increased exposure of this section to wave activity is reflected by the defences comprising predominantly of a vertical blockwork/concrete walls with a promenade and rear wall arrangement. This typical arrangement is presented in Figure 5-8.

Figure 5-7: Typical defences in Section 2 at 205m 30ch (left); 206m 00ch (right)

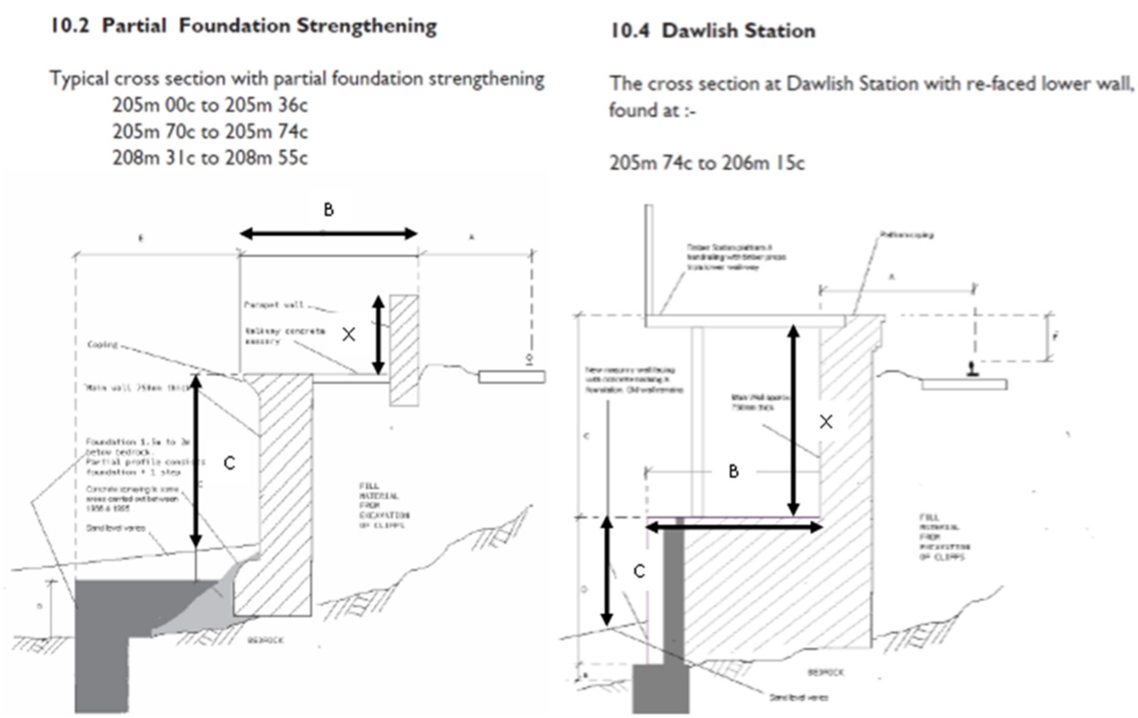

Figure 5-9: Defence cross-sections between Langstone Rock and Kennaway Tunnel
Source: Mouchel Parkman, 2006

A number of beach control structures are also located along this section, although many of these are historic, in a dilapidated state and are therefore not working efficiently.

The section also encompasses the outlet to a small river catchment, referred to as “Dawlish Water”, which is understood to be subject to occasional tidal locking. Any solutions proposed in future phases of this commission will therefore need to consider their impact on tidal locking.

5.5.2 Condition assessment and residual life

The sea walls are recorded as being fair (Condition Grade 3) or good (Condition Grade 2) with a corresponding residual life best estimate of between 35 and 55 years. The upper end of the best estimate range also takes into account the reconstruction work completed in 2015 following the 2014 storm damage referred to below.

5.5.3 Performance analysis

Section 2 contains the area where significant damage to the sea wall and railway was sustained during the February 2014 storms (205m 36ch to 205m 75ch).

The overtopping results provided in Table 5-6 indicate that the defences:

1. Fail to satisfy the public safety overtopping criteria for the 1 in 1 year return period event and greater;
2. Generally provide a good standard of protection against structural safety in the present day. Areas of concern are Pinewood Close to Riviera Terrace (205m 51ch - 205m 57.8ch) and between Dawlish Water and Kennaway Tunnel (206m 18ch - 206m 33ch).
3. The performance is reduced in 2065 with many areas predicted to sustain damage under relatively common events (e.g. 1 in 5 RP). By 2115 NR could expect significant disruption from damage on an annual basis.

The logic of the results listed above is as expected, given both the location of the 2014 storm damage (205m 51ch - 205m 68ch) and also discussion with Tim Maddocks regarding the frequency of stoppages adjacent to Kennaway Tunnel (206m 18ch - 206m 33ch); in this location, the track ballast has been glued to reduce movement under wave loading. This area also has the lowest defence crest level and is approximately 1 to 1.5 m lower than other areas along the Dawlish Beach frontage.

Table 5-6: Standard of Protection for defences in Section 2

Chainage	Standard of protection against structural damage (50 l/s/m)			Standard of protection for pedestrians (0.1 l/s/m)
	2015	2065	2115	2015
204m 29.5ch - 204m 42ch	>1 in 200	>1 in 200	< 1 in 1	1 in 50 RP
204m 42ch - 204m 56.5ch	>1 in 200	1 in 20	< 1 in 1	< 1 in 1 RP
204m 56.5ch - 204m 70ch	>1 in 200	1 in 200	1 in 1	< 1 in 1 RP
204m 75ch - 205m 0ch	>1 in 200	>1 in 200	1 in 20	< 1 in 1 RP
205m 0ch - 205m 36ch	>1 in 200	>1 in 200	1 in 2	< 1 in 1 RP
205m 36ch - 205m 51ch	1 in 5	1 in 2	< 1 in 1	< 1 in 1 RP
205m 51ch - 205m 57.8ch	>1 in 200	1 in 100	1 in 2	< 1 in 1 RP
205m 57.8ch - 205m 68ch	1 in 20	1 in 5	< 1 in 1	< 1 in 1 RP
205m 36ch - 205m 51ch	>1 in 200	1 in 100	1 in 1	< 1 in 1 RP
205m 74ch - 206m 6.5ch	>1 in 200	>1 in 200	1 in 10	< 1 in 1 RP
206m 6.5ch - 206m 15ch	>1 in 200	1 in 50	< 1 in 1	< 1 in 1 RP

206m 15ch - 206m 18ch	>1 in 200	1 in 50	< 1 in 1	< 1 in 1 RP
206m 18ch - 206m 33ch	< 1 in 1	<< 1 in 1	<< 1 in 1	< 1 in 1 RP

5.5.4 Summary

There are no areas where the defence condition is currently critical although there are sections that will need upgrading in the future (approximately 30 years' time).

The standard of protection against storm damage to the railway is generally good in the present day, with most of the defences providing protection against moderate to high return period storm events. However, there are areas of significant concern; namely Pinewood Close to Riviera Terrace (205m 36ch to 205m 51ch) and adjacent to Kennaway Tunnel (206m 18ch to 206m 33ch). Additionally, the full extent of the promenade fails to satisfy recognised thresholds for pedestrian safety.

A full asset inventory for Section 2 is included within Appendix F of this baseline report and summarises the topographic levels, condition grades, residual life and standard of protection provided by each individual asset.

5.6 Kennaway Tunnel to Parson's Tunnel (Section 3)

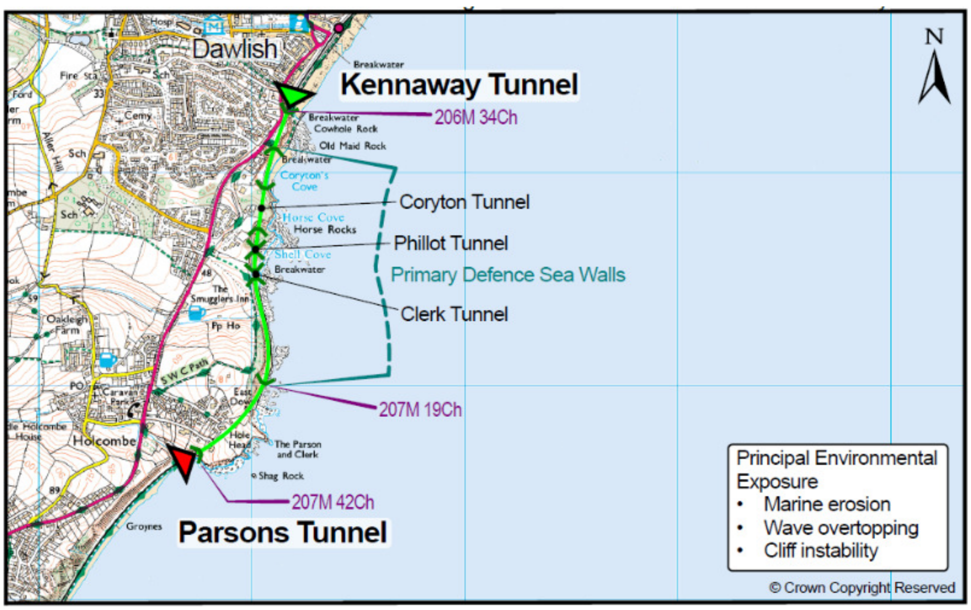

Figure 5-10: Defence overview (Section 3)

5.6.1 Asset inventory

Section 3 (206m 34ch to 207m 42ch) runs for approximately 1.5 kilometres through five tunnel sections and behind sections of masonry sea wall situated at the base of high vertical sandstone cliffs. This section also includes Parson's Tunnel (207m 18.5ch to 207m 42ch) as this is considered a cliff asset and is therefore considered amongst the coastal defences.

Refinement of the AIMS database has resulted in the identification of 7 key asset IDs. The breakdown of defence type against percentage length is presented in Table 5-7:

Table 5-7: Asset summary (Section 3)

Asset Type	No. Asset IDs	Percentage Length of Frontage
Sea wall	5	72%
Cliff	2	28%
Total	**7**	

As can been seen in Table 5-7, the primary defences essentially form a continuation of Section 2, interspersed by cliffs where the mainline runs through the Kennaway, Coryton, Phillot, Clerk and Parson's Tunnels. Examples of the typical defences are shown in Figure 5-10.

Figure 5-8: Typical defences in Section 3. Coryton's Cove (left) and between Clerk and Parson's tunnels (right)

10.6 Coryton's Cove

Coryton's Cove cross typical section can be found between 206m 42c and 206m 52c

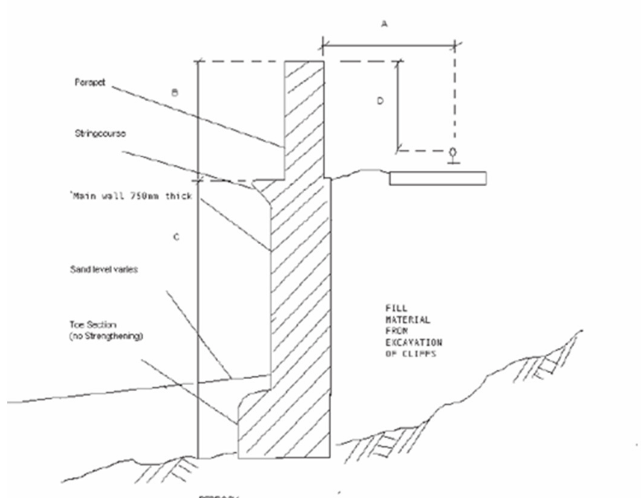

Figure 5-12: Typical cross-section in Section 3.
Source: Mouchel Parkman, 2006

5.6.2 Condition assessment and residual life

The sea walls are recorded as being fair (Condition Grade 3) with a corresponding residual life best estimate of between 30 and 35 years. Parts of this section are not easily accessible and this accounts for some of the data gaps (crest and toe levels) within the AIMS database. The latter part of the sea wall (between Clerk and Parson's Tunnels) sits on a wave-cut platform and therefore there are no beach levels for this defence ID. The topographical levels provided in Appendix F for this section are mostly informed by the Western Territory document (NR, 2007).

5.6.3 Performance analysis

The standard of protection provided by the defence assets under present day conditions is shown in Table 5-8.

Table 5-8: Standard of Protection for defences in Section 3

Chainage	Standard of protection against structural damage (50 l/s/m)			Standard of protection for pedestrians (0.1 l/s/m)
	2015	2065	2115	2015
206m 42ch - 206m 52ch	>1 in 200	>1 in 200	1 in 20	< 1 in 1
206m 63ch - 206m 66ch	>1 in 200	>1 in 200	1 in 20	1 in 10
206m 68ch - 206m 72ch	>1 in 200	>1 in 200	>1 in 200	< 1 in 1
206m 74ch - 206m 77.5ch	>1 in 200	>1 in 200	>1 in 200	< 1 in 1
206m 77.5ch - 207m 6.5ch	>1 in 200	>1 in 200	1 in 200	< 1 in 1
207m 6.5ch - 207m 18ch	>1 in 200	>1 in 200	1 in 200	< 1 in 1

Section 3 performs well under present day storm conditions, with all sections analysed providing a Standard of Protection against structural damage under a 1 in 200 year return period event. There is no promenade along this wall and therefore the pedestrian safety threshold of 0.1 l/s/m is included for information only to inform line-side working for NR staff.

5.6.4 Summary

All defences in Section 3 perform well under present day and 2065 conditions and as such are not in urgent need of attention. The residual life is approximately 30 years, indicating that these defences will need to be renewed or reinforced in the medium term.

In terms of operational performance of the route, Section 3 performs well with minor disruption to be expected by 2065. This is largely due to the height of the walls between Clerk and Parson's Tunnel and the presence of a relatively healthy beach in Coryton's, Horse and Shell Coves.

A full asset inventory for Section 3 is included within Appendix F of this baseline report and summarises the topographic levels, condition grades, residual life and standard of protection provided by each individual asset.

5.7 Parson's Tunnel to Teignmouth Station (Section 4)

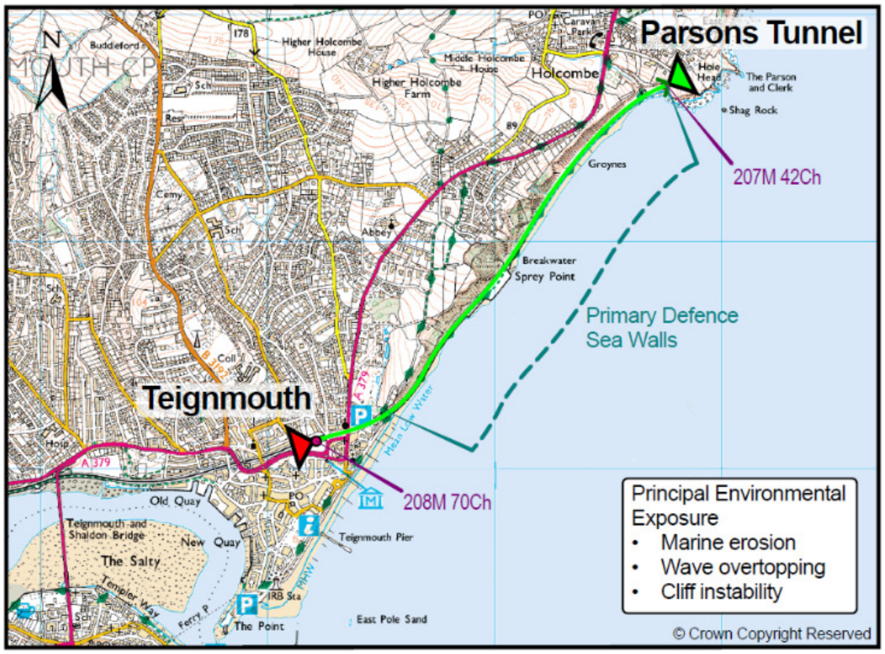

Figure 5-9: Defence overview (Section 4)

5.7.1 Asset inventory

In Section 4 (207m 29.5ch to 208m 70ch) the railway runs for approximately 2.2 kilometres between Parson's Tunnel and Teignmouth Station. This section marks the end of the open coast frontage as the line diverts inland away from the defence line at 208m 56c. Refinement of the AIMS database has resulted in the identification of 4 key assets – as noted in Table 5-9:

Table 5-9: Asset summary (Section 4)

Asset Type	No. Asset IDs	Percentage Length of Frontage
Sea wall	4	100%

As can be seen from Table 5.9, the primary defences essentially form a continuation of Sections 2 and 3. The defence arrangement is shown in Figure 5-12 and the typical cross-sections included in 5-9 are applicable for much of Section 4.

Figure 5-13: Typical defence structure in Section 4

5.7.2 Condition assessment and residual life

The sea walls are recorded in the AIMS database as being very poor (Condition Grade 4) with a corresponding residual life estimate of 0 years. This did not match up with observations recorded either on site in May 2015, see Figure 5-13 or information held within previous NFCCD condition surveys (2008).

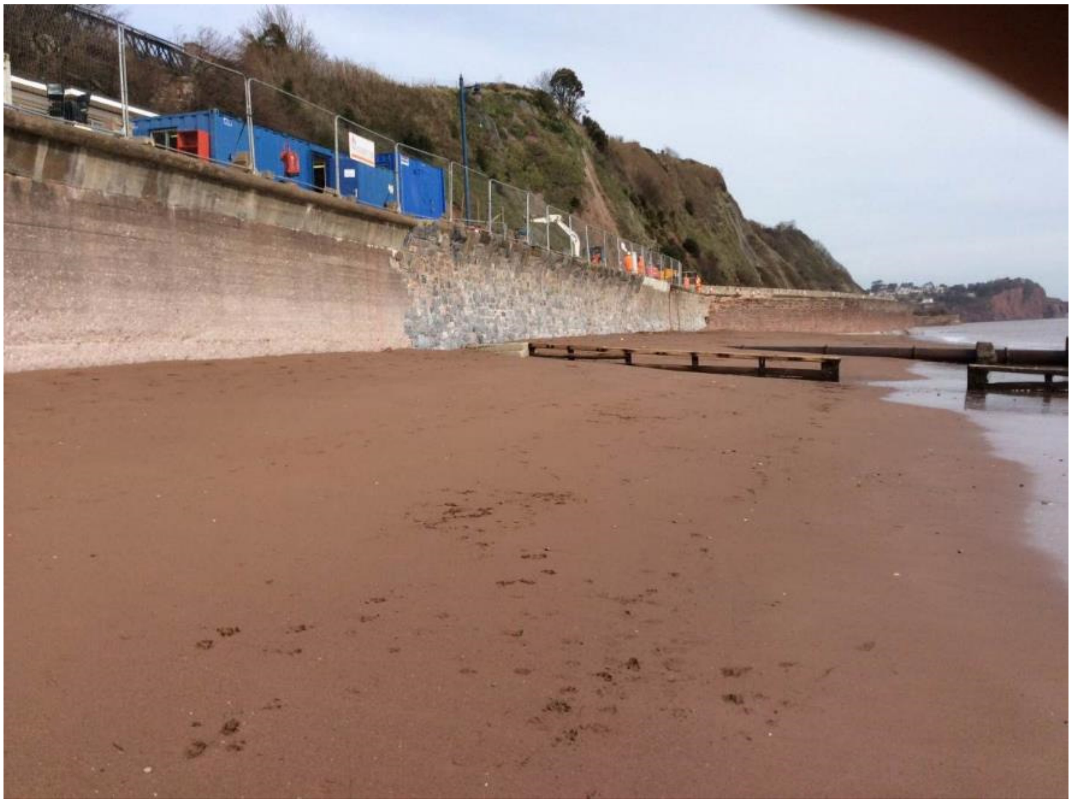

Figure 5-104: Survey photo for defence ID 113FBS3400501C03, immediately downline of Sprey Point

The emergency works pictured above (Figure 5-14), were undertaken to stabilise the cliff above the railway and are therefore not related to the condition of the coastal defence. It is possible that the surveyor was not aware of this fact and therefore assigned a lower condition grade.

As a result, the condition has been raised to "fair" (Condition Grade 3) which results in a residual life best estimate of 35 to 60 years to account for different construction materials.

5.7.3 Performance analysis

The standard of protection provided by the defence assets under present day conditions and with climate change in 2065 and 2115 is evaluated in Table 5-10.

Table 5-10: Standard of Protection from overtopping in Section 4

Chainage	Standard of protection against structural damage (50 l/s/m)			Standard of protection for pedestrians (0.1 l/s/m)
	2015	2065	2115	2015
207m 42ch - 207m 46ch	>1 in 200	1 in 50	1 in 1	< 1 in 1 RP
207m 46ch - 208m 9ch	1 in 10	1 in 2	< 1 in 1	< 1 in 1 RP
208m 9ch - 208m 13ch	1 in 10	1 in 2	< 1 in 1	< 1 in 1 RP
208m 13ch - 208m 22.7ch	1 in 5	1 in 1	< 1 in 1	< 1 in 1 RP

208m 22.7ch - 208m 31ch	1 in 20	1 in 10	1 in 1	< 1 in 1 RP
208m 31ch - 208m 55ch	1 in 20	1 in 10	1 in 1	< 1 in 1 RP

From the results presented in Table 5-10 it can be seen that in general the standard of protection against structural damage in 2015 is approximately a 1 in 10 year return period. This standard decreases to 1 in 2 by 2065 and to a greater than annual frequency by 2115.

The section from 207m 46ch to 208m 9ch sustained some damage during the February 2014 storm and sections of the parapet wall have been rebuilt. Locally, the rebuilt parapet wall is higher than the typical defence by approximately 300 mm. The typical height of the original structure has been analysed in the above results.

The standard of protection for pedestrians is currently less than a 1 in 1 year return period along the full promenade.

5.7.4 Summary

The defences in Section 4 currently do not provide a sufficient level of protection against storm damage with damage likely to occur to the splash wall and trackside equipment under a 1 in 10 or 1 in 20 year return period event. This means there is on average a 6.5% chance of damage occurring in a given year.

The residual life of the main defence in Section 4 is approximately 35-60 years. However, work to raise the standard of defence to a suitable level to prevent damage would be required before 35 years.

A full asset inventory for Section 4 is included within Appendix F of this baseline report and summarises the topographic levels, condition grades, residual life and standard of protection provided by each individual asset.

5.8 Teignmouth Station to Newton Abbot Station (Section 5)

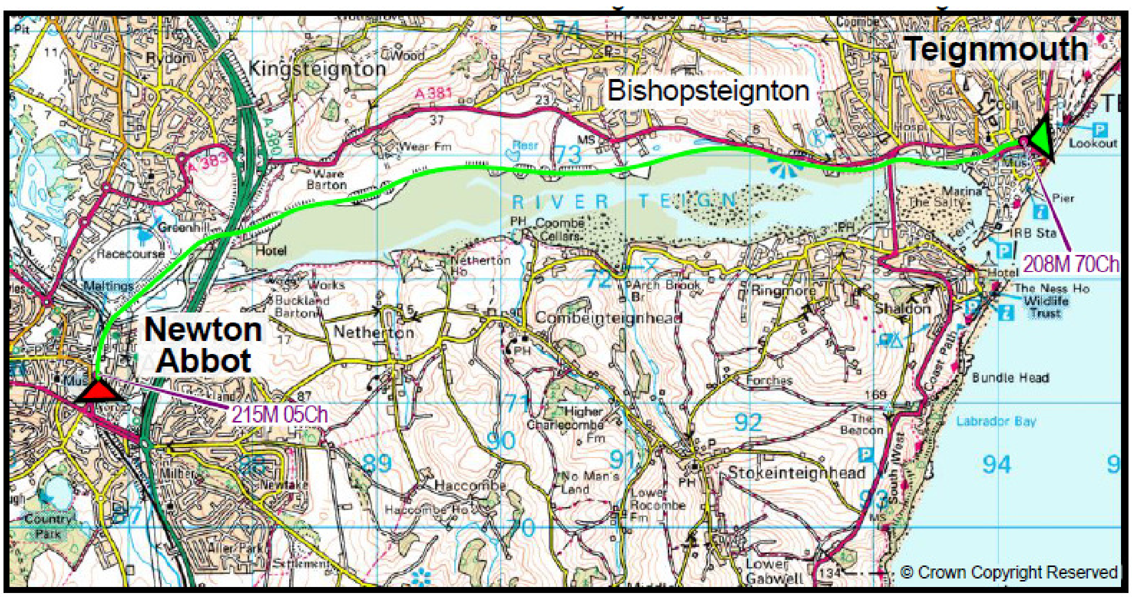

Figure 5-15: Defence overview (Section 5)

5.8.1 Asset inventory

The rail line runs for approximately 8.2 kilometres alongside the River Teign wall situated on the north bank of the Teign Estuary. Refinement of the AIMS database has resulted in the identification of 28 key assets – as noted in Table 5-11:

Table 5-11: Asset summary (Section 5)

Asset Type	No. Asset IDs	Percentage Length of Frontage
Sea wall	2	8%
Bridge Abutment	4	2%
Embankment	6	17%
High Ground	16	73%
Total	**28**	

This section runs within a sheltered estuary and therefore has reduced exposure to wave activity. This is reflected by the defences being predominantly low estuary walls and embankments. Many of the defences are designated as "high ground", indicating that in some areas there is no formal defence.

The locations of these different asset types is presented in Figure 5-14:

5.8.2 Condition assessment and residual life

The general condition grade of the primary defence type (embankments and high ground) are generally recorded as being fair or good with a corresponding residual life best estimate of 80 to 100 years.

5.8.3 Performance analysis

With no proven hydrodynamic model available for the Teign, a simple Infoworks 1D-2D model was built to assess the performance of the assets in Section 5. The flood extent for the 1 in 200 year return period event (0.5% annual exceedance) in 2015, 2065 and 2115 is shown in Figures 5-16, 5-17 and 5-18 respectively. In 2015 the extent of flooding is extremely limited and looks to be contained within the carpark and playing fields behind the railway at approximately 209m 30ch to 209m 40ch. The extent of flooding at this location increases with climate change, with additional areas around 212m 0ch becoming affected from 2065 and from 210m 25ch to 210m 70ch flooded by 2115.

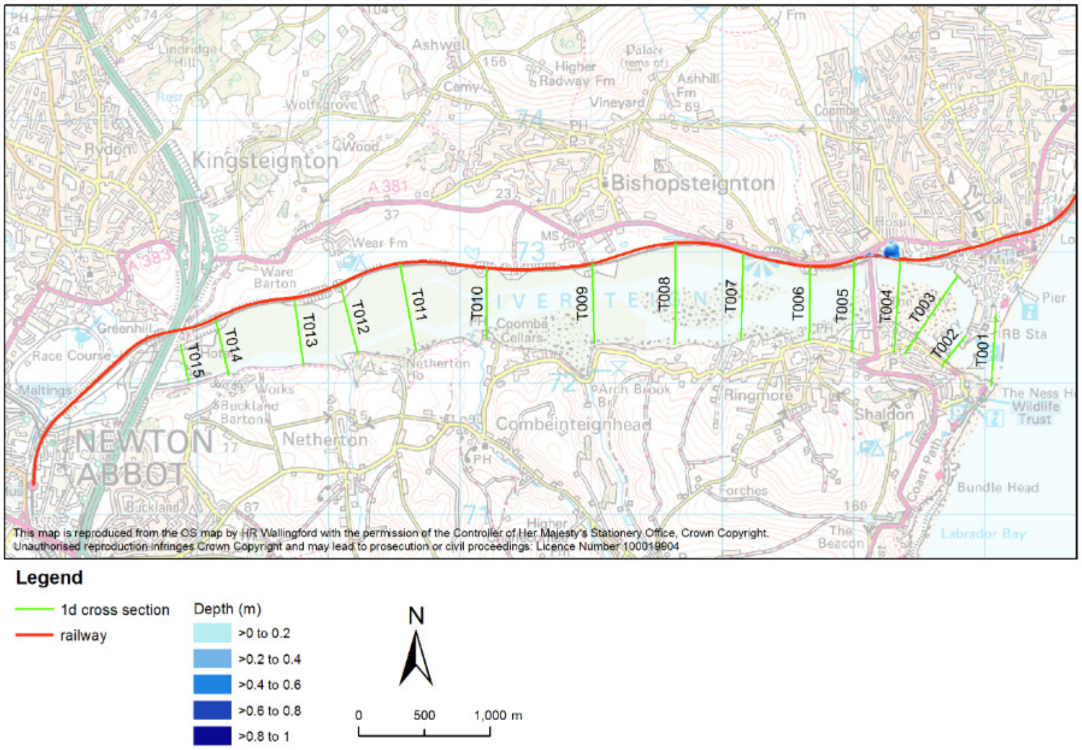

Figure 5-116: 1 in 200 year return period flood extent for the Teign Estuary in 2015

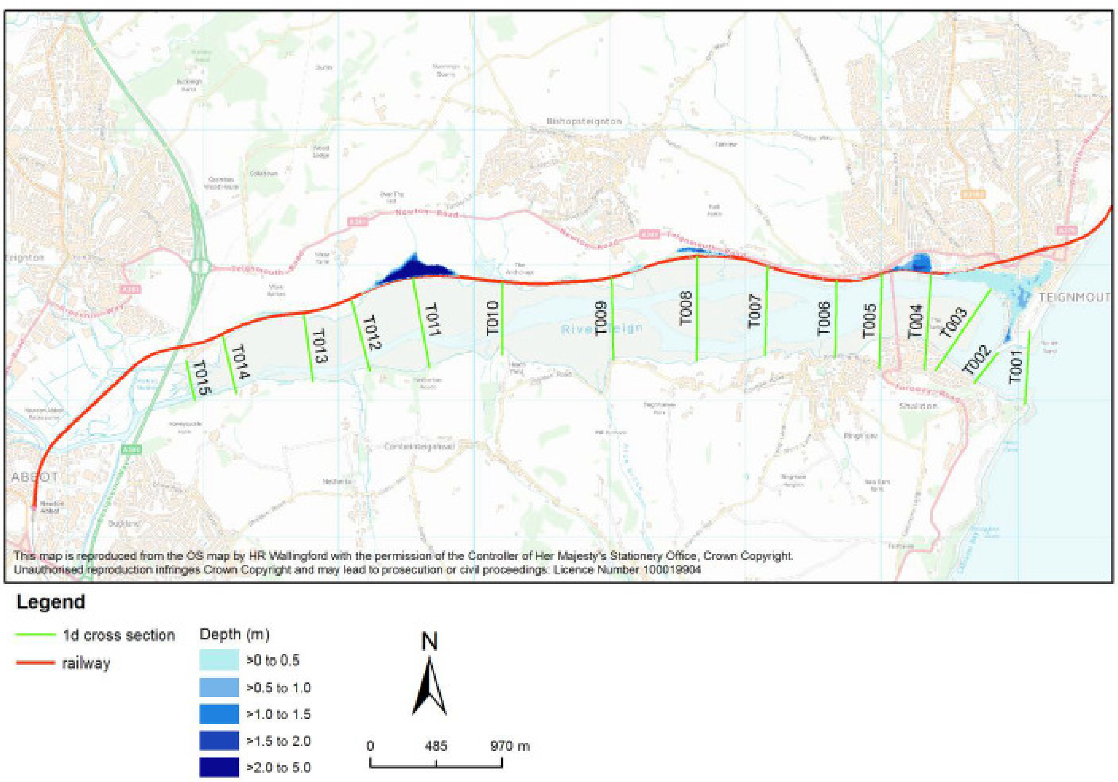

Figure 5-127: 1 in 200 year return period flood extent for the Teign Estuary in 2065

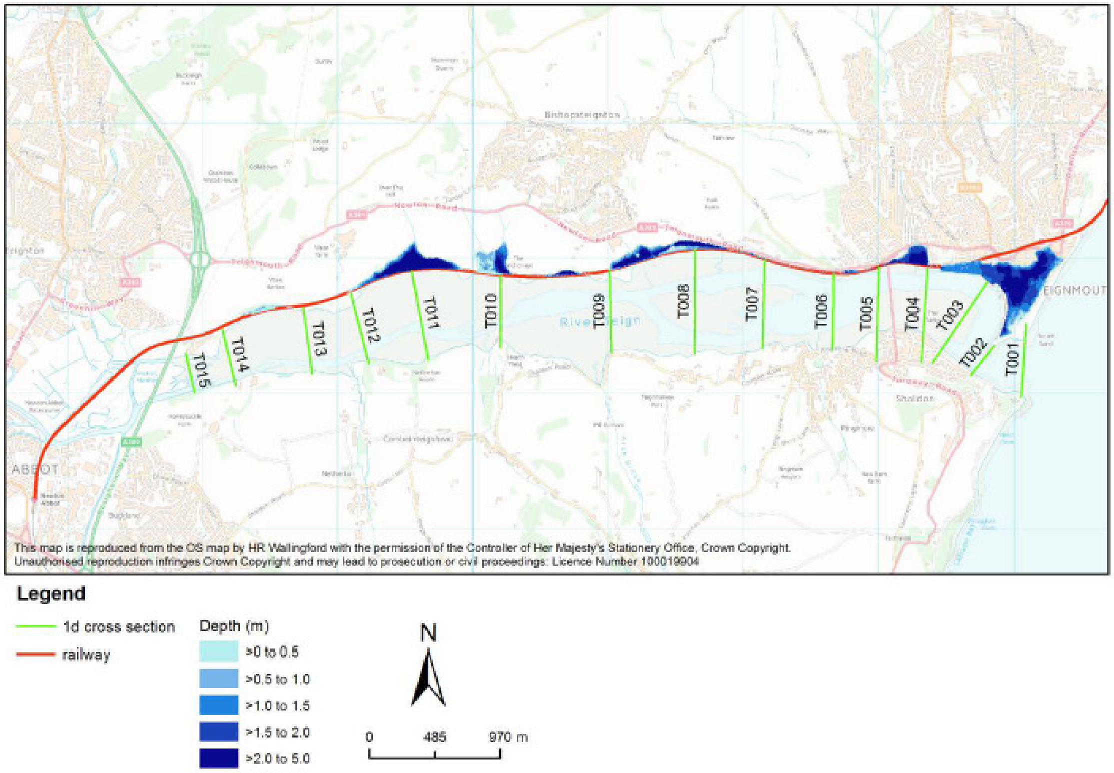

Figure 5-18: 1 in 200 year return period flood extent for the Teign Estuary in 2115

5.8.4 Summary

The defence condition is generally fair with a high residual life of 80 to 100 years. The standard of protection provided in Section 5 is high with all of the defences providing a 1 in 200 year return period standard of protection. This is due to the Teign Estuary being much less exposed to wave action than the open coast.

A full asset inventory for Section 5 is included within Appendix F of this baseline report and summarises the topographic levels, condition grades, residual life and standard of protection provided by each individual asset.

Geology, geomorphology and geotechnics

6.1 Introduction

Cliff failure and recession is a naturally occurring process which, along the coast between Dawlish Warren and Teignmouth, is constrained at its toe by the railway and sea wall on its seaward face. The sea cliffs are considered to present a significant risk to NR's infrastructure and the ability to ensure the operation of a reliable railway. Cliff instability has been a regular issue since the railway was constructed. Recent cliff failures are thought to be a result of rising groundwater levels following prolonged periods of rainfall. That instability continues, related at least in part to rainfall and groundwater levels. In other areas along the frontage, the slopes are subject to physical and chemical weathering causing degradation and a resultant reduction in shear strength leading ultimately to slope failure.

Since the construction of the railway, there have been many schemes to repair, strengthen, and improve the resilience of the cliffs including the installation of soil nails and netting, drape netting and catch fences.

This section describes the methods taken to look at the geology, geomorphology and geotechnics as part of this investigation. To facilitate understanding of the behaviour of cliff sections, the coastal frontage between Dawlish Warren and Teignmouth has been divided into discrete Cliff Behaviour Units (CBUs). Each CBU is characterised according to the morphology, behaviour and geology, which provides an important framework for the investigation, characterisation and management of cliffs (Lee 1997, Moore et al. 1998). North of Dawlish Warren and west of Teignmouth, the railway is not flanked by cliffs, and therefore the CBU approach is not appropriate.

6.2 Methodology

System) model was developed to compare and interpret spatial data on the geology, geomorphology and past behaviour of the cliffs in order to define the nature of the cliff hazards (Table 6-1). Information on existing hazard mitigation measures was assembled, including the location and type of slope stabilisation measures, debris catch fences and of slope monitoring and early warning systems.

Table 6-1: Spatial data used for cliff characterisation

Dataset	Date	Scale/resolution	Source/copyright
Vertical aerial photography	1986	1:5,700	National Monuments Records (NMR)
Oblique aerial photography	1941 to 1960s	n/a	NMR
LiDAR	2007 to 2014		Channel Coastal Observatory, NR
Bedrock and superficial geology	Unknown	1:10,000	British Geological Survey (BGS)
Bedrock and superficial geology	Unknown	1:50,000	BGS
Records of past failures	Various	n/a	Various

A site visit was undertaken to make observations and ground truth the findings of the GIS-based interpretations. In addition, a desk review of relevant survey data and reports was undertaken to understand the mechanisms of failures, the frequency of failures, and the processes thought to control cliff behaviour. This data was synthesised in the GIS model and informed the delineation of CBUs using the method described by Moore *et al.* (2003).

The deliverables of the fast-track geotechnical study comprised a non-technical briefing report (CH2M 2015), including CBU characterisation and hazard classification, and a GIS database. This report provides an elaboration of the information provided in the fast-track study. The CBU characterisation including supporting information such as historical photography and transects is presented in Appendix G.

6.3 Regional context

6.3.1 Geology

Between Exeter and Dawlish Warren (Section 1) the route is underlain by a series of breccia[1] and sandstone formations of Permian age (c. 250-300 million years BP). Due to erosion, the oldest strata outcrop beneath the superficial deposits closest to Exeter, and the youngest towards Dawlish. The regional geology is described by the BGS (BGS 1999) and the litho-stratigraphy of the Teignmouth to Langstone Rock cliff section was logged in detail by Lamming (1954).

From Exeter at the start of the alignment the route is underlain by the following formations (Figures 6-1 to 6-3):

- Alphington Breccia Formation: reddish-brown, clayey, silty and fine-grained breccia with clasts of shale and sandstone;
- Heavitree Breccia Formation: reddish-brown, mainly fine-grained breccia;
- Dawlish Sandstone Formation: reddish-brown cross-bedded sand/sandstone with thin lenses of breccia and mudstone;
- Exe Breccia Group: reddish-brown breccias with subordinate sandstones;

Limited structural information is available; however, a series of geological faults are recorded to cross the route in the vicinity of Exminster.

Superficial deposits over this section (Figures 6-1 to 6-3) are recorded as (BGS 1999):

- Alluvium (associated with the River Exe): upper unit of clay/silt, lower unit of gravel. Thin peat beds and gravel bands are recorded in the upper unit between Exeter and Bridge Road (southeast of Matford);
- Tidal Flat Deposits (associated with the River Exe): clay, underlain by gravels between Bridge Road and the commencement of the coastal rail section;
- Wind Blown Sands in the vicinity of Dawlish Warren.

Between Dawlish Warren and Kennaway Tunnel (Section 2) the solid geology transitions from the Exe Breccia Group breccias to outcropping Dawlish Sandstone Formation (Figure 6-4). To the southwest of Dawlish Water, this transitions into undifferentiated Alphington & Heavitree Formation sandstones.

Superficial deposits for this area (Figure 6-4) are recorded as (BGS 1999):

- River Terrace Deposits, 2: clast-supported sands and gravels of Quaternary age, deposited in fluvial environments to the northeast, in the vicinity of Langstone Rock;
- Alluvium: Quaternary-age clays, silts, sands and gravels associated with Dawlish Water. These are underlain by River Terrace Deposits, 1: Quaternary gravels.

Lamming's section (Figure 6-5), logged in the early 1950s, provides excellent detail of the exposed litho-stratigraphy and occurrence of faults in the cliffs across Section 2.

Sections 3 and 4 (Kennaway Tunnel to Teignmouth) display largely similar bedrock geology. The northern part of Section 3 alternates between sandstone- and breccia-dominant undifferentiated

[1] Rock consisting of angular fragments of stones cemented by finer calcareous material

Alphington & Heavitree Breccias (Figures 6-6 and 6-7). This transition is marked by a series of outcropping faults in the vicinity of Coryton's Cove and Horse Cove. South of Horse Cove, the geology is consistently breccia-dominant Alphington & Heavitree Breccias through to Teignmouth.

Superficial deposits are limited to undifferentiated Beach and Tidal Flat Deposits to the seaward side of the track, and Alluvium associated with a number of streams (e.g. at Smugglers' Inn and to the east of the Smugglers' Lane compound).

Lamming's section (Figure 6-5), logged in the early 1950s, provides excellent detail of the exposed litho-stratigraphy and occurrence of faults in the cliffs across Sections 3 and 4.

From Teigmouth to Newton Abbot the route is underlain by varying geology (Figures 6-8 to 6-10). These units include (BGS 1999):

- Oddicombe Breccia Formation: Silty sandy Permian breccia, with some gravel-sized clasts of limestone and sandstone, from the rail/Lea Road intersection to the east of Wear Farm Holiday Park;
- Whiteway Mudstone Formation: Red and purple, with subordinate green and grey-black locally-laminated mudstones of Devonian/Carboniferous age. Minor intrusive igneous gabbro units are also locally present. From east Wear Farm Holiday Park to the bridge crossing the River Teign;
- Bovey Formation: Deposits of sands and clays of Palaeogene age. These are the youngest rocks in the area and lie under a fault-bounded block in the vicinity of Newton Abbot Station.

Little structural information is recorded by the BGS, apart from the localised faulting around Newton Abbot and in the section of the route lying between the Wear Farm and the Anchorage.

Few superficial deposits are recorded in this section (Figures 6-8 to 6-10). Those that are recorded comprise (BGS 1999):

- Tidal Flat Deposits: variable silty clays associated with the River Teign. Some peaty layers are present;
- Alluvium: clayey silts and gravels. Thin peat beds and gravel bands are also recorded.

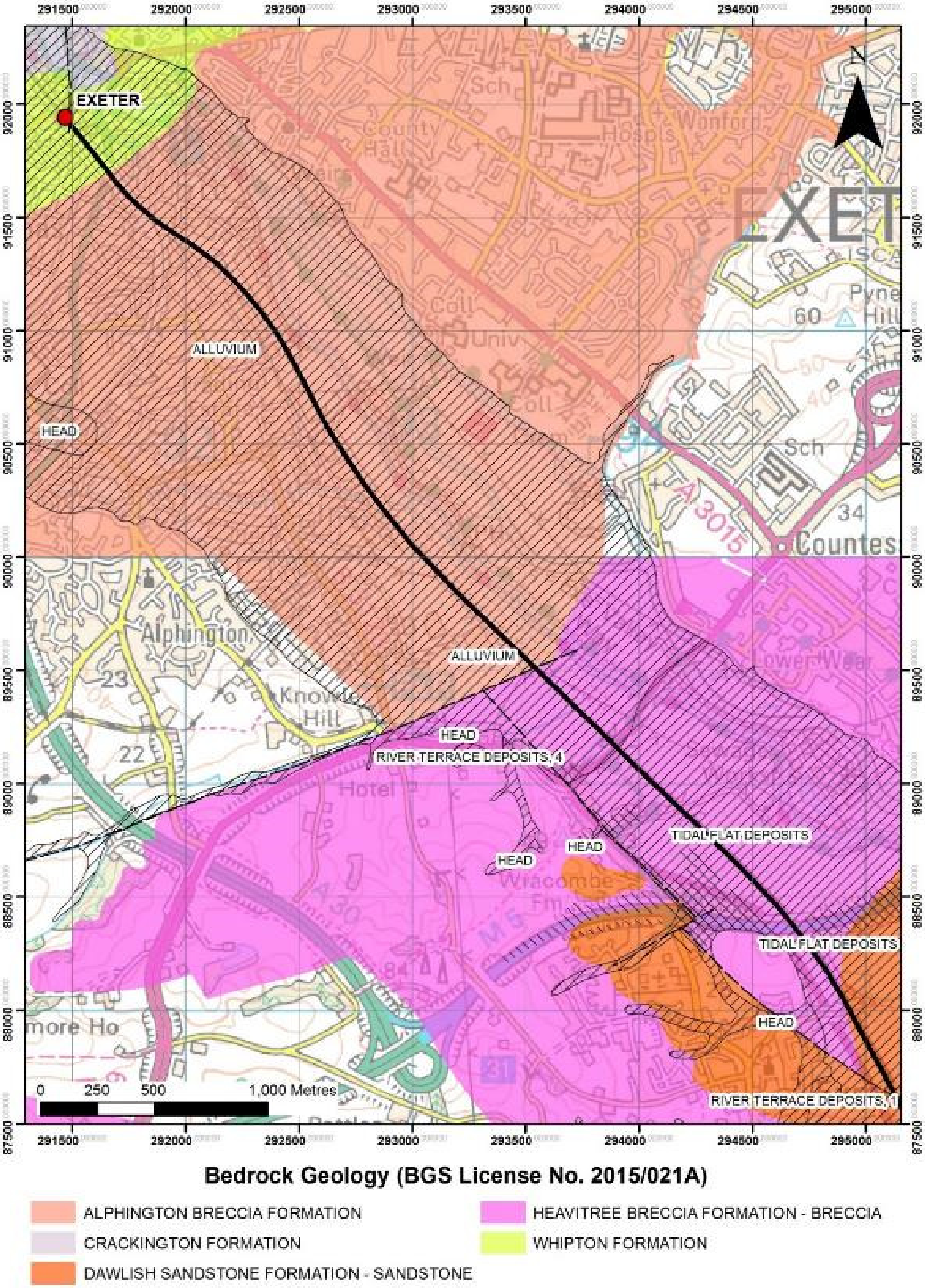

Figure 6-1: Geological mapping for Section 1 – Exeter to Dawlish Warren (1) (BGS, 2015)

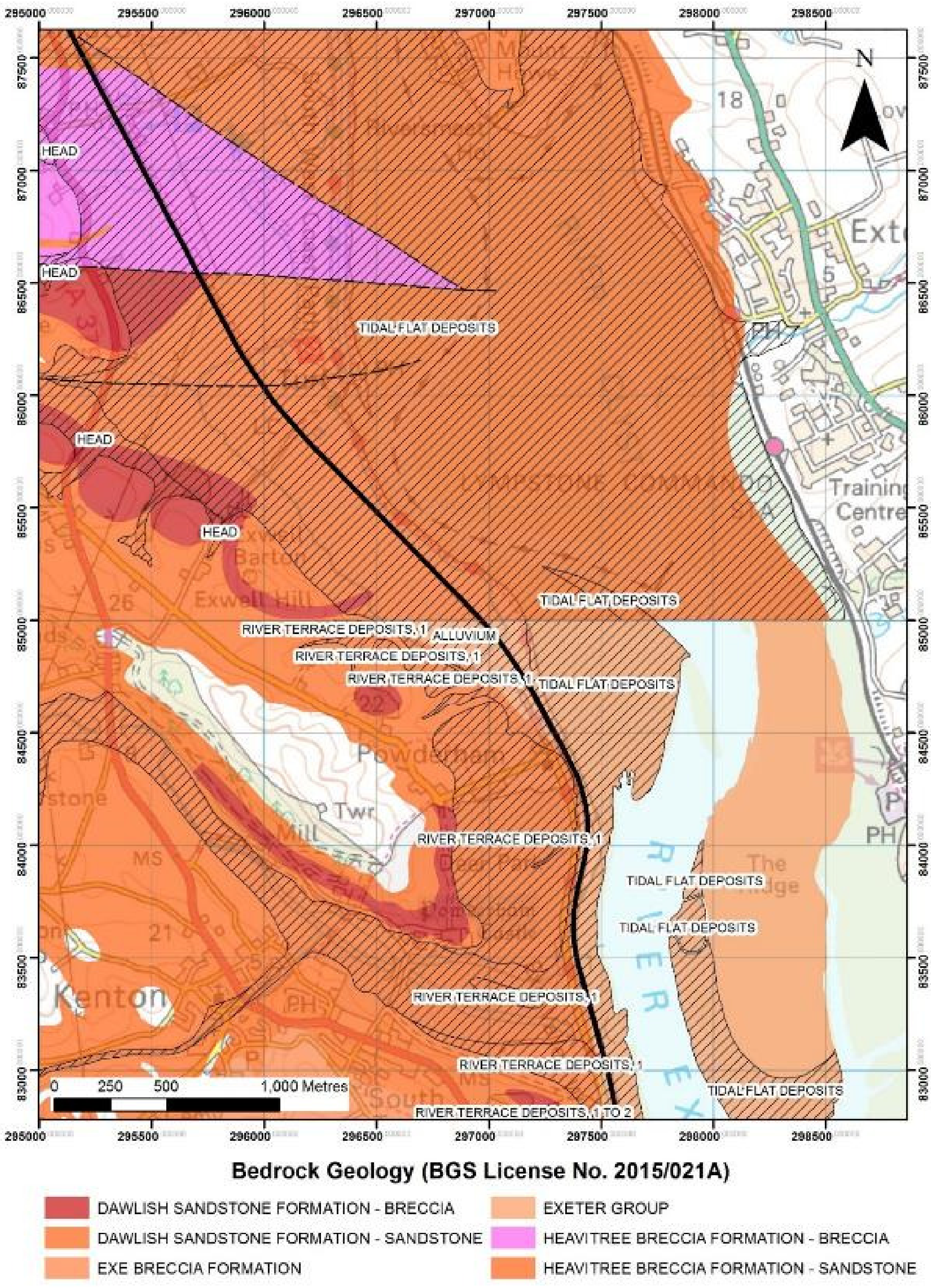

Figure 6-2: Geological mapping for Section 1 – Exeter to Dawlish Warren (2) (BGS, 2015)

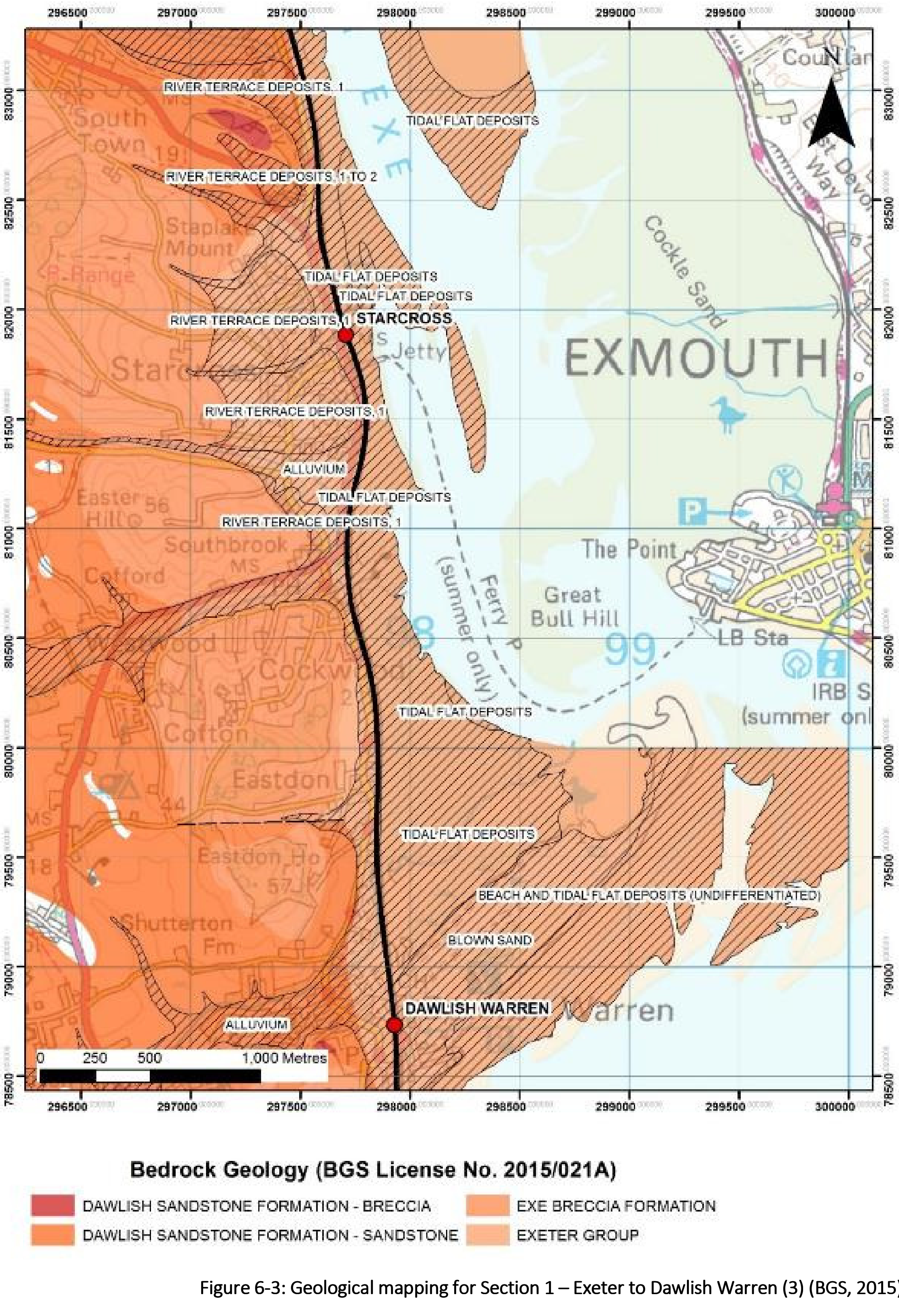

Figure 6-3: Geological mapping for Section 1 – Exeter to Dawlish Warren (3) (BGS, 2015)

Figure 6-4: Geological mapping for Section 2 – Dawlish Warren to Kennaway Tunnel (BGS, 2015)

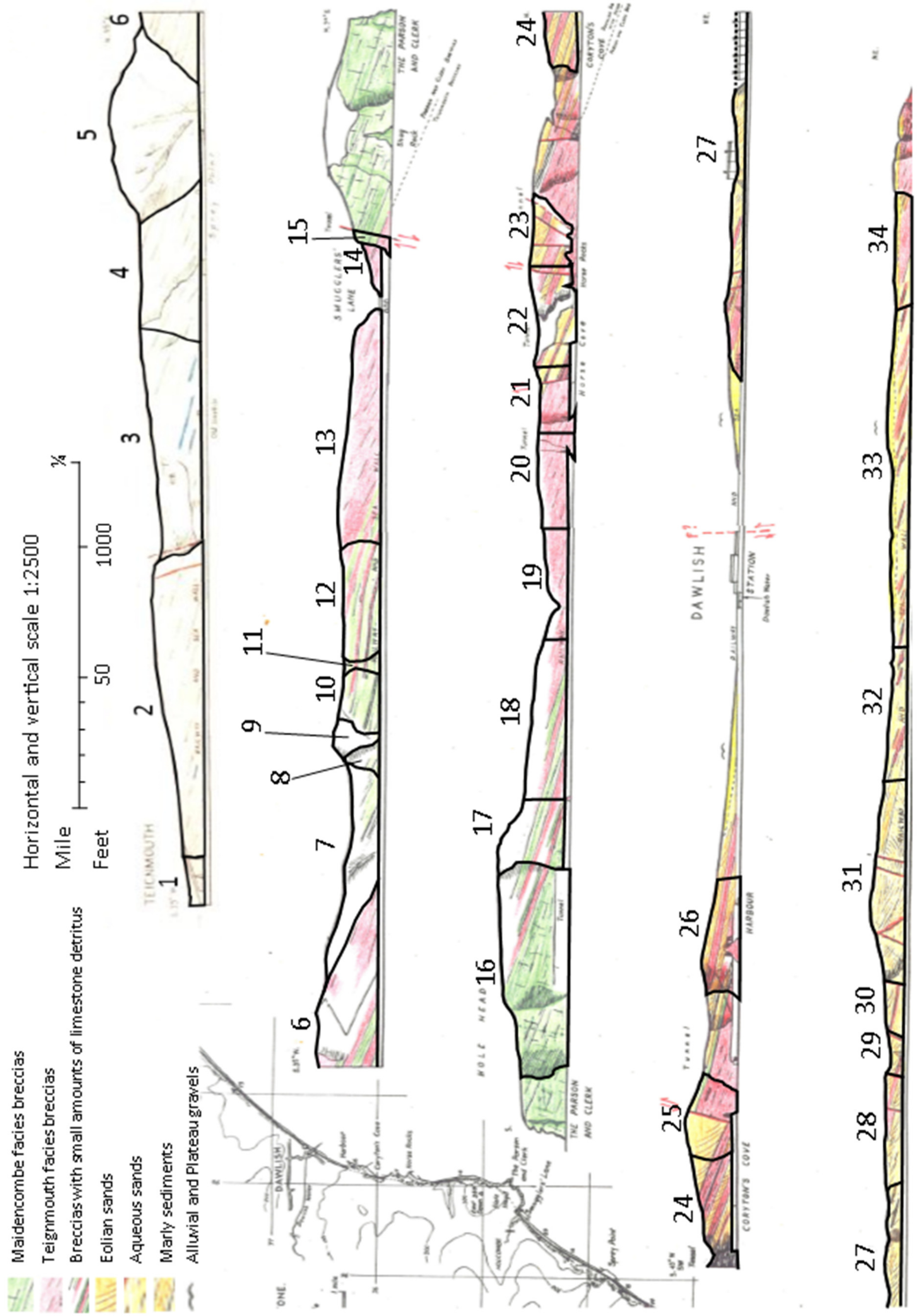

Figure 6 5: Lamming's 1954 geological cliff section from Teignmouth to Langstone Rock

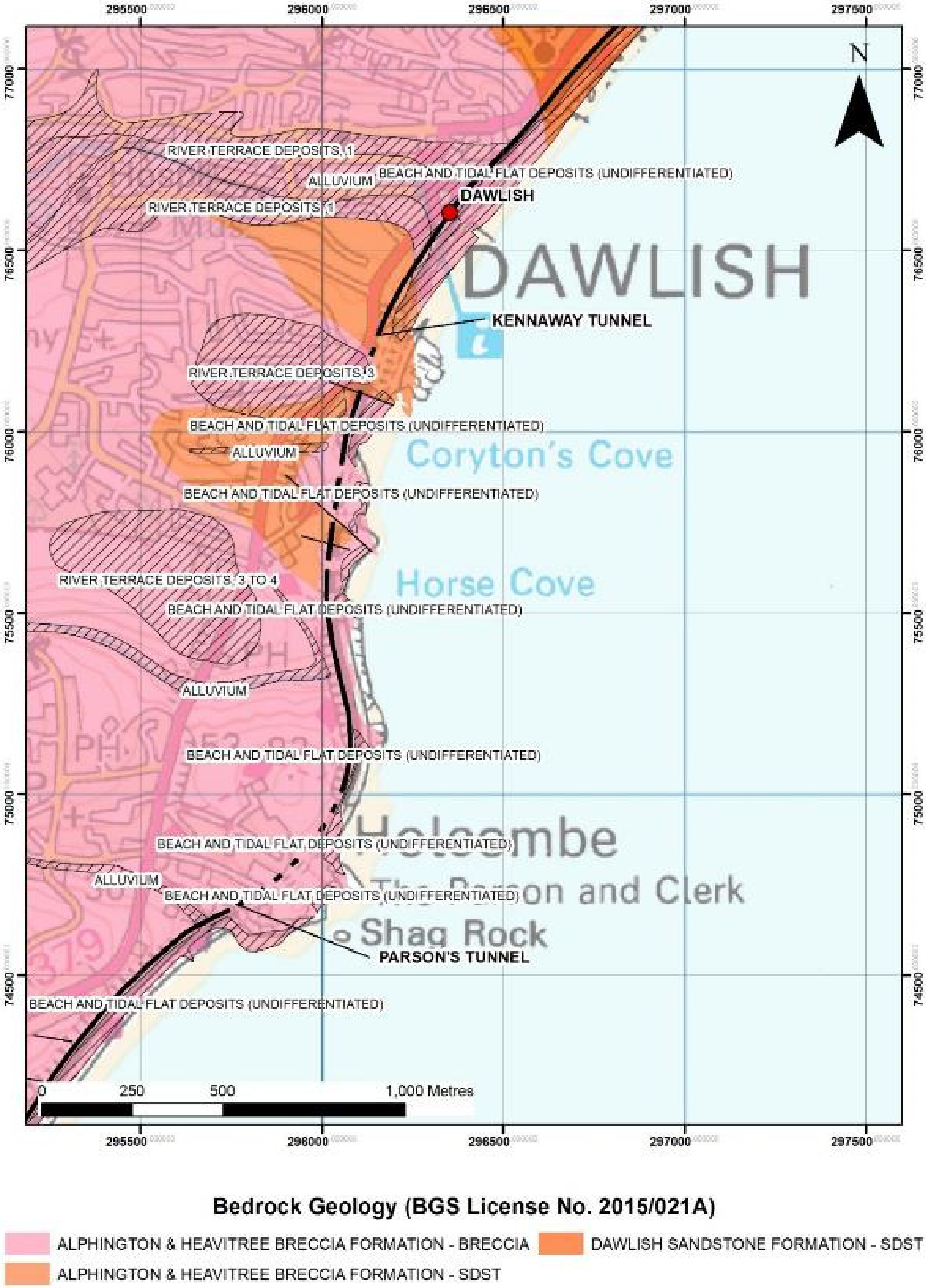

Figure 6-6: Geological mapping for Section 3 – Kennaway Tunnel to Parson's Tunnel (BGS, 2015)

Figure 6-7: Geological mapping for Section 4 – Parson’s Tunnel to Teignmouth (BGS, 2015)

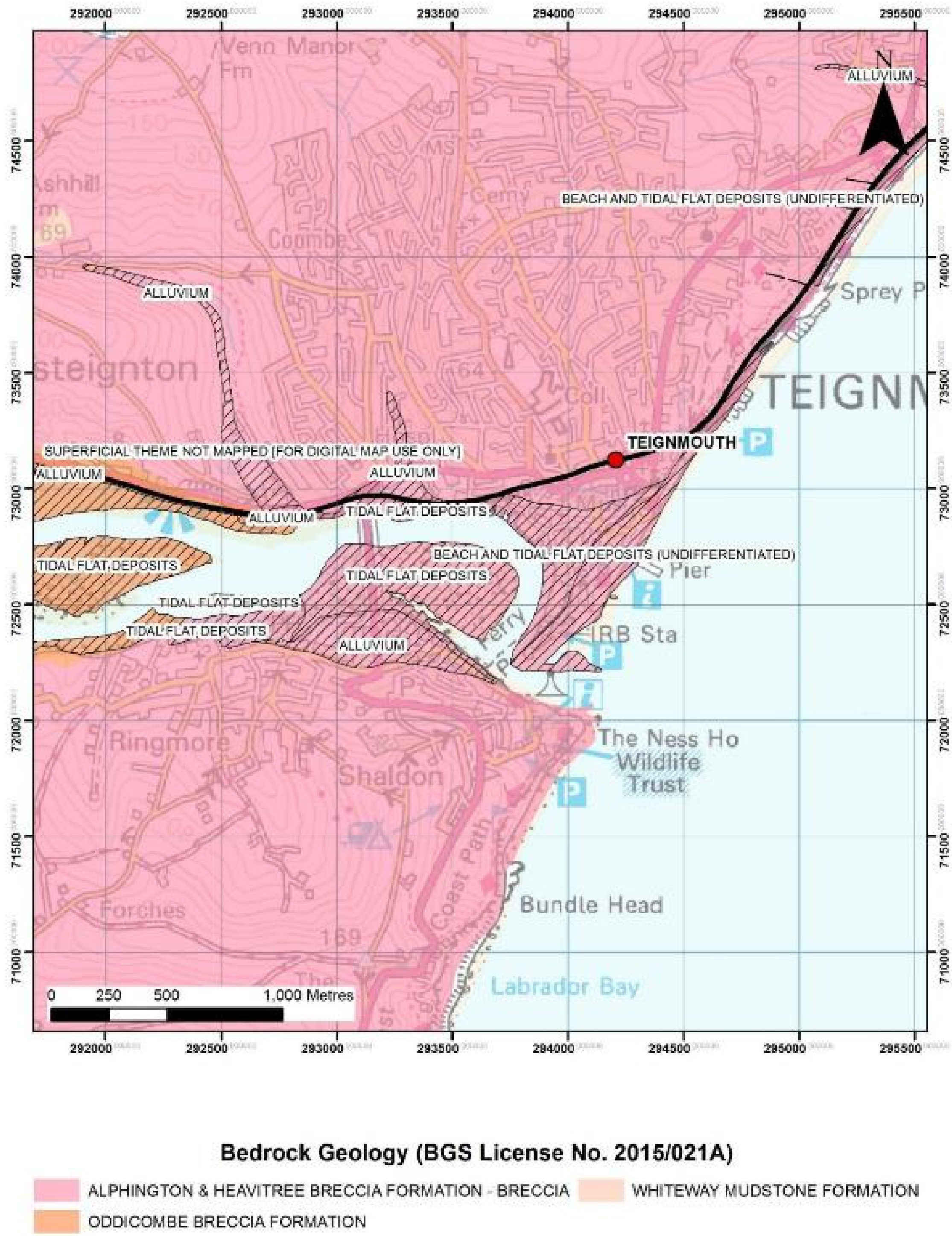

Figure 6-8: Geological mapping for Section 5 - Teignmouth to Newton Abbot (1) (BGS, 2015)

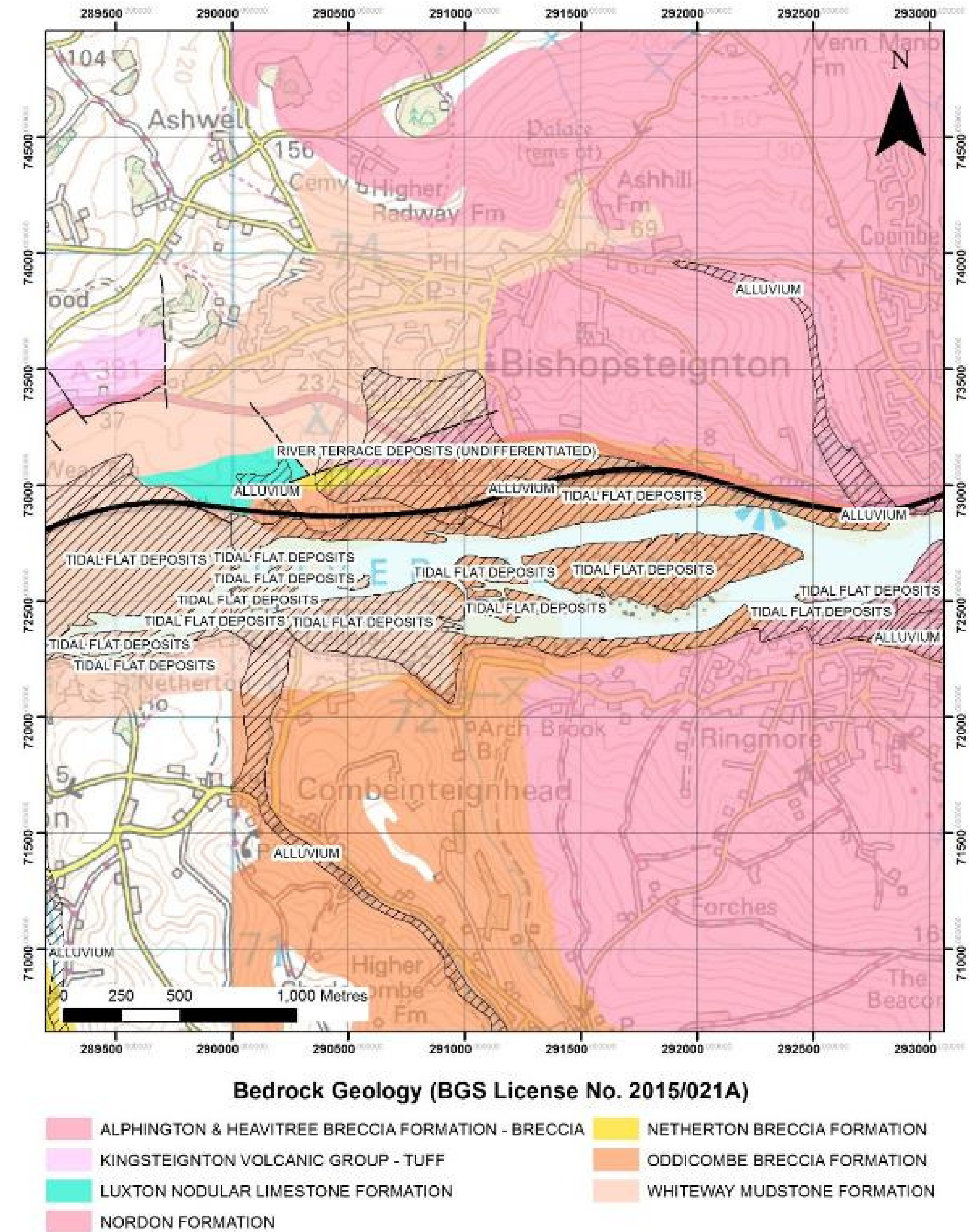

Figure 6-9: Geological mapping for Section 5 – Teignmouth to Newton Abbot (2) (BGS, 2015)

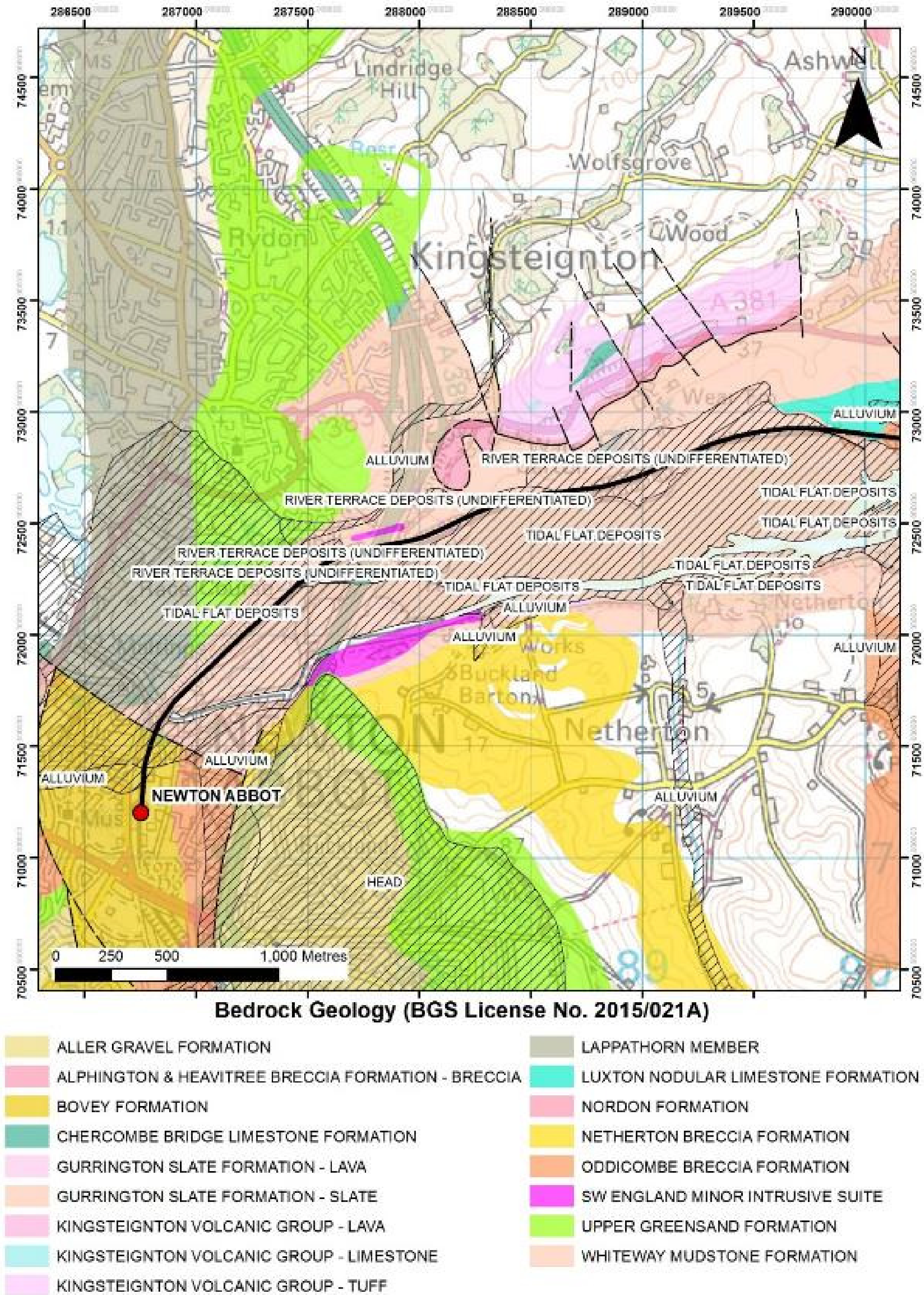

Figure 6-10: Geological mapping for Section 5 - Teignmouth to Newton Abbot (3) (BGS, 2015)

6.3.2 Geological material properties

The material properties of the cliffs from Teignmouth to Dawlish Warren are controlled by the variable strength of strata, structure and faulting. Faults occur intermittently along this section of coast. They create structural weakness in the cliffs, particularly where they act as a conduit for groundwater seepage. Other weakness occur because of joint and dip orientation, and through the influence of sub-aerial weathering of rock and soil, which leads to localised rock falls, spalling and the creation of talus slopes.

Previous ground investigation records indicate that the material is exceedingly difficult to characterise in terms of geotechnical parameters, given its complex stratigraphic arrangement and history of poor core recovery. Consequently, any data that is available is from specific sites (such as Woodland Avenue) can only be extrapolated over a limited area. The following table summarises observed engineering properties of the geological material from previous ground investigation:

Table 6-2: Geology material properties

Material	Location	
Alphington & Heavitree Breccia Group	East Cliff Walk	Dynamic probe depth penetration range 1.0-4.5 m
	Sprey Point	Dynamic probe depth penetration range 1.1-4.3 m
	Woodland Avenue	Dynamic probe depth penetration range 1.4-3.9 m Ø = 24° (modelled) c' = 19 kN/m^2 (weathered); 15 kN/m^2 (unweathered)
	Smugglers' Lane	Dynamic probe depth penetration range 0.7-4.6 m
	Shell Cove	SPT N value 31-50 c_u = 12-92 kPa
Dawlish Sandstone Formation	Dawlish	Dynamic probe depth penetration range 1.4-4.9 m
	Ladies' Mile	Ø = 35-40° (breccia); 30-35° (sandstone) DCP refusal at 4.0-6.5 m
Exe Breccia Group	Langstone Rock	DCP refusal at 3.0-4.5 m

6.3.3 Cliff failure mechanisms

Cliff failure mechanisms along the frontage comprise rock falls and block topples, shallow debris flows or 'washouts' from gullies, and deep-seated failures. In the absence of ongoing exposure to toe erosion through marine processes, the main factors responsible for slope instability in the cliffs are direct effects of weathering and also groundwater. All failure mechanisms present in CBUs are indicated and the principal mechanisms noted in **Appendix G**. There is a broad correlation between the geology and failure mechanism, with the Alphington and Heavitree Breccia Formation being typified by joint-/fault-controlled washouts, rock falls and local deep-seated failures such as that seen at Woodland Avenue; and the Dawlish Sandstone more commonly failing through rock falls that tend to disaggregate into sand on impact with the ground, posing a different hazard to the railway. At various locations along the frontage, the aggregation of rock fall deposits have formed large talus slopes at the foot of the cliffs. These are believed to be primarily composed of the Permian-age material and the overlying Quaternary river terrace deposits where these are present.

6.3.4 Preliminary ground model

The CBU mapping shows that the cliff behaviour between Teignmouth and Dawlish is complex with various failure processes occurring. Material structure and groundwater are important factors controlling the behaviour of the cliffs. The CBU characterisation documents the main controls for each unit, the cliff failure mechanisms and any mitigation measures currently in place (**Appendix G**).

Figures showing the preliminary ground model are interspersed through sections 6.4 to 6.6. These should be reviewed when the results of a ground investigation and UAV survey commissioned in 2016 by NR become available.

6.4 Dawlish Warren to Kennaway Tunnel

6.4.1 Geology

Between Dawlish Warren and Dawlish the geology varies:

- At Langstone: formation is from Exe Breccia Group with superficial gravel river terrace deposits. The bedrock geology is notified as a Site of Special Scientific Interest (SSSI).
- At Dawlish: the geology is Dawlish Sandstone Formation with a dip of 20 degrees to the east

Each CBU along this frontage is shown in Figures 6-11 to 6-12 and the geology for each CBU along this frontage is outlined in more detail in Table 6-3.

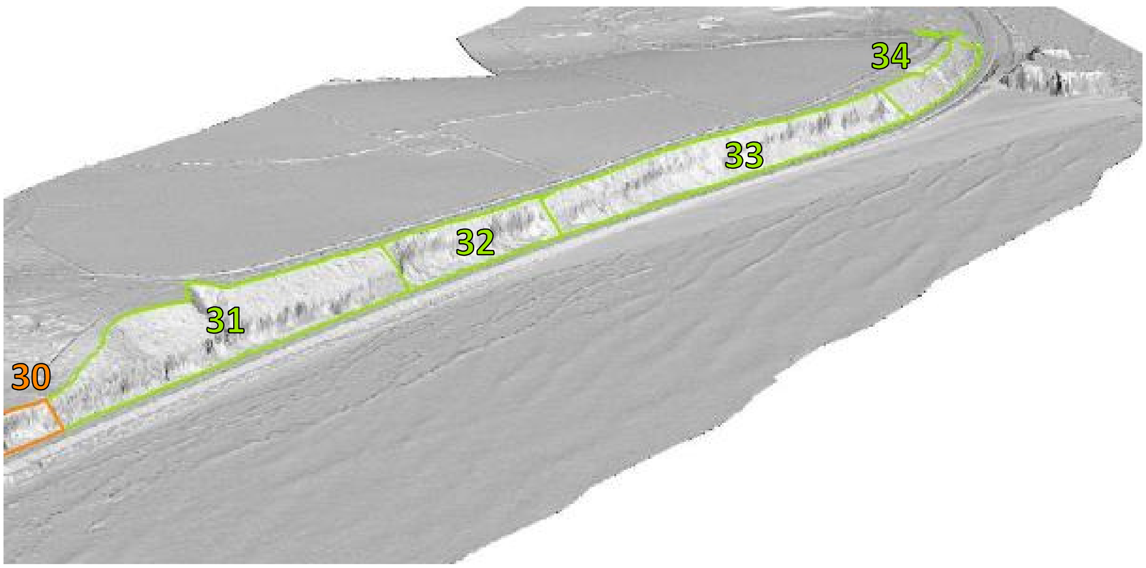

Figure 6-5: Section 2 - CBU 34 to 31

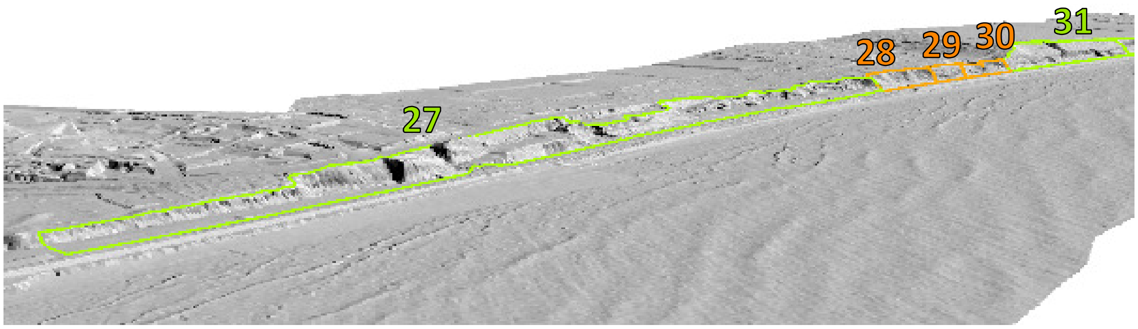

Figure 6-6: Section 2 - CBU 31 to 27

Table 6-3: CBU summary (Section 2)

Name	CBU No.	Geological Description
Langstone Cutting - Timaru Gardens	CBU 34 and 33	Exe Breccia Group with superficial gravel river terrace deposits. The bedrock geology is notified as a Site of Special Scientific Interest (SSSI)
Ladies' Mile - Dawlish	CBU 32 - 27	Dawlish Sandstone Formation dipping c. 20° northeast to east overlain by terrace gravels and slope wash. Numerous sub-vertical joints and faults observed in the field.

6.4.2 Cliff failure mechanisms

The cliff failure mechanisms vary along this frontage and are summarised in Table 6-4. Failures are either rock falls or shallow landslides. None of the cliffs appear to be controlled by groundwater seepage (being well drained), which may account for the nature of the failures here.

Table 6-4: Cliff failure mechanisms (Section 2)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
Langstone Cutting	CBU 34	Rock fall (weak sandstone)	Sub-vertical cliff with regraded upper section at c. 45°. The cliff is heavily vegetated. Talus slope at c. 55° mantles the cliff toe and is heavily vegetated.
Timaru Gardens	CBU 33	Rock fall (weak sandstone)	Embayment in the cliff where superficial river gravels over 2m thick are deposited in a channel eroded in surface of breccia. The lower cliff is sub-vertical but the upper cliff has been regraded to c. 45°. The toe of the cliff is mantled by a large talus slope that is largely derived from the overlying gravels. Small joint-controlled rock falls in the lower sandstone cliff and small falls from the overlying terrace gravels. Sediment fans at base of cliffs fed by spalling rock faces.
Ladies' Mile Central	CBU 32	Rock fall (weak sandstone)	Large embayment within cliff morphology with overhanging cliff tops and some sea caves at base at approximately 30-40°. Talus slope at c. 55° mantles lowermost cliff faces, which are heavily vegetated. Vertical sections of cliff have no vegetation and exposed jointing. Small joint-controlled rock falls in the lower sandstone cliff and small falls from the overlying terrace gravels. Sediment fans at base of cliffs fed by spalling rock faces.
Pinewood Close	CBU 31	Rock fall (weak sandstone)	Large joint-controlled embayment with preferential weathering and erosion of beds, leading to overhangs and cavities. The lower cliff face is sub-vertical and the upper cliff has been regraded to c. 45°. A vegetated talus slope at c. 50° mantles much of the cliff toe. Vertical sections of the cliff contain widespread joints that promote small block failures. There are also small falls from the overlying terrace gravels. A small gully midway along the cliff section has no surface water catchment and is probably related to preferential weathering and erosion along a small fault.
Rockstone Footbridge	CBU 30	Rock fall (weak sandstone)	Joint-controlled embayment in the cliff with sub-vertical sandstone cliff and vegetated talus slope. The sandstone shows preferential weathering and erosion of certain beds, leading to overhangs and cavities. Joint-controlled slab failures and localised failures of the overlying terrace gravels are common.
Rockstone Cliff	CBU 29	Rock fall	Sub-vertical sandstone cliff with regraded top section and talus slope at base. Talus slope at c. 50° and heavily vegetated. Vertical sections of cliff have no vegetation, widespread jointing and preferential weathering of sandstone beds to produce cavities and overhangs. Small joint-controlled rock falls in the sandstone cliff and small falls from the overlying gravels.

Table 6-4: Cliff failure mechanisms (Section 2)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
Riviera Terrace	CBU 28	Rock fall	Embayment with locally overhanging strata and small cavities at base of cliff. Vegetated talus slope at c. 55° mantles the lower cliff. Sandstone cliff has no vegetation and exposed jointing. Small joint-controlled rock falls in the lower sandstone cliff and small falls from the overlying soils.
Dawlish	CBU 27	Rock fall, shallow slide	Sub-vertical cliff with vegetated talus slope at c. 40° mantling the cliff toe that projects out from the typical cliff alignment. Upper cliff has no vegetation and evidence of small joint-controlled rock falls. Much of the CBU contains human development and the cliff has been cut back to accommodate this.

6.5 Kennaway Tunnel to Parson's Tunnel

6.5.1 Geology

The geology for each CBU are defined within Table 6-5 and the CBU locations are shown in Figures 6-13 to 6-15. Most of the frontage is dominated by undifferentiated Alphington and Heavitree Formations – breccias. However, as the following table demonstrates, there are localised changes in the geology with superficial layers of alluvium and some sandstone in places.

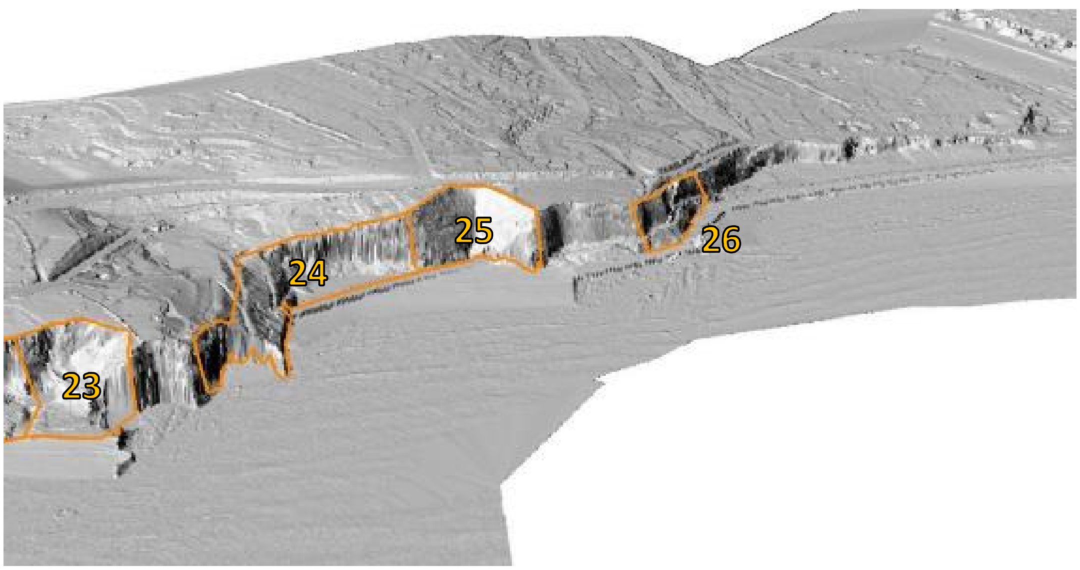

Figure 6-7: Section 3 - CBU 26 to 23

Note: gaps are tunnel sections or where there are no cliffs adjacent to the line

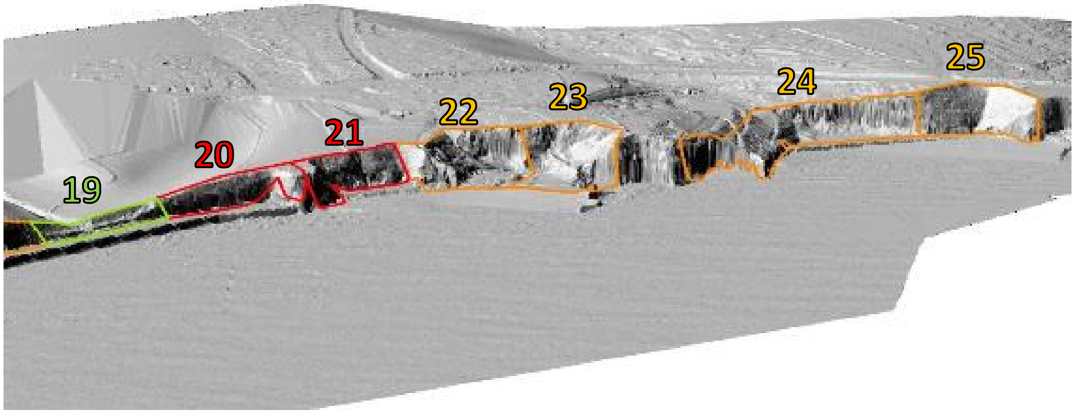

Figure 6-8: Section 3 - CBU 25 to 19

Note: gaps are tunnel sections or where there are no cliffs adjacent to the line

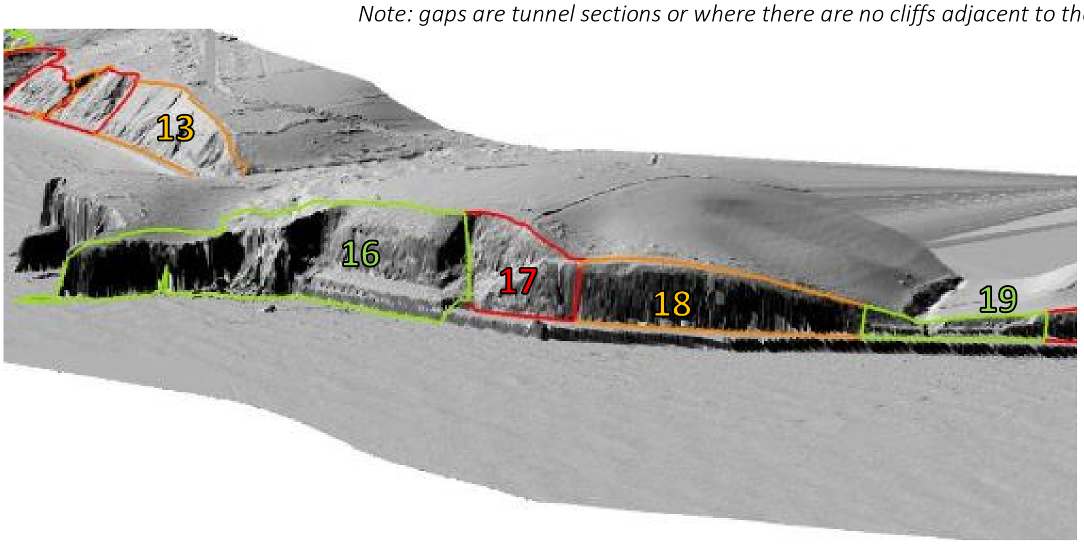

Figure 6-9: Section 3 - CBU 19 to 16

Note: gaps are tunnel sections or where there are no cliffs adjacent to the line

Table 6-5: CBU summary (Section 3)

Name	CBU No.	Geological Description
Kennaway Tunnel North Portal	CBU 26	Undifferentiated Alphington & Heavitree Breccia Formations – sandstone and breccia. The bulk of the cliff is formed in sandstone with numerous thin breccia beds, the uppermost part of the cliff is formed from breccia. A thin gravel layer caps the cliff. The slope above Kennaway Tunnel is aligned with a fault. The bedrock geology is notified as a Site of Special Scientific Interest (SSSI).
Kennaway Tunnel South Portal	CBU 25	Undifferentiated Alphington & Heavitree Breccia Formations – sandstone and breccia. The bulk of the cliff is formed in sandstone with numerous thin breccia beds, the uppermost part of the cliff is formed from breccia. A thin gravel layer caps the cliff. The slope above Kennaway Tunnel is aligned with a fault. The bedrock geology is notified as a Site of Special Scientific Interest (SSSI).
Coryton Tunnel South Portal – Coryton Cove	CBU 23 and 24	Undifferentiated Alphington & Heavitree Breccia Formations – breccia and sandstone. North portal of Coryton Tunnel cut in cliff of breccia. Cliffs of Coryton Cove cut in sandstone. Thin gravel layer caps the cliff. All beds dip at around 10° to the north to northeast. Sandstones are affected by honeycomb weathering. Sub-vertical joints and small faults observed in field. The bedrock geology of the cliffs backing Coryton Cove is notified as a Site of Special Scientific Interest (SSSI).

Shell Cove (includes Phillot's Tunnel)	CBU 22	Undifferentiated Alphington & Heavitree Breccia Formations – sandstone. The breccias comprise sandy, gravelly silt/clay; silty/clayey sand; and clayey, sandy gravels. There is a normal fault with a downthrow of about four metres to the north. Bedding has a strike of 355°, dip of 32°, and spacing of 400mm.
Clerk's Tunnel South Portal – Clerk's Tunnel to Phillot's South Portal	CBU 21 and 20	Undifferentiated Alphington & Heavitree Breccia Formations – breccia overlain by sandstone.
Smugglers' Inn Stream	CBU 19	Undifferentiated Alphington & Heavitree Breccia Formations – breccia. Superficial alluvium from the Smugglers' Inn stream.
Parson's Tunnel Rock fall shelter – East Down Cliff	CBU 18 - 16	Undifferentiated Alphington & Heavitree Breccia Formations – breccia.

6.5.2 Cliff failure mechanisms

Cliff failure mechanisms for each CBU are defined in Table 6-6. Failures for these units are predominately rock falls. CBU 22 is controlled by washouts with rock falls being a secondary failure mechanism.

Table 6-6: Cliff failure mechanisms (Section 3)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
Kennaway Tunnel North Portal	CBU 26	Rock fall	Sub-vertical cliff at c. 40°. The tunnel portal is capped by talus. All slopes are thickly vegetated with many mature trees.
Kennaway Tunnel South Portal	CBU 25	Rock fall	Sub-vertical cliff at c. 40°. The tunnel portal is capped by talus. All slopes are thickly vegetated with many trees.
Coryton Cove	CBU 24	Rock fall	Sub-vertical cliffs. Differential weathering of beds means sandstone beds are eroded to leave thin projecting breccia beds. These beds have accumulated small talus slopes that have become vegetated. Spalling widespread. Joint-controlled rock falls around entrance to Coryton's Tunnel.
Coryton Tunnel South Portal	CBU 23	Rock fall	Sub-vertical cliffs that are set back from the railway. Sandstone cliffs extensively affected by honeycomb weathering. Small joint-controlled rock falls. Talus slope forming at base of cliff
Shell Cove (includes Phillot's Tunnel)	CBU 22	Shallow slide/washout. Rock falls are secondary hazard mechanisms	Cliff face is set back from the railway that runs along a low embankment. Cliff is sub-vertical and fronted by a talus slope. A perched water table is present within the cliffs. Drainage from cliff top is directed through a network of pipes to the shoreline, but the talus remains marshy. The north portal of Phillot's Tunnel is mantled with thick debris that has seepage and is unstable. The sandstone cliff face is affected by honeycomb weathering. Joint-controlled rock falls are evident.
Clerk's Tunnel to Phillot's South Portal	CBU 21	Rock fall	Steep cliffs with talus slope at the base.
Clerk's Tunnel South Portal	CBU 20	Rock fall	Steep cliffs adjacent to and above tunnel portal. Joint-controlled rock falls.
Smugglers' Inn Stream	CBU 19	Rock fall	Steep rock face with overhangs and benches that is bisected by the Smugglers' Inn stream.
East Down Cliff	CBU 18	Rock fall	Near-vertical cliffs cut when railway line was constructed. Spalling and jointing evident within rock face. Joint-controlled rock falls.
Rock fall Shelter Portal	CBU 17	Rock fall	Steep rock faces with overhangs. Rock falls and spalling dominate.

Table 6-6: Cliff failure mechanisms (Section 3)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
Parson's Tunnel Rock fall Shelter	CBU 16	Rock fall	Steep (c. 40°), reprofiled cliff. Joint-controlled rock falls and shallow spalling dominate.

6.6 Parson's Tunnel to Teignmouth

6.6.1 Geology

The geology of this frontage is predominately undifferentiated Alphington and Heavitree Breccia Formations - breccia. Within some CBUs (as denoted in Table 6-7), sub-vertical joints have been observed in the field. The locations of each CBU are shown in Figures 6-16 to 6-18.

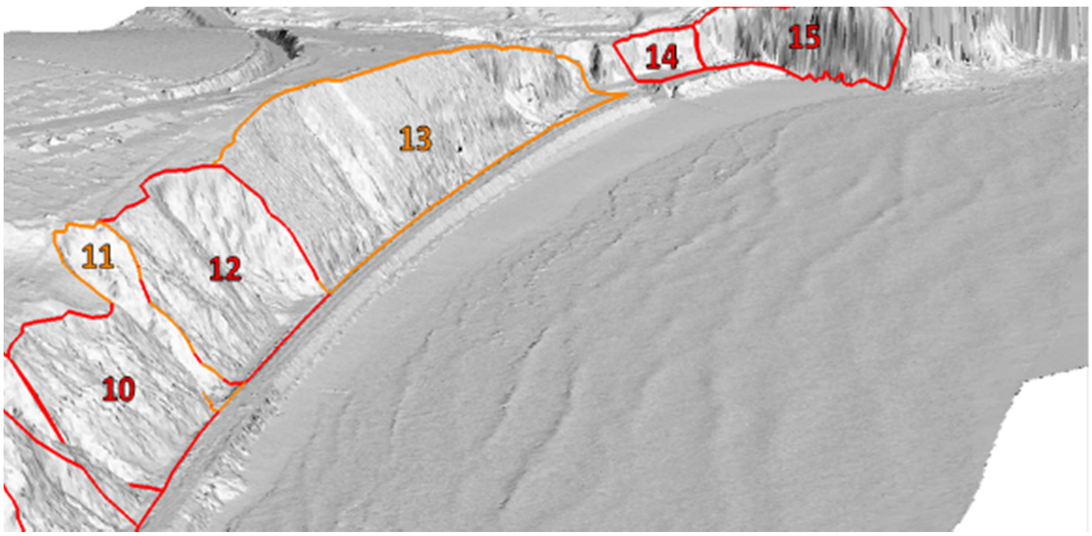

Figure 6-10: Section 4 - CBU 15 to 10

Note: gaps are tunnel sections or where there are no cliffs adjacent to the line

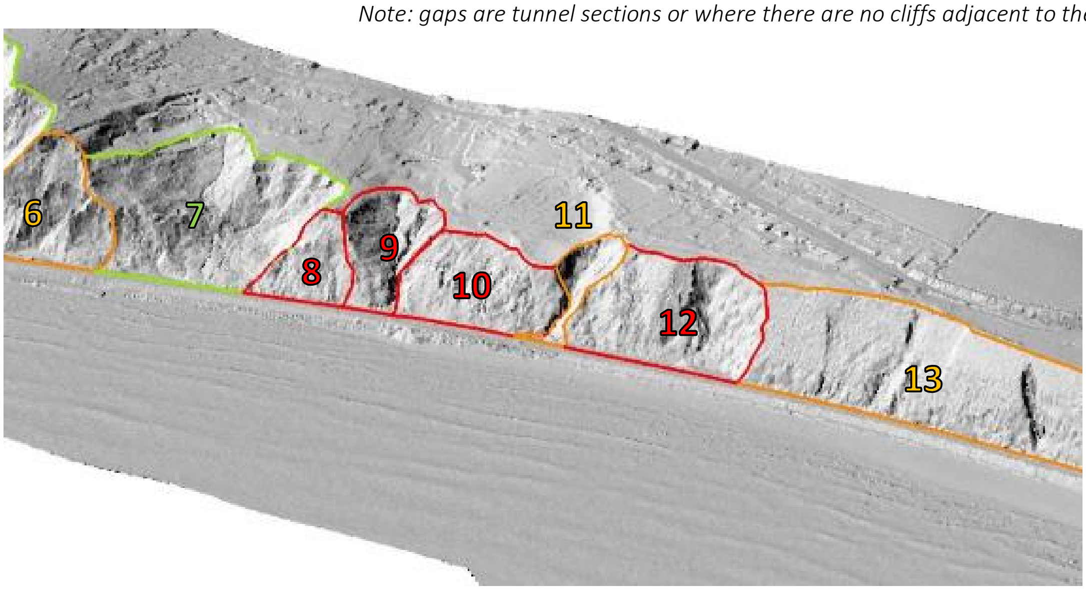

Figure 6-11: Section 4 - CBU 13 to 6

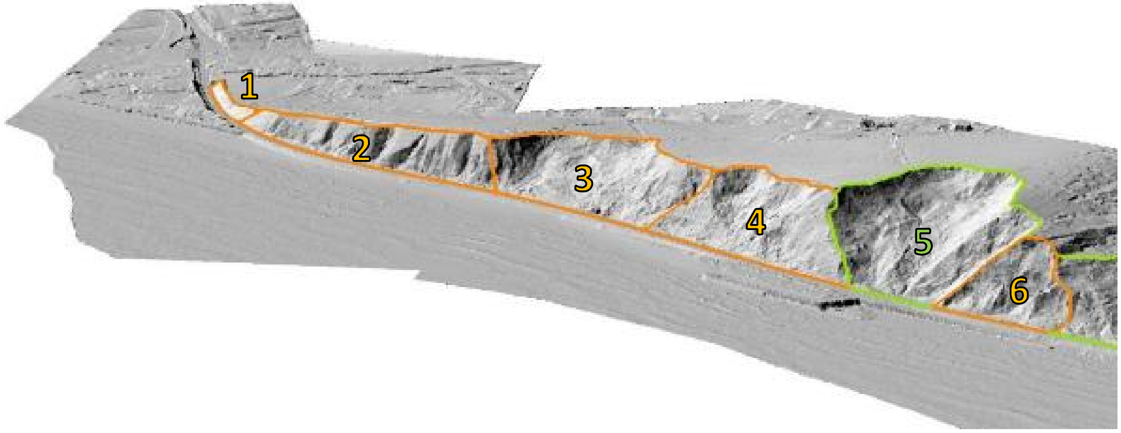

Figure 6-12: Section 4 - CUB 6 to 1

Note: gaps are tunnel sections or where there are no cliffs adjacent to the line

Table 6-7: CBU summary (Section 4)

Name	CBU No.	Geological Description
Parson's Tunnel – Southwest Portal	CBU 15	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Slope wash ('Head') mantles the cliff top.
Smugglers' Lane Compound	CBU 14	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Overlain by slope wash ("Head") and Alluvium in the valley of the Holcombe Stream that flows down Smugglers' Lane.
Smugglers' Lane	CBU 13	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Slope wash ("Head") and Alluvium towards the valley of the Holcombe Stream that flows down Smugglers' Lane.
Windjammer Track	CBU 12	Undifferentiated Alphington & Heavitree Breccia Formations – breccia.
Windjammer	CBU 11	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. BGS mapping shows a fault obliquely dissects the CBU.
Woodland Avenue	CBU 10	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Upper cliff formed in deeply-weathered breccia.
Bungalow Ravine	CBU 9	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Fault dissects this CBU.
Bungalow Headland	CBU 8	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Sub-vertical joints observed in field.
Footpath Hollow	CBU 7	Undifferentiated Alphington & Heavitree Breccia Formations – breccia.
Pine Close	CBU 6	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Sub-vertical joints and faults observed in field and recorded on geological maps.
Cliff Road	CBU 5	Undifferentiated Alphington & Heavitree Breccia Formations – breccia.
Sprey Point	CBU 4	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Sub-vertical joints and faults observed in field and recorded on geological maps.
Dingley Dell	CBU 3	Undifferentiated Alphington & Heavitree Breccia Formations – breccia.
East Cliff Walk	CBU 2	Undifferentiated Alphington & Heavitree Breccia Formations – breccia. Sub-vertical joints and faults observed in field and recorded on geological maps.

Slocums Bridge	CBU 1	Undifferentiated Alphington & Heavitree Breccia Formations - breccia. Sub-vertical joints and faults observed in field and recorded on geological maps.

6.6.2 Cliff failure mechanisms

In the west, cliff failure mechanisms are predominately rock falls with shallow debris flows forming secondary mechanisms of failure. Other failure mechanisms include debris flows and debris slides, particularly where groundwater is an important control within the CBU. The failure mechanisms are summarised in Table 6-8.

Table 6-8: Cliff failure mechanisms (Section 4)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
Parson's Tunnel Southwest portal	CBU 15	Rock fall	Cliff face formed by northwest-southeast trending joint and forms the side of Hole Head. Other joints form rock falls. Superficial sediments are prone to spalling. The upper cliff includes several large, shallow-rooted trees.
Smugglers' Lane Compound	CBU 14	Rock fall	The cliff is set back from the railway and has probably not been cut back or regraded. It is sub-vertical, with weathered beds and thick vegetation. Small joint-controlled rock falls occur that place the engineering compound at risk. Surface spalling evident, and small falls from the overlying terrace gravels.
Smugglers' Lane	CBU 13	Rock fall, washout	Regraded c. 45° slope bisected with a series of small joint-controlled gullies. The cliff cuts across the valley of the small south-eastwards-flowing Holcombe Stream. Joint-controlled rock falls occur in the cliff and are particularly evident towards the river valley where the cliff is cut in alluvium and slope wash materials as well as breccia. Breccia is particularly weathered in this location and no bedding can be seen.
Windjammer Track	CBU 12	Deep slide, washout	The cliff can be subdivided into a south-western section with a steep, regraded cliff subject to small joint-controlled rock falls, and a north-eastern section with a small washout embayment and with debris fan that is subject to periodic washouts/debris flows.
Windjammer	CBU 11	Washout (high sediment load)	Deep incised washout gully/mudslide system with well-defined embayed sediment source, narrow transport route and broad debris fan. Ongoing seepage at the top of the cliff, despite drainage measures. Potential for further debris washouts.
Woodland Avenue	CBU 10	Deep-seated failure (upper cliff)	The present cliff morphology is largely a result of slope regrading following the March 2014 landslide; however, two general morphological units can be observed. The upper and lower cliffs are separated by a shallow angle bench that slopes at c. 20° towards the northeast (broadly coincident with the geological dip). Below this bench, the lower cliff has been regraded to a uniform c. 40° slope, but the cliff toe is mantled by a series of small debris lobes. The upper cliff is a marginally shallower angle uniformly regraded slope. The BGS map shows the CBU is bisected by a fault that is normal to the coastline, but this is not evident in the field. The cliff has been interpreted as a composite landslide, with a bedding-controlled translational failure in the upper part and rock mass failure/rock fall in the lower part. The associations of the two systems are unclear. A high level of antecedent rainfall is thought to have triggered the failure. Other causes, such as the influence of geology, remain unclear.
Bungalow Ravine	CBU 9	Washout, debris flows	CBU is a deeply incised gully at the margin on the Woodland Avenue landslide (CBU 10). The upper part of the gully is a concrete

Table 6-8: Cliff failure mechanisms (Section 4)

Name	CBU No.	Process	Cliff Morphology, Mechanics and Dominant Processes
		(high sediment load)	channel, but drainage in the lower section is unconstrained by engineering. Washout/debris flows occur as a result of high discharges entraining weathered breccia debris in the gully.
Bungalow Headland	CBU 8	Rock fall	CBU is a regraded rock headland between two washout embayments. Sub-vertical lower cliff with lower angle, regraded upper cliff. Small joint-controlled rock falls in the lower sandstone cliff and small falls from the overlying terrace gravels.
Footpath Hollow	CBU 7	Washout	The CBU comprises two coalescing washout embayments with head scarps that are set back by up to 130m from the railway line. The north-eastern embayment closely follows the alignment of a fault. The lower slopes are relatively shallow (<30°) and mantled with debris that has been subject to small debris slides. The upper slopes are steeper at around 40° and exposed faces are subject to surficial rilling from surface water flows. Seepage was observed along joints.
Pine Close	CBU 6	Rock fall	CBU is a regraded rock headland between two washout embayments. The lower cliff is sub-vertical, entirely netted, and generally free of vegetation and marked by steeply-angled bench formed by jointing. The upper cliff is thickly vegetated, un-netted and has been regraded to c. 45°. Small joint-controlled rock falls are seen in in the lower cliff.
Cliff Road	CBU 5	Washout	The CBU comprises two coalescing washout embayments with head scarps that are set back by up to 180m from the railway line. Both embayments closely following the alignment of faults. The slopes are relatively shallow (<45°), thickly wooded and mantled with debris. No seepage was observed to the railway, but the lower slopes are marshy and include damp-loving vegetation. Head scarps and flanking cliffs are among the highest seen at c. 80 mOD.
Sprey Point	CBU 4	Washout and rock fall	Sub-vertical lower cliff with regraded upper cliff at c. 45° and lower section at c. 70°. Talus slope comprising a series of superimposed debris lobes at c. 40° mantles cliff toe. Much of this material is sourced from a joint-controlled washout in the south-western half of the CBU. Small joint-controlled rock falls from the lower cliff. The cliffs are among the highest seen at c.78 mOD.
Dingley Dell	CBU 3	Debris flow	Thickly wooded embayment set back up to 120m from the railway formed by past debris flows/ sediment washouts that is flanked by cliffs. Lower cliff of embayment is a shallower angle slope (<30°) made from several debris lobes. The upper slope has been locally regraded to permit construction of a property. The flanking cliffs have been regraded to c. 45°.
East Cliff Walk	CBU 2	Rock fall, washout	Sub-vertical lower cliff with regraded upper cliff at c. 45°. Vegetated talus slope at c. 40° mantles the cliff toe. The cliff is characterised by alternating joint or fault-controlled gullies that are prone to washout and flat-faced buttresses that are prone to joint-controlled rock falls.
Slocums Bridge	CBU 1	Rock fall	Sub-vertical lower cliff with regraded upper cliff at c. 45° all cut in breccia beds. Largely vegetated talus slope at c. 40° mantles the toe of the cliff. Small joint-controlled rock falls occur in the lower sandstone cliff.

6.6.3 Hydrogeological study

To support the above characterisation, CH2M undertook a hydrogeological study to identify and characterise the influence of surface water drainage and groundwater on cliff instability and behaviour of the Teignmouth cliffs between Parson's Tunnel and Sprey Point. The study developed a conceptual model of the groundwater and surface water flows and placed particular focus on:

- Regional groundwater characteristics and flow
- Hydrological characteristics including response to long term and short term (storm) rainfall events
- Surface water drainage networks, including highway and other surface drainage, the foul drainage network and other potential inputs to the local water regime
- The nature (location, type, function) of NR drainage

The hydrological and hydrogeological conceptual model sets out an understanding of the broad characteristics of the water regime and how this may influence the behaviour of both surface water and groundwater, and thus, in particular, the stability of the cliffs in the study area. This understanding is summarised in Figure 6-19.

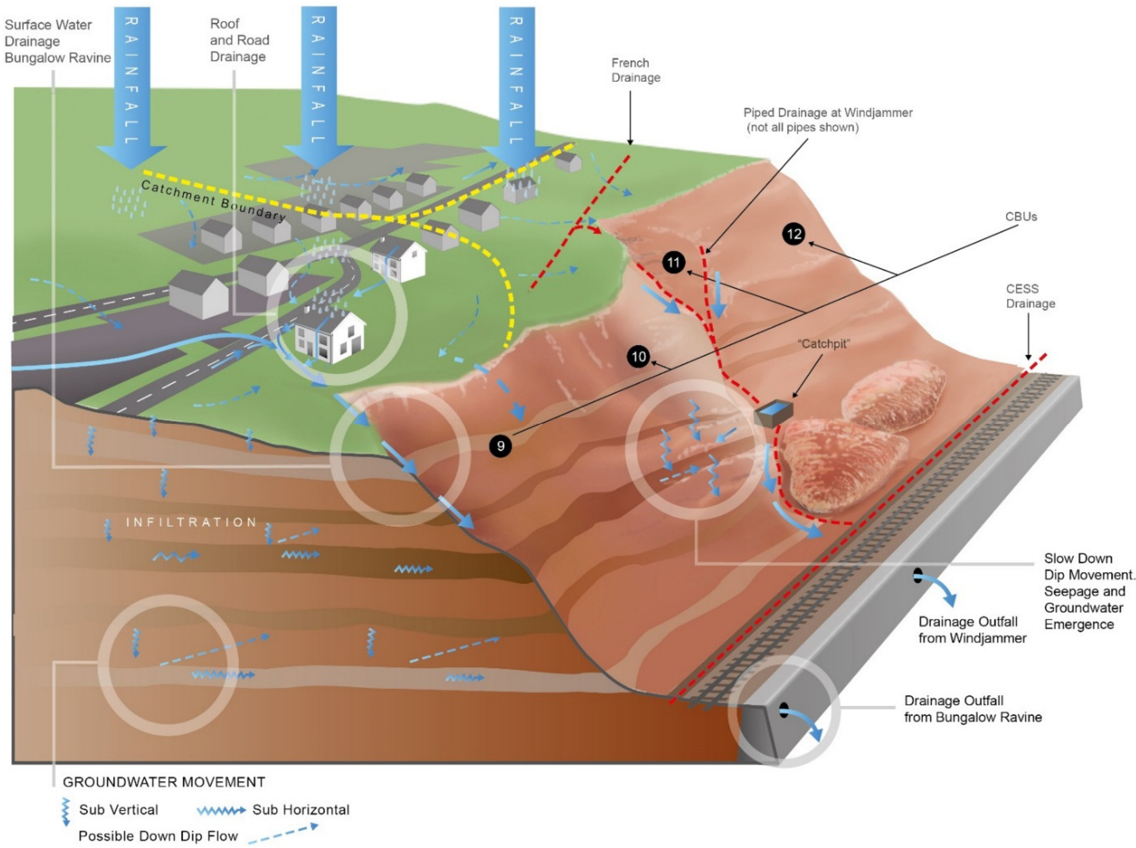

Figure 6-19. Schematic Conceptual model

Based on the conceptual model, it is concluded that in the lower parts of the cliffs, where the rock matrix is more competent (albeit quite clayey) and bedding is better defined, groundwater flow is dominantly via secondary features such as vertical and horizontal fractures and fissures, jointing and bedding planes. These lower beds produce regional flow of groundwater drawing from a catchment area beyond the immediate surface water catchment and appear to respond more directly to rainfall events due to better connectivity of the fissure flow systems.

Recharge may also occur from the upper aquifer layers directly above, as well as from a wider more remote (albeit not large) groundwater catchment. In this case, the lower fissure system aquifer will drain the overlying more weathered strata.

A possible mechanism of groundwater recharge and movement is proposed as follows:

- In response to rainfall, there is a slow downward flow through the weathered matrix in the top third of the cliffs. In this case, the flow is greater than the bypass (rapid or fissure) flow in the upper aquifer.
- More sustained rainfall leads to super saturation of soil layers, this in turn leads to bypass flow (in the upper aquifer layers) and sub-horizontal interflow during more extreme events. In this case bypass flow becomes a more important mechanism than matrix flow.

The change from predominantly matrix flow to predominantly bypass flow may be accompanied by significant changes in local groundwater pressures in the upper aquifer. Furthermore, in this situation (i.e. (ii) above) there might be expected to be more groundwater flux through the lower aquifer (possibly from recharge not directly associated with the local surface water catchment) and the lower aquifer would have no capacity to drain the upper aquifer. Groundwater pressure may be expected to increase as a result.

Whilst this is speculative, it is considered possible that the onset of bypass flow mechanisms could be related to increased incidence of cliff failure and landslides.

It is also conceivable to consider that where the lower parts of the aquifer are more open and allow better drainage of the upper aquifer, the onset of bypass flow (in the upper aquifer) will lead to a slower and more controlled build-up of groundwater pressures, perhaps less liable to trigger a failure.

Additional groundwater monitoring throughout the cliffs (i.e. in both high hazard and lower hazard CBUs) will be needed to establish the credibility of this hypothesis which can only be substantiated if there are further cliff falls.

Further discussion of the data and conclusions can be read in Appendix H.

Rail assets

7.1 Introduction

The following sections describe the various rail assets that are situated in the study area which support the current and future rail operations. The sections are divided into asset categories that coincide with the Route Asset Manager remit, describing each group of asset types in turn.

7.1.1 Regional setting

In considering the rail assets, the study area has been agreed to be between the following points:

- Exeter (city side of the “up” abutment of the River Exe bridge) 194 miles 0116yds (194.0116)
- Newton Abbot (“down” abutment of the River Teign bridge) 213 miles 1406yds (213.1406)

The logic for adopting these limits, which exclude both Exeter St David’s and Newton Abbot stations, is that outside these two points on the line the risk of flooding is low on the assumption that the EA’s Phase 2 Flood Protection proposals for Exeter is implemented.

This section of the MLN1 line is within the Strategic Route Section (SRS) between Exeter and Plymouth, which is identified as “band 3” criticality (discussed in more detail below).

Within the Great Western Rail Utilisation Strategy (RUS) scope area there are a significant number of major, high-profile, high-investment enhancement schemes planned or proposed during Control Period 4 (CP4) which continue into the current control period CP5 (from 2014 to 2019). These major enhancement schemes include:

- Electrification of the Great Western Main Line;
- Intercity Express Programme (IEP);
- European Rail Traffic Management System (ERTMS);
- Reading Station Area Redevelopment and Crossrail.

Although predominantly associated with the Thames Valley area, some of these schemes will impact on the Exeter- Plymouth section.

7.1.2 Strategic Route Section (SRS)

An SRS is a section of the network having broadly homogeneous traffic levels and infrastructure type. It is therefore the appropriate level of segmentation for track asset policy decisions. SRSs vary in length, averaging 100 track kilometres; there are 39 SRSs in the Western Region, of which Exeter to Plymouth is one.

Route criticality is a measure of the consequence of the infrastructure failing to perform its intended function. This consequence may be felt in a number of ways; for this work, criticality has been assigned on the basis of the impact of an infrastructure fault on safety and train performance.

Different criteria were considered for setting the dividing lines between the five criticality bands. The criteria chosen are set relative to the national average cost per train delay incident caused by the track assets, as indicated in Table 7-1. As mentioned above, Exeter-Plymouth SRS (K.02) is rated as band 3.

Table 7-1: Strategic Route Section (SRS) criticality bands

Band	Definition
Band 1	SRS with costs per incident more than two times the mean

Band 2	SRS with costs per incident between the mean and two times the mean
Band 3	SRS with costs per incident between the mean and half the mean
Band 4	SRS with costs per incident between half the mean and one quarter the mean
Band 5	SRS with costs per incident less than one quarter the mean

7.2 Asset data sources

7.2.1 Introduction

NR stores asset data in a variety of systems, using a variety of formats, reference numbers and locational data. A key source of "asset inventory" has been Ellipse but this does not typically store the age or condition of the asset.

7.2.2 Data sources

The data from the following sources have been used**:**

- **Ellipse** – used for the planning and recording of works management within the Infrastructure Maintenance function
- **Geogis** – Geography and Infrastructure System providing information on the type and age of the track assets
- **Structures Dashboard** – providing a summary of a variety of 7 different IT databases used for storing data on Structures assets; Databases include BCMI, CARRS, CMS, Geogis, HCE, Scour and Vera.
- **Network Rail Examinations** –an externally hosted GIS based system storing Earthworks Examination records.

A key source of asset degradation information and approach to maintenance is provided in the relevant asset policy. Table 7-2 indicates the documents received.

Table 7-2: List of asset policies

Asset Group	Asset Policy – Document Title	Pub Date
Track	Track Asset Policy Dec 2012 Final	December 2012 v1
Earthworks	CP5 Earthworks Asset Policy	August 2014
Buildings	NR CP5 Buildings Asset Policy for IIP	Sept 2011
	RAM Guidance on Asset Management Buildings Policy Level 2	
	Guidance on Asset Management Policy (Buildings) (Level 3)	Nov 2011
Drainage	NR CP5 Drainage Asset Policy	Sept 2011
Structures	BCAM-TP-0165 Structures Asset Policy	July 2014 v1.1
Signals	NR CP5 Signalling Asset Policy	Sept 2011 v1.0
Telecoms	SBPT3014 Telecoms Asset Policy	Dec 2012 Issue 4
Off Track	*(Vegetation management Process) Outstanding*	
E&P	*Outstanding*	
Level Crossings	LX CP5 Policy	Nov 21012 v2

7.2.3 Data accuracy

Any further analysis conducted by CH2M on the data provided by NR is dependent on the accuracy and completeness of the data provided. It is not possible to verify or check the data provided as part of this exercise, although where conflicts in data from different sources have been identified, attempts have been made to resolve them.

7.3 Asset inventory

The full Asset Inventory can be seen in Appendix I; a summary of the data is included below in Table 7-3.

Table 7-3: Asset inventory index

Asset Group		Section	Source
Track		Section 7.3.1	GEOGIS
Switches & Crossings		Appendix I – Table I-4	Ellipse
Signalling		Appendix I – Table I-5	Milton Keynes
Telecoms		Appendix I – Table I-6	Ellipse
Electrical & Power (E&P)		Appendix I – Table I-7	FORM A schematics for CP5 650V Cable Renewal project
Level Crossing		Appendix I – Table I-8	
Buildings		Appendix I – Table I-9, H-10, H-11, H-12	% Remaining Life and Element Intervention
Structures	Bridges	Appendix I – Table I-13	
	Tunnels	Appendix I – Table I-14	
	Retaining Walls	Appendix I – Table I-15	
	Ancillary Structure	Appendix I – Table I-16	
Earthworks		Appendix I – Table I-17	
Drainage		Appendix I – Table I-18	
Off Track		Appendix I – Table I-19	

7.3.1 Track – rail, sleeper & ballast

7.3.1.1 Rail – age profile

Using the Geogis database the age profile of the rail assets has been reviewed. Figure 7-1 below indicates the wide range of ages and the "peaks & troughs" of track renewal over past 55-60 years. However, the age of the asset is not always a measure of the "useful life", particularly where the "usage" varies over time.

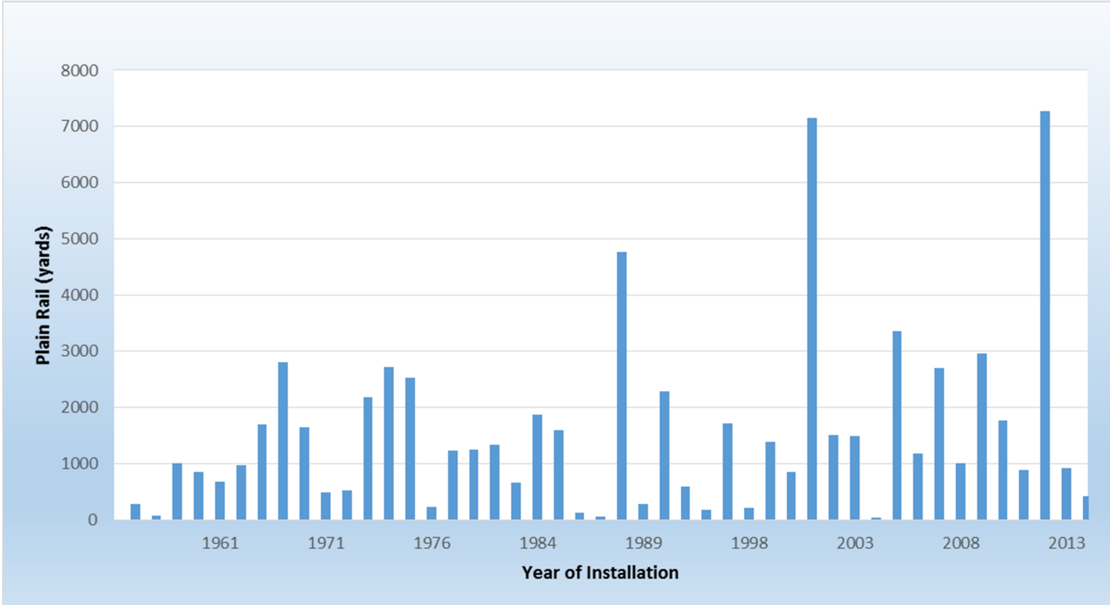

Figure 7-1: Age profile for the up and down mainline

7.3.1.2 Rail condition – percentage used life

A more useful measure, in terms of asset management, is "accumulated used life" – this measure represents a combination of the following factors:

- Rail type and specification
- Rail category (determines speed and tonnage allowed)
- Equivalent Gross tonnes (EGT) – accumulative measure of usage

NR has developed an algorithm (Hind, 2013) which calculates the "accumulated used life" for each asset, the results being listed against each section of track within Geogis. Analysis of "used life" data from Geogis indicates that around 54% of rail asset have 60% "accumulated used life" to date. More significantly 17% rail, 18% of sleepers have an "accumulated used life" percentage > 100%, some factors as high as 250% i.e. some assets are more than double their useful life, taking into account actual usage in EGT.

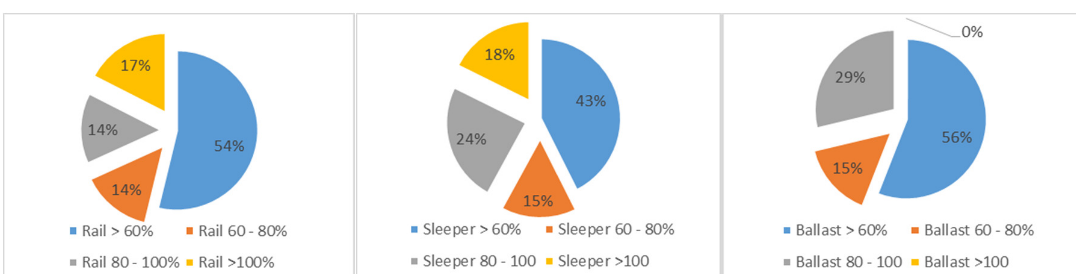

Figure 7-2: Rail assets - used life analysis

7.3.1.3 Materials of construction

Table I-5 (Appendix I) indicates the range of materials for each asset type. As the previous section described the range of age profile for all of these types of assets, so consequently there is a range of specifications and materials across this portfolio.

7.3.2 Switches and crossings (S&C)

The Ellipse data base appears to shows 28 "half sets" of each "hand" whereas the GEOGIS data indicate a total of 23. These are shown in Table I-4 (Appendix I).

7.3.3 Signalling

Data on signalling assets have been extracted from Ellipse download and filtered by age and replacement date (see Appendix I, Table I-7). There are over 700 signalling assets; generally these have been installed since 1987 and are due for replacement in 2026.

7.3.4 Telecoms

Data on Telecoms Assets have been extracted from Ellipse download. There are 307 assets between the agreed limits. To date there is no further information; the assets are listed in Table I-8.

7.3.5 Electrical and power (E&P)

A limited number of "E&P" assets are listed in the Ellipse download. To date there is no further information. All the "new" assets listed in Appendix I (Table I-9) are detailed in FORM A schematics for the CP5 650V Cable Renewal project, planned date of installation remains unconfirmed. A full list of existing assets, with age and condition, was not provided.

7.3.6 Level crossings

There are 12 minor level crossing assets which provide pedestrian access across the railway to the foreshore in the Exe Estuary. These assets are listed in Table I-10.

7.3.7 Buildings

NR has provided asset data on various building assets associated with the various stations (Table 7-4). Due to later clarification, the assets within Exeter St. David's and Newton Abbot Stations are not considered within this study. The Buildings RAM also covers Line Side Buildings of which there are six buildings within the study limits (see Table I-12).

Table 7-4: Building assets

Station	Building Assets						
	Access Route	Building	Canopy	Footbridge	Curtilage	Platform	Waiting Room
Dawlish	2	3	3	1	1	2	-
Dawlish Warren	3	1	1	-	1	2	2
Exeter St Thomas	3	1	-	-	2	-	2
Teignmouth	2	3	3	1	-	2	-
Starcross	2	2	2	1	-	2	2

The interventions planned for each building element can be seen in Appendix I (Table I-11). Of note are the multiple "sub components" for each building score in the above table. The detailed % used life would be required for each element in order to produce a detailed lifecycle model.

7.3.8 Structures

7.3.8.1 Bridges

Based on the analysis of information extracted from the CARRS database, the numbers of bridge assets are as summarised in Table I-13 (Appendix I). A number of those in the database download are responsibility of a third party, typically either the Highways Agency or Devon County Council, a number have been removed or infilled and a number of the culvert structures are registered as being "unlocated" and it is not apparent whether these are present or not. Those bridges identified as being removed are not shown, but all others are, including those owned/maintained by an outside party.

Structures Condition Marking Index (and BCMI) scores along with the Route Availability rating (RA) are available for a number of the assets, but not all. Currently no information has been received on the Primary Load Bearing Element rating for each structure. Sizing information, which will dictate maintenance and renewal costs, is only available from the inspection reports and therefore is limited to those assets with such a report (29% of bridge assets do not have an inspection report).

It should also be noted that three of the footbridges listed are within the confines of stations, and so are also covered by the Buildings RAM. The culverts, associated with watercourses, are also covered under the Drainage RAM.

7.3.8.2 Tunnels

There are 5 tunnels along the line of the route; Kennaway Tunnel, Coryton Tunnel, Phillot Tunnel, Clerk Tunnel and Parson's Tunnel. From the asset management viewpoint, each tunnel is sub-divided into the tunnel bore plus an east and west portal. In addition, Parson's Tunnel also incorporates a tunnel component described as "External elements of extension" which is a protection wall. The lengths of the tunnels are as given in Table I-14 (Appendix I). Tunnel Condition Marking Index (TCMI) scores and size information are contained within the inspection reports where available.

7.3.8.3 Retaining walls

There are a total of 156 retaining walls listed in CARRS, subdivided into the categories of Catch Wall, Coastal/Estuarine/River defences, Gabion Wall and general Retaining Walls, as summarised in Table I-15 (Appendix I).

In addition to the above there are a further 10 walls classified as being "duplicates" in CARRS, although with no apparent duplicate entry. Furthermore a total of 170 wall inspection reports have been provided, with no obvious duplicates. As a result the total number of wall assets is unclear.

Condition and size data is only available from the inspection reports and therefore is limited to those with assets with such a report.

It should be noted that the assets listed as Coastal/Estuarine/River Defences are considered further in Section 5.

7.3.8.4 Ancillary structures

After removing duplicate structure records and those stated as having been removed, the number and type of ancillary structures on the line can be summarised; see Table I-16 (in Appendix I). No information of their condition, age or size has been made available, nor has any information on their construction/materials although it has been assumed that they are all likely to be galvanised steel, and possibly also painted if within the confines of a station. Although each of the ancillary structures are listed within the CARRS system, it is noted that all are owned by other RAMs, primarily Telecoms and Signalling.

7.3.9 Earthworks

NR Earthwork assets comprise cuttings, embankments and natural slopes lying within the NR boundary meeting the following criteria:

- Earthworks equal to or greater than 3m in height, including earthworks lying above a retaining wall where the earthwork component is greater than or equal to 3m in height
- Earthworks less than 3m in height whose failure could pose an unacceptable risk to network safety or performance
- Any embankment that acts as a coastal, estuarine or river defence, irrespective of height

- All earthworks which lie above a tunnel portal
- Approach embankments to overline bridges with a height equal to or in excess of 3m (unless owned by another competent body)
- Nailed or reinforced soil structures with a face angle <70deg from the horizontal

The following items are not considered to be Earthwork assets:

- Track formation, ballast, blanketing and geosynthetics that form an integral track part of the track support system
- Level ground or areas with earthworks of less than 3m in height (subject to the exceptions listed above)

In addition to the above NR also examines 3rd party earthworks of any height whose failure could pose an unacceptable risk to the network safety or performance.

It is both logical and NR convention to consider earthwork assets on the up and down side of the line individually, with the two sides being separated by an imaginary line running down the centre of the track(s). NR procedures also sub-divide the assets into the following categories:

- Earthwork Asset – A segment of earthwork (soil cutting, rock cutting or embankment) up to 5 chains in length on one side of the railway
- Earthwork inspection 5 chain – A 5 chain length of the network on one side of the railway that contains one or more Earthwork Assets of similar or different earthwork type.
- Whole Earthwork – The full unsegmented length of an earthwork of given construction type on one side of the railway, composed of one or more adjacent Earthwork Assets.

With the above conventions and protocols in mind and based on the information provided from the NR Earthworks Examination Database, the Earthworks Assets along the Exeter to Newton Abbot line have been recorded and sub-divided into condition (see Table I-17, Appendix I). It should be noted that some of the assets indicated are considered in more detail in Section 6. 25% of the earthwork assets are missing inspection reports.

7.3.10 Drainage

The Ellipse database downloads subdivided drainage assets into two main disciplines (CE and OT) and it was suspected that those with the CE classification are for those assets adjacent to or under the lines, whilst those marked OT are remote and potentially fall under the remit of the Off-track RAM. The more recent IDP data (see Table I-18, Appendix I) which, at the time of provision, had not been converted and imported into Ellipse, also classified each drainage asset in a similar fashion. In total the IDP survey indicates just over some 14.3 linear km of drainage being present (e.g. culverts, ditches and pipes) and 206 nodes (e.g. catchpits, headwalls and the like).

Whilst the old Ellipse data did not contain any condition data on any of the assets, the IDP data does for the majority of the assets. As appropriate to the asset type and taking into account the general scope of the inspection programme, assets were provided with some combination of structural condition rating, vegetation condition rating and a status rating. Due to the differing combinations of rating provided across the different asset types, detailed analysis of the whole drainage asset is not possible. Information on the location, purpose of all asset types was provided, as was limited sizing information, as relevant to the particular asset type.

In considering the data contained within the IDP survey, the potential overlap with some of the assets listed under the Structures (i.e. culverts) and Off-track section needs to be acknowledged.

7.3.11 Off-track

Off track assets comprise the following asset types: vegetation, fencing (boundary etc) and drainage.

Of the above asset types, drainage has been covered within Section 7.3.10. For the remaining categories, the assets that are listed within the Ellipse database download are summarised in Table I-19, Appendix I. No condition, age or size information was provided.

7.4 Asset vulnerability to climate change factors

The vulnerability of the key rail asset groups to the climate change factors discussed in Section 3 of this report is summarised in Tables 7-5 and 7-6 below.

Table 7-5: Climate change factors and supporting evidence

Climate Change Factor	Evidence	Priority	Result
Rainfall and River Flows	2050 Mid: Change Factor: +20% 2050 High: Upper End Estimate: +40% 2100 Mid: Change Factor: +30% 2100 High: Upper End Estimate: +75 %	High	Predicted Days Above Max
Flooding - Storm Surge (sea water)	2020s, +20cm 2050s, +35cm 2080s, +70cm	High	Predicted Frequency of Extreme
Wind	There is significant uncertainty over the impacts of climate change on wind and wave climates, particularly for extremes. In the absence of other guidance, it is recommended that a 10% increase in extreme wind speeds is considered for the 'high' climate scenario in order to understand the potential vulnerability of the system to changes in wind speed and wave height.	High	Predicted No Days above max
Earthslips	21-25% increase in February mean daily precipitation	High	Predicted Frequency of Extreme
Heat	2050 Mid: Medium Emissions, 50% Median: +2.7 ºC 2050 High: High Emissions, 90% non-exceedance: +5.1 ºC 2100 Mid: Medium Emissions, 50% Median: +3.9 ºC 2100 High: High Emissions, 90% non-exceedance: +7.9 ºC	Medium	No of days > max temperature
Adhesion	Complex relationship between adhesion issues and future climate change.	Medium	Predicted Days of Speed restriction
Sea level rise	2050 Mid: Medium Emissions, 50%: +14.5cm 2050 High: Upper End Estimate: +20.8cm 2100 Mid: Medium Emissions, 50%: +40.8cm 2100 High: Upper End Estimate: +81.2cm	Medium	

Table 7-6: Impact of climate change factors on key asset types

Asset Type	Climate Change Factors						
	Rainfall and River Flows	Flooding - Storm Surge (sea water)	Wind	Earthslips	Heat	Adhesion	Sea level rise
P-Way	Minor Impact	Severe Impact	No impact	Severe Impact	Severe Impact	Moderate Impact	Moderate Impact
Ballast / Track Bed	Minor Impact	Severe Impact	No impact	Severe Impact	Limited impact	Limited impact	Moderate Impact
S&C	Moderate Impact	Severe Impact	No impact	Severe Impact	Severe Impact	No impact	Minor Impact
Location Box	Moderate Impact	Severe Impact	No impact	Severe Impact	Severe Impact	No impact	Minor Impact
Cabling	Moderate Impact	Severe Impact	No impact	Severe Impact	Moderate Impact	No impact	Minor Impact
Bridge	Minor Impact	Severe Impact	Minor Impact	Severe Impact	No impact	No impact	Minor Impact
Tunnel	Minor Impact	Severe Impact	No impact	Severe Impact	No impact	No impact	Minor Impact
Embankment / Cutting	Moderate Impact	Severe Impact	No impact	Severe Impact	No impact	No impact	Moderate Impact
Walls	Moderate Impact	Severe Impact	No impact	Severe Impact	No impact	No impact	Moderate Impact
Culvert	Moderate Impact	Severe Impact	No impact	Severe Impact	No impact	No impact	Moderate Impact
Ancillary	Moderate Impact	Severe Impact	Minor Impact	Severe Impact	No impact	No impact	Minor Impact
Track	Minor Impact	Severe Impact	No impact	Moderate Impact	No impact	No impact	Moderate Impact
Off Track	Minor Impact	Severe Impact	No impact	Moderate Impact	No impact	No impact	Moderate Impact
Station	Minor Impact	Severe Impact	Moderate Impact	Severe Impact	Moderate Impact	No impact	Moderate Impact
Car Parks	Minor Impact	Severe Impact	Moderate Impact	Severe Impact	Moderate Impact	No impact	Moderate Impact
Switch Rooms	Minor Impact	Severe Impact	Moderate Impact	Severe Impact	Moderate Impact	No impact	Minor Impact
Cabling	Minor Impact	Severe Impact	Moderate Impact	Severe Impact	Moderate Impact	No impact	Minor Impact

Resilience and operational requirements

The purpose of this Section is to set out CH2M's understanding of NR's key performance and operational expectations for the Western Route. It is vital that these expectations are now agreed to ensure that an appropriate resilient adaptation strategy is defined.

8.1 Resilience

There are two key facets to resilience in the context of the Exeter to Newton Abbot mainline: (1) adaptability and versatility of the assets with regards to future operational requirements; and (2) resilience against environmental events including flooding, cliff failures and wave overtopping.

In the context of this study, the vulnerability of the Exeter to Newton Abbot section of the Western Route to closures being limited to 48 hours was put forward as an aspiration by NR. This along with the subsequent suggestion that as far as possible sea views from carriages should be maintained helped limit the options to be considered.

The versatility of the line to adapt to potential future changes in traffic frequency and make-up can be best addressed by the rail asset options. The aspirational resilience of the Western Route will be addressed by the adoption of a combination of cliff stabilisation measures and rail asset and coastal defence options.

8.2 Operational requirements

8.2.1 Current operational requirements

The Extreme Weather Protocol for the Dawlish Coast (Maddocks, 2010) describes the process by which forecasts of extreme weather, in particular combinations of high tide and high winds, will activate corrective action in NR. This is informed by a warning system based on weather forecasts provided by MetDesk at 0300 hours every day. This protocol consists of 3 levels which trigger different actions depending on the severity of the warning.

A key part of this protocol is to assess the severity of the sea conditions being predicted and determine the level of risk. The Protocol defines the actions to be taken and the key personnel to be contacted. The main group to be consulted is the Extreme Weather Action Team (EWAT). The EWAT telephone conference is held as soon as reasonably practical following the receipt of the warning and is chaired by the Route Control Manager. The factors in generating the severity of this warning are:

- Predicted wave action/surge effect on the sea wall
- Predicted wave periods/frequency – peaks and troughs affecting overtopping
- Predicted tide height exceeding laid down levels
- Predicted wind speed exceeding laid down limits
- Predicted wind direction being 'adverse'
- Atmospheric pressure

Each progressive Operating Level from 1 to 3 involves greater restriction on services and therefore results in greater disruption to passengers. Level 1 is triggered by winds greater than Force 5 approaching from the east or southeast on a very high tide or greater than Force 7 under any other tide level. Actions include a temporary speed restriction on the downline to 30 mph in daylight and 20 mph in poor visibility and/or darkness. Level 1 normally applies for 2 hours either side of high tide. Level 1 working can only be withdrawn after the downline has been inspected by members of the permanent way team.

The Level 2 protocol is prompted by winds exceeding Force 9 and stops all services running on the downline between Dawlish Warren and Teignmouth stations. Down services must run on the up (reversible) line instead. Level 2 working can be withdrawn with a temporary speed restriction after the downline has been inspected by members of the permanent way team. Full operation can be resumed after the sea wall has been inspected from beach level.

Level 3 operation refers to the full closure of the line with no services running in either direction on either the down or up lines. Following closure, a full inspection of both lines by permanent way staff is required before reopening. The restrictions following a Level 2 period also apply.

It is important to note that specific rolling stock are withdrawn during adverse weather. For example, the Class 220/221 “Voyager” units (operated by CrossCountry) are withdrawn prior to the commencement time of a Level 1 warning. Under the previous warning system (provided by Mouchel) NR was provided with a warning specific to the withdrawal of these services.

The Western Route WRCCA (NR, 2014) refers to “a review of the EWAT process and definitions of normal and extreme weather”. It has been suggested that the network-wide Future Weather Management and Intelligence-Led Decision Support System which is currently being developed may result in changes to the protocol. It is assumed that this will incorporate the review of the EWAT process described by the Western Route WRCCA (NR, 2014).

8.2.2 Future operational requirements

The project’s aim is to develop options that systematically increase the resilience of the rail system as a whole. To ensure a holistic system-wide approach, the resilience needs of operations and all asset groups will need to be integrated.

Although the Study would have benefitted from a greater understanding of where future operational aspirations for the Western Route lie, the project team has provided versatile solutions which allow for some adaption to take account of changing operational requirements and the uncertain outcomes of climate change predictions .

Economics

9.1 Introduction

Economic appraisal is designed as a means of assessing the benefit of investment to society versus the cost of that investment to Government. Government uses the results of this type of appraisal as part of its set of wider decision making criteria. Department for Transport (DfT) uses economic appraisal to inform rail investment decisions, and NR is typically required to produce an economic appraisal to support its submissions to DfT for funding of changes to the capability of the railway infrastructure.

The purpose of the economic appraisal of the coastal resilience strategy is to assist NR in the selection of a preferred coastal resilience strategy, and to enable NR to demonstrate to DfT and other Government departments the economic value of the investment required to support this strategy.

The appraisal will comply with DfT's WebTAG appraisal guidance as the eventual funder of the potential investment required as part of the eventual preferred Geo-Environmental Resilience strategy is likely to be the UK Government. WebTAG is DfT's interpretation of HM Treasury investment appraisal guidance, which covers all UK Government departments.

9.2 Structure of the strategy development process and the economic appraisal

This section explains how the evidence produced in the other work streams will be used to undertake the economic appraisal, to develop the various strategies for consideration, and to articulate the benefits and costs of the strategies. The approach will be structured in the following six stage process.

9.2.1 Stage 1 – Define disruption events

A categorisation of the severity of disruption events that could affect the railway between Exeter and Newton Abbot will be developed. The following are envisaged:

- **Extreme.** This is an event resulting in a closure of the railway between Exeter and Newton Abbot for a duration of at least a week. Examples of this type of event include the 2014 collapse of the sea wall at Dawlish, and the landslip at Woodlands Avenue, also in 2014. Events of this nature typically involve a closure of several weeks or months.
- **Severe.** This is an event resulting in a closure of the railway between Exeter and Newton Abbot for a duration of between 48 hours and one week. Examples of this type of event include an extensive track ballast wash out.
- **Moderate.** This is an event resulting in disruption to the railway of a severity up to the equivalent of a 48 hour closure. Examples of this include the imposition of temporary speed restrictions, single line working, and short duration closures to clear debris or repair small infrastructure faults such as track circuit failures. The data available on the historical number of this type of event is less comprehensive than for extreme and severe events. This is because the underlying cause of more moderate disruption is less clear. Based on anecdotal evidence the team's suspicion is that the number of moderate events attributed in the data to poor weather and the coastal environment underestimates the actual number of these occurrences.

9.2.2 Stage 2 – Define and estimate the frequency of disruption events

The frequency of disruptions events will be estimated on the basis of a "mid" range climate change scenario to 2065 and "high" range scenario to 2115. The rationale for this decision is to have a "likely as not" scenario for the first 50 years of the Resilience Strategy whilst exploring options to adapt to the more aggressive "high" scenario to 2115.

Section 3 of this baseline report provides a full description of the climate change scenarios considered.

9.2.3 Stage 3 – Define categories for level of resilience

Categories for the level of resilience to be provided by the various strategies will be defined. This will enable the development of one or more strategies designed to provide a given level of resilience, under varying climate change scenarios. This level of resilience relates to the whole of the route section between Exeter and Newton Abbot. We will work in partnership with NR to define these levels of resilience in a way which will enable credible investment choices to be presented for both NR and for Government. Initial analysis suggests that the available engineering solutions may limit the number of potential strategies to two.

Table 9-1 illustrates the team's view on the levels of resilience to be investigated.

Table 9-1: Example levels of route resilience

Disruption event	Level A	Level B
Moderate	Reduced probability, no target specified	No planned reduction, although some reduction possible
Severe	< once every 20 years	Reduced probability, no target specified
Extreme	< once every 100 years	< once every 100 years

9.2.4 Stage 4 – Define the baseline (do-minimum) scenario

The baseline (do-minimum) scenario is the situation that would be reasonably expected to occur in the absence of the interventions contained within the strategies presented in this report.

In the do-minimum scenario it will be assumed that additional funding to improve the resilience of the route is not provided and that assets continue to be maintained on a modern equivalent like-for-like basis.

9.2.5 Stage 5 – Produce alternative strategies

Options designed to deliver a given level of resilience as per the above categorisation will be produced. Each strategy will comprise of a number of pieces of infrastructure investment, and of differing schedules of asset management.

At present we are seeking to develop at least two strategies (A and B) corresponding to the level of resilience described in Table 9-1.

9.2.6 Stage 6 – Quantification of costs and benefits

The costs and benefits for the baseline scenario and the strategies considered will be quantified, in order to assess the value of each potential strategy, under each climate change scenario.

9.3 Economic appraisal summary

WebTAG states that projects requiring public investment should be assessed against a do-minimum case where this investment is assumed not to occur. The economic appraisal in this study will quantify the incremental costs and benefits of investment, beyond the level that Government has already committed to fund in the do-minimum (baseline) scenario. Table 9-2 describes the types of incremental impact that will be monetised in the economic appraisal.

This monetised appraisal will therefore consider the incremental impacts of each of the strategies developed, separately, against a base of the do-minimum scenario.

WebTAG states that the impacts of public investment should be monetised over an appraisal period which reflects the life of the new assets, suggesting a 60 year default appraisal period for major infrastructure.

The life of the main interventions contained within the strategies is broadly 100 years with a potential phasing of these interventions at intervals over the next 100 years. This means that there would be a significant residual asset value remaining after 60 years. Discussion with DfT sought to, amongst other things, determine the most appropriate appraisal period and treatment of residual asset value. As a consequence it is intended to undertake appraisal under three scenarios as follows:

- **Central scenario.** In this central appraisal scenario, a 60 year appraisal period will be used and a residual asset value at the end of this period assumed.
- **Very long term scenario.** In this very long term scenario, a 100 year appraisal period will be used and a zero residual asset value assumed.
- **Sensitivity test.** This is a sensitivity test which will use a 60 year appraisal period and assuming no residual asset value. The purpose of this test is to illustrate the impact of the residual asset value on the appraisal results.

The key appraisal statistics are as follows:

- Present Value of Benefits (PVB). This is the value of all of the benefits and other impacts of the strategy, (see the categorisation in Table 9-2).
- Present Value of Costs (PVC). This is the value of all of the costs and savings to DfT as a result of the strategy, (see the categorisation in Table 9-2). A positive PVC indicates the strategy will increase DfT's funding requirement.
- Net Present Value (NPV). This is the PVB minus the PVC. A positive NPV indicates that the strategy has an overall monetised benefit in net terms.
- Benefit to Cost Ratio (BCR). This is the PVB divided by the PVC. DfT categorises the value for money of a scheme as follows:
    - BCR < 1.0 = poor (value for money)
    - BCR 1.0 - 1.49 = low
    - BCR 1.5 – 1.99 = medium
    - BCR 2.0 – 3.99 = high
    - BCR 4.0 or higher = very high

Table 9-2: Monetised impacts

Impact type	Impact	Description
Benefit	Passenger travel time	Under the resilience strategies the level of disruption to rail services will reduce. This will result in a reduction in passengers' travel time. Benefits will be estimated based upon the value of this reduction using the industry standard MOIRA software, along with Passenger Demand Forecasting Handbook (PDFH) evidence on late time multipliers and passengers' awareness of short-notice disruption to services.
Benefit	Externalities from increased use of road transport	Under the resilience strategies the number of rail journeys made will increase, partly through a switch from highway travel to rail travel. WebTAG states that harmful externalities of transport usage are higher per car user mile than per rail passenger mile. The switch from road to rail will therefore reduce these harmful impacts, which can be split between the following categories: • Congestion • Greenhouse Gases • Local Air Quality • Noise • Accidents Quantification of these impacts will use the same data as calculation of passenger travel time impacts, as well as unit values of these impacts from WebTAG.
Benefit	Reduced vehicle operating costs	WebTAG states that travel by rail is less expensive than travel by car. There is therefore a financial dis-benefit for passengers who transfer from rail to road thereby increasing vehicle operating costs.
Other impact	Reduced other taxation receipts	WebTAG convention is that passengers fund new trips by rail by forgoing expenditure on goods or services to which VAT applies. As VAT is not applied to rail fares, the VAT is forgone. This revenue is lost by HM Treasury, so is treated as an "other impact" and not a cost to DfT.
Other impact	Non-rail property repair saving	It may not be possible to monetise this impact due to a lack of information.
Other impact	Rail freight cost saving	It may not be possible to monetise this impact due to a lack of information.
Cost (to DfT)	Infrastructure investment	This is the cost of the infrastructure interventions which comprise the resilience strategies. Costs estimates will be produced by CH2M and its team. Optimism bias at 66% will be added to these estimates for appraisal purposes, which is the rate recommended by WebTAG for early stage development projects (GRIP stage 1).
Cost (saving to DfT)	Infrastructure repair	This is the avoided cost of infrastructure repairs due to the improved resilience provided by the strategies. Costs estimates will be based on actual costs and no optimism bias is applied
Cost (saving or cost to DfT)	Maintenance	This is the change in maintenance costs after the interventions will be implemented. Costs estimates for new maintenance activities will be produced by CH2M and its team. Optimism bias at 66% will be added to these estimates for appraisal purposes, which is the rate recommended by WebTAG for early stage development projects (GRIP stage 1). Costs estimates for existing activities will be based on actual costs and no optimism bias is applied
Cost (saving or cost to DfT)	Renewals	It may not be possible to monetise this impact due to a lack of information.
Cost (saving to DfT)	Passenger revenue increase	This is the avoided loss of passenger fares revenue as a consequence of the reduced level of disruption provided by the two strategies. Values will be calculated using industry standard information, and exogenous growth rates will be taken from NR's Western Route Study.

9.4 Baseline (do-minimum) level of resilience

As discussed above, in the do-minimum scenario it will be assumed that additional funding to improve the resilience of the route is not provided and that assets continue to be maintained on a modern equivalent like-for-like basis.

Figures 9-3, 9-4 and 9-5 show a forecast annual frequency of disruption event by category of event and by asset type over the 50 years from 2015. Also shown are the combined frequencies of the three types of disruption events. These combined frequencies are lower than the sum of the individual frequencies by asset type, based on an estimate of the proportion of events by type that are likely to occur concurrently.

These frequencies will define the bulk of the monetised impacts in the do-minimum scenario.

The change in frequency of disruption events under the do-minimum scenario from 2015 to 2115 are shown in Figures 2-3 to 2-5 and summarised in Table 9-3 below. These demonstrate that a significant increase in all types of disruption event is forecast by 2065 with the reliability of undisrupted service drastically reduced by 2115.

Table 9-3: Disruption likelihood under Do Minimum
Likelihood expressed as once every X years

	2015			2065			2115		
	Extreme	**Severe**	**Moderate**	**Extreme**	**Severe**	**Moderate**	**Extreme**	**Severe**	**Moderate**
Geotech	1/50	1/10	1/1	1/19	1/3.5	1/0.33	1/7	1/1.4	1/0.14
Coastal	1/42	1/4.5	1/1	1/5	1/1	1/0.75	1/2	1/0.5	1/0.25
Estuarine	1/200	1/145	1/64	1/75	1/10	1/7.5	1/10	1/7.5	1/2.5
Overall	1/25	1/3.5	1/0.5	1/4	1/0.75	1/0.25	1/1.5	1/0.38	1/0.08

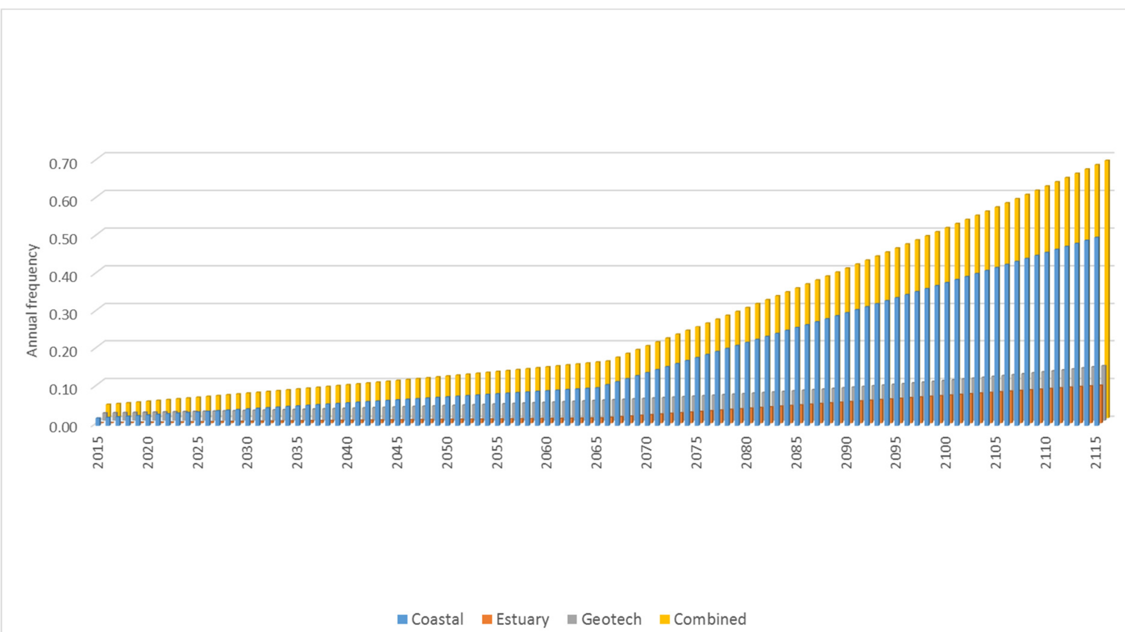

Figure 9-3: Probability of an extreme disruption event: do-minimum scenario

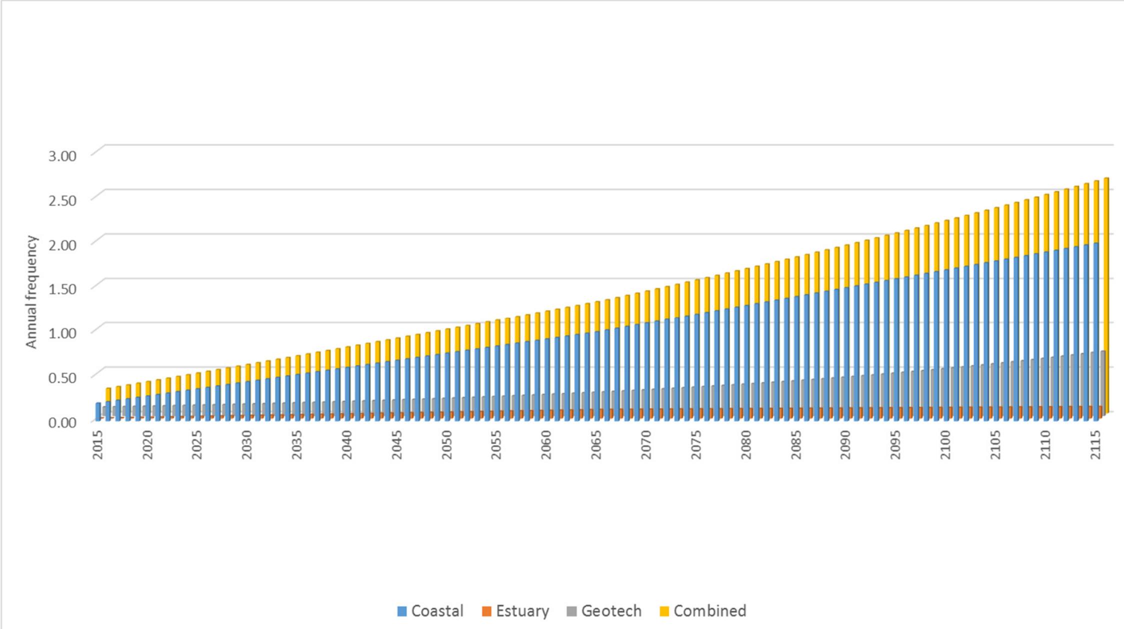

Figure 9-4: Probability of a severe disruption event: do-minimum scenario

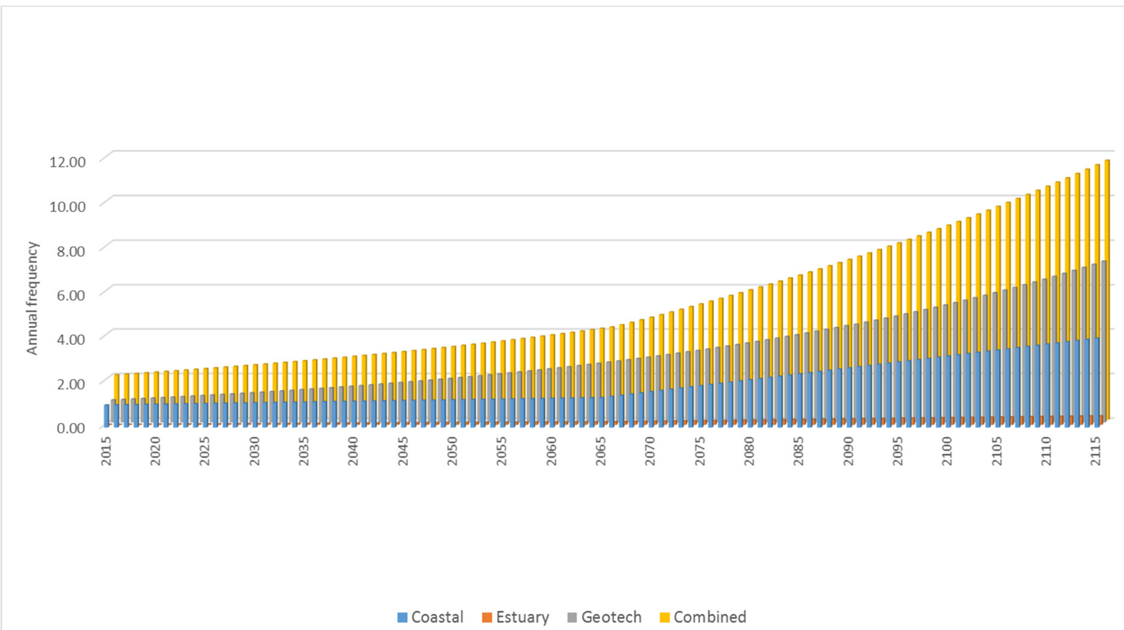

Figure 9-5: Probability of a moderate disruption event: do-minimum scenario

Environmental baseline

The study area is of significant biodiversity, cultural, social, archaeological and landscape value, which is described in detail in Appendix J. Some of the key environmental features are illustrated in Figures 9-1 and 9-2, and an environmental summary of the areas along and beside the railway, and the issues, constraints and opportunities that should be considered is included in Table 10-1 below:

Table 10-1: Summary of environmental baseline

Environmental Baseline	Environmental Issues, Constraints and Opportunities
Population and Human Health	
• Predominantly rural area with large conurbations at Exeter, Teignmouth, Dawlish and Newton Abbot; all connected by the mainline railway, which is at risk from tidal flooding and erosion. • Popular tourist destinations at Dawlish Warren, Dawlish and Teignmouth, including five designated bathing beaches around these towns. • Fishing is economically important in the Exe and Teign, particularly mollusc shellfish farming and both estuaries are bass nursery areas.	• Increasing risk to railway infrastructure from erosion and flooding. • Recreational and tourist facilities along the estuaries and coast may be affected by the Strategy. • Opportunities for recreation (e.g. to improve public access and link footpaths), and tourism. • Any potential changes in estuarine processes due to the Strategy could affect the quality of shellfisheries and bathing waters around the Exe and Teign.
Material Assets	
• M5, A379, A381 and A380 are key transport routes running through study area, in addition to mainline railway. • Several ferries operate on the Exe and Teign.	• Existing road infrastructure has the potential to constrain the Strategy. • Important to maintain access to ferry terminals.
Biodiversity	
• Exe Estuary Special Protection Area (SPA), Ramsar and Site of Special Scientific Interest (SSSI), and Dawlish Warren Special Area of Conservation (SAC), SSSI and National Nature Reserve fall within the study area. These support internationally important habitats; saltmarsh, mudflats, coastal and floodplain grazing marsh and estuaries, and important bird populations. • Local Nature Reserves and County Wildlife Sites • The River Exe, River Teign and their tributaries support fish populations of conservation importance, including sea trout, wild brown trout, rainbow trout, eel, grayling and Atlantic salmon.	• Potential requirement for Habitat Regulations Assessment (HRA) Screening with regard to the SPA, Ramsar site and SAC in line with the Conservation of Habitats and Species Regulations 2010 (as amended). • Opportunity to improve conservation status of designated sites, and for habitat creation/ improvement (e.g. providing wildlife corridors and linking existing habitats) elsewhere. • The Strategy has the potential to affect water quality.
Soil, Geology and Geomorphology	
• A geological SSSI in study area (Dawlish Cliffs). • See Section 6 for detailed geological description. • 6 landfill sites in study area; of these, the railway line runs over Flowerpot Playing Field at Exeter and Water Lane landfill at Clapperbrook is located on the seaward boundary of the railway line.	• Natural erosion helps to maintain the geological SSSIs by exposing rock sequences. The Strategy has the potential to be detrimental to the SSSI objectives. • Landfills, which may present a pollution risk to soils and water, may constrain the Strategy. • Future changes in the evolution of Dawlish Warren spit have the potential to affect flood protection currently afforded to the railway.

Environmental Baseline	Environmental Issues, Constraints and Opportunities
Land Use	
• Land use comprises residential, amenity land, commercial/industrial development, and agricultural land (the latter encompasses 64% of study area, of which 31% is very good to moderate quality for crop production).	• The presence of notable land uses such as very good quality agricultural land may constrain the Strategy.
Water and Hydromorphology	
• Exe Estuary and Teign are designated Shellfish Waters • All bathing waters in the study area (except Teignmouth Town Beach) met the higher standard for bathing water cleanliness in 2014. • The study area from north of Dawlish to Exeter lies within a groundwater Nitrate Vulnerable Zone. • Key waterbodies in study area are 1 coastal waterbody (Lyme Bay West), 2 transitional waterbodies (Exe Estuary and Teign), numerous river waterbodies and groundwater bodies.	• The Strategy is likely to be subject to the Water Environment (Water Framework Directive (WFD)) Regulations 2003. A WFD Assessment will be undertaken during the SEA. • Changes in coastal processes can cause siltation, which decreases the water quality for shellfisheries and thus affect objectives set by the WFD. • Railway embankments in the study area often provide the primary form of flood defence that requires careful management to ensure the Strategy do not affect flood or erosion risk.
Landscape and Visual Amenity	
• Landscape character of Devon Redlands National Character Area, which occupies the majority of the study area, is characterised by rolling hills with striking red soils formed by permo-triassic desert deposits, ploughed fields, cliffs and exposures, open flood meadows with little tree cover in the lower valleys, extending to open salt marsh on the coast and large parks and manor houses near the towns. • The main study area further falls into five distinct Devon-wide landscape character assessment areas for Teignbridge: 6.7 Exe Estuary and Farmlands; 4.1 Dawlish; 6.11 Dawlish Hinterland; Teignmouth 4.1; 6.12 Teign Estuary. • The Exeter section of the study area partially falls within areas 24, 41 and 42 of Exeter's landscape sensitivity zone rated high/medium high sensitivity. • The railway line offers scenic views of the South Devon coast from onboard (that would otherwise be difficult to access), and is an important tourist attraction. • Areas undergoing active / planned landscape change being delivered through land allocations in the Teignbridge Local Plan within the study area include; the planned urban expansion of Southwest Exeter. The Villages of Ide, Exminster, Kenton and Bishopsteignton are undergoing limited development to protect their rural character.	• New or improved railway infrastructure (or defences) need to be in keeping with the existing landscape character, sensitively sited to avoid affecting distinct landscape components to conserve and enhance the distinctive character, features and special qualities of the landscape, in order, for example to maintain the character of the undeveloped coast. • The Strategy should consider cumulative effects on landscape character and visual amenity from combined measures adjacent to railway. • Current scenic views afforded by train passengers along the route of the railway are an important factor in determining its appeal to visitors.

Environmental Baseline	Environmental Issues, Constraints and Opportunities
Air and Climatic Factors	
• 4 Air Quality Management Areas - Exeter, Newton Abbot and Kingsteignton, Bitton Park Road (Teignmouth) and Iddesleigh Terrace (Dawlish) - designated by the local authorities where there is exceedance of air quality objectives • Sea level rise, and a predicted increase in storm surge wave activity is likely to increase existing flood risk posed to the railway infrastructure.	• No significant issues relating to air quality. • Climate change may affect the physical character of the estuaries and coastline and there is a need to retain flexibility within the study to adapt to unforeseen climate changes
Historic Environment	
• Numerous unscheduled features of archaeological, palaeo-environmental and historical importance including maritime heritage. • 2 Scheduled Monuments, over 200 Listed Buildings, 13 Conservation Areas and 1 Registered Park and Garden within study area.	• The Strategy measures should consider the potential to affect archaeological assets including their character and setting. • Specific impacts on known features and further consideration of undiscovered archaeological resources will be addressed during detailed projects • The Strategy may be constrained by the need to protect the setting of areas of existing archaeological value. • The Strategy should consider both designated and non-designated heritage features.

Data gaps and outstanding issues

11.1 Coastal defence site appraisal

The overtopping results have been assessed against the EurOtop thresholds (EA/ENW/KFKW, 2007) for structural damage. This has allowed a standard of protection against structural damage to be determined. Although it had been considered beneficial to determine a threshold related to operational disruption and its aspirational frequency of occurrence which could be aligned with the Future Weather System currently being developed by MetDesk, this proved not to be possible.

11.2 Cliff behaviour site appraisal

Characterisation of the CBUs has highlighted that intrusive ground investigations and associated geotechnical testing of material strength are limited, and have generally been collected to support construction of remedial measures following cliff failure. Therefore the geotechnical database is incomplete and is generally focussed on sites where past cliff failures have occurred, rather than characterising the whole frontage to determine where failures may occur in the future. Ground investigation and geotechnical testing is therefore needed to fully characterise the ground conditions along the coastal cliff frontage and near-hinterland area.

A geotechnical investigation along the frontage was scoped under this commission for further implementation by NR. The first phase of this covering the frontage from Parson's Tunnel to Teignmouth was commenced in June 2016.

11.3 Rail Infrastructure

Although there were many iterations and individual meetings with the key RAM contacts during the course of the project, there were still many areas where information was missing, lacking in detail or not available. Measures to resolve these in the future should be considered.

11.4 Strategic Environmental Assessment (SEA)

A Strategic Environmental Assessment (SEA) has been recommended under the Environmental Assessment of Plans and Programmes 2004, for the Geo-environmental Resilience Strategy to meet best practice requirements. This is required for a variety of plans where the Government's consent is to be secured for project implementation, and is generally applied to flood risk management plans and strategies as best practice.

An SEA Environmental Report and Non-technical Summary will be produced to accompany the publication (and advertising) of the Geo-environmental Resilience Strategy. A Water Framework Directive (WFD) assessment will be integrated into the SEA process.

Additionally, a Habitat Regulations Assessment (HRA) may be required under the Conservation of Habitats and Species Regulations 2010 (as amended) following discussion with Natural England, with regard to the international conservation sites that border the study area.

11.5 Stakeholder Engagement

It is important that consultation continues with both EA and Teignbridge District Council, particularly as project emphasis is put onto more formal lines of communication, including press releases and public events. Their experience in implementing communication strategies and involvement in other projects within the study area will be invaluable.

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Appendix A Data register
Appendix B Cliff and coastal events index
Appendix C Climate change scenarios
Appendix D Coastal and estuarine processes
Appendix E Wave modelling and overtopping
Appendix F Coastal defence asset index
Appendix G Cliff behaviour units
Appendix I Hydrogeological study
Appendix I Asset inventory
Appendix J Environmental baseline