The Response of Railway Planners to the Risks of Flooding Caused by Climate Change

A comparative case study between England and The Netherlands

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Colophon

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Cover Photo:	Flooded railway tracks in England in 2007 (source: generalizing, www.flickr.com)

Abstract

This research examines how climate change-induced flooding may affect the infrastructure of railways in England and the Netherlands and what steps should be taken to mitigate such measures. To detect such vulnerabilities, GIS data is analysed along with a review of policy documents from each railway network. Two case studies are considered, one in each country, which examine how the interventions align with three evaluation frameworks. The Dutch case study involved coastal flooding in an industrial port, which is a common vulnerability in the Netherlands because such ports are often outside of the standard flood defence system. The English case involves the destruction of the Dawlish railway on the South Coast of England during a storm in 2014 and how combining projects will improve the spatial realm. The research identified that institutional responses may be the most effective at combatting this problem, particularly in England. Proactivity, coordination between agencies and combining projects to improve the overall spatial realm are highlights of the interventions.

Contents

1.0 Introduction

1.1 Background

Climate change is a well-known and widely accepted problem, which is expected to lead to increased flooding around the world. The world's railways, as highly complex, sensitive, safety-critical, digital systems, which are operated in large part using electricity and directly exposed to the elements, will likely face a great impact. It is worth investigating the potential impact of such additional climate change-induced flooding will be and what measures can be taken to adapt to it. This research will examine these questions by comparing the infrastructure responses and institutional framework of two countries: the Netherlands and England.

When used in place of private cars and trucks, transportation by railway provides a significant opportunity for the reduction of greenhouse gas emissions. For it to play its part, railway systems must be kept functioning in top operational condition as much as possible and increased flooding poses a threat to this.

Climate-change-related damage threatens to cost substantial amounts of public money. The European Commission-funded "Weather Extremes-Assessing the Impacts on Transport and Hazards for European Regions" (WEATHER) project suggested about €2.5 billion per year (Doll et al., 2014). While the greatest amount of *money* would be spent on road infrastructure, the greatest susceptibility to *risk* was found to be to the railway network. Railway infrastructure is also classified as "critical" in the sense that it is vital for the continued health, safety and functioning of society. (Bubeck et al., 2019)

The consequences of flooding can affect all parts of the railway, including tracks, electrical cabling, signalling, passenger access areas and the surrounding environment used to access the railway. Tracks can be affected if the track bed underneath is saturated by water or there is a large difference in the water levels on both sides of the track. This can cause the soil body and/or sleepers to slide out of place or float up. All of this can affect the safe bearing capacity of the tracks (Jak et al., 2019). Beside the tracks, it is expected that the additional flooding induced by climate change will bring less stability of earthworks during heavy rainfall and strain on drainage systems (Baker et al., 2010).

Signalling (usually in the modern form of Train Protection Systems) is used to keep trains a safe distance apart. It affected because these systems rely upon a grounding circuit using the running rails. If these rails contact water during flooding, they can short out, which results in the system "failing safe" and defaulting to indicating the presence of a train, even where one is not present. Water on tracks also prevents operators from seeing the track itself, which is a safety hazard and prevents operation.

The above impacts also accelerate the deterioration of railway assets, which starts a vicious cycle, where assets that are not in a good state of repair become more vulnerable to catastrophic failure during flooding conditions than they otherwise would be. (Hodges, 2011)

Such physical consequences cause service disruptions and delays. For example, when two sections of track in the Netherlands were analysed, most disruptions which were related to weather involved heat, snowfall, and low temperatures (Oslakovic et al., 2012). These kinds of disruptions will have a financial impact on operator budgets which were already strained after years of austerity (particularly in the United Kingdom) and especially after the €42 billion of losses suffered by the railways of Europe as a result of the Covid-19 pandemic (CER, 2021). Already railways in Britain are losing revenue due to extreme weather events. In addition to a loss of short-term revenue, disruptions due to flooding induced by climate change hamper the opportunity of a railway to attract future custom through its reputation as a reliable and environmentally-sound mode of transportation (Quinn et al., 2017). To maintain functioning and fiscally sustainable railways it is important that these risks are properly assessed and addressed.

The scientific relevance of this research is to increase our understanding of flooding vulnerabilities of railways and how to most effectively respond to them.

1.2 Geographic Scope of this Research

This research is focused on the railway networks of the Netherlands and of England (i.e., to the exclusion of Scotland, Wales, and Northern Ireland). These two countries take staunchly contrasting institutional approaches to flood protection.

The Netherlands was chosen for this research because of its complex and modern railway network, along with its extensive flood protection infrastructure—about 3,000 kilometres of primary flood protection structures (Pilarczyk, 2007)—and its extensive institutional history in this area, with the first of the country's 21 *Waterschappen* (water boards) dating from the twelfth century.

England was chosen because its pioneering history of railways presents a challenge of a mixture of old and new infrastructure. It also offers a similar climate and existing challenges with flooding, but without the extensive flood protection infrastructure and institutional history of water management.

Scotland, Wales and Northern Ireland were excluded because, while they are part of the United Kingdom, flood monitoring and protection measures are devolved from the central UK government in Westminster. As a result, this suggests that they might take a different approach to flooding, and, crucially for one of the research sub-questions in this study, feature entirely different institutional structures with different actors. Another reason for the exclusion of Northern Ireland in particular from this research is that its railway network is entirely separate from the one in Great Britain, features different technical specifications (e.g., using the wider Irish rail gauge) and vertically-integrated, unlike other railways in the UK and EU (Nash, 2008).

1.3 Research Problem

The **research gap** identified is a lack of literature about selecting which transformative and proactive measures are appropriate for use in the Netherlands. Studies have quantified the *amount* of flood damage (Bubeck et al., 2019), but there is a lack of literature on which measures are more effective in Europe, particularly the Netherlands. The UK has more literature describing measures and their effectiveness than the Netherlands does.

The **aim** of this research is to learn which measures are most effective at countering the disruption to the railway caused by climate change-induced flooding and excessive heat. The intent is to apply this research in a European context, with a focus on the Netherlands and England. This will be done by a comparative study of the policy documents and literature in the responses to flooding of railways in England and the Netherlands.

The **research question** posed is: What are the most appropriate responses to increased flooding induced by climate change for railway operators in the Netherlands and England?

This suggests the following **sub-questions**:

- What vulnerabilities are faced by the railway networks of the Netherlands and England?
- What measures are most suitable to combat the problem in the Netherlands and England?
- What actors are involved in implementing such measures?

1.4 Reader's Guide

The second section of this research features the theoretical framework, introducing three frameworks through which potential adaptive interventions can be viewed.

In the third section, the details of the GIS datasets, policy papers and relevant academic literature are laid out, as are details of the analysis process.

The fourth section provides the results, along with two case studies, one from each country. For each case study, a map is provided, along with an identification of the problem or vulnerability, the interventions that were taken or are proposed, and the lessons that can be drawn from that case.

A discussion of the results is provided in the fifth section, which zooms out and considers how generalizable the results are. In the conclusion, the process and outcomes of the research are reflected upon (Section 6.1).

2.0 Theoretical Framework

2.1 How to Find Areas Vulnerable to Flooding

Knowing where flooding is more likely to take place (e.g., near rivers) can aid in the selection of appropriate remediation methods relevant to that locality. An efficient way of getting a bird's eye view of this is using Geographic Information Systems (GIS) data, particularly using Digital Elevation Models. The Transit Inundation Modelling Method (TIMM) provides a standardised five-step method of using GIS to identify transportation infrastructure that is vulnerable to flooding (Oswald & Treat, 2013). It has been used in the coastal areas of United States to prepare transit agencies for climate adaptation, for example in Philadelphia. The operationalisation of TIMM will be discussed in 3.0 Methodology. The conceptual model in Figure 1 shows the location of vulnerabilities being analysed in the top left (green) using GIS and TIMM.

2.2 Frameworks for Evaluation of Interventions

There are three different frameworks by which interventions can be evaluated: those of Hodges (2011), Quinn et al. (2017) and Masood et al. (2016). In the results sections these will be applied to the case studies and in the 5.0 Conclusion section they will be applied to the railway planning institutions of the Netherlands and England as a whole. Figure 1 shows this analysis taking place in the bottom left (yellow.)

Hodges (2011) proposes a classification system with four broad categories of adaptation strategies that are available to transit agencies in response to the threat of climate change: (1) maintain and manage; (2) strengthen and protect; (3) enhance redundancy; and (4) abandon.

The full Rail Adapt Framework (Quinn et al., 2017) does not fit well with this research because it focuses on broader qualities of governance which are outside the scope of this research. But its four underpinning principles are a useful lens for evaluating potential future interventions. These include: (1) embodying the future climate for the life of the system; (2) how the system will be used in the future economic and social environment; (3) use the best available information; and (4) implementation should integrate with existing asset management systems.

Adaptation to climate change is a form of future-proofing and Masood et al. (2016) proposed a set of criteria to evaluate the quality of a future proofing effort. They are: resilience, adaptability, replaceability, reusability, and system stability.

2.3 Institutional Frameworks for Railway Planning in England and the Netherlands

England and the Netherlands have very different institutional frameworks for infrastructure planning. Both have agencies controlled by central government responsible for maintaining and extending their railways (Network Rail and ProRail respectively.) The Netherlands has provincial governments which usually participate in infrastructure planning and proposals, plus water boards dedicated to water management. It also features a more collaborative planning environment. Planning in the UK could be described as more top-down with central government taking the lead in a less collaborative approach with other stakeholders.

In terms of the institutional differences in flood risk management (FRM), the main focus in the Netherlands has traditionally been on physical infrastructure as probability-reducing measures (a “battle against the water.”) This includes things like dikes and dunes, storm surge barriers and water storage. In the mid-1990s there was a shift in perspective to a concept of “living with the water,” such as with the Room for the River programme. Later, the National Water Plan of 2009 brought about the “multi-layered safety” approach. (Hegger et al., 2020)

England has pursued a diversified approach to FRM since 1947. This approach has been criticised for being fragmented and unnecessarily complicated and expensive. A series of major flood events have caused the institutional focus to turn to better integration of FRM activities and coordination at the local governance level. (Hegger et al., 2020)

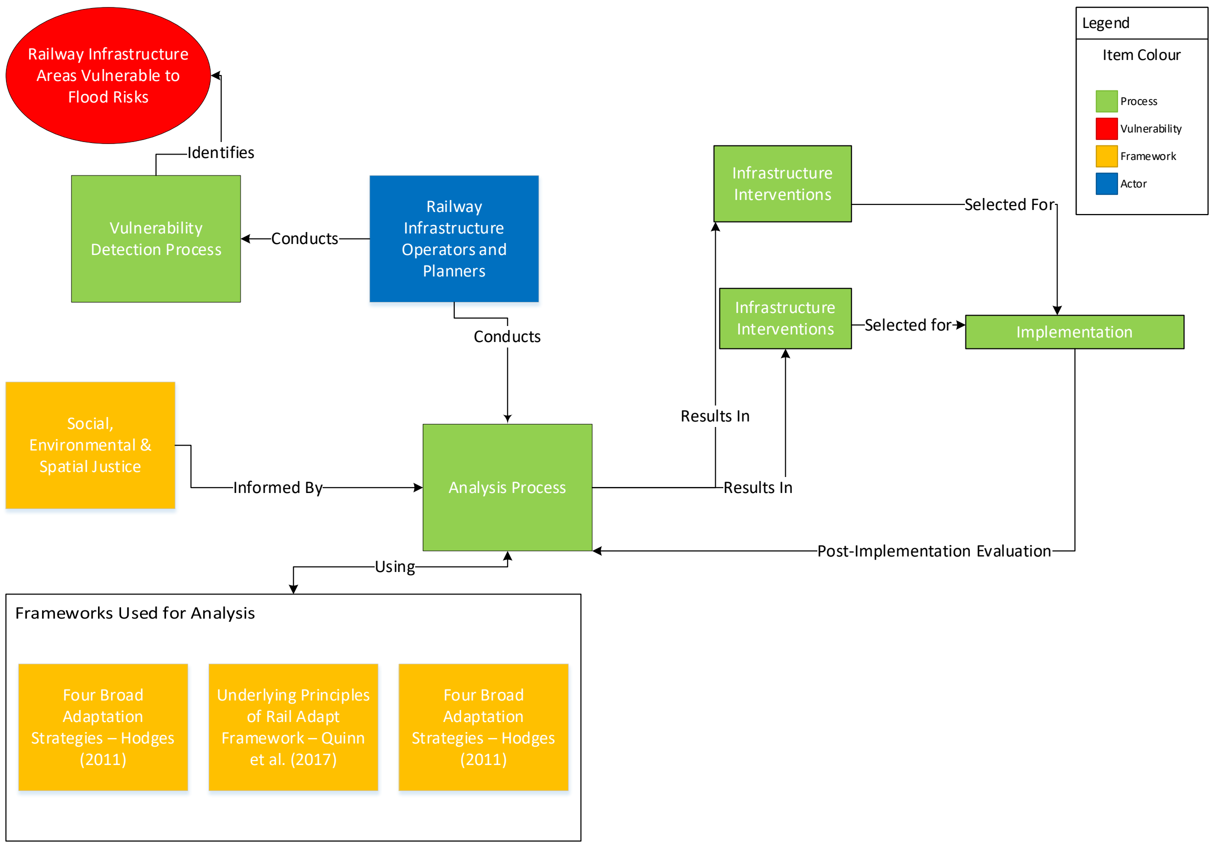

Figure 1: Conceptual Model showing the Railway Operators identifying the vulnerabilities, analysing them using the frameworks, producing potential infrastructure interventions, implementing them, then re-evaluating them after implementation.

3.0 Methodology

The research strategy taken was to combine the analysis of policy documents with spatial analysis using GIS. GIS was selected as a suitable tool for empirically identifying areas vulnerable to flooding. It was thought that policy documents would provide for more insight on what actors are actually doing (if anything) to address the problem, and to establish potential best practices. Quantitative methods were not selected because

3.1 Locating Vulnerability using TIMM and GIS

This study uses a procedure adapted from TIMM to first identify what areas are most susceptible to climate change-induced flooding. The biggest difference in this research's application of TIMM is that it is being applied to entire countries as opposed to the city level. This means that an extremely high level of detail is not practical or useful in this research.

The first step is to define the study areas, which have been set to the railway infrastructure of each country. The second step is to gather data using the datasets indicated in Table 3. Oswald and Treat (2013) rely on Digital Elevation Models (DEMs) referencing the datasets that were available in 2010. Since the governments of the Netherlands and England both now publish GIS datasets indicating areas vulnerable to flooding, the third step of TIMM (of reproducing such datasets) is made redundant in this research. The fourth and fifth steps involve analysing and synthesising the data, which will be done in Section 4.0 Results.

3.1.1 GIS Datasets used in this research

It is intended that these GIS datasets will indicate where the railway networks are vulnerable to flooding (sub-question 1) and what types of areas are most vulnerable to flooding (sub-question 1 and to be used to answer sub-question 3.)

Dataset	Countries Covered	Source	Description	Date (Last Updated)	URI
Spoorwegen (Railways)	(European) Netherlands	Publieke Dienstverlening Op de Kaart (PDOK)	All railway trackage in the Netherlands	19-10-2021	https://www.pdok.nl/introductie/-/article/spoorwegen
Richtlijn Overstromingsrisico EU 2018 (EU 2018 Flood Risk Directive)	(European) Netherlands	Nationaal Georegister (NGR)	Designated areas with potentially significant flood risk from the report 'Flood risks in the Netherlands, 2018' pursuant to the EU Flood Risk Directive	12-12-2018	https://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/ror-9d8e-4758-83fx-28b057f185e1?tab=general
Global Railways	United Kingdom, Netherlands	OpenStreetMap (OSM)	A digital map database of the world's railways built through crowdsourced	September 2016	https://wwf-sight-maps.org/arcgis/rest/services/Global/Global_Railways/MapServer

			volunteered geographic information (VGI)		
Overstromingskansen norm (2021 & 2050)	Netherlands (used for detail in the Rotterdam – Botlek case in Section 4.0)	Rijkswaterstaat	Detailed raster maps of flooding probabilities	22-09-2021	https://basisinformatie-overstromingen.nl/#/maps
Indicative Flood Risk Areas	England	Environment Agency	Indicative Flood Risk Area for local risk.	19-03-2020	https://data.gov.uk/dataset/7792054a-068d-471b-8969-f53a22b0c9b2/indicative-flood-risk-areas-shapefiles

Table 3: GIS Datasets used in this research

This study collected secondary data in the form of a comparative review based on literature and policy documents, plus GIS datasets.

3.2 Evaluating Interventions using Policy Papers

The following policy documents were selected for evaluation and analysis because they are directly relevant to flood prevention measures on railways, and they are from reputable sources (usually the agencies which are directly responsible for the railway network.) They provide a unique insight into the intentions and evaluation process of such actors. The policy documents were analysed collectively for both countries.

3.2.1 Policy Papers analysed in this research

Paper Title	Paper Title (Dutch)	Agency	Date Published	Applicability to this research
ProRail Climate Adaptation Guide	*Handreiking Klimaatadaptatie ProRail*	ProRail	25-03-2019	Summary of ProRail's approach overall to climate adaptation. Does not list

				specific interventions but general policy directions.
Flood Risks in the Netherlands	*Overstromingsrisico's in Nederland*	Ministerie van Infrastructuur en Waterstaat	18-12-2018	Explains how to interpret the flood risks in the GIS dataset
Tomorrow's Railway and Climate Change Adaptation (T1009)		Rail Safety and Standards Board Ltd.	May 2016	Extensive details of the engineering interventions recommended in England.
Transport Resilience Review A review of the resilience of the transport network to extreme weather events		Department for Transport	July 2014	How to approach resiliency in the British railway network in terms of climate change-induced flooding.
Landscape Planning for the Rails handbooks I, II & III: Planting in the travel domain, station area and railway verge	*Landschapsplan voor het Spoor I, II & III Handboeken Beplanting in het Reisdomein, Stationsomgeving & Spoorberm*	ProRail, NS & Bureau Spoorbouwmeester	2020	

3.3 Ethical Considerations

The ethical considerations in this research include social, environmental and spatial justice issues. Social justice considerations in this research include considering how marginalised communities affected by the interventions can be heard and their needs considered.

Environmental justice is a concern because marginalised communities often lack access to green space.

Gentrification is another ethical concern relating to spatial justice. This research must not be used as justification for gentrification.

4.0 Results

4.1 GIS Analysis of the flood vulnerability of Railways in the Netherlands

Overall the analysis of the vulnerability of the Netherlands revealed relatively few sections of vulnerability. This is because most railways are located within the main flood defence system and rarely run along major rivers, which are often quite vulnerable.

The most prominent were the port areas with railways, especially the Port of Rotterdam with its freight *Havenspoorlijn* railway connection to the *Betuweroute* as the largest segment of railway vulnerable to flooding. This is examined further in a case study in Section 4.4.1. Other seaports with railways faced similar vulnerabilities to flooding, such as Eemshaven, Vlissingen-Oost, Moerdijk and De Merwedehavens in Dordrecht.

Other areas with vulnerability include:

- Between Baarn and Amersfoort
- Nijmegen to Molenhoek
- Roermond, particularly to the north where the railway follows the River Meuse to Tegelen
- Kampen station on the IJssel river
- Through Winschoterdiep and Haren near the junction south of Groningen

4.2 GIS Analysis of the flood vulnerability of Railways in England

England features a far more scattered flood vulnerability pattern with far less area of the country protected by formal defence structures. This suggests that it is not just coastal, pluvial or fluvial flooding which poses a danger, but all three.

Some of the more extensive vulnerabilities include the following areas:

- The line between Peterborough and Lincoln faces extensive vulnerability, particularly around Spalding.
- In Gloucester where the Severn River and Estuary
- The lines via the west (River Thames) and north (River Cherwell) of Oxford, which also hamper development within a close proximity to Oxford station and the railway line.
- The South Coast Line east of Eastbourne in Sussex. Despite being on the coast, this line is affected by pluvial flooding because of the cliffs separating it from the coast.
- London's railways are more protected than these areas, but there are still concerns between Stains and Windsor and Eton Riverside in the west.
- The East Coast Main Line is an important route between London and Scotland, and it is vulnerable south of Berwick-upon-Tweed due to coastal flooding.
- The River Leith poses some risk to the West Coast Main Line, which is a busier route between London, Manchester, Liverpool and Scotland. This is south of Carlisle.
- The single-track Tarka Line to Barnstaple in Cornwall is vulnerable, though the line is not electrified.

4.3 Results of Policy Document Analysis

A number of recommendations appeared consistently in the policy documents of both countries.

4.3.1 Infrastructure Interventions Recommended in the Policy Documents

In general, strategies combining approaches are most effective at reducing risk. This applies in a spatial sense too in that combining flood defence solutions with other spatial aspects, such as improvements to the public realm is also a recommendation. Other institutional interventions include developing a multi-agency cooperation model, conducting detailed vulnerability mapping of assets and their condition and enhanced weather incident reporting risk (*Tomorrow's Railway and Climate Change Adaptation (T1009)*, 2016).

Engineering approaches suggested included: improved vegetation to improve slope stability, better maintenance, the use of modular systems to speed up repairs, designing with climate change in mind, raising signalling, installing flood-detection sensors on vulnerable structures, allowing rainwater to find its way to greenery, and good vegetation management (*Tomorrow's Railway and Climate Change Adaptation (T1009)*, 2016).

4.3.2 Institutional Interventions Recommended in the Policy Documents

International Cooperation Efforts

One notable finding within the railway policy documents was a seeming resistance among English infrastructure agencies to seeking out international best practice.

"It is tempting to believe that adaptation can easily be achieved by importing technology, strategies and practices from other railway undertakings that are experiencing the climate/weather that the UK will experience in future. International supply chains, conferences and electronic sharing of information etc. mean that, if there were a revolutionary idea being used in another country, it is likely to be known to the GB industry." (*Tomorrow's Railway and Climate Change Adaptation (T1009)*, 2016)

This contrasts with an explicit stance taken by the Environment Agency (who are responsible for overall flood defences within England). They, when discussing a visit to the Netherlands, tout their international cooperation in solution-seeking. "we are always learning and sharing with partners around the world to improve how we protect people. Our local flood defences are stronger because of international expertise." (Boyd, 2017) Additionally there is a formal Memorandum of Understanding (MOU) between the Environment Agency and Rijkswaterstaat covering, among other topics, "learning exchange, knowledge and innovation management." (Rijkswaterstaat, 2021)

4.4 The Actors

4.4.1 The Actors in the Netherlands

Parties involved in the operation of the railways (and relevant to this research) in the Netherlands include some at the national government and many sub-national levels of government, along with private parties.

Actor (English Name)	Actor (Dutch Name)	Level of Governance	Responsibilities
Ministry of Infrastructure and Water Management	*Ministerie van Infrastructuur en Waterstaat*	National Government (*Rijk*)	Overall national policy planning in the area of railways and water management.
Rijkswaterstaat[1]	*Rijkswaterstaat*	Executive agency of a ministry of	Executive agency of this Ministry in the

[1] The name "*Rijkswaterstaat*" is not translated into English. As an executive agency, it should not be confused with the Ministry of Infrastructure and Water Management itself.

		the National Government	area of road and water infrastructure.
ProRail N.V.	*ProRail N.V.*	Task organisation of the national government	Maintenance and control of the railway infrastructure.
NS N.V.	NS N.V. (*Nederlandse Spoorwegen*)	Task organisation of the national government	passenger railway operator, with a monopoly on most main routes
Other Private Railway Operators (Arriva, QBuzz, Connexxion (Transdev) and Keolis Nederland)	[same]	Private Companies contracted by government	Operate passenger services on some regional branch lines under a franchise agreement.
Municipalities	*Gemeenten*	Municipal	Local spatial planning and land use
Water boards (21 across the country)	*Waterschapen*	Water boards are their own level of government	Arranging local flood defences (about 2700 km of 3000 km). (Pilarczyk, 2007)

Table 1: Railway Planning Actors in the Netherlands

At the end of the 20th century, and in line with European Union directive 91/440, the existing vertically integrated, state-owned railway company NS (which was officially known as *Nederlandse Spoorwegen* N.V.) was split into two organisations with full institutional separation: ProRail N.V. and NS N.V. (van de Velde, 2013).

4.4.2 The Actors in England

Parties involved in the planning and operation of the railway network of England include the national government, county and municipal councils, Network Rail and private & government rail operators.

Actor	Level of Governance	Responsibilities
Department for Transport (DfT)	National Government	Oversees the overall planning of the railway network.
Environment Agency	National Government	Flood vulnerability detection, planning and mitigation.
Office of Rail and Road (ORR)	National Government	Regulation of safety on the railways.

Network Rail	"Arm's Length" body of the National Government	The management, construction and maintenance of 32,000 km of railway infrastructure in Great Britain (including England, Scotland and Wales, but excluding Northern Ireland.) They also coordinate the 22,000 passenger and 700 freight trains that operate each day in Britain. (Secretary of State for Transport, 2014)
Train Operating Companies (TOCs)	Private Companies represented by the Rail Delivery Group (trading as National Rail)	Responsible for planning and operating passenger service during their franchise terms.
County Councils	County	
Municipal Councils	Municipal	
Regional transport management organisations, such as Transport for London and Transport for Greater Manchester	Sub-National	

Table 2: Railway Planning Actors in England

4.4 Case Studies

4.4.1 Case 1: Port of Rotterdam (Botlek Area), Netherlands

Background and Problem

The Port of Rotterdam is Europe's biggest seaport. Serving it in an east-west orientation is the freight-only *Havenspoorlijn Rotterdam* (Rotterdam Port Railway Line), (Figure 5) which connects to the *Betuweroute* freight railway east to the German border. The *Havenspoorlijn* is entirely electrified and uses ETCS for its signalling and train control. No passenger services are operated on this line.

Preliminary analysis using GIS pointed to the port as a railway line which is vulnerable to climate change-induced flooding. One major reason is that most of the Port of Rotterdam (and the *Havenspoorlijn*) are outside of the official flood defence system.

This means that private actors (shipping companies) are individually responsible for their own flood protection, though not all companies are aware of this liability.

De Botlek is a port and industrial area located within the Port of Rotterdam, west of the city, about 20 km inland from the North Sea. Its main approach is a connection to the north to the *Nieuwe Waterweg* (New Waterway) and the Scheur River. The New Waterway is protected from storm surges in the North Sea by the *Maeslantkering* (Maeslant barrier), which is one of the largest movable objects on earth.

But De Botlek's main vulnerability comes from two nearby canals: the Hartelkanaal and Calandkanaal from the west and south, which do not have protection from the Sea. This is despite Botlek's docks not being connected to the Hertelkanaal.

One vulnerability to flooding lies with the portals to the Botlek Railway tunnel. The tunnel does not feature doors shielding it from flooding. In January 2021 the tunnel suffered from minor from a burst water pipe. (van Gompel, 2021)

Interventions

One intervention was to reroute vulnerable track, bypass the Caland Bridge and construct a 4 km viaduct (named the *Theemswegtracé*) on a different route to increase resilience and prevent delays due to bridge openings for shipping traffic (Figure 3). This is an example of the "abandon" adaptation strategy proposed by Hodges (2011).

Figure 2: Rendering of the Theemswegtracé Viaduct Source: Mobilis

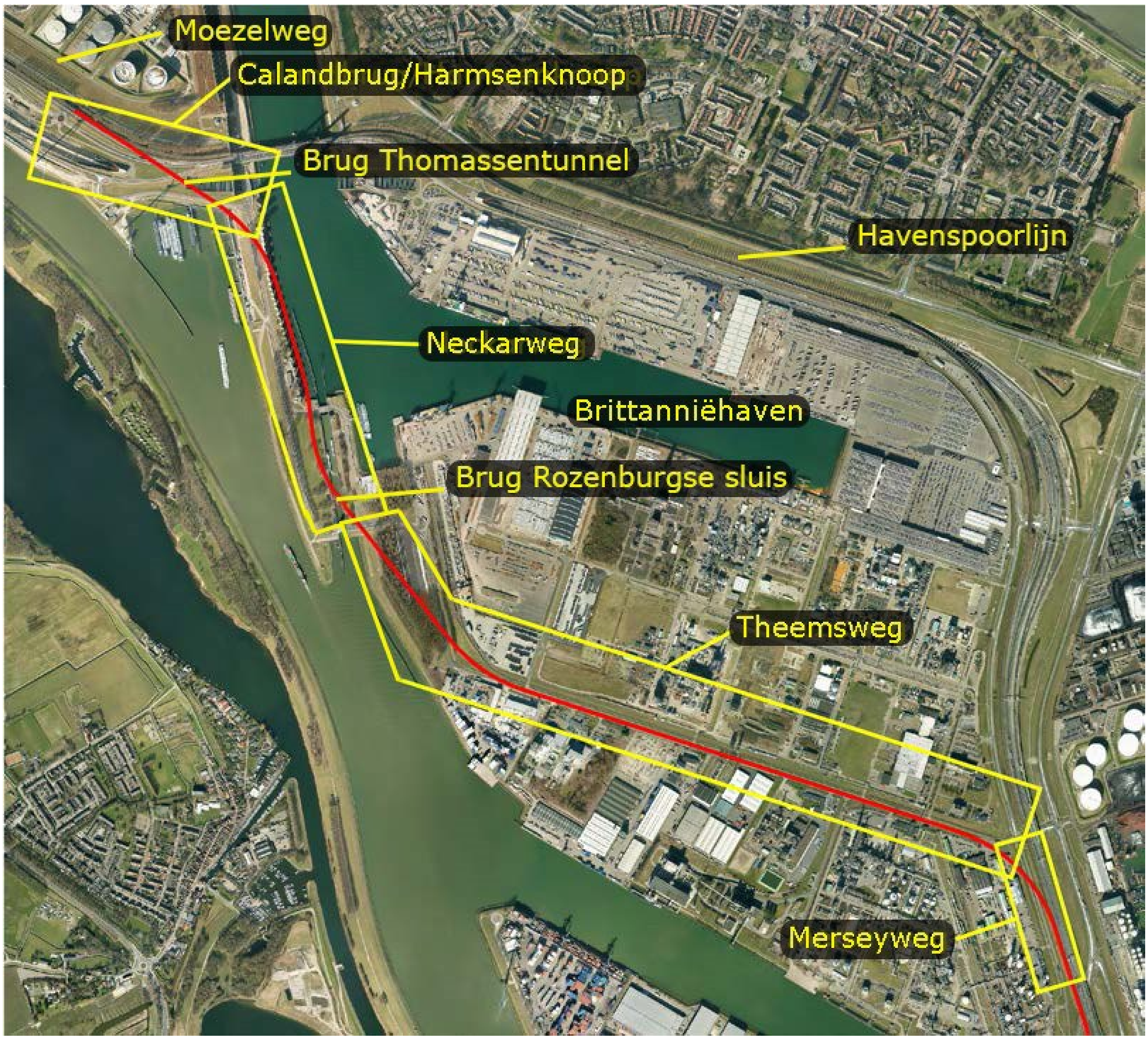

Figure 3 Map of the new route of the Havenspoorlijn line over the Theemswegtracé (red). Source: RailwaySafe BV

Take Away Lessons from this Case

The combination of increasing flood resilience and relieving railway traffic disruption in the construction of the *Theemswegtracé* is an example of combining flood resilience practices with other infrastructure interventions to increase the overall spatial quality and functionality of an area.

Figure 4: Map showing the vulnerability of the Rotterdam Port Area and its railway lines (in blue) to Flooding (in orange)

4.4.2 Case 2: Dawlish, Devon, England

Background and Problem

The South Devon Main Line railway serves the south of England from Exeter St. David's to Plymouth to the south and west. The line is carried for 6.5 km along the English Channel by the Dawlish Sea Wall, which was designed by Isambard Kingdom Brunel and constructed in 1845 (R. S. S, 1869). The wall consists of a masonry seawall and unconsolidated material which was blasted from soft, red sandstone cliffs and used to backfill the space between the cliff face and the frontage of the masonry seawall (Adams & Heidarzadeh, 2021).

This seawall has been subject to multiple instances of costal storm damage over its existence, such as during the winter storms of 2013-2014. On 4 February 2014, a storm severely damaged the wall, causing it to collapse, leaving the rails hanging in mid-air and closing the line for two months (Figure 6).

Figure 5: Damage from the 2014 storm in Dawlish closed the line for several weeks. Source: Network Rail

Over the past 30 years, only reactive maintenance has been performed on the seawall (except for the most recent interventions over the past two years.) In the early 2000s £10 million was spent to form a concrete “toe” at the base of the wall. The intent was to increase the wall’s resistance to undermining. (Masood et al., 2016)

Interventions

The Institute for Civil Engineering (ICE) has suggested five criteria on which to evaluate future-proofing schemes: resilience, adaptability, replaceability, reusability and system stability (Masood et al., 2016).

The latest and ongoing intervention involves the construction of a new seawall, with an increased hight of 2.5 m and a “wave return” feature, which is a curved top to deflect the waves back to the English Channel.

Take Away Lessons from this Case

Proactive and consistent maintenance is essential to protecting railway structures vulnerable to flooding.

Improvements to flood prevention infrastructure offer a prime opportunity to combine other spatial changes with the improvements to flood prevention infrastructure. In this case the old pedestrian walkway along the coast was regularly cut off at high tide will be improved to provide a far better pedestrian environment, which will remain regularly accessible. Other components of this project include station improvements (such as a new, accessible station footbridge with lifts) and a new ramp to the beach. (Network Rail, 2020)

Figure 6: Artist's impression of completed phase 2 of the seawall improvement project. (Source: Network Rail)

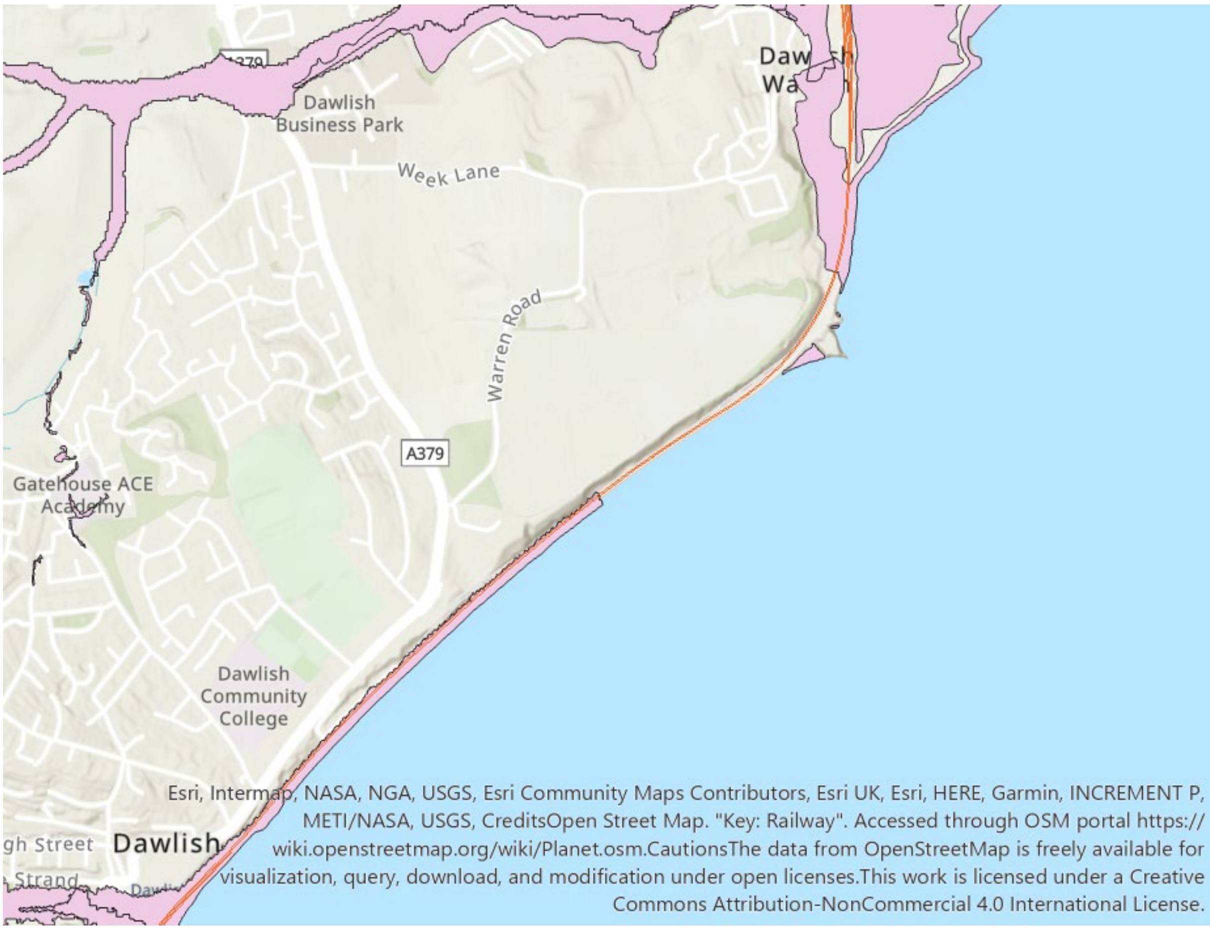

Figure 7 Map showing the vulnerability along the coast of the Dawlish railway. The seawall in this area is currently under construction.

5.0 Discussion

The results of this study indicate that there are a wide variety of responses taken by railway planning agencies in response to flooding induced by climate change. Some of them are institutional and some are on the engineering side and some are both. If we consider the three frameworks for evaluating interventions introduced in Section 2.0 Theoretical Framework, we can synthesise how these are implemented in a country's policy.

Many of the policy papers advocated for enhancing proactive maintenance as part of the Maintain and Manage strategy of the Four Broad Adaptation Strategies (Hodges, 2011). "The potential for disruption to transport infrastructure and the services it supports is of particular concern in countries like that have under-invested in their transport operations for many decades." (Heinz-Peter, 2017, p. 3)

The replacement of the Caland Bridge with the new Theemswegtracé in the Port of Rotterdam is an example of the. In future it will be unusual to replace an entire corridor in the Netherlands as most of the country should be relatively well protected anyway. In England, the abandonment of railway infrastructure has been a common practice in the past, but this was for reasons of economy. The future may require more track abandonment, though this will be a difficult strategy to implement in England because of the geographical limitations creating the flooding situations in the first place.

6.0 Conclusions

This research shows that some of the most stand-out measures to combat flooding induced by climate change are institutional in nature. The analysed policy papers suggest a coordinated approach in terms of actors, involving all stakeholders. Another of the best interventions advocated for in the policy papers is to combine flood protection interventions with other projects to improve the spatial realm in an area. This is consistent with the underlying principles of considering the future social environment and integrating with existing investments. (Quinn et al., 2017)

The vulnerabilities are considerably less in the Netherlands, owing to the existing centuries-old main flood defence system. Areas outside this system, such as industrial ports are highly vulnerable. River basins were less vulnerable than expected because, unlike England, few railways run through such locations, instead being located on higher ground.

The vulnerabilities are varied across England, both pluvial and coastal in nature. This requires further subdivided research, which Network Rail is undertaking by dividing England into six major "routes," each with its own managerial structure.

This research shows that England could be more proactive in this area like the Netherlands has been. This has been identified in several of the policy papers but not implemented.

6.1 Reflection on Research Process

This research involved consulting numerous policy papers and academic studies. I relied partially on my previous knowledge of the institutional setup of the railways of England and my geographic knowledge of the Rotterdam area.

Two cases were affected by construction work that was ongoing during this research: in Rotterdam, the Theemswegtracé opened to rail traffic on 8 November 2021, replacing the adjacent route via the Caland Bridge, which has since closed to rail traffic. This change is not yet reflected on maps and satellite images of the area, including the flood vulnerability maps of the municipality. To catch spatial changes like this, in future it would be prudent to visit research sites as much as possible.

Another change was the Dawlish seawall which will be reconstructed in two phases: the first completed in June 2020 and the second phase now underway.

During the course of the research it was decided to narrow the scope—from all of Great Britain to focusing only on England, for reasons identified earlier. As a result of this it would have been prudent to select a more narrow scope in the beginning to prevent wasted effort.

One limitation of this research is that it was difficult to analyse the entirety of the English railway network. Network Rail breaks England down into six sections for management and climate change adaptation purposes and that may be a wise approach here. Flood protection measures are also handled on a local scale.

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Appendix A: Coding Results from Policy Document Analysis

Code	Description	Number of Occurrences
Interventions--Institutional	Interventions recommended for institutions.	24
Interventions--Infrastructure	Recommended interventions related to physical infrastructure and engineering.	21
Vulnerabilities--Railway	Types of, and examples of, vulnerabilities to flooding of the railways identified in the policy documents.	19
Vulnerabilities--Flooding	Comments about flooding vulnerability not directly	7

	related to the railways, including those about climate change.	
Conclusions	Noteworthy statement made in the documents about flood management on railways as a whole.	11
Proactive	Remarks specifically about behaving proactively—usually with regards to maintenance.	5
Actors	Mentions of the various actors that may be involved.	13
Strengthen and Protect	Implementation of the "Strengthen and Protect" category of the classification of adaption strategies. (Hodges, 2011)	3
Enhance Redundancy	Implementation of the "Enhance Redundancy" category of the classification of adaption strategies. (Hodges, 2011)	3
Financing	Remarks related to financing and cost	11