Network Rail

Weather Advisory Task Force

Final Report

February 2021

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Executive Summary

Following the Carmont accident in August 2020, Network Rail commissioned an independent Weather Advisory Task Force (WATF) to review Network Rail's capability to understand and manage adverse weather, particularly with regard to earthwork failures, with the aim of equipping Network Rail with the knowledge base and competencies, so that it becomes better prepared and more resilient in the future.

The formation of the WATF is very timely. In recent years, there has been considerable progress in weather/climate science and its applications, including new analyses of past rainfall, improvements in observing systems, significant advances in early warning systems, local-scale nowcasting and forecasting, and the emergence of innovative digital technologies for gathering, combining and sharing information.

The WATF has gathered evidence on Network Rail's current procurement and usage of weather information and services across the organisation. The WATF has also sought to accelerate progress by demonstrating the 'art of the possible' with the latest Met Office operational forecasting capabilities and their potential utilisation within operational controls.

Finally, the WATF has considered how Network Rail should procure its weather services and keep abreast of the latest developments in the future, so that it benefits more immediately from advances in science and technology.

The WATF makes the following major recommendations:

Recommendation 1: **Cogent arguments in favour of a new approach to Network Rail's Weather Service provision have been presented throughout WATF report. Advances in forecasting across minutes, hours to weeks are not being exploited by Network Rail**. These would open up some major opportunities to deliver better early warnings to aid logistic planning, as well as new real-time, dynamic, location-specific forecasts and warnings that will improve operational safety and performance. A joint Met Office/Network Rail 'sandpit' trial has already demonstrated the substantial potential of these new forecasting tools to transform Network Rail's weather services, as well as showing the benefits of working together, through partnership, sharing information and action plans. **Latest forecasting capabilities should be formally trialled, under a structured framework agreement with the Met Office with the goal of implementing a full operational service.**

Recommendation 2: **Under asset management, the search for appropriate, spatially-varying thresholds for assessing the probability of earthwork failures, using statistical analysis, has proved to be very challenging for Network Rail.** Earthwork failures are rare, and each is unique in some way, so it is always going to be difficult to tease out the drivers/indicators using statistics. **Instead, the WATF recommends an alternative approach in which a forensic analysis of selected events is conducted, using all available evidence, including new databases on weather regimes, rainfall and local hydrogeomorphology indicators, to provide a complete picture of the hydro-meteorological context surrounding the failure.** This may help to identify

discriminating factors which can be used subsequently in a risk-based system for earthwork management. The WATF also recommends that Network Rail places less weight on soil moisture indices and considers alternative metrics linked directly to soil hydrology.

Recommendation 3: The Rail Technology Strategy is providing stepping-stones towards a data-driven railway. **The evidence gathered has cemented WATF's view that Network Rail urgently needs to transform the delivery of its weather services, by considering the development of a new hazard and impact-based digital platform which integrates all the relevant information to provide accessible, flexible and seamless services, driven by dynamic user specifications.** Network Rail should actively explore opportunities to embrace digital technologies, especially the Data Cloud and APIs, that could revolutionise how it delivers its weather services, from operations to asset management.

Recommendation 4: **The WATF has considered various ways in which Network Rail may procure its future weather services, including through more digital applications. The preferred option is a partnership-driven, integrated transport hub for the benefit of transport providers, passengers and freight users.** This will provide 24/7 access to all operational services and expert advice, including flooding, and thus deliver an authoritative set of services across Network Rail and its Routes and Regions. The Met Office already serves Highways England and NATS (National Air Traffic Services) and it would be logical to combine this expertise to deliver a fully integrated transport service.

Recommendation 5: **Network Rail needs to build its professional competencies in meteorology, hydrology and climate change so that its staff can act as intelligent users of science and services across all its functions. The WATF proposes the creation of an 'Academy' which will act to transform the culture of decision making in Network Rail.** By bringing together a diverse body of academics, service providers, Network Rail staff and its stakeholders, the Academy will engender a service-oriented culture under a common mission to deliver the safest, most efficient and resilient rail service for the UK, today and into the future.

Finally, we make two other points for Network Rail's consideration. First, the WATF was not tasked with assessing how Network Rail is responding to the challenge of future climate change, although its recommendations will strengthen Network Rail's capacity to do so. The UK's 3rd Climate Change Risk Assessment (CCRA3) will be published this year, and we recommend that Network Rail uses this opportunity to commission an in-depth study of its future climate risks.

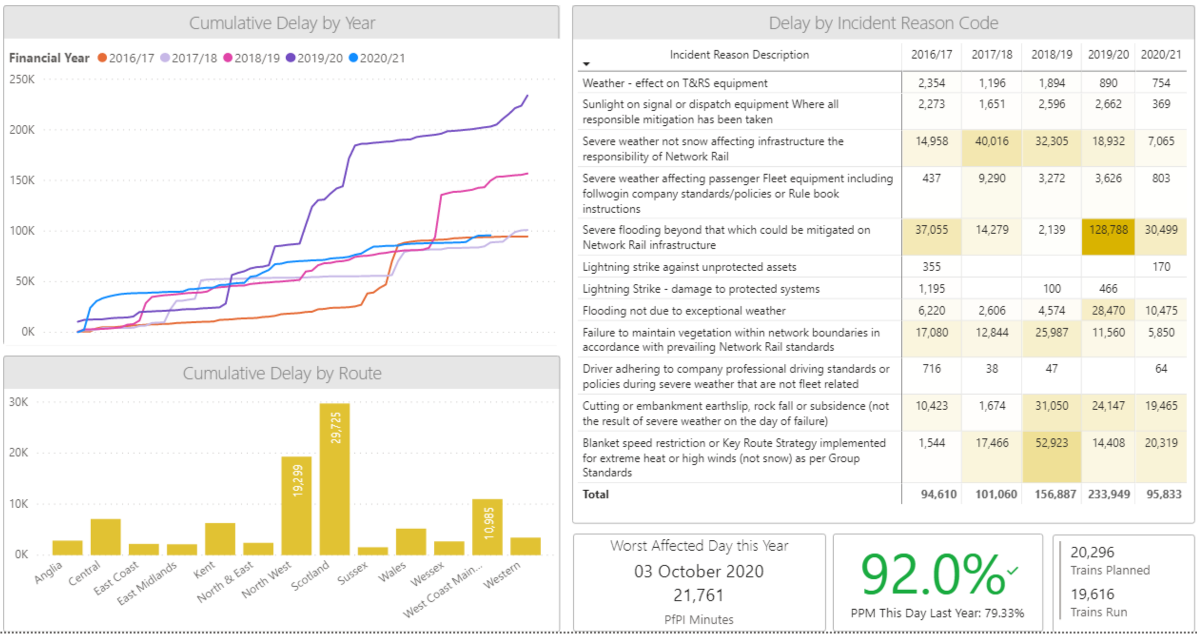
Second, Network Rail is a science and technology-driven organisation, from engineering to data-driven operations. This review has highlighted the need for Network Rail to develop stronger mechanisms for ensuring that it stays abreast of the latest scientific and technological advances and, where appropriate, exploit them. Network Rail should consider whether the establishment of external Scientific Advisory Committee(s) would serve it well and help to keep it at the forefront of the international rail industry.

In conclusion, the WATF would like to thank Network Rail and its staff, for their support, engagement and, indeed, enthusiasm for our work, which has made the creation of this report a truly rewarding experience.

1. Introduction

On 12 August 2020 at 0938 BST, a passenger train was derailed near Carmont as a result of washout from a drainage system following very heavy rain and thunderstorms during the preceding few hours. These thunderstorms were part of the breakdown of a period of high temperatures during the preceding week. The likelihood of widespread thunderstorms spreading from the South, across Eastern Scotland was well-forecast.

This event raised important questions about the resilience and safe performance of the railway in the context of extreme rainfall and its impacts on earthworks, and how the risk of such an event happening again can be minimised. Beyond that, Network Rail is increasingly exposed to hazardous weather with significant consequences for its performance (Figure 1.1). Delay minutes have grown year-on-year with the majority associated with severe weather and flooding. Consequently, this report will look beyond earthwork failures, to the wider implications of severe weather on the rail network and what can be done to mitigate its impacts.



Incident Reason Description	2016/17	2017/18	2018/19	2019/20	2020/21
Weather - effect on T&RS equipment	2,354	1,196	1,894	890	754
Sunlight on signal or dispatch equipment Where all responsible mitigation has been taken	2,273	1,651	2,596	2,662	369
Severe weather not snow affecting infrastructure the responsibility of Network Rail	14,958	40,016	32,305	18,932	7,065
Severe weather affecting passenger Fleet equipment including follwogin company standards/policies or Rule book instructions	437	9,290	3,272	3,626	803
Severe flooding beyond that which could be mitigated on Network Rail infrastructure	37,055	14,279	2,139	128,788	30,499
Lightning strike against unprotected assets	355				170
Lightning Strike - damage to protected systems	1,195		100	466	
Flooding not due to exceptional weather	6,220	2,606	4,574	28,470	10,475
Failure to maintain vegetation within network boundaries in accordance with prevailing Network Rail standards	17,080	12,844	25,987	11,560	5,850
Driver adhering to company professional driving standards or policies during severe weather that are not fleet related	716	38	47		64
Cutting or embankment earthslip, rock fall or subsidence (not the result of severe weather on the day of failure)	10,423	1,674	31,050	24,147	19,465
Blanket speed restriction or Key Route Strategy implemented for extreme heat or high winds (not snow) as per Group Standards	1,544	17,466	52,923	14,408	20,319
Total	**94,610**	**101,060**	**156,887**	**233,949**	**95,833**

Figure 1.1: *Summary of Delay Minutes since 2016/17. These have increased substantially in the last 2-3 years with the majority of delays associated with adverse weather. Source: Network Rail.*

Network Rail therefore commissioned an independent Weather Advisory Task Force (WATF) to review Network Rail's capability to understand and manage the implications of rainfall, with the aim of equipping Network Rail with the expertise and competences so that it can better manage the impacts of rainfall in the future.

The terms of reference of the WATF are to explore the following questions with the objective of shaping the organisation for moving forward, better equipped to understand the risk of rainfall to its infrastructure and operations:

i. What level of expertise in rainfall should Network Rail employ in order that it can either manage rainfall itself, or so that it can act as an informed client when procuring specialist services?

ii. To what extent is Network Rail availing itself of data and research on historical, current and future rainfall and its effects on the operational railway? How should such information be used to:

   a. understand the likely levels of rainfall today, at a location level, that may pose a risk to the operational railway;

   b. understand the potential levels of rain today and up to 10 years ahead, that could fall at a location, in order to estimate the potential damage to infrastructure that such levels could inflict;

   c. ensure that future engineering decisions (such as for drainage specifications) take account of local weather factors, and to identify where existing assets are insufficient; and

   d. track how changing land use and/or river management policies near the railway affect how quickly rain enters and leaves the system.

iii. How effectively does Network Rail make use of available forecasting technology to identify where rainfall could create a risk to the railway?

   a. How can it make better use of weather monitoring technology (such as rainfall radar) and state-of-the-art nowcasting to guide decision-making during a high-impact weather event?

   b. How can Network Rail ensure that it manages the risk while keeping the system open to passengers and freight who depend on the system?

iv. How extensively has Network Rail explored the potential of real-time weather monitoring technology, particularly with augmenting of different data sources (such as its asset databases), to introduce better means of identifying location specific risks?

   a. How could the EWAT process be improved to take advantage of such processes?

   b. What real-time weather competence and capability would support a national organisation with devolved accountability?

v. How should Network Rail use such weather expertise and competence to provide input into longer term planning or procurement decisions? This could be in earthworks engineering or providing guidance to track and rolling stock design specifications.

The formation of the WATF is very timely. In recent years, there has been considerable progress in weather/climate science and its applications, including new analyses of past rainfall, improvements in observing systems, significant advances in early warning systems, local-scale nowcasting and forecasting, and the emergence of innovative digital technologies for gathering, combining and sharing information.

Reflecting these recent advances, the following WATF members were appointed. The Chair of the WATF is Prof. Dame Julia Slingo (former Met Office Chief Scientist, 2009-2016); she is joined by Paul Davies (Met Office Chief Meteorologist and Principal Research Fellow) and Prof. Hayley Fowler (Professor of Climate Change Impacts, Newcastle University).

The WATF has gathered evidence on Network Rail's current procurement and usage of weather information and services across the organisation. Although Network Rail understands the importance of weather to its operations, it currently does not have the capabilities and resources to keep abreast of the latest scientific and technological advances. Consequently, the WATF has focused on bringing Network Rail up to speed on these latest advances, looking forward to how these can be utilised across Network Rail's distinct weather needs – (i) operational controls and (ii) route asset management - with the goal of reducing operational disruptions and reducing asset vulnerability. Where appropriate the WATF has interacted with the Earthworks Task Force led by Lord Robert Mair.

Rather than just making recommendations for future actions, the WATF has also sought to accelerate progress by demonstrating the 'art of the possible' with the latest Met Office operational forecasting capabilities and their potential utilisation within operational controls. It has commissioned two scoping studies, firstly on the potential drivers of Earthwork failures, and secondly a joint 'sandpit' trial, in real-time, of the opportunities afforded by access to the latest forecasting techniques. The focus is on extreme rainfall, reflecting the remit of the WATF, but the generalisation to other weather variables has also been considered.

Finally, the WATF has considered how Network Rail should procure its weather services and keep abreast of the latest developments in the future, so that it benefits immediately from advances in science and technology.

The main body of the report summarises the following range of outputs from the WATF which are available on request. These include:

(i) WATF Briefing Report on '*Current National Capabilities in Observing and Forecasting Rainfall and its Impacts*': The aim of this briefing is to bring Network Rail up to speed on the latest scientific and technological advances in these areas so that further work starts from a common understanding of what is now possible. Julia Slingo, Paul Davies and Hayley Fowler, November 2020.

(ii) Met Office Report on '*Identifying high-risk weather patterns associated with landslide and flood-related impacts on the rail network*': Preliminary analysis of earthwork failures, daily rainfall accumulations and daily weather pattern occurrences to identify 'high-risk weather patterns' relevant to hydro-meteorological failures across the rail network in England, Scotland and Wales. Jo Robbins and Paul Davies, November 2020

(iii) WATF Report on '*A Critical Enabler for a Digital Railway: Hazard Impact-based Predictions for the Railway System*': Outlines a new hazard, impact-based services framework providing accessible, flexible and seamless predictions, driven by dynamic user specifications for data analysis, visualisation and integration into platforms, tools and technologies. Paul Davies and Brian Haddock, December 2020

(iv) Summary report on '*Forecasting Sandbox Trial*': Outcomes of the joint sandbox trial between Network Rail and the Met Office to access, exploit and explore next generation forecast capabilities and expertise across the whole '*awareness – preparedness – response – recover*' cycle to improve decision making. Paul Davies and Brian Haddock, January 2020

The report is structured as follows. Chapter 2 sets out the context and complexity of Network Rail's exposure to weather hazards, and Chapter 3 discusses the emerging signals of climate change. Chapter 4 summarises Network Rail's current procurement and utilisation of weather data and services. Chapter 5 sets out the current status of observing rainfall and the generation of new rainfall climatologies, while Chapter 6 summarises the latest advances in weather forecasting, and Chapter 7 outlines some new products and services that would benefit Network Rail. Chapter 8 considers the challenging question of identifying the hydro-meteorological thresholds for earthwork failure and outlines some possible ways forward. Chapter 9 summarises the results of the WATF Sandpit Trial of latest forecasting capabilities. Chapter 10 presents some innovative ideas for how Network Rail might use the latest digital technologies to advance its hazard warning systems. Finally, Chapter 11 puts forward some proposals for future business models for Network Rail's weather service provision, and possible structures to secure its future professional competencies in managing adverse weather. Chapter 12 provides a summary of the WATF recommendations.

Throughout, the WATF has benefited enormously from the strong engagement and enthusiasm of Network Rail staff and we thank them for their support. In particular, much of the work would not have been possible without Brian Haddock, Head of Seasonal and Weather Resilience, and we gratefully acknowledge his commitment and contribution.

2. Context of the challenges facing Network Rail and its weather risk management

Managing weather risks has been challenging for Network Rail and its predecessors from the very beginning. Extreme weather events that cause loss of life and damage to infrastructure have always occurred due to the high levels of weather and climate variability that the UK experiences. This is because of the complex place in the global climate system in which the country sits - at the end of the North Atlantic jet steam where cold, polar and warm, sub-tropical air masses collide, and with maritime influences from the ocean to the west, and continental influences from Europe to the east (Figure 2.1). In reality, the type of air mass affecting the British Isles only gives an indication of the type of weather that may occur. The actual weather depends upon the detailed history of the air, the speed of movement and the surface over which it flows.

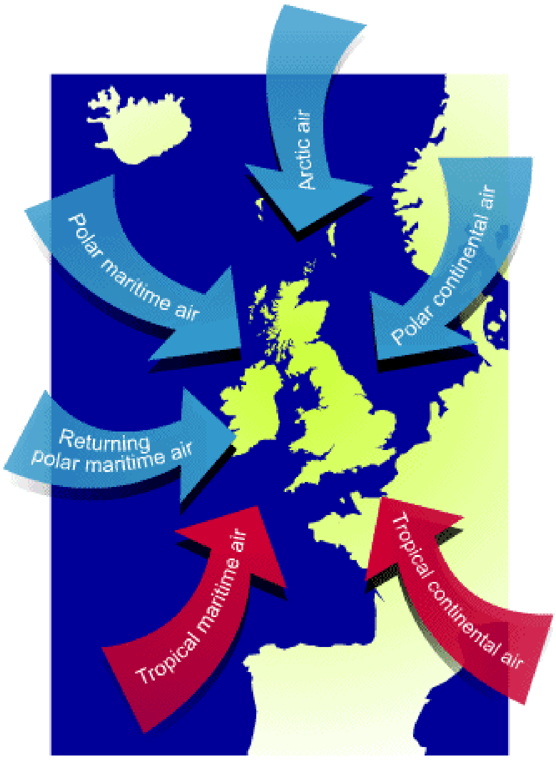


Figure 2.1*: Schematic of the various airmasses that affect the UK.*

The four principle airmasses are:

i. Tropical maritime – warm and moist
ii. Tropical continental – warm and dry
iii. Polar maritime – cold and (fairly) moist
iv. Polar continental – cold and dry

To these must be added two further air masses:

- *Returning polar maritime, which consists of polar air that has moved southwards over the sea and then turns northwards and approaches the British Isles from the south.*
- *Arctic, which consists of air which has travelled southwards from the Arctic.*

Source: MetLink, Royal Meteorological Society

All these factors create a unique set of challenges for weather forecasting, which when combined with the UK's complex landscape, makes managing the impacts of day-to-day weather particularly complicated compared with other countries. Furthermore, estimating risks from extreme or high-impact events is difficult because of the limited length of the observational record and because extremes are by definition rare.

Network Rail's exposure to earthwork failures depends on understanding the hydrological factors that cause these failures. Unfortunately, the translation of rainfall into hydrological impacts is extremely difficult at the local scale of Network Rail's assets. We do not fully understand how the terrestrial water cycle functions, how water moves between reservoirs and how long water is stored in them. Without knowledge to constrain rates of flow and soil moisture residence times, it is hard to make informed management interventions. This gap was identified in the National Flood Resilience Review (2016)[1] which advocated a more structured end-to-end system to evaluate and respond to hydrological risks (see red box in Figure 2.2). The Natural Environment Research Council (NERC) subsequently commissioned a major research project to develop an integrated hydrological model. This will ultimately help to make an end-to-end assessment of Network Rail's exposure to flooding a reality and enable it to plan its response and test its mitigation options.

Current capabilities in predicting hydro-meteorological risks are largely confined to river (fluvial) flooding and are increasingly skillful, associated with better monitoring of rainfall and river/stream flows, advances in modelling individual catchments and more joined up forecasting systems (e.g. joint Met Office/EA Flood Forecasting Centre). Forecasting for surface water flooding is also improving and this will also help Network Rail which is currently very vulnerable to flooding.

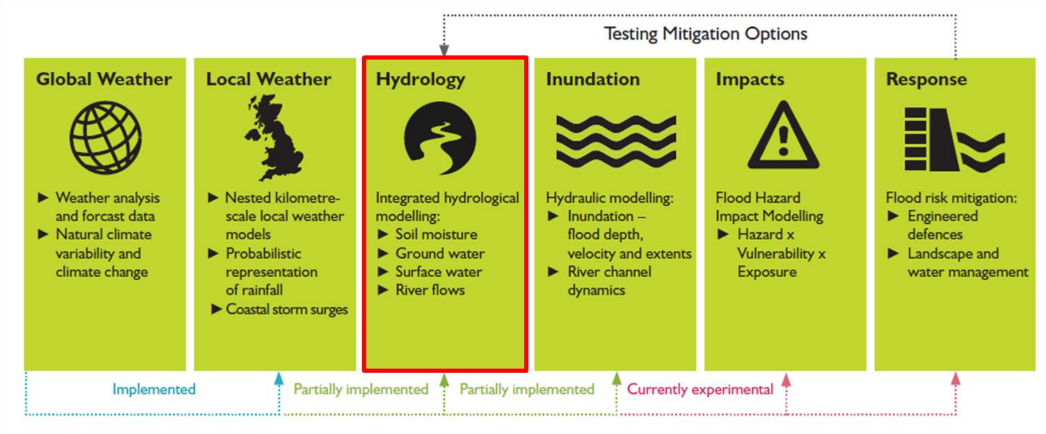


Figure 2.2: *Schematic of an end-to-end simulation system to quantify and predict hydro-meteorological risks and to test mitigation options (based on NFRR 2016).*

It is important to understand, therefore, that whilst there now exists considerable skill in observing and forecasting rainfall, the science behind the translation of rainfall into geohazards, such as washouts, earth slides and other earthwork failures, is immature and remains the biggest gap in going from the meteorological hazard to the impact on the ground. This is one of the biggest challenges for Network Rail in assessing the exposure of its assets to extreme rainfall events.

[1] National Flood Resilience Review, 2016: See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/551137/national-flood-resilience-review.pdf

3. Emerging signal of climate change

As well as dealing with our highly variable weather and climate, we now have to factor in the influence of anthropogenic climate change. There is no doubt that climate change is affecting the UK and shifting the odds of certain high-impact weather events. This means that infrastructure that was previously designed to be resilient to the UK's past weather and climate may no longer be so. This is especially so when we consider that much of the UK's rail network is over a century old.

Each year the Met Office publishes its annual State of the UK Climate (e.g. Kendon et al. 2020[2]) which provides a comprehensive analysis of our changing climate. The latest evidence shows that the Earth has continued to warm, with 2020 joining the other years since 2015 as the warmest five years on record; indeed 2020 concludes the Earth's warmest 10-year period on record. The same evidence for continued warming is also seen in UK surface temperatures (Figure 3.1). In the context of the Central England Temperature record going back to 1659, the 21st century has so far been warmer overall than any of the previous three centuries.

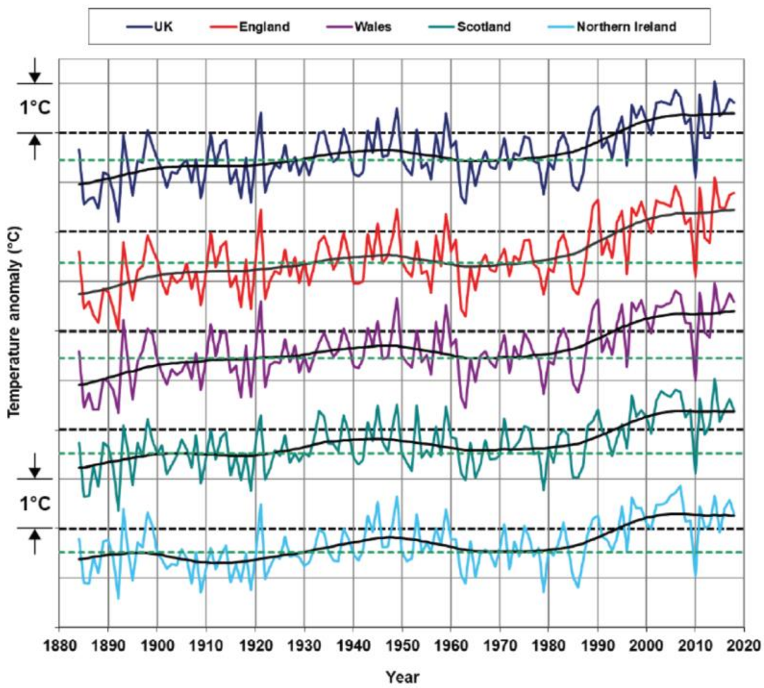


***Figure 3.1**: Annual mean surface temperature for the UK and countries, 1884-2018, expressed as anomalies relative to the 1981-2010 average (dashed black line). The lower dashed green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of +/- 1°C. Source: Kendon et al. (2020)*

Unlike UK temperatures where there is a clear signal of climate change, annual mean rainfall climatologies (Figure 3.2) are dominated by natural variations from year to year. Nevertheless, there are indications of small increases over the UK and its nations since the 1970s, especially

[2] Kendon, M., M. McCarthy, S. Jevrejeva, A. Matthews, T. Sparks, and J. Garforth, 2020: State of the UK Climate 2019. Int. J. Climatology, DOI: 10.1002/joc.6726

for Scotland where there has been an 8% increase in the last decade compared to the 1961-1990 long-term average.

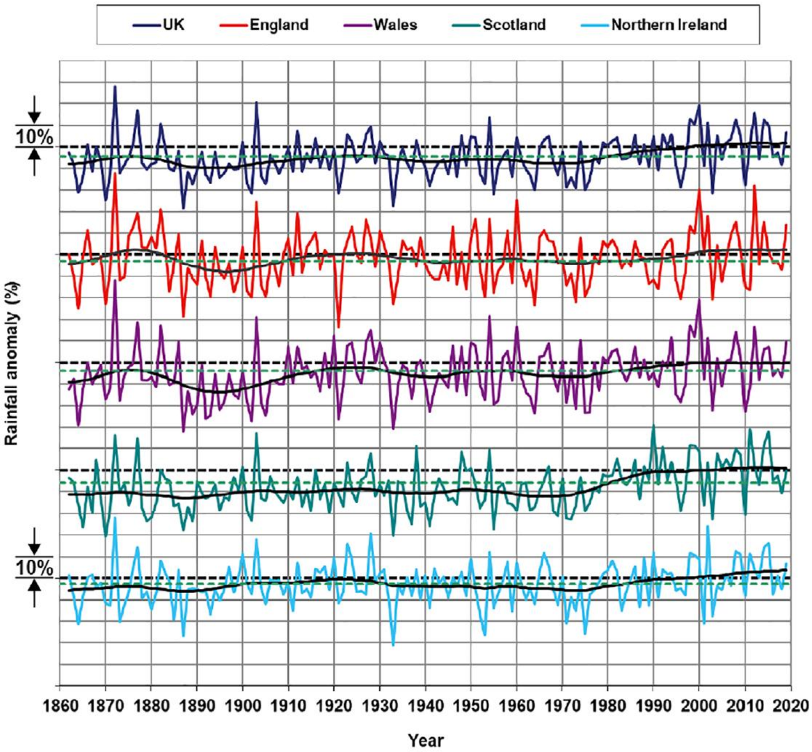
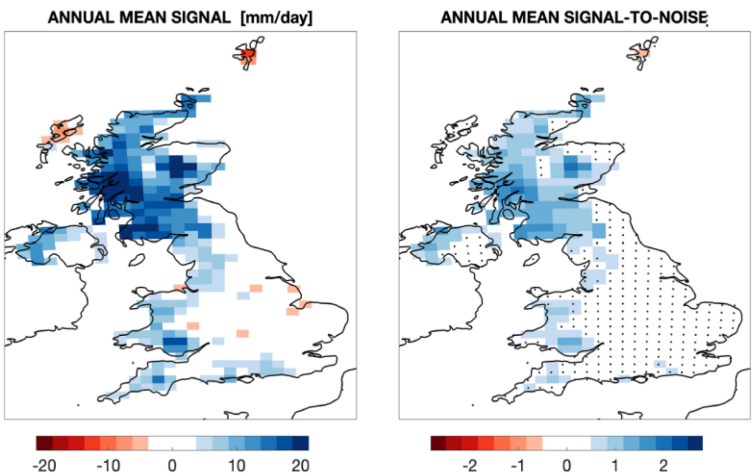


Figure 3.2: *Annual mean rainfall for the UK and nations, 1862-2018, expressed as % anomalies relative to the 1981-2010 average (hatched black line). The lower hatched green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of +/-10%. Source: Kendon et al. (2020).*

A new analysis of UK gridded rainfall data for 1862-2017[3] has recently shed some further light on the detection of long-term trends in rainfall observations at the regional scale, potentially due to climate change. By expressing the signal as the % change in rainfall per 1°K change in the global mean surface temperature, regional variations in rainfall trends across the UK can be detected in the context of global warming (Figure 3.3).



[3] Hawkins, E., D. Frame, L. Harrington, M. Joshi, A. King, M. Rojas and R. Sutton, 2020: Observed Emergence of the Climate Change Signal: From the Familiar to the Unknown. *Geophysical Research Letters*, https://doi.org/10.1029/2019GL086259

***Figure 3.3**: Signal (left) and signal-to-noise ratio (right) for UK annual mean precipitation for 1862 to 2017. The signal is presented as the % change in rainfall per degree of change in the global mean surface temperature. Blue colours represent regions that are getting wetter, and red colours, those that are getting drier. Source: Hawkins et al. (2020).*

Figure 3.3 (left) shows that the signal (S) in trends in annual mean rainfall is dominated by increases, mainly over the west side of the UK and especially over Scotland. However, this does not necessarily mean that there is a direct link between warming and this signal for increased rainfall, because of the large natural multi-decadal fluctuations in the UK's climate. By considering how much of this signal (S) is due to natural variability ('noise', N), regions where the signal exceeds the noise (S/N is greater than 1) can be interpreted as places where the climate is definitely changing. This can be interpreted as places where we are now moving from the 'familiar' towards being 'unusual', relative to lived experience; in other words where there might be unexpected impacts or consequences that are outside our ability to handle them. Figure 3.3 (right) identifies Scotland and the mountainous regions of western England where S/N exceeds 1 and therefore where the influence of climate change is already emerging and potentially challenging our resilience.

In all regions, the influence of climate change is to increase rainfall, consistent with the fundamental physics that says that warmer air holds more moisture (i.e. for 1^{o}K rise in temperature, moisture content increases by 7%.). In heavy rain situations, this translates to similar increases in rainfall. So, what we can say is that higher rainfall totals and the severity of the flooding in recent years (for example 2013/14 and 2015/16 events) are consistent with the basic premise that a warming world holds more moisture; in other words, the same weather system 50 years ago would have produced less rainfall than today.

There is also a growing body of literature which argues that the effects of climate change will also be manifested in changes in the frequency and intensity distributions of daily and sub-daily rainfall, even when averages over longer timescales are stable.

There is some evidence for the increasing occurrence of widespread heavy daily rainfall across the UK in the last few decades, and similarly, the statistics on local extreme daily rainfall also suggest an increasing occurrence. A major review[4] of the current anthropogenic intensification of short-duration rainfall extremes concludes that:

- Heavy rainfall extremes are intensifying with warming at a rate generally consistent with the increase in atmospheric moisture (i.e. 7% per ^{o}K), for accumulation periods from hours to days.

[4] Fowler, H. J., G. Lenderink, A. F. Prein, S. Westra, R. P. Allan, N. Ban, R. Barbero, P. Berg, S. Blenkinsop, H. X. Do, S. Guerreiro, J. O. Haerter, E. Kendon, E. Lewis, C. Schaer, A. Sharma, G. Villarini, C. Wasko and X. Zhang, 2020: Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth and Environment*, in press.

- In some regions, stronger increases in short-duration, sub-daily, extreme rainfall intensities have been identified, up to twice what would be expected from atmospheric moisture increases alone.
- Stronger local increases in short-duration extreme rainfall intensities are related to convective cloud feedbacks involving local storm dynamics.
- The evidence is unclear whether storm size has increased or decreased with warming; however, increases in rainfall intensity and the spatial footprint of the storm can compound to give significant increases in the total rainfall during an event.
- Evidence is emerging that sub-daily rainfall intensification is related to an intensification of local flash flooding.

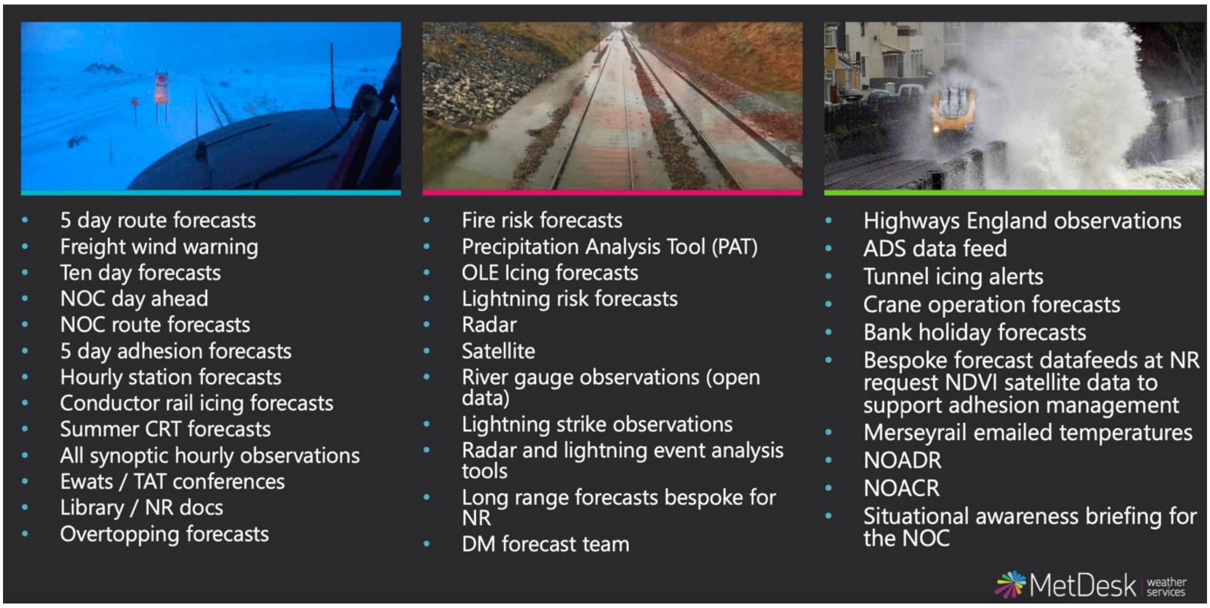
In summary, the UK's climate is already changing in significant ways for Network Rail's operations and assets. Down the west coast, rainfall has already increased, particularly in autumn and winter, extremes of daily and sub-daily rainfall are intensifying, sea levels are rising, and summer high temperatures are becoming more prevalent. This means that Network Rail must begin now to adapt to a changing climate.

4. Current procurement and application of weather data and services

Network Rail currently procures its weather advice from MetDesk Ltd, a private sector weather service provider. This is done through the standard commercial procurement process where Network Rail defines its requirements, and companies tender to deliver them. There are economic advantages to commercial procurement, but also disadvantages in that the procured services are pre-defined based on information at the time of procurement. This means that advances in science and technology that may occur during the contracted period (e.g. 5 years) will not necessarily be made available to Network Rail.

MetDesk bases its services on observational and forecast data that it purchases from a data catalogue that is populated by the leading forecast producers, such as the Met Office and the European Centre for Medium Range Forecasts (ECMWF) based in Reading. As far as we could ascertain, MetDesk bases its forecast products on the deterministic ECMWF global forecast at 12km resolution and does not directly incorporate probabilistic information in its weather warnings. In addition, MetDesk creates a precipitation nowcast using the Met Office radar-derived precipitation intensities; these have been quality-controlled and interpolated to a 1km grid. It also accesses a number of other data products from satellites, river gauges etc. as listed below in Table 4.1. From these data, MetDesk creates a wide range of bespoke products and services for Network Rail (Table 4.1).

Table 4.1: *Summary of the current weather and data services provided to Network Rail through its contract with MetDesk Ltd. Source: MetDesk Ltd.*



The value of these private-sector weather service providers is the emphasis they place on understanding and being responsive to customer needs, and on the capabilities to develop algorithms and applications that take account of the customer's exposure and vulnerability. Network Rail has a small team of weather specialists, Network Rail Weather Services (NRWS), who work with MetDesk to support the operational railway with forecasts, and who work with the engineering standards team to help improve weather resilience. Our assessment is that MetDesk has served Network Rail well, but as we discuss later, it is limited by its capacity to access, absorb and process the very large data volumes now being produced by the major forecast producers, and to keep up with the latest advances in weather science and technology.

One of the challenges that any weather service provider to Network Rail faces, is the rigidity and complexity of the decision tree that has to be in place to translate weather alerts to actions, and to propagate these alerts through the management structure out to the routes and regions.

The current approach to weather forecast management uses Extreme Weather Action Teleconferences (EWATs) to advise routes and regions of forthcoming adverse weather. MetDesk provides a five-day outlook of weather conditions at a national and local level to raise awareness of possible adverse or extreme events. These forecasts are updated daily at 0300hours and communicated to operations control centres and to EWATs.

When action is triggered, the regional EWAT brings together route control, maintenance, operations, and train and freight operators to amend timetables and make critical decisions to reduce safety risk. Route teams inform the national team and information is distributed across the industry. Plans and processes are reviewed based on learning points from events. Within these calls the Route teams and train operators agree their plan. If certain thresholds are forecasted to be breached then both Network Rail and the operators agree on a plan to reduce speeds, and mobilise operational and maintenance staff.

When two or more routes may be affected by an impending weather event, a national EWAT is invoked led by the National Operations Centre (NOC) and attended by the Department for Transport (DfT). An equivalent system operates in Scotland's Railway with Transport Scotland.

The forecasts are provided in tabular form for routes, regions and specific assets, colour coded in terms of the alert level. Alert levels are defined through a set of thresholds (Table 4.2), which reflect the sensitivity of the network and train operators to a range of weather factors, such as high temperatures and the risk of rail buckling.

Table 4.2: Current national meteorological thresholds for triggering alert levels. Source: Network Rail.

National Table				
Wind				
Category	**Normal**	**Aware / Level 1**	**Adverse / Level 2**	**Extreme / Level 3**
Sustained (mph)	29 or less	30 to 39.9	40 to 49.9	50 mph or more
Hourly Gusts (mph)	39 or less	40 to 49.9	50 to 59.9	60 mph or more
Rain				
Category	**Normal**	**Aware / Level 1**	**Adverse / Level 2**	**Extreme / Level 3**
Hourly (mm)				
3 Hourly (mm)	less than 3mm	3 to 4.9mm	5 to 9.9 mm	10mm or more
12-hour	less than 15mm	15 to 19.9mm	20 to 24.9 mm	25mm or more
12-hour on 100% Wet Soil (mm)	less than 5mm	5 to 7.9 mm	8 to 10 mm	10mm or more
Daily (mm)	less than 30mm	30 to 39.9	40 to 49.9	50 or more
Daily on 100% Wet Soil (mm)	less than 10mm	10 to 14.9 mm	15 to 19.9 mm	20mm or more
15 Daily (mm)	less than 70mm	70 to 99.9 mm	100 to 149.9 mm	150mm or more
Temperature				
Category	**Normal**	**Aware / Level 1**	**Adverse / Level 2**	**Extreme / Level 3**
Heat (°C)	less than 20 C	20 to 24.9	25 to 28.9	29 or more
Cold (°C)	warmer than -0	0 to -2.9	-3 to -7	-7 or colder
Frost (°C) (Minimum air temperature - wind >12 mph)	warmer than -0	-0 to -0.9	-1 to -2.9	-3 or colder
1 Day Diurnal Cycle (°C)	less than 13 C	13 to 15.9	16 to 17.9	18 or more
Snow				
Category	**Normal**	**Aware / Level 1**	**Adverse / Level 2**	**Extreme / Level 3**
Daily Snowfall (cm)	1.9 or less	2 to 4.9	5 to 14.9	15 or more
Accumulation	TBD	TBD	TBD	TBD
Drifting Risk	None	Low	Medium	High

Despite the granularity of the forecasts, these thresholds are fixed in time and applied nationally, and so do not reflect the different levels of exposure across the network, for example the type of track and its susceptibility to high temperature stress, or the evolving vulnerability due to antecedent weather conditions.

The rainfall thresholds are particularly problematic. It is not clear how they have been set and what risks they are intended to mitigate – adhesion, flooding, earthwork failures? Although there is a distinction between the thresholds for saturated and unsaturated soils, presumably to address the heightened risks of flooding and earthwork failure, this takes no account of regional and local variations in exposure related to terrain, hydrogeomorphology, or proximity to rivers, for example. Also, as we discuss later in Chapter 8, soil wetness alone is not necessarily a good indicator of flood or earthwork risk.

We further note that the thresholds for sub-daily rainfall are rather low and need some further work with regard to understanding the likely occurrence of different rainfall intensities and the potential impact on the railway, such as flash flooding and wash-outs. The new climatologies of daily and sub-daily rainfall, described later in Section 5.2, provide opportunities to refine these thresholds.

It is clear that the weather alert thresholds require a major overhaul. They need to be dynamic in space and time, to be based on multiple predictors and to reflect the variations in exposure and vulnerability across the network.

MetDesk also produces a Precipitation Analysis Tool (PAT) based on radar observations, which provide NWRS with up-to-the-minute visualisations of instantaneous precipitation intensity at 1km resolution, along with a nowcast for the next 2 hours. These serve to inform NRWS of the evolving weather situation, which provides important additional advice in rapidly evolving weather conditions and complements the daily forecast. The PAT also produces time-aggregated precipitation amounts for a set of assets nominated by the Geotechnics team to be used to assess earthwork failure risk.

Following Carmont, Network Rail has acted swiftly to improve its preparedness for adverse and extreme rainfall events, and their potential impacts on earthworks through the development of a Convective Alert Tool. A revised decision tree for these events has been implemented, based on thresholds separated into extreme convective intensity (see Table 4.3) and heavy rainfall accumulation (see Table 4.4).

***Table 4.3**: Extreme convective intensity thresholds, introduced following Carmont, for triggering alert levels, nationally.*

Threshold	Alert Level	Response
3 hour: <30mm convection rainfall	Normal	No action required
3 hour: 30mm – 39.9mm convection rainfall	Adverse	Review forecast continuously. Prepare to manage train speed and service.
3 hour: ≥40mm convection rainfall	Extreme	Reduce speed of trains appropriately (see 20.2).

The convective intensity thresholds in Table 4.3, are much higher than the sub-daily thresholds in Table 4.2, and much closer to those typically observed in localised storms and intense convection, such as occurred at the time of Carmont. Further refinement of these thresholds to include hourly thresholds should be pursued using the latest evidence from observations and weather models.

For heavy rainfall, where the risks of earthwork failure and/or surface water flooding are likely to be elevated, a new set of PAT thresholds has been defined (Table 4.4), which uses a combination of rainfall intensity and soil moisture conditions, defined here in terms of a Soil Moisture Index (SMI). However, the definition of these thresholds is very challenging because of the complexity of earthwork assets and the local nature of surface water flooding. This will be discussed more comprehensively in Chapter 8.

Table 4.4: Proposed implementation of the Precipitation Alert Tool, PAT, in combination with soil moisture levels to act as an alert system for earthwork failures during heavy rainfall. The thresholds are intended to be location-specific based on the statistical analysis discussed in Chapter 8.

Rainfall & Soil Moisture Levels	PAT Alert Level	Response
*hr rainfall ≥**mm AND SMI≥**	Normal	No action required.
*hr rainfall ≥**mm AND SMI≥**	Adverse	Review forecast regularly. Prepare to manage train speed and service.
*hr rainfall ≥**mm AND SMI≥**	Extreme	Reduce speed of trains appropriately in the affected location (see 20.2)

Beyond the operational weather forecasts and alerts discussed above, Network Rail and its various bodies also use weather data and services to inform a variety of activities, from earthwork management to rail safety. In gathering our evidence, it became clear that there is a wide range of unilateral initiatives across these various bodies, using different evidence bases and procuring services from a range of providers. It was not clear to us that the NRWS was adequately engaged or consulted.

In our assessment of the current use of weather information by Network Rail, we do not have the expertise to judge the effectiveness of the control mechanisms used in Network Rail to mitigate the effects of adverse weather. We will however make the following general comments:

(i) The current operational weather services are quite static, based primarily on a daily forecast update, and with only limited capability (e.g. through the PAT) to adjust alerts and operational controls to the evolving weather situation. This reflects the current granularity of the forecast provision in space and time, as well as the complexity of the decision tree required to translate alerts into operational decisions, due to the diversity of regional controls and train operators. The result is that blanket restrictions are frequently imposed.

(ii) The weather alert thresholds, used operationally to mitigate weather-associated risks and manage safe train operations, require a major overhaul. They need to be dynamic in space and time, to be based on multiple predictors and to reflect the variations in exposure and vulnerability across the network. Unless this action is taken it is clear that blanket restrictions will continue, that there will be more instances of poor preparedness for adverse weather, and that passengers will continue to suffer from unexpected delays and cancellations.

(iii) The current procurement process means that there is limited opportunity to evolve the current services during the contract period, as new science and technology emerges, and operational and asset management needs change. That being said, MetDesk seems to be responsive to Network Rail's needs, and we note particularly the rapid development of new services following Carmont.

(iv) Weather pervades many aspects of Network Rail's operations, beyond daily weather alerts, and with a diverse range of needs. There does not seem to be a central core of expertise - an 'authoritative voice' - that can be drawn on to ensure that weather science and data are used correctly and coherently across the organisation. There also seemed to be a lack of coherence on the procurement of expert weather and flooding services combined with a lack of knowledge of existing, external capabilities that could be levered rather than procuring something new. The risks of duplication, of divergent evidence, and sub-optimal decision-making are potentially significant.

5. Current advances in understanding the characteristics of the UK's rainfall

5.1 Observing and Measuring Rainfall

Today, there are three main platforms for observing and measuring rainfall – gauges, radar and satellites. Each has their strengths and weaknesses, and it is important to appreciate these, especially in the context of heavy rainfall or extreme events.

The Met Office operates a network of 15 C-band weather radar in the UK. During the period 2012-18 the Met Office radars were all renewed to offer Doppler and dual-polarisation capability. This has enabled the quality of radar precipitation estimates to be improved, through better filtering of non-precipitation echoes, improved estimation of high intensity precipitation and ability to distinguish between different types of precipitation, such as hail and snow. There are nevertheless some limitations in radar observations in complex landscapes, such as the Lake District, and in situations with exceptionally high rain rates (Figure 5.1).

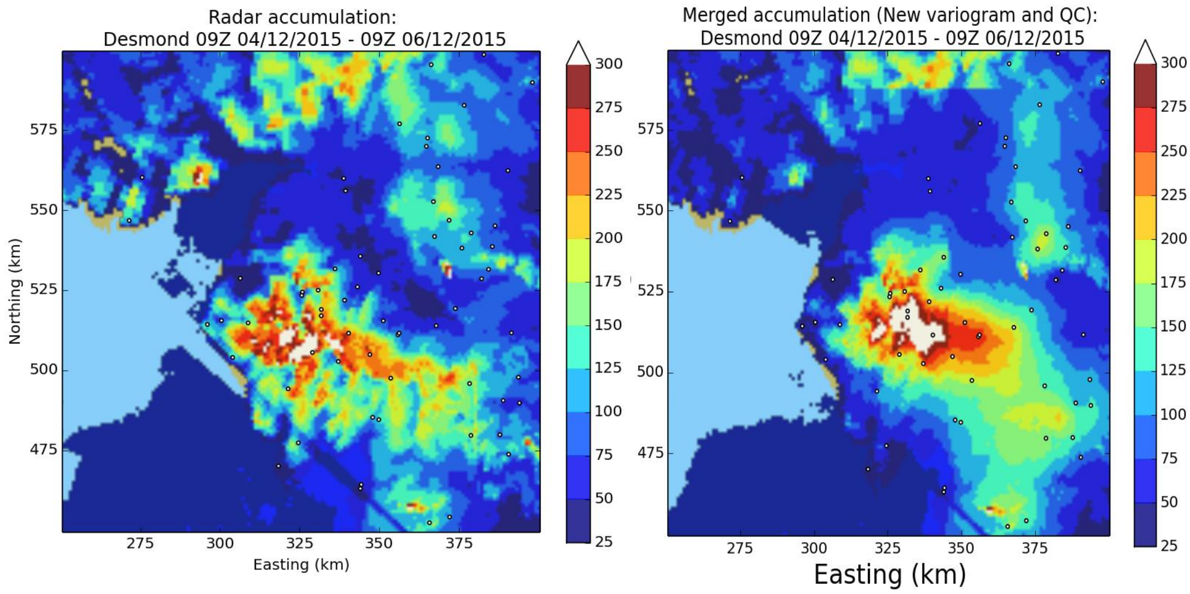


Figure 5.1: *Example from Storm Desmond of the limitation of radar rainfall observations (left panel) in complex terrain such as the Lake District. By merging in rain gauge observations (right panel) a more accurate assessment of rainfall accumulations is achieved.*

There is also ongoing development of products which more fully exploit the vertical information in the latest radar platforms. The advantage of these products is that the evolving vertical structure of storms can be followed as well as their horizontal rainfall footprint (Figure 5.2). The vertical structure identifies how the storm is growing, whether this is in terms of precipitation intensities, wind velocities, or in hail formation and the likelihood of lightening. This provides a view inside storms and enables the detailed location and characterization of associated hazardous weather. As will be shown later (see Section 6.3), this is enabling new advances in nowcasting severe convective storms, of the type seen over Stonehaven.

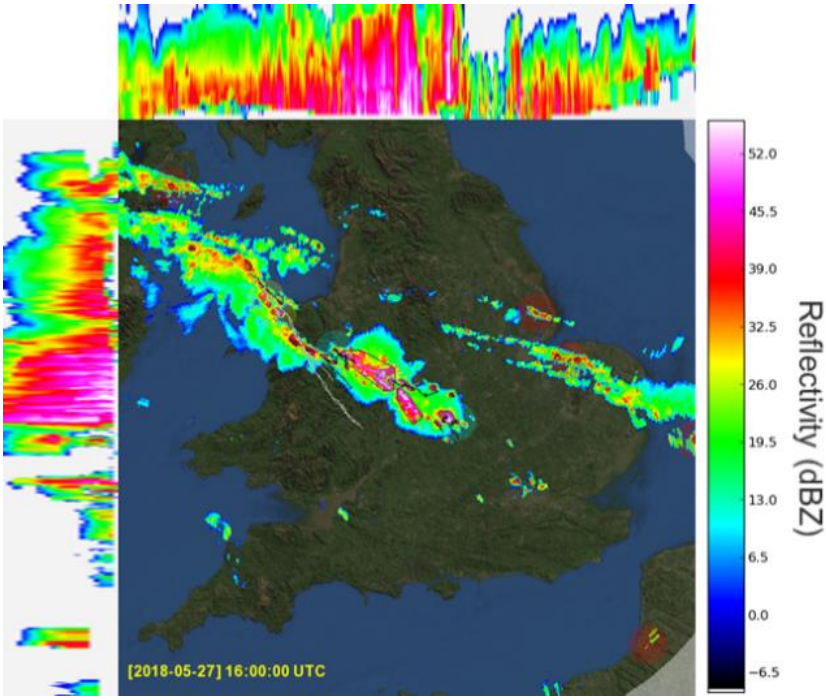


***Figure 5.2**: Example of 3-dimensional radar information showing the horizontal distribution of heavy rainfall and the vertical structure through the line of convective elements. Three-dimensional radar observations allow the horizontal location and depth of convective cells to be easily identified, enabling better advice and warnings during a severe weather event.*

The Met Office also operates a network of around 250 tipping-bucket rain-gauges, which record every time 0.2 mm rainfall is measured. The Environment Agency (EA), Natural Resources Wales (NRW), and the Scottish Environment Protection Agency (SEPA) operate more extensive rain gauge networks in England, Wales and Scotland respectively, a sub-set of which are shared with the Met Office in near real time. Data from around 1000 EA, NRW and Met Office rain gauges are used as input to a radar-gauge merged product, covering England and Wales. This product combines the strengths of both sources of rainfall data to generate 15 minute and 1-hour rainfall accumulations. Initial products are produced within 1 hour, and a delayed product, produced 24 hours in arrears, but incorporating more rain gauge data, is generated for post-event analysis.

The Meteosat Second Generation (MSG) geostationary satellites offer data with sufficient temporal and spatial resolution over the UK to be beneficial for estimating precipitation. This enables precipitation rates to be estimated beyond the maximum range of the weather radar network, albeit with lower quantitative accuracy. There are other satellite products which are useful for monitoring severe weather, including severe convection, daytime microphysics and overshooting tops. Visualisation of data from multiple observation sources (e.g. radar, satellite and lightning detection networks) is particularly useful for real-time monitoring of the evolution of high-impact convective storms. The combined radar and satellite precipitation rate product is used as the basis for precipitation nowcasts (see Section 6.3).

Today, weather radar is often the preferred option for estimating rainfall, but ideally, the best outcome is achieved when this is combined with gauge and satellite data and quality-controlled (Figure 5.3). A new UK hourly rainfall dataset is currently being constructed, beginning in 2004, which merges gauge, radar and satellite observations (UKGrsHP), and which will provide more robust estimates of local extremes[5].

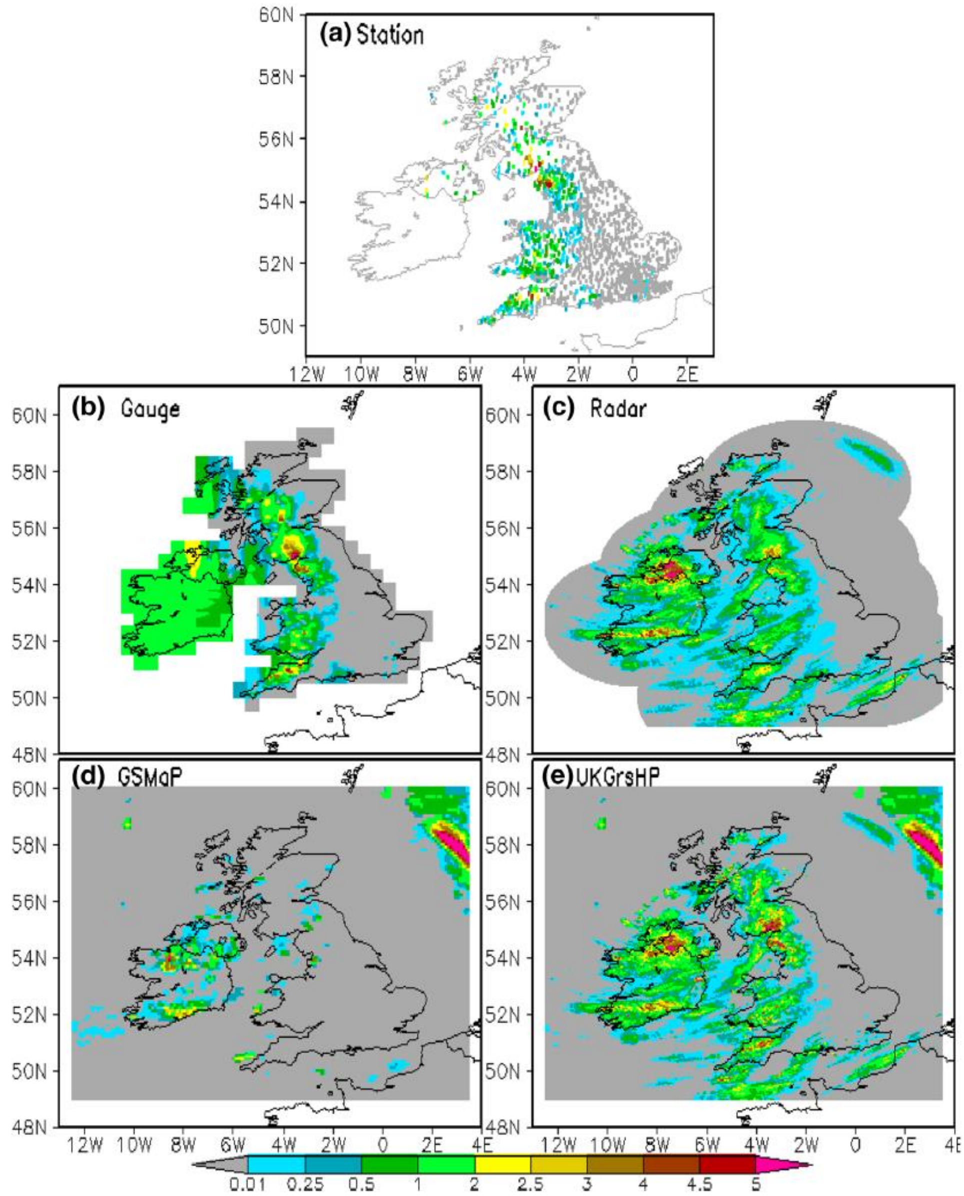


Figure 5.3*: Spatial distribution of hourly precipitation (mm/h) at 12Z, 1st February 2014. (a) Station observations; (b) gauge analysis data interpolated from 1903 station observations*

[5] Yu, J., X-F. Li, E. Lewis, S. Blenkinsop and H. J. Fowler, 2020: UKGrsHP: a UK high-resolution gauge–radar–satellite merged hourly precipitation analysis dataset. *Climate Dynamics*, 54, 2919–2940. https://doi.org/10.1007/s00382-020-05144-2

shown in (a); (c) Nimrod radar analysis data; (d) GSMaP satellite analysis data; and (e) the merged UKGrsHP product.

In summary, radar observations have significant limitations (i) in complex terrain, (ii) when the beam may be saturated by high rainfall intensities, and (iii) when the location is distant from the radar site itself. There are a number of merged products available now which should be used for nowcasting and for assessing the risks of earthwork failures. These are enabling much better understanding of UK rainfall from hours to days, how it relates to weather patterns and how it is changing under global warming.

5.2 New rainfall climatologies

One way forward in understanding Network Rail's exposure to rainfall-related hazards, such as earthwork failures, is to explore the relationship of past events with the prevailing meteorological conditions and related rainfall statistics.

In the last few years, several UK climate records have been extended further into the past through data archaeology and the digitisation of past weather records. There has also been significant progress in producing more robust records on finer spatial scales (1 km) and finer timescales (daily, hourly and even sub-hourly), which is enabling much greater understanding of past extremes. UK daily rainfall data are now available back to 1862. These provide new opportunities to explore in more detail the prevailing and antecedent conditions surrounding earthwork failures and other major railway disruptions much further into the past.

As the Carmont event emphasised, the rainfall intensity on hourly (or even shorter) timescales may be a critical driving factor in earthwork failures. Here the records are much more limited in length and density across the UK and have had severe quality issues. Recent work has quality controlled ~1900 hourly gauge records for the UK and these have been used to construct a new 1 km resolution gridded *hourly* rainfall dataset for Great Britain for the period, 1990–2014 (CEH-GEAR1hr)[6].

In summary, recent advances in developing high spatial and temporal resolution rainfall climatologies have provided new insights on the nature of UK rainfall, especially extremes, and on the emerging signals of climate change. These new datasets provide unprecedented opportunities to explore the links between past earthwork failures, the concurrent and antecedent rainfall and the weather patterns that prevailed at the time. This presents a real opportunity for updating the alert thresholds that Network Rail uses (see Chapter 4, Table 4.2).

[6] Lewis, E., N. Quinn, S. Blenkinsop, H. J. Fowler, J. Freer, M. Tanguy, O. Hitt, G. Coxon, P. Bates and R. Woods, 2018: A rule based quality control method for hourly rainfall data and a 1 km resolution gridded hourly rainfall dataset for Great Britain: CEH-GEAR1hr. *Journal of Hydrology*, 564, 930-943. https://doi.org/10.1016/j.jhydrol.2018.07.034

6. Current advances in forecasting the weather from hours to weeks

The purpose of this chapter is to introduce the latest advances in weather forecasting and what could be available to Network Rail. This is based on the current operational products from the Met Office, which is the UK's National Weather Service and the main provider of weather forecasts and warnings to government and related agencies.

The Met Office has been at the forefront of weather science and forecasting for many decades, and in 1990 the Hadley Centre for Climate Research and Prediction was established within the Met Office. As well as being the National Weather Service, the Met Office is a world-leading research centre, with over 500 scientists working across a broad portfolio of research with the ultimate goal of delivering the best weather forecasts and climate predictions.

It is important to understand how weather forecasts are produced if Network Rail is to extract the greatest benefits from what is available. Forecasting begins with knowing the current state of the global atmosphere which is achieved by gathering observations from all over the world and using a wide range of platforms in real time (Figure 6.1). Each day over 100 million observations are processed and stored.

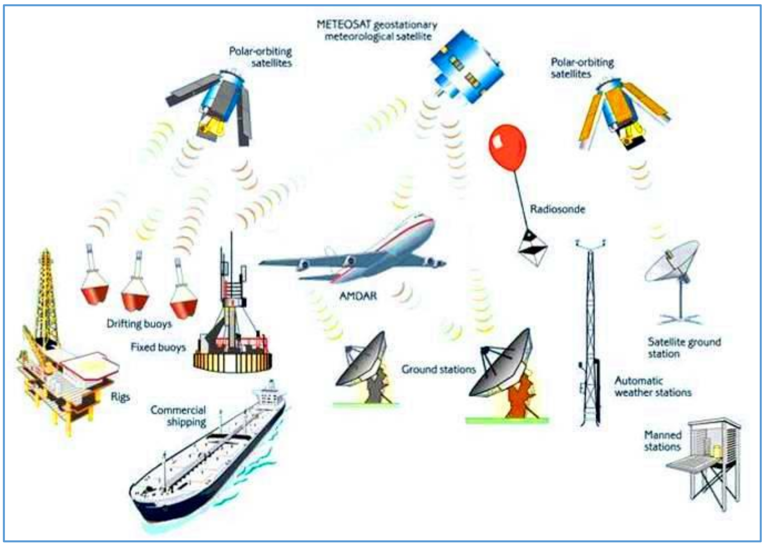


Figure 6.1: *Schematic of the constellation of observing system that are used operationally to create the starting conditions for all weather forecasts. These observations are transmitted in real time from across the world under international agreements.*

These observations are processed to produce the global initial condition for the forecast, from which a set (termed an ensemble – see Section 6.1) of global forecasts out to a week or so ahead are produced. The reason why we always start with the global forecast is that it sets the stage for all regional and local forecasts, because very often the UK's weather has its roots in the weather on the other side of the globe.

Once we have the global forecasts then these provide the boundary conditions for much finer-scale regional forecasts over the UK (Figure 6.2). This whole end-to-end process from observations to forecasts takes only 2 hours to deliver and is repeated every 6 hours. During that time 20 quadrillion (10^{15}) calculations are performed, and 10 trillion (10^{12}) bytes of model data are archived. This is why weather forecasting represents one of the most complex applications of supercomputing; the codes typically run to over a million lines of code and the time constraints on forecast production require dedicated machines with world-class compute capability[7].

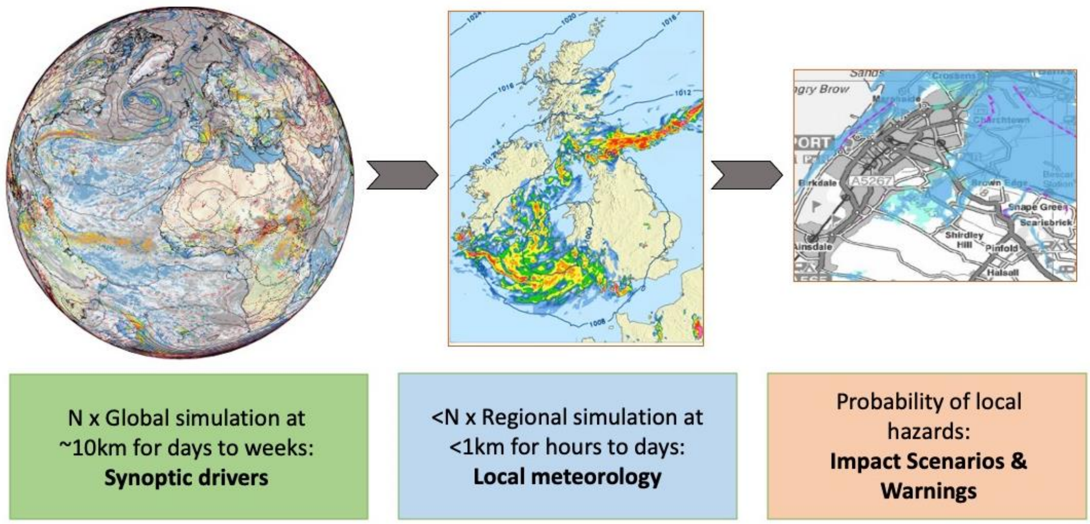


Figure 6.2: *Schematic of the sequence of forecasts produced every 6 hours at the Met Office. The global forecast produces information on the likely prevailing weather patterns (synoptic weather); this is fed into the regional forecast which translates the synoptic weather into local detail. From there, the forecast can be interpreted in terms of a wide range of products and services relevant to decision-makers.*

Finally, the outputs from the range of forecasts from global to local and from hours to days is post-processed to produce user-specific products and services. It is at this stage that the private sector providers, such as MetDesk, come into play. They depend on the major forecast producers, such as the Met Office and ECMWF, to produce and post-process the forecasts because what they can access is necessarily restricted by the huge data volumes involved.

Today, the Met Office operates a suite of forecasting systems based around a common computational code, the Unified Model that go from nowcasting for the next few hours to the season ahead (Figure 6.3). The same code is also used to produce scenarios of future climate change, such as the latest set of UK Climate Projections (UKCP18).

[7] In 2016, the Met Office procured its current data centre at a cost of £97M. This included a Cray supercomputer with a performance of 13 petaflops (1015 Floating Point Operations per Second), spread over 480,000 cores and with 2 petabytes of memory. The data volumes produced by the forecasts are huge, so the machine also had 17 petabytes storage; this has since been upgraded. A new data centre is currently starting procurement.

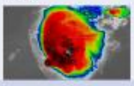
Definition	Nowcast	Very Short	Short	Medium	Extended	Long range
Leadtime	0 to 2 hrs	2 to 12 hrs	12 to 72 hrs	3 to 10 days	10 to 30 days	30 days +
Scale Met Feature	1km Tornado 	10km Thunderstorm 	50km MCS 	100km Cold Front 	500km Airmass 	1000km Heatwave 
Lifetime	10 min	1 hr	12hr	1 day	3 days	5 days
Predictability	30 min	3 hr	36 hr	2 days	7 days	10 days
Absolute resolution	300 m	2 km	2 km	10 km	10 km	20 km

Figure 6.3: The range of Met Office forecast products across lead times showing the spatial resolution of each forecast, the frequency of updates and the inherent limits of predictability.

The focus for this chapter is on those aspects of forecasting that go beyond what Network Rail is currently able to access through its contract with MetDesk. It will cover the methodology of ensemble forecasting and why it is important for improved warning and risk assessments; it will describe the UK-specific kilometer-scale forecasts out to 3 days and how these can be used to localize warnings; and it will introduce the latest developments in nowcasting for the next 1-2 hours, of special value when intense, localized rainfall is likely.

6.1 Risk-based forecasting on all timescales using ensembles of forecasts

Uncertainty is an inherent property of the fluid motions of the atmosphere and oceans. This was recognized in 1963 by Ed Lorenz in his seminal paper on '*Deterministic non-periodic flow*'[8] in which he introduces the concept of the atmosphere as a chaotic system subject to small perturbations that grow through non-linear processes to influence the larger scale – as Lorenz said, '*the flap of a seagull's wings may forever change the course of the weather*'.

The concept of the weather and climate as chaotic systems has had a profound impact on the way in which forecasting has evolved over recent decades. No longer do we produce a single, deterministic forecast, but instead we perform an ensemble of forecasts that seek to capture the plausible range of future states. This provides a range of forecast solutions, which allows the forecaster to assess possible outcomes, estimate the risks and probabilities of those outcomes and to gauge the level of confidence in the final forecast. From the users' perspective, the forecast probabilities allow them to decide on the level of risk they are prepared to take depending on their vulnerabilities, and to take appropriate action within a proper understanding of the uncertainties.

[8] E. N. Lorenz, 1963: Deterministic Nonperiodic Flow. J. Atmospheric Science, 20, 130-141. https://doi.org/10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2

The following example for Storm Desmond on 5-6 December 2015 demonstrates this well. Figure 6.4 shows the ensemble of global forecasts of mean sea level pressure made 5 days before Storm Desmond hit the UK, bringing extreme rainfall and causing devastating floods. The ensemble consisted of 24 forecasts each with very slight differences in initial conditions and in model parameters, designed to capture the inherent uncertainties in how the weather might evolve in the next 5 days.

Every forecast in Figure 6.4 shows low pressure to the north of the UK and a significant number show very strong south westerly flow into the UK (e.g. blue box) indicating wet conditions; on the other hand a few forecasts indicate that the winds could come from a more northerly direction (see red box) which would indicate much colder and drier conditions. In this case the ensemble gave a strong enough indication of wet, windy conditions for early warnings to be issued.

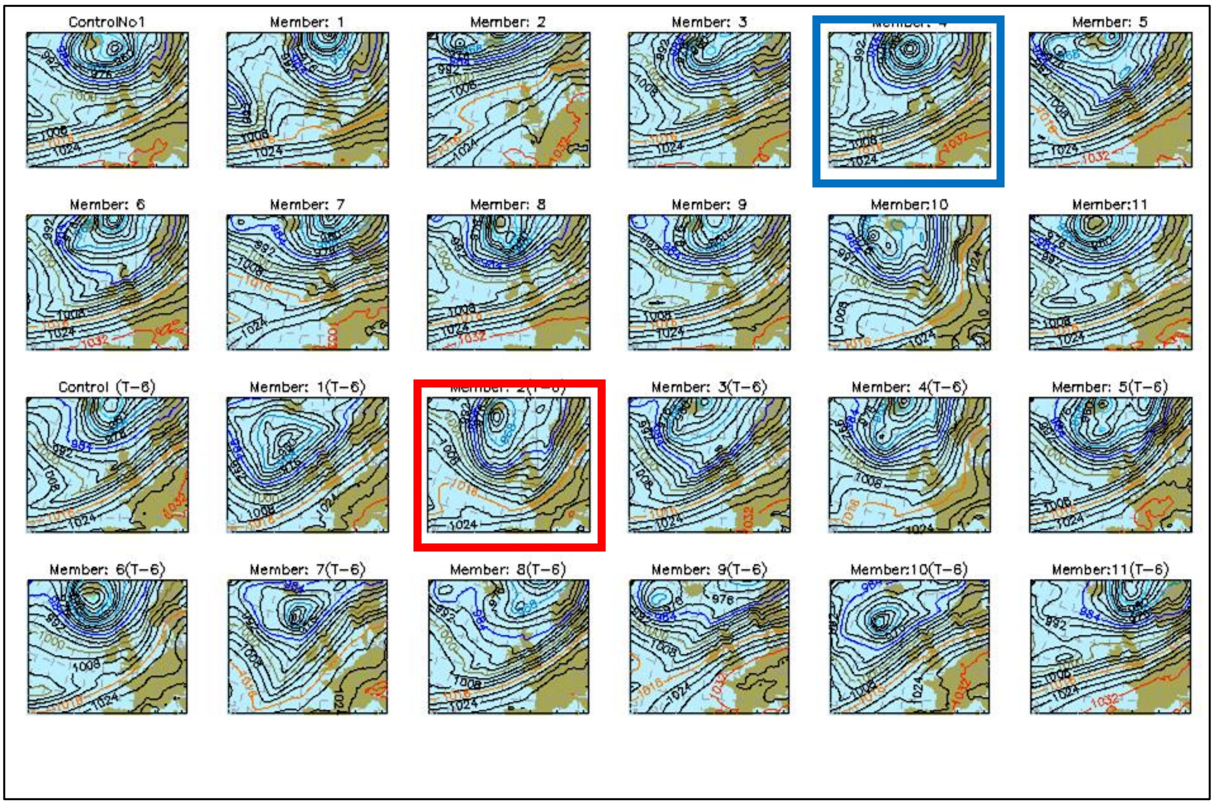


Figure 6.4: Example of an ensemble of 24 global forecasts of mean sea level pressure produced 5 days ahead of Storm Desmond in December 2015. The blue box highlights one forecast which is close to what happened with strong south westerly flow across much of the UK and therefore heavy rainfall. In contrast the red box shows another forecast with a similar position of the cyclone near Iceland, but in this case, air is being drawn down from the north with much less rainfall. The challenge for the forecaster is to decide which weather pattern is more likely. Source: Met Office

By 2-3 days before Storm Desmond arrived (Figure 6.5), the global ensemble showed a much narrower spread in the forecasts, with all showing strong south-westerly flow into the UK and with clear indication of cyclones forming on the northern flank of the river of south westerly winds.

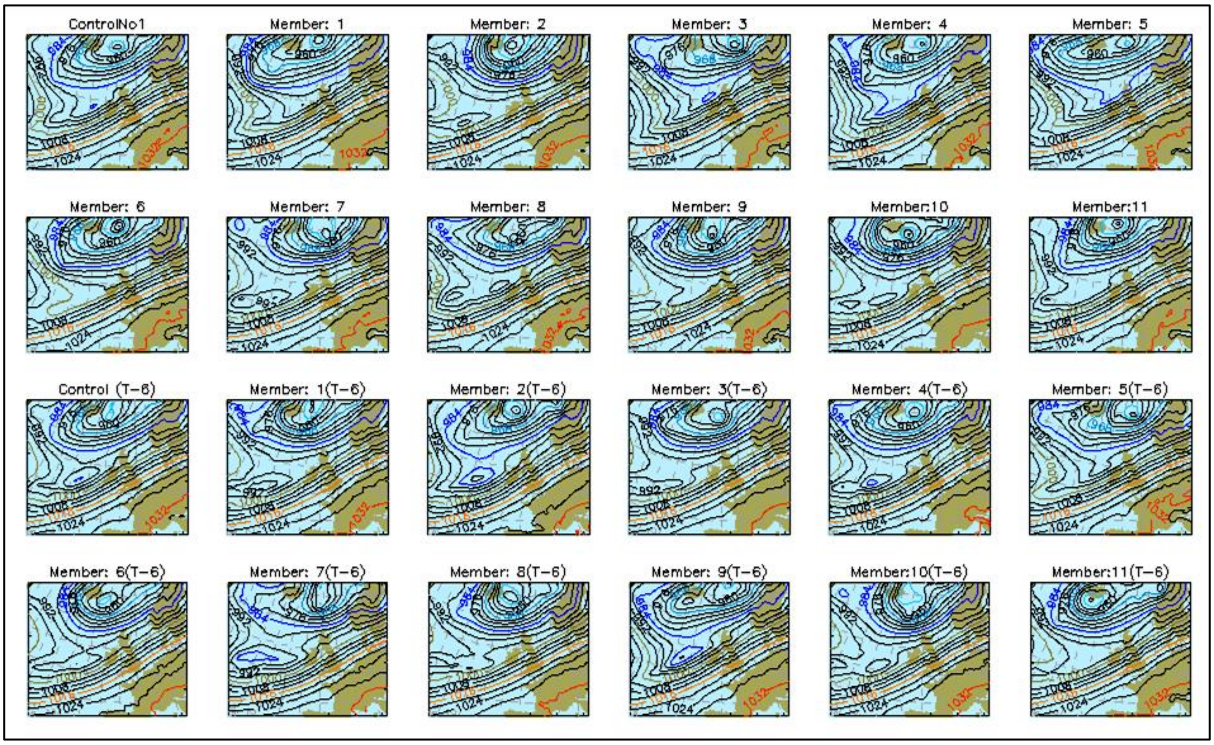


Figure 6.5: *As Figure 6.4 but for the ensemble of global forecasts made 2 days ahead. Note the consistency of the forecasts with no indication now of possible northerly airstreams. Source: Met Office*

Forecasters were by then very confident that the UK would be hit by a major storm with high winds and heavy and prolonged rainfall. It is clear that north-western parts of the UK were likely to be badly affected and widespread warning were put in place, but the global forecasts were still giving uncertainties about the exact location and intensity of the heaviest rain.

As this exam[le demonstrates, global ensemble forecasts now provide excellent guidance on impending high impact weather, raising awareness and enabling preparatory actions to be put in place (See Section 7.1). Similarly, they can also provide indications of extended periods of fair weather in which, for example, track works can be scheduled. Whilst these global forecasts are increasingly skillful at predicting weather systems, such as depressions and fronts, several days or even a week or so in advance, they are not ideally suited for local forecasting, especially for rainfall that has such fine structures and is strongly influenced by the local landscape.

Beyond global forecasts the new generation of kilometre-scale UK forecasts (see Section 6.2) now provides more detailed, nearer term information which can guide specific regional and local warnings and actions to mitigate the risks of severe weather (Figure 6.6). Again, an ensemble of forecasts is run because we know that however much we improve models and forecasts, including much higher resolution, there will always be an irreducible level of uncertainty - '*flap of the seagull's wings*' - because of the chaotic nature of the system even at the local level.

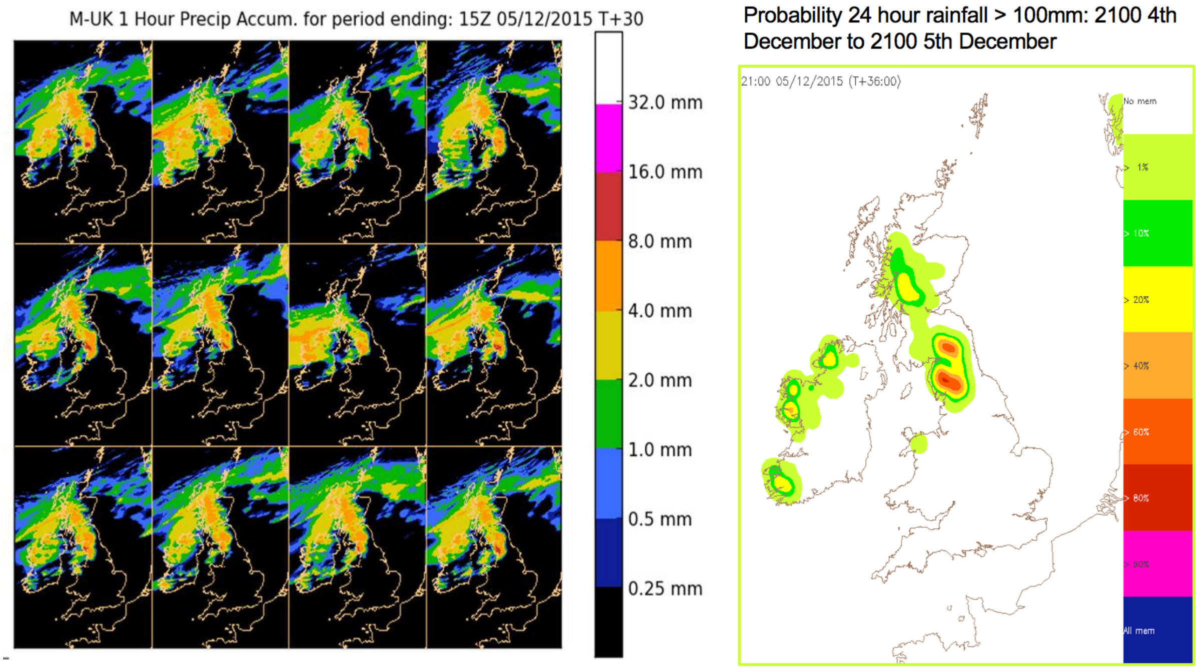


Figure 6.6: *Example of the value of local-scale forecasting for Storm Desmond, highlighting the main areas of risk from heavy rainfall and flooding. Left panel: Hourly rainfall accumulations (mm) from an ensemble of 12 forecasts with the UK kilometer-scale system made 30 hours ahead of the main impacts of Storm Desmond. Note that although the forecasts all have the same flavour, the location and intensity of the heaviest rainfall differs. Right panel: Interpretation of the ensemble of kilometer-scale forecasts, made 36 hours ahead, in terms of the probability (%) of exceeding daily accumulations of 100mm. The highest probability, in excess of 80%, is located close to Ullswater where some the worst flooding occurred. These probabilities provided very clear indications of where resources needed to be deployed. Source: Met Office*

6.2 High resolution, kilometer scale forecasting for the next 1 - 3 days.

Of particular relevance to Network Rail has been the introduction of the kilometer-scale forecasting system (UKV) over the UK in the last decade. This has transformed the forecasts of extreme rainfall and other local extremes, such as wind gusts; at these scales the model not only represents the landscape more accurately (Figure 6.7), but also captures the fundamental physics of thunderstorms and of embedded convection within weather fronts.

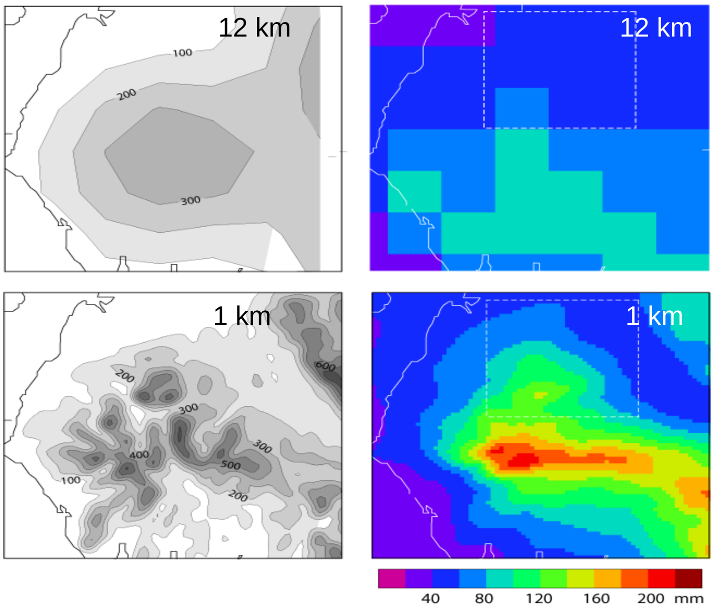


***Figure 6.7**: Example of the differences in the representation of the mountains of the Lake District with model resolution and the rainfall forecast for the Cockermouth Floods in 2009. It demonstrates the value of the kilometer-scale UK forecast model versus global forecasts models, such as ECMWF that currently runs at 10km. Source: Met Office*

As the Carmont accident demonstrated, Network Rail is vulnerable to severe convective events. The extraordinary value of kilometer scale modelling to forecast these events was demonstrated in an early example from the famous Boscastle flood (Figure 6.8). As the radar image shows, a line of convection was formed by on-shore winds that perfectly aligned with the topography of Boscastle. These storms became self-reinforcing and led to very high rain rates and accumulations. The 12km model, similar to the ECMWF global model which forms the basis of Network Rail's weather advice from MetDesk, has no chance of capturing these localized extremes. It is only at 1km that the resolution is high enough for the physical processes behind these extremes to be represented at some level of accuracy. Even a 4km model struggles.

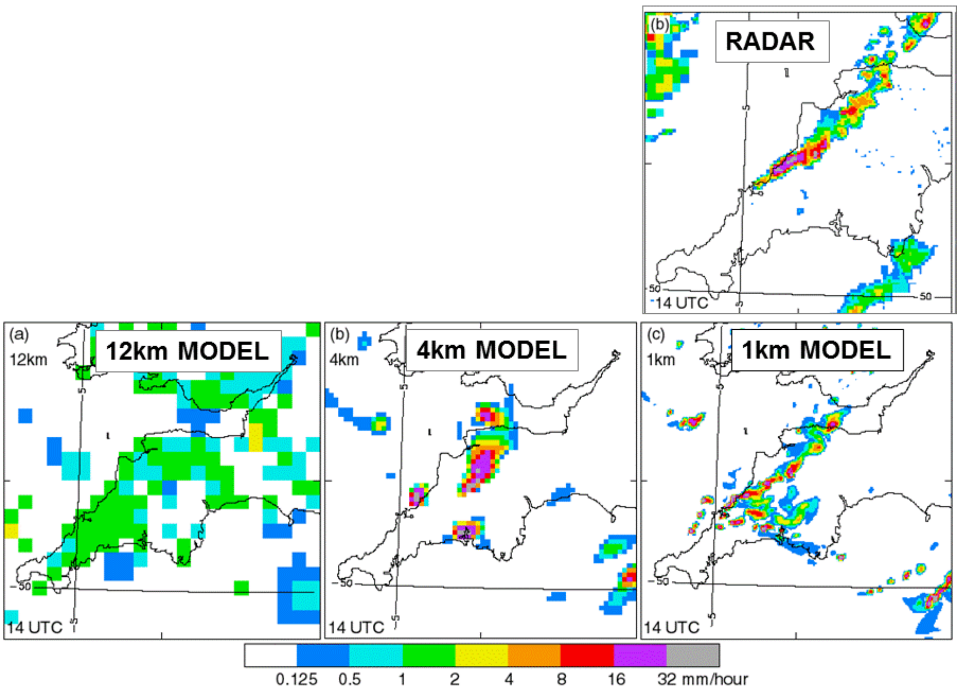
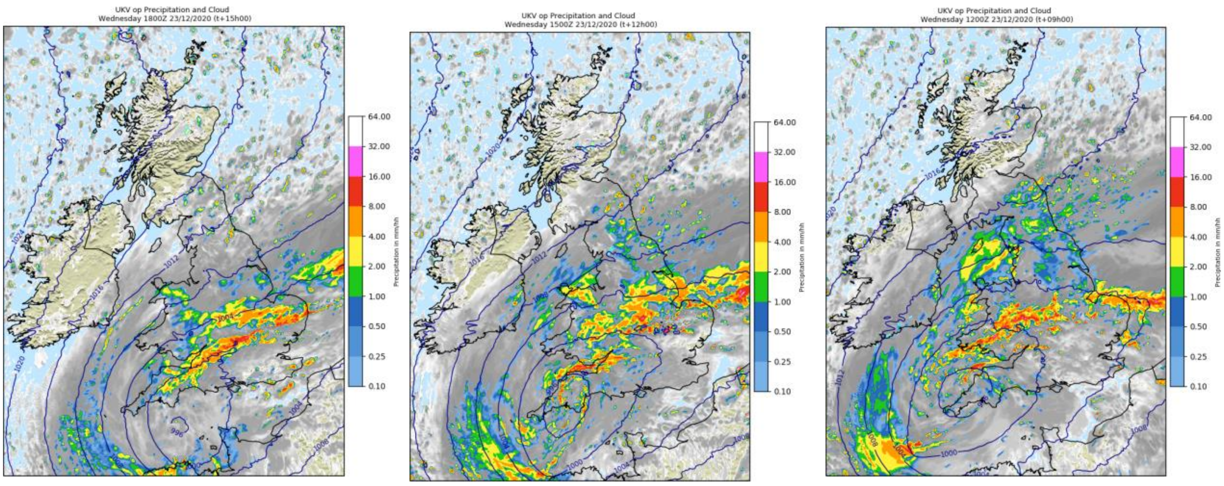


Figure 6.8: *Forecast of rainfall intensities (mm/hr) at 14 UTC on 16th August 2004 associated with the Boscastle flooding event from 12km, 4km and 1km resolution UK forecast models compared to 1km radar observations Source: Met Office.*

The example for the Boscastle Flood shows that there is a real scale gap in the ability to forecast extreme convective events and that only models at the kilometer scale have skill. Since these forecasts were made, the skill of the kilometer-scale forecast model has improved substantially. Figure 6.9 gives an example of model skill for the extreme rainfall event on 23 December 2020 when the UK was affected by severe, low pressure system that brought strong, heavy, persistent rain and major disruption to Christmas travel. In the sequence of forecasts with lead times from 15 to 9 hours ahead, the model has captured the range of intensities across the UK and the formation of intense lines of convection. There is not a perfect match to the radar, nor would we expect there to be, but the overall agreement is striking.



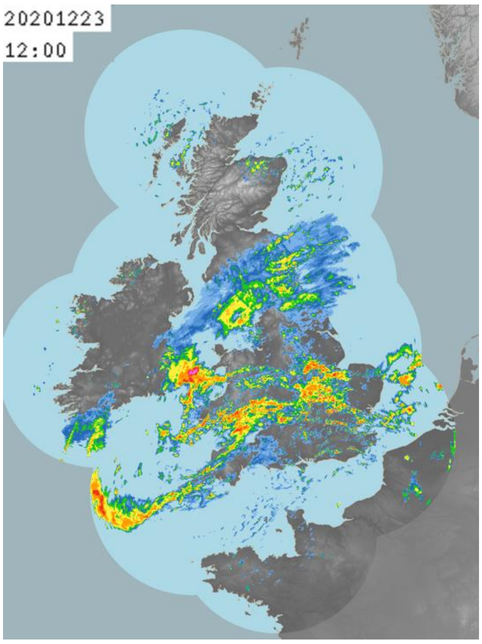


Figure 6.9: *Example of the detail in kilometer-scale rainfall forecasts 15 to 9 hours ahead for severe weather on 23 December 2020 (upper panels). The structure and intensity of the rainfall compares well with the radar observations at 12.00 on 23 December using the same colour scale. Source: Met Office*

Quantifying forecast uncertainty is particularly relevant to the prediction of highly variable parameters like rainfall, especially at the local level and even over short lead times. Figure 6.10 gives a specific example from a recent event on 11 November 2020, in which the UKV ensemble forecast (MOGREPS-UK) provided valuable information on the most likely position of heavy rainfall, which was not correctly forecast by the single deterministic forecast. In this case the ensemble consists of 12 members, with each member being driven by the latest 12 members of the global forecasts.

An active cold front was moving into Wales and SW England from the west with embedded lines of strong convection giving localised heavy rainfall (Figure 6.10, left). The individual kilometer-scale model forecasts, 21 hours ahead of the event, picked up this intense line convection (Figure 6.10, middle), but there was uncertainty on the speed of the front and where the lines would form. By using the ensemble of forecasts and analysing the mean of the within-hour maximum rainfall, the main areas of risk were correctly identified, with South Wales having the highest risk of in-hour rainfall exceeding 16mm (Figure 6.10, right).

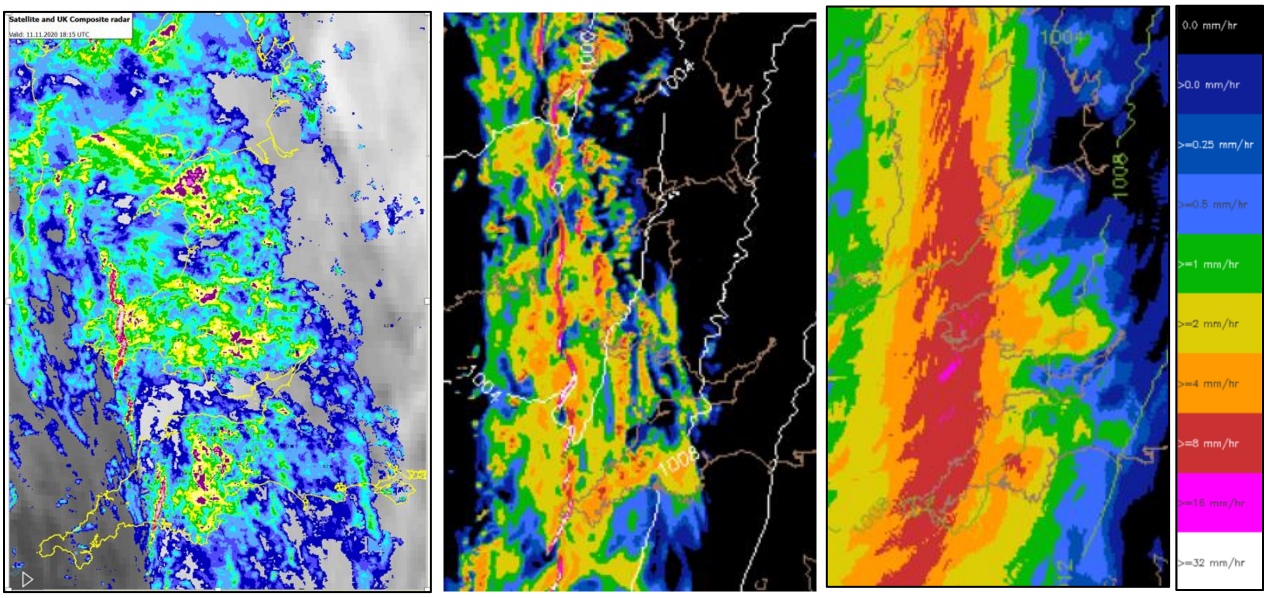


***Figure 6.10**: Example of the value of ensemble, probabilistic forecasting of an active cold front crossing the UK during 11 November 2020. Embedded convection within the front can give lines of very heavy rainfall, as seen in the composite radar and satellite observations (left panel). Individual forecasts 21 hours ahead were able to capture these lines of intense convection (middle panel), but there was uncertainty in their position and how quickly they would move eastwards. By using all the information in the ensemble, the probability of within-hour maximum rainfall exceeding 16mm, indicative of intense line convection (right panel), correctly highlighted South Wales and the West Country as being at greatest risk. Source: Met Office*

In summary, in terms of rainfall intensities and location, the differences between forecasts made at 10km and 1km are profound. Network Rail currently has access only to the ECMWF global forecast which, although world-class, can only be produced at a resolution of 10km because of the computational cost. Furthermore, the availability of an ensemble of kilometer-scale forecasts is immensely valuable for assessing the most likely locations of maximum risk from intense rainfall, such as line convection and thunderstorms.

6.3 Nowcasting for the next 1-2 hours

Nowcasting is a technique used for very short-range forecasting, in which, traditionally, the current weather is mapped and then an estimate of its speed and direction of movement is used to forecast the weather a short period ahead. Precipitation nowcasting has typically been based on extrapolation of radar images using optical flow techniques, as is the case for MetDesk's provision of nowcasts for Network Rail and the recent development of the Convective Alert Tool

With the advent of kilometre-scale forecasting (see Section 6.2), it is now possible to blend the latest forecast products with the radar extrapolations, which provides improved probabilities on the likely track and intensity of precipitation features. Although the blending of radar and forecast products definitely adds value, there can be problems with very localised extremes because of slight positioning differences. A new post-processing method has been introduced to deal with these problems.

As well as the new, blended nowcast, the use of Deep Learning is being explored, in a collaboration between the Met Office, Google DeepMind and Leeds University. Specifically, this involves the use of machine learning to predict subsequent rainfall radar fields given a series of input fields up to that point. An example of nowcasts generated by the operational system, and using neural networks is given in Figure 6.11.

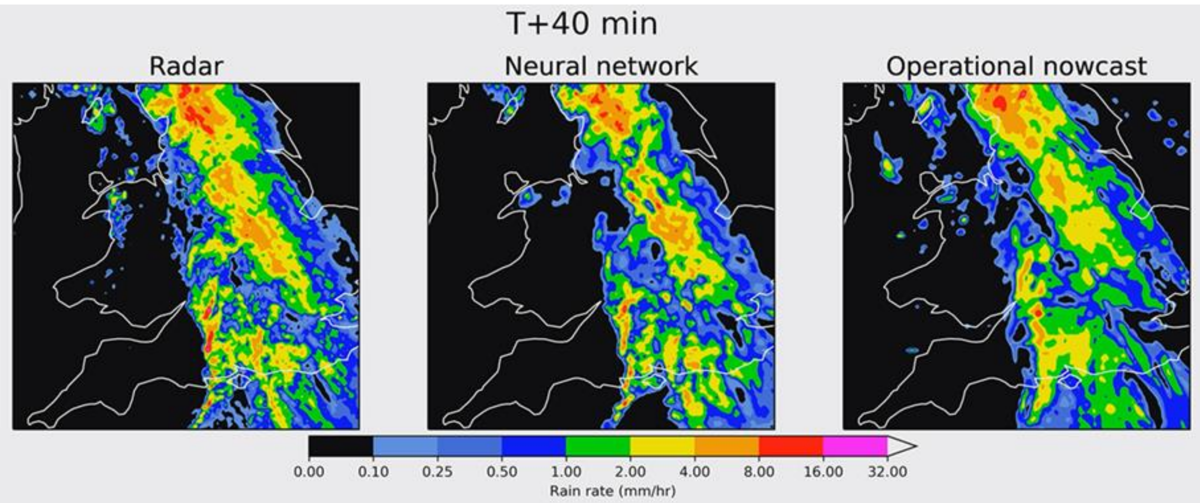


Figure 6.11: *Example of the potential applications of Machine Learning to future Nowcasting. (Left panel) Radar observation. (Centre) Nowcast using a neural network and radar observations from 40 minutes prior to the validity time. (Right) Operational nowcast from 40 minutes prior to the validity time. Credit: Claire Bartholomew, University of Leeds & Met Office.*

Other applications of machine learning for nowcasting may include the automated identification of features of interest, such as heavy thunderstorms, in observational data. A good example of its potential has already been demonstrated by the operational nowcasting system at the German Weather Service (DWD), and a similar approach is being prototyped at the Met Office. DWD has already demonstrated that these techniques have helped to improve, significantly, the quality of the official warnings for severe convective weather events (Figure 6.12).

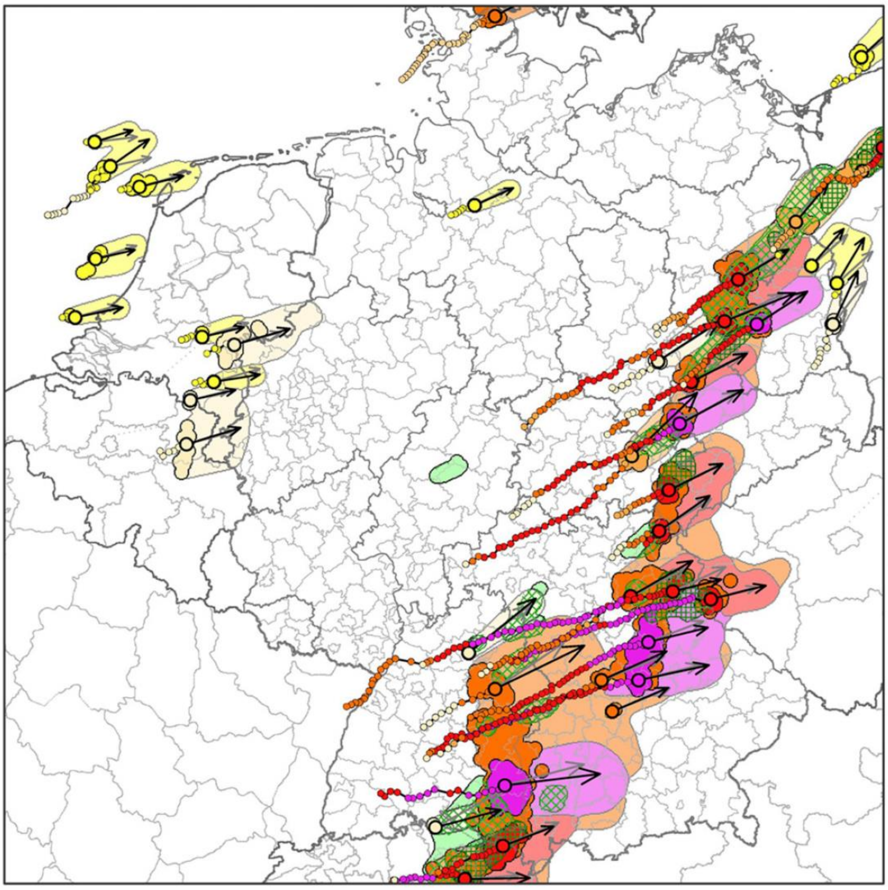


Figure 6.12*: Example of object-oriented nowcasting during a severe thunderstorm outbreak 0ver Germany on 18 Aug 2017. Current thunderstorm activity is shown as solidly colored polygons whose centers are indicated by black-outlined circles of a specific severity, colored inside according to the following categories: Moderate (Yellow), Strong (Amber), Severe (Red) and Extreme (Purple). The past tracks of each cluster object are shown with small joined circles. The respective tracking vectors are given as black arrows. The resulting integrated warning areas for the next 60 min are shown as opaque-colored polygons. Heavy rain areas are shown as green polygons that are hatched where they overlap with thunderstorm polygons. Source: DWD and James et al. (2018)*[9]

This capability could be available, operationally, in the UK in the next few years, and development could be accelerated if there is a clearly expressed need. The advantage of this

[9] James, P. M., B. K. Reichert and D. Heizenreder, 2018: NowCastMIX: Automatic Integrated Warnings for Severe Convection on Nowcasting Time Scales at the German Weather Service. *Weather and Forecasting*, DOI: 10.1175/WAF-D-18-0038.

approach is that the data volumes are massively reduced so that the content is easily shareable and discoverable by other digital systems. This is critical when a fast response is required, and content needs to be discovered and consumed rapidly by a downstream content management system.

Currently and into the future, nowcasting is critically important for Network Rail to inform the safe but optimal performance of the railway. Network Rail currently has access to deterministic nowcasting based on extrapolation of the observed radar signal. This can be improved by using the combination of radar and forecast products and through embracing probabilistic approaches.

Severe convective storms represent major risks to Network Rail's infrastructure and improved nowcasting capabilities are urgently needed to manage their risks and reduce operational delays. Emerging data technologies may revolutionise the management of these risks and their development should proceed at pace.

7. New products and services

There has been significant progress in recent years in 'bridging the valley of death' from weather to impacted-based services, often within private sector companies, such as MeteoGroup and MetDesk. The impact-based National Severe Weather Warning Service (NSWWS)[10] and the Natural Hazards Partnership (NHP)[11] are examples of best practice in the public sector, relating hazardous weather to its impacts to provide local and regional warnings, and enabling mitigation of those impacts.

One important factor in 'bridging the valley of death' is the need for weather forecast providers to understand the needs, as well as manage the expectations, of the users. This means establishing good working relationships, being able to communicate the uncertainties inherent in the forecasts and demonstrating how expert judgement can be used to reach the most confident forecast as a function of lead time. It is also clear that a 'good' forecast is defined by the degree to which it enables decision-making, and that good decision making is highly dependent upon (user) context. It often means post-processing the weather forecast to provide user-relevant information, as well as bringing in the user's decision-making process and understanding the impact on their business or operations. In these respects, MetDesk seems to serve Network Rail well and to be responsive to its needs.

With the availability of a seamless suite of forecasts from hours to weeks described in Chapter 6 and summarised in Figure 6.3, it is now possible for users to be better prepared than ever before for adverse weather conditions. To do this effectively means being aware of (i) the scales of adverse weather – is it local rainfall or widespread heat? (ii) the regime[12] in which the adverse weather occurs – is it in cyclones or anticyclones? and (iii) the predictability of adverse weather across timescales – is the forecast more or less certain?

Managing the expectations of users is about ensuring that they are scale aware and predictability aware. The predictability of a thunderstorm of the scale of 10km has on average a limit of around 3 hours, while frontal rain of the size of 100km's can be forecast at least 2 days ahead. The larger the system, the more predictable it is on average. By having this awareness, it is possible to be pro-active rather than reactive to impending weather hazards. Access to the full range of available forecasts, shown in Figure 6.3, and implementing them within an '*Awareness – Preparedness – Response – Recover*' framework, means that the user can be better prepared to deal with more eventualities.

[10] NSWWS: https://www.metoffice.gov.uk/weather/guides/severe-weather-advice
[11] NHP: http://www.naturalhazardspartnership.org.uk
[12] A regime can be described as one of many circulation types over a defined region that vary on a daily basis and which differs in its characteristics from other regimes over the same region. An example of a regime over the UK is a cyclonic westerly type which brings mild, wet and windy conditions.

In this chapter we will review the latest developments in exploiting the seamless suite of forecast across this framework through new approaches to translating forecasts into actionable information.

7.1 'Awareness and Recover': The 'Decider' tool

Network Rail is challenged by local extreme events, but it is important to note that these are all tied to specific weather regimes or climate patterns. We can lever the predictability of these weather regimes, combining it with their relationship with extreme weather and potential impacts on the rail network, and use this intelligence to raise awareness.

The complexity of the UK's weather has already been discussed. However, detailed analysis of 150 years of mean sea level pressure data (Neal et al. 2016) has shown that UK weather can be clustered into just 30 regimes, which describe a range of patterns from blocked easterlies to mobile westerlies (Figure 7.1).

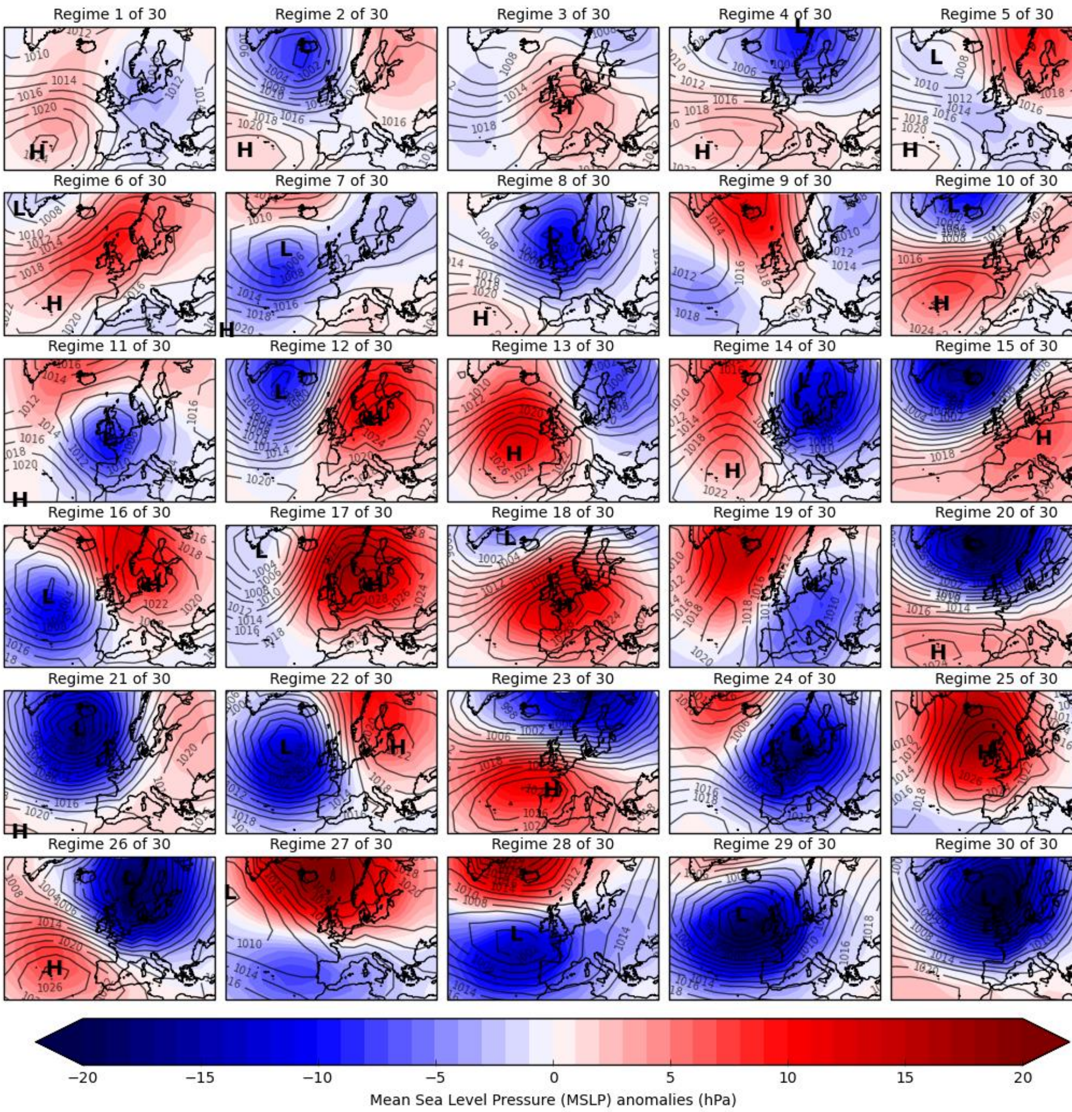


Figure 7.1: Set of 30 weather patterns or regimes identified from 150 years of data. Mean sea level pressure (MSLP) anomalies plotted as filled contours (hPa) and MSLP mean values plotted in foreground (2 hPa intervals). Weather patterns are numbered according to their annual historic occurrences, with

lower numbered patterns occurring most often. Lower numbered patterns occur more in summer (with weak MSLP anomalies) and higher numbered patterns occur more in winter (with strong MSLP anomalies). Source: Neal et al. 2016[13]

These patterns are ordered according to their mean annual occurrence, from high to low, and show that more extreme cyclonic (blue) or anticyclonic (red) conditions are relatively less frequent. Low numbered patterns tend to occur more often in summer and high numbered patterns, in winter.

The evolution of the probability of occurrence of these regimes over a number of days can provide important information for anticipating transitions to more hazardous weather and the likelihood of extreme events and raising awareness of potential impacts. This has been implemented operationally in the 'Decider' forecasting tool, based on the evolving population of weather regimes in the global ensemble forecasting system.

Figure 7.2 gives an example of the 'Decider' forecasting tool looking two weeks ahead from 8 November and encompassing the disturbed period of weather on 11 November shown in Figure 6.10. Up to the ten most likely weather regimes through the forecast period are shown, with the probabilities expressed in the depth of blue shading.

	Sun 8 Nov	Mon 9 Nov	Tue 10 Nov	Wed 11 Nov	Thu 12 Nov	Fri 13 Nov	Sat 14 Nov	Sun 15 Nov	Mon 16 Nov	Tue 17 Nov	Wed 18 Nov	Thu 19 Nov	Fri 20 Nov	Sat 21 Nov	Sun 22 Nov
1st	17	17	12	12	21	21	21	21	15	15	18	25	18	13	18
2nd		12	17	15	12	15	15	15	21	12	13	18	25	25	17
3rd					22	12	12	20	12	18	12	15	23	23	13
4th					15	20	20	12	20	20	15	13	17	18	25
5th									22	23	25	17	15	17	23
6th									16	17	3	12	13	9	20
7th									18	16	17	16	3	8	3
8th									2	21	23	23	16	15	9
9th									23	22	5	2	1	3	5
10th									3	2	16	5	12	6	12
Total variability	100%	100%	100%	100%	100%	100%	100%	100%	100%	90%	90%	86%	90%	73%	78%

Figure 7.2*: Example of the 'Decider' forecasting tool based on weather regimes, looking two weeks ahead from 8 November and encompassing the disturbed period of weather on 11 November. Up to the ten most likely weather regimes through the forecast period are shown, with the probabilities expressed in the depth of blue shading.*

The near-term forecasts show a high level of confidence that the weather will be dominated by high pressure to the east and low pressure to the west (Regimes 12 and 17 in Figure 7.1), a

[13] Neal, R., D. Fereday, R. Crocker and R. E. Comer, 2016: A flexible approach to defining weather patterns and their application in weather forecasting over Europe. *Meteorological Applications*, 23, 389–400. DOI: 10.1002/met.1563

typical situation for a slow moving, cold front to affect the western areas of the UK as indeed happened on 11 November (see Figure 6.10).

As the forecast range increases, the number of possible regimes increases and the probabilities of each regime fall, reflecting the chaotic nature of the weather. Nevertheless, there is high degree of confidence in the first week that the weather will remain unsettled with strong south-westerly flow (see Regimes 21 and 15 in Figure 7.1). There is also a very high degree of confidence that the weather will transition from more settled conditions on 8 November (Regime 17) to more wet and stormy weather on 11 November (Regime 12), with active weather fronts across the western UK as low pressure pushes in against the high pressure over the continent.

The use of weather regimes can be further simplified by clustering them together in terms of low and high pressure scenarios. In Figure 7.3, this example of 'Decider' uses the ensemble of 15-day global forecasts made every 12 hours in the days leading up to the most recent forecast on 25 October. It shows clearly that there is a very high probability of unsettled, cyclonic conditions continuing for the next 4-5 days; it also highlights the chance of cyclonic, wet conditions returning briefly at the start of November which, if this materialised (as it did), would lead to disruption because soils are already saturated.

Probabilistic Pressure Trend

	Sun 25 Oct	Mon 26 Oct	Tue 27 Oct	Wed 28 Oct	Thu 29 Oct	Fri 30 Oct	Sat 31 Oct	Sun 1 Nov	Mon 2 Nov	Tue 3 Nov	Wed 4 Nov	Thu 5 Nov	Fri 6 Nov	Sat 7 Nov	Sun 8 Nov
Latest model run (25/00 UTC)	100%	100%	100%	100%	96%	61%	--	80%	61%	39%	59%	59%	53%	55%	59%
Previous model run (run -1)	100%	100%	100%	100%	88%	80%	47%	75%	47%	45%	67%	61%	57%	55%	51%
Previous model run (run -2)	100%	100%	100%	100%	63%	65%	45%	39%	35%	--	69%	65%	65%	69%	
Previous model run (run -3)	100%	100%	100%	100%	75%	45%	47%	47%	41%	55%	73%	73%	63%	67%	
Previous model run (run -4)	100%	100%	100%	100%	84%	49%	37%	47%	55%	65%	71%	69%	67%		
Previous model run (run -5)	100%	100%	100%	100%	92%	53%	43%	41%	49%	63%	67%	65%	49%		
Previous model run (run -6)	100%	100%	100%	92%	53%	55%	39%	--	51%	61%	71%	71%			
Previous model run (run -7)	100%	100%	94%	73%	57%	47%	65%	67%	73%	78%	82%	73%			
Previous model run (run -8)	100%	98%	98%	80%	47%	49%	39%	45%	49%	51%	57%				
Previous model run (run -9)	100%	96%	98%	59%	59%	47%	55%	57%	51%	61%	53%				
Previous model run (run -10)	92%	82%	92%	59%	47%	37%	39%	43%	41%	51%					

RED	High pressure most likely
GREEN	Unbiased conditions most likely
BLUE	Low pressure most likely
WHITE	Equal likelihood of two or three of the above tendencies occurring

Figure 7.3: Example of the Decider tool applied to the 15-day forecasts leading up to the latest forecast made on 25 October. In this case the weather is categorised as cyclonic (unsettled; blue) or anti-cyclonic (settled; red). This example shows two things, firstly how the confidence of the forecast has evolved from the oldest to the newest forecasts, and secondly the likely course of the weather in the coming 15 days. In this case there is high confidence that cyclonic conditions will persist for the next few days and that these will be followed by more settled conditions, although the timing of the transition is uncertain. The most recent forecasts suggest that this transition is likely to be delayed and that a short period of unsettled weather will return at the beginning of November.

What this example also shows is a reasonable probability of a transition to more anticyclonic and thus settled, drier weather in week 2 of the forecast. This means that there will be a period of more benign conditions in which '*Recovery*' can be planned and take place. The trend in confidence from the oldest forecast (bottom row) to the latest (top) also provides further additional information to aid decision making and logistic planning.

As these examples show, the 'Decider' forecasting tool provides the user with important information on the confidence of future transitions to more benign or more hazardous weather regimes. This guidance could form an important component of the '*Awareness*' function that Network Rail needs. The beauty of this tool is that it reduces the complexity and massive data volumes of the global forecasting system into a simple table that can be communicated rapidly to the user and which the user can interpret easily. Although the focus has been on weather regimes, more user-specific metrics, such as probabilities of surface flooding and earthwork failure (see Chapter 8), can be implemented.

7.2 'Preparedness and Response': Route-based forecasting using kilometer-scale forecasting.

Kilometer-scale forecasting has opened up some major opportunities to provide more location-specific forecasts and warnings which Network Rail can benefit from significantly. As Section 6.2 showed, these are particularly effective in the in the day or two leading up to adverse weather conditions and allow targeted preparations to be made where the risk is greatest. On the day itself the hourly-updated forecasts provide insight on the evolving weather situation beyond the currently available rainfall nowcast, allowing the routes and regions to respond so that they can deliver the most efficient service and minimise disruption.

With the support of the Met Office, the WATF produced a demonstration of this potential capability on 11 November (see Figure 6.10) when Wales and the South West were exposed to active cold front entering the region in the evening. Figure 7.4 shows the evolving levels of risk from hourly rainfall across the network from 1700 hours onwards, based on the forecast made at midnight (~18 hours ahead).

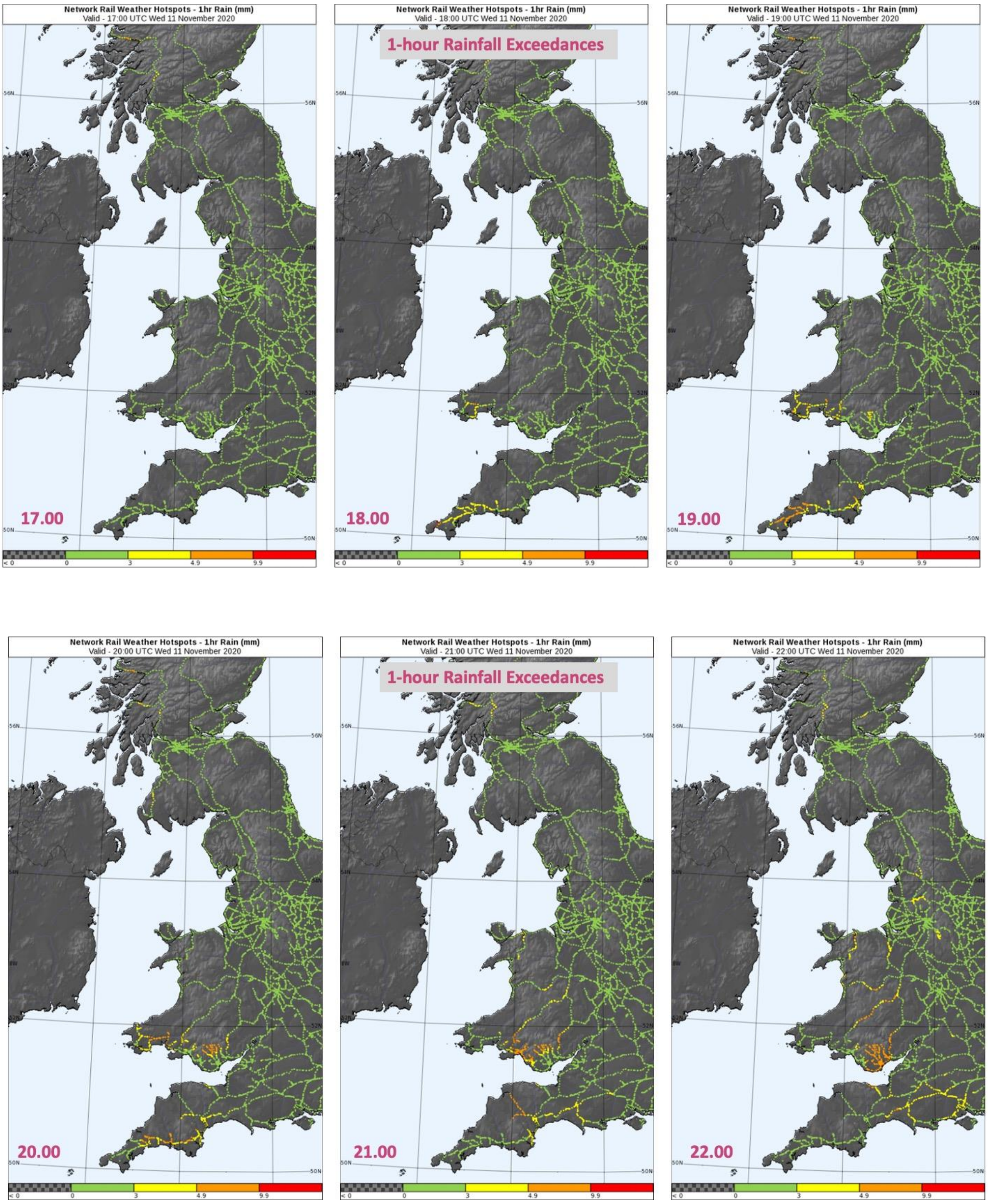


Figure 7.4: Maps of the rail network at different times during the evening of 11 November showing the evolving levels of risk from heavy hourly rainfall during the passage of an active cold front (see Figure 6.10), based on real-time kilometer-scale forecasts issued at midnight by the Met Office. The individual routes are coloured in terms of alert levels based on exceeding certain thresholds of hourly rainfall. The progression of the maps shows how the routes are gradually impacted and then become clear as the cold front moves east, and provides an example of how more dynamic, localised alert systems might perform and avoid extended blanket speed restrictions.

There are a few points to take away from this example. First, despite the disturbed weather, most of the network has stayed green. Second the alert levels evolve quite rapidly in time so that any mitigation, such as speed restrictions, need only be short-lived. Third, with this information with this lead-time, it should be possible to advise passengers on when best to make their journey to avoid delays. This example illustrates the benefits of the new generation of forecasting capabilities and opens the door to much more dynamic management of the network and services. An extended 'sandpit' trial of these capabilities has been undertaken and described in Chapter 9.

7.3 Risk-based Impact Modelling

Beyond the actual forecasts, what is critical for many users is the translation of those forecasts into information content relevant to their business/operations, that takes account of their exposure and vulnerability and enables decisions to be made that mitigate the overall risk.

In many cases this mean- translating the forecast weather into hazards, such as flooding and wind damage, which enable the likely the impact to be assessed. The development of hazard impact models has grown substantially over the last decade. Through these models, hazard definitions can be determined using thresholds, above which potential losses or impacts can be incurred. This has enabled the Met Office and Flood Forecasting Centre to refine their severe weather and flood warnings so that they are targeted at where the risk is greatest. The decision on the level of warning is determined using a risk matrix which combines the likelihood of the hazard event and the severity of its potential impacts.

Figure 7.5 gives an example of this matrix for flood risk in Cumbria from Storm Desmond. It shows the decision-making process for the Flood Guidance Statements (FGS) over the preceding few days as the likelihood of flooding increased and the severity of the impacts became apparent, culminating in a red warning on 5/6 December. Note that this example relates to the sequence of forecasts shown in Chapter 6, Section 6.1 on risk-based forecasting.

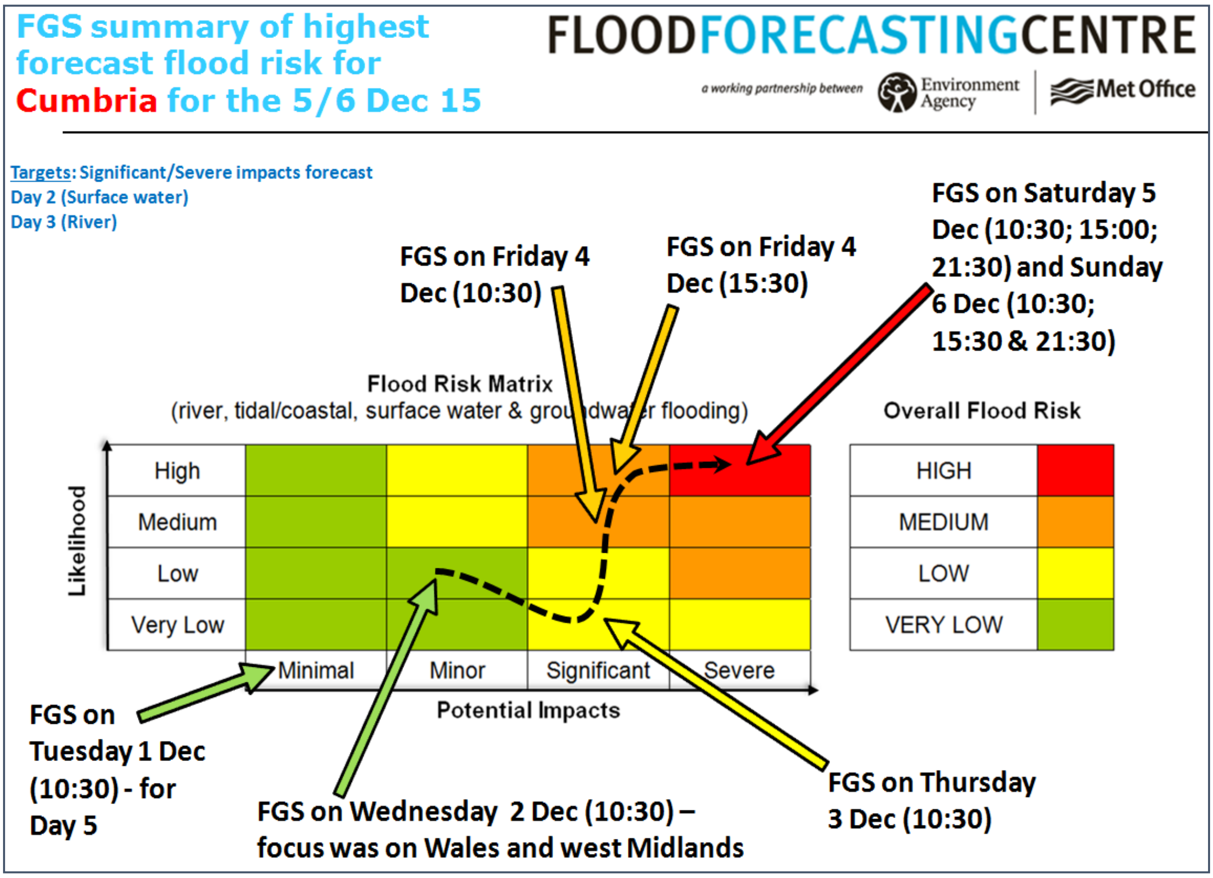


Figure 7.5: Example of the risk matrix used by the Met Office and Flood Forecasting Centre to determine when severe weather warnings and flood alerts should be issued. It depends on two factors, the likelihood of the severe hazard event occurring and the level of potential impacts if it does. This example shows the evolution of the flood guidance statements (FGS) during the forecasts leading up to Storm Desmond on 5/6 December 2015. It shows a combination of increasing confidence in the rainfall forecasts followed by the move from significant to severe impacts in Cumbria as the location of the highest probabilities for extreme rainfall became clear (see Figure 6.6). Source: Joint Met Office/EA Flood Forecasting Centre.

This type of risk matrix can be used in many settings and enables the full value of the ensemble forecasting system to be used alongside detailed understanding of the potential impacts in space and time. A good example of this is impact-based forecasting for the road network (Figure 7.6). Here the risk levels depend not only on user-relevant meteorological thresholds (e.g. wind for overturning high-sided vehicles), but also on the time of day and the traffic density at that time (e.g. rush hour). The network is then coloured-up in terms of traffic-light warnings, which enable the user to see at a glance where disruption is most likely and where traffic controllers may need to impose speed restrictions.

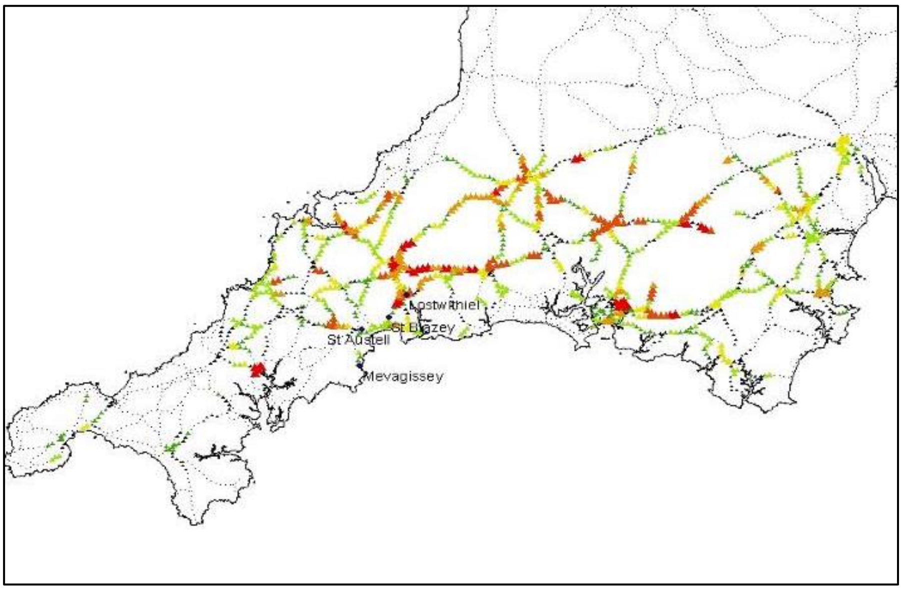


Figure 7.6: Example of a risk-based warning system for the road network (Source: Met Office)

This example of the application of the risk matrix requires access to, and the development of vulnerability and exposure datasets for a range of infrastructures, such as the road network and the users of the network. With rapid advances in digital technologies, interactive, real time platforms that display this multi-faceted information in a user-friendly fashion is entirely possible (see Chapter 10). The simplicity of the end result, from terabytes of forecast data to a simple, coded map is very efficient and effective. It allows the information to be updated continuously as the risk matrix evolves.

7.4 Beyond Meteorology to Hydro-meteorology

As noted in Chapter 2, Network Rail is particularly susceptible to hazards such as surface flooding, wash-outs and earthwork slides, and yet the translation of rainfall into these hazards is particularly challenging. Current capabilities in predicting hydro-meteorological risks are largely confined to river flooding and are increasingly skillful, associated with better monitoring of rainfall and river/stream flows, advances in modelling individual catchments and more joined up forecasting systems (e.g. joint Met Office/EA Flood Forecasting Centre and SEPA).

As concerns about the risks of surface water flooding have grown, a joint effort to develop a surface water hazard impact model across several agencies, research establishments and the private sector has been initiated (Figure 7.7). This effectively takes existing capabilities and data and combines them in innovative ways to provide new real-time warning systems, which are then disseminated using digital technologies. The involvement of multiple agencies from science to services ensures that the hazard impact model encapsulates the best elements across the value chain. Network Rail's needs could be incorporated through the impact library and be visualised at the route level.

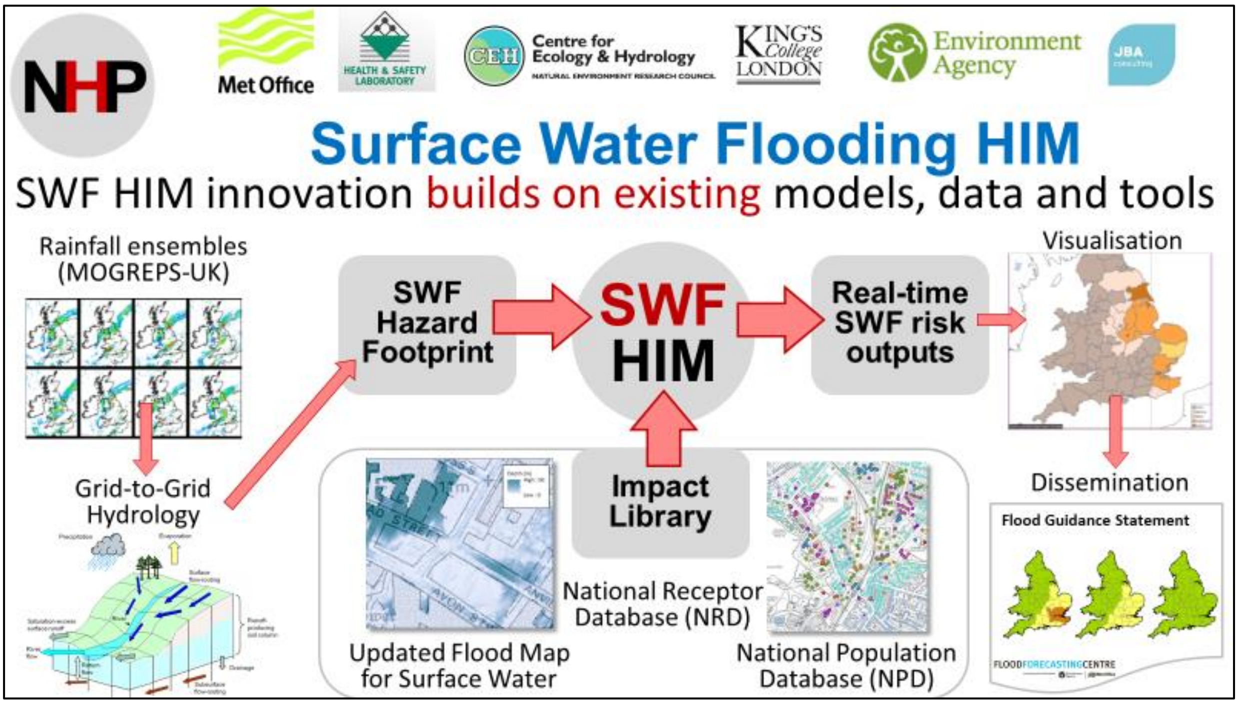


Figure 7.7: Schematic demonstrating the cross-disciplinary, multi-institutional process for developing hazard impact models, in this case for surface water flooding. In this example, the hazard impact model starts with the hazard forecast which is then interfaced with databases on exposure/vulnerability, through to visualisation and informatic layers and finally dissemination of products and services that aid decision-making. For Network Rail, the impact library could include information on routes, assets, train and passenger numbers.

Another application of these hazard impact models is in stress-testing infrastructure against unprecedented weather extremes or future climate change. In the National Flood Resilience Review (2016), the viability of the national extreme flood outlines was stress-tested against meteorologically-plausible, extreme rainfall that was up to 30% higher than past observations. This uplift was derived from very large event sets (1000's of events) generated by state-of-the-art simulations of today's weather and climate. These allow robust identification of 1-in-100 year (i.e. 1% probability) extremes[14], something that is difficult from the limited observational record. Figure 7.8 shows an example for Exeter where the railway is particularly exposed. This test case was based on the 1960 severe flooding event and shows that with 30% more rainfall, extensive areas of Exeter would be flooded, including the railway line south of Exeter St David's Station. We recommend this type of approach for stress-testing aspects of Network Rail's infrastructure using worst-case scenarios.

[14] Thompson, V., N. J. Dunstone, A. A. Scaife, D. M. Smith, J. M. Slingo, S. Brown and S. E. Belcher, 2017: High risk of unprecedented UK rainfall in the current climate. *Nature Communications*, 8, 107, DOI: 10.1038/s41467-017-00275-3

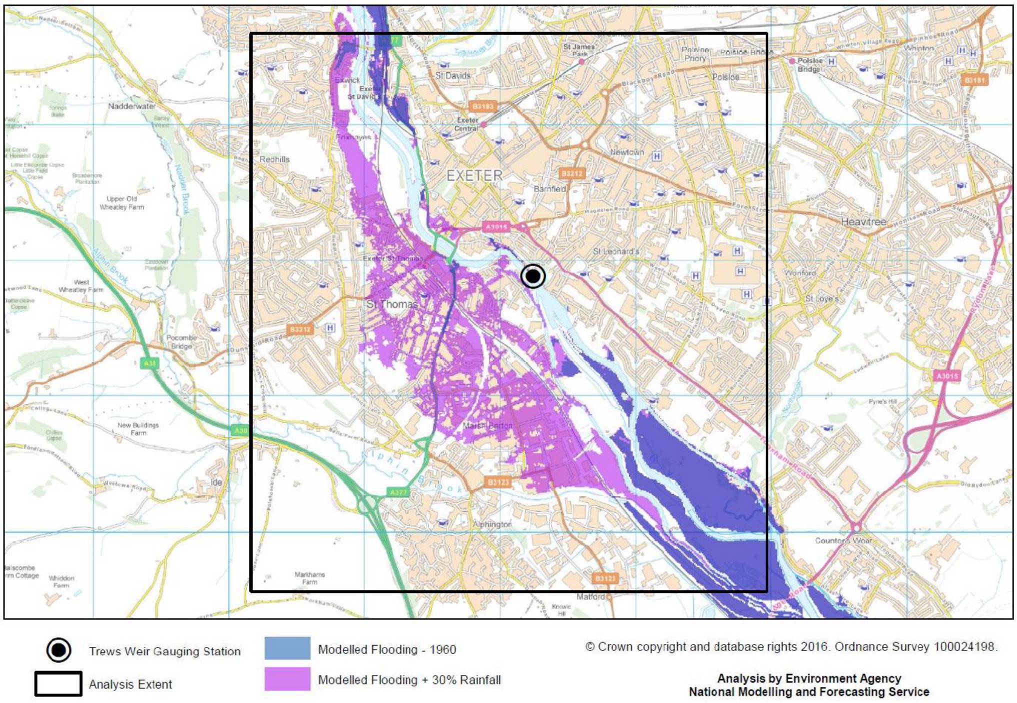
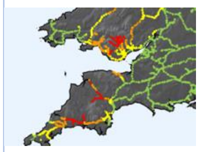
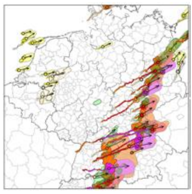
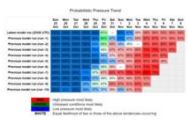


Figure 7.8: Simulation of the Exeter case study of December 1960 by the Environment Agency and the Met Office. The actual flood extent (blue) and the stress test scenario (purple) with a rainfall uplift of 30% (both with present day alleviation schemes in place) have been simulated. Source: National Flood Resilience Review (2016)

In summary, this and the previous chapter have summarised some important advances in weather forecasting and services that could improve Network Rail's performance across the whole '*Awareness – Preparedness – Response - Recover*' cycle. These can be best summarised in the following Table 7.1. It highlights the value of a more seamless approach to weather service provision, along with new interpretative tools, which have the potential to transform decision-making and allow Network Rail to be better prepared and more resilient.

Table 7.1: Summary of the new forecasting tools that are available to Network Rail across the whole '*Awareness – Preparedness – Response - Recover*' cycle.

Stages	Actions	Scale	Methodology	Tool	Visualisation
Awareness	When weather conditions, which might merit a red alert status, are 4-5 days out on the extended range forecast ensemble	Region, 10 days lead time Synoptic scale: Weather systems, e.g. cyclones	Network Rail sensitivity analysis correlated to predicted weather regimes.	'Decider'	
Preparation	Route Operations Control has assigned red alert status to weather conditions 2 days out; preparatory actions begin	County, 24 hours lead time Mesoscale: e.g. Cold fronts, thundery lows,	Kilometer-scale ensembles with post-processing tailored to Network Rail impact thresholds and network vulnerabilities	'Hazard Impact Models'	
Response	During an extreme weather event, Route Operations Control shall: a) conduct further EWATs as appropriate; b) provide updates to TOCs, managed stations and media teams to keep the travelling public informed; and c) initiate the Service and Performance Recovery Conference	Track and steer, 2 hours lead time Storm scale	Nowcast objects and feature-based tracking. Monitoring and alerting dashboard capabilities	Nowcasting	
Recovery	Service and Performance Recovery Conference shall establish the priorities and timescales for recovery of the network. Weather forecasts out for the next week can provide weather windows of opportunity for scheduling recovery work.			'Decider'	

8. Earthwork management and assessing risks of failure due to weather events

Network Rail has inherited and manages 190,000 earthworks assets, comprising 70,000 soil cuttings, 20,000 rock cuttings and 100,000 embankments, the majority of which are over a century old. They encompass a vast range of complex geologies and engineered structures, and they fail in many different ways (Figure 8.1). These aspects are covered in detail in the Earthworks Management Task Force, led by Lord Robert Mair. Here we focus on the impacts of weather on earthwork failures and how weather intelligence can be used to assess and mitigate the risks associated with such failures.

Figure 8.1*: Examples of the diverse range of earthwork failures.*

Earthwork failures occur throughout the network (Figure 8.2) with 1900 reported failures between 2003 and 2020. Although there are many factors that contribute to earthwork stability, the most dominant association is with the weather (Figure 8.3), and with periods of heavy rainfall in particular (Figure 8.4). Failures occur throughout the year but are most prevalent in winter months (Nov. to Feb.) when rainfall is most prolonged and the soils are wet. However, the causal factors are clearly much more complex and difficult to tease out because earthwork failures are still relatively rare events; as Figure 8.4 shows, heavy monthly rainfall predisposes earthworks to fail, but there are many months with similar rainfall where earthworks do not fail.

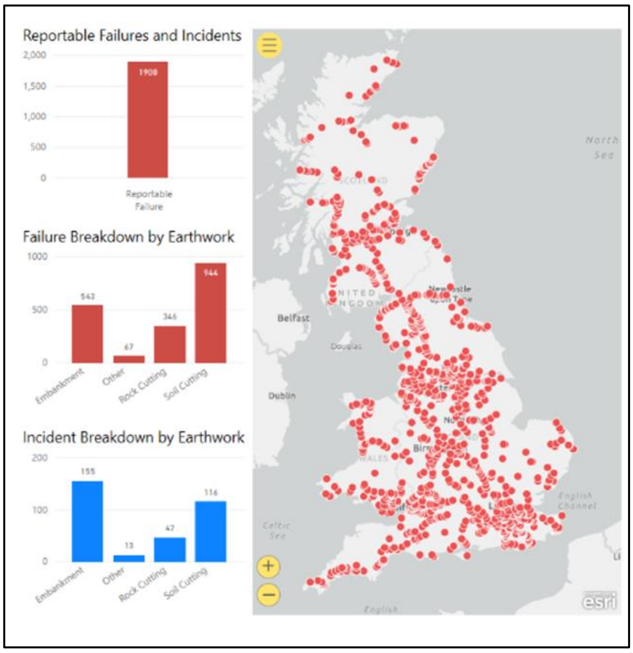


Figure 8.2: Distribution of earthwork failures and incidents across the UK between 2003 and 2020. As the bar charts show, these are dominated by embankment and soil cutting failures. Source: Network Rail

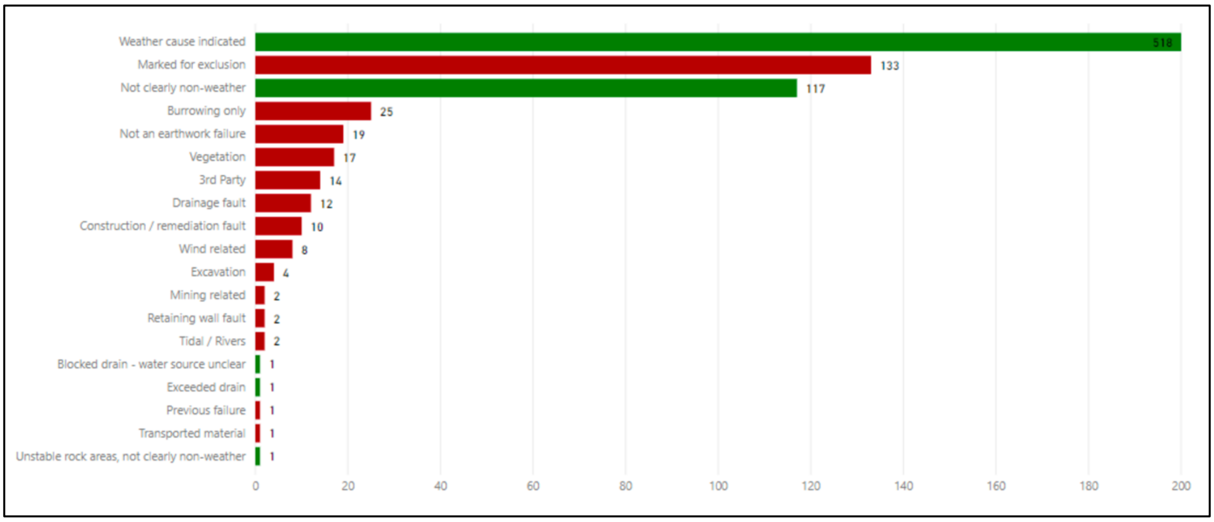


Figure 8.3: Summary of the attribution of earthwork failures to different potential causes. Source: Network Rail

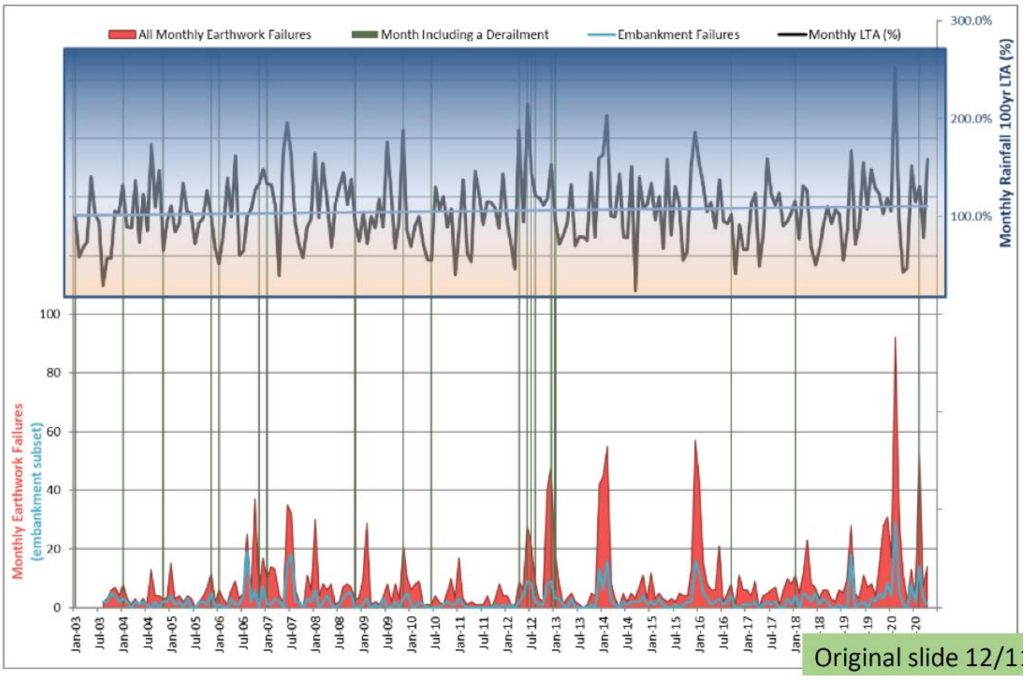


Figure 8.4: Timeseries from 2003 to 2020 of monthly rainfall expressed as a percentage of the long-term average (upper panel) and the monthly incidence of all earthwork failures (red) and the embankment subset (blue; lower panel). The months where a failure led to a derailment are highlighted by the vertical lines. Source: Network Rail

As Figure 8.4 demonstrates the number of failures has increased significantly in the last couple of years. Addressing the question of '*why are both the cuttings and embankments in a range of geologies continuing to fail*', the EMTF report notes that '*the stability of the assets is strongly related to weather patterns, in particular to antecedent rainfall and rainfall intensity. It follows that, while reductions in drained strength parameters over time and changes in vegetation may play a part, the dominant reason for continuing failures is the exposure of oversteep and previously failed slopes, including their weathered zones, to rainfall patterns not previously experienced at particular locations*'. In other words, the emerging signal of climate change, with increases in rainfall, especially down the western side of the UK (See Chapter 3, Figure 3.3) may be a contributory factor. This makes the management of earthworks and forecasting where they might fail even more pressing.

There are number of aspects that make this a thorny - or perhaps even a 'wicked' problem. The link between rainfall and earthwork failures involves consideration of antecedent, cumulative rainfall and rainfall intensities, hydrogeomorphology, infiltration, run-off, localisation, and installed stabilisation measures, including drainage. Interaction of these, often compounding, factors makes each failure unique, and so there is unlikely to be an easily defined rainfall (or soil moisture) threshold above which an earthwork may fail. It is also the case that failures do not necessarily occur coincidently with bad weather but may be triggered several days in advance. Identifying the trigger event is very difficult in complex landscapes and hydro-geomorphologies.

Network Rail currently uses a combination of rainfall and soil moisture/wetness indices as indicators of earthwork risk and considerable work has been undertaken to explore these connections. Working with ARUP, a major analysis of recent failures has been performed, which attempts to include multiple aspects of the problem, from trigger events and antecedent soil conditions, to different rainfall intensities over different time windows. It is fair to say that this has not been entirely successful. The multi-faceted nature of the problem, combined with the rarity of failure events, the large volumes of weather data, and limited expertise in analysing rainfall and using soil moisture, has meant that there are a number of issues with the results.

New approaches are needed. Earth failures are rare, and each is unique in some way, so it is always going to be difficult to tease out the drivers/indicators. Our experience with analysing extreme weather events, which have similar complexities, suggests that using event-based diagnostics provide a better approach to finding causalities. Using all available evidence, a forensic analysis of particular events can be conducted to provide a complete picture of the context and weather drivers surrounding the failure, and from which some key properties or indicators may emerge. These results may prove to be more robust and easier to understand and implement than from a very complex statistical analysis.

In the following sections we have looked at other indicators beyond rainfall and soil moisture indices that may help to make progress in this challenging area.

8.1 Weather regimes and extreme daily/sub-daily rainfall

Previous work to relate weather regimes to high impact hydrometeorological events has predominantly focused on various types of flooding; there has been less done with landslide occurrence. However, there are examples internationally which show that it is possible to identify specific weather patterns that are more likely to result in natural landslides being triggered. Identifying high-risk weather patterns or developing risk indices for each weather type, which combine the weather type assessment with vulnerability and exposure datasets, can prove useful for heads-up warning. Such approaches align with many disaster risk reduction frameworks and could be utilised to provided extended-range forecast guidance.

In a preliminary study, the Met Office has used the weather regimes described in Section 7.1 (Figure 7.1), combined with gridded rainfall data, to explore the feasibility of this approach. Using earthwork failure data for 2003 to 2020 (see Figure 8.2), daily rainfall accumulations and daily weather pattern occurrences in the 15 days prior to the event, have been analysed to produce lists of 'high-risk weather patterns' relevant to hydro-meteorological failures across the UK rail network (Table 8.1). A subset of the failure data was used, to focus on those failures where flood or landslide is referenced.

Table 8.1*: Summary of high-risk weather patterns relevant to landslide and/or flood earthwork failures for different climatological regions of the UK. Patterns are identified by comparing the weather pattern*

percentage contributions to the total observed rainfall and the rainfall accumulation distributions for each pattern type. Source: Met Office

Region	High-risk patterns for earthworks failure	Number of high-risk patterns (out of 30)
Northern Scotland	7, 15, 20, 21, 23, 29 and 30	7
Southern Scotland	11, 15, 20, 21, 26, 27 and 30	7
Eastern Scotland	2, 5, 16 ,20, 21, 22, 23, 29 and 30	9
North-west	11, 20, 23, 26 and 30	5
South-west	11, 21, 24, 29 and 30	5
South-east	11, 19, 24, 28, 29 and 30	6
North-east	11, 14, 24, 29 and 30	5
Central	19, 24, 26, 28, 29 and 30	6

The results of this preliminary study are encouraging. High-risk weather patterns have been identified across the UK (Table 8.1) and the number are small enough that they can be used within an alert framework to discriminate situations where the risk of earthwork failure may be elevated. Used alongside the 'Decider' tool presented in Section 7.1, there is real potential to give early warnings, particularly if other indicators beyond the weather regime can be included in the tool.

This feasibility study has not distinguished between landslide types and/or flooding/washout events; all events have been processed in the same way regardless of the failure mechanism (e.g. translational or rotational failures and falls). There would be value in extending this work to explore whether further sub-setting would provide additional insights.

8.2 Soil conditions

Network Rail currently uses indices of soil moisture to identify elevated risks of earthwork problems. Soil moisture is not a directly observed variable because of the complexity of the geology and landscape. Instead, it is derived as a product from a weather prediction model (e.g. Soil Moisture Index), from interpretation of surface meteorological observations (e.g. Soil Moisture Deficit), or very recently as a product of satellite measurements (e.g. Soil Wetness Index). More details of these products are provided in the WATF Briefing Report; suffice to say that none of them is intended to be a detailed representation of the land surface hydrology, and any products that derive from them should be treated with caution.

As the EMTF report notes, soil moisture is not necessarily a good proxy for pore water pressures and suctions which are closely linked to the mechanics of earthwork failures. It is also not very discriminatory once the soil is wet, which is the case for much of the winter. However, soil moisture deficit (SMD) has been used with some success for clay soils under dry conditions (Figure 8.5). Clays are susceptible to both shrinkage and swelling which act to destabilise slopes and affect track geometry. The link with SMD has proved particularly useful in summer droughts where dessication is a problem.

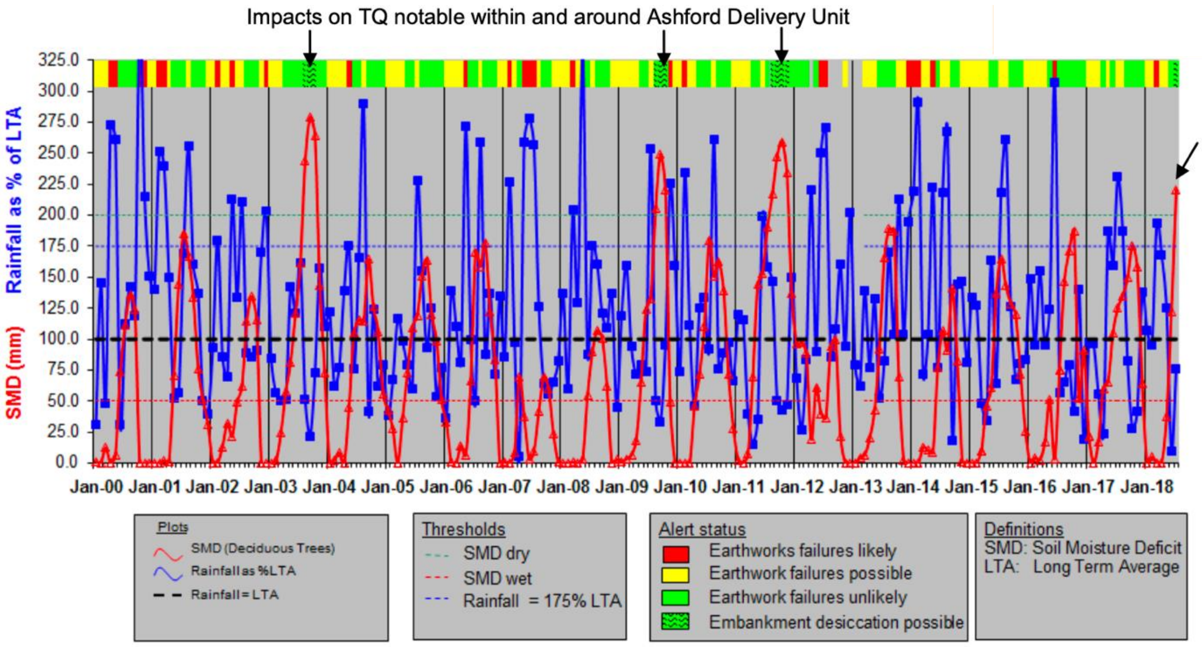


Figure 8.5: Chart showing the earthwork alert status from the varying conditions in ground moisture (measured as SMD) and monthly rainfall. In clay soils there is a fair trend using these metrics to assess the potential for earthwork failures (SMD = 0 and monthly rainfall >175%). Track geometry issues may arise from embankment desiccation when SMD exceeds 200mm (dry threshold). The chart shown is for a 40km2 area in the SE associated with the Ashford DU, where SMD exceeded 200mm in 2003, 2009 and 2011. Courtesy: Southern Region

As we discuss in the WATF Briefing Report, there is no index for soil moisture that does not have serious limitations. We need to be able to discriminate between soils that are wet from those that are beginning to exceed field capacity and run-off is likely. A possible way forward is to use more hydrologically based metrics, such as those developed by the Centre for Ecology and Hydrology for the operational Hydrological Outlook UK (https://www.hydoutuk.net) produced by the EA/Met Office Flood Forecasting Centre.

Of particular relevance to Network Rail are the relative wetness and dryness indices that are produced at kilometer-scale using the Grid-to-Grid (G2G) hydrological model of surface, subsurface and river flows (Figure 8.6)[15], which forms the basis of operational flood forecasting at the kilometer scale. The model is driven by observed or forecast rainfall at the same scale, and it uses the 'Hydrology of Soil Types (HOST)' dataset, which classifies the UK's soils in terms of their permeability and run-off characteristics (Figure 8.7)[16], to determine the partitioning of rainfall between run-off and soil retention, again at a kilometer-scale. Apart from its granularity, the HOST dataset is far more sophisticated in terms of soil types and their hydraulic properties, than anything that is used to produce soil moisture indices.

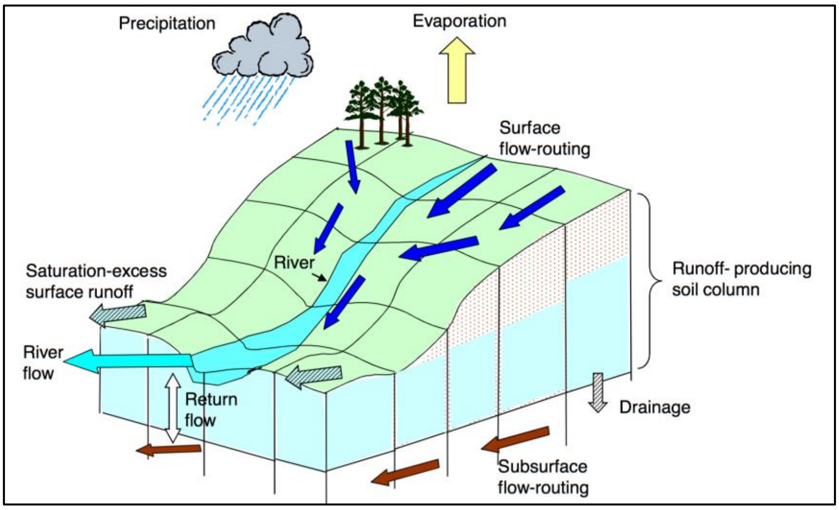


Figure 8.6: *G2G is a national-scale hydrological model for the UK that runs on a 1 × 1 km grid at a 15-min time-step, and is parameterized using digital datasets (e.g., soil types, land-cover). The effect of urban and suburban land-cover on runoff and downstream flows is accounted for in the model.*

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15 Bell, V.A., Kay, A.L., Davies, H.N. *et al.* An assessment of the possible impacts of climate change on snow and peak river flows across Britain. *Climatic Change* **136,** 539–553 (2016). https://doi.org/10.1007/s10584-016-1637-x

16 See: http://nora.nerc.ac.uk/id/eprint/7369/1/IH_126.pdf
https://www.hutton.ac.uk/learning/natural-resource-datasets/host/introduction

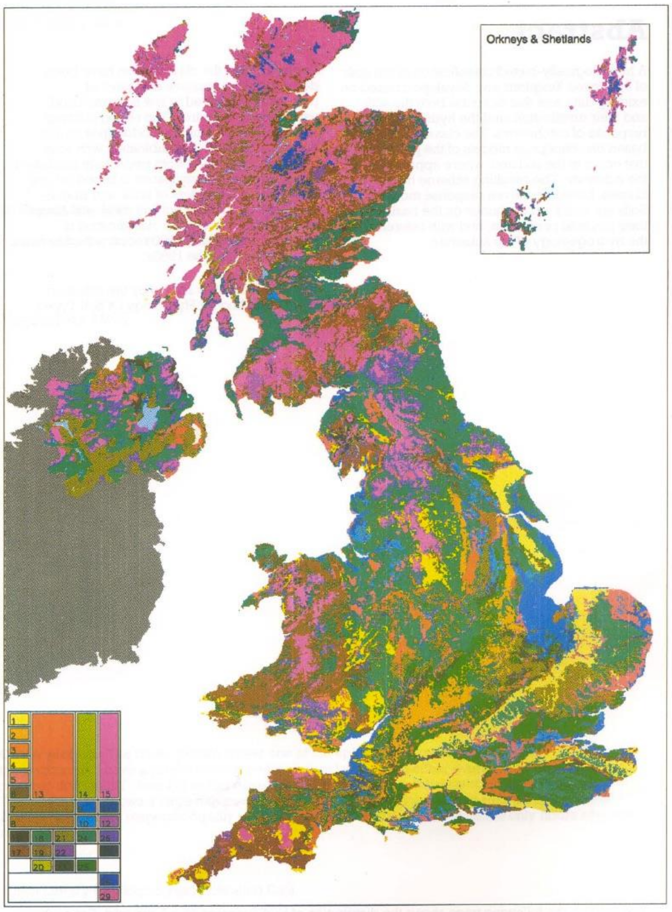


Figure 8.7: *Hydrology of Soil Types (HOST): A hydrologically based classification of the soils of the United Kingdom at kilometer-scale resolution. Using information on soil types as provided by UK Soil Observatory (UKSO), 29 classifications of soil hydrology types are identified based on permeability and run-off characteristics.*

Taking Met Office kilometer-scale rainfall as input, the G2G Hydrological Model is run continuously over the period 1981-2010, to produce a climatology of recent hydrological conditions across Britain, from which an estimate is made of the normal climatological depth of monthly subsurface water storage (S_{mean}) across the UK at 1-kilometer resolution. Here, the depth of subsurface water storage consists of the sum of the unsaturated soil and the groundwater stores (mm). The maximum or minimum monthly storage (S_{max}, S_{min}) in the climatological record is also computed.

In real time, the G2G then calculates the current water storage based on rainfall over the previous month and produces maps of the storage anomaly, relative to the long-term mean, highlighting where the current storage exceeds, or falls below, the long-term monthly mean storage. To highlight areas that are particularly wet or dry and therefore sensitive to future rainfall, the storage anomaly is also presented in terms of current water storage relative to historical extremes. Termed 'relative wetness' and 'relative dryness', these maps highlight areas that are prone to flood or drought impacts.

Figures 8.8 and 8.9 show the latest assessments of relative wetness and dryness, respectively, at the end of December 2020 based on the previous month's rainfall and antecedent soil conditions. The evolution of these indices over the previous four months are shown, as are examples of two past extreme months. The influence of the hydro-geomorphology is clearly evident in these examples emphasising the importance of including information on the local hydraulic properties of the soils.

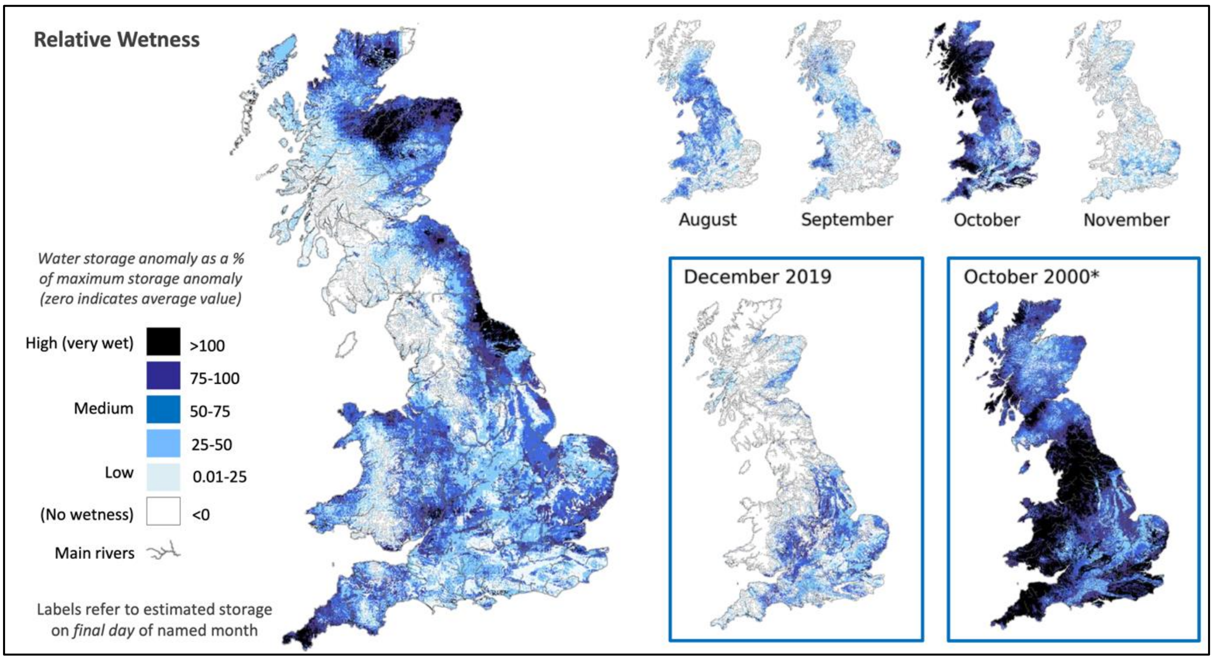
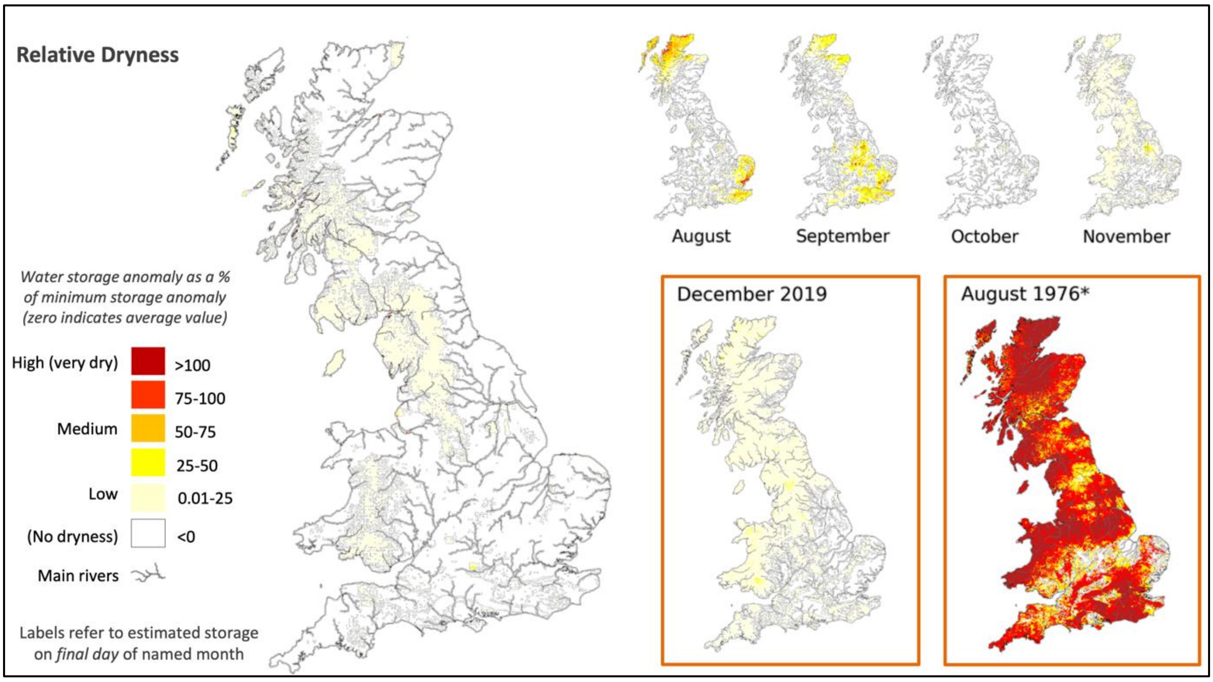


Figure 8.8: *Map of relative wetness (%) at the end of December 2020 (main image). This highlights areas (in blue/purple/black) where the G2G simulated subsurface storage anomaly ($S- S_{mean}$) is as high as, or exceeds, its historical maximum anomaly for the month ($S_{max} - S_{mean}$). The upper right maps show the evolution of relative wetness through the preceding months and demonstrate how rapidly the hydrological system changes. The two lower maps give examples of typical extremes of winter dryness and autumn wetness (Autumn 2000 was exceptionally wet with widespread flooding). Specifically, the maps show ($S- S_{mean}$)/ ($S_{max}-S_{mean}$)*100. Source: Hydrological Outlook UK*

Figure 8.9: *Map of relative dryness (%) at the end of December 2020 (main image). Relative dryness*



*highlights areas (in orange/red/dark red) where the G2G simulated subsurface storage anomaly (S- S_{mean}) is as low as, or below, its historical minimum anomaly for the month (S_{min} - S_{mean}). The upper right maps show the evolution of relative dryness through the preceding months. The two lower maps give examples of typical extremes of winter and summer (Summer 1976 is renowned for its extreme heat and drought). Specifically, the maps show (S- S_{mean})/ (S_{min}-S_{mean})*100. Source: Hydrological Outlook UK*

The Hydrological Outlook UK provides an official monthly summary that is shared with a range of users from farmers to water resource managers. In addition, 'relative wetness' is also computed on a daily basis in the Flood Forecasting Centre to monitor real-time risks of flooding, and especially surface water flooding. Figure 8.10 gives an example ahead of heavy rain on 23 December 2020 and shows that subsurface conditions were so saturated across broad swathes of the country, that only small rain accumulations would likely cause severe surface water flooding, as indeed was the case. It also shows how quickly the soils recovered as we entered a more settled, cold but dry spell of weather in January 2021.

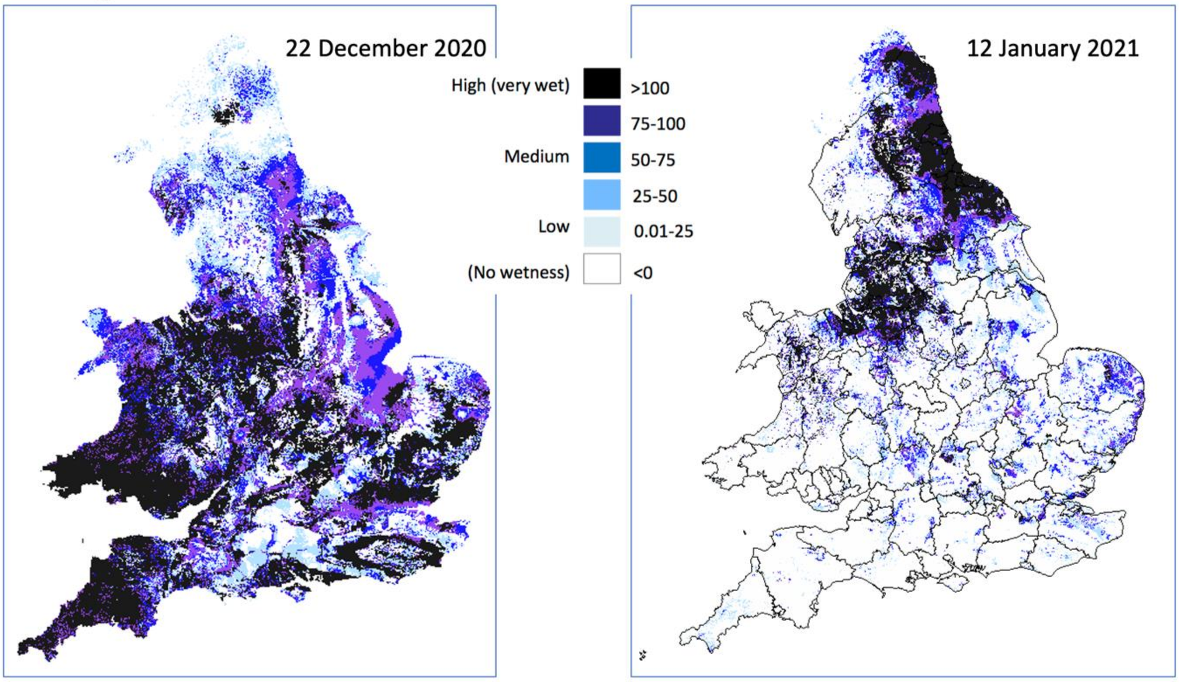


***Figure 8.10**: Example of daily maps showing the evolution of relative wetness from pre-Christmas flooding and the subsequent dry spell in January. Source: Joint Met Office/EA Flood Forecasting Centre*

Our opinion is that these new indices have considerable potential for assessing risks of earthwork failures and should be explored. The link through to the hydraulic properties of the soil, the use of a well-tested hydrological model driven by high-quality rainfall, and the horizontal resolution of the whole system, together, bring this much closer to the specificity of individual assets. It begins to close the gap between the weather and the hydrogeomorphology, and it gets nearer to the pore water pressures and suctions that link to the mechanics of earthwork failures.

In summary, we recognise that earthwork failure is immensely complex and that being able to forecast possible failures is extremely challenging, both from a weather and a geotechnical standpoint. We do not have the expertise to comment on the geotechnical issues, but we offer the following suggestions with respect to managing the effects of adverse weather:

(i) Network Rail currently uses a combination of rainfall and soil moisture/wetness indices as indicators of earthwork risk. Soil moisture is not a directly observed variable because of the complexity of the geology and landscape and is derived fairly crudely from forecast models or weather observations. They are not intended to be a detailed representation of land surface hydrology and any products that derive from them should be treated with caution. We recommend that Network Rail places less weight on soil moisture indices and considers alternative metrics.

(ii) The search for appropriate spatially-varying thresholds for assessing the probability of earthwork failures has proved to be very challenging. The project with ARUP has not been successful for various reasons, which we have discussed with the team. We recommend that new approaches are considered.

(iii) Early warning of specific weather regimes that predispose earthworks to failure could be very beneficial in activating inspection and monitoring of vulnerable assets well ahead of adverse weather. The 'Decider' tool could be re-purposed to provide bespoke guidance for routes and regions.

(iv) Earthwork failures, and indeed the broader problems of surface water flooding, could be addressed more effectively using hydro-meteorological approaches that incorporate local hydrogeomorphology aspects. We have demonstrated the potential utility of products from the Hydrological Output UK which could be combined very effectively with the latest kilometre-scale forecasting capabilities. These should be explored as a more appropriate metric than soil moisture. We also recommend closer engagement with the EA/Met Office Flood Forecasting Centre to explore the potential for operational surface water flooding alerts across the rail network.

9. 'Sandpit' trial of kilometre-scale forecasting

The value of running a route-based weather service was demonstrated for a wind and rain event that occurred on 11 November 2020 (see Section 7.2, Figure 7.4). Building on this, Network Rail and the Met Office agreed to perform a 3-week 'sandpit' trial in real time, and to engage the Routes and Regions in assessing its potential value. The aim of the trial was to jointly explore next generation forecast capabilities and expertise across the whole '*awareness – preparedness – response – recover'* cycle to improve decision making.

The trial commenced on 30 November and officially ended on 21 December 2020. It was decided to continue the delivery of these products to cover the Christmas period and beyond; this proved useful in providing guidance during the flooding event of 23 December, Storm Bella and subsequent ice and snow events. In addition to the kilometer-scale forecast products, the regime-based, Decider tool provided advance notification of a changes in the current and future weather regimes, which aided improved logistical actions and mitigation planning days in advance.

The trial was successful. All products were issued on time at 0700, and there were no service failures. Fortunately, the weather cooperated, and the trial was conducted during a period of disturbed weather. Consequently, a number of impactful events occurred which demonstrated the value of delivering a route-based service.

On 5th December an active system brought very localised weather hazards including snow, flood and an earthwork failure in eastern Scotland as well as flooding in Kent. The route-based forecasts did a remarkable job in correctly identifying areas affected (Figure 9.1) while the rest of the network remained green.

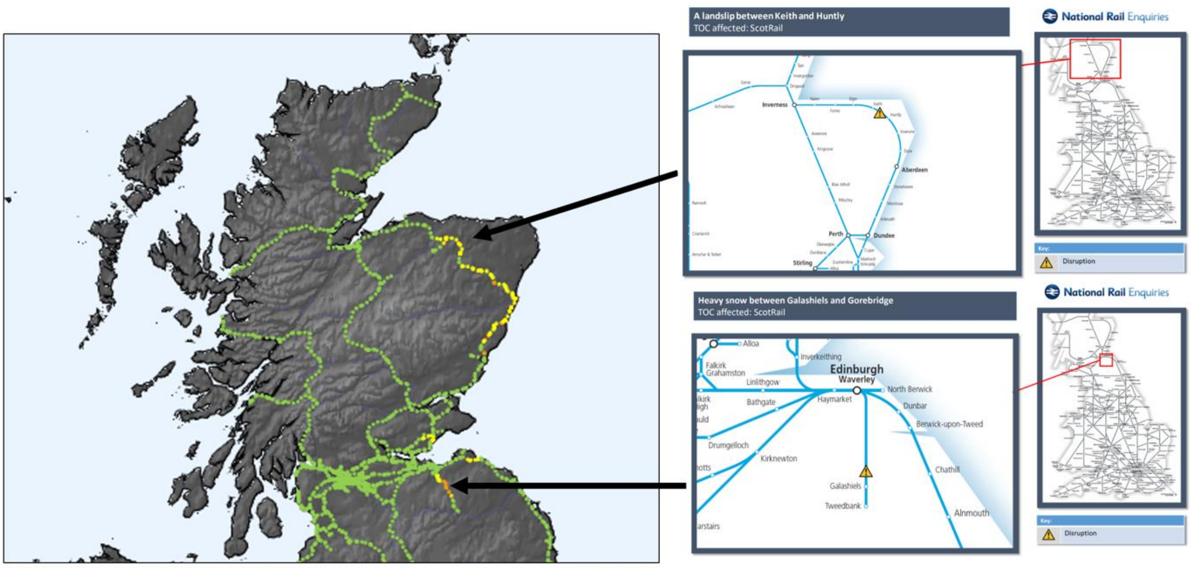


Figure 9.1: *Example from 5 December 2020 showing where the kilometer-scale forecast has identified specific parts of the network that are likely to be exposed to adverse weather (left panels). The right panels show where incidents were reported as a result of the weather. Source: met Office and Network Rail*

The flood event on 23/24th December also showed the benefit of using the 'Relative Wetness' product to identify flood and earthwork failure risk (See Section 8.2 and Figure 8.9). Hydrometeorological conditions leading up to 23rd December flood were primed for a major incident, in terms of both flood and associated earthwork failure risk. Based on long experience, forecasters recognised that with this type of weather system, there is propensity for extreme rainfall and that when ground is saturated this can lead to serious local flooding.

With the forecast continuing to signal a major risk to the transport network, Network Rail announced Red status on 8 routes. Brain Haddock (NR) and Paul Davies (Met Office) jointly briefed Sir Peter Hendry (DfT Tsar) on the threat to rail, road and critical national infrastructure. The Environment Agency and other partners instigated mitigation plans with mobile flood defences deployed in areas most at risk. These actions were based on the continuing and consistent advice from the kilometer-scale forecast over 2 days before the event (Figure 9.2), with robust warnings of a period of heavy rain in the right areas; this was complemented by expert advice on flooding from the Flood Forecasting Centre.

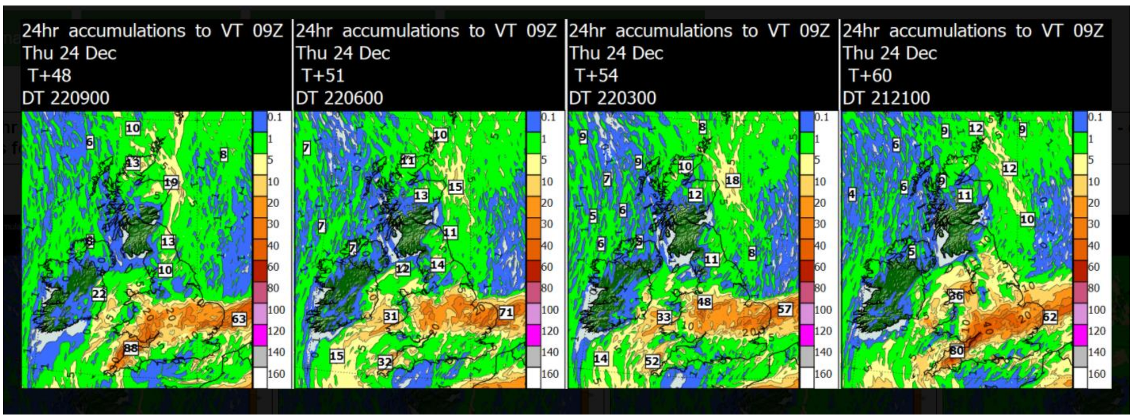


Figure 9.2: *Sequence of forecasts made 48 to 60 hours ahead of daily rainfall accumulations (mm) for the flood event of 23/24 December 2020. The forecasts successfully captured the location of the main band of rainfall across central England. Source: Met Office*

On the day itself the trial predicted the following impacts on the rail network, which corresponded remarkably well with the observed locations of heaviest rainfall (Figure 9.3). The hydrological response was large, though not surprising given the saturated state of the ground. A plethora of significant impacts to the rail and road network, stretching from SE Wales, Gloucestershire, Midlands to Norfolk, were reported during the event, including a landslip in Mansfield, Nottingham

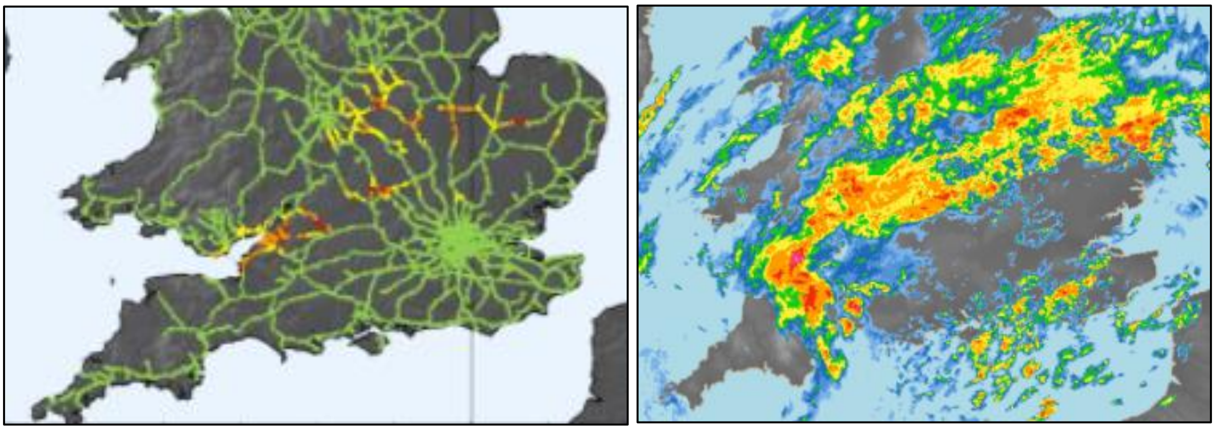


Figure 9.3*: Route based weather warnings for heavy rainfall and flooding (left), based on the kilometer-scale forecast for 1800utc issued at 0300utc (left) with expert advice from the Flood Forecasting Centre and the EA. Observed rainfall for the same time (right) shows that the forecast (Figure 9.2) has captured well the broad swathe of heavy rainfall and the network locations most at risk at that time. Source: Met Office and Network Rail*

The Routes and Regions enthusiastically participated in the trial and provided very helpful feedback on the prototype products, and endorsement for a change to more dynamic approaches:

(i) James Stockall (Programme Manager, Geotechnics, Drainage, Lineside, DEAM team - Wales & Western Region)

From the Wales and Western region perspective, we have the some of the most varied geologies on the network stretching from Cornwall to London to Pwllhelli and often experience the Atlantic frontal systems before our counterparts. The ability to improve on our existing forecasting tools and statistically derived thresholds at better temporal and spatial granularity from outputs of the task force will hopefully provide much needed support and assurance to a very complex challenge.

Our asset engineers deal with tricky decisions on a regular basis involving the balancing of safety of the railway with unpredictable natural assets whilst maintaining a performing railway. Tools to allow backed up dynamic decision making that are embedded with hydrological sensitive mapping, antecedent condition knowledge and probabilistic pressure trends relative to likelihood of earthwork failure will help how we manage the regions considerable variations, where decisions made in NW Wales have very different impacts to the Thames Valley and into London.

The ability to 'use' powerful data in planning, processes and reacting dynamically when needed at the sharp end, is challenging, but progressing any outputs from the weather taskforce coupled with a more *controllable railway at heightened weather risk from other workstreams will allow for further support in decision making for the region.*

(ii) Neil D Jones (NW&C Regional Engineer Buildings & Civils)

The trial has demonstrated that emerging technology can offer significant benefits to the mitigations of weather-related risks on the operation of the railway. Dynamic provision of weather forecasts interpreted against thresholds informed by expert analysis and directly connected to operational route sections provides the opportunity for performance impacting mitigations to be more effectively and reliably implemented. It will need close cooperation between the railway and weather professions to develop these solutions, but the trial has proved the concept.

(iii) Simon Constable, Route Operations Manager - Scotland

I became involved in the trial after the accident at Stonehaven with a vested interest in finding a way of adding to the current level of detail contained within our existing weather forecasts. This enhanced level of detail will enable us to react to an anticipated weather pattern and apply the necessary precautions in advance at our high-risk earthworks and structures. The outputs I have seen so far are incredible in relation to the detail and granularity the trial provides. As an operator, due to its user friendliness, I will be easily be able to identify specific sections of ELRs and target with a high degree of confidence mitigation measures in the right place, and equally as important, none placed where they are not required. I believe that the trial offers a significant benefit for safety and also train performance and could see the end of miles upon miles of blanket speed restrictions.

I consider the outputs that the trial produces would be incredibly useful for determining the operational response required when presented with a predicted challenging weather pattern therefore making it a 'must have' for the control to facilitate the decision-making process for arranging EWATs. The idea of aligning the trial with a similar trial for flooding being undertaken by SEPA will, if successful, provide a forecasting methodology that covers all of our at-risk weather-related issues.

The Sandpit trial has demonstrated the potential value of dynamic, site specific forecasting for optimising the management of the network during adverse weather. More importantly it has shown the benefits of working together, through partnership, sharing information and action plans.

10. Towards a digital railway

The evidence we have gathered and the experience we have gained from the forecast trials have reinforced our view that Network Rail needs to embrace digital technologies to deliver a new hazard and impact-based service framework that integrates all the relevant information and provides ***accessible, flexible*** and ***seamless*** services, driven by ***dynamic user*** specifications for data analysis, visualisation and integration. We have come to this conclusion based on the following points:

(i) Weather hazards affect many aspects of the rail system, but multi-disciplinary science and data are not fully exploited by industry. Some impacts, such as flooding and earthwork failure, require a ***multi-disciplinary*** and ***collaborative*** approach.

(ii) Integration of new weather and impact-based forecasting capabilities into Network Rail's processes are too slow; there is a ***disconnect with 'state of the art'*** and yet these advances have the potential to revolutionise management of weather hazards.

(iii) Internal and external stakeholders have varying user requirements requiring ***flexible*** and yet ***consistent messaging.*** The current system does not capture all requirements leading to inefficiencies and misleading evidence.

(iv) Rail Technology Strategy is providing stepping-stones towards a data-driven railway, but this needs to be ***inclusive***. Not including the latest hazard science, insights and forecasts, could mean infrastructure and asset investments are not realised.

(v) Digital railway transformation is leading to increasing automation and new technologies for optimised train operations, with the potential to ***overcome fragmentation*** within the industry and better passenger services. This needs to be underpinned by a more dynamic and location-specific hazard warning service.

We have concluded that Network Rail needs a ***'systems of systems'*** approach to predicting and managing weather hazard perturbations, from operations to asset management. Today, this is greatly facilitated by the application of Geographic Information System (GIS) mapping. GIS is a digital framework for gathering, managing, and analysing data of all types, from regular (e.g. gridded weather) to heterogeneous (e.g. earthwork locations), from static (e.g. track geometry) to dynamic (e.g. speed restrictions, weather alerts). GIS organizes layers of information into visualizations using maps, 3D scenes and other tools (e.g. Figure 10.1), which the user can manipulate.

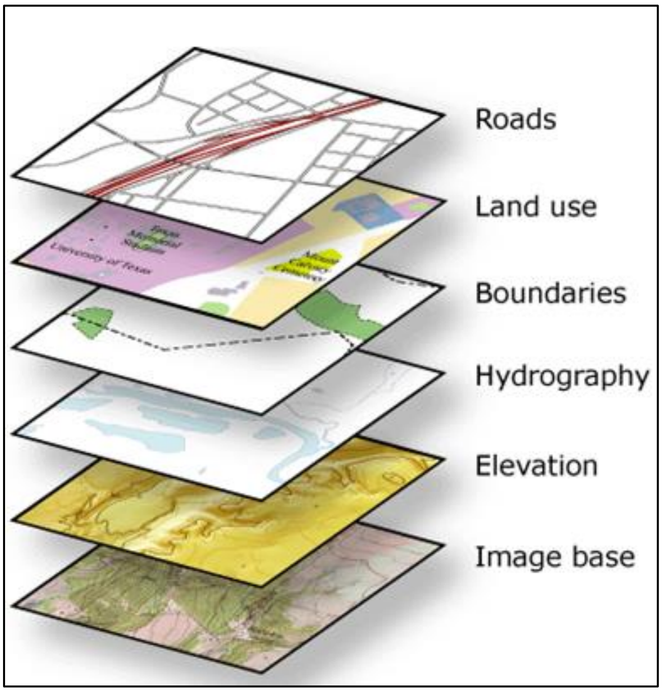


Figure 10.1: *Example of GIS overlays showing how information from heterogenous sources can be brought together to deliver a multi-faceted risk assessment.*

Network Rail's needs are complicated by the dynamic nature of its risks and the data volumes of some of its processes and controls. Weather data are particularly challenging because they change minute by minute and hour by hour, and the volumes are potentially huge. One way to avoid 'drowning' in the sheer volumes of data, is to automate the extraction of relevant data and products that best aid effective decision making (see Chapter 7 for examples).

Today, data are stored less and less in siloed data archives, but more and more in the Data Cloud. The Data Cloud allows organisations to unify and connect to a single copy of all of their data with ease, but more importantly also connecting to other organisations by effortlessly sharing and consuming shared data and data services. The Data Cloud makes the vast and growing quantities of valuable data connected, accessible, and available. No longer is it necessary for the customer/user to transfer large data volumes but instead only transfer the bespoke information that they need, say for use in a GIS platform. The traditional view that an organisation must hold and, in some cases, own all the data it needs is outmoded and imposes substantial barriers to progress.

In recent years, the Met Office has been sharing its data over the Cloud and this is transforming the way in which weather services can developed and delivered (Figure 10.2). The 'raw' data from the observations and model simulations/forecasts are now post-processed and productised in a series of pipelines before they even reach the operational weather forecaster in the Met Office Weather Centre. The bespoke services are then produced using APIs (Application Programming Interfaces) that combine information from a range of sources (e.g.

post-processed weather forecast, rail network map, asset conditions, hydrological conditions etc).

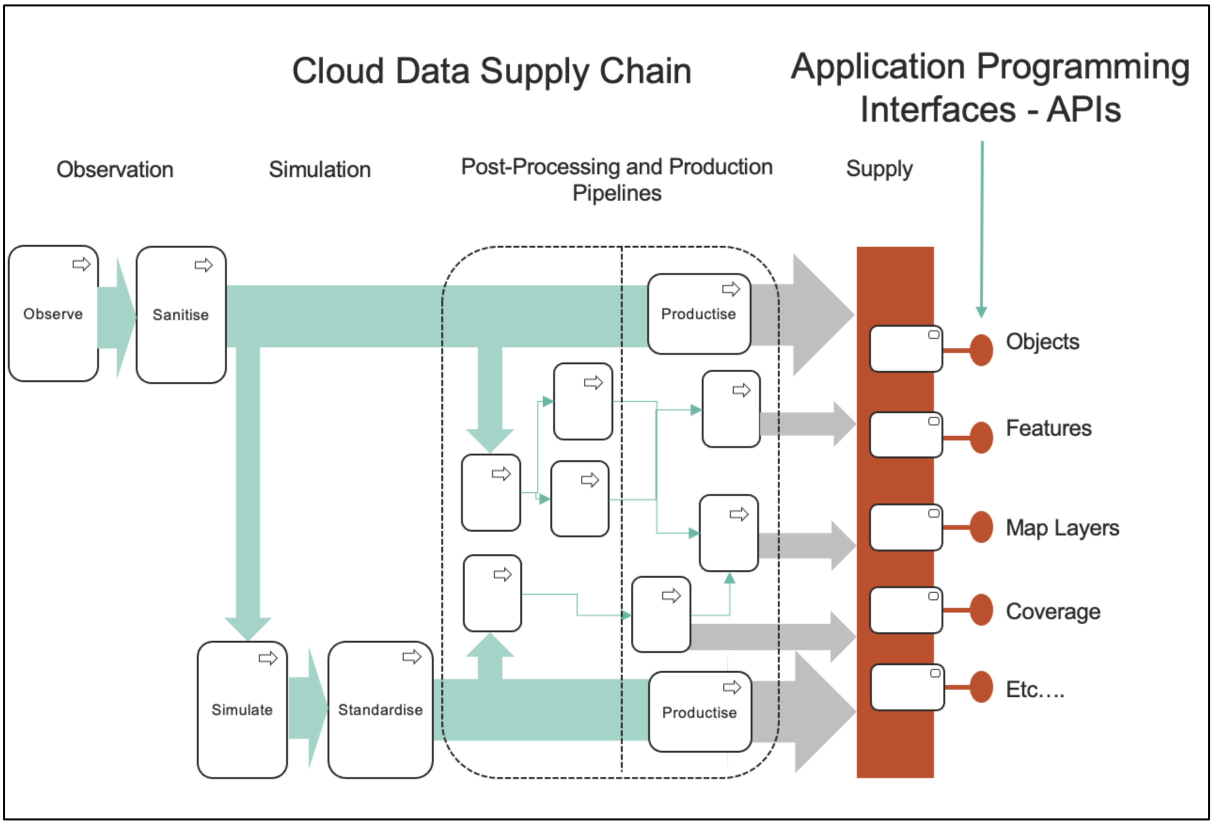


***Figure 10.2**: Example from the Met Office showing how its data-processing capability is being transformed by the Data Cloud and APIs. The gathering of observations and the construction of the forecasts, as described in Chapter 6, are the beginning of the supply chain. The Data Cloud enables these large data volumes to be interrogated, post-processed and pushed through a production line where APIs allow other data to be interfaced to produce user-defined products and services. Source: Met Office*

Taking an API approach to delivering data services emphasises what is required by the consumer and decouples the consumer from how it is to be achieved. In contrast, current systems typically focus on delivering large file-oriented datasets, from which consumers (e.g. Network Rail) must then mine for the parameters they need (e.g. alert status). This produces highly dependent systems which create challenges when changes are made in the data supply chains (e.g. forecast system updates). Rather than working with predefined datasets that need to be dissected, APIs deliver dynamically-defined data products, retrieved on-demand. APIs also mean moving smaller data packages, reducing costs and improving timeliness (reduced delay); the processing and storage of the potentially massive source dataset are at the provider side not the consumer side.

APIs offer a way of embodying higher-level abstractions which are at the application level and in terms of the domain of interest. The data returned from an API call are the result of the service behind the API, which embodies the skill and experience of the provider. APIs then become part of the consumer's digital platform. Being on-demand, the continuous improvement of the service can be decoupled from the invocation of the API. Lifecycle management and dependency control becomes much simpler; audit trails of activity become more specific and problem focused; and information on usage can be used to optimise the service by the supplier.

Delivering data via explorable APIs also opens up opportunities to think about extensive automation using purely machine-to-machine connections at the API level. Coupled with newer approaches, such as machine-learning, it is possible to envisage highly automated decision aids, consuming interoperable data from multiple API enabled data sources, and providing a machine-assisted, context-specific, overview of meteorological data blended with application and domain data.

This is a bold vision for the future delivery of Network Rail hazard and impact services, but it is entirely feasible with GIS, the Data Cloud and the data pipeline to APIs all in place. Figure 10.3 provides a demonstration of how it could be constructed to deliver seamless, optimal solutions for the whole rail industry

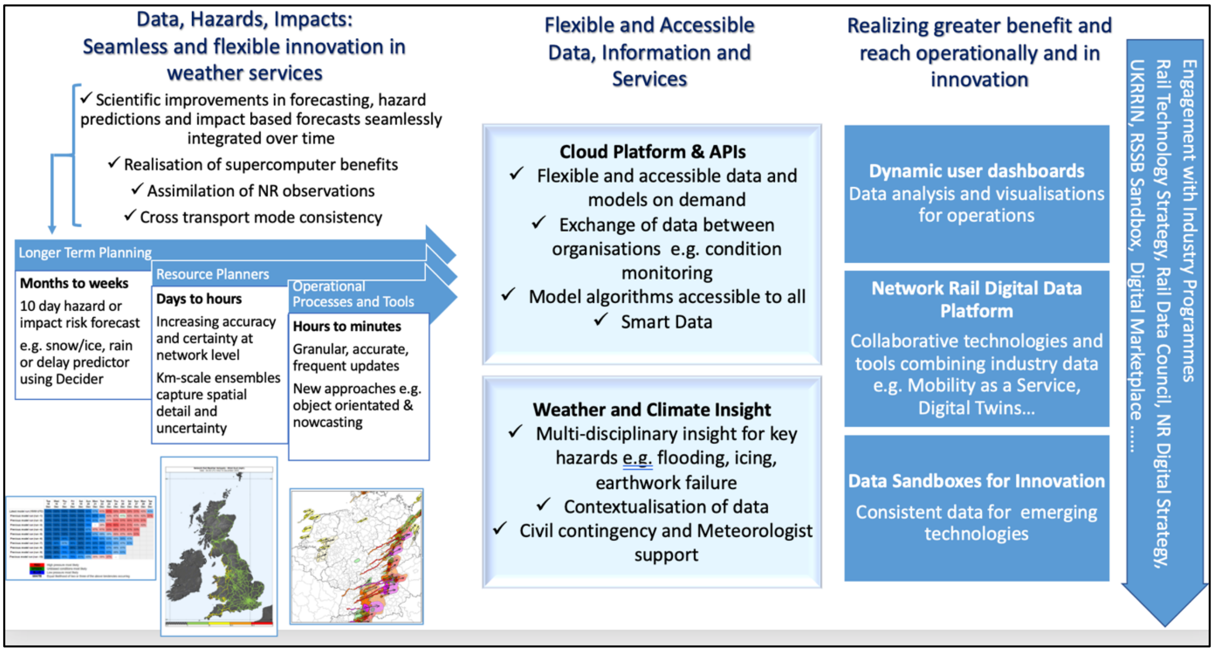


Figure 10.3: Summary schematic showing how the latest capabilities in weather forecasting and digital technologies can be brought together to deliver seamless, optimal solutions for the whole rail industry

Beyond just weather hazards, the possibilities for advanced risk management through digital, interactive platforms that can display a wealth of information in real time are considerable. It should be perfectly possible to overlay other information from rail network sensors, in-cab cameras, SMART devices and so on. The interpretation of these layers of information can be aided by new tools, such as Machine Learning and Artificial Intelligence, and then be disseminated rapidly to planners, control centres and drivers – 'SatNav' in the cab.

11. The future of Network Rail's Weather Services: Working in Partnership

Cogent arguments in favour of a new approach to Network Rail's Weather Service provision have been presented throughout this report. It is clear that the existing paradigm for procuring weather services through the 'waterfall' approach of capturing requirements and then procuring the service based on those requirements, is not sufficient. It potentially excludes the latest scientific and technological developments, and risks 'setting in stone' the services that are provided.

In this era of 'Big Data' and rapidly evolving weather science and technology, as well as the complexities of managing the impacts of adverse weather, there is a compelling case for future services to be based around a partnership between customer and supplier. The delivery of the services then become a shared endeavour in which Network Rail has access to high-level expertise and continual forecast and technology improvements, and the provider benefits from in-depth knowledge of Network Rail's operations and future planning. In this way the value of the service is optimised. The 'Sandpit' trial documented in Chapter 9 is a great example of partnership working.

Network Rail is classed as a Category 2 Provider by Government and an essential part of critical national infrastructure. Likewise, the Met Office, as the UK's Public Weather Service is the authoritative voice on weather and climate for Government and the designated supplier of severe weather warnings to all Category 1 and 2 providers. It seems logical to us that a strong case can be made that Network Rail should be working directly with the Met Office to ensure consistency of advice. In this way it would benefit from much more than just the latest weather forecasts. A partnership with the Met Office would give access to the Flood Forecasting Centre and its products, to other operational products such as Space Weather alerts, and to the latest scientific advances. Opportunities for joint R&D to deliver improved services, are another beneficial aspect of the proposed partnership.

We have considered possible business models for a strategic partnership between Network Rail and the Met Office and these are outlined in Table 11.1. It might be argued that these proposals are anti-competitive and, potentially, exclude the private sector weather service providers. This need not be the case. Indeed, we would argue that MetDesk's experience in providing bespoke interpretive services (see Table 4.1) is immensely valuable, and that there is a real opportunity to break down the perceived competitive barriers between the Met Office and private sector providers, by working together to each other's mutual benefits.

Table 11.1: *Summary of possible future options for delivery through partnership of Network Rail's Weather Services.*

Strategic Option	Example	Pros	Cons
Virtual Network Rail Hub	Scottish Flood Forecasting Service (SFFS)	Tailor-made virtual transport hub for Network Rail delivered in partnership.	Limited opportunity for innovative development and R&D activities.
Physically located Network Rail Hub with integrated expertise, shared vision and joint R&D programme.	Flood Forecasting Centre (FFC)	Opportunities to develop a partnership-based profession leading to faster, more accurate decision-making and advice. Reduced costs and quicker pull-through from science to service if underpinned by a joint R&D programme.	Upfront costs and managing change – staff may feel threatened by this change.
Integrated Transport Centre covering rail, road and aviation. Delivers operational and strategic planning advice.	World First	Covering nowcasting to climate, hazards to impact, and science to service activities for all transport operators. Ensures consistent action and advice for all UK passengers and a climate resilient transport network.	May incur additional costs and effort to seek agreement across partner agencies and to implement.

Our preferred option is an integrated transport centre with 24/7 access to all operational services and expert advice. The Met Office already serves the Highways Agency and NATS (National Air Traffic Services) and it would be logical to combine this expertise to deliver a fully integrated transport service. Although this report has not addressed the risks from future climate change, a consistent approach to adaptation and mitigation across all transport sectors, would be wise, sharing plans and evidence bases as we move to a more automated and integrated transport system.

Beyond a closer alliance with the Met Office, it is clear that the hazards that Network Rail faces today cannot be tackled effectively unless a more multi-disciplinary approach is taken. The importance of bringing together various science disciplines, forecast providers and decision-makers involved in the resilience and preparedness to natural hazards, has been recognised in the formation of the Natural Hazards Partnership (Figure 11.1). Network Rail would definitely benefit from being a member of the Natural Hazards Partnership; it would give them access to a diverse scientific community in academia and the public sector, who can help them find solutions to the challenges they face.

Figure 11.1: The Natural Hazards Partnership and its participating organisations as of December 2019

Weather already plays a critical role in Network Rail's operations and going forward, climate change is likely put many new challenges in its path. Our evidence gathering during the preparation of this report has highlighted the gulf in expertise between those who create weather information and those that receive it. The NRWS has done well with limited resources and limited information, but Network Rail needs to be a much more intelligent customer across all its activities, from operational controls and asset management, to future planning and investments in new infrastructure which will need to be climate proofed.

In order to deal effectively with these challenge, Network Rail must embrace agility to move quickly with ease, adaptability and resilience to be able to withstand and recover from increasingly adverse weather and its associated impacts. Gone are the days of working in isolation. Partners need to embrace diversity, iron out rivalries and differences in culture. Like an ecosystem, diversity typically breeds resilience.

We do not currently have a mechanism in place to '*bridge the valley of death*' between cutting edge weather forecasting and climate change prediction, and those who must exploit these capabilities at pace, to mitigate their current risks, and to make *wise* investments for managing future climate change risks. This will mean (i) fostering new, cross-disciplinary research at the interfaces of, for example, environmental hazards and geotechnics and engineering, (ii) creating new partnerships between scientists, forecasters and users, including the co-creation of new products and services with an emphasis on digital technologies, and (iii) ensuring that the professional development of Network Rail's staff and stakeholders includes becoming well-informed and intelligent users of weather and climate science and services.

This leads us to make a bold proposal for an 'Academy' for weather and climate resilience, which will act to transform the culture of decision-making in Network Rail. This would encompass the joint education and training of service-oriented meteorologists and Network Rail staff to ensure the best application of weather and climate intelligence in their specific areas of responsibility; enable joint development of next generation weather and climate services aligned to advances in digital technologies; and foster a new culture of joint innovation, exploration and experimentation – 'learning by doing'. Initially, this Academy may serve just Network Rail, but ultimately reach out across the whole transport sector which faces similar challenges.

The Academy would be formed from an alliance of universities, Public Sector Research Establishments (PSREs e.g. Met Office, National Physics Laboratory), transport sector professionals and stakeholders, and private sector providers (e.g. digital technologies). By bringing diverse expertise to the fold, strengths and weakness can be balanced, new lessons learnt, experience, knowledge and insights shared. As a team of teams, the Academy would develop and create a unified 'one voice' professional response to the challenges we face, and with the intellectual edge required for success.

12. Summary

Our evidence-gathering and the projects undertaken specifically for this report leads us to conclude that major changes are needed within Network Rail to make it more resilient and better prepared for adverse weather today and into the future. The key points from our evidence gathering, in the context of opportunities available to Network Rail from 'state-of-the-art' science, observations and forecasting, are presented. These set the stage for our 5 major recommendations. Finally, we make two further additional points for consideration.

12.1 Key Points

For ease of use these have been placed under the two categories that, separately, address Network Rail's distinct weather needs – (i) operational controls and (ii) route asset management.

Operational Controls

- Network Rail currently has access only to the ECMWF global forecast which, although world-class, can only be run at a resolution of 10km because of the computational cost. It has been demonstrated that the differences between a 10km-scale forecast and a 1 km-scale forecast, in terms of rainfall intensities and location, are profound. It is essential that Network Rail explores the operational benefits of kilometer-scale forecasting as soon as possible.
- Weather is inherently chaotic which means there is no single, deterministic forecast; instead, an ensemble of forecasts is always produced operationally. It is essential that Network Rail gains access to ensemble forecasting capabilities. They currently receive advice from a single deterministic forecast, which although of high quality, may misplace or fail to capture some extreme events.
- Similarly, Network Rail currently has access to deterministic nowcasting based on extrapolation of the observed radar signal. However, radar observations have some limitations in complex terrain, or when the beam may be saturated by high rainfall intensities, or the location is distant from the radar site itself. These can be overcome by using the latest developments which combine radar and numerical weather prediction products, and by embracing probabilities.
- Severe convective storms represent major risks to Network Rail's infrastructure and improved nowcasting capabilities are urgently needed to manage their risks and reduce operational delays. Emerging data technologies may revolutionise the management of these risks and their development should proceed at pace.

Route Asset Management

- Recent advances in developing high spatial and temporal resolution rainfall climatologies, some going back more than a century, have provided new insights on the nature of UK rainfall, especially extremes, and on the emerging signals of climate change. These new datasets provide unprecedented opportunities to explore the links between past earthwork failures, the concurrent and antecedent rainfall and the weather patterns that prevailed at the time.

- Network Rail uses indices of soil moisture to identify elevated risks of earthwork problems. This is potentially problematic because there is no index for soil moisture that does not have serious limitations and uncertainties. That being the case, the use of soil moisture within a risk assessment is fraught with difficulties. An appropriate way forward may be to use hydrologically-based metrics, including information from the Flood Forecasting Centre, to produce a probability of exceeding saturation based on all the evidence. This fits with the concerns expressed by the EMTF on the need for estimating pore pressures and the relationship with soil wetness.
- New scientific developments have delivered innovative ways of assessing the risks of unprecedented but plausible rainfall extremes. There is potential to use these advances to look more locally at Network Rail's exposure to extreme daily/sub-daily rainfall and to stress-test the resilience of its earthworks. Event-based, end-to-end storylines that explore unprecedented or worst-case scenario weather events and their impacts, could be used to develop actionable risk scenarios that would complement traditional approaches based on probabilities, likelihoods and return values.

12.2 Major Recommendations

We make the following five recommendations. We believe the proposed actions will substantially improve Network Rail's operations and the resilience of its assets. These will lead to greater efficiency and lower costs for its business, they will deliver an improved, reliable rail network for train and freight operators, and finally, but most importantly, they will deliver greater safety and satisfaction for its passengers.

Recommendation 1: **Cogent arguments in favour of a new approach to Network Rail's Weather Service provision have been presented throughout WATF report. Advances in forecasting across minutes, hours to weeks are not being exploited by Network Rail**. These would open up some major opportunities to deliver better early warnings to aid logistic planning, as well as new real-time, dynamic, location-specific forecasts and warnings that will improve operational safety and performance. A joint Met Office/Network Rail 'sandpit' trial has already demonstrated the substantial potential of these new forecasting tools to transform Network Rail's weather services, as well as showing the benefits of working together, through partnership, sharing information and action plans. **Latest forecasting capabilities should be formally trialled, under a structured framework agreement with the Met Office with the goal of implementing a full operational service.**

Recommendation 2: **Under asset management, the search for appropriate, spatially-varying thresholds for assessing the probability of earthwork failures, using statistical analysis, has proved to be very challenging for Network Rail.** Earthwork failures are rare, and each is unique in some way, so it is always going to be difficult to tease out the drivers/indicators using statistics. **Instead, the WATF recommends an alternative approach in which a forensic analysis of selected events is conducted, using all available evidence, including new databases on weather regimes, rainfall and local hydrogeomorphology indicators, to provide a complete picture of the hydro-meteorological context surrounding the failure.** This may help to identify discriminating factors which can be used subsequently in a risk-based system for earthwork management. The WATF also recommends that Network Rail place less weight on soil moisture indices and considers alternative metrics linked directly to soil hydrology.

Recommendation 3: The Rail Technology Strategy is providing stepping-stones towards a data-driven railway. **The evidence gathered has cemented WATF's view that Network Rail urgently needs to transform the delivery of its weather services, by considering the development of a new hazard and impact-based digital platform which integrates all the relevant information to provide accessible, flexible and seamless services, driven by dynamic user specifications.** Network Rail should actively explore opportunities to embrace digital technologies, especially the Data Cloud and APIs, that could revolutionise how it delivers its weather services, from operations to asset management.

Recommendation 4: **The WATF has considered various ways in which Network Rail may procure its future weather services, including through more digital applications. The preferred option is a partnership-driven, integrated transport hub for the benefit of transport providers, passengers and freight users.** This will provide 24/7 access to all operational services and expert advice, including flooding, and thus deliver an authoritative set of services across Network Rail and its Routes and Regions. The Met Office already has desks serving Highways England and NATS (National Air Traffic Services) and it would be logical to combine them to deliver a fully integrated transport service.

Recommendation 5: **Network Rail needs to build its professional competencies in meteorology, hydrology and climate change so that its staff can act as intelligent users of science and services across all its functions. The WATF proposes the creation of an 'Academy' which will act to transform the culture of decision making in Network Rail.** By bringing together a diverse body of academics, service providers, Network Rail staff and its stakeholders, the Academy will engender a service-oriented culture under a common mission to deliver the safest, most efficient and resilient rail service for the UK, today and into the future.

12.3 Concluding Remarks

Finally, we make two other points for Network Rail's consideration. First, the WATF was not tasked with assessing how Network Rail is responding to the challenge of future climate change, although its recommendations will strengthen Network Rail's capacity to do so. The UK's 3rd Climate Change Risk Assessment (CCRA3) will be published this year, and we recommend that Network Rail uses this opportunity to commission an in-depth study of its future climate risks.

Second, Network Rail is a science and technology-driven organisation, from engineering to data-driven operations. This review has highlighted the need for Network Rail to develop stronger mechanisms for ensuring that it stays abreast of the latest scientific and technological advances and, where appropriate, exploit them. Network Rail should consider whether the establishment of external Scientific Advisory Committee(s) would serve it well and help to keep it at the forefront of the international rail industry.