02 - IDENTIFICATION AND MANAGEMENT OF FLOOD RISK TO THE NATIONAL ROAD NETWORK

***Barry Hankin[1]**, Ross Bryant[1], Vincent O'Malley[2]*
1. *JBA Consulting*
2. *National Roads Authority*

Abstract

Flooding of roads has the potential to cause a range of major difficulties, from harm to people, damage to vehicles, damage to the road infrastructure and the resulting economic disruption. The US FEMA website, 2012 states:

Flooding is the leading cause of severe weather-related deaths in the U.S., and this is especially tragic since many are preventable. Of the nearly 100 flood-related fatalities each year, most occur as people attempt to drive on flooded roads".

Recent flooding events across eastern counties in October 2011 led to disruption of the national road network with the M50, M1, N11, M7, N81 and the N54, all suffering varying degrees of inundation and possible erosive damage. A number of local routes were also similarly affected There can also be wide-scale disruption, as experienced in the UK during the Summer flooding in 2007 which resulted in the abandonment of 10,000 vehicles on the M5, many major roads and motorways were disrupted with the associated major economic costs of re-surfacing and bridge repairs.

This paper explores the use of detailed topographic lidar data in combination with an advanced graphics card based shallow water equation solver, JFLOW+, to define the flood risk to the Irish national road network. The modelling was used to generate flood maps of extreme surface water (pluvial), fluvial, and coastal flood probability, which were queried using advanced GIS techniques in order to generate flood risk metrics for every 100m segment of carriageway. These metrics were used to identify and prioritise areas for intervention to manage the flood risk. Metrics were calculated per 100m segment and include: peak depth of flooding; peak flood hazard rating (here defined as depth*[velocity + 0.5]); peak traffic exposure to hazard (hazard * annual average daily traffic); the difference between the peak hazard for two design storm floods to investigate climate change sensitivity; and the length of road flooded for other sources of flooding (river and coastal).

Additional modelling was undertaken to elucidate the sensitivity of flooding to climate change, storm duration sensitivity and potential culvert blockage. Based on the outcome of this modelling, a protocol was developed for prioritising and managing the risks. This included reference to different suites of detailed maps to identify a course of action, and guidance on what to collect on-site with a decision tree for proposed mitigation or management measures.

1. BACKGROUND

This flood risk to roads research was couched within the European Road Network's 'Risk Management for Roads in a Changing Climate' (RIMAROCC) framework, whereby the core risks to the network were first identified and used to prioritise where to focus more detailed assessment of core vulnerabilities and consequences. The approach used here combines a range of historic data and predictive modelling of extreme flood hazard using improved topography and advanced flow modelling. The topography was based on the NRA's new 2m LiDAR, covering a 600m strip either side of the carriageway, with a root mean squared vertical error of 0.15m. The use of detailed topographic data in combination with an advanced graphics card based shallow water equation solver, JFLOW+, gives the best understanding to date of the flood risk to the national road network. The modelling was used to generate flood maps of extreme surface water (pluvial), fluvial and coastal flooding, for every 100m segment of carriageway.

Using the detailed modelling methods it was possible to investigate the use of flood risk metrics to assist in the risk ranking of a 1km grid covering the entire national road network. This allowed a full review of the network to be achieved based on both historic and predictive information; a Flood Risk Management Protocol was then developed The Protocol is based on a decision-tree, which in combination with the easily accessible PDF maps of the risks and site risk assessment sheets for collecting data on different flood mechanisms will ensure that the outputs of the research will be useful in the long term, and at a local level. The maps comprise detailed geo-PDF maps at 1:5000 scale for which the layers of different flood risk data can be switched on or off in the free Adobe Reader software. They are an integral part of the Protocol and use the different layers to identify a course of action, and guidance on what on-site information is required based on the hazard mapping. The Protocol comprises four phases of investigation:

- Maximising the use of detailed outputs from the flood hazard modelling work and the collated historic evidence to assess need for a site visit;
- Site visit and assessment of flooding mechanisms;
- Assess potential need for intervention and the detailed data required for further modelling;
- Detailed assessment/modelling of flooding mechanism and intervention options.

2. METHODOLOGY

An integrated method based on flood risk metrics was used, similar to the approach used in the national scale appraisals of flood risk (PFRAs) under the EC Floods Directive. This enabled the combination of flood risk information, across different flood sources, extreme events, climate change sensitivity and historical knowledge of flooding. A key vulnerability identified from the outset, was that of extreme surface water, or pluvial flooding from strong localised events, which have been witnessed with increasing frequency across Ireland in recent years.

The modelling method and topographic accuracy takes the detail of national flood risk appraisal to a new level. It has been possible to go beyond the 'blue spot' type approach adopted in the

European SWAMP[1] project and use more accurate predictive hazard maps rather than GIS interpolation approaches from the outset, before prioritising sites for more detailed assessment. Taking advantage of the huge efficiencies of computation using Graphics Processing Technology, JBA's JFLOW+ software has been used to undertake 2D overland flow modelling.

The 'blanket rainfall' method[2] was used whereby storm hyetographs for extreme rainfall were prepared based on the FSR approach using Met Éireann rainfall depth data. The process of generating a map of extreme surface water flooding has been developed over the past 10 years with increases in computer power enabling whole countries to be mapped using a 'blanket rainfall' approach using 5m resolution numerical grids. The following steps are applied:

- Rainfall storm profiles are estimated for a design rainfall event (e.g. 1 in 200 year return period) for a particular storm duration;
- These are stored on overlapping 5km grid squares that cover the study area and represent the limit of the hydrological contributing area for a pluvial-dominated, short duration surface water flooding event;
- The water is placed onto the DTM and is allowed to spread based on the 2D shallow water equations using JFLOW+ software using a 5m numerical grid;
- A variable Manning's roughness grid with different values depending on rural/urban or road cover to a 5m resolution;
- A rural or urban Percentage Runoff is applied depending on the land class to a 5m resolution, with an urban drainage factor to take account of drainage;
- Where an embankment remains in the DTM, water will not be able to spread across it, whereas in reality there may be a flow pathway through a culvert or bridge that was not picked up by the LiDAR. In reality, there would be an opening such as a bridge or culvert that water can flow through. This is not represented within the DTM so an artificial gap is made taking the elevations from either side of the structure and interpolating the surface, to force a flow pathway;
- The surface water simulation is continued typically for twice the duration of the design storm. The maximum depth in every numerical cell (typically 5m) is recorded and stored at the end of the simulation to represent the maximum hazard. The maximum velocities and hazard rating (depth * (velocity + 0.5)) are also stored.

The approach allows an accurate representation of the different flooding mechanisms including identification of flood flow pathways and areas of flow accumulation, whilst accounting accurately for hydrological contributing area.

2.1 Flood Risk Metrics

A new approach to understanding the impacts to the carriageway based on the modelling was developed, in which flood risk metrics are generated for every 100m segment of carriageway using advanced, automated GIS queries. This resulted in every road segment being attributed with the peak flood depth, velocity and hazard (combination of depth and velocity). This had to

[1] Storm Water prevention -Methods to Predict damage from the water stream in and near road pavements in lowland areas
[2] For example see Hankin, B., Waller, S., Astle, G., Kellagher, R. 2008. Mapping Space for Water: Screening for Urban Flash Flooding. Journal of Flood Risk Management, June 2008 Vol 1, Issue 1, pp13-22

be combined with risk from other flood sources and historic knowledge. This was done by up-scaling the linear metrics to a 1km grid covering the national road network, deriving the maxima of the linear metric within each tile. This allowed for a national appraisal at a similar scale used for EC Floods Directive PFRA.

The grid was also attributed with other metrics including the lengths of road within the fluvial, coastal flood outlines from JBA's Comprehensive Flood Map, and a count of road related historic flood incidents based on floodmaps.ie. was also included. In this way, the 1km grid data were attributed with a range of data that were combined in a systematic way to identify areas of worst risk to focus on.

The 1km grid was attributed with the following flood risk metrics after some combinations with other datasets described above.

- Maximum Annual Average Daily Traffic (AADT) within 1km grid;
- Maximum Depth per 100m of carriageway encountered within 1km grid based on the new 200 year RP Surface Water Modelling;
- Maximum Velocity per 100m of carriageway encountered within 1km grid based on the new 200 year RP Surface Water Modelling;
- Maximum Hazard Rating (Depth*(Velocity+0.5)) per 100m of carriageway encountered within 1km grid based on the new 200 year RP Surface Water Modelling;
- Maximum Exposure to extreme Surface Water flooding = (Peak Hazard per 100m * peak AADT) over 1km grid for Q200;
- Maximum Sensitivity of hazard to Climate Change (Difference of Hazard for 200 year and 100 year RP) over 1km grid;
- Length of carriageway flooded for the 100 year JBA CFM Fluvial Flood Map;
- Length of carriageway flooded for the 100 year OPW PFRA Fluvial Flood Map;
- Length of carriageway flooded for the 200 year JBA CFM Coastal Flood Map;
- Count of historic flooding events from floodmap.ie weighted for re-occurring flooding over 1km grid.

The different metrics were ranked and the ranks were weighted equally and combined to form an overall 'combined' flood risk metric. The worst 50 sites over Ireland were then focussed on using this overall measure as a way of prioritising interventions for the development of the Protocol. Figure 1 highlights some of the flood resulting flood risk data for three of the higher risk 1km tiles, with a nested 250m grid that was used to differentiate fluvial and coastal flood risk further.

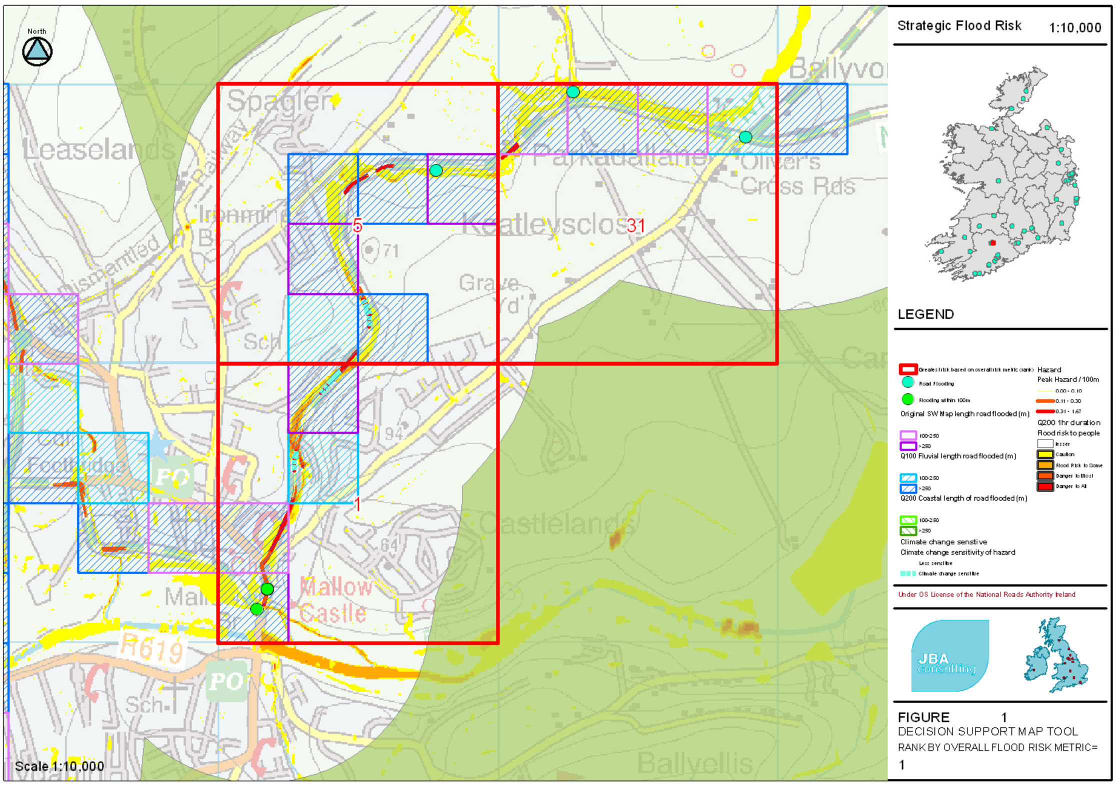

***Figure 1:** Example output of linear and gridded flood risk indicators for a high priority site*
Ordnance Survey Ireland, Licence No. EN0045212 (Digital Contract) © Ordnance Survey Ireland/Government of Ireland

Historical evidence for each of the 50 sites was also collated, in addition to the reported events from floodmaps.ie, also shown in Figure 1. The NRA provided corroboration of ten areas of known flooding, and four additional sites where flooding was considered to be a problem, but which were not all ranked highly owing to groundwater flooding mechanisms. These 14 sites were then taken forward to develop the Protocol.

3. DEVELOPMENT OF THE FLOOD RISK MANAGEMENT PROTOCOL (THE PROTOCOL)

The 14 priority sites were then taken forward to help design the Protocol. The Protocol was applied to the priority sites, and follows a four phase strategy:

- An initial assessment that maximises the use of detailed outputs from the flood hazard mapping work;
- A site visit to provide evidence for further investigation where necessary;
- A detailed assessment of options for management intervention, and;
- Management and mitigation based on the detailed assessment.

The Protocol will ultimately be applied by Local Authorities and it provides information sheets, and signposting of appropriate actions are also presented to implement any interventions. The four phases of the Protocol draw on different material, and this has been linked together in a Microsoft Excel workbook with live links to other information for ease of use. To supplement the Protocol, a suite of linked Geo-PDFs have been created nationally.

At the outset of an individual site investigation it is important for the end user (Local Authority) to consider the placement of the site within the National CFRAMS Programme or other FRAM; whether it is within an 'Area for Further Assessment' and how the risk to the site can be effectively managed and potentially funded in the future. Options for mitigation/management can be progressed jointly under the CFRAMS and/or within a minor works application, or under a separate budget.

A flow chart was set up in a Microsoft Excel workbook that used hyperlinks to bring together different sources of information, including:

- A summary of the historic evidence of flooding at the site;
- Detailed flood risk maps for phase 1 to help identify:
    - Areas of worst strategic (combined) flood risk;
    - Areas susceptible to greater dependence on longer storm duration;
    - Areas of higher velocities that may give rise to scour or erosion risk;
    - Areas where culvert blockage would result in worse flood risk;
- Site visit check sheets with information on what data to collect for particular flooding issues.

The Excel flow chart has hyperlinks that allow the user to choose between sites, and links to the different maps are refreshed so the user is directed to, for example the detailed risk map highlighting storm duration sensitivity. A detailed Geo-PDF can be accessed for any of the 6,601 tiles covering the national road network. This is possible through the use of an index PDF map of Ireland, with hyper-links to more detailed geo-PDFs at a county level. The county PDFs highlight the 1km tiles covering the road network, themed according to overall flood risk metric. Any of the 6,601 1km tiles can then be clicked on, and this opens up a detailed, 1:5000 scale map with the different flood hazard data (Figure 2). These layers can be switched on and off in Adobe Reader using the layer control.

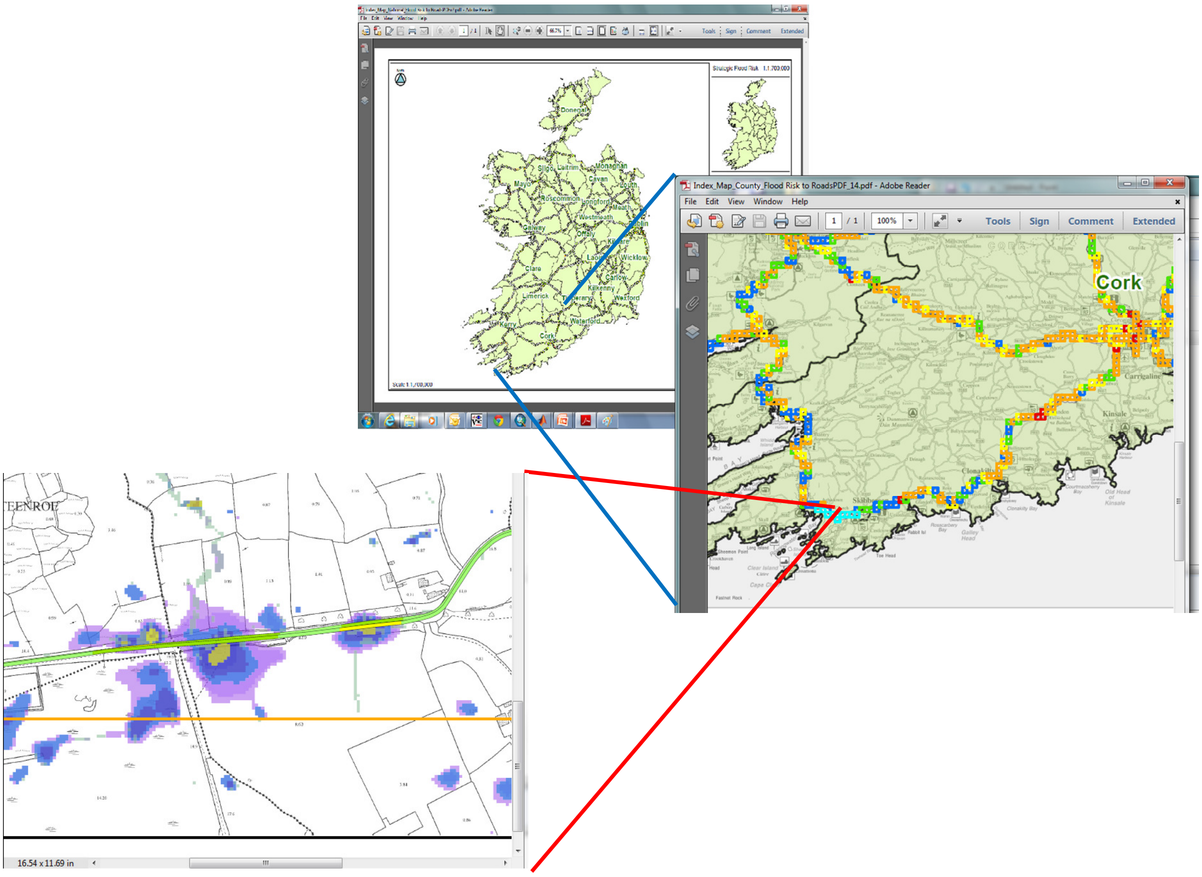

Figure 2: *Schematic of index linked Geo-PDFs covering the National Road Network*
Ordnance Survey Ireland, Licence No. EN0045212 (Digital Contract) © Ordnance Survey Ireland/Government of Ireland

The aim of the Protocol is to allow an individual appraisal of sites that have been highlighted as potentially being at risk of flooding. This involves four phases of investigation and is centred around deriving a meaningful interpretation of the risk metrics concluding with mitigation and management options. Figure 3 shows an example Protocol record applied to a test site. The following sections describe the phased Protocol assessment procedure.

Phase 1

Phase 1 is applied to all sites assessed and provides a review of the flood risk metrics and historic information. It is intended that the user should familiarise themselves with the site through the use of the detailed Geo-PDFs, GIS mapping, OSi mapping and Google Streetview. In many cases it is possible to gain a significant amount of additional information through viewing the area from the available internet mapping sources, particularly Google Streetview. Phase 1 concludes by outlining the path for further assessment; either highlighting that a site-visit is required to define risk more clearly and/or complete a structure, culvert or drainage assessment. It also flags whether there is need to investigate scour further at this location.

The Phase 1 Protocol Assessment Record consists of Sections 1.1 to 1.6 that summarise the output from the different risk maps. It concludes with Section 1.7 that summarises the findings recommending further assessment. In general, if there is potential for structural blockage and high velocity then the scour flag would be triggered. In combination a site based bridge or culvert assessment would be triggered if it is thought that there is a risk of flooding in relation to a structure. If the main source of flood risk is identified as being due to Pluvial (Surface Water) sources and/or drainage issues then a drainage assessment would be triggered. There are individual forms for culvert/bridge/drainage assessments and the output of these assessments may result in suggestions for mitigation and management.

Protocol Assessment Record

Site:	M50-N32 Clonshagh
Index Ref:	8 (11)
Unique Ref:	X318000Y241000

SCOUR FLAG: NO

	Phase	Description	Comment	Conclusion
PHASE 1	1.1	FLOOD SOURCE	Majority of the risk seems to be from small fluvial watercourses, pluvial may form some element of the risk.	Fluvial and Pluvial
	1.2	HISTORICAL OR OTHER FLOOD RECORD	FID Point 12 - M1/M50 Turnapin Interchange- NRA staff were stuck in the Nov 2011 flooding near the slip road S of Toberbunny - site extended to encompass this location if outside of red square	Yes
	1.3	CC SENSITIVITY	None shown	No
	1.4	SENSITIVE TO STORM DURATION	Some	No
	1.5	SENSITIVE TO BLOCKAGE	Only one structure has been modelled and did not show a large degree of sensitivity. There may be an un-modelled culvert that causes problems. Potentially yes.	Yes
	1.6	SUBJECT TO HIGH VELOCITY	Some high velocities along the route of the modelled culvert.	Possibly
	1.7	**PHASE 1: RISK REVIEW FINDINGS**	The level of risk presented in the mapping suggests that the section of the M50 and N32 is at risk but initial analysis of the Google streetview mapping has not provided sufficient additional information. Potential site visit and clarification with NRA may provide greater understanding.	YES, PROCEED TO PHASE 2 AND TRIGGER INITIAL CULVERT ASSESSMENT AND DRAINAGE ASSESSMENT
PHASE 2	2.1	SITE VISIT DETAIL		
	2.2	**PHASE 2: SITE VISIT FINDINGS**		
3	3.1	**PHASE 3: DETAILED INVESTIGATION**	Unlikely but will be stipulated by any site visit	Await results of Phase 2
PHASE 4	4	**MANAGEMENT & MITIGATION**		
	4.1	ASSETS	Uncertain	Maintenance, pending further analysis of scour risk
	4.2	DRAINAGE	Uncertain	Pending Drainage Assessment
	4.3	FLOOD WARNING	Unlikely on such small watercourses, but an extreme rainfall warning may be of use.	Investgate further

Figure 3: *Example Protocol Assessment Record for high risk site*

Phase 2

Phase 2 (a site visit) is triggered to assess a potential cause of flooding at the site (culvert, bridge or drainage assessment) or investigate the cause of flooding further if it is not initially clear from the Phase 1 appraisal. Culvert, bridge and drainage information is contained within the individual Forms and the Protocol Assessment Record can summarise the findings. Phase 2 will then potentially trigger a more detailed assessment under Phase 3 (if required) or simply move to the Phase 4 mitigation and management recommendations.

Phase 3

Phase 3 consists of a bespoke detailed assessment with the aim of providing sufficient additional information as required to implement any mitigation or management scheme. An example would be detailed hydraulic modelling of a culvert or bridge structure to allow for the effective capacity designed for exceedance. It may also include for detailed drainage system modelling and subsequent design.

Phase 4

Phase 4 clearly states the resulting management and mitigation measures and recommendations that have been developed as part of the phased assessment process. This can range from simple management procedures to more detailed reconstruction solutions in the most extreme cases. The promotion of flood warning systems should be investigated further in most cases as there is significant underutilised potential in this area. These are used effectively by infrastructure maintainers in England, Wales and Scotland and prove very efficient at providing an advance warning of flooding at key locations.

4. CONCLUSION AND RESEARCH OUTPUTS

This research into the assessment and management of flood risks at a structural level on the national road network has resulted in a practical appraisal of flood risk to the national road network. During the initial phase of the project, in addition to the clearly laid-out objectives of the study, four research questions were identified, and it was recommended that these were re-visited throughout the project.

- How can we best model and represent flood hazard to roads?
- How can we best identify areas of greatest potential impact/risk?
- How can this information be best use to manage flooding, and mitigate damage, disruption and harm to people?
- How best can we take into account the effects of climate change?

Flood risk outputs were continually refined, right up to the final stages of the study, where 6,601 detailed, index mapped geo-PDFs were generated to supplement the central Protocol. These maps include consideration of climate change sensitivity to flooding, and different ways of visualising risk have been presented.

The deliverables demonstrate a practical approach to differentiate levels of flood risk based on a range of modelling outputs and historic data. A range of flood risk information has been generated (see below), including new flood outlines for extreme surface water flooding and fluvial and coastal flooding. The use of the NRA detailed topographic data (LiDAR) and the rapid, accurate overland flood routing model JFLOW+, has lead to detailed hazard maps including predicted flood depth, velocity and hazard data. The impact of the predicted flooding on the road system and its users has been summarised over grid squares to help prioritise areas for flood risk management. This has lead to a new way of displaying flood hazard as a linear metric along 100m segments of the carriageway.

The worst impacted areas overall have been investigated further, and 14 sites were taken forwards for the development of a Flood Risk Management Protocol. The Protocol makes the most of the new mapping data to help prioritise site visits, and this links to the other major output of the research, which are some engineer-lead site risk assessment sheets. These help identify what information is needed to gather further evidence to help build up a more detailed understanding of flood risk from culverts, bridges, drainage and scour issues.

Finally, the Project delivered a suite of indexed geo-PDFs covering the whole of the NRA road network, so that engineers at the county level can apply the Protocol and make use of the wealth of new flood risk information.

4.1 Outputs

- A large volume of well-organised flood risk information has been supplied, including:
    - Existing CFM flood outlines for the roads network;
    - Updated Extreme Surface Water Maps including climate change sensitivity;
    - A carriageway dataset broken into 100m segments with flood risk metrics attributed;
    - A strategic 1km grid similarly attributed with flood risk metrics;
    - A Strategic Tool based in Excel with summary metric information;
    - Culvert blockage mapping scenarios for 50 high risk areas.
- A four phase Flood Risk Management Protocol was developed to help manage flood risk.

To help with implementation of the four phases, the following additional material has been prepared:

- 200 layered 'Geo-PDFs' showing detailed hazard/risk maps of the 50 highest risk areas;
- 6,601 1km grid squares covering the entire road network – accessed interactively via an index.