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MAPPING CLIMATE RISK & VULNERABILITY ONTO THE WEST MIDLANDS TRANSPORT NETWORK

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A guidance document from the WM-Air project

Version 2.0 February 2025

The climate is changing. As mean global surface temperatures rise, it brings changes to climate and weather patterns. In the West Midlands, the likely changes are warmer, wetter winters; hotter, drier summers; and more extreme weather events.

We need to adapt to a changing climate. Extreme weather causes damage and disruption to transport networks. Without adaptation, transport infrastructure is at risk from the impacts of climate change.

The impacts of climate change vary across the West Midlands transport system, as climate hazards are not evenly spread and transport assets vary in condition, criticality and hazard vulnerability. It is important to understand these spatial patterns.

Transportation is a cornerstone of modern society, allowing people to access education, healthcare, leisure activities, employment, and more. Extreme weather such as high temperatures, high winds, heavy rainfall and associated hazards such as flooding, landslips, and treefall and debris cause damage and disruption to transport networks. Transport organisations must manage these climate hazards alongside other factors such as maintaining ageing infrastructure and increasing electrification to meet Net Zero targets[1].

Climate hazards do not impact all areas of the transport network equally[2]. Moreover, some parts of the network are more vulnerable, and/or more critical for network functioning, or serve vulnerable sections of the population.

Hazards

The green box shows some climate hazards that affect transport networks in the West Midlands. The blue box shows the consequences of these impacts. Local and regional authorities need to understand how climate risk and vulnerability varies across their area so they can take appropriate actions to reduce climate impacts to their transportation infrastructure now and in the future, to limit societal and economic impacts.

This guidance document describes the methodology used to develop a Climate Risk and Vulnerability Assessment (CRVA) map for the West Midlands transport network; co-created by the WM-Air project, the West Midlands Combined Authority (WMCA) and Transport for West Midlands (TfWM).

Climate impacts on Transport Networks include:

- Disruption and delays
- Loss of Service
- Emergency Services disruption
- Operational Challenges
- Increased Maintenance
- Unsafe Structures
- Injury to Staff
- Knock-on impacts

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HOW IS THE TRANSPORT CRVA MAP BUILT FOR THE WEST MIDLANDS?

What is a Transport CRVA map?
A Transport CRVA map requires several layers of data that would contribute to climate risk. The data parameters build a picture of climate risk as a function of data representative of **Hazards**, e.g. flood zones, temperature; **Criticality**, e.g. relative importance of a particular section of the network; **Vulnerability**, e.g. how transport modes respond to hazards; and **Exposure**, e.g. length and number of transport assets in a given location. Each risk layer is standardised in terms of both spatial scale and values. This allows them to be combined into one single layer that represents the total climate risk across the map. Therefore, it is important to note that this CRVA map is not an absolute assessment of climate risk and vulnerability, rather relative within the boundary of the area being assessed, which in this case, is the West Midlands regional boundary. This means that it is not directly comparable with other areas.

What tools and functions are required for a CRVA map?
A Geographic Information System (GIS) application is required to build a CRVA map. Throughout this guidance document, the Quantum GIS (QGIS)[3] free, open-source application was used; the approach is also compatible with ArcGIS. Several functions are used, combining raster (or matrix) algebra with vector functions. Data is summarised to a resolution of 100m x 100m cells, with each cell containing hazard and risk scores which are combined into a total "relative risk" value using agreed weighting factors.

Data used for this CRVA map of the West Midlands
This CRVA map comprises several datasets to produce 16 underlying layers that create the CRVA map of total risk, shown in Table 1. Most data are open source or publicly available, so it is a replicable process for other regions or local authorities to produce similar outputs. The CRVA mapping process is iterative, as shown in Figure 1. It works through four stages: (i) data collection, (ii) the scoring of the data, (iii) the publication of the maps and (iv) adaptation engagement. This process is then repeated when new data are available and the map can then be updated.

Why are CRVA maps important for the West Midlands?
The West Midlands conurbation is the second most populous metropolitan county in the United Kingdom. While it has undergone substantial redevelopment in recent decades, transport related challenges remain relating to climate change, enabling economic growth, and addressing public health issues against a backdrop of high car and motorbike use, low levels of public transport use and active travel, and increasing difficulty accessing strategic centres by public transport during peak times[4]. The CRVA map provides a means of understanding where challenges may be concentrated. It helps the WMCA and TfWM with adaptation planning and provides supporting evidence for climate change adaptation reporting to the Government under the Climate Change Act 2008[5] and understanding climate related risks. WMCA's adaptation report (ARP4) sets out climate risks and adaptation action plans[6].

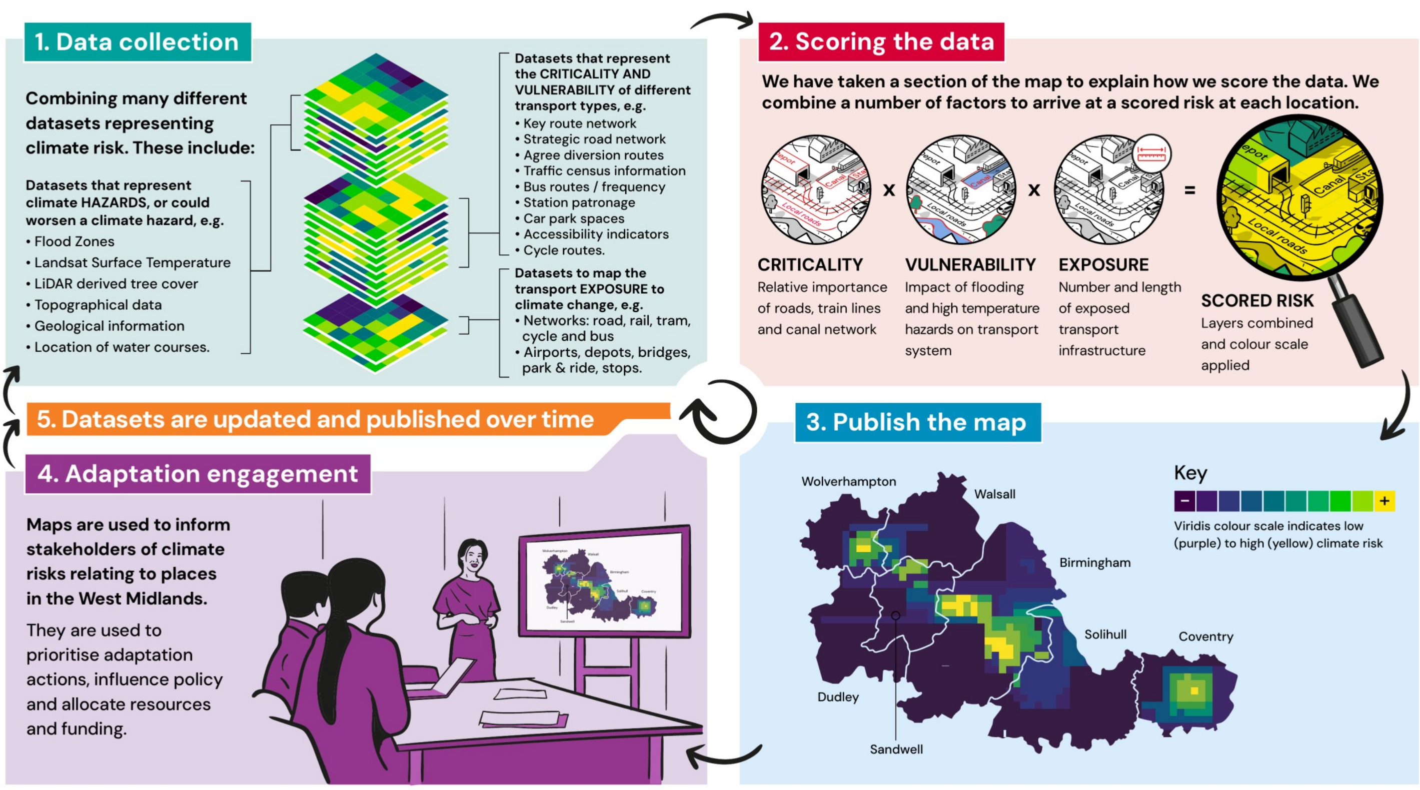

Figure 1. The cyclical process of developing a Transport CRVA map

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Table 1. Key information on each layer used to build the Transport CRVA map

Layer	Data type	Layer score parameters
Topographical Exposure (strong wind/ storm risk)[7]	Hazard	Calculated risk score; normalised and binned into 20 quantiles
Surface Temperature/ UHI risk[8]	Hazard	Raster average; normalised and binned into 20 quantiles
Fluvial flood risk[9-11]	Hazard	Combined layer risk score; normalised and binned into 20 quantiles
Pluvial flood risk[12-14]	Hazard	Combined layer risk score; normalised and binned into 20 quantiles
Vegetative windthrow risk[15]	Hazard	Summed proximity score per grid square and binned into 20 quantiles
Landslide/ embankment failure risk[7,9-11,15,16]	Hazard	Field calculations of combined inputs and binned into 20 quantiles
Transport Network - Routes[17-20]	Exposure	Field calculations of risk using weightings and adjustment factors
Transport Network - Nodes[21-26]	Exposure	Field calculations of risk using weightings and adjustment factors
Strategic Road Network[27]	**Criticality**	Used as an adjustment factor for the criticality weighting
Average annual daily flow (AADF) [28]	**Criticality**	Used as an adjustment factor for the criticality weighting
Bus Routes with Service Frequency[29]	**Criticality**	Used as an adjustment factor for the criticality weighting
Highways England Agreed Diversion Routes[30]	**Criticality**	Used as an adjustment factor for the criticality weighting
TfWM Key Route Network[31]	**Criticality**	Used as an adjustment factor for the criticality weighting
ORR Rail Patronage Figures[32]	**Criticality**	Used as an adjustment factor for the criticality weighting
Spatial Evidence - Transport Metrics Place Types[33]	**Criticality**	Used as an adjustment factor for the criticality weighting
Elevated Sections (DSM-DTM)[7]	**Vulnerability**	Used as an adjustment factor for the vulnerability weighting

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PRODUCING THE TRANSPORT CRVA MAP

Risk scoring was introduced to aggregate the climate hazards, accounting for factors which determine the resulting impact to the transport network.

Once the mapping of transport routes and nodes (e.g. bus stops, car parks, bridges) and climate hazards is completed, a scoring system is applied to each section and node based on network criticality, asset vulnerability and exposure to hazards, as shown in the second panel in Figure 1. The criticality and vulnerability "weightings" were determined through a series of stakeholder workshops which included practitioners involved in transport policy, planning, implementation, and asset management.

Risk scoring is carried out within the asset layers for both routes and nodes and combined to give a total risk score to a 100m grid. These gridded scores can then be rescaled to create a total risk score range of 0-1 across the West Midlands region. At this stage, raster maps for total risk and component risk (for each climate hazard) can be produced.

Using QGIS functions of zonal statistics (for raster layers) or join by location (for vector layers), the 100m results can be aggregated to different administrative boundaries. Figure 2 shows the average total risk score map for the West Midlands region at Lower Super Output Area (LSOA) scale. These are areas of between 400 and 1,200 households and have a usually resident population between 1,000 and 3,000 persons[34]. It shows that climate risk and vulnerability are unevenly distributed across the West Midlands. Many areas most at risk are within Birmingham, Sandwell, Coventry, and Walsall.

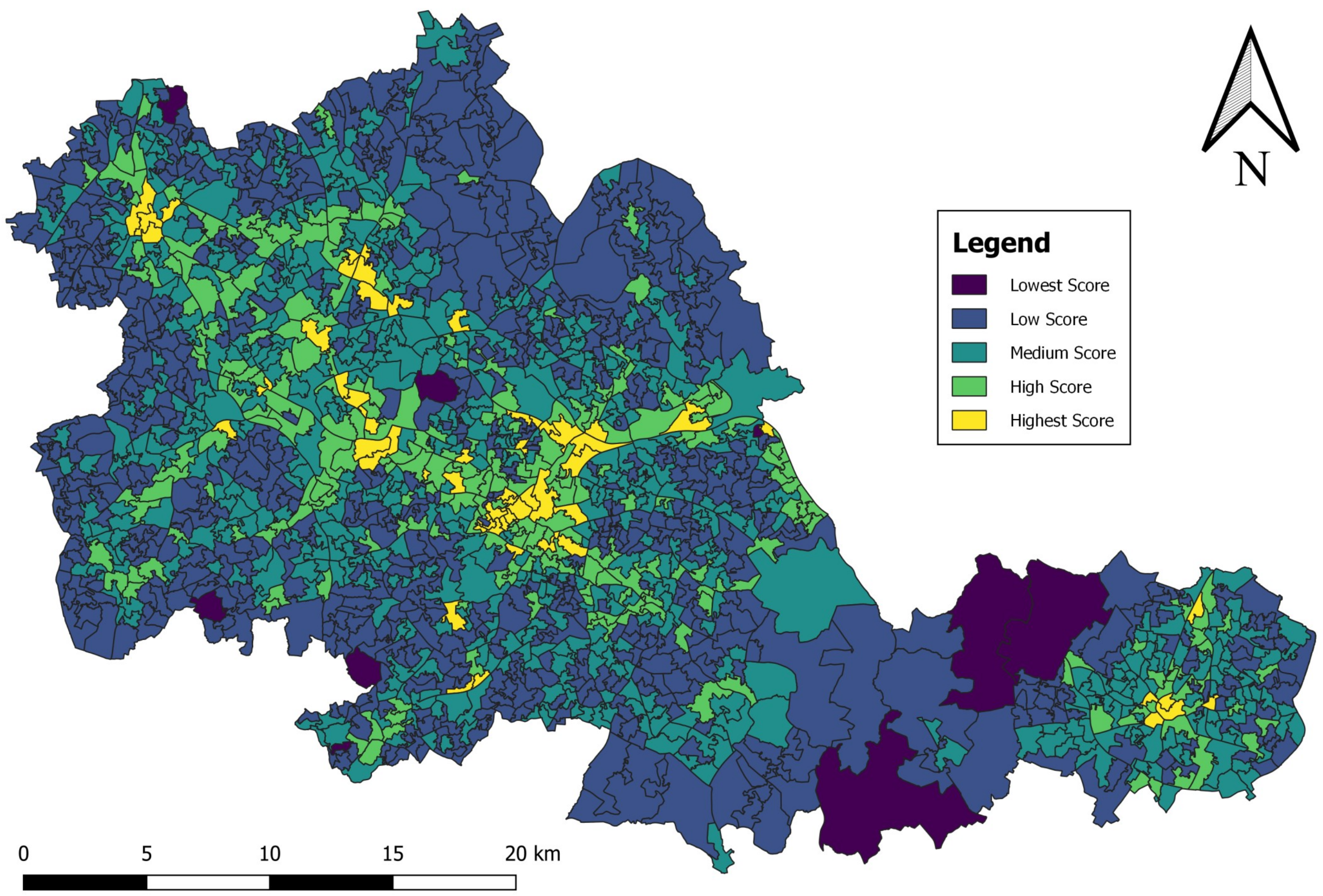

Figure 2. CRVA map of Total Risk for the West Midlands Transport Network at LSOA level (using 5 "natural breaks-jenks" bins).

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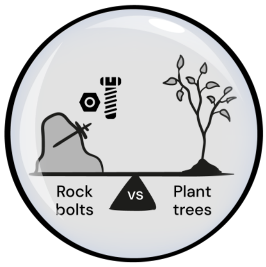
UTILISING THE CRVA MAP: HOW CAN IT HELP?

Monitor and evaluate adaptation progress

An important feature of the climate change adaptation process is that plans are monitored and evaluated. Adaptation works effectively when handled as an iterative process. In a transport context, monitoring and evaluation takes place each time data inputs are updated and the map is recalculated. As adaptation plans are carried out, adjustments are made to the associated risk in that location (e.g. electrical cabinets are elevated, so flooding vulnerability is reduced). Consequently, associated risk reduces and total CRVA score may decrease in that location.

Prioritise adaptation actions for specific locations

A benefit of CRVA maps is that the data layers can be reviewed to understand what may be primarily influencing the overall scores in different areas. This is particularly useful where areas have similar scores. By reviewing the drivers beneath the scores, decision-makers have greater insight into what might be a more suitable adaptation solution e.g. road drainage system upgrades to address flood risk in one area compared with slope retention and planting to tackle railway embankment collapse in another.

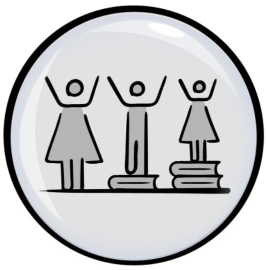


Engage with transport organisations and the community on climate change

Engaging with stakeholders is essential as part of the adaptation process, particularly those directly affected by the impacts of climate change, or jointly responsible. The CRVA map functions as a communication tool for stakeholders to discuss risk extent and responsibilities for adaptation. Outcomes could include development of coordinated solutions to address climate risks, such as floodwater management across all impacted transport modes in an area, and may even lead to more productive relationships between decision-makers.

Review proposals capital expenditure proposals

More emphasis is needed in addressing climate risk and vulnerability as part of new proposals to extend or alter the transport network, including links into new development sites. The CRVA map is a useful tool to review these. If a new proposal altered transport network infrastructure through an area where a CRVA score is high, the underlying layers can be reviewed to ensure that designers address these specific climate change challenges. An example may be the raising of equipment locations above ground level at a proposed tram stop.

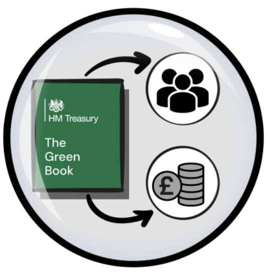


Support inclusive growth

There are correlations between areas of high climate risk and areas of socio-economic deprivation. Although the causes of this are extremely complex, focusing on adaptation in these areas (i.e. those with high overall CRVA scores) helps prevent climate change from further exacerbating existing inequalities. One such intervention could be the implementation of climate-adapted public transport routes linking vulnerable areas to strategic centres for employment and leisure.

Influence local and regional policies and strategies

The Transport CRVA map is a clear and simple communication tool. It can help decision-makers both in and outside of climate teams mainstream climate risk and adaptation considerations within their local and regional protocols. The CRVA map can encourage a "call to action" to senior representatives on climate-related issues by demonstrating the links across multiple factors of strategic importance to ensure that climate change issues are addressed.



Allocate resources and funding

In an environment with fixed and limited budgets, the weighted Transport CRVA maps gives an overview of the areas of highest climate risk and most in need of adaptation. Decision-makers are able to review the areas and the factors generating high relative climate risk and draw up detailed adaptation proposals. This will ensure appropriate and proportionate levels of funding and resources are allocated, enabling adaptation plans to be delivered where most needed.

Table 2. Conversion processes of each layer underpinning the CRVA process

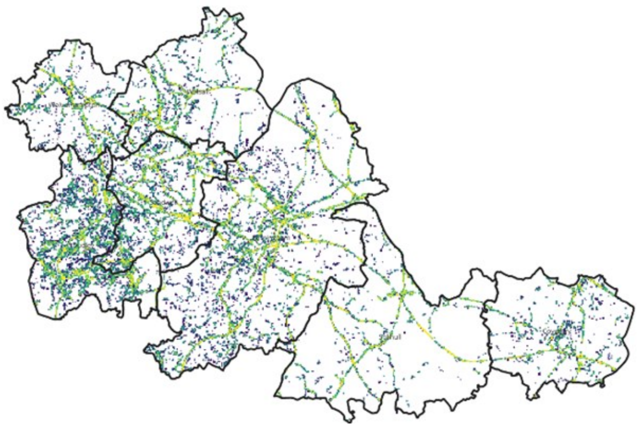
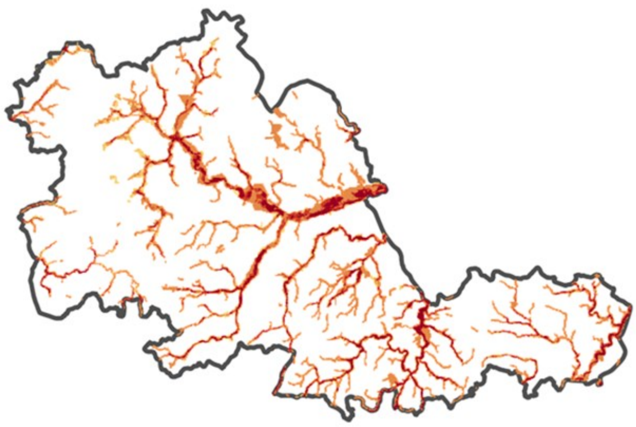
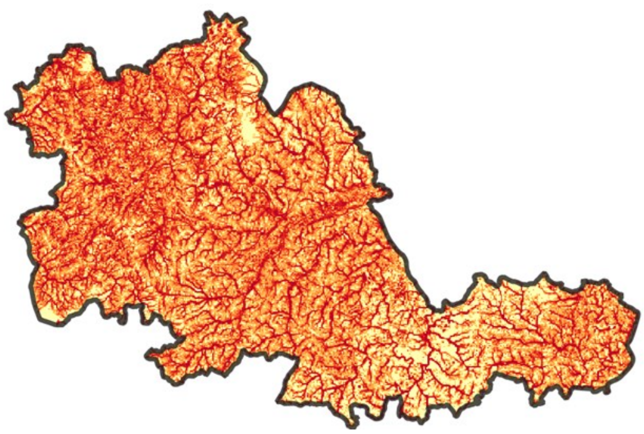
	Converted layer	GIS processing
Landslide Hazard and associated shapefile		• Use Digital Elevation Model (DEM) to determine slope • Use Raster calculator to render slopes $>20^0$,then vectorise • Use extract by attribute for shapes >= $50m^2$, then smooth • Use extract within distance for shapes <100m from transport • Use join attribute by nearest to obtain closest network type • Use Zonal Statistics to bring in average slope • Use Zonal Statistics to bring in max/ min elevation > height • Use Zonal Statistics to bring in VOM layer (mean = % cover) • From linear faults layer, extract by attribute (fault) > rasterize • Use proximity (raster distance) of faults to transport layer • Use Zonal Statistics to bring in fault proximity • Use join attributes by location for bedrock info (rcs_d & rcs_x) • Use join attributes by location for superficial (rcs_d & rcs_x) • Use join attributes by location for artificial (lex_d & lex) • Use join attributes by location for mass movement (lex_d) • Rasterize (vector to raster) waterbodies sources > proximity • Use zonal statistics (min) to bring water prox' into asset layer • Use join attributes by location to bring in flood zones/ indicators • Use zonal statistics to bring in average pluvial hazard • Generate vulnerability score (V_x) for each hazard using CASE statements for scoring each imported variable • Use field calculator to sum Vulnerability scores (V_sum) • Use field calculator to apply Criticality score (C_Net) for assets • Using field calculator, Asset Risk, Risk_VC = C_Net * V_sum • Use rasterize (vector to raster) to burn In Risk_VC at 5m res • Use Zonal Statistics to sum Risk_VC (SumRisk) into 100m grid • Use field calculator to scale risk 0-1, Rn = ("SumRisk" - min ("SumRisk"))/(max("SumRisk")-min("SumRisk")) • Use r.quantile and reclassify by layer to produce final raster
Fluvial flood Hazard		• Merge EA Flood zone layers then dissolve to "layer" field • Merge BGS and EA flood risk layers so that there are 4 features representing EA Zone 2, EA Zone 3, BGS High potential and BGS low potential • Create "Weight" field and assign a value of 0.25 to EA features and 0.5 for BGS features (as EA Zones 2 and 3 features can overlap). The maximum value will be 1 • Use "union" tool to create duplicate shapes where overlaps occur • Use "aggregate" tool to sum the weightings with grouping expression "geom_to_wkt($geometry)" • Rasterise to a 5m grid with layer extents set to 100m fishnet grid to align grids and use "maximum" function • Use Zonal Statistics to read mean values into the 100m fishnet grid then rasterise • Clip raster to fishnet grid extent • Use quantile function to determine 20 quantile bins (5%iles) • Reclassify by table according to bin values (0-1, 0.05 intervals)
Pluvial flood Hazard		• Merge all downloaded shapefiles for region (repeat for each risk level: 1 in 30, 100 and 1000) • Dissolve (to "layer" and "hazard" fields) • Use field calculator to create a numerical hazard field from 1 (Low) to 4 (High) • Create "likelihood" field using "layer" field as guide (1in30, 1in100 or 1in1000) • Use extract by attribute for each likelihood, then rasterize to a 5m grid, using 100m fishnet grid extents • Sum all three layers using raster calculator (maximum value will be 12) • Use Zonal Statistics to read mean values into the 100m fishnet grid then rasterize • Clip raster to fishnet grid extent • Use quantile function to determine 20 quantile bins (5%iles) • Reclassify by table according to bin values (0-1, 0.05 intervals)

Table 2. Conversion processes of each layer underpinning the CRVA process

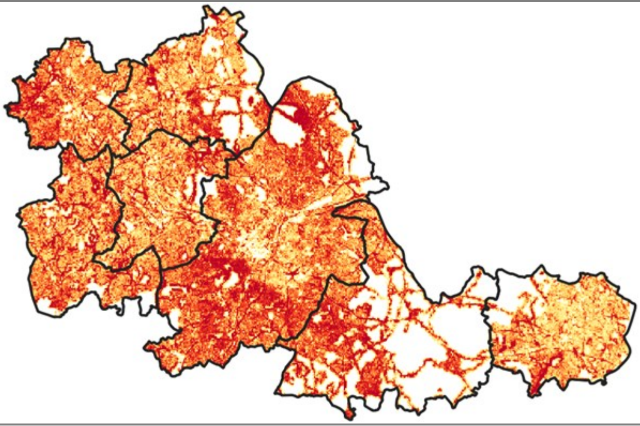
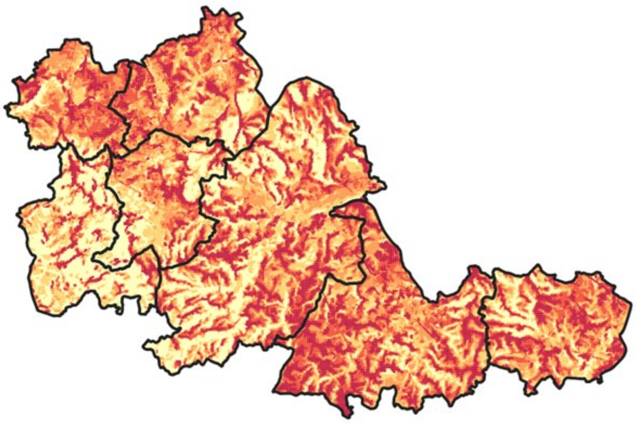
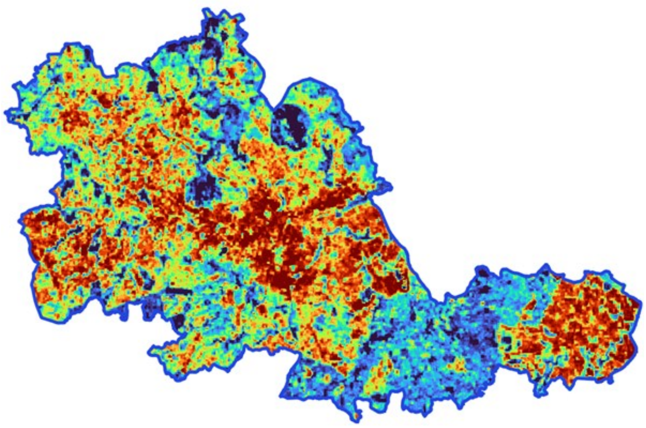
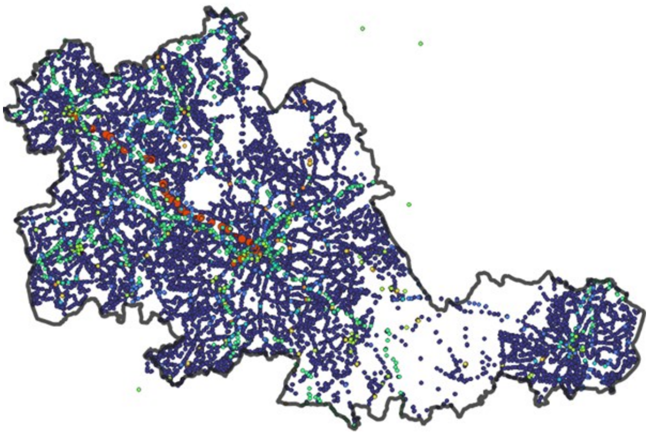
	Converted layer	GIS processing
Vegetative Windthrow Hazard		• Use Rasterize (vector to raster), then Proximity (raster distance) to create proximity to transport network • Using Raster Calculator, show only proximity <100m • Reverse using Raster Calculator (VOM Binary x (100-Proximity) giving 0 at 100m and 100 at roadside • Use FillNoData to set null to Zero so that average can be taken over 100 grid • Use Warp (Reproject) to align with 100m gridsquares using average function. This gives measure of tree cover combined with proximity • Use Translate - to set zero to nodata so that quantiles can be calculated with good spread
TOPEX (Storm) Hazard		• Use Merge to combine DEM tiles into a single raster, extending at least 100m beyond regional boundary • Use Warp (reproject) to resample to 10m resolution • Use r.mapcalc.simple to produce 8 rasters of topographical exposure for each of the cardinal compass directions • take the maximum inclination for all distances from 100m to 2000m for 8 points of the compass e.g. for north: • max(atan((A[10,0]-A)/100),atan((A[20,0]-A)/200),atan((A[30,0]-A)/300),atan((A[40,0]-A)/400),atan((A[50,0]-A)/500),atan((A[60,0]-A)/600),atan((A[70,0]-A)/700),atan((A[80,0]-A)/800),atan((A[90,0]-A)/900),atan((A[100,0]-A)/1000),atan((A[110,0]-A)/1100),atan((A[120,0]-A)/1200),atan((A[130,0]-A)/1300),atan((A[140,0]-A)/1400),atan((A[150,0]-A)/1500),atan((A[160,0]-A)/1600),atan((A[170,0]-A)/1700),atan((A[180,0]-A)/1800),atan((A[190,0]-A)/1900),atan((A[200,0]-A)/2000)) • Use raster calculator to sum all 8 rasters • Use zonal statistics to bring into 100m grid • Use field calculator to rescale scores 0 to 1 then reverse so that 0 is low and 1 is high to reflect exposure risk • Use rasterize, then r.quantile using 20 bins • Use reclassify by layer to create final normalised raster
Land Surface Temperature Hazard		• (LS)Landsat Search Criteria: Daytime: Path = 203, row = 023, Cloud cover = 0 > 5%, Data set: Landsat 8-9 OLI/TIRS C2 L2 • Files to download: ST_B10.tif (choose summer peak temps time periods and clearest images) • Surface Temperature (K) = Digital Number (DN) * scale_factor + offset: (B10) > Raster calculator > ("ST_B10" * 0.00341802 + 149) - 273.15 • Use Fill nodata, to remove artefacts (accept default values) • Use raster calculator to produce average of all years, summer peak temp maps • Use warp (reproject) to convert to OSGB grid • Use zonal statistics (mean) • Use rasterize, then r.quantile using 20 bins • Use reclassify by layer to produce normalised raster
Transport Network (Nodes) Asset layer		• Import shapefile 'NAPTAN Access Nodes' then extract by expression: "StopType" IS NOT 'TMU' AND "Status" = 'active' , then Remove all fields except: ATCOCode, NaptanCode, CommonName, Street, Bearing, NptgLocali, LocalityNa, StopType, BusStopTyp • Import shapefile for Tramstop Nodes:then remove all fields except: 'station_na' & 'naptan' and rename as CommonName and NaptanCode respectively, then create text field "StopType" and populate field with 'TMU' • Import shapefile for car park nodes then remove all fields except: Car_Park_N, Operator, Type and No_spaces. Rename Car_Park_N as CommonName , then create text field "StopType" and populate field with 'CPK' • Perform similar steps for any other nodes to import • Combine all node shapefiles into a single shapefile using the merge function

Table 2. Conversion processes of each layer underpinning the CRVA process

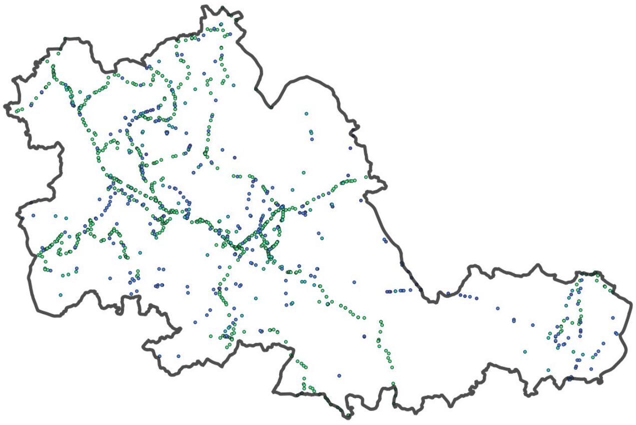
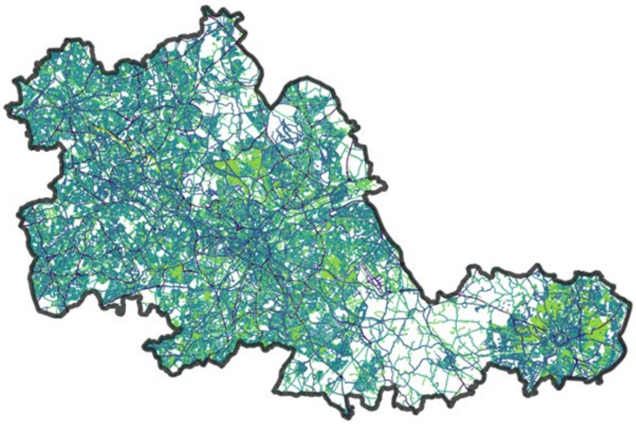
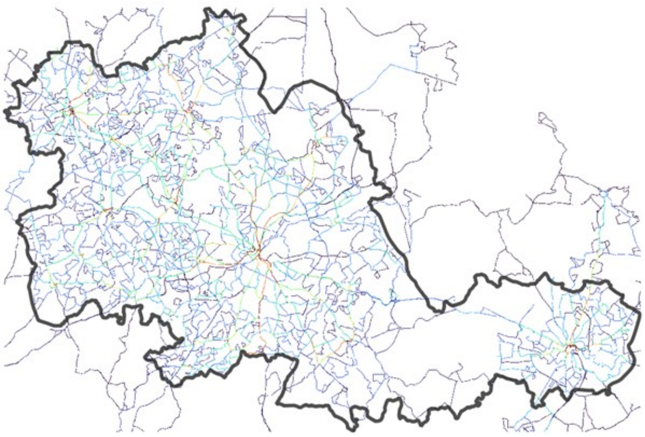
	Converted layer	GIS processing
Transport Network (Nodes) Bridge Asset layer		• Import Canal and River Trust (CRT) and KRN bridge layers and reproject both layers to OSGB36 • On KRN layer, add text field 'StopType' with the following formula to determine bridge type: CASE WHEN "rail_asset" = 'Y' AND "overbridge" = 'Y' THEN 'BR_ROvH' WHEN "rail_asset" = 'N' AND "overbridge" = 'Y' THEN 'BR_?OvH' WHEN "rail_asset" = 'Y' AND "overbridge" = 'N' THEN 'BR_HOvR' WHEN "rail_asset" = 'N' AND "overbridge" = 'N' THEN 'BR_HOv?' WHEN "rail_asset" IS NULL AND "overbridge" = 'Y' THEN 'BR_?OvH' WHEN "rail_asset" IS NULL AND "overbridge" = 'N' THEN 'BR_HOv?' ELSE "StopType" END • For KRN layer, rasterize with a burn-in value of "1" • Snap points in CRT to points in KRN layer using a distance of 7m. This will identify overlapping assets, for duplicate removal • Create new text field 'StopType' with formula: 'BR_WTR' • Create text field "KRN" with expression: If(raster_value ('raster',1,$geometry) = 1, 'Duplicate' , NULL), where ‘raster’ is the KRN raster described above • Select by expression and choose "KRN" = 'Duplicate' and "StopType" = 'BR_WTR'. Delete selected features • Add the KRN and CRT layers to the other Nodes Asset Layer using merge function
Transport Network (Lines) Asset layer		• Import Road Network shapefile and remove all fields with the exception of the ‘function’ field, then dissolve to "function" field • Use refactor: change field name to "Network" with length to 20 • Import shapefiles for Rail Network, Tram Network, Airport Infrastructure and for each layer , use dissolve all then add a new 20 char text field "Network" with value 'railway', ’tramway’ or ’airport’; then remove all other fields • To create a combined Cycle Network (using ‘starley network’ layer and main cycle routes layer), bring in shapefiles and reproject to OSGB36, merge vector layers, then use dissolve all and add a new 20 char text field "Network" with value 'cycle route'; then remove all other fields • To combine all transport modes, Use merge to form single polyline shapefile of Transportation Network • Divide combined layer into 100m grid elements using Intersection • Use split with lines to disaggregate each line within the 100m grid, using the line layer for both input and split layer • Using Field calculator, add "length" field using expression: $length
Bus Service routes and frequency - Adjustment factor		• Bring in shapefile then use Buffer (20m). This will create an overlapping section in centre which will contain summed values • Use rasterize (vector to raster), 1m resolution to 100m grid using command line prompts: -add -at (this will sum the values). Use field values from "m-f_daytime" • On transport network shapefile, use select by expression: for A, B, minor and local roads • Create new field 'BusFreq' with the following applied to selected items: coalesce(raster_value ('raster',1,line_interpolate_point($geometry,$length/2)),0) • Create calculated field with values 0 to 1 based on rank (percentile): (1 + array_find(array_agg("Bus_freq" , "Bus_freq" IS NOT NULL,order_by:= "Bus_freq"), "Bus_freq")) / array_length(array_agg("Bus_freq" , "Bus_freq" IS NOT NULL))

Table 2. Conversion processes of each layer underpinning the CRVA process

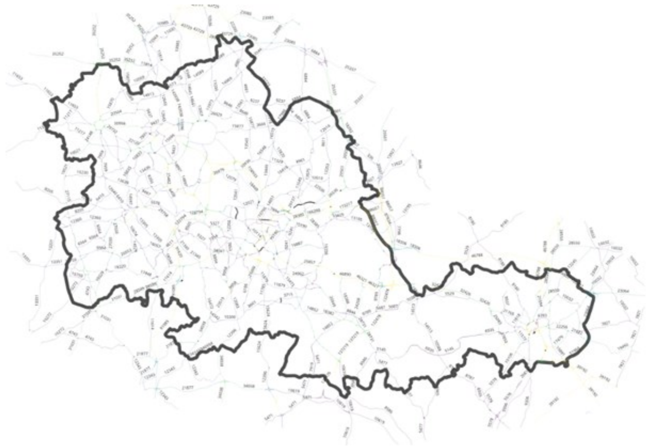
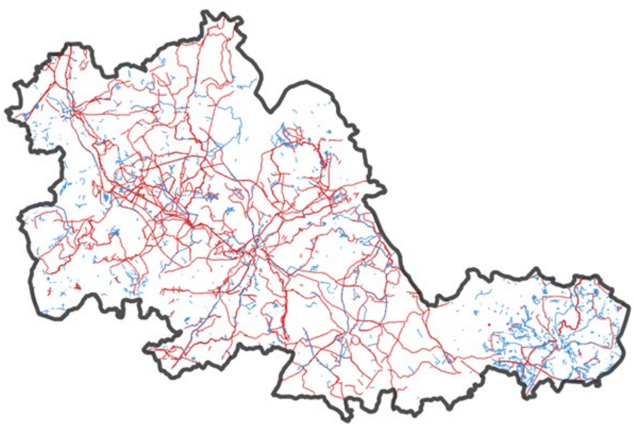
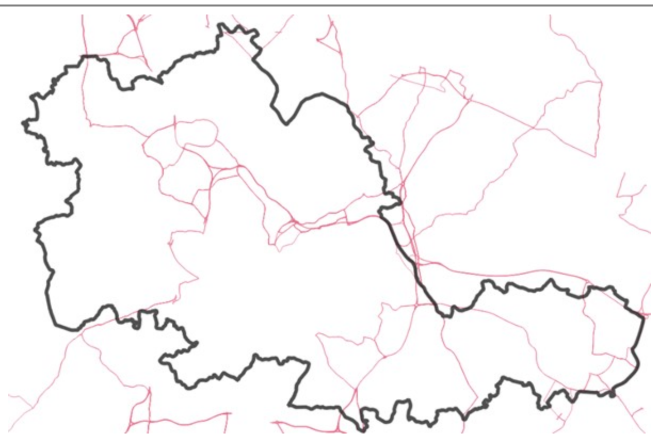
	Converted layer	GIS processing
Traffic Counts -Adjustment factor	 Close-up view of detail: 	• Clip OS Roads layer to WMCA with 5km buffer • Download and import AADF CSV from website into QGIS then refactor fields - convert counts and year to integers • Use create points layer from table, then clip to boundary • Use extract by expression to extracts most recent counts: "year" = maximum("year" ,group_by:= "count_point_id") • Use extract by expression to obtain all B road counts: (left ("road_name" ,1)= 'B') then same for major roads • Dissolve OSRoads layer to "function" field, remove other fields • Use extract by attribute to create "B Road" and “Motorway or A Road” shapefiles then create spatial indexes for these • Use snap geometries to layer with both categories to align counts with roads, selecting "prefer closest points, don’t insert new vertices". Increase tolerance until all points captured • Use fix geometries to remove invalid geometry for both line and structure attributes • Use split line at points with an epsilon value of circa 20m • Use join attributes by nearest - use 1 nearest neighbours , with no max distance set for both B roads and Major roads • Use merge vector layers, then extract by expression: "all_motor_" = maximum("all_motor_" ,group_by:= x (line_interpolate_point ($geometry, $length / 2)) \|\| y (line_interpolate_point ($geometry, $length / 2))). This will gives max traffic count for each duplicated attribute • Use rasterize (vector to raster) with a 5m pixel size. Add "-at" in "additional command line parameters" field (always covers line) • To bring values into transport network shapefile, use select by expression "Network" = 'Motorway', 'A road' or 'B road' • Create traffic count field using formula: coalesce (raster_value ('raster', 1, line_interpolate_point($geometry, $length/2)),0) - apply to selected features only • Create percentile field using formula: array_find(array_agg ("tcountall" ,group_by:= "network" , filter:= "tcountall" IS NOT NULL,order_by:= "tcountall"), "tcountall") / array_length(array_agg("tcountall" ,group_by:= "network" , filter:= "tcountall" IS NOT NULL,order_by:= "tcountall"))
Starley Cycle Network - Adjustment factor		• Download Starley network and create 5m buffer and reproject to OSGB36 if necessary • Use rasterize (vector to raster) with burn in value of 1 and '-at' for additional command line prompt • On Transport Network shapefile, select by expression > "network" = 'cycle route' • Use field calculator to add field with expression: coalesce (raster_value ('raster', 1, line_interpolate_point($geometry, $length/2)),0) - make sure 'only update selected features' is checked
HE Agreed Diversion Routes - Adjustment Factor		• Download shapefile then use buffer (20m). This is required as linestrings do not overlap exactly with roads layer • Use delete holes function and vary ‘size’ setting to ensure roads linestrings fall within buffer region • Use rasterize (vector to raster) with burn in value = 1 • To bring into road network shapefile, select roads, then use field calculator with expression: coalesce (raster_value ('raster', 1, line_interpolate_point($geometry, $length/2)),0), making sure ‘apply to selected features’ is selected

Table 2. Conversion processes of each layer underpinning the CRVA process

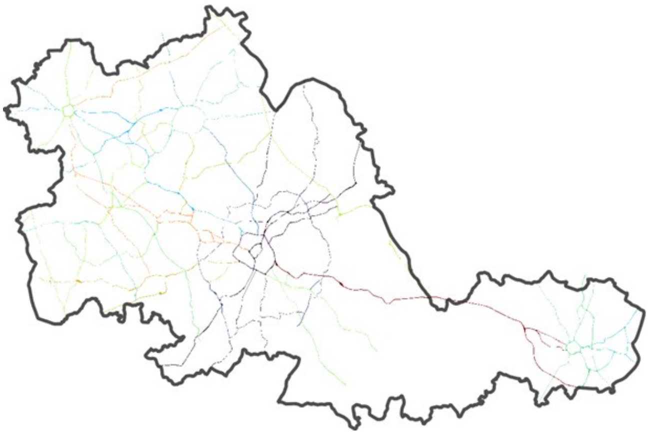
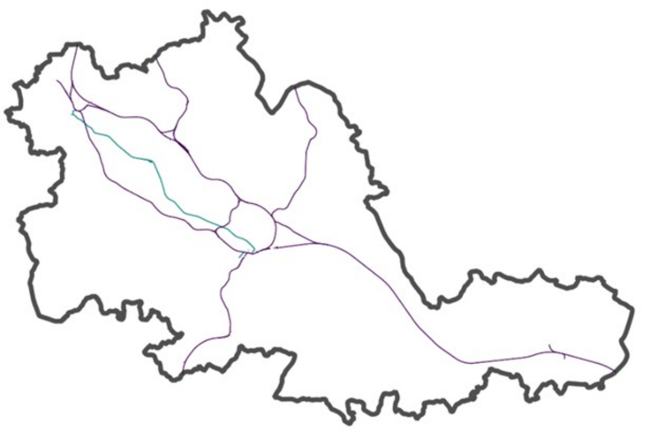
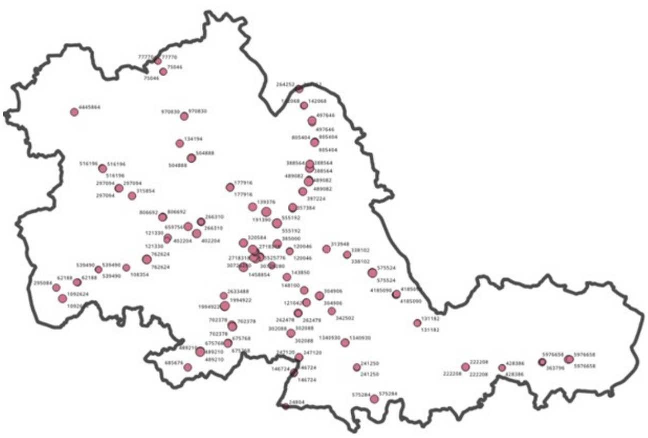
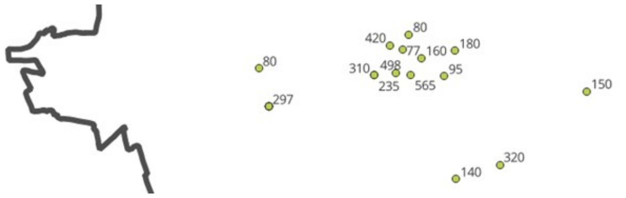
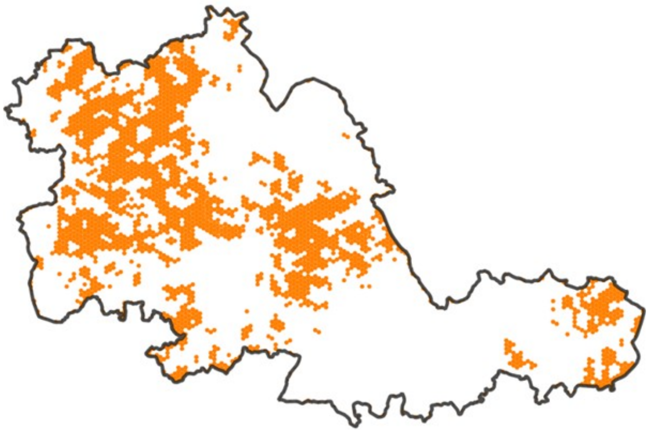
	Converted layer	GIS processing
Key Route Network - Adjustment factor		• Bring in Shapefile and reproject to OSGB36 • Use buffer to create a 10m wide KRN network • Use delete holes (experiment with size variable) to ensure that road network overlay sits within the buffer region • Use rasterize (vector to raster), using "route_id" as burn in field and "-at" as additional command line prompt • Using transport network layer, select by expression: "network" = 'A Road' or "network" = 'B Road' or "network" = 'Motorway' • Create KRNid field using field calculator: coalesce (raster_value ('raster', 1, line_interpolate_point($geometry, $length/2)),0) and apply to selected items only • Manually fill in any holes by opening attribute table in edit mode and selecting gaps - change KRNid to adjacent value • Create an adjustment value field, e.g. "C5_KRN": with expression: if ("krn_id" IS NOT NULL,1,0) *- assumes adjustment value = 1*
Elevated Structures - Adjustment factor		• For both DEM and DTM, bring in raster grids for study area use merge to create single rasters for elevation and terrain • For VOM layer, bring in raster grids for study area and merge to create single raster for vegetation > 2.5m height • Use raster calculator with expression: if ("VOM" >0,1,0). This will identify areas with zero tree cover • Using warp (reproject), reduce all 3 rasters to 10m resolution using 100m grid extents • Use raster calculator with expression: ("VOM">0) * (("DSM"-"DTM") > 2])* ("DSM"-"DTM") for non-tree elevated objects over 2m height • Use rnull to convert any null values to Zero, then use sieve to clear noisy pixels (I used 10m as sieve variable value) • Using transport network layer, create a decimal (real) field for elevated road sections: if ("elevation" >=2,0,1) Note that this is a multiplier, so 0 if elevated, which reduces flood vulnerability
Overhead line (Rail/ Tram) - Adjustment factor		• Use Quick OSM to filter for Transport/Railway/Rail then extract line layer by attribute > "electrified" = 'contact_line' • Create a buffer (10m), then rasterize (vector to raster) using a 2m resolution to 100m grid limits and a burn-in value of 1 • Within the transport network asset layer, select by expression: "network" = 'railway', then use field calculator to create a decimal (real) field: Coalesce (raster_value ('raster', 1, line_interpolate_point($geometry, $length/2)),0) • Manually fill in any holes by opening attribute table in edit mode and selecting gaps • Again, use select by expression: "network" = 'tram' and update newly created field with a value =of 1, then manually change the few non-ocs sections to 0 using local knowledge
Rail Patronage - Adjustment factor		• Save RPATS as CSV file and Import into QGIS as Table • Rename "Entries and exits - all tickets" to "Rail_patronage" • Use field calculator (new decimal, real field) to Calculate Percentile 0 to 1 (C2_RailPat): array_find(array_agg ("Rail_patronage" , "Rail_patronage" IS NOT NULL,order_by:= "Rail_patronage"), "Rail_patronage") / array_length(array_agg("Rail_patronage" , "Rail_patronage" IS NOT NULL)) • Within transport node asset shapefile, assign patronage figures to station nodes using field calculator under a new Integer field "Rail_patronage": attribute(get_feature('ORR_railpatronage', map('Full Station Name','CommonName')), 'Rail_Patronage') • Do the same for percentile field "C2_RailPat": attribute (get_feature('ORR_railpatronage',map('Full Station Name' , "CommonName")), 'C2_RailPat')

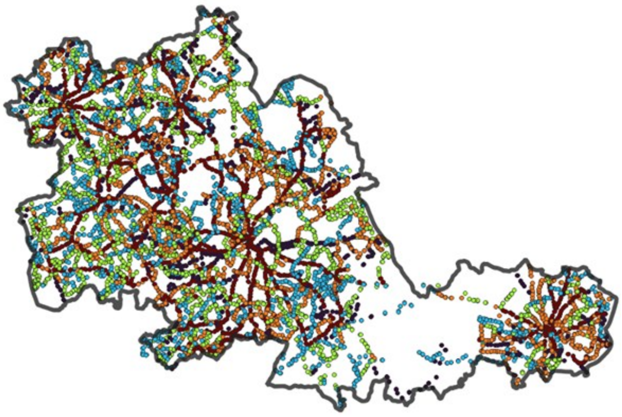
Table 2. Conversion processes of each layer underpinning the CRVA process

<table>
<tr><th></th><th>Converted layer</th><th>GIS processing</th></tr>
<tr><td>Car park Space - Adjustment</td><td>
</td><td>

- In network nodes, select by expression stoptype = CPK:
- Create a 0 to 1 field (decimal, real) for CarPark space adjustment factor ("C1_CPK") using field calculator (applied to selected items only): (1 + array_find(array_agg("No_spaces" , "No_spaces" IS NOT NULL,order_by:= "No_spaces"), "No_spaces")) / array_length(array_agg("No_spaces", "No_spaces" IS NOT NULL))

</td></tr>
<tr><td>Low PT use + Low car use -Adjustment factor</td><td></td><td>

- Import shapefile and use select by expression to choose low car use and low public transport use
- Create field "AccessScore" with a value of 1 for "low access, low car". Can include other scores but currently only this one
- Use rasterize (vector to raster), burn in value = "AccessScore".
- In network nodes layer, select "StopType" = 'BCT' and create a New field (decimal, real) using field calculator: 'C3_BusAcc' with the following applied to selected features: coalesce (raster_value('raster',1,$geometry),0)
- A value of 1 represents high bus demand in remote areas, and has been applied to all bus stops in the region

</td></tr>
<tr><td>Bus Stop Service Frequency -Adjustment factor</td><td></td><td>

- In network nodes layer, select by expression: "StopType" = 'BCT' then create new field 'BusFreq' with the following applied to selected items: coalesce (raster_value('raster', 1, $geometry),0)
- Then create a new decimal (real) field "C4_BusFrq" for the adjustment factor with values 0 to 1 based on rank (percentile): (1 + array_find(array_agg("Busfreq" , "Busfreq" IS NOT NULL,order_by:= "Busfreq"), "Busfreq")) / array_length (array_agg("Busfreq" , "Busfreq" IS NOT NULL))

</td></tr>
<tr><td>Risk Calculation - Transportation Assets (Lines)</td><td>

Criticality and vulnerability weighting table for network lines:

<table>
<tr><th></th><th>fid</th><th>network</th><th>Criticality</th><th>FI_V</th><th>PI_V</th><th>Ex_V</th><th>Vg_V</th><th>LS_V</th><th>Ts_V</th></tr>
<tr><td>1</td><td>1</td><td>Motorway</td><td>4</td><td>1.5</td><td>1.5</td><td>3</td><td>1.5</td><td>2</td><td>2.75</td></tr>
<tr><td>2</td><td>2</td><td>A Road - SRN</td><td>3.5</td><td>1.5</td><td>1.5</td><td>2.75</td><td>2.5</td><td>2.75</td><td>2.75</td></tr>
<tr><td>3</td><td>3</td><td>A Road</td><td>2.5</td><td>1.5</td><td>1.5</td><td>1.75</td><td>2.5</td><td>2.75</td><td>3</td></tr>
<tr><td>4</td><td>4</td><td>B Road</td><td>1.5</td><td>2</td><td>2</td><td>1.75</td><td>2.5</td><td>1.666666667</td><td>2.5</td></tr>
<tr><td>5</td><td>5</td><td>Minor Road</td><td>1</td><td>2</td><td>2</td><td>1.25</td><td>2.5</td><td>1</td><td>2.5</td></tr>
<tr><td>6</td><td>6</td><td>Local Road</td><td>1</td><td>2</td><td>2</td><td>0.75</td><td>2.5</td><td>0.75</td><td>2.5</td></tr>
<tr><td>7</td><td>7</td><td>Local Access Ro...</td><td>1</td><td>2</td><td>2</td><td>1.25</td><td>2.5</td><td>0.75</td><td>2.5</td></tr>
<tr><td>8</td><td>8</td><td>Restricted Local...</td><td>1</td><td>2</td><td>2</td><td>1.25</td><td>2.5</td><td>0.75</td><td>2.5</td></tr>
<tr><td>9</td><td>9</td><td>Secondary Acce...</td><td>1</td><td>2</td><td>2</td><td>1.25</td><td>2.5</td><td>0.75</td><td>2.5</td></tr>
<tr><td>10</td><td>10</td><td>railway</td><td>3.4</td><td>3</td><td>3</td><td>2.5</td><td>3</td><td>3</td><td>2.8</td></tr>
<tr><td>11</td><td>11</td><td>tram</td><td>2</td><td>1.5</td><td>2.5</td><td>2.5</td><td>2.4</td><td>3</td><td>2</td></tr>
<tr><td>12</td><td>12</td><td>cycle route</td><td>1.25</td><td>1</td><td>1.5</td><td>1.25</td><td>1.8</td><td>1.5</td><td>2.5</td></tr>
<tr><td>13</td><td>13</td><td>Public footpath</td><td>1.25</td><td>1</td><td>1.5</td><td>1</td><td>1.8</td><td>0.5</td><td>2.5</td></tr>
<tr><td>14</td><td>14</td><td>Airport</td><td>3</td><td>1.5</td><td>3</td><td>3</td><td>1</td><td>1.5</td><td>3</td></tr>
</table>

Transport network risk indicator, Tot_CVH:

</td><td>

- Drag Criticality and Vulnerability Weightings CSV file into QGIS then refactor as type Decimal Number (real)
- In Network layer, create fields for criticality and vulnerability weightings: attribute(get_feature('weightings_table', 'network' , "network"),'Criticality') - do this for all weighting factors
- Use field calculator to bring in Hazard raster values: coalesce (raster_value('raster',1,line_interpolate_point($geometry), $length/2)),0)
- Create Adjusted Criticality and Vulnerability fields using pre-agreed multipliers, e.g. for criticality: "net_crit" + coalesce ("C1_TCount",0) + (0.5*(coalesce("C2_Bus_frq",0) + coalesce("C3_Starley",0) + coalesce("C4_HEdiv",0) + coalesce("C5_KRN",0)))
- Create Risk Scores (Crit * Vul * Haz * Length) for each hazard , e.g. for fluvial: FI_R = "Crit_Adj" * "FI_V_Adj" * "FI_H" * "Length", then create Total Risk Score, Tot_R = coalesce ("FI_R",0) + coalesce("PI_R",0) + coalesce("Ex_R",0) + coalesce("Vg_R",0) + coalesce("LS_R",0) + coalesce ("Ts_R",0)
- Create a linear scale from 0 to 1 (tot_r_norm), using field calculator - decimal (real) : scale_linear("tot_r" ,minimum ("tot_r"),maximum("tot_r"),0,1)
- Create Risk Indicator Scores (Crit * Vul * Haz) for each hazard to be used within the network risk shapefile as risk indicator at the asset level, e.g.: FI_CVH = "Crit_Adj" * "FI_V_Adj" * "FI_H", and total these to obtain combined risk, Tot_CVH
- Apply similar approach for nodes, although the length element does not come into the risk calculation

</td></tr>
</table>

Table 2. Conversion processes of each layer underpinning the CRVA process

Combined Risk Scores at 100m Grid scale

Field Calculator Expressions

1. Combined Risk Totals:

type	field	Field calculator expression
Total Combined Risk to common scale	XTOTAL_R	coalesce(scale_linear("tot_r_sum",minimum ("tot_r_sum"),maximum ("tot_r_sum"),0,1),0) + coalesce (scale_linear("Nd_tot_R_sum",minimum ("Nd_tot_R_sum"),maximum ("Nd_tot_R_sum"),0,1),0)
Total combined risk normalised	XTOTAL_R01	scale_linear("XTOTAL_R" ,minimum ("XTOTAL_R"),maximum ("XTOTAL_R"),0,1)

2. Rescale total risk from 0 to 1 for line and point totals:

type	field	Field calculator expression
Line component of common scale	ZTOT_RL	*coalesce(scale_linear("tot_r_sum",minimum ("tot_r_sum"),maximum("tot_r_sum"),0,1),0)*
Point component of common scale	ZTOT_RP	*coalesce(scale_linear ("Nd_tot_R_sum",minimum ("Nd_tot_R_sum"),maximum ("Nd_tot_R_sum"),0,1),0)*

3. calculate hazards component by rescaling fraction of hazard risk score for each component:

type	field	Field calculator expression
Fluvial	ZFL_R	Coalesce(ZTOT_RL * (fl_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_fl_r_sum/nd_tot_r_sum),0)
Pluvial	ZPL_R	Coalesce(ZTOT_RL * (pl_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_pl_r_sum/nd_tot_r_sum),0)
Exposure	ZEX_R	Coalesce(ZTOT_RL * (ex_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_ex_r_sum/nd_tot_r_sum),0)
Windthrow	ZVG_R	Coalesce(ZTOT_RL * (vg_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_vg_r_sum/nd_tot_r_sum),0)
Landslide	ZLS_R	Coalesce(ZTOT_RL * (ls_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_ls_r_sum/nd_tot_r_sum),0)
Surface Temp	ZTS_R	Coalesce(ZTOT_RL * (ts_r_sum/ tot_r_sum),0) + coalesce(ZTOT_RP * (nd_ts_r_sum/nd_tot_r_sum),0)

4. Rescale combined hazard scores to add up to normalised total risk:

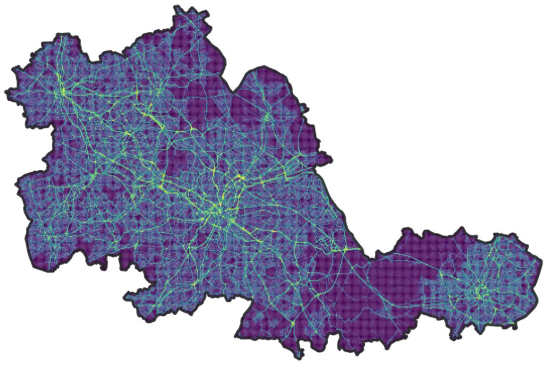
type	field	Field calculator expression
Fluvial	ZFL_R01	ZFL_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)
Pluvial	ZPL_R01	ZPL_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)
Exposure	ZEX_R01	ZEX_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)
Windthrow	ZVG_R01	ZVG_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)
Landslide	ZLS_R01	ZLS_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)
Surface Temp	ZTS_R01	ZTS_R * coalesce(XTOTAL_R01/ XTOTAL_R,0)

GIS processing

- Bring Line and Points Risk Values into 100m Gridspace using join attributes by location (summary). Fields to summarise will be all the risks for each hazard (fl_r….etc) as well as total risk (tot_r). Ensure the features selected for summation are "contain" or "within" (important). Use "Sum" function and "_sum" as prefix
- Next, combine Network and Nodes grids into single grid using join attributes by field value. Join layers by "id" field. Bring in all hazard risks as well as totals. Add prefix for node import "Nd_" and leave network without prefix
- Calculate Combined Risk Levels (all fields created with field calculator and will be decimal (real):
- First (1) Create Combined Totals by converting to a common scale (0>1)and adding, then re-scale combined score to a 0>1 scale:
- Next (2), rescale total risk from 0 to 1 for each of the line and point totals (ZTOT_RL + ZTOT_RP = XTOTAL_R):
- Then (3) calculate hazards component by rescaling fraction of hazard risk score for each component (line/ point) and adding to get total risk (ZFL_R + …..+ ZTS_R) = XTOTAL_R)
- Next (4) Rescale combined hazard scores to add up to normalised total risk:
- Now, the Total risk score for each gridcell will be between 0 and 1 and the hazard totals will add up to the normalised Total :

XTOTAL_R01 = ZFL_R01 + ZPL_R01 + ZEX_R01 + ZVG_R01 + ZLS_R01 + ZTS_R01

Total Risk Score (XTOTAL_R01):



Example of rescaled Hazard Risk (ZFL_R01):

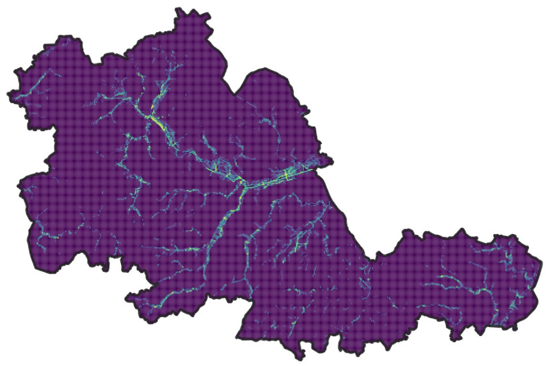
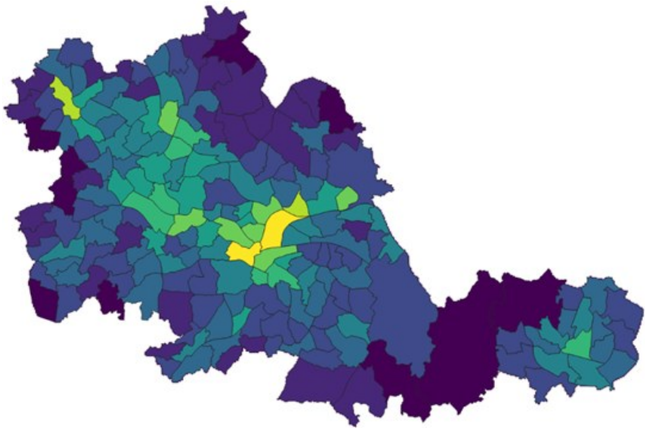


Table 2. Conversion processes of each layer underpinning the CRVA process

	Converted layer	GIS processing
Combined Risk scores - Regional	Mean Total Risk at Ward Level 	• To reference each 100m grid score into the regional polygons, convert the grid into centroid points for referencing into the summary polygons. The point layer carries all risk scores for easy conversion into regional scores • An alternative to this approach would be to a raster of the risk score in combination with zonal statistics (see additional information) • First, for R01 fields use field calculator to make sure all zeros are set to NULL. This will ensure that when taking mean values into the region polygons, areas points with no transport network do not skew the score • Next, use join attributes by location (summary). Select intersect and bring in all the normalised fields (xxx_R01). Choose 'Mean', 'Max' and 'Sum' summary calculations • repeat above step for the other regional shapefiles

ADDITIONAL INFORMATION ON GIS TECHNIQUES

This CRVA map used tools within the QGIS application (version 3.28.11 Firenze long-term release).

Creating a fishnet grid
Vector > Research Tools > Create Grid
A fishnet grid is a vector layer, which is a conversion of another vector file into gridded squares. It is used for the CRVA map as the reference layer to align all raster conversions.

Resampling: Bilinear interpolation
Raster > Projections > Warp (Reproject)
Resampling creates a new raster layer based on sampling from another raster layer. The reasons for doing this include reprojecting or aligning raster cells to a new grid size or position. Bilinear interpolation is a resampling method using the weighted four nearest cell centres[35].

Resampling: Nearest neighbour
Raster > Projections > Warp (Reproject)
Using the same process as bilinear interpolation, nearest neighbour resampling is determined by the nearest cell centre on the input grid.

Joining attributes by location (summary)
Processing toolbox > Vector general > Join attributes by location (summary)
This process takes vector attributes and assigns them to each grid square. It is therefore a step before converting vector data into a raster layer.

Identifying percentile values of continuous layer data
Processing toolbox > GRASS > Raster > r.quantile
This produces a table with the percentile boundaries of continuous raster data. To establish 5%ile bins, the number of quantiles is set to 20.
Processing Toolbox > Raster Analysis > Reclassify by table
After identifying the boundary ranges, the percentile break ranges can be set using reclassify by table.

Rescaling raster layer 0-1
Processing Toolbox > Raster Analysis > Rescale raster
This process quickly normalises a raster layer, where the highest value is scaled to 1 and the lowest scaled to 0. This is used when rasterising a layer creates cell values between 0 and 255, reflective of colour band values, or after the summing of other layers to normalise the value range.

Converting total CRVA scores to other geographic boundaries
Processing toolbox > Raster Analysis > Zonal statistics
CRVA score can be averaged in accordance with vector files that include smaller boundaries, such as wards or hex grids.

Raster calculations outside pixel
GRASS > r.mapcalc.simple
To generate the Topographical exposure hazard layer, it was necessary to apply formulae to a DEM layer to take into account pixel values outside the focus pixel at distances of 100m to 1000m for 8 compass directions.

Performing risk calculations inside vector layer
Open attribute table > open field calculator
Once values are brought into the vector layer's attribute table from the hazard layers as fields, calculations can be applied to these fields to combine the variables into the weighted risk score.

Merging raster tiles
Raster > miscellaneous > merge
Digital elevation model (DEM) datasets are usually in tiled format. The merge function will allow several tiles to be merged to cover the study area.

Grouping linestring information into asset types
Vector > geoprocessing tools > dissolve
For example, to create linestrings for each road type (e.g. local, b roads, a roads, motorway), the appropriate field would be selected in the "dissolve field" dropdown box.

Dealing with NULL values
Null values in raster layers sometime help and sometimes hinder GIS processing operations. The following approaches can be followed to control null values:

Reset the NoData values in the input raster to a chosen value
Raster tools > Fill NoData cells
Assign a specified no data value
Raster > conversion > translate (convert format)
Sets values to null
Grass>Raster>r.null

References

35. ESRI (2023) FAQ: What is the difference between Nearest Neighbor, Bilinear Interpolation and Cubic Convolution? Available at: https://support.esri.com/en/technical-article/000005606 (last accessed 20/03/2023)