Supplementary Information

Van Ginkel, Dottori, Alfieri, Feyen and Koks (2020): *Direct flood risk assessment of the European road network: an object-based approach*

The structure of this supplementary information follows the numbered headings of the main article.

2. Method

Risk calculation

The flood risk, in terms of expected annual damage (EAD) in Euro per year, is calculated by integration over the damage per return frequency. This requires several assumptions that significantly impact the outcomes (Olsen et al., 2015). We use the trapezoidal rule to numerically integrate over six known combinations of the return frequency (1:10, 1:20, 1:50, 1:100, 1:200, 1:500 y^{-1}) and damage, as shown in Figure S1. The integration shown in this figure has two implicit assumptions:

1) The damage for events beyond the 1:500 y^{-1} event (i.e. return period > 500 y, or frequency < 1/500 y^{-1}), is the same as the damage in the 1:500 y^{-1} event. In contrast, one could also argue that in theory, the damage for the 1:infinity could go up till infinity (as suggested by the shape of some extreme value distributions), and that the corresponding damage also could go up till infinity. However, the amount of observed discharges underlying the extreme value distribution from which the water depths are sampled do not allow for accurate estimates of events beyond the 1:500 year.
2) For events more likely than the 1:10 y^{-1} event (i.e. return period < 10 y), no damage will occur. We reason that roads will usually not be constructed such that they flood more than every 10 years. Note that in practice, the 1:10 y^{-1} damage is hardly used, because the return period of the flood protection is larger than 10 year almost everywhere in Europe.

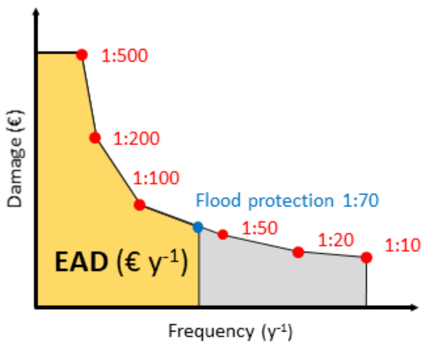


Figure S1 Example of trapezoidal integration (not to scale), for a hypothetical case with flood protection level 1:70 y^{-1}

2.2 Grid-based exposure and vulnerability

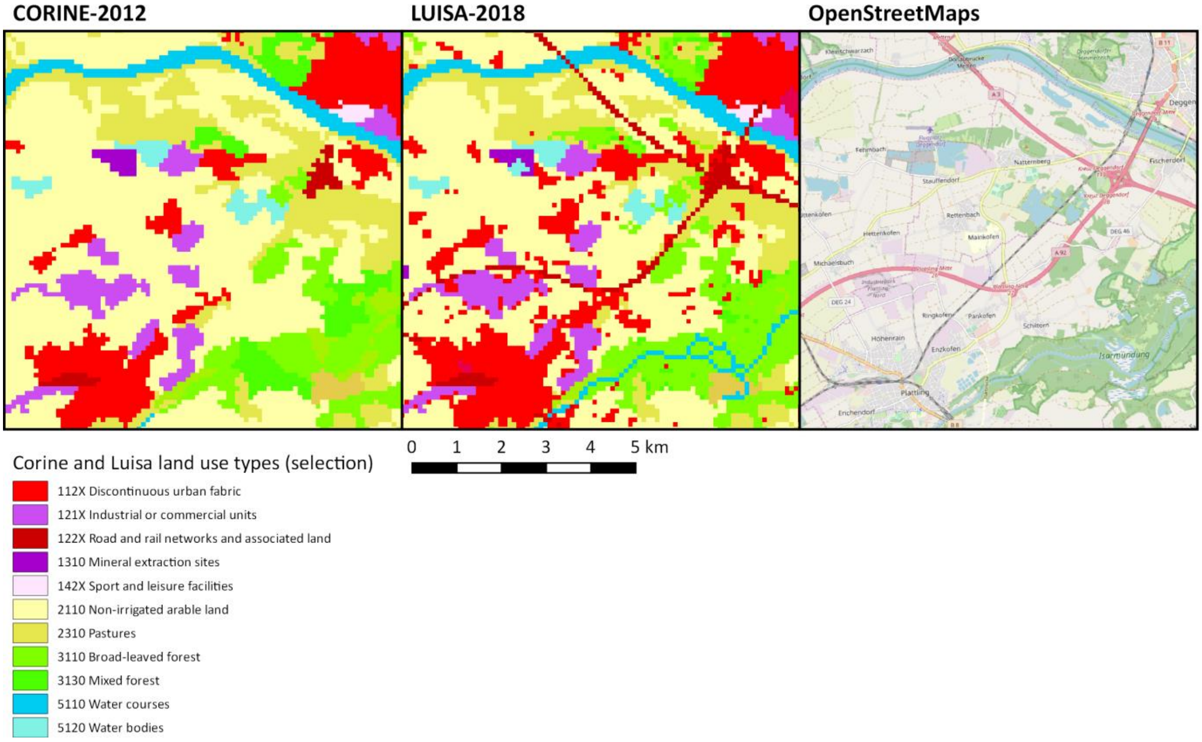


Figure S2 Comparison of CORINE, LUISA and OpenStreetMap
Each panel shows the Deggendorf junction of the A92 and A3 and the towns of Deggendorf (top-right) and Platting (bottom left) in Bavaria, Germany. The large river is the Danube River. The CORINE land cover map (left-hand panel) is CORINE-2012, version 18.5 (Büttner et al., 2014). The LUISA land cover map (central panel) is LUISA version 2 (Rosina et al., 2018). The OpenStreetMap extract (right-hand panel) is made on 26 August 2019 (© OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.) with the QuickMapServices plugin of QGIS.

Table S1 Blending of Huizinga (2007) damage curves per CORINE land use type, showing only damage to rail and road infrastructures

CORINE landcover		Land use percentage (%) for which damage is calculated						
Code	Name	residential	commerce	industry	infrastructure	agriculture	transport	forestry
111	Continuous urban fabric	0	0	0	18	0	0	0
112	Discontinuous urban fabric	0	0	0	12	0	0	0
121	Industrial or commercial units	0	0	0	21	0	0	0
122	Road and rail networks and associated land	0	0	0	54	0	0	0
123	Port areas	0	0	0	50	0	0	0
124	Airports	0	0	0	69	0	0	0
141	Green urban areas	0	0	0	10	0	0	0
511	Water courses	0	0	0	27	0	0	0
522	Water bodies	0	0	0	30	0	0	0

Table S2 Blending of Huizinga (2007) damage curves per LUISA land use type, showing only damage to rail and road infrastructures

LUISA landcover		Land use percentage (%) for which damage is calculated						
Code	Name	residential	commerce	industry	infrastructure	agriculture	transport	forestry
1111	Urban fabric dense (>50% built-up)	0	0	0	18	0	0	0
1121	Urban fabric medium density (30-50% built-up)	0	0	0	12	0	0	0
1122	Urban fabric low density (10-30% built-up)	0	0	0	6	0	0	0
1123	Urban f. very low density and isolated (<10% built-up)	0	0	0	2	0	0	0
1211	Production facilities	0	0	0	21	0	0	0
1212	Commercial service facilities	0	0	0	21	0	0	0
1213	Public facilities	0	0	0	21	0	0	0
1221	Road and rail networks and associated land	0	0	0	27	0	0	0
1222	Major railway stations	0	0	0	15	0	0	0
1230	Port areas	0	0	0	40	0	0	0
1241	Airport areas	0	0	0	40	0	0	0
1242	Airport terminals	0	0	0	15	0	0	0
1410	Green urban areas	0	0	0	10	0	0	0
1422	Leisure and touristic built-up	0	0	0	10	0	0	0
6011	Post-flooding or irrigated croplands (or aquatic)	0	0	0	5	0	0	0
6014	Rainfed croplands	0	0	0	5	0	0	0
6190	Artificial surfaces and assoc. areas (Urban areas >50%)	0	0	0	8	0	0	0

2.3 Object-based exposure and vulnerability

OpenStreetMap uses the key “highway” to indicate that an object is any kind of road (rather than a building, tree etc.). The highway-key often has an attribute indicating the type of road. Since many different attribute values are allowed in OSM, these values were mapped to eight different road types in this study, according to Table S3. Keys not included in the list are mapped as ‘none’. For ‘track’ and ‘none’, no damage is calculated.

Table S3 OpenStreetMap ‘highway’ key value mapped to the road types used in this study

Road type	Key value
Motorway	Motorway, motorway_link, motorway_junction
Trunk	Trunk, trunk_link
Primary	Primary, primary_link
Secondary	Secondary, secondary_link
Tertiary	Tertiary, tertiary_link
Other	Unclassified, residential, living_street, service, pedestrian, bus_guideway, escape, raceway, road, cycleway, construction, bus_stop, crossing, mini_roundabout, passing_place, rest_area, turning_circle, traffic_island, yes, emergency_bay
Track	Track, unsurfaced, corridor, trail, footway, path
None	None, bridleway, steps, proposed, elevator, emergency_access_point, give_way, speed_camera, street_lamp, services, stop, traffic_signals, turning_circle, toll_gantry, stop, disused, dummy, planned, razed, abandoned (and all other unknown tags)

Object-based implementation of the Huizinga damage curves

The grid-based Huizinga (2007, 2017) infrastructure damage function is expressed in euros damage per inundated area (€/m^2). The maximum damage for road infrastructure is 25 €/m^2. To apply this function in the object-based model, they are multiplied by typical road widths (m) to obtain damage functions per unit road length, as tabulated in Table S4. Road widths were estimated from a sample of roads in the European Union using Google Earth satellite imagery[1]. Roads measurements included road toes and berms, and for motorways and trunk also any (median) space in between the lanes.

Table S4 Typical road with (m) per road type in the European Union

Road type \ # lanes	1	2	3	4	5	6
Motorway*	7	14	18	22	26	30
Trunk*	7	12	16	19	23	26
Primary	5	10	13	17	20	23
Secondary	5	9	12	16	19	22
Tertiary	4	7	10	14	17	20
Other	3	6	9	12	15	18
Track	3	6	9	12	15	18

* Note that in OSM, both directions of motorways and trunks are usually mapped as separate one-way streets, so that for example the total width of a 2 * 3 lane motorway is 2 * 18 m = 36 m.

[1] For comparison, note that EU motorway lanes have a typical width of 3.50-3.75 m (European Road Safety Observatory, 2018. *Motorways 2018*. Retrieved from https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/ersosynthesis2018-motorways.pdf , latest accessed 6 August 2019).

Road construction and road maintenance costs

On the following pages, we list road construction and road maintenance costs in several tables. First, we give a detailed overview of the cost structure of motorways in The Netherlands (Table S5) and list construction costs of new motorways in Europe (Table S6). For motorways, the largest amount of data was available. Second, we therefore put the construction costs of other road types in perspective of the construction costs of motorways, both in relative percentages (% of construction costs of motorways mentioned in the same source) and in an absolute costs (Table S7). Third, we list the maintenance costs of roads (Table S8).

These tables are used to construct the object-specific depth-damage curves.

Table S5 details the cost structure of motorways in The Netherlands for 2018, Dutch price levels. In the other tables, these are corrected to represent 2015, former EU-28 average price levels, as follows. In 2018, Dutch real GDP per capita was 41,600 euro. In 2015, this was 39,200 euro, a factor 0.942 lower. The EU-28 average real GDP per capita in 2015 was 26,700 euro: a factor 0.681 lower than in The Netherlands.

$$Cost_{EU28,2015} = \frac{GDP_{NL,2015}}{GDP_{NL,2018}} * \frac{GDP_{EU28,2015}}{GDP_{NL,2015}} * Cost_{NL,2018} = 0.942 * 0.681 * Cost_{NL,2018}$$

For converted values, see Table S6 and further.

Table S5 Detailed cost structure of motorway construction in The Netherlands (Netherlands Ministry of Infrastructure and Water Management: Rijkswaterstaat, 2019)

Road type	Lanes	Unit costs[1]	
		10^6 €/km	-
Base cost of simple road on ground level: no bridges, tunnels or junctions			
Motorway	2*2	8.05	
Relative costs of extra lanes			**Factor**
Motorway	2*2	8.05	1
Motorway	2*3	10.29	1.28
Motorway	2*4	12.16	1.51
Motorway	2*5	14.04	1.74
Trunk	2*1	5.34	1
Trunk	2*2	6.23	1.17
Extra construction costs		**Total**	**Factor**
Motorway: lighting and signalling	2*2	8.05 + 1.8	1.22
Motorway: elevating + 1 m	2*2	8.05 + 1.8	1.22
Motorway: elevating + 2 m	2*2	8.05 + 3.78	1.47
Motorway: lighting and signalling and elevating + 2 m	2*2	8.05 + 1.8 + 3.78	1.69
Trunk: lighting and signalling	2*2	6.23 + 1.73	1.28
Trunk: elevating + 1 m	2*2	6.23 + 1.54	1.25
Trunk: elevating + 2 m	2*2	6.23 + 3.28	1.53
Trunk: lighting and signalling and elevating + 2 m	2*2	6.23 + 1.73 + 3.28	1.8

1) Pricelevel 2018.

Table S6 Motorway construction costs

Source	Country	Project name	Road type	Tunnels/ bridges	Lanes	Length	Total costs	Unit costs	To NPV-2015[1]	To EU-avg GDP[2]	Corrected unit costs
						km	10^6 €	10^6 €/km	-	-	10^6 €/km
European Court of Auditors (2013)											
ECA (2013)	Spain	Mediterranean Motorway A7 section Tramo Castell de Ferro–Polopos	Motorway	yes	2*3	3.6	28.2	7.83	1.055	1.156	9.5
ECA (2013)	Spain	Mediterranean Motorway A7 section La Herradura– Almunecar	Motorway	yes	2*2	9.1	280	30.7	…	…	37.5
ECA (2013)	Spain	Motorway A66 section Caceres North– Aldea del Cano	Motorway		2*2	29.3	96.7	3.30	…	…	4.0
ECA (2013)	Spain	Motorway A66 section Enlace de Hinojal–Caceres North	Motorway		2*2	21.4	88.1	4.1	…	…	5.0
ECA (2013)	Germany	Motorway A17 from Dresden to the Czech border	Motorway		2*2	40.8	655.5	16.1	1.027	0.776	12.8
ECA (2013)	Germany	Motorway A20 Grimmen-East to Strasburg	Motorway		2*2	91.2	367.6	4.0	…	…	3.2
ECA (2013)	Greece	Motorway E75/ PATHE section Agios Konstantinos– Kamena Vourla	Motorway	yes	2*2	20.0	378.8	18.9	1.018	1.563	30.1
ECA (2013)	Greece	Motorway A2 Egnatia Odos, section Asprovalta– Nymphopetra	Motorway		2*2	31.0	184.1	5.9	…	…	9.4
ECA (2013)	Poland	Motorway A1, section Sosnica-Belk	Motorway		2*3	15.4	307.9	20.0	1.069	2.451	52.3*
Other European sources											
Heralova et al. (2013)	Czech rep.	Summary statistics of 74 highway projects in Czech Republic	Motorway		-	-	-	15.1	1.052	1.647	26.2
Nijland et al. (2014)	Netherl.	Motorway A5 'Verlengde Westrandweg'	Motorway		2*2	7.0	295	42.1	1.092	0.681	31.3
Pryzluski et al. (2012)	Germany	Average unit replacement cost of motorway	Motorway		-	-	-	13	1.154	0.776	11.7
Ministry of Transport (2016)	Germany	Motorway A23 from Hamburg (Itzehoe-S) to Heide (Itzehoe-N)	Motorway		2*2	7.5	159	21.2	0.986	0.776	16.2
Ministry of Transport (2016)	Germany	Motorway A21 from Stolpe (Stolpe) to Kiel (Nettelsee)	Motorway		2*2	5.9	66.3	11.2	…	…	8.6
Ministry of Transport (2016)	Germany	Motorway A7 Hamburg to Bordesholm	Motorway		2*3	59.6	1548.6	25.6	…	…	19.9
Rijkswaterstaat (2019)	Netherl.	Construction of simple motorway (unit costs)	Motorway		2*2	-	-	8.05	0.942	0.681	5.2
Rijkswaterstaat (2019)	Netherl.	Motorway 2m elevated with electronic signalling (unit costs)	Motorway		2*2	-	-	13.6	…	…	8.7
Bouwkostenkompas (2015)	Netherl.	Motorway (unit costs)	Motorway		2*2	-	-	7.80**	1	…	5.3
Beyond Europe***											
Carruthers (2013)	-	Cost figure 4-lane divided paved road (3.5 mln USD)	Motorway		2*2	-	-	4.7	1.047	1	4.9
Collier et al. (2015)	-	New 6L expressway in low- and middle-income countries (5.6 mln USD)	Motorway		2*3	-	-	6.1	-	-	-
Collier et al. (2015)	-	New 4L expressway in low- and middle-income countries (2.8 mln USD)	Motorway		2*2	-	-	3.1	-	-	-
Australia (2017)	Australia	Average unit road costs (total cost) road class 1	Motorway		2*2	-	-	13.3	-	0.64	8.5

Australia (2017)	Australia	Average unit road cost (st andardised average cost) road class 6	Motorway	2*2	-	-	18.1	-	…	11.5
Arkansas highway (2014)	USA	6 lane freeway urban areas	Motorway	2*3	-	-	14.0	-	0.68	9.5
Arkansas highway (2014)	USA	4 lane freeway	Motorway	2*2	-	-	11.8	-	…	8.0

1) Time pricelevel correction, factor indicating the real GDP-per capita in the reported priceyear compared to the reference year 2015 (EUROSTAT, 2019).

2) Space pricelevel correction, factor indicating the real GDP-per capita of the EU-member state compared to EU-28 average (EUROSTAT, 2019).

* Omitted from the analysis, seems to be an outlier because the GDP per capita of Poland is disproportionally low compared to the reported construction costs.

** The Bouwkostenkompas gives a low (6.1 million) and a high (7.8 million) estimate. We took the higher estimate, because the consulted experts considered the values in the Bouwkostenkompas rather low.

*** Corrected for representative local currency/euro rate.

Table S7 Ratios between average construction costs

Source	Country	Project name	Road type	Lanes	Unit costs	To NPV-2015	To EU-avg GDP	Corrected unit costs	% of 2*2 motorway	% of 2*2 trunk
					10^6 €/km	-	-	10^6 €/km		
European Court of Auditors (2013)										
ECA (2013)	EU avg.	Motorways	Motorway	2*2	10.94	1.039	1	11.4	100%	-
…	…	Express road	Trunk	2*2	6.23	…	…	6.5	57%	100%
…	…	Two lane	Trunk	2*1	4.16	…	…	4.3	38%	67%
EU-WEATHER										
Przyluski et al. (2012) …	Germany	Motorway	Motorway	2*2	13	1.154	0.776	11.7	-	-
…cited in Doll et al. (2014)	…	Federal road	Trunk	2*2[2] 2*1	3.6	…	…	3.2	28% 55%	-
COMRISK										
De Bruijn et al. (2014)	Denmark	Roads in Ribe Country	Secondary	2*1	0.87	0.987	0.585	0.50	-	-
…	…	…	Tertiary	2*1	0.50	…	…	0.29	-	-
…	…	…	Other	2*1	0.15	…	…	0.085	-	-
World Bank (ROCKS)										
Collier et al. (2015) …	global	New 4-lane expressway	Motorway	2*2	2.8*	-	-	-	100%	-
… appendix p. 4	…	New 4-lane highway	Trunk	2*2	2.2*	-	-	-	77%	100%
…	…	New 2-lane highway	Primary	1*2	0.75*	-	-	-	26%	34%
…	…	New 1-lane road	Other	1	0.09*	-	-	-	3%	4%
Rijkswaterstaat (2019)										

[2] Unclear if this figure refers to 2*2 or 2*1 trunk roads.

Rijkswaterstaat (2019)	Netherlands	Autosnelweg	Motorway	2*5	14.0	0.942	0.681	9.01	174%	-
…	…	…	…	2*4	12.2	…	…	7.80	151%	-
…	…	…	…	2*3	10.3	…	…	6.60	128%	-
…	…	…	…	2*2	8.05	…	…	5.17	100%	-
…	…	Autoweg	Trunk	2*2	6.23	…	…	4.00	77%	-
Bouwkostenkompas GWW (2015)										(for max of range)
…	Netherlands	‘Snelweg’/’Rijksweg’	Motorway	2*4	11.5-14.8	1	0.681	7.8-10.0	190%	-
…	…	‘Snelweg’/’Rijksweg’	…	2*3	8.0-10.3	…	…	5.5-7.0	132%	-
…	…	‘Snelweg’/’Rijksweg’	…	2*2	6.1-7.8	…	…	4.2-5.3	100%	-
…	…	‘Provinciale weg’	Trunk	2*2	4.0-5.4	…	…	2.8-3.7	69%	100%
…	…	Div.	Primary	2*2	2.5-2.8	…	…	1.7-1.9	36%	52%
…	…	Div.	Primary	2*1	1.8-2.8	…	…	1.2-1.9	36%	52%
…	…	Div.	Secondary	2*1	1.7-1.9	…	…	1.2-1.3	24%	35%
…	…	Div.	Tertiary	2*1	0.51-1.8	…	…	0.35-1.3	23%	33%
…	…	Div.	Other	2*1	0.35-2.0	…	…	0.24-1.3	26%	37%
EU MEDPRO project										
Carruthers (2013)	Mediterranean	4-lane divided paved road	Motorway	2*2	3.5	-	-	-	100%	-
…	…	2-lane paved road	Primary	2*1	1.0	-	-	-	29%	-
HIS-SSM (max damages)										
De Bruijn et al. (2014)	Netherlands	Highways	Motorway	-	1.45	1.117	0.681	1.10	100%	-
…	Netherlands	Regional roads	Primary	-	0.89	1.117	0.681	0.75	68%	-
…	Netherlands	Other roads	Other	-	0.03	1.117	0.681	0.02	2%	-
Arkansas highways (2014)										
Arkansas highways (2014)	USA	6-lane freeway	Motorway	2*3	13.95	-	0.68	9.5	118%	-
…	USA	4-lane freeway	Motorway	2*2	11.81	-	0.68	8.0	100%	-
…	USA	4-lane divided	Trunk	2*2	9.06	-	0.68	6.2	65%	100%
…	USA	2-lane arterial	Secondary	2*2	4.03	-	0.68	2.7	29%	44%
…	USA	2-lane collector	Tertiary	2*2	2.68	-	0.68	1.8	19%	33%

Table S8 Road maintenance costs

Source	Country	Description	Road type	Lanes	Unit costs	To NPV-2015	To EU-avg GDP	Corrected unit costs	% of Huizinga max damage	% of construction costs[1]
Reference						-	-			
Huizinga (2007)	EU-avg	Max damage costs	Avg	-	-	-	-	25 €/m^2	100%	-
Cleaning costs										
Reese (2003)	Germany	Cleaning paved surface per m^2	-	-	6 €/m^2	1.17	0.776	5.5 €/m^2	22%	3.1%[3]
Reese (2003)	Germany	Cleaning unpaved surface per m^2	-	-	3 €/m^2	…	…	2.7 €/m^2	11%	-
Resurfacing costs										
Carruthers (2013)	Mediter.	Resurfacing a 4-lane road	Motorway	2*2	1,000,000 USD/km	-	-	-		29 %
…	…	Resurfacing a 2-lane road	Primary	2*1	50,000 USD/km	-	-	-		5.0 %
Road improvement (from very poor to very good condition)										
Carruthers (2013)	Mediter.	Improvement 4-lane road	Motorway	2*2	350,000 USD/km	-	-	-		10 %
…	…	Ibid. 2-lane road	Primary	2*1	150,000 USD/km	-	-	-		10 %
…	…	Ibid. 1-lane road	Other	1*1	100,000 USD/km	-	-	-		10 %
Tecno Carretas[3]	Spain	Reference: motorway construction costs	Motorway	2*2	4,000,000 €/km	-	-	-		100%
…	…	Pothole repair costs (minimum estimate)	-	-	35,000 €/km	1.04	1.16	42,100 €/km		0.9%
…	…	Pothole repair costs (maximum estimate)	-	-	65,000 €/km	1.04	1.16	78,200 €/km		1.6%
Work categories World-Bank (ROCKS)										
Archondo-Callao (2000)	-	Reconstruction	-	-	220,287 USD/km	-	-	-		29 %[2]
	-	Strengthening	-	-	139,371 USD/km	-	-	-		19 %[2]
	-	Asphalt mix resurfacing	-	-	64,551 USD/km	-	-	-		8.6 %[2]
	-	Surface treatment resurfacing	-	-	25,090 USD/km	-	-	-		3.3 %[2]
	-	Gravel resurfacing	-	-	18,169 USD/km	-	-	-		2.4 %[2]
Rijkswaterstaat (2019)										
	Netherlands	Reference: Dutch motorway (30 m wide)	Motorway	2*2	268 €/m^2	0.942	0.681	172.2 €/m^2	689%	100%
	…	Major clean-up costs	…	-	20 €/m^2	…	…	12.8 €/m^2	51%	7.5%
	…	Replacement top layer asphalt	…	-	30 €/m^2	…	…	19.3 €/m^2	77%	11%
	…	Replacement top and deeper layers asphalt	…	-	90 €/m^2	…	…	57.8 €/m^2	231%	34%
	…	Sand replacement after subsidence of road foundation …	…	-	100 €/m^3	…	…	64.2 €/m^3	-	-

[3] Tecno Carreteras (2012, February 22). Sabemos cuánto nos cuesta tener de forma óptima las infraestructuras y servicios que garantizan nuestra seguridad vial? (latest accessed 23 December 2019).

...	... assume 1 meter elevated road	...	-	100 €/m²	...	...	64.2 €/m²	257%	37%

1) Relative to construction costs stated within the same source; 2) compared to development ‘New 2L Highway’; 3) Compared to ‘Dutch motorway 30 m-wide’

New damage curves: motorway curves (for OSM’s motorways and trunk roads)

Figure S3 Damage curves for motorways and trunks as a percentage of maximum damage (left) and in absolute terms for illustrative* combinations of damage curves and max damages of motorways (right)
*The selection is based on the assumption that the sophisticated accessories curves (C1 and C2) are best applicable to more expensive roads (the upper 75% of the max damage range); whereas the simple curves (C3 and C4) are best applicable to cheaper roads (the lower 25% of the max damage range). This assumption is also used for sampling the uncertainty space.

Table S9 Narratives supporting damage curves of motorways and trunks

Curve 1	Curve 2	Curve 3	Curve 4
Road with accessories (lighting, electronic traffic management systems, etc.)*		**Simple road without accessories**	
Low flow	**High flow**	**Low flow**	**High flow**
Little structural damage while the top of the embankment has not yet been reached [0-100 cm], but some damage to electric installations. When the embankment is overtopped [100-150 cm] the pavement needs a clean-up, minor asphalt repairs and replacement of some electronic signalling. When the water gets well above the pavement [150-250 cm], a larger share of the road accessories is damaged, and a major clean-up is required. With even higher water levels [250 – 600 cm], the maximum damage to road accessories is reached, and damage only slowly increases.	Before the water reaches the top of the embankment [0-100 cm] already some erosion and stability issues arise to the embankment caused by the high flow velocity. When the water starts overtopping the embankment [100-150 cm] the pavement needs to be resurfaced, and part of the electronic signalling needs to be replaced. With increasing water depths [150-250 cm], more and more of the road accessories are damaged, until the curve starts levelling off [250-600 cm].	Little structural damage while the top of the embankment has not yet been reached [0-100 cm]. When the embankment is overtopped [100-150 cm], a clean-up of the road is required. Well above the pavement [150-250 cm], road clean-up costs slowly increase up till depths where the water may carry larger objects damaging the road [250-600 cm], requiring a clean-up + minor resurfacing works.	The high flow velocity causes embankment erosion and stability issues before the water reaches the top of the embankment [0-100 cm]. When the water starts overtopping the embankment [100-150 cm], the pavement needs a clean-up and some resurfacing. When the water is well above the pavement [100-200 cm], road clean-up costs slowly increase up till full resurfacing costs (30% of construction costs). When the water gets even higher [200-600 cm], damage only slowly increases to the maximum damage of 35% of construction costs.

*Important assumption here: not all the extra costs for sophisticated roads can be attributed to electronic signalling devices. Some of the extra costs are structural and therefore flood-insensitive. Therefore, the maximum potential damage deviates less than the maximum construction costs, when comparing values for simple and sophisticated roads.

New damage curves: other curves (for OSM's primary, secondary, tertiary and other roads)

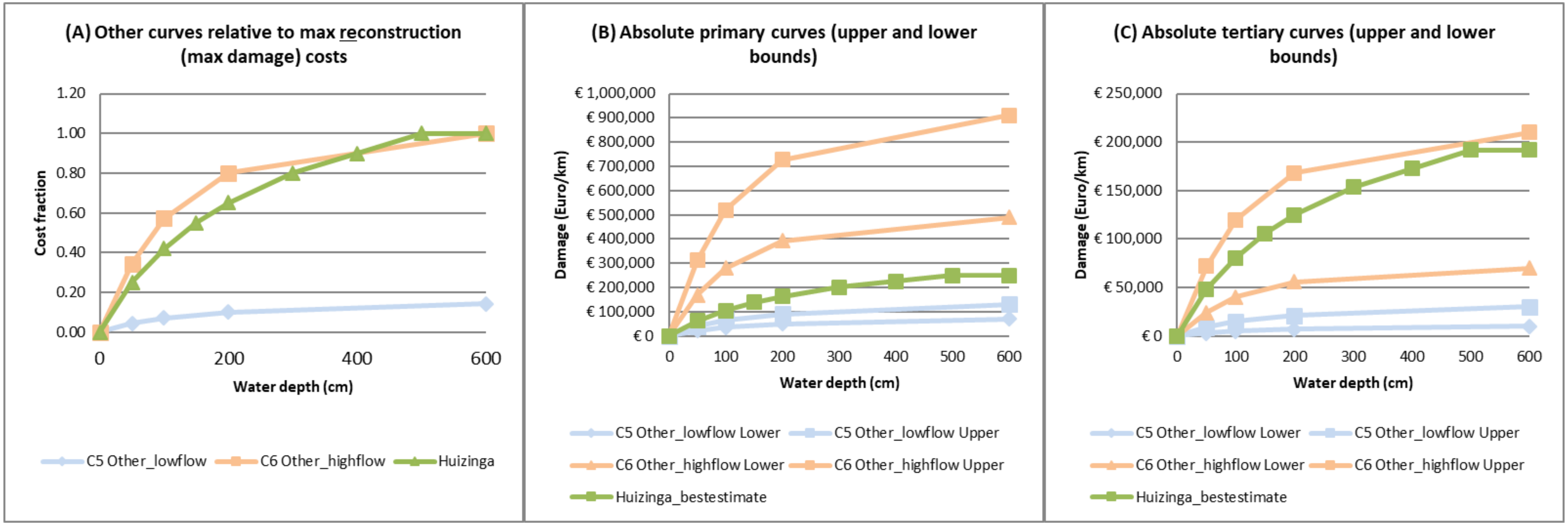


Figure S4 Damage curves for other road types, (A) as percentage of max reconstruction (max damage) costs, and in an absolute sense for (B) primary roads and (C) tertiary roads.

Table S10 Narratives supporting damage curves for primary, secondary, tertiary and other roads

Curve 5	Curve 6
Low flow	**High flow**
Under low flow conditions, the max damage is limited. With relatively shallow water depths [0-50 cm], the costs are in the order of minor clean-up costs (1.5% of construction costs). The flow velocity is too low to significantly harm the pavement. Small cracks in the pavement can wait till the next regular maintenance cycle, because the maintenance standards for these roads are not so high as for motorways and trunk roads. With increasing water levels, larger objects like trees maybe transported by the flow which may cause some additional damage to the roads as well as an increase in clean-up costs, which is in the order of a major road-clean-up (5% of construction costs).	Under high flow velocities, significant damage to the road pavement will occur. For shallow water depths [0-50 cm], already some damage to the pavement will occur, comparing to major clean-up costs with small asphalt repair works (11% of road construction costs). For larger water depths, also deeper asphalt layers may erode, and because larger objects are carried by the stream the costs may add up to 35%, which compares to complete road reconstruction.

Model implementation of new damage curves

In the model, the damage curves were implemented as being relative to the road construction costs (rather than a cost fraction relative to the maximum damage).

Step 1: minimum and maximum construction cost per road type

Table S11 Minimum and maximum construction costs per road type (price level: average of the former EU-28, in 2015-euro per km)

Road type	Default number of lanes	Minimum construction costs	Maximum construction costs
Motorway*	1*2	€1,750,000	€17,500,000
Trunk*	1*2	€1,250,000	€3,750,000
Primary	2*1	€1,000,000	€3,000,000
Secondary	2*1	€500,000	€1,500,000
Tertiary	2*1	€200,000	€600,000
Other	1*1	€100,000	€300,000

* In OpenStreetMap, a 2*2 motorway or trunk road is mapped as 2 individual unidirectional lines, so that the costs of a 2*2 motorway are 3.5 million – 35 million euro per km.

Step 2: correction factors for roads with more (or less) than the default number of lanes

Table S12 Factors for correcting constructing costs deviating from the default number of lanes per road type

Road type / # lanes	1	2	3	4	5	6
Motorway	0.75	1	1.25	1.5	1.75	2
Trunk	0.75	1	1.25	1.5	1.75	2
Primary	0.75	1	1.25	1.5	1.75	2
Secondary	0.75	1	1.25	1.5	1.75	2
Tertiary	0.75	1	1.5	1.75	2	2.25
Other	1	1.25	1.5	1.75	2	2.25

Step 3: curves relative to total construction costs

Table S13 Damage as fraction of the construction costs

Curve 1		Curve 2		Curve 3		Curve 4		Curve 5		Curve 6	
Motorways and trunk roads (with embankment)								Other roads (no embankment)			
Sophisticated accessories*				Simple roads*							
Low flow		High flow		Low flow		High flow		Low flow		High flow	
Depth (cm)	Damage (-)	Depth (cm)	Damage (-)	Depth (cm)	Damage (-)	Depth (cm)	Damage (-)	Depth (cm)	Damage (-)	Depth (cm)	Damage (-)
0	0	0	0	0	0	0	0	0	0	0	0
50	0.01	50	0.02	50	0.002	50	0.015	50	0.015	50	0.12
100	0.03	100	0.06	100	0.004	100	0.04	100	0.025	100	0.2
150	0.075	150	0.1	150	0.025	150	0.2	200	0.035	200	0.28
200	0.1	200	0.12	200	0.03	200	0.25	600	0.05	600	0.35
600	0.2	600	0.22	600	0.04	600	0.35				

* Curves for roads with sophisticated accessories should be combined with average to maximum construction cost estimates, curves for simple roads should be combined with minimum to average maximum construction cost estimates. For reasons of model performance, we first calculated all possible combinations, and then delete unlikely combinations of damage curve and construction cost estimates.

3. Results

3.2 Object-based damage using new damage curves

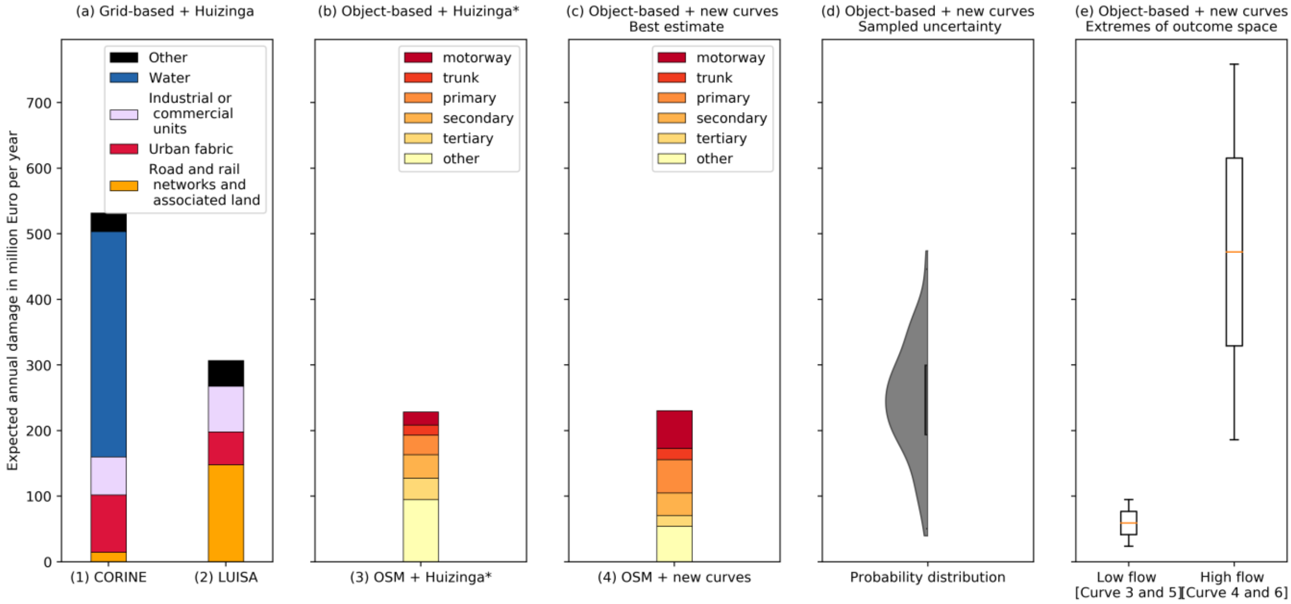
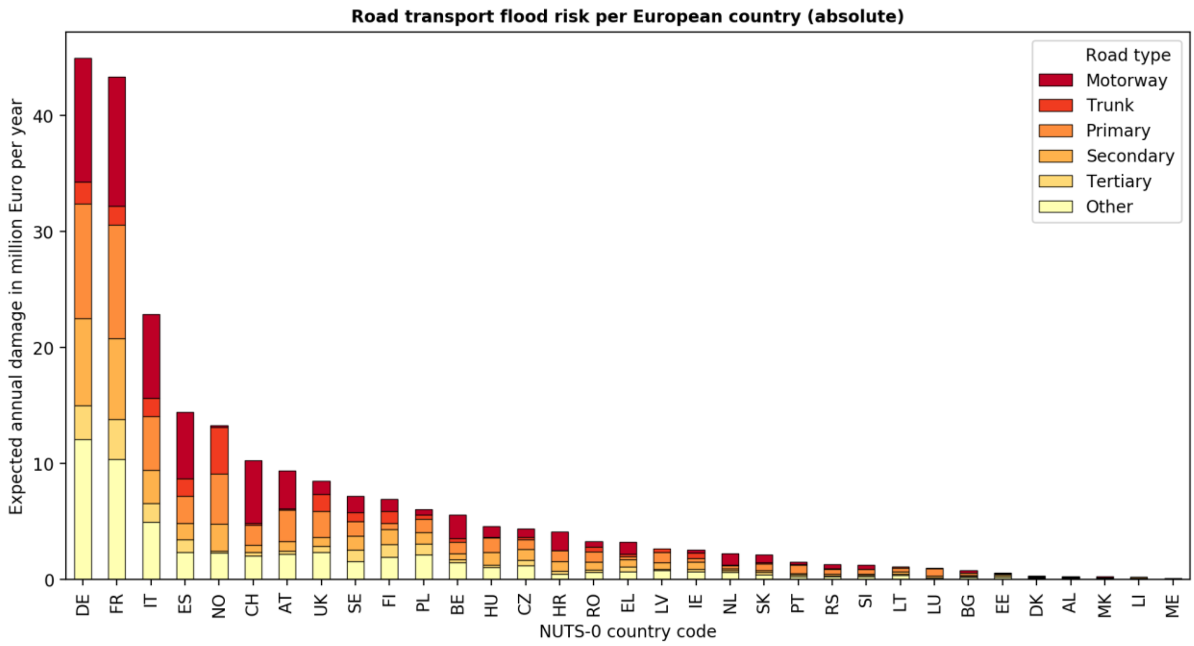


Figure S5 Figure is similar to Figure 4 of the main article, but with an extra panel (e).
Panel e shows the results of object-based approach with the new damage curves (similar as c), but indicates the extremes of the outcome space, showing the possible outcomes when the min, 1st quartile, average, 3rd quartile and max damage estimates (boxplots) for all assets are combined with the low-flow curves C3 and C4 (left) and high-flow curves C4 and C6 (right).



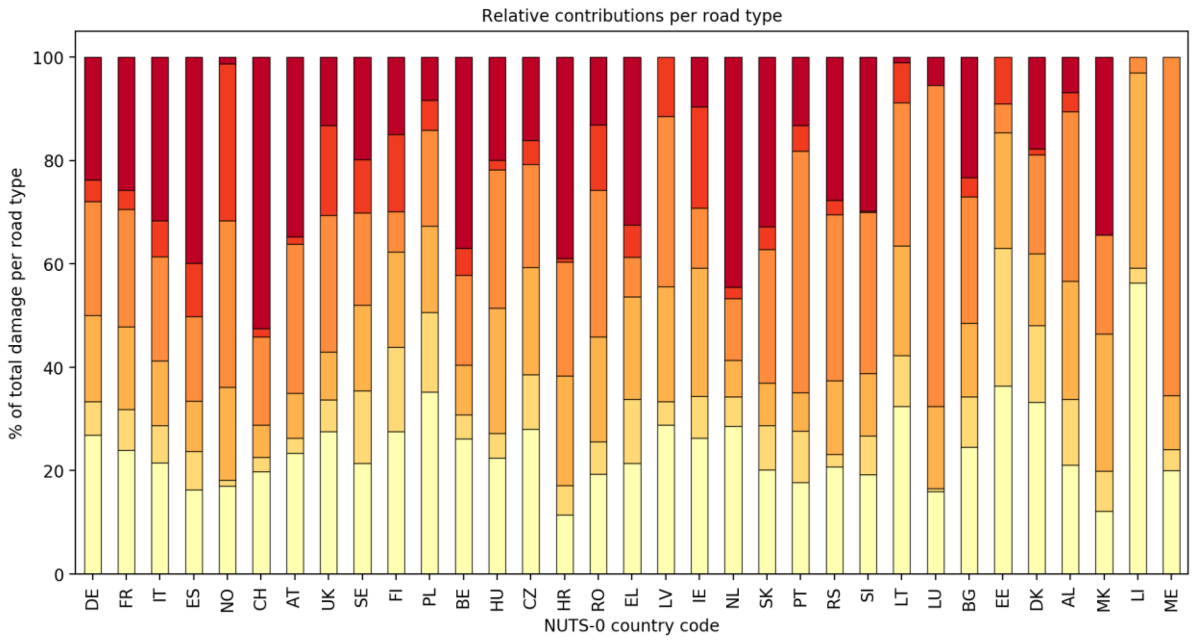


Figure S6 Flood risk per European country in the object-based approach with the new damage curves

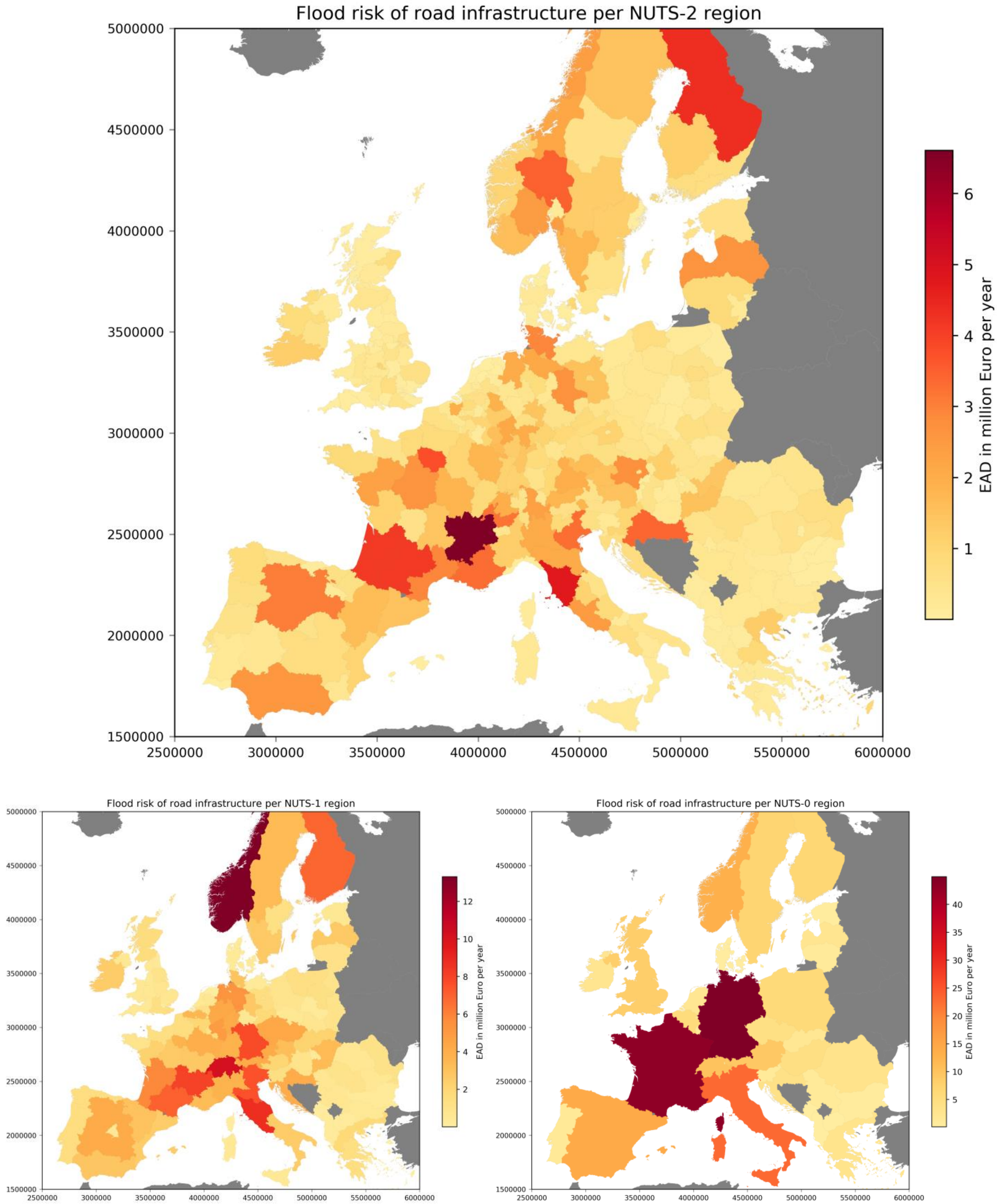


Figure S7 EAD to road infrastructure in the EU28 at different levels of aggregation using the NUTS-classification
All maps are shown in the EPSG:3035 – ETRS89 / LAEA Europe coordinate reference system.

Table S14 Top-20 NUTS-3 regions with the largest expected annual damage

NUTS-3 code	NUTS-3 name	EAD (million €/y)
CH012	Valais	2.62
FI1D7	Lappi	2.31
NO060	Trøndelag	2.19
FRK26	Rhône	2.08
NO021	Hedmark	2.06
ITI14	Firenze	1.83
ITI17	Pisa	1.69
DE600	Hamburg	1.69
ITI43	Roma	1.62
FRI12	Gironde	1.58
SE232	Västra Götalands län	1.52
NO022	Oppland	1.42
ES243	Zaragoza	1.40
FRJ23	Haute-Garonne	1.40
NO032	Buskerud	1.36
DEF0E	Steinburg	1.31
FR105	Hauts-de-Seine	1.29
AT126	Wiener Umland/Nordteil	1.24
FRK24	Isère	1.24
FI1D9	Pohjois-Pohjanmaa	1.23

Table S15 Top-20 NUTS-3 regions with the largest expected annual damage as share of the NUTS-3 GDP

NUTS-3 code	NUTS-3 name	EAD (million €/y)	GDP (million €/y)[4]	EAD/GDP (%)
HR032	Ličko-senjska županija	0.46	388	0.120
HR04A	Brodsko-posavska županija	0.50	896	0.056
HR04D	Karlovačka županija	0.41	979	0.042
HR04C	Vukovarsko-srijemska županija	0.42	1040	0.040
LV009	Zemgale	0.69	1884	0.037
FI1D7	Lappi	2.31	6348	0.036
DEF0E	Steinburg	1.31	4056	0.032
BG311	Видин	0.09	295	0.032
NO073	Finnmark	1.10	3695	0.030
HR04E	Sisačko-moslavačka županija	0.36	1238	0.029
LV008	Vidzeme	0.45	1590	0.028
AL013	Kukës	0.05	186	0.027
HU333	Csongrád	0.94	3460	0.027
SI031	Pomurska	0.37	1471	0.025
HR046	Međimurska županija	0.25	1011	0.025
DEF05	Dithmarschen	1.02	4081	0.026
NO021	Hedmark	2.06	8275	0.025
DEB1C	Cochem-Zell	0.43	1787	0.024
HU322	Jász-Nagykun-Szolnok	0.63	2721	0.023
DEE01	Dessau-Roßlau, Kreisfreie Stadt	0.54	2347	0.023

[4] Eurostat (2020). Gross domestic product (GDP) at current market prices by NUTS 3 regions. Retrieved from https://ec.europa.eu/eurostat at 2 March 2020.

Table S16 Top-20 NUTS-2 regions with the largest expected annual damage

NUTS-2 code	NUTS-2 name	EAD (million €/y)
FRK2	Rhône-Alpes	6.61
ITI1	Toscana	4.73
FI1D	Pohjois- ja Itä-Suomi	4.35
FRI1	Aquitaine	4.14
FRJ2	Midi-Pyrénées	4.13
FR10	Ile-de-France	3.79
NO02	Hedmark og Oppland	3.47
HR04	Kontinentalna Hrvatska	3.38
FRL0	Provence-Alpes-Côte d'Azur	3.33
ITH3	Veneto	3.30
CH01	Région lémanique	3.21
ES41	Castilla y León	3.06
DEF0	Schleswig-Holstein	2.93
FRJ1	Languedoc-Roussillon	2.93
AT12	Niederösterreich	2.72
DEE0	Sachsen-Anhalt	2.68
FRB0	Centre - Val de Loire	2.65
LV00	Latvija	2.64
ES61	Andalucía	2.53
ITI4	Lazio	2.46

Table S17 Data of the Deggendorf flood event, used for validating the damage estimates

Data	Type	Title	Source and credits
Rehabilitation costs Deggendorf Motorway: € 3,806,968.03	Grant agreement	A3/ A92, Sanierung Hochwasserschäden Autobahnkreuz Deggendorf	EU Solidarity Fund, data retrieved from Bayerisches Staatsministerium für Wohnen, Bau und Verkehr (19 March 2019)
Construction of a temporary sand barrier along the A3 motorway	Video	05.06.13 Hochwasser Dammbau auf der A3 DEG	https://www.youtube.com/watch?v=rPDrgbwvv1Q (latest accessed 29 August 2019) bushidofighter89 / Youtube
Milling of small asphalt strips at the overleaf Map showing the extent of the asphalt works Cleaning activities: logs, plastic bags, plastic containers, wooden pallets	Video	Aufräumarbeiten an der A3: Scheuer bedankt sich bei Helfern I pnp.de	https://www.youtube.com/watch?v=OPVtO-2XNIY (latest accessed 29 August 2019) Passauer Neue Presse / Youtube
Water depth and inundation extend	Video	Luftaufnahmen vom HOCHWASSER in DEGGENDORF und Umgebung	https://www.youtube.com/watch?v=NF60x1ALNHI (latest accessed 29 August 2019) Niederbayern TV / donauTV / Youtube
	Video	Hochwasser Deggendorf 2013 A3 A92 kurz vor Vollsperrung	https://www.youtube.com/watch?v=iXBwHnVceXg (latest accessed 1 October 2019)
Water depth and inundation extend	Photo	The swollen Danube river has flooded the motorways A3 and A92	https://media.gettyimages.com/photos/the-swollen-danube-river-has-flooded-the-motorways-a3-and-a92-and-picture-id170028902? (latest accessed 29 August 2019) Joerg Koch / Getty Images
Water depth at the A3 after the inundation (June 7, 2013): 50-100 cm (at inner lane, truck wheels are completely submerged, at the outer side of the road the water depth is larger) Temporary sand barrier A3 is overtopped and eroded Debris on the A3: gas tank, wood, round hay bale in plastic cover Sand bags on the A92 near the small depression. Sand and mud on the A92 after the event	5 Photo's	Event DEU: Flood Hit Germany: Danube and Inn	https://www.gettyimages.nl/fotos/autobahn-flood?events=170142879 (latest accessed 29 August 2019) Joerg Koch / Getty Images
Water depth at the A3 after the inundation (June 5, 2013)	Photo	Trucks stand on the flooded motorway A3 near the eastern Bavarian city of Deggendorf	https://stock.adobe.com/ee/editorial/trucks-stand-on-the-flooded-motorway-a3-near-the-eastern-bavarian-city-of-deggendorf/155930701 (latest accessed 29 August 2019) REUTERS / Wolfgang Rattay / stock.adobe.com
Water depth at the A3 after the inundation	Photo	The Autobahn A3 has been flooded by the Danube after the bursting of a dam in Deggendorf	https://previews.agefotostock.com/previewimage/medibigoff/7859334682d1f108f989b259d0064ab7/pah-40011758.jpg Armin Weigel / dpa / AGEFotostock
A92 is submerged at small depression	Photo	The A92 motorways stands submerged in the floodwater of the river	https://media.gettyimages.com/photos/the-a92-motorway-stands-submerged-in-the-floodwater-of-the-river-a-picture-id1042250004 Getty Images / Picture Alliance
Strips of replaced asphalt at the A3 Clearly, the road is not completely repaved (old repairs are still visible) Replaced strips of asphalt at the A3 (west of the junction) and on the junction. The strip replacements at the A3 east of the junction seemed to exist already in 2011	Satellite imagery	lat: 48.8150°, lon: 12.9527° lat: 48.8184°, lon: 12.9399°	Comparison of map (24 September 2014 with 8 July 2011) Maxar Technologies / Google Earth

4. Discussion

Table S18 Reported road repair and emergency costs from flooding of the Missouri River in Iowa, USA (Vennapusa et al., 2013)

County	Road name	Road repair activities	Road type	Lanes**	Length	Emergency unit costs*	Permanent unit costs*	Total unit costs*
					km	10^6 €/km	10^6 €/km	10^6 €/km
Motorways								
Monona	I-29N and I-29S between MP 105 and 110	Sand bags and pumps to avoid flooding	Motorway	2*2 + e	8.0	162,871	0	162,871
Monona	I-29 between MP 107 and 110	Emergency response and major cleanup	Motorway	2*2 + e	4.8	107,891	116,056	223,946
Fremont	I-29 from MP 0 to 1.8	Major repair	Motorway	2*2 + e	2.9	46,784	135,051	181,836
Multiple counties	I-29 from MP 0 to 71.6	Replacement of underground electric wiring and one damaged luminary	Motorway	2*2 + e	115.2	0	2,586	2,586
Fremont	I-29S from MP 1.8 to 10.1	Repair	Motorway	2*2 + e	13.4	33,677	88,117	121,794
Fremont	I-29S from MP 10.1 to 15.5	Repair	Motorway	2*2 + e	8.7	14,438	134,525	148,963
Fremont	I-29S MP 15.5 to 20	Repair	Motorway	2*2 + e	7.2	467	76,658	77,125
Fremont	I-29S between MP 20 and 25	Minor repair	Motorway	2*2 + e	8.0	0	53,754	53,754
Fremont	IA2W between MP 0 and 8	Major repair	Motorway	2*2 + e	12.9	319,763	68,683	388,446
Pottawattamie	I-29N between MP 43.6 and 46	Major cleanup	Motorway	2*2 + e	3.9	65,340	0	65,340
Pottawattamie	I-29S between MP 57 and 62	Major repair	Motorway	2*2 + e	8.0	110,559	174,827	285,386
Pottawattamie	I-29N between MP 62 to 66.4	Repair	Motorway	2*2 + e	7.1	9,147	308,815	317,962
Pottawattamie	I-29N between MP 66.4 and 71.6	Minor repair	Motorway	2*2 + e	8.4	7,900	134,278	142,178
Pottawattamie	I-680W between MP 0.0 to 3.1	Complete reconstruction	Motorway	2*2 + e	5.0	5,746,455	0	5,746,455
Pottawattamie	I-680E from MP 0.0 to 3.1	Cleanup	Motorway	2*2 + e	5.0	17,957	0	17,957
Other								
Harrison	US30W between MP 0 and 4	Minor repair	Primary	2*1	6.4	0	67,206	67,206
Harrison	US30E between MP 1 and 3	Sand bags to avoid flooding	Primary	2*1	3.2	1,344,535	0	1,344,535
Fremont	220th St. (J34) West from 195th Ave. (L31)	Repair	Secondary	2*1	0.9	60,802	0	60,802
Fremont	195th Ave. South from 230th St. to IA2	Major repair	Secondary	2*1	3.4	8,192	109,494	117,686
Fremont	Waubonsie Ave. (J10) South from east of 200th Ave. (L31)	Cleanup and minor repair	Secondary	2*1	3.1	11,091	0	11,091
Monona	IA175 between MP 0.0 to 0.7	Emergency response and major repair	Secondary	2*1	1.1	5,962,832	698,679	6,661,511
Fremont	310th St. (J64) from west of I-29 to 240th Ave.	Major repair	Tertiary	2	6.5	166,381	163,280	329,661

* Obtained by multiplication of original data with 1.609 mile/km; 1.29 Euro/USD (January 2012 exchange rate); and 1.039 (2015/2012 GDP growth correction)

** e = emergency lane

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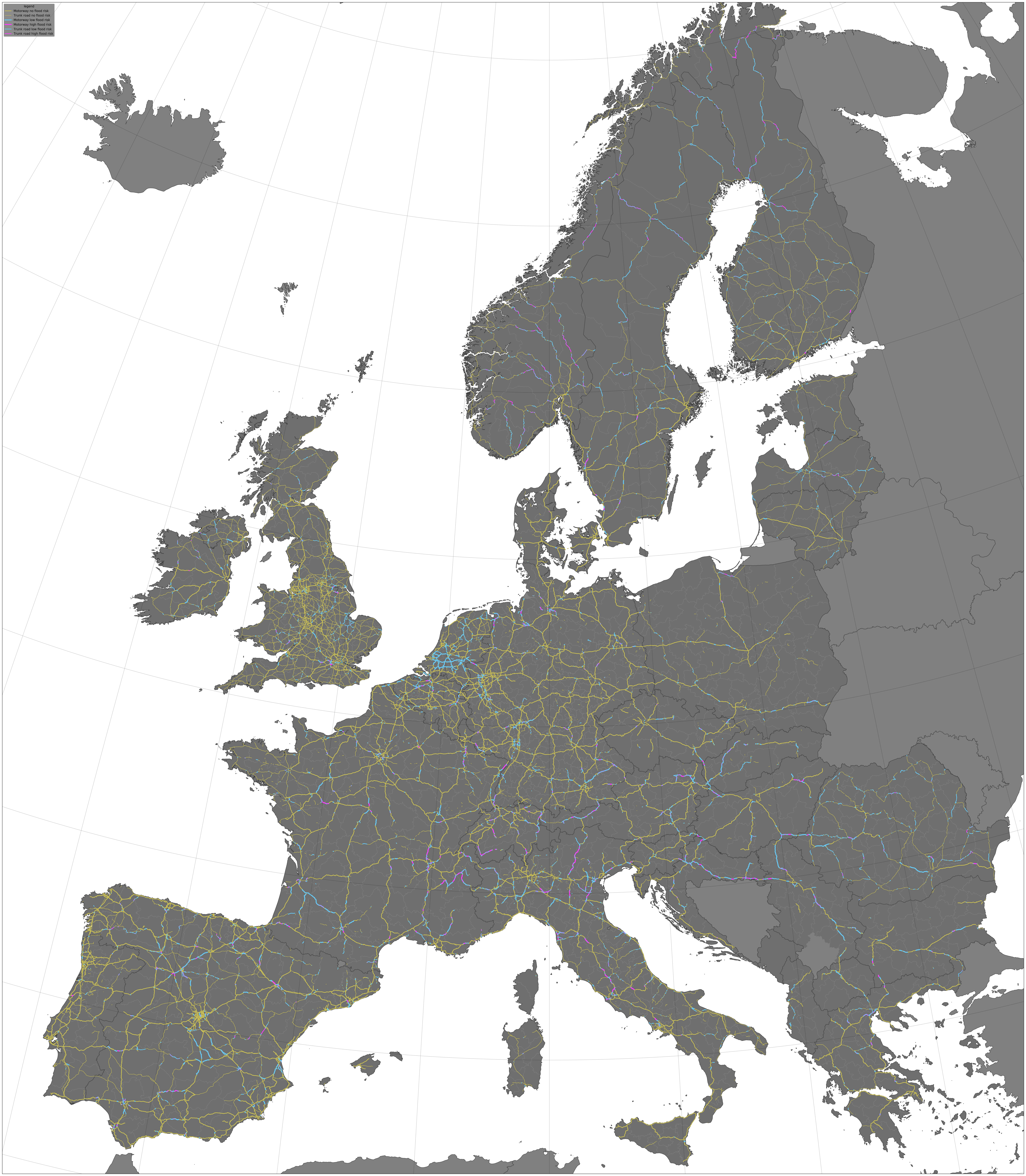
Figure S8 (next page): Flood risk of motorways and trunk roads of the European road network


legend
Motorway no flood risk
Trunk road no flood risk
Motorway low flood risk
Motorway high flood risk
Trunk road low flood risk
Trunk road high flood risk