

Detection of Flood Damage in Urban Residential Areas Using Object-Oriented UAV Image Analysis Coupled with Tree-Based Classifiers

Supplementary Materials

Table S1 Aggregation of land cover classes present in the OS MasterMap topographic layer used as an ancillary dataset in the automated procedure for detection of flood damage. Field “CLASS” corresponds to the main land cover classes used in the study; the remaining columns contain land cover features descriptors provided by the Ordnance Survey.

CLASS	Theme	Descriptive	Descript_1	Make	Key
Buildings	Buildings	Building		Manmade	Buildings_Building
	Buildings	Building	Archway	Manmade	Buildings_Building
	Buildings	Glasshouse		Manmade	Buildings_Glasshouse
Land	Land	General Surface		Manmade	Land_General Surface
	Land	General Surface		Natural	Land_General Surface
	Land	General Surface	Multi Surface	Multiple	Land_General Surface
	Land	General Surface	Step	Manmade	Land_General Surface
	Land	Landform	Slope	Manmade	Land_Landform
	Land	Natural Environment	Coniferous Trees	Natural	Land_Natural Environment
			Coniferous Trees,		
	Land	Natural Environment	Nonconiferous Trees	Natural	Land_Natural Environment
			Coniferous Trees,		
	Land	Natural Environment	Nonconiferous Trees, Scrub	Natural	Land_Natural Environment
	Land	Natural Environment	Nonconiferous Trees	Natural	Land_Natural Environment
	Land	Natural Environment	Nonconiferous Trees, Scrub	Natural	Land_Natural Environment
	Land	Natural Environment	Scrub	Natural	Land_Natural Environment
	Land	Natural Environment	Scrub, Coniferous Trees	Natural	Land_Natural Environment
	Land	Natural Environment	Scrub, Nonconiferous Trees	Natural	Land_Natural Environment
	Land	Unclassified		Unclassified	Land_Unclassified
		General Surface,			Land, Structures_General
	Land, Structures	Structure		Manmade	Surface, Structure
	Roads Tracks and Paths	Path		Manmade	Roads Tracks and Paths_Path
	Roads Tracks and Paths	Path	Step	Manmade	Roads Tracks and Paths_Path
	Roads Tracks and Paths, Structures	Path, Structure		Manmade	Roads Tracks and Paths, Structures_Path, Structure
	Roads Tracks and Paths, Structures	Structure, Path		Manmade	Roads Tracks and Paths, Structures_Structure, Path

CLASS	Theme	Descriptive	Descript_1	Make	Key
Land	Structures	Structure		Manmade	Structures_Structure
Road	Roads Tracks and Paths	Road or Track		Manmade	Roads Tracks and Paths_Road or Track
	Roads Tracks and Paths	Road or Track	Track	Natural	Roads Tracks and Paths_Road or Track
	Roads Tracks and Paths	Road or Track	Traffic Calming	Manmade	Roads Tracks and Paths_Road or Track
	Roads Tracks and Paths	Roadside		Manmade	Roads Tracks and Paths_Roadside
	Roads Tracks and Paths	Roadside		Natural	Roads Tracks and Paths_Roadside
	Roads Tracks and Paths, Structures	Road or Track, Structure		Manmade	Roads Tracks and Paths, Structures_Road or Track, Structure
	Roads Tracks and Paths, Structures	Roadside, Structure		Manmade	Roads Tracks and Paths, Structures_Roadside, Structure
	Roads Tracks and Paths, Structures	Roadside, Structure		Natural	Roads Tracks and Paths, Structures_Roadside, Structure
Water	Water	Inland Water		Natural	Water_Inland Water

Table S2 ANOVA analysis for selected descriptors of objects belonging to ancillary land cover classes used for refinement of buildings delineated by the topographic map. Significance levels are marked as follows for respective *p*-values: *p*-value < 0.001 ***, *p*-value < 0.01 **, *p*-value < 0.05 *, not significant 'ns'. GLCM—grey-level co-occurrence matrix, RGB—red, green, blue bands of the UAV image.

Asymmetry	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	ns			
White wall	***	***	***		
Heaps of debris	***	ns	ns	***	
Conservatory	***	***	***	***	***

Brightness	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	**	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	ns	***

Distance to buildings	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	***			
White wall	ns	**	***		
Heaps of debris	***	***	**	***	
Conservatory	***	*	***	***	***

GLCM contrast	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	*	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	***	***

Length/Width Ratio	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	ns			
White wall	***	***	***		
Heaps of debris	***	ns	ns	***	
Conservatory	***	***	***	***	***

Mode of maximum values in B	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	ns	***

Mode of maximum values in G	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	ns	***

Mode of maximum values in R	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	ns	***

Relative border to buildings	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	***	*			
White wall	***	***	**		
Heaps of debris	***	**	***	***	
Conservatory	***	ns	***	***	*

Relative border to land	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	*	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	***	***	***	***	***

Width	Roof	Dark land	Tiling	White wall	Heaps of debris
Dark land	***				
Tiling	*	***			
White wall	***	***	***		
Heaps of debris	***	***	***	***	
Conservatory	**	***	***	***	ns

Table S3 Building refinement procedure.

Step	Source class	Target class	Condition	No of cycles
1	Land	Buildings	Brightness > 80 AND border to buildings > 9 AND mode[max]R > 80 AND mode[max]R < 180 AND mode[max]G > 80 AND mode[max]G < 210 AND mode[max]B > 125 AND mode[max]B < 210	1
2	Land	Buildings	Brightness > 175 AND Relative border to buildings > 0.1 AND Width < 10 AND mode[max]R > 180 AND mode[max]G > 180 AND mode[max]B > 180	1
3	Land	Buildings	Relative border to buildings > 0.6	3
4	Land	Buildings	Brightness > 90 AND Brightness < 130 AND Border to buildings > 20 AND mode[max]R > 80 AND mode[max]R < 130 AND mode[max]G > 80 AND mode[max]G < 130 AND mode[max]B > 90 AND mode[max]B < 130	1
5	Land	Buildings	Relative border to buildings > 0.6	3
6	Land	White wall	Brightness > 160 AND Width < 10 AND Relative border to buildings > 0.1 AND mode[max]R > 170 AND mode[max]G > 170 AND mode[max]B > 170	3
7	Land	Buildings	Brightness > 190 AND Relative border to buildings > 0.1 AND Relative border to land < 0.8 AND mode[max]R > 190 AND mode[max]G > 190 AND mode[max]B > 190	Infinite
8	Land	Buildings	Brightness > 190 Border to buildings > 0 AND Relative border to land < 0.8 AND mode[max]R > 190 AND mode[max]G > 190 AND mode[max]B > 190	Infinite
9	Land	Buildings	Brightness > 100 AND Border to buildings > 0 AND Relative border to buildings > 0.3 AND Relative border to land < 0.8 AND mode[max]R > 130 AND mode[max]G > 140	3

Step	Source class	Target class	Condition	No of cycles
10	Land	Buildings	AND mode[max]B > 150	Infinite
			Brightness > 200	
			AND Distance to buildings > =5	
			AND Distance to buildings < =10	
			AND mode[max]R > 190	
			AND mode[max]G > 190	
11	Land	Buildings	AND mode[max]B > 190	3
			Brightness > 120	
			AND Relative border to buildings > 0.1	
			AND mode[max]R > 120	
			AND mode[max]G > 120	
			AND mode[max]B > 120	
12	Land	Buildings	AND mode[max]B > =mode[max]R	3
			Relative border to buildings > =0.75	
13	Buildings	Land	Brightness > 190	Infinite
			AND Relative border to land > 0.4	
			AND Asymmetry < 0.75	
			AND Length/Width <2.5	
			AND GLCM Contrast (all. Directions) < 4000	
			AND mode[max]R > 190	
			AND mode[max]G > 190	
			AND mode[max]B > 190	

Table S4 Variable importance determined by the RF model trained with a sample that excluded vehicles. Letters R, G, and B refer to the red, green and blue bands of the Unmanned Aerial Vehicle (UAV) image. Variable type refers to its capacity to describe spectral (Sl) or geometric (Gc) properties of an image object. The definitions are based on the eCognition Developer 10.0 Reference Book.

ID	Feature	Type	Definition	Importance
1	Area	Gc	The number of pixels forming an image object	0.0535
2	Width	Gc	Width of an object calculates as the number of pixels within the object divided by the length to width ratio of the object	0.0501
3	Mean of inner border R	Sl	Mean layer intensity value of red band pixels belonging to the inner border of an object	0.0414
4	Length of longest edge (polygon)	Gc	Length of the longest edge of polygons vectorised from image objects	0.0294
5	Border contrast R	Sl	Mean value of the red band pixel edge contrasts of all edges of an object	0.0256
6	Border length	Gc	Sum of edges of the image object located within inner and outer borders	0.0241
7	Border contrast B	Sl	Mean value of the blue band pixel edge contrasts of all edges of an object	0.0228
8	mode[Maximum](R)	Sl	The largest pixel value occurring most often within an object in the red band	0.0225
9	Length	Gc	Length of an object calculated as a square root of the product of the number of pixels and length to width ratio	0.0223
10	Perimeter (polygon)	Gc	The sum of lengths of all edges of the polygon vectorised from the image object	0.0213
11	Average length of edges (polygon)	Gc	The average length of edges of the polygon vectorised from the image object	0.0211
12	Border contrast G	Sl	Mean value of the green band pixel edge contrasts of all edges of an object	0.0206
13	StdDev of length of edges (polygon)	Gc	Measure of deviation of the lengths of edges of the polygon vectorised from an image object from their mean value	0.0195
14	Ratio R	Sl	Contribution of the red image band to the total brightness of the object	0.0192
15	mode[Median](R)	Sl	The median value of the most frequently occurring red band pixel values within an object	0.0188

ID	Feature	Type	Definition	Importance
16	Ratio G	SI	Contribution of the green image band to the total brightness of the object	0.0186
17	Mean of inner border B	SI	Mean layer intensity value of blue band pixels belonging to the inner border of an object	0.0177
18	Density	Gc	The number of pixels of an image object divided by its approximated radius, with a square shape having the highest density	0.0164
19	Max. diff.	SI	The ratio of the maximum value of the difference between intensity of image bands and brightness within an image object	0.0163
20	Mean of inner border G	SI	Mean layer intensity value of green band pixels belonging to the inner border of an object	0.0156
21	Edge Contrast of neighbor pixels (Prototype) R (3)	SI	The contrast between intensity of red band pixels belonging to an object and its surrounding area 3 pixels wide calculated as the difference between the mean intensity value of the brighter and darker pixels, where the latter are determined by values larger or smaller than the mean intensity value of the object	0.0151
22	Contrast to neighbor pixels R (3)	SI	The mean difference in contrast compared to a surrounding area 3 pixels in size in the red band	0.0143
23	mode[Maximum](G)	SI	The largest pixel value occurring most often within an object in the green band	0.0141
24	mode[Maximum](B)	SI	The largest pixel value occurring most often within an object in the blue band	0.0140
25	Edge Contrast of neighbor pixels (Prototype) B (3)	SI	The contrast between intensity of blue band pixels belonging to an object and its surrounding area 3 pixels wide calculated as the difference between the mean intensity value of the brighter and darker pixels, where the latter are determined by values larger or smaller than the mean intensity value of the object	0.0140
26	mode[Median](G)	SI	The median value of the most frequently occurring pixel values within an object in the green band	0.0139
27	mode[Minimum](R)	SI	The smallest pixel value occurring most often within an object in the red band.	0.0138

ID	Feature	Type	Definition	Importance
28	mode[Median](B)	SI	The median value of the most frequently occurring pixel values within an object in the blue band.	0.0137
29	mode[Minimum](G)	SI	The smallest pixel value occurring most often within an object in the green band.	0.0136
30	Mean of outer border R	SI	Mean layer intensity value of the red band pixels belonging to the outer border of an object.	0.0136
31	Edge Contrast of neighbor pixels (Prototype) G (3)	SI	The contrast between intensity of green band pixels belonging to an object and its surrounding area 3 pixels wide calculated as the difference between the mean intensity value of the brighter and darker pixels, where the latter are determined by values larger or smaller than the mean intensity value of the object.	0.0133
32	Ratio B	SI	Contribution of the blue image band to the total brightness of the object.	0.0133
33	Contrast to neighbor pixels G (3)	SI	The mean difference in contrast compared to a surrounding area 3 pixels in size in the green band.	0.0132
34	Contrast to neighbor pixels B (3)	SI	The mean difference in contrast compared to a surrounding area 3 pixels in size in the blue band.	0.0132
35	Shape index	Gc	A measure of shape complexity of and object, calculates as the border length divided by four times the square root of the object's area.	0.0131
36	Mean of outer border G	SI	Mean layer intensity value of the green band pixels belonging to the outer border of an object.	0.0131
37	Skewness R	SI	The asymmetry of distribution of object's pixel values in the red band.	0.0131
38	Number of edges (polygon)	Gc	The number of edges of a polygon formed by vectorization of an object.	0.0130
39	Border index	Gc	Measures irregularity of an object. Similar to the Shape index except that it uses a rectangular approximation of an object instead of a square.	0.0130
40	StdDev. to neighbor pixels G (3)	SI	Standard deviation of green band pixel values in the surrounding area 3 pixels away from the object and not belonging to the object.	0.0130
41	StdDev. to neighbor pixels B (3)	SI	Standard deviation of blue band pixel values in the surrounding area 3 pixels away from the object and not belonging to the object.	0.0130

ID	Feature	Type	Definition	Importance
42	Mean of outer border B	Sl	Mean layer intensity value of the blue band pixels belonging to the outer border of an object.	0.0130
43	mode[Minimum](B)	Sl	The smallest pixel value occurring most often within an object in the blue band.	0.0130
44	Compactness (polygon)	Gc	The ratio of the area of a polygon representing a vectorized object to the area of a circle with the same perimeter.	0.0129
45	Brightness	Sl	The value of intensity of pixels contained in an object for all image bands.	0.0128
46	StdDev. to neighbor pixels R (3)	Sl	Standard deviation of red band pixel values in the surrounding area 3 pixels away from the object and not belonging to the object.	0.0128
47	Skewness B	Sl	The asymmetry of distribution of object's pixel values in the blue band.	0.0128
48	Skewness G	Sl	The asymmetry of distribution of object's pixel values in the green band.	0.0128
49	Number of inner objects (polygon)	Gc	The number of inner polygons within a polygon representing a vectorized object.	0.0128
50	Length/Width	Gc	Length to width ratio returned as the smallest value of the ratio of the eigenvalues of the covariance matrix, with the larger value being the numerator or the width to length ratio of the bounding box of an object.	0.0128
51	Rel. border to image border	Gc	The relative border length an object shares with the scene border.	0.0128
52	Asymmetry	Gc	Comparison between an image object with an approximated ellipse around the given object, based on the variance in the x and y directions.	0.0128
53	Compactness	Gc	The product of the length and width of an objects divided by the number of pixels within the object.	0.0128
54	Elliptic fit	Gc	A measure of how well an object fits into an ellipse with the same area as the object.	0.0128
55	Radius of largest enclosed ellipse	Gc	The ratio between the radius of an ellipse of an area equal to the area of the object and an ellipse scaled down until it fully fits inside the object.	0.0128
56	Radius of smallest enclosing ellipse	Gc	The ratio between the radius of an ellipse of an area equal to the area of	0.0128

ID	Feature	Type	Definition	Importance
57	Rectangular fit	Gc	the object and an ellipse scaled up until it fully encompasses the object. The ratio of the area outside and inside the rectangle with the same area as an object, i.e., the same width and length as the object.	0.0128
58	Roundness	Gc	A measure of how similar an object is to an ellipse calculated as the difference between the radius of the largest enclosed ellipse and the smallest enclosing ellipse.	0.0128

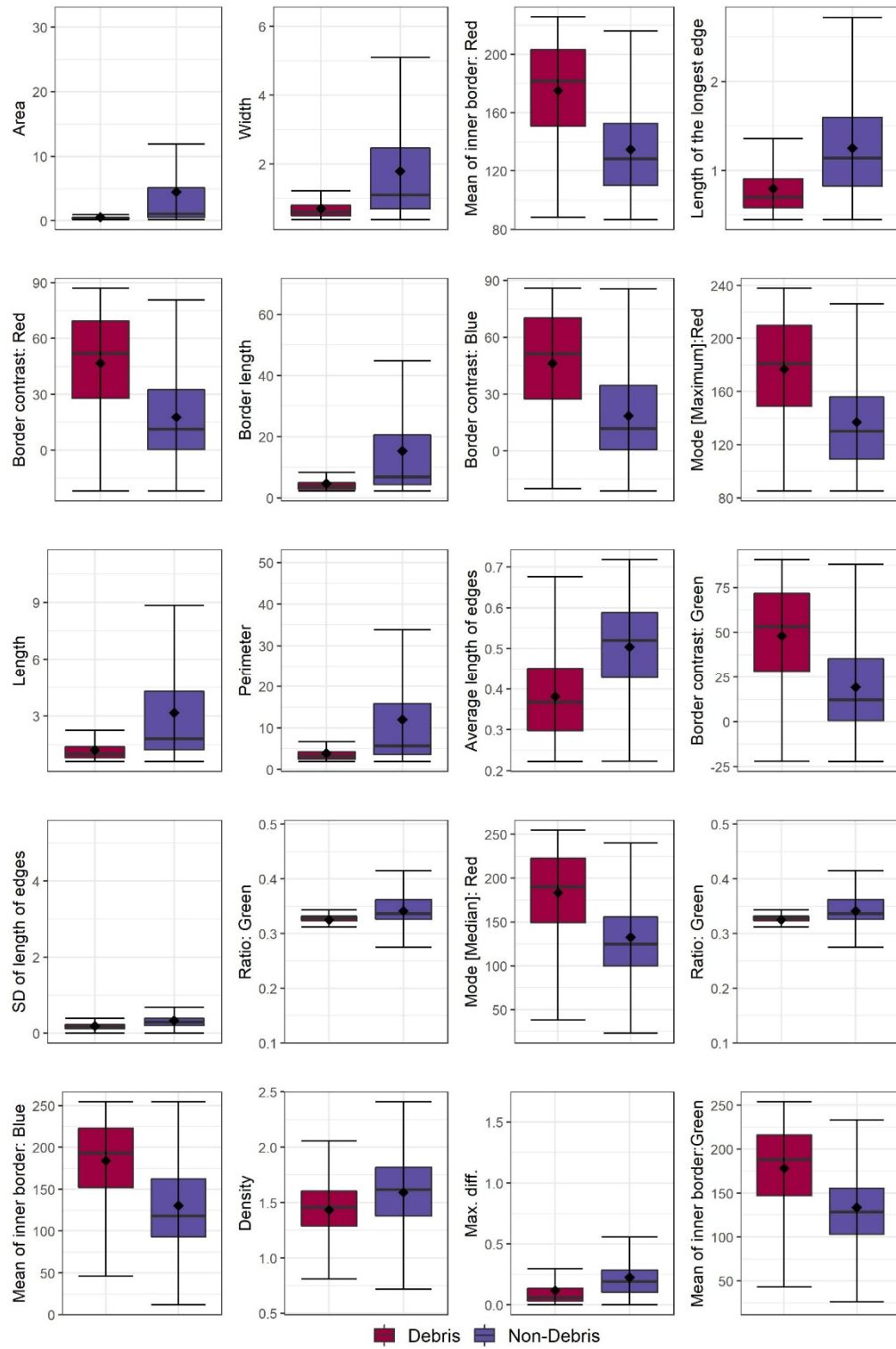


Figure S1 Distribution of the top 20 predictor variables of debris and non-debris features identified by the Random Forest model training dataset including vehicles.