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A practical method to assess risks from large wood debris accumulations at bridge piers

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Abstract

Accumulations of large woody debris can worsen scour at a bridge pier and thereby lead to structural damage. Accumulations can also increase the flood risk in adjacent areas. These consequences can cause disruption to local communities and even pose a risk to human life. Current methodologies acknowledge the existence of these effects of debris but do not provide a practical method, usable by engineers and practitioners, to assess the potential for debris accumulation at a bridge structure based on readily available data. This work aims to address this practical need by proposing a methodology based on direct and indirect observations. Using this methodology, a desk-based analysis can be performed to assess whether a bridge is prone to the formation of debris accumulations. Direct observations may include information from inspection reports, satellite imagery and tree removal works, while indirect observations may use information related to the geographical location of the bridge such as on other structures that share the watercourse or the presence of forested areas in its proximity. This methodology has been applied to local authority-owned bridges in Devon, UK. Results show that a large number of the structures (100 out of over 3000 bridges) are liable to debris accumulations. Direct observations served as primary evidence for over 80% of the bridges liable to debris accumulations. For many cases, direct observations existed to corroborate indirect observations suggesting that indirect observations can also be relied upon. The proposed methodology has also been applied to the prioritisation of bridge inspections for scour assessment. Results showed that many of the bridges prone to debris accumulations would need to be prioritised for scour inspections over other bridges in the aftermath of floods due to their significantly higher risk to scour in the presence of debris.

Keywords: Debris accumulations , Scour , Bridge collapse , Flooding , River management

1. Introduction

Woody debris, also known as drift wood, large wood or in-stream wood in literature (e.g. *Bradley et al.*, 2005) is generally defined as logs having length greater than 1 m and diameter of at least 10 cm (e.g. *Gippel et al.*, 1996). Woody debris that are transported by rivers can accumulate at bridge piers, particularly during flood events (*Braudrick et al., 1*997, *Diehl,* 1997; *Lagasse et al.,* 2010). The resulting obstruction to the river flow causes an increase of the upstream water level (often referred to as afflux) that significantly increases the flood risk in adjacent areas. The accumulation also exacerbates local scour (*Lagasse et al., 2*010, *Pagliara and Carnacina* 2011), which could expose the pier foundations and eventually result in bridge failure. In the United States, almost one third of bridge failures are attributed to excessive scour induced by debris accumulation (*Diehl*, 1997), whilst in the UK, debris has been cited as the main or secondary reason (*Benn*, 2013) for 20 out of 69 railway bridge failures. Furthermore, the costs of debris-related flood damage is considered to be in the order of millions of US dollars (*Lassettre and Kondolf,* 2012) and events with transport of wood are known to have devastating effects on areas adjacent to bridges by blocking bridge openings and causing severe flooding (*Steeb et al.*, 2017). In recent years, substantial research has hence focused on the shape of these accumulations, the maximum size they could attain (*Panici and de Almeida* 2018, 2020a,b), the backwater effects that are caused by such accumulations (*Schalko et al.*, 2018), the forces they apply to the bridge pier (*Parola et al., 2*000, *Wu et al., 2*014, *Panici and de Almeida*, 2018) and the increased scour that accumulated debris could yield (e.g. *Melville and Dongol,* 1992, *Lagasse et al., 2*010, *Pagliara and Carnacina*, 2011; *Ebrahimi et al., 2*018).

The knowledge created by recent research into debris accumulations and their consequences enhances our understanding of debris effects on the flow field around bridge piers (*Pagliara and Carnacina*, 2013), and therefore has applications for bridge management (e.g. evaluating risk of damage to bridges, assessing flood risk) as well as the potential to create economical and societal benefits (*Pregnolato*, 2019) by reducing the direct and indirect costs (*Arrighi et al.*, 2019) incurred by bridge operators and society (e.g. avoid road closures, enable rapid post-flood recovery). The realisation of these benefits are however dependent on the ability to assess whether a bridge is liable to large wood accumulations. Some guidance on this aspect is available from previous research that have predominantly been based on field observations or laboratory experiments as outlined below.

Few studies have examined the initiation of debris transport from bank erosion; for example, *Lagasse et al.* (2010) showed that the probability of debris recruitment by bank erosion depends on the distance of a tree from the channel bank. Others have also investigated the initiation of debris transport from large wood already within the channel system (*Braudrick et al.*, 1997, *Crosato et al.*, 2013; *Ruiz-Villanueva et al.*, 2016). However, despite past research, the flow conditions that are necessary to initiate debris transport from bank erosion are still not adequately understood (*Bradley et al.*, 2005). Other studies have developed methodologies to estimate the probability of debris anchoring at obstacles (*Bocchiola et al.*, 2008) including piers (*De Cicco et al.*, 2016, *Gschnitzer et al.*, 2017, *Schalko et al.*, 2019) and bridge decks (*Schmocker and Hager*, 2011), and correlated the anchoring probability to flow velocity and debris length (*Schalko et al.*, 2019). However, these studies are based on assumptions (e.g. continuous supply of debris elements or burst release of debris pieces, use of single logs), which are difficult to justify in practice. The reliability of the estimations are also dependent on several bridge-specific factors (*Comiti et al.*, 2016) (e.g. approaching flow characteristics, debris transport processes, frequency of transported debris) that may not be understood thoroughly or expensive to measure in the field. On the contrary, it has been observed that debris are typically recruited by the same type of processes (e.g. 73% of debris input in rivers is believed to be originated by bank erosion and mass-wasting (*Diehl*, 1997, *Lyn et al.*, 2003, *Lagasse et al.*, 2010)); furthermore, debris elements tend to follow preferential paths (*Diehl* 1997; *Bradley et al.*, 2005) and accumulations are likely to occur again at similar flow conditions (*Lyn et al.*, 2007), although reasons for this well-marked transport have yet to be investigated (*Lagasse et al.*, 2010). Therefore, despite existing methodologies providing important insights and shedding light on the key factors that contribute to formation of debris accumulations at bridge piers, there is currently no systematic approach to identify bridge piers liable to debris accumulations in real-world situations (*Comiti et al.*, 2016).

The aim of this paper is to bridge the gap between existing knowledge on debris accumulations and its hydrodynamic effects, and the practical management of flooding-related risks to bridges prone to debris accumulations. It proposes to do this through the development of a robust and pragmatic approach for assessing the potential for debris accumulation formation at a bridge pier. The methodology, that is based on direct and indirect observations, has been applied to bridge structures in Devon, UK. Results from this research are expected to expand existing practitioner guidance for flood risk and scour assessment to include efficient debris management and mitigation techniques. This research will also be relevant to researchers and engineers working on the flood resilience of structures and its impact on other human activities (e.g. transport, connectivity, social and economical impacts).

2. Methodology

A key factor in the development of the methodology for assessing the potential for debris accumulation was ensuring that it relied on data that is readily available with bridge operators or on other data sources (e.g. satellite images) that can be easily accessed without incurring significant costs. Our investigations into the data that operators hold and can gain access to on debris accumulations revealed that the data can be grouped into two categories. The first category is *direct* evidence, which is essentially documented evidence of debris accumulations at the bridge under assessment. The second category is indirect evidence, i.e. factors that may be suggestive of likelihood of the formation of debris accumulations. The two types of evidence and their potential sources are discussed in further detail below.

2.1. *Direct evidence*

Past research has shown that debris elements tend to follow a self-consistent trajectory for similar flow events and form periodic accumulations (*Diehl,* 1997, *Lyn et al., 2*007). Therefore, direct evidence can indicate that

1. the river is able to recruit and transport debris elements;
2. the bridge structure is likely to entrap debris elements and favour the formation of debris accumulations; and
3. debris accumulations may occur again as and when similar environmental conditions arise.

We thus propose that data that can constitute direct evidence may be classified into three categories as defined below.

2.1.1. *Bridge inspection reports*

The most trivial form of direct evidence is records of visual observation of debris accumulation during a site visit by a bridge engineer. However, site visits are usually only carried out as part of routine mandatory inspections. For example, in the United Kingdom, General Inspections (GI) are carried out every two years and involve simple visual inspection of key-elements of the structure. Principal Inspections (PI) are conducted every 6 years and provide a more thorough analysis in which every part of the bridge is examined visually from within touching distance. Inspectors may note accumulated trees during the inspection process and this may be recorded within the inspection reports which are typically stored within the asset management system of the bridge operator. The chances of accumulations being noted during an inspection is however limited by the frequency of PIs and GIs and due to the seasonal nature of debris accumulations.

2.1.2. *Photographic imagery*

Evidence of woody debris from photographic (or video) material constitutes a direct and effective way to establish the extent of the accumulations and the time at which these occurred. We therefore propose to use satellite or aero imagery. The photographic resolution of modern satellite images, the frequency at which these images are collected (which can be short as a few months) and the availability of these images to the wider public make their consultation a quick and cost-effective solution for debris monitoring and assessment. An example of the use of this type of imagery is shown in figure 1. The figure shows a large accumulation at a railway bridge on the River Tagliamento in Italy (flow direction downwards). The semi-circular planar shape of the accumulation, the individual large trees forming the debris jam and the location upstream of the bridge are also clearly visible in the image. As such if images are taken at regular time intervals - e.g. photos available through Google Earth, these can serve as reliable sources of information on debris accumulation.

Figure 1: Satellite image of a large wood accumulation at a railway bridge crossing the River Tagliamento in Latisana, Friuli, Italy. The planar shape of the accumulation is typical of other large wood accumulations observed for this study. Source: Google Earth. Image: Landsat/Copernicus.

2.1.3. *Tree removal and repair work logs*

Tree removal works are typically carried out by bridge owners once woody debris have been entrapped at a structure and have been reported by bridge inspectors or members of the public. This kind of evidence may provide useful information such as quantity of debris removed (or cost incurred for tree removal), frequency of occurrence, and location and date details. Table 1 shows an example of three bridges under management of the Devon County Council (England) for which tree removal works occurred in the years 2013-2018. This table shows the total cost (in GBP) for each structure, the total number of occurrences, and the highest cost for a single event (in GBP).

Table 1: Cost for tree removal works and number of occurrences for three bridges in Devon (UK) in the period 2013-2018

Bridge name	Total cost (£)	Highest cost of single event (£)	Number of removal works
Old Rothern (river Torridge)	47,686.00	29,476.00	4
Gunnislake (river Tamar)	4,799.59	1,880.00	3
Staverton (river Dart)	3,983.72	2,718.00	3

2.2. *Indirect evidence*

Indirect evidence refers to those observations that are suggestive of woody debris accumulations at a bridge despite there being no direct evidence to support the same. Three types of indirect evidence are explained in the following paragraphs, mostly based on data on the geography of the region near the bridge under assessment or data on the bridges in its vicinity.

2.2.1. *Debris data on upstream bridges*

We propose that a bridge may be prone to debris accumulations if it is located downstream of other structures that have a history of debris accumulation. Since woody debris accumulated at a bridge are recruited in upstream areas, debris elements seen at structures upstream could be transported downstream and accumulate at the bridge under consideration. There is however a caveat: attention needs to be given to factors that may impede the transport of debris to downstream bridges. For example, in-line structures such as gates or dams would prevent floating debris to be conveyed, thus significantly reducing any risk of blockage.

2.2.2. Debris data on downstream bridges

A second form of indirect evidence can be the converse of the one mentioned above. Bridges that are located upstream of others with debris history could also be considered liable to large wood accumulations. The assumption is that the debris observed at downstream bridges may be recruited from sources further upstream of the bridge in consideration. This assumption is less robust than the previous case in section 2.2.1 and hence only downstream bridges in close proximity to the bridge in consideration need to be included for this type of assessment. Also, the analysis needs to examine whether there are potential sources for debris recruitment between the bridge in consideration and downstream bridges.

2.2.3. Forested area location

The last form of indirect evidence can be through an analysis of the area upstream of a bridge. Presence of heavily forested floodplains or river banks suggests that, with high flows, trees could be mobilised by bank erosion, depending on catchment areas and river bank characteristics (*Comiti et al., 2*016, *Steeb et al., 2*017). This has been indicated as the process responsible for the large majority of floating debris in rivers (*Diehl*, 1997, *Lagasse et al., 2*010). Thus, while this assumption may be considered the weakest among the three indirect approaches proposed, it is still based on the physical processes responsible for large wood transport in rivers. Other factors related to channel stability and vegetation can also be considered. If the channel shows signs of instability, likelihood of tree recruitment and transport is high. Known presence of abundant in-stream wood deposited along the river is also another factor that can be taken into account. On the other hand, when the debris length is greater than the channel width, downstream transport is unlikely as the debris is likely to be stuck between the river banks (*Chang and Shen*, 1979, *Wallerstein et al., 1*997, *Diehl,* 1997, *Bradley et al., 2*005). Debris accumulations can thus be expected mostly in channels of intermediate or large widths (*Diehl*, 1997, *Bradley et al., 2*005), e.g. in lowland rivers with width larger than the log length.

2.3. Method development

The direct and indirect evidence that were defined above need to be examined in a systematic manner for practical applications. Figure 2 shows the flow chart of a process designed for this purpose. The flowchart allows for an orderly examination of direct and indirect evidence based on the methodologies that have been outlined in the previous sections. As a result, the likelihood of a debris accumulation occurring at a bridge pier could be noted as highly likely - in the presence of direct evidence, likely - in the presence of indirect evidence, and unlikely if there is no evidence.

The data collected for the assessment of each bridge and that will be shown in section 3 was based on the geographic coordinates of the bridge (approximate) centre and graphically combined using a GIS mapping software.

2.3.1. Priority of bridges

Large bridge operators (e.g. local councils) lack resources for conducting detailed inspection programmes or scour risk assessments on all the bridges in their possession. They require an optimal management approach, i.e. to promptly identify structures at higher risk of damage so as to prioritise

1. detailed assessments of bridges;
2. inspections during a flood and post-event; and
3. interventions to protect structures from flooding damage.

The management approach may also have a further impact on issues unrelated to the structural performance of the bridge such as preparedness for increased flooding in the adjacent areas and disruption to mobility or community severance.

The procedure proposed in this paper amends the principles outlined in the *Design Manual for Roads and Bridges BD 97/12* (2012), the guidance in use in the UK for assessing scour risk for road bridges. A key-step in the assessment procedure is determination of a priority factor P_f , which is an index defining the vulnerability of a bridge based on several factors such as its history of scour and the type of foundation of its pier. Here we propose to include debris as a further factor affecting the vulnerability of the bridge to scour. The amended equation for P_f can be expressed as:

$$P_f = H \cdot F \cdot M \cdot Tr \cdot V \cdot D \qquad (1)$$

H is a factor dependent on the scour history of a bridge and varies between 1 and 1.5; *M* is a factor determined according to the bridge's foundation material and varies between 0.5 and 1; *F* is a factor dependent on the type of foundations and varies between 0.75 and 1; *Tr* is a factor dependent on the type of river and varies between 1 and 1.5; *V* is a factor dependent on the type of road supported by the bridge and varies between 0.7 and 1; and *D* is the newly introduced factor that depends on the likelihood of debris accumulations occurring at the bridge. The underlining principle of the priority factor P_f is simple; the higher the priority factor is for a bridge, the more vulnerable (and, hence, the more at risk) it is to scour. Note that while some individual factors in Equation (1) may have a non-linear relationship with scour - for example *D* and *H* may non-linearly effect scour when there are debris accumulations (*Pagliara and Carnacina*, 2011), the influence of factors such as *V* and *H* cannot be characterised exactly. Consequently the values chosen for the factors do not reflect strictly the scientific relationship; they are instead chosen to ensure that all parameters have a similar weight in the computation of P_f *Design Manual for Roads and Bridges BD 97/12* (2012). Keeping to the same principles, the value assigned for the debris factor *D* is as follows:

- $D = 1.3$ for bridges with history of debris accumulations (i.e. direct evidence indicating that accumulations of debris are highly likely to occur)
- $D = 1.1$ for structures where there is no history of accumulation but there is a likelihood of it happening (i.e. structures for which there is no direct evidence but there is indirect evidence)
- $D = 1$ for structures for which debris accumulations are unlikely

The levels of likelihood are determined through the flow chart in Figure 2. The values of 1.3 and 1.1 are indicative of the increase in bridge vulnerability to scour due to the likelihood of debris accumulations. The values have been chosen on the basis of engineering judgement to be consistent with those values given to other factors in equation (1).

2.3.2. Scour assessment

The methodology in Figure 2 can be used in combination with a scour assessment approach. The scour risk assessment of UK highway bridges is carried out following the approach in the *Design Manual for Roads and Bridges BD 97/12* (2012) and is used to identify structures at risk of scour damage and hence in potential need of protection measures. The approach computes the ratio between total scour depth (D_T) and pier foundation depth (D_F) - namely the relative scour depth D_T / D_F. It will then assign a rating between 1 and 5, depending on its position within a chart that relates D_T / D_F and P_f. A rating of 1 represents a structure at immediate risk to scour and 5 a structure at no risk to scour. In this study, the scour assessment includes the scour effects of debris by having an additional factor ϕ_D, defined by *Ebrahimi et al.* (2020) using experimental results (*Melville and Dongol*, 1992, *Lagasse et al.*, 2010, *Ebrahimi et al.*, 2018), within the equation recommended by *CIRIA C742* (2015) for local scour that is used by leading bridge owners in the UK. The equation is defined as:

$$\frac{D_L}{W_P} = \phi_{ps}\phi_{\alpha}\phi_{v}\phi_{h}\phi_{D} \tag{2}$$

where D_L is the maximum depth of scour at the pier, W_P is the width of the pier, ϕ_{ps} is a factor depending on the pier shape, ϕ_{α} is a factor depending on the angle of attack of the flow to the pier, ϕ_v is a factor depending on the approach velocity, ϕ_h is a factor depending on the depth of flow and ϕ_D is the previously defined debris factor that depends on the size of debris accumulations. This scour assessment approach is the most appropriate for the type of study reported in this work (e.g. the type of pier used, the equations employed), but other approaches from existing literature can be used in other contexts. The size of the debris accumulations has been computed using the regression function by *Panici and de Almeida* (2018).

Figure 2: Proposed flow chart for assessing debris accumulation potential at bridge piers.

3. Results

In this section, the methodology outlined in section 2 is applied to real-world bridges and the results from such applications are analysed.

3.1. Likelihood of debris accumulations

In order to analyse the likelihood of debris accumulations at bridges, the process in figure 2 has been applied to the bridge portfolio of the Devon County Council, UK. The Council owns over 3200 bridges, the highest number in the United Kingdom for a local council; the majority of these structures are masonry bridges.

In total, 100 bridges were identified to be liable to debris accumulations. The locations of these bridges are shown in figure 3. In the figure, blue circles indicate bridges identified through direct observations and red circles represent those identified through indirect observations. Table 2 summarises the number of bridges affected by debris accumulations per each river and the type of observation that supported the assessment.

Figure 3: Map showing locations of bridges operated by Devon County Council, UK that were identified as prone to debris accumulations on the basis of direct evidence (blue triangles) and indirect evidence (red circles).

Figure 4 shows a histogram of the occurrence of the various types of evidence indicating the potential for debris accumulation at bridges. For each type of evidence, the figure shows two bars. One represents the number of bridges that were assessed as prone to debris accumulation by using that type of evidence. The second represents the percentage of assessed bridges for which the particular type of evidence was the only type of evidence available. The histogram shows that direct evidence is available for a large number of bridges. In fact, of the 100 bridges found liable to debris accumulations, 29% were identified by direct evidence from inspection reports; 14% of bridges were assessed by using satellite/aero imagery; 41% were identified using tree removal work reports. Thus, using the flowchart in figure 2 these three types of direct evidence together account for 84% of the total number of bridges identified as likely to accumulate woody debris. Indirect evidence on the basis of debris history of downstream structures was available for 8% of the bridges. The remaining 8% of the bridges were assessed using the two other types of indirect evidence - i.e. 5% of bridges using data on upstream structures and 3% of bridges due to being downstream of forested areas. Furthermore, Figure 4 illustrates that only a small portion (14%) of bridges had a single type of evidence; in the large majority of cases, two or more types of evidence were available.

Table 2: The number of bridges that have a particular type of evidence of debris accumulation for a given river in Devon. A bridge may have multiple kinds of observations.

	Number of observations for type of evidence					
River	Inspection reports	Satellite imagery and photos	Tree removal	Downstream structures	Upstream structures	Forested areas upstream
Avon	2	0	5	3	2	5
Dart	3	1	3	3	1	5

Exe	3	4	8	9	3	10
Otter	1	0	2	2	0	2
Tamar	1	2	3	2	0	2
Tavy	2	0	5	3	2	3
Taw	2	4	5	9	4	9
Teign	2	0	6	5	1	8
Torridge	5	7	10	11	7	13
Yarty	0	0	4	2	1	4
Others	8	5	20	11	5	21
Total	29	23	71	60	26	82

Figure 4: Histogram of the types of evidence available for bridges in Devon (UK) assessed as prone to debris accumulation; dark grey bars show the percentage of bridges for which a certain type of evidence facilitated assessment, and light grey bars show the percentage of bridges for which no other form of evidence was available.

3.2. Practical applications

The methodology outlined in 2.3.1 for prioritising bridges has been applied to structures within Devon County Council's portfolio and based on the results shown in the section 3.1. The priority factor for these bridges has been evaluated both with and without debris factor *D*. Table 3 lists the 20 bridges assessed to have the highest P_f values amongst the whole bridge stock when using Equation 1, i.e. considering debris effects. This table also shows the P_f values for the same bridges when evaluated without considering debris effects, i.e with $D = 1$ in Equation 1. It also notes the change in priority ranking resulting from the inclusion of debris effects within P_f. It can be observed from the table that the top two bridges (namely, Steps and Newnham) did not change due to the inclusion of debris effects within P_f. On the other hand, the Mole bridge, which originally had the same value for P_f as Steps and Newnham, dropped down 13 positions to the 16th position due to the bridge not being likely to suffer from debris accumulations. Also, several bridges that were further down the list had moved up 24 positions due to the inclusion of the factor *D*. Devon County Council are using the priority ranking of bridges in table 3 to determine the frequency of general inspections, and notably are increasing inspections in winter time when flooding is prevalent. On the other hand, Table 4 shows the priority that would be obtained by changing the debris factor *D* for direct observations and compares the change in ranking with table 3.

Table 3: Bridges operated by the Devon County Council prioritised according to the Priority factor P_f. The number within brackets indicates the change in ranking due to the inclusion of

debris effects in the calculation of P_f .

Priority rank	Bridge name	Priority factor P_f (no debris)	Debris factor	Priority factor P_f (with debris)
1 (+1)	Newnham	1.56	1.3	2.028
2 (+2)	Steps	1.44	1.3	1.872
3 (+24)	Hatch	1.26	1.3	1.638
3 (+24)	Lifton	1.26	1.3	1.638
3 (+24)	Puslinch	1.26	1.3	1.638
3 (+24)	Crocombe	1.26	1.3	1.638
3 (+24)	Taw	1.26	1.3	1.638
3 (+24)	Staverton	1.26	1.3	1.638
3 (+24)	Loddiswell	1.26	1.3	1.638
3 (+24)	New Mill	1.26	1.3	1.638
3 (+24)	Fordton	1.26	1.3	1.638
3 (+24)	Beaford	1.26	1.3	1.638
3 (+24)	Weare Gifford	1.26	1.3	1.638
14 (-13)	Bedford	1.62	1	1.62
15 (-10)	Stoke Canon	1.44	1.1	1.584
16 (-13)	Mole	1.56	1	1.56
17 (-5)	Brayford	1.365	1.1	1.502
17 (-5)	Black Torrington	1.365	1.1	1.502
19 (-13)	Weycroft	1.44	1	1.44
19 (-13)	Buckland	1.44	1	1.44

Table 4: Priority ranking of bridges outlined in Table 3 for different values of D chosen when there is direct evidence of debris accumulations. Numbers in brackets indicate the increase or decrease in priority ranking compared to Table 3 with D=1.3.

Bridge name	D=1.2	D=1.4	D=1.5
Newnham	1.872 (0)	2.184 (0)	2.34 (0)
Steps	1.728 (0)	2.016 (0)	2.16 (0)
Hatch	1.512 (-1)	1.764 (0)	1.89 (0)
Lifton	1.512 (-1)	1.764 (0)	1.89 (0)
Puslinch	1.512 (-1)	1.764 (0)	1.89 (0)
Crocombe	1.512 (-1)	1.764 (0)	1.89 (0)
Taw	1.512 (-1)	1.764 (0)	1.89 (0)

Staverton	1.512 (-1)	1.764 (0)	1.89 (0)
Loddiswell	1.512 (-1)	1.764 (0)	1.89 (0)
New Mill	1.512 (-1)	1.764 (0)	1.89 (0)
Fordton	1.512 (-1)	1.764 (0)	1.89 (0)
Beaford	1.512 (-1)	1.764 (0)	1.89 (0)
Weare Gifford	1.512 (-1)	1.764 (0)	1.89 (0)
Bedford	1.62 (+11)	1.62 (0)	1.62 (0)
Stoke Canon	1.584 (0)	1.584 (0)	1.584 (-5)
Mole	1.56 (0)	1.56 (0)	1.56 (-8)
Brayford	1.365 (0)	1.365 (-5)	1.365 (-8)
Black Torrington	1.365 (0)	1.365 (-5)	1.365 (-8)
Weycroft	1.44 (0)	1.44 (-8)	1.44 (-14)
Buckland	1.44 (0)	1.44 (-8)	1.44 (-14)

To further show the importance of including debris in bridge management practice, we completed the scour risk assessment of two bridges in Devon according to the methodology shown in section 2.3.2. We use two multi-span masonry bridges, with sharp-nose piers, namely Newnham bridge on the River Taw and Steps bridge on the River Teign, both in Devon, to illustrate the impact of the proposed methodology for assessing debris accumulation potential in the context of scour risk assessment. These two bridges are known to have a history of debris accumulations (through tree removal work reports and past inspections), and are thus assessed as liable to debris accumulations with the debris factor $D = 1.3$. Furthermore, Newnham and Steps bridges were first and second, respectively, in the list of priority bridges, as shown in table 3. The scour risk rating that is then evaluated is shown in figure 5. The figure shows the risk rating computed with (round markers) and without (square markers) consideration of scour effects of debris accumulations. The consideration of scour effects of debris increases the risk rating by one level for each structure.

Figure 5: Scour risk rating computed using *Design Manual for Roads and Bridges BD 97/12* (2012) for Newnham bridge and Steps bridge in Devon, UK. The solid lines define the boundaries between different rankings, whilst the numbers define the region of the graph for each risk rating assigned to the structure.

4. Discussion

This section discusses the robustness of the proposed methodology as well as its potential applications. It also examines the pros and cons of relying on direct and indirect evidence on the formation of debris accumulations.

Previous studies have used physical modelling to define probability of blockage at bridges (e.g. *Schmocker and Hager*, 2011, *Schalko et al., 2*019) and concluded that blockage probability is related to approach flow, wood characteristics, pier characteristics. Despite providing a valuable method, many other variables, not considered in these studies, need to be also accounted for reliability (*Comiti et al., 2*016, *De Cicco et al., 2*018); this may hinder the applicability of these methods to estimate the potential for debris blockage in practice. In the present approach, we assumed that *i)* the physical processes that originated previous accumulations will repeat under similar circumstances (*Diehl*, 1997, *Bradley et al., 2*005, *Lyn et al., 2*007, *Lagasse et al., 2*010); and *ii)* debris accumulations are possible when the physical processes causing these obstructions (e.g. wood recruitment and transport) are observed. Thus, our methodology is a simplified version compared to other experimental studies, but proposes a robust approach which has less dependence on variables that are difficult to quantify in the field while still being based on the physical processes that are responsible for debris accumulations. Furthermore, this method has been tested for practical applications in real-world cases (i.e. the bridge stock in Devon) and in the next sections further applications are discussed.

4.1. Direct Observations

Direct observations are observed to support a reliable approach to assess the potential for debris accumulation at a bridge structure. In particular, satellite or aero imagery enables tracking of debris accumulations in time, and can show how accumulations grow and are removed (either by the flow or for bridge maintenance) over time. For example, a bridge on the River Skagit (WA, USA) - shown in the supplementary material figure 1, shows such tracking between 2007 and 2018 for four different years. It can be noted that the accumulations are formed almost periodically and that they change dynamically over time. Other satellite photos in between the period 2007-2018 display the bridge cleared from debris, potentially confirming field (*Lyn et al.*, 2007) and laboratory (*Panici and de Almeida*, 2018) observations of debris self-removal.

For medium to small size rivers, this type of imagery may not be appropriate for the assessment. For example, vegetation growth on the surrounding of the river banks, low resolution photos, the bridge’s own shadow, and other factors could impede a clear view and thereby prevent a correct assessment of debris accumulation potential. Thus, satellite and aerial photos are typically more suited for medium to large rivers. To this end, we extended the application of this type of methodology to the two main (and widest) rivers in Italy - Po and Tiber (shown in supplementary figure 2), and compared results with bridges in Devon. It was observed that a large number (up to 70% of the total) of bridges crossing the two main Italian rivers were blocked by woody debris, especially in urban areas (e.g. the River Po in Turin or the River Tiber in the area nearby Perugia and in Rome) where bridge openings are generally smaller. On the other hand, in Devon, observations by satellite or aero imagery were available only for a small portion of the total number of assets. In fact, satellite images revealed debris accumulations in the widest stretches of the three largest rivers in Devon - from Table 2 River Torridge (7 bridges out of 13), River Taw (4 out of 14) and River Exe (4 out of 17), whilst no such observations were available for other rivers despite the extensive availability of other types of evidence (e.g. tree removal works). For example, no satellite or aero images could be provided for the bridges on the River Teign, but up to 10 bridges were identified liable to debris accumulations through other direct and indirect evidence. As a result, the history of tree removal and repair work becomes pivotal for structures crossing smaller water courses, which is the large majority of water streams in countries like the UK.

Photographic material and satellite imagery also allows to establish when accumulations consisted of a single log, two or more logs (but not forming a large accumulation), a large single pier accumulation, and a complete span blockage accumulation. Supplementary material table 1 summarises these observations for rivers in Devon and River Po and River Tiber where data was available (e.g. from satellite imagery or from inspection photos). The large majority of observations is constituted by single pier large accumulations, consistently with past field studies (*Diehl*, 1997, *Lagasse et al.*, 2010). This would indicate that typical applications (e.g. scour assessment) might be treated as single pier accumulations, unless other evidence would be suggestive of the contrary (e.g. bridges with short spans compared to the width of the expected accumulation).

4.2. Indirect Observations

Indirect methods have a much higher uncertainty than direct approaches, since many factors may prevent debris elements to accumulate at a bridge pier. Therefore indirect methods require a more thorough analysis of the river stretch that is being considered, including potential trapping structures (e.g. dams, gates, mills, retention works); factors that may inhibit debris transport (e.g. non-forested lowlands) may also need to be considered. For example, on the River Tiber there is a stretch of the river in which bridges were not observed to trap woody debris, despite many other structures upstream and downstream having a long history of accumulations. A careful examination of the river stretch showed that these river areas were located downstream of large dams, which prevented the transport of woody debris. However, in the case of the River Po, which is almost completely on lowlands and without any dams to block the river flow, a much larger rate of bridges were found to be suffering from debris accumulations.

Indirect methods are also more time consuming and more prone to inaccuracies than direct methods. In this study, they were the sole mode of assessment for a small portion (16%) of the bridges identified at risk. 75% of the bridges that had indirect evidence to support the formation of woody debris accumulations, also had direct evidence; this would suggest that using indirect evidence can be a suitable tool to determine the potential for debris accumulation formations.

4.3. Vulnerability and Scour Risk Assessment

The priority ranking of the bridges relies on the values chosen for the factor D in Equation 1. To assess the influence of the factor D on the priority ranking process, the priority rankings of the bridges originally considered in Table 3 are investigated for various values of D. Table 4 shows the change (increase or decrease) in the priority ranking of these bridges when the value of D in the presence of direct evidence is increased to 1.2, 1.4 and 1.5. These values are all within the range used by *Design Manual for Roads and Bridges BD 97/12* (2012) for other factors (e.g. $1 \leq H \leq 1.5$ and $1 \leq Tr \leq 1.5$). The value of D for indirect evidence is however kept at 1.1.

Table 4 shows that the changes to the priority ranking are minimal for $D = 1.2$ and $D =$ 1.4. For D=1.2, only Bedford bridge would significantly increase its priority rank, whilst with D=1.4 other bridges not listed in table 3 will have higher priority than bridges such as Black Torrington and Weycroft. D=1.5 would demote many bridges with no risk of debris accumulations from the list and lead to potentially underestimation of the vulnerability of these structures. On the other hand, without the use of D, debris-prone structures might have been neglected or given secondary importance for inspections and mitigation measures.

Overall, consideration of the scour effects of debris can have a significant impact on the scour risk rating of bridges. The risk rating for the two structures investigated in this paper jumped by a level, i.e. from 3 to 2 for Newnham bridge and from 4 to 3 for Steps bridge. Since debris accumulations are a key factor in more than one third of UK and USA bridge failures (*Diehl*, 1997, *Benn*, 2013), the reliable, early detection of at high-risk bridges using a method as proposed in this paper can be pivotal to prevent and mitigate catastrophic consequences to bridge structures as well as threat to human life and economic losses. For example, results from this research are already being employed by Devon County Council and Highways England in the UK for bridge inspections, mitigation measures, scour assessments, and river management measures.

5. Conclusions

This paper proposes a pragmatic approach to take into account the risks due to woody debris accumulations at bridges for practical bridge management. The approach relies on a methodology to identify bridges liable to debris accumulations. This methodology is based on readily available data that constitute two different types of evidence of debris accumulation - namely, direct and indirect evidence. Direct evidence is clear, documented evidence of historical debris accumulations at the bridge site and may be from inspection reports, photos from aerial or satellite imagery or tree removal works. Indirect evidence (e.g. bridges with accumulated debris upstream or downstream of a structure, location of the bridge downstream of large forested banks or floodplains) suggests that debris accumulations are likely to form even though there is no documented history of such accumulations at the bridge site. The approach has been applied to the bridge stock of the Devon County Council and to bridges across a few rivers outside of the UK.

The main conclusions from this study are as follows:

- The vast majority of bridges found liable to debris accumulations had a combination of direct and indirect observations. Most bridges (84%) were identified through direct evidence, whilst identification through indirect methods were limited to 16% of the total number of bridges liable to debris accumulations.
- Direct evidence in the form of satellite imagery is available primarily for bridge structures across medium to large size rivers. For example, a large number of bridges across the rivers Po and Tiber in Italy were subject to large debris accumulations whilst similar evidence was not available for the bridges across rivers in Devon.
- Debris increased the scour vulnerability of affected bridges. Many structures that were assessed liable to debris accumulations required a higher priority ranking and therefore necessitate amendment of inspection plans.
- The inclusion of the scour effects of debris in scour risk assessment led to a significant increase in the overall scour risk rating of structures affected by debris accumulations; the higher risk rating is suggestive of the need for interventions that enhance scour protection or mitigation.

In conclusion, the methodology proposed in this paper showed that assessing bridges liable to debris accumulations can be performed with readily available data and low-cost resources. Benefits can be immediate to bridge operators and public communities alike, and this approach paves the way to further developments for studies on debris mitigation measures, management and resilience. Further research should be focused on developing a fine-tuned priority factor P_f that will take into account the non-linearities among factors, especially when related to debris. The application of the methodology highlighted how applications to real-world cases (e.g. scour risk) revealed bridge structures that can be liable to higher levels of risk. This would pave the way for engineering solutions to existing bridges as well as when planning new bridges in order to mitigate or reduce the risks from debris; for example, the inclusion of scour protections around bridge piers, systems to trap debris elements in the upstream areas, policies and plans for management of wood in rivers to reduce the wood load, measures for stable log-jam formation in channels away from structures.

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Credit Author Statement

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Slobodan Djordjević: Supervision
Kevin Dentith: Resources

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 1: Cost for tree removal works and number of occurrences for three bridges in Devon (UK) in the period 2013-2018

Bridge name	Total cost (£)	Highest cost of single event (£)	Number of removal works
Old Rothern (river Torridge)	47,686.00	29,476.00	4
Gunnislake (river Tamar)	4,799.59	1,880.00	3
Staverton (river Dart)	3,983.72	2,718.00	3

Table 2: The number of bridges that have a particular type of evidence of debris accumulation for a given river in Devon. A bridge may have multiple kinds of observations.

	Number of observations for type of evidence					
River	Inspection reports	Satellite imagery and photos	Tree removal	Downstream structures	Upstream structures	Forested areas upstream
Avon	2	0	5	3	2	5
Dart	3	1	3	3	1	5
Exe	3	4	8	9	3	10
Otter	1	0	2	2	0	2
Tamar	1	2	3	2	0	2
Tavy	2	0	5	3	2	3
Taw	2	4	5	9	4	9
Teign	2	0	6	5	1	8
Torridge	5	7	10	11	7	13
Yarty	0	0	4	2	1	4
Others	8	5	20	11	5	21
Total	29	23	71	60	26	82

Table 3: Bridges operated by the Devon County Council prioritised according to the Priority factor P_f. The number within brackets indicates the change in ranking due to the inclusion of debris effects in the calculation of P_f.

Priority rank	Bridge name	Priority factor P_f (no debris)	Debris factor	Priority factor P_f (no debris)
1 (+1)	Newnham	1.56	1.3	2.028
2 (+2)	Steps	1.44	1.3	1.872
3 (+24)	Hatch	1.26	1.3	1.638
3 (+24)	Lifton	1.26	1.3	1.638
3 (+24)	Puslinch	1.26	1.3	1.638
3 (+24)	Crocombe	1.26	1.3	1.638
3 (+24)	Taw	1.26	1.3	1.638
3 (+24)	Staverton	1.26	1.3	1.638
3 (+24)	Loddiswell	1.26	1.3	1.638
3 (+24)	New Mill	1.26	1.3	1.638
3 (+24)	Fordton	1.26	1.3	1.638
3 (+24)	Beaford	1.26	1.3	1.638
3 (+24)	Weare Gifford	1.26	1.3	1.638
14 (-13)	Bedford	1.62	1	1.62
15 (-10)	Stoke Canon	1.44	1.1	1.584
16 (-13)	Mole	1.56	1	1.56
17 (-5)	Brayford	1.365	1.1	1.502
17 (-5)	Black Torrington	1.365	1.1	1.502
19 (-13)	Weycroft	1.44	1	1.44
19 (-13)	Buckland	1.44	1	1.44

Table 4: Priority ranking of bridges outlined in Table 3 for different values of *D* chosen when there is direct evidence of debris accumulations. Numbers in brackets indicate the increase or decrease in priority ranking compared to Table 3 with *D*=1.3.

Bridge name	*D*=1.2	*D*=1.4	*D*=1.5
Newnham	1.872 (0)	2.184 (0)	2.34 (0)
Steps	1.728 (0)	2.016 (0)	2.16 (0)
Hatch	1.512 (-1)	1.764 (0)	1.89 (0)
Lifton	1.512 (-1)	1.764 (0)	1.89 (0)
Puslinch	1.512 (-1)	1.764 (0)	1.89 (0)
Crocombe	1.512 (-1)	1.764 (0)	1.89 (0)
Taw	1.512 (-1)	1.764 (0)	1.89 (0)
Staverton	1.512 (-1)	1.764 (0)	1.89 (0)
Loddiswell	1.512 (-1)	1.764 (0)	1.89 (0)
New Mill	1.512 (-1)	1.764 (0)	1.89 (0)
Fordton	1.512 (-1)	1.764 (0)	1.89 (0)
Beaford	1.512 (-1)	1.764 (0)	1.89 (0)
Weare Gifford	1.512 (-1)	1.764 (0)	1.89 (0)
Bedford	1.62 (+11)	1.62 (0)	1.62 (0)
Stoke Canon	1.584 (0)	1.584 (0)	1.584 (-5)
Mole	1.56 (0)	1.56 (0)	1.56 (-8)
Brayford	1.365 (0)	1.365 (-5)	1.365 (-8)
Black Torrington	1.365 (0)	1.365 (-5)	1.365 (-8)
Weycroft	1.44 (0)	1.44 (-8)	1.44 (-14)
Buckland	1.44 (0)	1.44 (-8)	1.44 (-14)

Highlights

- Bridges likely to accumulate debris assessed by direct and indirect observations
- Direct observations include satellite imagery and inspection reports
- Indirect observations are based on the location of the bridge
- Direct observations are robust and provide a more solid evidence than indirect
- Applications include river and bridge assessment and management

Figure 1

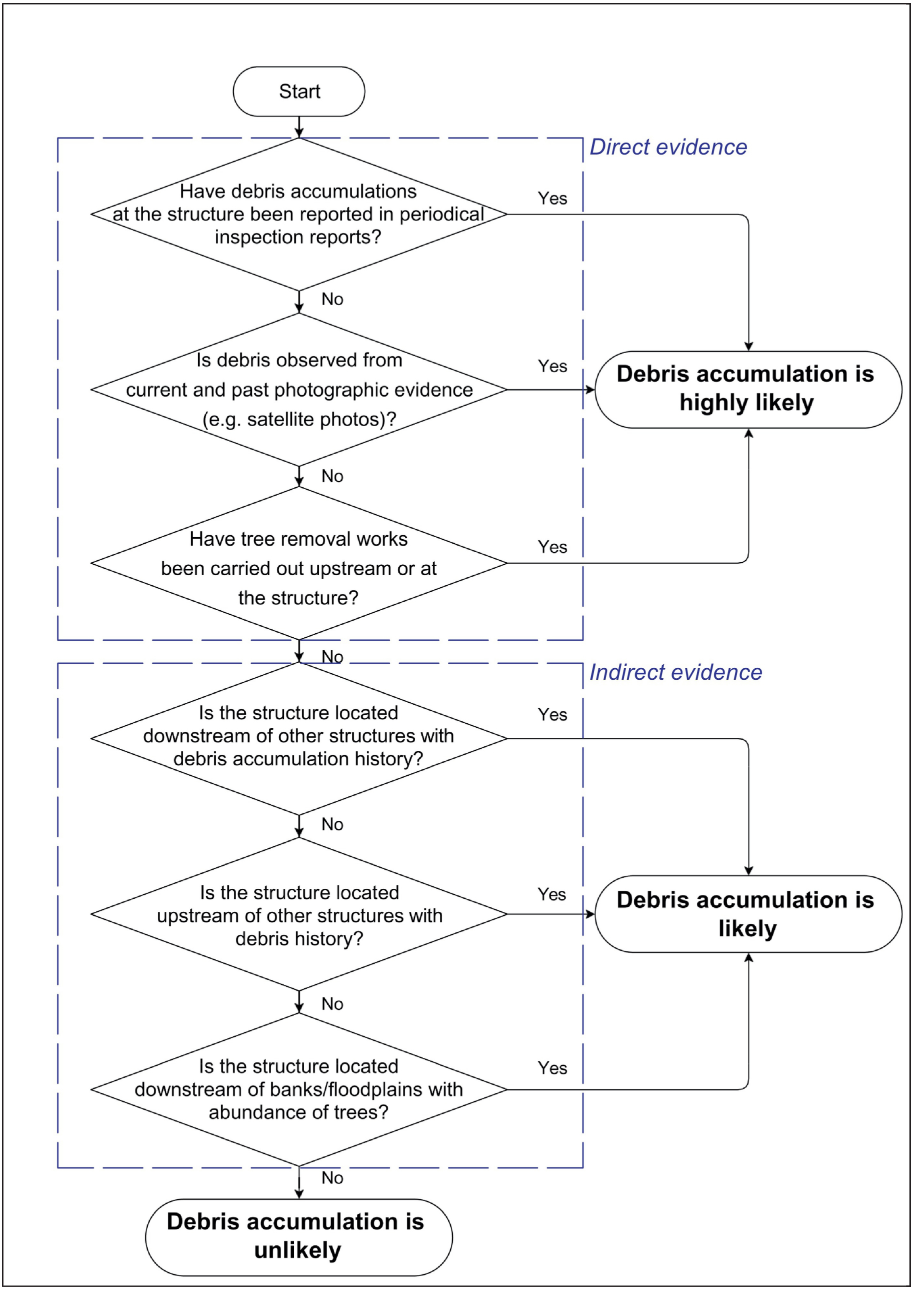

Start
Direct evidence
Have debris accumulations at the structure been reported in periodical inspection reports?
Yes
No
Is debris observed from current and past photographic evidence (e.g. satellite photos)?
Yes
Debris accumulation is highly likely
No
Have tree removal works been carried out upstream or at the structure?
Yes
No
Indirect evidence
Is the structure located downstream of other structures with debris accumulation history?
Yes
No
Is the structure located upstream of other structures with debris history?
Yes
Debris accumulation is likely
No
Is the structure located downstream of banks/floodplains with abundance of trees?
Yes
No
Debris accumulation is unlikely

Figure 2

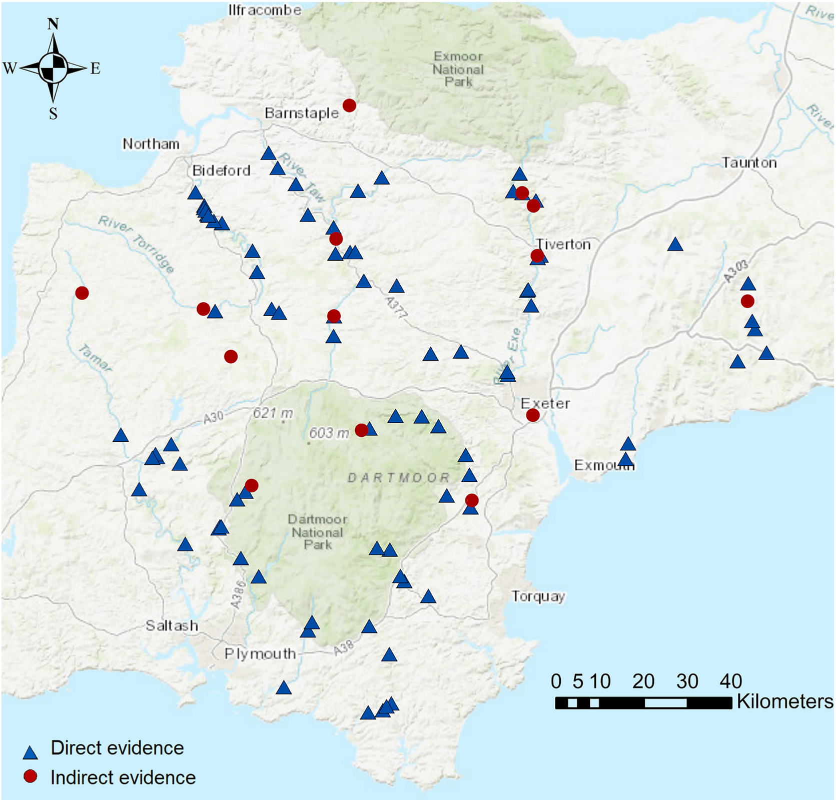

Ilfracombe
N
W
E
S
Exmoor National Park
Barnstaple
Northam
Bideford
River Taw
Taunton
River Torridge
Tiverton
A303
A377
Tamar
River Exe
Exeter
A30
621 m
603 m
DARTMOOR
Exmouth
Dartmoor National Park
A386
Torquay
Saltash
Plymouth
A38
0 5 10 20 30 40
Kilometers
▲ Direct evidence
● Indirect evidence

Figure 3

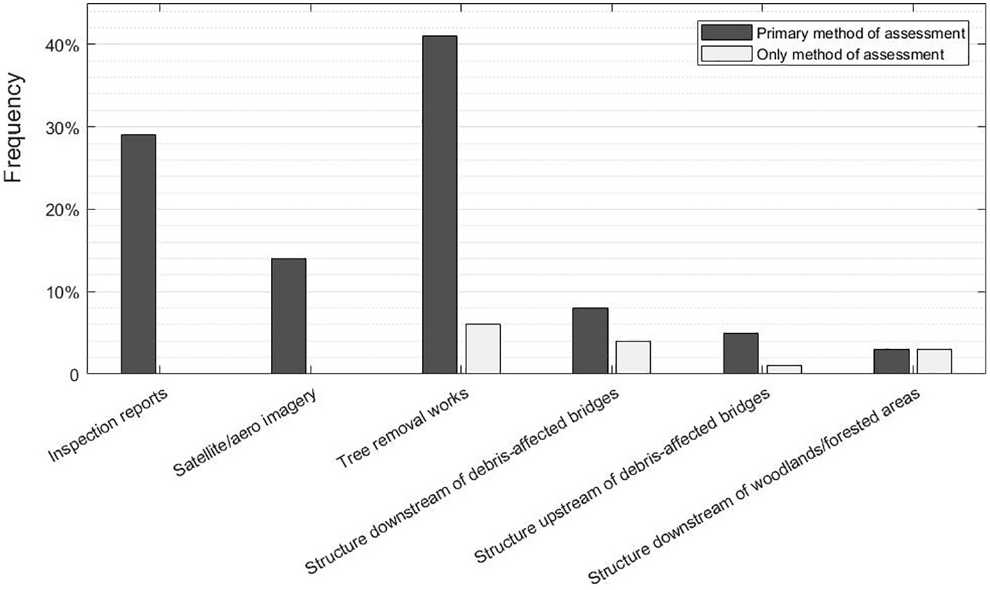
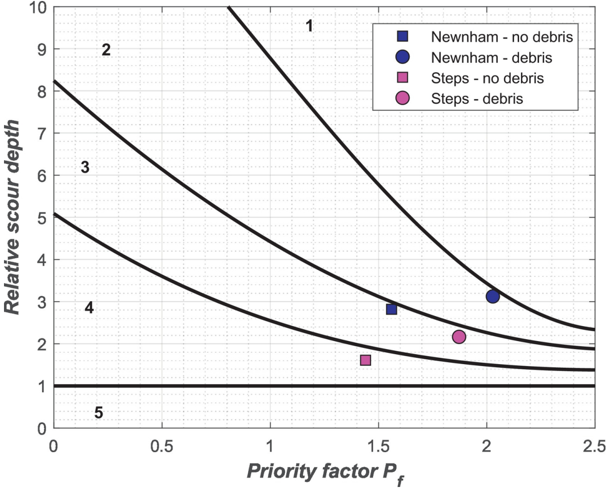

Frequency
40%
30%
20%
10%
0
Primary method of assessment
Only method of assessment
Inspection reports
Satellite/aero imagery
Tree removal works
Structure downstream of debris-affected bridges
Structure upstream of debris-affected bridges
Structure downstream of woodlands/forested areas

Figure 4



Relative scour depth
Priority factor P_f
0
0.5
1
1.5
2
2.5
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
■ Newnham - no debris
● Newnham - debris
■ Steps - no debris
● Steps - debris

Figure 5