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Manuscript title: A decision support tool for assessing risks to above ground river pipeline crossings

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Abstract

Infrastructure assets require suitable management and assessment protocols due to age-related deterioration, extreme weather events and climate change impacts. Above ground river crossings are weak links in pipe networks since bank erosion and scour can undermine the integrity of built structures. A simple protocol was developed to assess river bank stability in the vicinity of river pipeline crossings. The Erosion Risk Index (*ERI*) follows established bank erosion estimation techniques, adapted for users who are not trained geomorphologists. The calculation of *ERI* is based on the analysis of photographs, acquired during an optimised inspection protocol using a custom app on a ruggedized tablet computer. *ERI* was tested across Scotland and proved to be adequate for a first order geomorphological assessment, and to provide a classification of crossings according to susceptibility to river bank erosion. *ERI* is transferable, with appropriate testing, to other infrastructure river crossing networks in the United Kingdom and beyond. The methodology used to develop and test *ERI* is applicable to the development of other protocols to manage and assess infrastructure assets.

Keywords: water supply; infrastructure planning; pipes and pipelines; river engineering

1. Introduction

Managers of infrastructure assets require databases that include high quality asset data and associated analytical tools to provide evidence for making operational and investment decisions. Such data are becoming increasingly important because ageing infrastructure systems (Hall et al. 2014) must be managed, made resilient to extreme weather events and adapted to mitigate climate change impacts (Garnaut 2008; Arnell et al. 2015; Thompson et al. 2017). National assessments of ageing infrastructure have been undertaken in countries including Australia (Sonnenberg 2012), Canada (Gaudreault and Lemire 2006) and New Zealand (Coleman and Melville 2001). In the United Kingdom (UK) the resilience of critical infrastructure to extreme weather events has been analysed extensively (Hall et al. 2016) and is recognised as a problem with important social implications (Pitt 2008; Cabinet Office 2010). Information and Communication Technologies (ICTs) enable enhanced decision making and asset management within an organisation (Campos et al. 2017; Emmanouilidis et al. 2009). However, the pace at which ICT tools and analyses progress has historically outstripped the rate at which decision support tools for infrastructure asset management were updated. There are thus opportunities for infrastructure asset managers to make better use of state of the art tools (e.g. Vaghefi et al., 2012; Dorafshan and Maguire, 2018) that are now cheaper, more easily integrated into other systems, and more versatile and configurable than tools that were available several decades ago. Using such technologies to improve and analyse the information contained in asset databases has potential to enhance decision making, as exemplified by the case of assessing river bank stability in pipe crossings.

Pipelines can be designed to cross rivers beneath a river's water surface, installed using either trenching or a Horizontal Directional Drill, or above a river's water surface using a bridge with piers and/or abutments. Bridges may have a sole purpose of supporting a pipeline or may also have other functions, for example to support roads or railways. River crossings are a particular area of vulnerability in national scale water infrastructure, energy (oil; gas) and transport networks (ICE 2009; van Leeuwen and Lamb 2014) because they are generally exposed and subject to external factors which speed up deterioration compared to buried infrastructure. Crossings are at risk from both vertical scour and lateral bank erosion (Johnson, 2005; Kim et al., 2013). The latter (Figure 1), particularly for crossing structures that have the sole purpose of supporting pipelines, has been given less attention than the former yet is an important contributor to pipeline crossing damage. For example, Scottish Water estimate that 30% of pipeline crossings with observed riverbank instability are associated with either leaks or damaged foundations.

Comprehensive manuals for bridge scour assessment are available for the UK (Kirby et al. 2015) and other countries (e.g. Arneson et al. 2012; Coleman and Melville 2001). These manuals are useful to engineers who design, construct, operate and maintain structures but do not meet the asset management challenge faced by pipeline infrastructure owners because guidance: (i) focuses on transport bridges rather than on above-ground pipe crossings, the latter being more at risk from bank erosion since pipe crossing structures are less likely to have bridge abutments; and, (ii) is not sufficiently comprehensive on how different types of information on river stability can be used to reduce uncertainty when making decisions about what stages of risk assessment to complete. With respect to this latter issue, asset inspections have recently been transformed by the development of bespoke software packages on relatively low-cost mobile computers that have embedded Global Navigation Satellite System (GNSS) technology for positioning using, for example, GPS, GLONASS, Galileo and/or BeiDou systems (Xu and Xu, 2016). Such software typically integrates data collection during inspections into Geographic Information Systems (GIS) that include other sets of spatially distributed data such as aerial and satellite imagery, and derived products such as vegetation growth and urban development. Asset management decision making practice has not kept pace with these technological developments in data collection and, for the case of assessing river stability in the vicinity of above-ground pipe crossings, tools are needed to interpret survey data that can be acquired using mobile computers.

A range of geomorphological classification methods have been developed to assess river stability. Examples include the MoRph Framework (Shuker et al. 2017), the Natural Channel Classification (Beechie and Imaki 2014), the River Styles Framework (Brierley and Fryirs 2013), the Fluvial Audit Method (Sear et al. 2009), and older approaches such as the Rosgen Classification System (Rosgen and Silvey 1996). In addition to bank stability and other geomorphological attributes, many of these methods implement a range of ecological and water quality indicators. Data gathering is increasingly complemented by low cost computational hardware and software such as portable GPS/GIS tools (Connell 2012). However, to specifically assess bank stability, these techniques require considerable information at the local and catchment scales, as well as input by trained geomorphologists. Ultimately, whichever classification system is used, geomorphic context is critical to separate river reaches based upon the capacity of a channel to adjust (Buffington and Montgomery 2013). The challenge for asset inspection is thus to establish inspection protocols that meet two requirements: (i) to enable rapid collection of data for input into a decision support framework that is informed by contemporary approaches to assess river stability; and, (ii) to be simple and versatile enough to be applied by asset inspectors and managers

who do not necessarily have specialist training in river engineering and fluvial geomorphology. This paper reports the development of enhancements to Scottish Water's field survey protocol and data analysis framework. The impact of these developments is evaluated through a validation exercise using Scottish Water's water and wastewater river crossing infrastructure.

2. Water and wastewater pipeline river crossings in Scotland

Scottish Water provides water and waste water services to 2.5 million homes and 156 000 business properties in Scotland. The drinking water network is 48 480 km long of which 7 000 km forms the trunk main network. There is an additional 51 199 km wastewater pipe network (Scottish Water, 2018). Across the drinking and wastewater pipe networks there are c.550 and c.800 river crossings, respectively (Figure 2). Many of these crossings span rivers of differing size and style with Scotland's diverse river environments (Perfect et al. 2013) posing a variety of management issues. Known problems include bank erosion, flooding, bridge damage, bed instability, degradation of instream habitat quality and channel confluence alignment (Hoey et al. 1998).

River crossings are vulnerable because they are at risk of failure from high-flow events with varying, and currently unknown, magnitudes. This vulnerability was highlighted by bridge failures in the 2015/2016 flooding in Northern England and Scotland (Marsh et al. 2016; Barker et al. 2016). Data from econometric modelling by Scottish Water indicates that the cost of repair and provision of temporary water supplies due to river crossing failure can range from tens of thousands of pounds in simple cases, to tens of millions in the most challenging of examples.

Inspections prior to the current project had identified examples where river instability presented a clear threat to the integrity of a pipe crossing. There were also cases where the effects of river instability were less clear but thought to warrant further assessment. Hence, Scottish Water identified the need to develop a decision support framework to: (i) direct further desk-based assessment of river stability; (ii) identify the need for scour or bank erosion prevention measures; and, (iii) establish the frequency of repeat asset inspections.

3. Approaches to bank erosion scoring

Erosion is the process of sediment removal from a particular location in a landscape. In fluvial environments, eroded sediment is likely to be deposited downstream on a river bar or delta, or deposited overbank on a floodplain. Subsequently, deposited material may be reworked by succeeding cycles of erosion and deposition. The size, geometry, and morphology of the river and its banks, bank material properties, hydraulics of flow in the channel, river flow hydrology, climatic conditions and vegetation cover are all controlling factors of river

bank erosion. However, three major controls have been identified that are independent of the type of river environment: bank height (H) and its relationship with the average water depth (associated with a critical bank height H_c), bank angle (Osman and Thorne 1988, Darby and Thorne 1996) and the presence or absence of protective vegetative cover (Micheli and Kirchner 2002).

A variety of bank erosion scoring indices have been proposed that include assessment of a number of components (Table 1; Connell, 2012). BEI is an index that requires only four input components and is the only index in the table that has been validated for desk-based assessments using accurately geolocated videos. However, inputs such as bank full width or root depth can only be extracted from photographs for very specific river environments, such as in South America and the tropics. BEHI was developed by Rosgen (2001) as part of a wider bank erodibility assessment. BEHI calculations require detailed field measurements and give an in-depth analysis of bank stability. It is extensively used in academia and industry, despite criticism of the broader Rosgen approach to natural channel design (e.g. Simon et al. 2007). BEHI and BEI (Wisconsin Division of Natural Resources, 2010) differ only on the type of required inputs and they follow almost identical reasoning and methodology. The USDOT index (Johnson, 2006) requires 13 independent inputs, all of which need to be measured in the field. It results in a detailed estimation for bank stability and is often the starting point for compatible river habitat assessments. EPIN (Genesee/Finger Lakes Regional Planning Council, 1998) is calculated from the sum of scores for bed material, slope condition value, vegetation and averaged hydraulics. EPIN requires information that cannot be extracted from photographs. However, it was historically the first erosion index that accounted for surveying efficiency (less inputs for more coverage; 221 successful assessments in less than a year). SEI (Michigan Department of Environmental Quality, 2001) includes field-based bank erosion measurements but was mainly used as a river management inventory recording, for example, river accessibility, condition, vegetative cover and apparent cause of the erosion (Seelbach, 1997).

To summarise, Table 1 shows that a number of semi-empirical indices have been developed that use different types of qualitative and quantitative data and have gone through different degrees of validation. Connell's (2012) extensive review of existing riverbank erosion indices showed that three of the methods have a clear focus on assessing bank erosion, in contrast to the majority of methods that have bank erosion as an input concentrate on habitat or water quality assessments. These methods were BEI, BEHI and BEPI. Table 1 provides an overview of the input variables used in each method. The three methods are similar in scope and development, and all three include the bank height : bankfull depth ratio, and bank angle as inputs. The main

difference between the methods is that both the BEHI and BEPI require an estimate of root density for calculating an erosion index score, but the BESI method does not. Although the inclusion of vegetation is similar for the three methods, the BESI method requires only a reference for any existing surface protection and an estimate of riparian diversity. Finally, BESI is the only method that has been applied using state of the art data acquisition techniques (detailed topographical surveys, Digital Terrain Model analysis and geo-located video inputs); all the other methods require field measurements which are typically beyond the scope of asset management inspections).

4. Methodology

In early 2016, Scottish Water began a programme of planned inspections of all pipe crossings as part of its developing water and wastewater infrastructure strategies. A customised app, for a ruggedized tablet computer, was used as a low-cost device to acquire baseline data on each of the crossings. The data captured varies, as appropriate, from simple yes/no responses, through multiple choice answers, to free text. The app also includes a form to acquire geo-referenced images. A protocol for data acquisition to assess bank erosion was implemented in surveys performed after October 2017 (Figure 3). The collected data, photographs and notes are stored in an online database for each one of the surveyed assets. All the desk-based assessments presented in this paper are performed using information and photographs stored in this database.

This paper reports on a simplified and purpose specific bank stability assessment that was developed using the frameworks described in Section 3. Individually, none of the bank erosion scoring methods presented in Section 3 were suitable for the determination of erosion risk since they all require detailed geomorphological assessment for each site or high-resolution Digital Terrain Models (DTMs) that do not yet exist for all crossings in Scotland. However, these scoring methods provided a framework for the development of a new empirical scoring system, which we called “the Erosion Risk Index (ERI)”. The score that is calculated for a particular asset and incorporates an assessment of data quality is termed ERI*. The main challenge was to replace the quantitative geomorphological inputs (such as the bank height and the bankfull depth) with qualitative evidence for erosion risk that can be determined directly from site photographs. In parallel, it was necessary to consider the quality of the data, the ease of application and the compatibility of this system with the existing risk scoring classes used by Scottish Water.

The ERI method was developed and tested in four phases (Table 2). The first phase focused on identifying the input variables and scoring method for ERI. The second phase investigated user bias, and the third and fourth

phases investigated the consistency of the methodology. For Phase 1 the selection of sites was random. For Phases 2 to 4, the sites were selected in a manner that allowed for the progressive increase of the variability of geomorphological settings: Phase 2 used sites in the Outer Hebrides; Phase 3 primarily used sites from the Central belt of Scotland with the addition of 5 sites of similar morphology from other areas; and Phase 4 used a diverse sample from across Scotland (Figure 2). All four phases used data from Scottish Water's asset inspection online database. The assessments undertaken during phases 2 and 4 were supplemented by data from field visits to 23 assets in the Outer Hebrides.

5. Results

5.1 Phase 1: Selection of variables, determining calculation method and assessment of ability to identify sites susceptible to erosion

The main purpose of the methodology was to assess the risk of bank erosion based on photographs taken by surveying personnel who may not be professional geomorphologists. This leads to the exclusion of morphological indicators that are difficult to determine directly from photographs such as the height of the bank. However, qualitative geomorphological indicators such as bank angle and the presence of vegetation are included and characterised using interval measurement scales. In addition, bank protection is characterised by its type and also in terms of its condition reflecting the degree of protection offered. Table 3 shows the input variables that were identified to form this new erosion risk index. Each variable was scored on a scale of 0-5. The number of graduations in this scale match those used by Scottish Water for other components of their asset risk management framework. Where it was not feasible to score a variable using all points in the scale, the number of points was reduced by removing the intermediate values 2 and 4.

Using the input variables defined above, the next steps were to develop an index to use for classification and to ensure this index was capable of correctly identifying sites susceptible to erosion. The formulation of this index can be carried out in many ways, with weightings designed to reflect local conditions. Four formulae were examined: (i) a probabilistic weighted index; (ii) a weighted addition; (iii) simple multiplication; and (iv) a weighted scaled mean. The scaling of the index is necessary to secure compatibility with Scottish Water's existing asset risk assessments which consider the structural condition and safety of pipes and associated infrastructure. After scaling, the total score is rounded up to an integer value from 1 to 5. This rounding is common practice in classification for engineering applications as it is preferable for an asset to be classified as more susceptible when the arithmetic index falls between two classes. After rounding, the only formula that

provided sufficient separation between the different sites was the Weighted Scaled Mean (WSM) given by Equation 1 (terms are defined in Table 3).

$$ERI = Mean[AE_{5w}, V, \beta, \{0.16 \times (BP_U * Condition_{BP_U} - 1) + 1\}, \{0.16 \times (BP_{5w} \times Condition_{BP_{5w}} - 1) + 1\}]$$

[Equation 1]

The *ERI* values obtained from Equation 1 are then adjusted using a Data Quality (*DQ*) score to reflect the quality of photographic evidence in the database (Equation 2). The *ERI* is multiplied by five as there are five independent terms in Equation 1.

$$ERI^* = [5 \times ERI + DQ]/6 \quad \text{[Equation 2]}$$

The Data Quality score (*DQ*) for a site uses the number of zeros for the input variables defined in Table 3 that represent the absence of photographic evidence of sufficient quality within the asset database. *DQ* values are defined in Table 4. Calculation of *ERI** using Equation 2 is not performed if the *DQ* is 'Low Data Quality'.

The calculations of Equations 1 and 2 are useful only if they correctly identify sites susceptible to erosion. The sensitivity and appropriateness of the Erosion Risk Index *ERI** were tested using 13 sites that Scottish Water considered to be particularly susceptible to bank erosion. These 13 sites were identified based on keyword searching in the asset management database prior to implementation of the outcomes from the present project. All of the 13 sites *ERI** scores are ≥ 3 (Figure 4), defined as medium risk sites, susceptible to erosion due to particular geomorphological characteristics. Thus, all sites *ERI** values are consistent with Scottish Water's prior, independent assessment of erosion risk so demonstrating the capability of the Erosion Risk Index to identify sites that are particularly susceptible to bank erosion.

5.2 Phase 2: User bias

To assess the effect of user bias on the Erosion Risk Index (Phase 2; Table 3), 31 further sites were evaluated using the scoring method outlined above by an expert geomorphologist (using both the on-line database and site visits) and three Scottish Water employees (using the on-line database only). Figure 5 compares the scores by these different operators and suggests convergence of results that implies limited sensitivity of the method to user bias. The sites scored with the *DQ* identifier were highlighted as having poor data quality in the on-line database as photographs either do not clearly show the banks close to the crossing or were taken when dense summer vegetation obscured the banks.

5.3 Phases 3 and 4: Consistency of methodology

The testing of the consistency of the methodology was separated into two phases (Table 2). In Phase 3, 23 sites from the Outer Hebrides were assessed by Scottish Water (SW) using the online database. Field data for these same sites were then collected by University of Glasgow (UoG) using the *ERI* categories (Figure 6). In Phase 4, a randomly selected set of 118 sites was scored by a University of Glasgow geomorphologist and a Scottish Water assessor, both using the online database (Figure 6).

For Phase 3, Figure 6 suggests that the desk based assessment overestimates the *ERI* score from direct field observation for 14 out of 23 sites, four sites gave the same score, and one site was scored with a higher *ERI* (4) after field assessment than from the desk-based scoring. Four sites in the on-line database were identified by the Scottish Water assessor as inadequate for performing a desk-based calculation of the *ERI*.

For Phase 4, comparison of desk based calculations of the *ERI* by Scottish Water and University of Glasgow assessors (Figure 7) demonstrates agreement for 69 of the 118 sites (58%). A total of 25 sites were identified as having low photographic quality and $ERI^* = 0$ (9 by Scottish Water and 16 by University of Glasgow geomorphologist). For the remaining 24 cases where there is disagreement, the differences are all either +1 (Scottish Water scores the *ERI* higher than University of Glasgow geomorphologist) or -1 (Scottish Water score is lower).

For the 118 surveys used in Phase 4, the differences in scores were analysed (Figure 8). The discrete nature of the data prohibits the application of traditional regression techniques, so Figure 8 is a graphical representation of the differences in *ERI* scores plotted against the calculated scores. The differences follow very similar patterns, suggesting that the differences in scores are not systematically biased by the severity of bank erosion risk.

6. Discussion

6.1 Evaluation of the Erosion Risk Index

The results from testing the Erosion Risk Index (*ERI*) and scoring using the *ERI** formula which takes into account photographic data quality, suggest that the approach is suitable for a first order classification of assets in relation to their exposure to river bank erosion, using the photographic evidence stored in Scottish Water's database. The index produces classification of pipeline crossings in a way which is compatible with Scottish Water's asset risk assessment scale (1 to 5 from low to high risk; Equation 1) and produces a reliable identification of the high-risk sites (Figure 4).

Comparisons between scores generated by Scottish Water's assessors and University of Glasgow geomorphologists show no systematic or structured bias (Figure 5) and that a significant proportion of the differences concerns the evaluation of the photographic evidence held in the online database (Figures 5, 7). Further, absolute differences between different *ERI* scorings from desk-based assessments very rarely exceed 1, indicating again the low sensitivity of the *ERI* to user bias. One area where user interpretations did differ significantly is in assessment of photographs as unsatisfactory for the required purpose. Training of database users and the provision of examples of unsuitable images that lack the required visual information is recommended to reduce this problem.

A characteristic of the desk-based *ERI* calculations is the tendency to overestimate the risk of bank erosion compared with field-based assessments using the same classification. The *ERI* is based on a simplified classification which can be applied to photographs and so cannot match the experience of a trained geomorphologist in the field. However, the desk based *ERI* scores systematically overestimate bank erosion risk so that critical high-risk cases are very likely to be identified as requiring further assessment. Since the *ERI* aims to produce an initial classification to inform decision making, this tendency for overestimation is a positive characteristic of the method.

A comparison between *ERI* and other first order morphological assessments cannot be direct, as all the existing approaches (Table 1) rely heavily on targeted field measurements. A good example here is the USDOT index (Johnson 2005, 2006) which is focused on assessing the stability of bridges using a set of inputs that can be rapidly assessed in the field. However, this assessment requires experience in geomorphological surveying. Components such as channel confinement, flood-plain activity or emerging flow patterns cannot be assessed by non-specialist personnel. In addition, the classification of simpler components, such as bank slope, relies on the selection of class ranges that cannot be determined from photographic input. Specifically, bank slope for the USDOT method includes an additional assessment of the composition of the bank material (Johnson 2005) which can only be reliably determined from physical sampling. Overall, existing methods such as the USDOT, do not correspond to the type of first order analysis that is presented in this paper. *ERI*'s unique characteristic is its ability to filter and classify assets from big photographic databases that have been acquired by inspectors without formal geomorphological training, making it versatile for the national scale assessment of spatially distributed infrastructure assets.

6.2 Using the *ERI* in a multi-factor risk assessment system

The overall aim of Scottish Water's pipelines crossing risk assessment system is to identify where change in the infrastructure environment causes a change in risk. The system thus includes component for health and safety, and structural integrity, in addition to erosion risk. Since the inspection of pipeline crossings involves high access costs because assets are spatially distributed (Figure 2), there is a need for each component of the risk assessment system to identify specific actions that need be taken in response to the resulting classification, including the frequency for subsequent asset inspections. For recommendations to be effective, both the specific site characteristics indicated by each class and the capacity of the organisation to undertake repeated asset inspections need to be considered. For the erosion risk component, the interpretation of each *ERI** class to aid in follow-up decision making is:

***ERI** = 5 Immediate Risk:** sites with severe ongoing bank erosion. Sites in this category require immediate further inspection and geomorphological assessment to assess the risk of bank failure and damage to the pipeline crossing.

***ERI** = 4 High Risk:** sites with ongoing erosional processes. Many of these sites have ongoing bank erosion upstream and/or downstream of the crossings. Their geomorphological characteristics, such as low bank angles, are not expected to lead to rapid bank failure during normal high flow conditions. These sites require immediate further inspection and geomorphological assessment.

***ERI** = 3 Medium Risk:** sites where erosion does not occur at present, but they have geomorphological characteristics that suggest that erosion and potential bank failure may occur during high flows. Many of these sites have existing bank protection that reduces the risk of erosion. As a result, these sites should be considered for routine re-survey every few years and should always be re-surveyed after major flood events to ensure that the protection is in good condition.

***ERI** = 2 Low Risk:** sites where visible erosion is absent and their geomorphological characteristics do not enhance erosional processes. Mainly small rivers with low bed slope and low bank angle that are not likely to be a significant threat to pipe crossing structures. Re-survey can be infrequent, except when other interventions such as construction or removal of a structure or upstream river restoration are likely to change the characteristics of the local environment.

ERI* = 1 Minimal Risk: sites where river stability does not impact the pipe crossing structure. They mainly consist of large bridges that accommodate part of the pipe network or crossings that are high above the river, as found in river gorges. The pipe crossing structures are unlikely to be eroded or damaged by river bank erosion.

ERI* is only calculated when there is sufficient photographic evidence for scoring (Table 4). Thus, if there are missing or poor-quality images then ERI* can only be calculated after a further asset inspection to acquire appropriate imagery. The scoring system can be directly applied or adapted for use by infrastructure owners and managers in the United Kingdom and internationally.

6.3 Geomorphological context, advanced techniques and future directions

The *ERI* scoring method was developed with the characteristics of Scottish rivers in mind and should be directly applicable in similar environments. Scottish rivers are diverse, but their overall rates of lateral adjustment are low. The new *ERI* scoring system has not been assessed across a greater variety of river planform styles (such as multi-channel systems) or for rivers with significant vertical adjustment. In different environments, more extensive and detailed classifications may need to be applied (such as the MoRph Framework and the River Styles Framework; see Introduction) especially if the assessment of stability of longer reaches is of interest.

Geomorphological assessments increasingly implement a variety of new technologies for the quantification of river change over a range of scales. River bank stability can be directly measured using repeat high-resolution topographic surveys using terrestrial laser scanning (Williams et al. 2015), structure-from-motion photogrammetry (Tamminga et al. 2015), airborne LiDAR (Jones et al. 2007) and satellite remote sensing (Syvitski et al. 2012). In addition, a number of analytical approaches for quantifying topographic change detection between surveys have been developed to include robust assessments of uncertainty (Wheaton et al. 2010; Williams 2012). The deployment of these approaches to support asset stability assessments depends on the rate and timing of geomorphic change. The *ERI* method is one way to pre-screen sites to inform decisions about the need to deploy additional, costly surveying resources.

Arising from developments in data collection technologies and advances in communications and protocols such as the Internet of Things (IoT), the efficient extraction, filtering and interpretation of large amounts of real time geomorphological data is a significant future challenge and opportunity. Simple frameworks, such as the one presented in this paper, can accept a range of data as input (eg replace approximations of bank erosion risk with volumetric changes measured from repeat wearable laser scanning, or repeat UAV/SfM surveys). Hence the *ERI*

can link the increasing complexity in data acquisition to derived information that is necessary for effective and scientifically informed decision making and asset management.

5. Conclusions

A new Erosion Risk Index (*ERI*) is proposed to assess the exposure of above ground river pipe crossings to bank erosion using only photographic data. Derivation of *ERI* requires collection of appropriate spatially distributed photographs collected during regular asset inspections which can then be assessed by asset managers who may not have comprehensive fluvial geomorphological training. The *ERI* is supplemented by an assessment of data quality, to calculate a final score *ERI**, which allows immediate identification of sites for which insufficient data exist to make a reliable risk assessment. The *ERI* was verified against independently identified medium to high risk cases, using a sequence of tests:

- Initial testing targeting the effect of user bias revealed that the *ERI* was stable and differences between users mainly concerned data-quality.
- The desk-based calculation of *ERI* overestimated susceptibility to bank erosion when compared with field-based calculations performed by expert geomorphologists using the same classification.
- Desk-based *ERI* scores obtained for 188 sites by Scottish Water assessors and a University of Glasgow geomorphologist showed agreement for the majority of cases. Differences were unbiased and they mainly occurred where there were data quality issues, where repeat site visits were needed.

Scottish Water have implemented the new scoring system based on the methods described in this paper. The scoring system could be applied by other owners of above ground river pipeline crossings. The procedure used to develop and test the *ERI* is transferable to the development of other asset management and assessment protocols.

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Table captions

Table 1. Summary of the components of erosion indices. The selected indices are: (i) the BESI Bank Erosion
Susceptibility Index (Connell 2012); (ii) the BEHI Bank Erosion Hazard Index (Rosgen 2001) and (iii)
the BEPI Bank Erosion Potential Index (Wisconsin Division of Natural Resources 2010).

Table 2. Sequence of testing of the Erosion Risk Index (*ERI*) method. UoG = University of Glasgow
geomorphologist. SW = Scottish Water assessor.

Table 3. Input variables for the proposed Erosion Risk Index.

Table 4. Attribution of Data Quality (*DQ*) scores according to the presence and quality of photographic evidence
for the input variables defined in Table 2. Calculation of *ERI** using Equation 2 is not performed if the
DQ is ‘Low Data Quality’.

Table 1. Summary of the components of a selection of existing erosion indices (based on Connell, 2012).

Component	BESI	BEHI	USDOT	EPIN	SEI	BEPI
Bank Erosion/Condition			X	X	X	
Bank height-bank full ratio	X	X				X
Root depth-bank height ratio		X				
Bank Angle	X	X	X		X	X
Vegetation		X	X	X	X	X
Surface protection	X					
Riparian Diversity	X					
Bank Material			X		X	X
Root density		X				X
Velocity			X	X	X	
Cause of Erosion					X	
Substrate Materials			X	X		
Thalweg Location			X		X	
Degree of Incision/Constriction			X			
Deposition			X			

BESI: Bank Erosion Susceptibility Index (Connell 2012). **BEHI:** Bank Erosion Hazard Index (Rosgen 2001).

USDOT: United States Department of Transportation (Henderson 2006). **EPIN:** Erosion Potential Index

Number (Genesee/Finger Lakes Regional Planning Council, 1998). **SEI:** Streambank Erosion Inventory

(Michigan Department of Environmental Quality, 2001). **BEPI:** Bank Erosion Potential Index (The Wisconsin

Division of Natural Resources, 2010).

Table 2. Sequence of testing of the Erosion Risk Index (*ERI*) method. UoG = University of Glasgow. SW = Scottish Water.

Phase	Purpose	Number of sites used	Source of information	Test carried out by
1	Selection of variables. Determination of calculation method. Assessment of whether method correctly identifies sites particularly susceptible to bank erosion.	13	Assets selected from online asset database that SW considered to be particularly susceptible to bank erosion.	UoG (1 geomorphologist)
2	User bias	31	Online asset database	UoG (1 geomorphologist); Scottish Water (3 assessors)
3	Consistency of methodology I	23	Online asset database for all sites in Outer Hebrides; field inspection	UoG (field-based geomorphologist); Scottish Water (database)
4	Consistency of methodology II	118	Random selection from online asset database	UoG (1 geomorphologist); Scottish Water (1 assessor)

Table 3. Input variables for the Erosion Risk Index.

Variable	Description	Scale	Description	Application	Description	Calculation
AE_u	A. Active bank erosion beneath the crossing	0	No, or un-satisfactory, photographic evidence	AE_{L_u}	A1. Erosion beneath the crossing: Left Bank	$AE_u = \max(AE_{L_u}, AER_u)$
		1	Absence of evidence of bank erosion	AER_u	A2. Erosion beneath the crossing: Right Bank	
		3	Evidence of bank erosion			
		5	Evidence of severe bank erosion			
AE_{5w}	B. Active bank erosion 5 channel widths (5w) upstream or downstream of the crossing	0	No, or un-satisfactory, photographic evidence	$AEUL_{5w}$	B1. Erosion upstream of the crossing: Left Bank	$AE_{5w} = \max(AEUL_{5w}, AEUR_{5w}, AEDL_{5w}, AEDR_{5w})$
		1	Absence of evidence of bank erosion	$AEUR_{5w}$	B2. Erosion upstream of the crossing: Right Bank	
		3	Evidence of bank erosion	$AEDL_{5w}$	B3. Erosion downstream of the crossing: Left Bank	
		5	Evidence of severe bank erosion	$AEDR_{5w}$	B4. Erosion downstream of the crossing: Right Bank	
BP_u	C1. Bank protection beneath the crossing	0	No, un-satisfactory, photographic evidence	BPL_u	C1a. Bank protection beneath the crossing: Left Bank	$BP_u = \max(BPL_u, BPR_u)$
		1	Hard structure (concrete/masonry/ steel piles).	BPR_u	C1b. Bank protection beneath the crossing: Right Bank	
		3	Soft structure (rip-rap, gabion basket, other)			
		5	No protection			
BP_{5w}	C2. Bank protection 5w	0	No, or un-satisfactory, photographic evidence	$BPUL_{5w}$	C2a. Bank protection	$BP_{5w} = \max(BPUL_{5w},$

upstream or downstream				upstream of the crossing: Left Bank	<i>BPUR</i> _{5w} , <i>BPDL</i> _{5w} , <i>BPDR</i> _{5w})
		1	Hard structure (concrete/masonry/ steel piles).	<i>BPUR</i> _{5w}	C2b. Bank protection upstream of the crossing: Right Bank
		3	Soft structure (rip-rap, gabion basket, other)	<i>BPDL</i> _{5w}	C2c. Bank protection downstream of the crossing: Left Bank
		5	No protection	<i>BPDR</i> _{5w}	C2d. Bank protection downstream of the crossing: Right Bank
Condition	Condition of bank protection	1	Undamaged –intact as new condition		
		2	Minor damage- intact but some isolated damage		
		3	Moderate- intact but widespread damage		
		4	Severe damage- intact but likely to fail and remedial work required to stabilize bank		
		5	Failed – in pieces, offers no protection		
β	D. Bank angle	1	<30°		
		3	30-80°		
		5	>80°/undercut		
V	E. Vegetation	1	Both high and low vegetation		
		3	Either low or high vegetation		
		5	No vegetation or very sparse cover		

Table 4. Attribution of Data Quality (*DQ*) scores according to the presence and quality of photographic evidence for the input variables defined in Table 2.

Data Quality (<i>DQ</i>) score	Number of input variables with 'No or unsatisfactory' photographic evidence
0	0
5	1-3
Low Data Quality	4-5

Figure captions

Figure 1. Example of geomorphological factors affecting bank stability. White arrows point to specific features:

(A) bank undercut close to pipe crossing abutment; (B,C) bank erosion close to pipe crossing pier and abutment; (D) very steep banks close to crossing; (E) highly erodible material close to crossing pier; and (F) undermined bank protection which is integrated into the crossing abutment construction.

Figure 2. Locations of river pipe crossings in Scotland. The left map shows the distribution of river pipe crossings across the country at time of writing. The right map shows the pipe crossings used for the development and testing of the Erosion Risk Index method described in this paper (listed in Table 2).

Figure 3. Suggested protocol for the collection of photographs during surveying. Simple rules are suggested to ensure that the photographs can be used for a first order geomorphological assessment.

Figure 4. Initial testing of *ERI** for 13 sites (Phase 1; Table 2) that were identified to be particularly susceptible to bank erosion from keyword searches of the asset management database prior to the current project.

Figure 5. Testing for user bias at 31 crossings (Phase 2; Table 2). The comparison is between three assessors from Scottish Water (SW; 1 to 3) and one University of Glasgow geomorphologist (UoG). DQ (Data Quality) indicates sites that cannot be scored using the Erosion Risk Index because of inadequate photographic evidence in the online database.

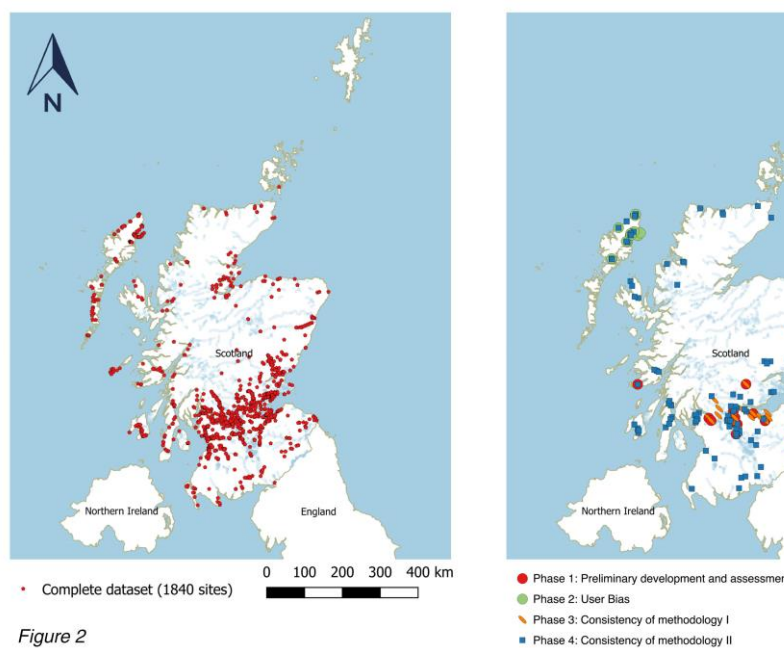
Figure 6. Differences between field measurements from University of Glasgow geomorphologists (UoG) and desk-based *ERI* assessment from Scottish Water (SW) assessors, used to assess consistency of the methodology (Phase 3; Table 2). Circled numbers are field *ERI* scores. Red dots identify the sites for which the database includes insufficient photographic evidence to calculate an *ERI* score.

Figure 7. Comparison of desk-based *ERI* scoring by Scottish Water (SW) and a University of Glasgow geomorphologist (UoG) used to assess the consistency of the methodology (Phase 4; Table 2). Circled numbers are the *ERI* scores derived by the University of Glasgow geomorphologist. Red (identified by Scottish Water) and blue (identified by UoG) dots represent the sites for which the database includes insufficient photographic evidence to calculate an *ERI* score.

Figure 8. Counts plot of differences in scores between Scottish Water (SW) assessors and University of Glasgow geomorphologist (UoG) for 118 sites versus *ERI* scores, used to assess the consistency of the methodology (Phase 4; Table 2).



Figure 1



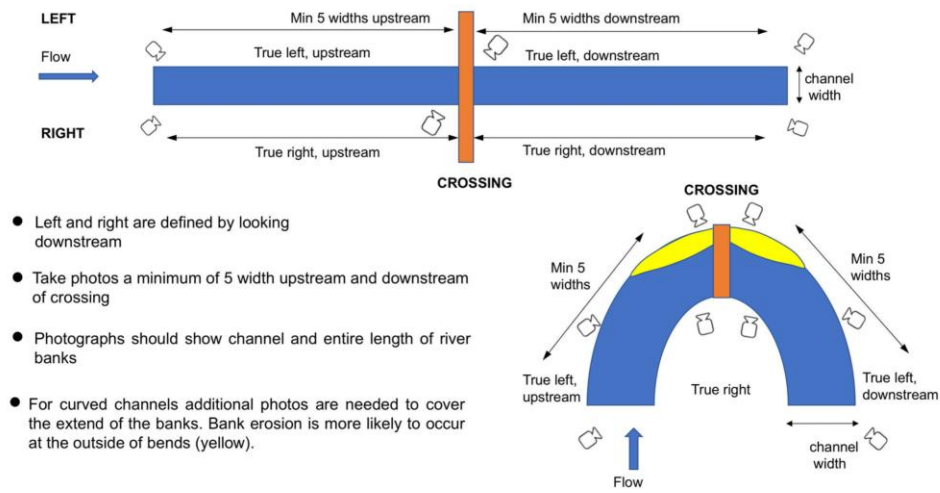


Figure 3

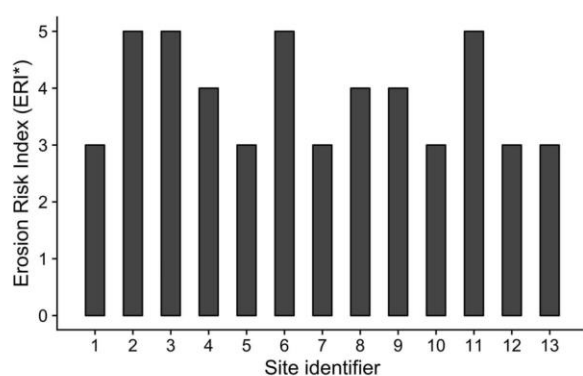


Figure 4

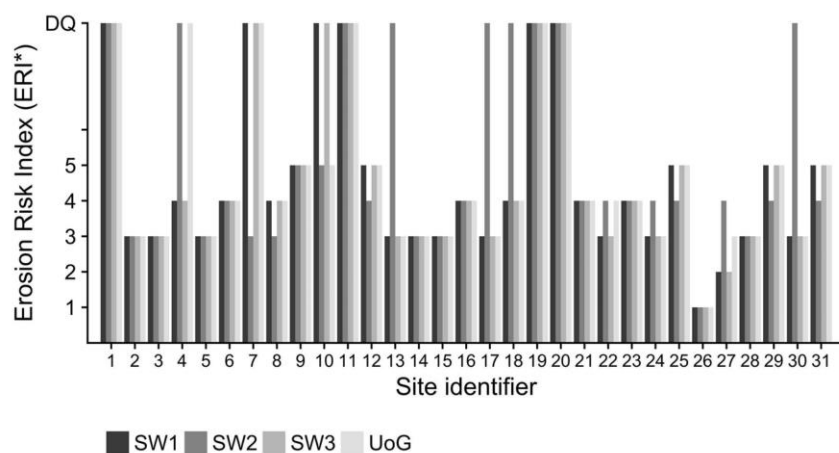


Figure 5

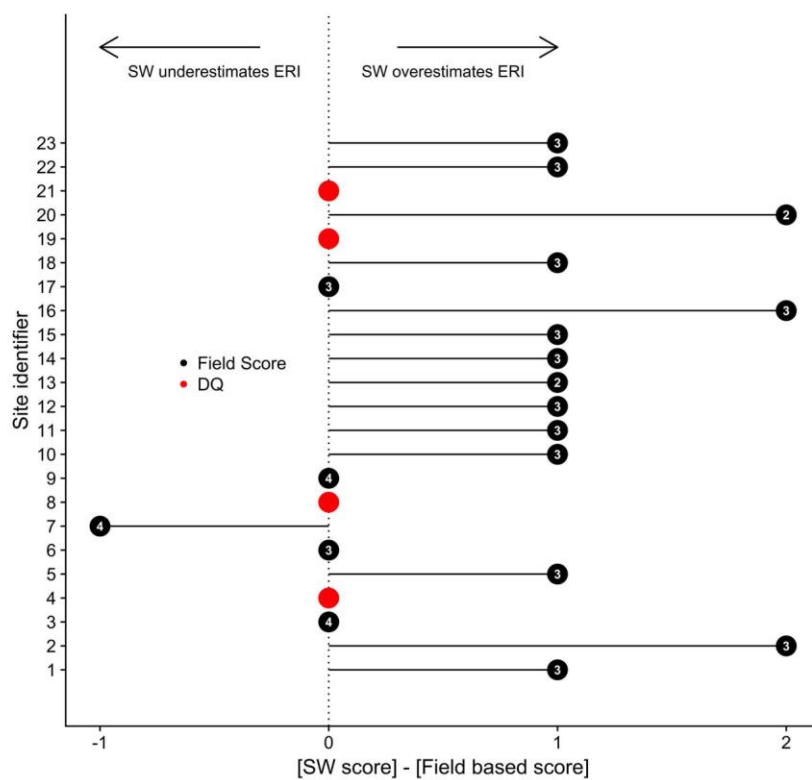


Figure 6

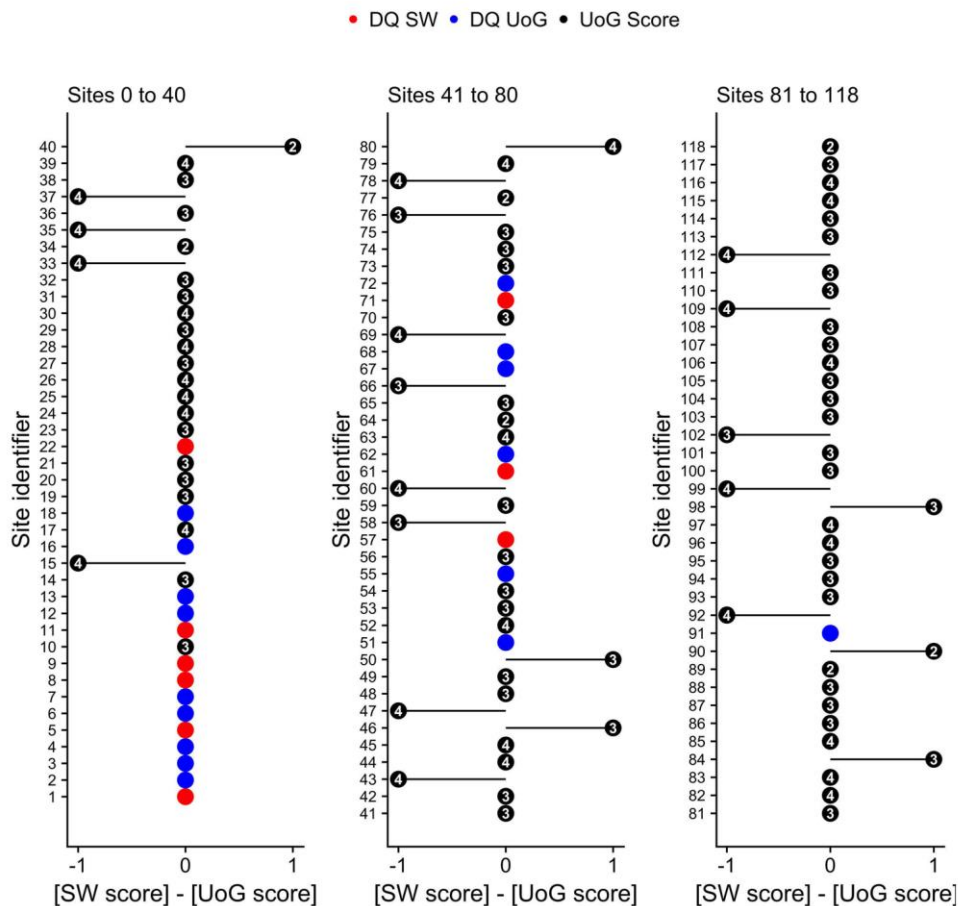


Figure 7

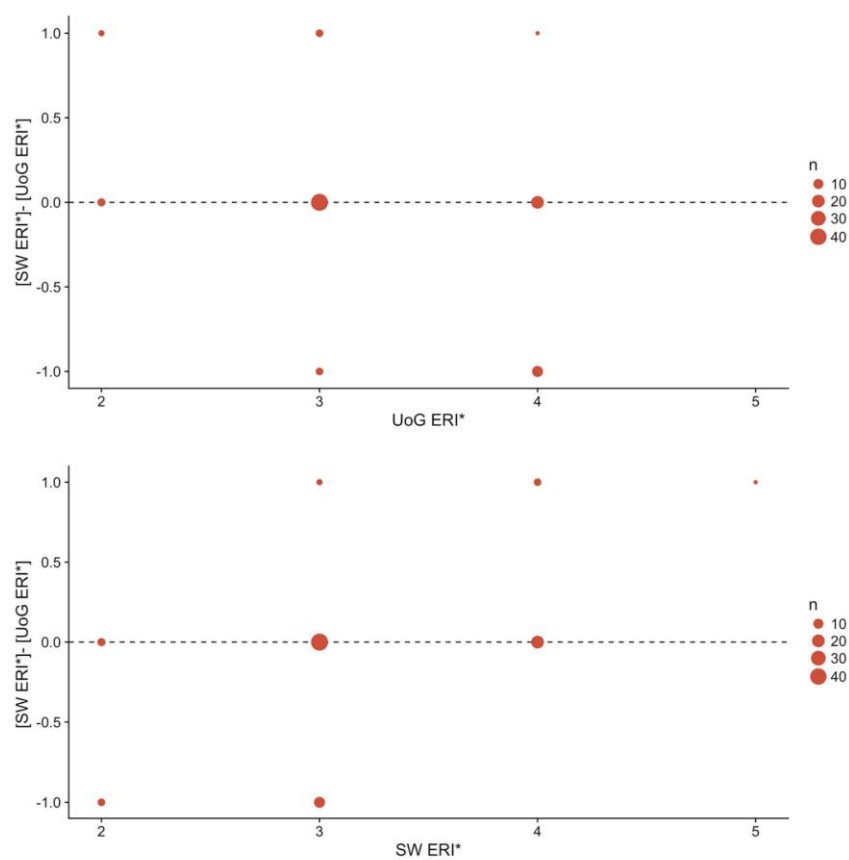


Figure 8