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Short communication

Supporting proactive planning for climate change adaptation and conservation using an attributed road-river structure dataset

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A R T I C L E I N F O

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A B S T R A C T

Freshwater species and their habitats, and transportation networks are at heightened risk from changing climate and are priorities for adaptation, with the sheer abundance and individuality of road-river structures complicating mitigation efforts. We present a new spatial dataset of road-river structures attributed as culverts, bridges, or fords, and use this along with data on gradient and stream order to estimate structure sensitivity and exposure in and out of special areas of conservation (SAC) and built-up areas to determine vulnerability to damage across river catchments in Wales, UK. We then assess hazard of flooding likelihood at the most vulnerable structures to determine those posing high risk of impact on roads and river-obligate species (fishes and mussels) whose persistence depends on aquatic habitat connectivity. Over 5% (624/11,680) of structures are high vulnerability and located where flooding hazard is highest, posing high risk of impact to roads and river-obligate species. We assess reliability of our approach through an on-ground survey in a river catchment supporting an SAC and more than 40% (n = 255) of high-risk structures, and show that of the subset surveyed >50% had obvious physical degradation, streambank erosion, and scouring. Our findings help us to better understand which structures pose high-risk of impact to river-obligate species and humans with increased flooding likelihood.

1. Introduction

Over the last century, freshwater species and populations have experienced significant declines globally (Tickner et al., 2020; Waldman and Quinn, 2022), with freshwater vertebrate populations having declined at more than twice the rate of land or ocean vertebrates (Grooten and Almond, 2018). The recent (2020) Living Planet Index for Migratory Freshwater Fish reported that since 1970 the abundance of 247 migratory fish species fell by an average of 76%, and linked losses to the density of infrastructure fragmenting waterways (Deinet et al., 2020).

Road-river infrastructure (from here, structures) such as culverts and bridges are more abundant than weirs or dams on waterways, sometimes substantially so (e.g., in the North American Great Lakes there were 38 times as many structures as dams; Januchowski-Hartley et al., 2013). In a recent review, Frankiewicz et al. (2021) outlined how improperly designed culverts restrict movement for a diversity of animals (fish, mammals, amphibians, invertebrates), and that both migratory and residential fish populations decline where road and river networks intersect (Pépino et al., 2012; Maitland et al., 2016; Bouska and Paukert, 2011; Makrakis et al., 2012). Structure design, installation, and age are key attributes that prohibit species' movements. For example, those

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structures that are undersized relative to the width of the waterway can prohibit use by larger bodied animals (such as otters, see Wilkinson and Chadwick, 2012), while also resulting in altered flows, debris jams, and disconnection between the bed of the structure and the river which causes additional obstacles (Fleming and Neeson, 2020; O'Shaughnessy et al., 2016; Gillespie et al., 2014; Wilkinson and Chadwick, 2012; Frankiewicz et al., 2021). Degraded structures not only negatively impact aquatic ecosystems, but also transportation systems (Sleight and Neeson, 2018; Pregnolato 2019; Arrighi et al., 2021). Negative impacts on nature and people from structures also intensify with storms and large flood events (Gillespie et al., 2014) and are likely to expand in scale and severity as rainfall patterns and event intensities change.

In the United Kingdom (UK), both freshwater species and habitats, and transportation networks have been assessed at medium to high risk of impacts from changing climate conditions (e.g., more intense flooding) between now (2021) and the future (2100) (Climate Change Committee, 2021). Metrics for heavy rainfall generally show an increase in "very wet days" across the UK (Climate Change Committee, 2021), with more winter rain falling in intense events in the last 50 years (Watts et al., 2015). Further, extreme event attribution studies indicate that human-induced climate change links some observed UK precipitation extremes to significant flooding impacts (Pall et al., 2011; Otto et al., 2018). Freshwater species and habitats in the UK are listed as highest priorities for climate change adaptation in the near future (2021–2023) by the Climate Change Committee (2021), and more action is needed for both these and transportation networks to lessen the impacts of climate change (Netherwood, 2021).

One response to the priority status of freshwater species and habitats is the proposed construction of fish passes (assumed at weirs or dams, but not explicitly stated) to support species' movements within and between aquatic ecosystems (Climate Change Committee, 2021). However, fish passes do not always facilitate species movements (Bunt et al., 2012; Noonan et al., 2012; Silva et al., 2018) and do not address altered freshwater habitats or disconnection caused by transportation networks. Rather than focusing on a specific intervention, there is a need for considering a wider portfolio of climate change adaptions around instream structures that consider the collective implications for nature and people.

In this paper, we describe the methods and results from a paired national and catchment-scale assessment as initial actions to support proactive adaptation planning across Wales, UK for smaller instream structures. We:

a. Produce a spatial dataset with all structures attributed a type: bridge, culvert, or ford.
b. Determine the distribution of different structure types in river networks.
c. Conduct a screening-level assessment of culvert and bridge vulnerability and current risk of impact from flooding.
d. Assess the reliability of our type-attribution and screening-level assessment with an on-ground visual survey (i.e., visually observable degradation at location) of structures.

We discuss how our dataset and findings help us to better understand where vulnerable structures occur and associated risks, in addition to limitations of our process and how these could be overcome with cross-sector collaboration and remote data collection.

2. Data and methods

2.1. Study area and intent

We focused on catchments conterminous to Wales because Welsh roads, rivers, and structures are managed by public bodies (e.g., Local Government Authorities, Trunk Road Agents, and Natural Resources Wales) that must work together to "make things better and achieve common goals" as established under the Future Generations (Wales) Act 2015 (from here: Well-being Act). The Well-being Act provides a legally binding common purpose for public bodies in Wales, and the associated goals mirror much of the United Nations 2030 Agenda for Sustainable Development. In the need for public bodies in Wales to work together in their commitment to the Well-being Act, we see an opportunity to minimise the impacts of structures on nature and people. Specifically, our research addresses data gaps that can support proactive planning of effective and sustainable management interventions to facilitate unimpeded passage of aquatic organisms, debris, and water during various flow conditions, including floods (see Gillespie et al., 2014).

2.2. Remotely attributing structures

We drew on an open-access spatially explicit dataset of structures derived from the intersection of OS Open Rivers and Open Roads networks in the UK (Januchowski-Hartley et al., 2021). From the UK-wide dataset, we extracted 12,575 structures in catchments conterminous to Wales and attributed each as either a bridge, culvert, or ford. The attribution of types to structures was done using Google Earth Engine (GEE; Gorelick et al., 2017) and the OS roaming tool in EDINA Digimap (Digimap; https://digimap.edina.ac.uk/, last accessed 30 January 2021). The use of GEE and associated high-resolution satellite images and aerial photography was made possible through a bespoke code adapted from Whittemore et al. (2020).

All the authors who located and attributed structures as bridges, culverts, or fords (from here, mappers) were provided a training document, completed the same training dataset in the River Usk catchment (~1500 locations), and attended several on-line group discussions about images and examples of structures that were challenging, unclear, or difficult to attribute. During a given session in GEE, a mapper used the script to load structure points and river polylines (from OS Open Rivers) overlayed on a satellite image background, which was a mosaic of recently captured high-resolution images from Google Earth Engine (Gorelick et al. 2017). Once the imagery and spatial data files were loaded, the mapper scrolled to a structure location, made a visual assessment of the structure type, and attributed the structure as either a bridge (Fig. S1a in Supplement), culvert (Fig. S1b in Supplement), or ford (Fig. S1c in Supplement). The OS roaming tool was used alongside GEE because it visualised additional information, such as labels for bridges (Fig. S2a in Supplement) and fords (Fig. S2b in Supplement) as well as shapes and extents of structures, such as culverts (Fig. S2c in Supplement), which assisted our visual assessment and attribution of a type.

Whenever a mapper was unsure about the type of a structure viewed in GEE, be that because of low-resolution imagery or an obstructed view because of vegetation cover, the structure was initially mapped as 'not clear' and further visually assessed in GEE and the OS roaming tool by two mappers. If a mapper (either in GEE or OS roaming tool) determined through a visual assessment that a mapped location did not have a structure present, it was flagged as 'not a structure' ($n = 336$; <2% of mapped locations) and excluded from the spatial dataset as well as subsequent analyses in this paper. In addition, a single structure can span more than one road, especially in urban areas (e.g., underground rivers culverted below entire settlements) and on small streams and roads. With that in mind, we determined structures within 10m of another along a river polyline and removed one location of any pair from subsequent analyses. In total, we attributed a type to 11,844 of the 12,575 (~94%) structures in Welsh catchments; a process that began in April 2020 and finished in December 2020.

2.3. Associating structures with river network

We analysed the Ordnance Survey (OS) Open Rivers (Open Rivers; https://www.ordnancesurvey.co.uk/business-government/products/open-map-rivers, last accessed 01 April 2020) in RivEX 10.35 (Hornby,

2020) to ensure the spatial river network was topologically correct. The geographical location of a structure is important to know because it relates to its inherent sensitivity (see Januchowski-Hartley et al., 2014) and vulnerability to damage. With that in mind we associated our structures to the topologically corrected OS Open Rivers dataset and determined Strahler stream order (representing river size) for each river segment and all associated structures.

2.4. Screening-level assessment of vulnerability and risk

Risk of impact is described by IPCC (2014) as the interaction of hazards with the vulnerability and exposure of human and natural systems, and we adopted this characterisation in our screening-level assessment (Fig. 1). Using our ascribed structure dataset, our topologically corrected OS Open Rivers network, and other publicly available spatial data (detailed in the following paragraphs of this section), we undertook a screening-level assessment (Fig. 1) of culvert and bridge vulnerability (*sensitivity* + *exposure*) and current risk (*vulnerability* + *hazard*) of impact from flooding on environmental and social connectivity because of structural damage. We excluded fords from this analysis because these structures had low prevalence in the landscape and, by design, interact with rivers and flows differently to culverts and bridges.

We represented *sensitivity*, or the propensity of structure damage because of location, with the intersection of river size (Strahler stream order) and gradient (sourced from Januchowski-Hartley et al., 2021) (Fig. 1). Structures on smaller rivers and higher gradients are frequently damaged and tend to incur repeated repair costs (Gillespie et al., 2014; Januchowski-Hartley et al., 2014; O'Shaughnessy et al., 2016). We categorised all culverts and bridges as either low (1–3) or high (4–6) stream order and as either low (≤5%) or high (>5%) gradient, where those with low stream order (≤3) and high gradient (>5%) had high sensitivity to damage. There were 98 structures (<1%) near river mouths without gradient estimates because the original elevation dataset used by Januchowski-Hartley et al. (2021) did not extend to their locations, and we assumed their gradient was ≤5% based on their proximity to the river mouth.

We considered *exposure*, or the assets that could be adversely affected by structure damage (IPCC, 2014), as represented with by the intersection of built-up areas (BAU) (Built-up Areas Boundaries; https://data.gov.uk/dataset/15e3be7f-66ed-416c-b0f2-241e87668642/built-up-areas-december-2011-boundaries-v2, last accessed 01 April 2021) and special areas of conservation (SAC) (Special Areas of Conservation; https://jncc.gov.uk/our-work/special-areas-of-conservation-overview/, last accessed 01 April 2021) designated for river-obligate species. As discussed by Finley et al., (2015), human populations outside of built-up areas generally face a lack of road-network redundancies or alternative routes, and so frequent structure damage can disconnect communities by disrupting traffic-flow, emergency management, production, logistics, and business (Pregnolato 2019). Special areas of conservation designated for river-obligate species were included in exposure (Table S1 in Supplement), because the life cycles and persistence of these fishes and mussels depend on aquatic habitat connectivity, which can be disrupted by poorly constructed and damaged structures (see Sleight and Neeson, 2018; Gillespie et al., 2014). We categorised all culverts and bridges as either inside or outside built-up areas or special areas of conservation, where those that were outside built-up areas and inside special areas of conservation had high exposure (Fig. 1).

We characterised *vulnerability*, or the predisposition of structures to adversely affect people and river-obligate species, as the intersection of high sensitivity (stream order ≤3 and gradient >5%) and the level of exposure (inside or outside of built-up areas and special areas of conservation) (Fig. 1). We extracted high vulnerability culverts and bridges (where both sensitivity and exposure were high) and intersected these with the *hazard*, or the potential occurrence of a climate-related event that could lead to physical damage of structures that impacts and disconnects communities and ecosystems. We represented hazard with flooding likelihood; data were accessed from Natural Resources Wales

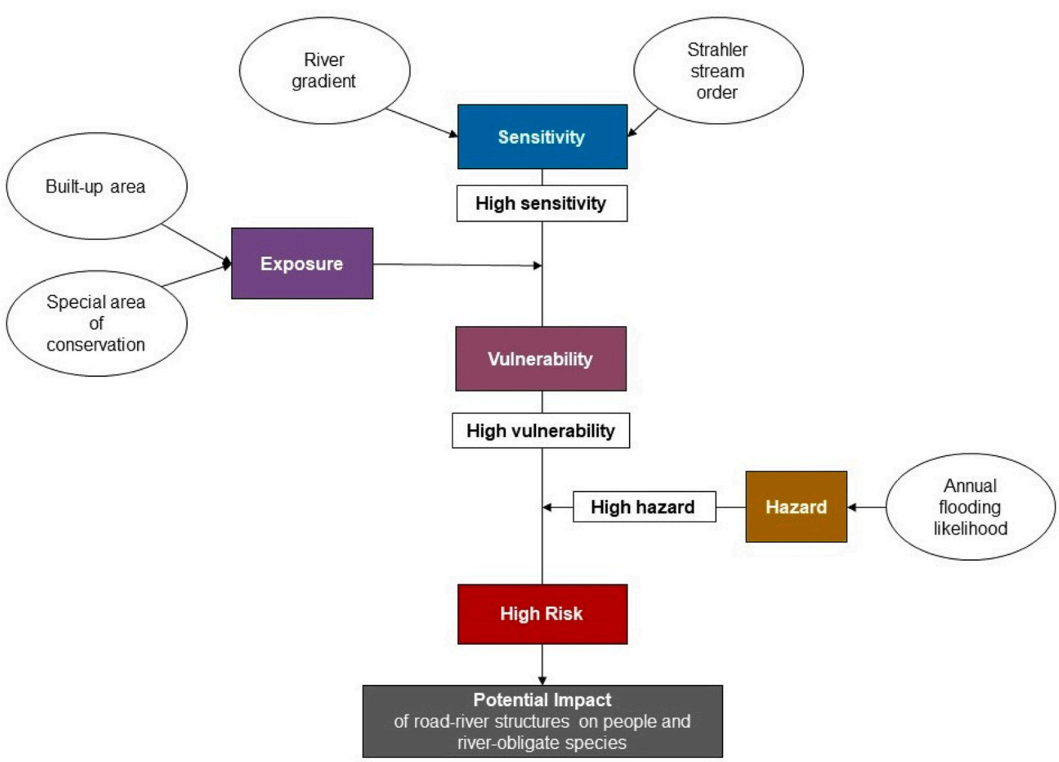

Fig. 1. Conceptual overview of screening-level assessment for culvert and bridge vulnerability (sensitivity + exposure) and risk (vulnerability + hazard) of potential structure impact on people and river-obligate species under flooding.

(NRW) (Flooding likelihood; https://datamap.gov.wales/layergroups/inspire-nrw:FloodRiskAssessmentWales, last accessed 30 December 2021). Annual flooding likelihood was modelled by NRW for both rivers and small watercourses (see Natural Resources Wales, 2019) and categorised as high (>3.3% likelihood/year), medium (1.0–3.3% likelihood/year), and low (0.1–1.0% likelihood/year). We determined hazard of flooding at each high vulnerability culvert and bridge as the category (high, medium, or low) occupying most of the area within a 100m buffer around each structure. We considered *risk*, or the potential for impacts on nature and people from structures under flooding, as the intersection of vulnerability and hazard, to identify high-risk culverts and bridges (Fig. 1).

2.5. Reliability of type attribution and screening-level assessment

We evaluated the reliability of our desktop-based approach to structure attribution and screening-level assessment of vulnerability and risk with an on-ground visual survey at a randomly selected subset of high-risk culverts and bridges in River Usk catchment. The assessment was carried out over three days in December 2021 and January 2022. At each structure visited, we did a visual assessment to confirm type (culvert or bridge) and sensitivity category (i.e., high - located on a smaller river and hillside or slope). We further assessed whether the subset of high-risk culverts and bridges showed physical structural or environmental degradation to further qualify our sensitivity criteria. Where possible, we collected images of each culvert or bridge, including of the inlet and outlet. We present these images as qualitative data to support our assessment findings and observed reliability of our structure attribution and screening-level assessment.

3. Results

3.1. Structure types and distribution in river networks

The majority of the 11,844 road-river structures that we attributed in Welsh catchments were culverts (n = 7,791), primarily found on Strahler steam order one (69%; n = 5,361) (Table 1). We found that bridges were half (n = 3,889) as abundant as culverts, and approximately evenly distributed across the lowest stream orders: one (24%; n = 939), two, (32%; n = 1,251) and three (27%; n = 1,036) (Table 1). Fords were just 1% of attributed structures in Welsh catchments (Table 1).

3.2. Culvert and bridge vulnerability and risk

Nearly a third (26%; n = 3,132) of culverts and bridges in Welsh catchments were classed as high sensitivity, the majority of which were culverts (85%; n = 2,667) (Fig. 2). Most culverts and bridges occurred on lower stream orders (≤3) in Welsh catchments, but because they occurred on lower gradients (≤5%), had lower sensitivity to damage (Fig. 2). The majority of culverts and bridges were outside built-up areas (85%; 10,037), of which more than a third (36%) were inside one of the six catchments designated a special area of conservation (n = 3,669; Fig. 2) and thus high exposure (Fig. 2). Nearly 10% (n = 873) of culverts and bridges intersected at both high sensitivity and exposure, giving them the highest vulnerability ranking (Fig. 2).

The majority (71%; n = 624) of structures classed as high vulnerability were also found to be in areas of high flooding hazard (i.e., >3.3% likelihood/year), and so classified as high risk (Fig. 2). The remaining high vulnerability culverts and bridges were in areas of predominantly low (n = 224) and medium (n = 10) flooding hazard; 15 structures did not have hazard data. High-risk culverts and bridges occurred across the six catchments with special areas of conservation, with the greatest number in River Usk (n = 255), followed by River Eden (n = 159) and River Tywi (n = 92) (Fig. 2).

Table 1
Number of bridges, culverts, and fords on Strahler stream orders 1–6, and total within Welsh river catchments.

Strahler stream order	Number of bridges	Number of culverts	Number of fords
1	939	5361	79
2	1251	1943	60
3	1036	456	19
4	513	30	6
5	136	1	0
6	14	0	0
Total	3,889	7,791	164

3.3. Reliability of attribution and screening-level assessment

More than 40% of all high-risk structures occurred in River Usk catchment, and we set-out to visit roughly 10% (n = 35) of those in our on-ground visual assessment. The majority (83%; 29/35) of the structures were correctly attributed (27 culverts and 2 bridges) and 3% (1/35) were attributed as a culvert when a bridge. A further 14% (5/35) of structures were located on private land and inaccessible for our visual assessment of sensitivity. Of the structures (n = 30) we assessed for sensitivity, 53% (n = 16) had obvious physical degradation, streambank erosion, and scouring (e.g., Fig. 3c and d), 17% (n = 5) showed little to no evidence of physical degradation but had obvious streambank erosion and scouring (Fig. 4a and b); and the remaining 30% (n = 9) could not be visually assessed because they were below human settlements (Fig. 4c).

4. Discussion

Our attribution and assessment process documents the abundance and distribution of structures with the potential for harm to riverine species and habitats and people in Wales. High sensitivity structures on small rivers commonly coincided with areas of high flooding hazard in Wales, and so heightened risk of impact to nature and people. Structures are more likely to be blocked, damaged, or fail under intensified flooding and negatively impact surrounding freshwater habitats and the movement of people and species (Gillespie et al., 2014). Our field-assessment indicated that a desktop-based approach can be reliable for attributing types (particularly culverts and bridges) to structures and identifying sensitivity to damage, highlighting the value and role that such assessments can have in proactive planning and monitoring our built and natural environment.

We were able to attribute a typology (i.e., bridge, culvert, or ford) to thousands of structures with a desktop-based method dependent on remotely collected imagery and data, which our catchment case-study indicated was highly accurate (83% correctly ascribed). Progressing toward more consistent and detailed spatial datasets of structures requires a willingness to use and accept remotely collected data alongside information obtained from on-ground assessments. Sheer numbers of structures and jurisdictional preferences in data collection and maintenance limit both the feasibility of on-ground assessments and synthesis of such datasets. Those limitations of on-ground assessments can be, in part, overcome with data collected remotely, such as 2-D and 3-D data derived from airborne photogrammetry or LiDAR, or imagery, which are increasingly available in many countries and can be used to manually or semi-automatically attribute some characteristics such as structure width or length. While remotely sensed 2-D and 3-D data are increasingly used to identify larger structures on rivers (e.g., Buchanan et al., 2022), the spatial resolution and perspective afforded by quasi-vertical-perspective methods (e.g., from most airborne or satellite sensors) can limit the quality of retrievable data, particularly underneath or alongside structures, or below vegetation along riverbanks. Therefore, attribution of additional structure characteristics such as size (e.g., length, width, height), condition (e.g., any cracking, scouring,

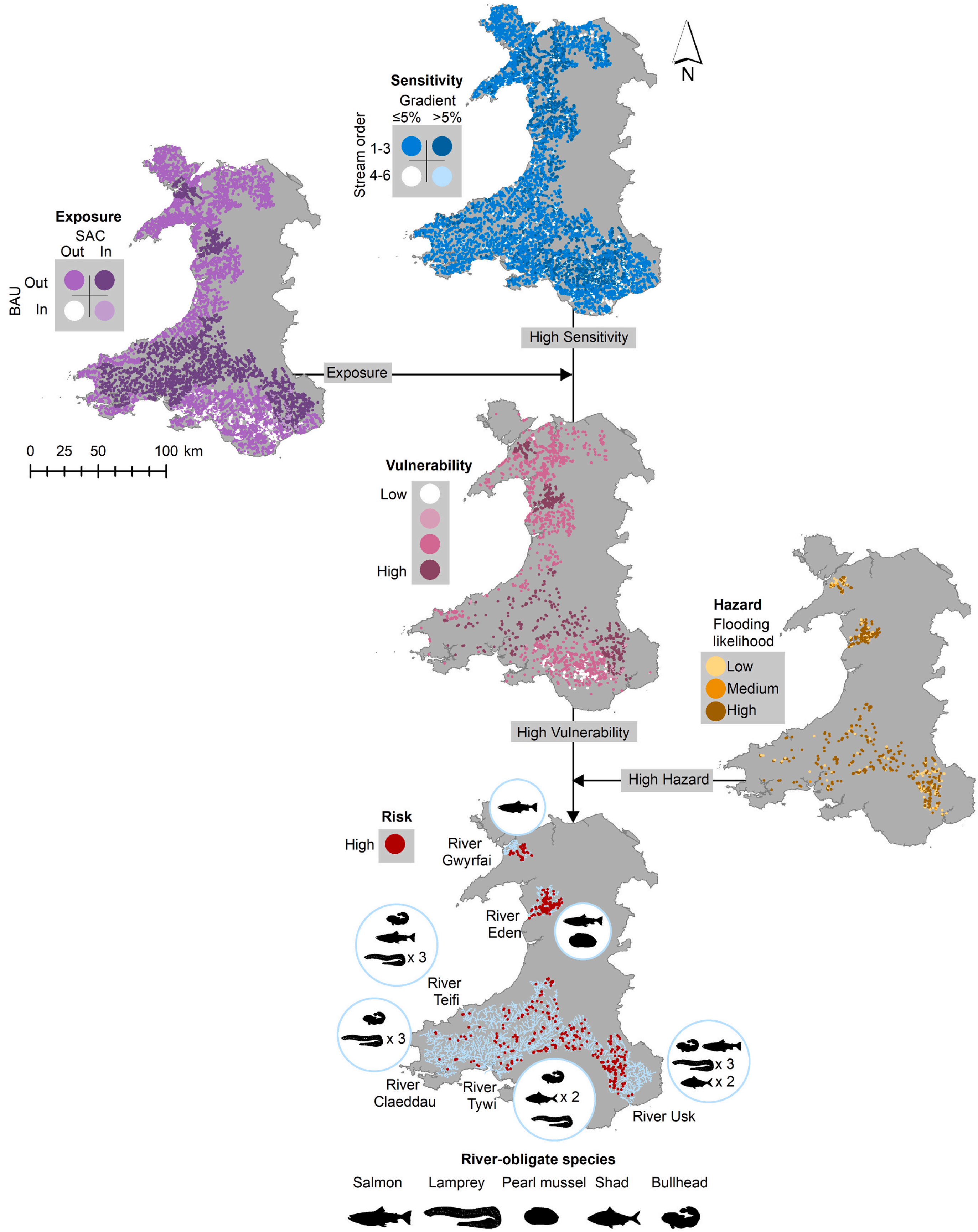

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Fig. 2. Distribution of road-river structure sensitivity (the intersection of gradient and Strahler stream order) and exposure (in relation to built-up areas and special areas of conservation designated for river-obligate species (shown at bottom of image)), where the intersection of high sensitivity and exposure (of any category) indicate vulnerability. Structures posing high risk of impact to the connectivity of rivers and communities (under flooding) intersect at high vulnerability (the intersection of high sensitivity and exposure) and high flooding hazard (where the initial hazard categories of yearly flooding likelihood were low (0.1–1.0%), medium (1.0–3.3%), and high (>3.3%)). All species images were sourced from PhyloPic (phylopic.org): Salmon was created by Timothy J. Bartley and included in this article under a CC BY-SA 2.0 license; Lamprey by Christoph Schomburg, Shad by Felix Vaux, Bullhead by Unknown, and Pearl mussel by Katie S. Collins are all included in this article under CC0 1.0 universal public domain dedication.

Fig. 3. Examples of culverts on small rivers with high gradients in River Usk catchment, United Kingdom. The culvert in (a) is viewed from the inlet and no outlet was visible; it had been filled with sediment. The culvert in (b) is viewed from the outlet, which is perched several metres above the riverbed. The culvert in (c) has substantial physical degradation, is perched >1 m above the riverbed, as well as erosion and scouring alongside and below the outlet of the structure. The culvert in (d) had moderate physical degradation, particularly scouring at the base of the structure and cracking of stones on the structure.

Fig. 4. Examples of culverts on small rivers with high gradients that either showed little to no evidence of physical degradation or could not be visually assessed in River Usk catchment, United Kingdom. The culverts in (a) and (b) were visually assessed and showed little to no evidence of physical degradation but had obvious streambank erosion and scouring at the structure. The culvert in (c) could not be visually assessed because it was under a human settlement.

washout, or collapse), or interaction with the river (e.g., presence of a drop from a structure outlet to the river or no substrate in the structure) that are relevant to decision making about transportation networks and freshwater species and habitats, are likely impractical or unobtainable from remote sensing methods alone. The way forward for consistent attributed spatial datasets of structures, in Wales and elsewhere, is to develop collaborative agreements that synthesise existing data and design targeted collection campaigns to address gaps through both on-ground and remotely sensed methods. Multi-method approaches are needed because not all attributes can be determined remotely and the enormity of the problem limits what can be achieved through site visits.

As discussed for roads in other regions (Chinowsky et al., 2013), as well as for larger river structures such as dams (Thieme et al., 2020), there is both a need and opportunity to replace high-risk culverts and bridges, both in Wales and elsewhere, with stream simulation designs that maintain geomorphic and hydrologic continuity with the river channel (Gillespie et al., 2014; Wagner, 2015; Frankiewicz et al., 2021). Our screening-level assessment identified some 600 structures that are likely to benefit from replacement with stream simulation designs. While infeasible for a single agency or group to visit all structures, co-ordinated effort by responsible public agencies (particularly those within common catchment areas) in Wales, as set forth in the Well-being Act, would make planning of ground-truthing and replacement priorities more achievable. As established by the UK's Climate Change Committee (2021), and discussed in other regions (e.g., North America; Bowden and Burns, 2019), such steps are critical given the challenges that communities and river-obligate species face with weather-related disasters and ongoing climate change (e.g., capacity to live with interannual variability in high and low flows and flooding).

While the opening of watercourses for species movements is an ongoing priority for Natural Resources Wales and similar agencies in England and Scotland, efforts to date have been done in opportunistic and *ad hoc* ways, including those pursued by Local Government Authorities and Trunk Road Agents who are responsible for structure maintenance. The lack of coordinated planning or priority setting is due in part to no environmental regulator in the UK holding a comprehensive dataset of watercourse structures that includes smaller culverts, bridges, or fords (Jones et al., 2019). The structure dataset presented in this paper is an essential component of catchment-based planning and management, and so should be part of associated workflows and partnerships such as those pursued through Catchment Based Approaches (CABA) (Catchment Based Approaches, https://catchmentbasedapproach.org/, last accessed 11 June 2022). In cases where catchments are nested within larger basins, then the structure dataset that we presented would be useful in cross-catchment or national-scale planning or priority setting that identifies more cost-effective solutions to restore connections that benefit nature as well as people (see Hermoso et al., 2021). The process towards proactive adaptation and maintenance, including repair, replacement, and monitoring of structures, is inherently a socio-cultural process that will require consultation among interested parties and stakeholders, including publics, as is pursued through the CABA partnerships growing in Wales and England. For example, we focused on two types of exposure (outside of built-up areas and inside special areas of conservation), but other forms (e.g., important fisheries areas or locations and density of emergency services) could also be considered. Further, local knowledge and priorities, such as granular information on the redundancy of a road network around a particular structure, or the habitat suitability for riverine fishes could also be relevant when considering community and ecosystem wellbeing. Such attributes could be integrated into screening-level assessments, planning or priority setting initiatives in the UK or elsewhere in the world.

Our fully attributed spatial dataset provides a starting point to initiate and support proactive climate change adaptation planning for transportation and freshwater systems in the UK. Our spatial dataset fills a gap in the under-reporting of small structures (particularly, culverts) previously highlighted for the UK (Jones et al., 2019) and for Europe more broadly (Belletti et al., 2020). We found that culverts and bridges, the two dominant structure types, tended to occur on smaller rivers (Strahler stream order 1–3). While our dataset is an important advance in systematic inventory, it also likely underestimates the smallest of structures. In part, this is because higher resolution river and road network data exist for the UK but are paywalled and not available through open licenses (Open Government License https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/, last accessed 31 January 2022). Making higher resolution river and road network data openly available would be invaluable to capture structures missed with our method, so to further our understanding of vulnerabilities, risks, and potential impacts linked with structures. We also anticipate more culverts and fords on rivers that intersect smaller, temporary (e.g., forestry or wind power roads and tracks) and private roads, many of which could be informal, and likely not captured by the UK's higher resolution road and river networks. Smaller, informal roads and tracks are difficult to monitor and assess, and often have poorly designed and installed structures that negatively impact surrounding aquatic and terrestrial environments (Maitland et al., 2016; Kuklina et al., 2021). It is critical to address these information gaps, requiring collaboration and agreements between governments, public bodies, and other groups to do so.

Author contributions

SJ managed the project and obtained funding. SJ, XY, MP, CG, JR, JW, SP, SM, and FJ conceived the research ideas and goals. All authors contributed to literature review and methodology. SJ and XY led data curation, and XY wrote the code for Google Earth Engine. SJ, SP, MJ, RB, SM, and JW generated the type-attributed structure dataset; SJ conducted the data analysis. SJ and FJ conducted the validation field surveys, and prepared and created the figure visualisations. SJ and FJ wrote the manuscript draft. All authors critically reviewed and edited the manuscript.

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Declaration of competing interest

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.

Data availability

Data available on Figshare: https://doi.org/10.6084/m9.figshare.16627873.v5.

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Appendix A. Supplementary data

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