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Assessing river condition: A multiscale approach designed for operational application in the context of biodiversity net gain

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Abstract

Assessments of river condition are needed to guide all aspects of river management. Such assessments have evolved over three decades from simply capturing the mosaic of river physical habitats to recognizing that habitat mosaics are dynamic, driven mainly by physical processes and modified by human (indirect) pressures and (direct) interventions. To embrace these broader aspects, riparian as well as in-stream environments need to be evaluated, going beyond subjective assessments to incorporate observations that support understanding of both physical habitat structure and cause-effect relationships. This paper reports on an operational approach to assessing the physical condition of rivers, which attempts to bridge the gap between a physical habitat and a geomorphic condition assessment. The approach forms part of Biodiversity Metric 2.0, a habitat-based methodology for measuring and accounting for biodiversity losses and gains resulting from development or land management change at individual project sites across England. The river condition assessment component adopts a bottom-up multi-scale approach that integrates field observations of physical habitats and of features indicative of geomorphic processes to deliver assessments of longer subreaches, whose condition is then evaluated within the context of the reach-scale geomorphological type of river. By applying the assessment before, immediately after, and following recovery from project implementation, changes in condition and their causes can be evaluated. The assessment method is presented to an international audience, outlining its structure, application and testing, and critically discussing its strengths and weaknesses, because the methodological approach could be helpful for devising methods for application in other environmental contexts.

KEYWORDS

biodiversity net gain, geomorphic condition assessment, river condition assessment, river habitat survey

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1 | INTRODUCTION

Assessments of river condition are needed to guide all aspects of river management from conservation to mitigation and restoration (Fryirs, 2015) and increasingly to inform decision-making around biodiversity net gain in relation to proposed river-related developments (Crosher et al., 2019). With the growing recognition, from the early 1980s, of the importance of physical habitat for river ecosystem health (see e.g., Calow & Petts, 1994; Maddock, 1999) numerous approaches to assessing the physical habitat quality of rivers have been developed in recent decades, often to complement more established methods for evaluating water quantity and quality and biological quality. Several reviews have compared the plethora of approaches developed and applied worldwide to meet different objectives and reflect local environments (Belletti, Rinaldi, Buijse, Gurnell, & Mosselman, 2015; Fernandez, Barquin, & Raven, 2011; Fryirs, 2015; Fryirs, Arthington, & Grove, 2008; Parsons, Thoms, & Norris, 2004; Raven et al., 2002; Tadaki, Brierley, & Cullum, 2014; Weiss, Matouskova, & Matschullat, 2008) and so we do not attempt such a review here. Instead, we use information extracted from these previous reviews to present a brief overview of river physical assessment approaches. Overall, such methods have evolved from early ones designed to capture the mosaic of river physical habitats at the time of survey to those that increasingly recognize that habitat mosaics are dynamic, driven mainly by physical processes and modified by human (indirect) pressures and (direct) interventions. The character and condition of river ecosystems depends on such physical dynamics.

In relation to early approaches, Raven et al. (2002) and Weiss et al. (2008) provided insights concerning methods devised to assess the "hydromorphological quality" of rivers, as required by the European Union's (EU) Water Framework Directive in establishing the ecological status of rivers. Parsons et al. (2004) made a similar call for standardization but at the national level following a review of existing methods of river habitat assessment in Australia. Some general observations on river habitat assessment approaches emerge from the international review by Fernandez et al. (2011). Of the 55 assessment methods analysed, most gather data at a single spatial scale, focusing either on a fixed river length or a river length scaled to the river's width but typically less than 1 km long (hereafter referred to as the subreach scale). Nearly all of the methods are field based and designed for single thread, perennial rivers and streams that are wadeable. Many of the methods are qualitative, providing subjective scores on groups of physical habitat characteristics. However, most record semi-quantitative observations of characteristics such as channel dimensions, flow types or flow status, channel substrate, bank stability, riparian vegetation structure, artificial structures, and adjacent land uses. Additionally, in most cases, the methods focus on instream and immediate riparian habitats, frequently omitting any information on the valley and river network structure. Nevertheless, some methods capture basic valley and river characteristics such as slope, stream order and presence of a floodplain, for longer river lengths (>1 km and typically 10 km or more in length, hereafter called the reach scale) within which field-surveyed subreaches are located.

Belletti et al. (2015) produced the most comprehensive review to date as a part of their work within the collaborative EU-funded project, REFORM, which aimed to develop guidance and tools to improve river restoration practice (http://www.reformrivers.eu/). They reviewed 121 hydromorphological methods published between 1983 and 2013, across 26 countries. These include 61 methods from 18 European countries, reflecting the increase in new approaches developed since 2000 in response to implementation of the EU Water Framework Directive. They assigned each method to one of four categories, identifying 11 hydrological methods that assess the nature and any alteration of a river's flow regime and 15 methods that focus on the assessment of riparian conditions. The most common group included 73 methods and protocols that characterize and classify physical habitat elements, which they described as physical habitat assessments or river habitat surveys. Lastly, a group of 22 "morphological assessment" methods provide a broader evaluation of river physical conditions, including assessments of channel forms, geomorphic adjustments, and human alterations. The distinguishing feature of these "morphological assessment" methods is that they go beyond a simple record of the physical habitats that are present. They emphasize river dynamics and processes, particularly through pressure and response variables or indicators, and they support understanding of not only physical habitat structure but also cause-effect relationships, something which Tadaki et al. (2014) stressed as important. Following from what Belletti et al. (2015) define as "morphological assessment" methods, Fryirs (2015) provides an in-depth review of "geomorphic condition assessments". She emphasizes the difference between classification procedures, which simply group similar morphologies, and condition assessments, which compare observed conditions with those that are "expected" for river reaches of the same geomorphic river type.

Here we report on an operational approach to assessing the physical condition of rivers that attempts to bridge the gap between a "physical habitat assessment" as defined by Belletti et al. (2015) and a "geomorphic condition assessment" as defined by Fryirs (2015). Although the method is designed for application within England, it is presented to an international audience because the broad approach could be helpful to others devising similar assessment methods for application in other environmental contexts.

Following an explanation of why a new condition assessment method was developed (Section 2), a brief overview is provided (Section 3) and the method is elaborated in more detail (Section 4). The method is then applied to a calibration data set (Section 5) to illustrate its performance and how it can be used to evaluate river condition at different levels of detail. The potential future development and broader applications of the method are discussed (Section 6) before some brief concluding remarks (Section 7).

2 | WHY A NEW CONDITION ASSESSMENT METHOD WAS DEVELOPED

The method for assessing river condition was designed to deliver one component of Biodiversity Metric 2.0 (BM2, Crosher et al., 2019), a methodology for measuring and accounting for biodiversity losses and gains resulting from development or land management change across England. Despite the availability of the numerous assessment methods described in the previous section, a new method was needed that would match the specific requirements of BM2.

First, BM2:

> "provides developers, planners, land managers and others with a tool to help limit damage to nature in the first place and to help it thrive. The metric uses habitat features as a proxy measure for capturing the value and importance of nature. It uses a simple calculation that takes into account the importance of these features for nature: their size, ecological condition, location and proximity to nearby "connecting" features. The metric enables assessments to be made of the present and forecast future biodiversity value of a site. This can be applied to an individual field or an entire river catchment" (Crosher et al., 2019, p. 6).

This context demanded that the rivers and streams component was habitat-based, emphasizing river condition, river length and connectivity. This constrained any potential reuse of previously-developed methods to those that assessed habitats.

Second, BM2 is applied to the area within the "red line" boundary which defines the perimeter of a development site. Many development sites in England are small, and so the method needed to be equally applicable to small as well as large sites. There was no suitable pre-existing pan-European method for assessing rivers that was habitat-based and delivered a condition assessment at the required scale(s) with a quantitative condition score appropriate to the BM2 scheme. The "River Habitat Survey" (RHS) is a "method designed to characterize and assess, in broad terms, the physical structure of freshwater streams and rivers" (Environment Agency, 2003) that was developed for application across the UK to identify and characterize broad contrasts in physical habitat within and between river networks. The RHS survey is widely used and very successfully achieves its stated aims, but it is applied to a fixed subreach length of 500 m, which is too long for the present application. Furthermore, in order to capture habitat across 500 m, RHS incorporates systematic transect sampling of certain physical habitats. Such systematic sampling is appropriate for the applications for which RHS was designed, but not for the present application. In the context of BM2, a habitat-based method was required that had sufficient spatial resolution for detailed monitoring and to support forecasting, while being sufficiently flexible to allow assessments of project sites regardless of their geographical extent.

The River Condition Assessment tool described in this paper meets both of the above requirements. Individual field survey units (modules) characterize a length of river that is 10 to 50 m long (depending on the river width), multiples of which are aggregated into subreaches 50 to 250 m in length. Within these short lengths the field survey records the presence, abundance or dominance of a long list of natural and human-related features across the bank tops, bank faces and river bed. This provides measurements at a sufficient spatial resolution to deliver a sensitive assessment of the physical condition of the river subreach, and to allow repeat surveys (monitoring) to capture even quite subtle changes over time. In addition, the surveyor takes three photographs from the bank top at the mid-point of each module to capture the central bank top to bank top cross section, and the upper and lower parts of the survey area. These photographs support precise relocation of survey sites for monitoring purposes as well as providing a pictorial impression of how the subreach changes between surveys.

In addition to meeting the requirements of BM2 and maintaining compatibility with RHS (the field survey incorporates the same suite of physical features as RHS), the opportunity was taken to develop a method that could help to bridge the gap between the required physical habitat survey and a more process-oriented geomorphic condition assessment by incorporating the following features:

1. The field survey data are interpreted in the context of the river's geomorphic type because different types of river support different suites of habitats and differ in the nature and rate of habitat turnover.
2. The field data are interpreted to reflect the fact that in the humid temperate and fairly low river energy environment of England, riparian and aquatic plants are important drivers of geomorphic dynamics (Cotton, Wharton, Bass, Heppell, & Wotton, 2006; Corenblit, Tabacchi, Steiger, & Gurnell, 2007; Gurnell, 2014; Gurnell, Bertoldi, & Corenblit, 2012, Gurnell, Corenblit, et al., 2016).
3. The method derives over 30 condition indicators from field survey data. The scores on each of the condition indicators illustrate the degree to which a surveyed river shows positive (natural) or negative (human modified) elements of condition.
4. Likely maximum values of the positive condition indicators are proposed for each river type, because different types of river should show different characteristics, allowing the functioning of different types of river to be accounted for in the assessment. For example, a low-energy, silt-bed river in good condition may not display diverse bed material or sedimentary bed features but in England it would be expected to support varied aquatic and riparian vegetation and vegetation-related physical features (e.g., vegetated bars, berms, benches, islands; see Gurnell, O'Hare, O'Hare, Scarlett, & Liffen, 2013).
5. A preliminary, integrative, condition score is calculated from the set of individual condition indicator scores in the same way for all river types, but it is then translated into a final condition score taking into account the geomorphic type of river under consideration. Furthermore, the expected (likely maximum) condition indicator scores for each river type can be used to identify why a particular river subreach is not achieving good condition, given its river type.
6. In addition to the typical habitats captured in a habitat-based assessment, the field survey records numerous features that are indicative of geomorphic processes and channel evolutionary trajectories (e.g., channel dimensions; bed siltation; bank

stratigraphy; process-specific bank profile types; marginal and in-channel geomorphic features including those initiated by naturally-functioning [unmanaged] dead and living vegetation).

While the proposed river condition assessment tool may not provide a fully-fledged geomorphic condition assessment, it is far more than a simple physical habitat assessment tool. It has been designed for application by river professionals, regardless of their scientific discipline, but it has a firm geomorphological underpinning.

3 | METHODOLOGICAL OVERVIEW

3.1 | The river condition assessment methodology

The river condition assessment methodology is designed for application to the relatively small rivers, subdued topography, humid-temperate climate and heavy human pressures and interventions experienced in areas of relatively high population density typically found in England. It is a multi-scale science-based approach, incorporating the following components:

1. At the finest spatial scale, a field survey that focuses on short lengths ("modules") of river, within which the type and abundance of all physical features are recorded comprehensively at the same spatial scale. The field survey (called MoRPh, see Section 3.2) records information within an area extending across the river to include the bed, bank faces and bank tops, and along the river for a length that approximates twice the river width. The broader floodplain is not surveyed because its characteristics are captured within other components of BM2.
2. The survey assesses riparian and aquatic vegetation structure and the variety and abundance of riparian and channel physical materials and features, including those that are indicative of contemporary physical processes. It also assesses the variety and abundance of human physical (direct) interventions and (indirect) pressures.
3. River module surveys provide the finest scale element of a three-tiered spatial assessment of river condition: "module" (river length approximately twice the river width); "subreach" (river length approximately 10 times the river width); and "reach" (river length typically >5 km).
4. One or more subreach surveys are conducted within a development site (hereafter called the project site) to provide a minimum coverage of 20% of the river length with at least one surveyed subreach located to capture the apparently most physically degraded part of the river.
5. The provisional physical condition of the river is assessed for each surveyed subreach using more than 30 condition indicators extracted from the field survey data. A final condition assessment and score (good-5, fairly good-4, moderate-3, fairly poor-2, poor-1) is then produced for each subreach to reflect its condition in relation to what might be expected to be achieved given the geomorphic type of the river reach within which the project site is located.

3.2 | The MoRPh survey

The river condition assessment method incorporates the pre-existing MoRPh field survey (Gurnell, England, Shuker, & Wharton, 2019; Shuker et al., 2017), which was developed to enable UK citizen scientists to survey physical habitat at a scale that is compatible with biological surveys. Since its launch in 2016, over 500 surveyors have been trained and over 3,000 MoRPh surveys have been undertaken for sites across the United Kingdom and Republic of Ireland. MoRPh's development was prompted by wide adoption within the UK of the Riverfly citizen science survey (www.riverflies.org, Di Fore & Fitch, 2016), which captures macroinvertebrate data, and the desire to characterize physical habitat at Riverfly monitoring sites.

MoRPh was designed to be applied to the small (≤30 m wide) single thread river channels that are typical of England. The field survey records the physical and vegetation structural features and human interventions and pressures across the river bed, the channel edge-water margins, the bank faces and the bank tops to a distance of 10 m (Table 1). Observed characteristics or features are recorded according to their cover abundance (i.e., A = absent, T = trace (<5% cover), P = present (5–33% cover), E = extensive (>33% cover)) or a count of the feature type or in a few cases simply by their presence. On the rare occasions where small (≤30 m wide) multithread rivers are encountered, a single MoRPh module survey is applicable where both outer banks are visible from the bank top location used as an observation point. This could be the case for bar-braided channels and channels containing small islands. Otherwise, the MoRPh survey is applied to individual channels within multithread systems, with the combined survey information capturing the river's integrated physical character. By surveying several contiguous modules, the survey can be upscaled to capture the range of physical habitats accessible to mobile species such as fish, and also the geomorphic properties of an extended river subreach.

An on-line information system supports input and storage of MoRPh survey data, calculation and mapping of indicators extracted from survey data, and data downloads into spreadsheets and GIS layers (www.modularriversurvey.org).

4 | ASSESSING RIVER CONDITION

The River Condition Assessment tool evaluates river condition within a project site (Figure 1). It incorporates field (MoRPh module) surveys of one or more MoRPh5 subreaches (sets of five contiguous MoRPh module surveys) and a desk-based assessment of the indicative geomorphic type of the river reach containing the project site (Figure 1).

MoRPh5 surveys are conducted to cover at least 20% of the river length within the project site, ensuring that no two subreaches are more than four subreach lengths apart and that one of the subreaches captures the apparently most degraded part of the river channel (Figure 1a). The length of each MoRPh module is 10, 20, 30, or 40 m depending, respectively, upon whether the river is <5 m, 5–<10 m, 10–<20 m or 20–<30 m wide. Additionally, rivers over 30 m wide or where the river is too wide and/or deep to adequately survey the

TABLE 1 Information captured by a MoRPh module survey

Location	Type of information	Summary of recorded properties
Channel cross section	Channel dimensions	Left and right bank heights, bankfull width, water width and water depth at time of survey
Bank tops within 10 m of channel edge (right and left banks surveyed separately)	Artificial ground cover	Abundance of: footpath-pedestrianized, transport infrastructure, industrial-commercial buildings, residential buildings, storage areas, landfill areas, arable agriculture-allotments, permanently-vegetated agriculture (pasture, orchard), permanently vegetated recreation (playing fields, parks, gardens), plantation woodlands, open water (canal, reservoir)
	Terrestrial vegetation	Abundance of: unvegetated, mosses/lichens, short/creeping herbs/grasses, tall herbs/grasses, scrub/shrubs, saplings/trees
	Tree features	Abundance of: fallen trees, leaning trees, J-shaped trees, branches trailing into river, large wood
	Non-native invasive plant species (NNIPS)	Abundance of: Himalayan Balsam, Japanese Knotweed, Giant Hogweed, Floating Pennywort, other species 1, other species 2
	Water-related features	Abundance of: disconnected ponds, connected ponds, side channels, wetlands (a) short non-woody vegetation (b) tall non-woody vegetation (c) shrubs and trees
Bank faces and water's edge (right and left banks surveyed separately)	Natural bank profiles	Dominant and subdominant types and abundance from: vertical, vertical with overhang, vertical undercut, vertical with toe, steep, gentle, complex
	Artificial bank profiles	Dominant and subdominant types and abundance from: resectioned, two-stage, embanked, set-back embankment, poached.
	Natural bank materials	Dominant and subdominant material types and abundance in upper and lower bank face: bedrock, boulder, cobble, gravel, earth, sand, silt, clay, organic, peat
	Artificial bank materials	Concrete, concrete and brick/stone (cemented), brick/stone (cemented), sheet piling, wood piling, builder's waste (rubble), rip-rap, gabions, willow spiling, planted reeds, biotextiles, washed out. Dominant and subdominant types, horizontal and vertical extents
	Bank and channel margin natural features	Abundance of: unvegetated and vegetated side bars, berms, benches, stable and eroding cliffs, toe deposits, nest holes/burrows, marginal backwaters, tributary confluences
	Bank and channel margin artificial features	Number and extent of: pipes/outfalls, jetties, deflectors
	Terrestrial vegetation	Abundance of: unvegetated, mosses/lichens, short/creeping herbs/grasses, tall herbs/grasses, scrub/shrubs, saplings/trees
	Tree features	Abundance of: fallen trees, leaning trees, J-shaped trees, branches trailing into river, large wood, exposed tree roots, discrete organic accumulations
	Aquatic vegetation at bank-channel margin	Abundance of: liverworts/mosses, emergent broad-leaved, emergent linear-leaved, amphibious, filamentous algae
	Non-native invasive plant species (NNIPS)	Abundance of: Himalayan Balsam, Japanese Knotweed, Giant Hogweed, Floating Pennywort, other species 1, other species 2

(Continues)

TABLE 1 (Continued)

Location	Type of information	Summary of recorded properties
Channel bed	Natural bed materials	Abundance of: bedrock, boulder, cobble, gravel, sand, silt, clay, organic, peat, continuous thin overlying silt layer, patchy thin overlying silt layer
	Artificial bed materials	Abundance of dominant and subdominant type from: concrete, concrete and brick, brick, sheet piling, wood piling, builder's waste, rip-rap, gabions
	Water surface flow types	Abundance of: free fall, chute, broken standing waves, unbroken standing waves, upwelling, ripples, smooth, imperceptible flow, dry
	Natural physical bed features	Abundance of: exposed bedrock, exposed vegetated and unvegetated boulders/rocks, vegetated/unvegetated mid-channel bars, islands, cascades. Counts of: Pools, riffles, steps, waterfalls
	Artificial physical bed features	Abundance of: large trash, bridge shadow. Count of: large, medium, and small weirs, bridge piers. Presence of culverts
	Aquatic vegetation within the wetted channel	Abundance of: unvegetated, liverworts/mosses, emergent broad-leaved, emergent linear-leaved, floating leaved, free floating, amphibious, submerged broad-leaved, submerged linear-leaved, submerged fine-leaved, filamentous algae
	Vegetation interacting with the wetted channel	Abundance of: shade, submerged tree roots, large wood, discrete accumulations of organic material. Count of: large wood dams, fallen trees
	Non-native invasive plant species (NNIPS)	Abundance of: Himalayan Balsam, Japanese Knotweed, Giant Hogweed, Floating Pennywort, other species 1, other species 2

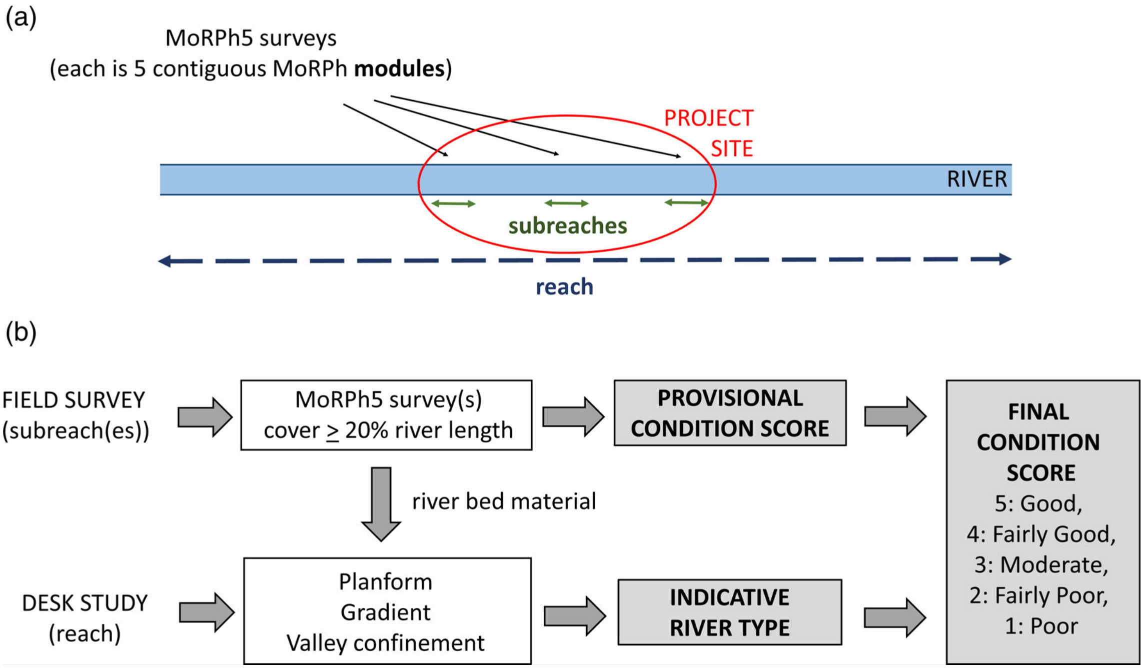

FIGURE 1 Structure of the river condition assessment: (a) Schematic of the three scales of spatial unit (module, subreach, reach) and their relationship to the project site; (b) Flow diagram illustrating how the provisional condition score, estimated from field surveys of 5-module subreaches is combined with the indicative river type estimated from a reach-scale desk study to assign a final condition score for each subreach

submerged bed are termed "large rivers" and are surveyed using a module length of 50 m. A 50 m module length is also used for canals and navigable rivers. Once field surveys are uploaded, the information system generates values of 35 indicators for each MoRPh5 subreach from the field survey data (Table 2).

Three of the subreach indicators describe the river's bed material. The values of these obtained for the coarsest surveyed subreach within the project site are combined with five river type indicators extracted from a desk-based assessment of the river reach containing the project site to define an indicative river type (Section 4.1, Figure 1b).

TABLE 2 Indicators extracted from desk study and field survey data and used to estimate the indicative river type and preliminary river condition for each subreach (Refer to Part 1 in Data S1 for definitions and formulations)

Indicator code	Indicator name	Source	Used to assess
A1	Braiding index (BI)	Desk study	Indicative river type
A2	Sinuosity index (SI)	Desk study	Indicative river type
A3	Anabranching index (AI)	Desk study	Indicative river type
A4	Level of confinement (U, PC, C)	Desk study	Indicative river type
A5	Valley gradient	Desk study	Indicative river type
A6	Bedrock reaches	Field survey	Indicative river type
A7	Coarsest bed material size class	Field survey	Indicative river type
A8	Average alluvial bed material size class	Field survey	Indicative river type
B1	Bank top riparian vegetation structure (+)	Field survey	Preliminary river condition
B2	Bank top tree feature richness (+)	Field survey	Preliminary river condition
B3	Bank top water-related features (+)	Field survey	Preliminary river condition
B4	Bank top NNIPS cover (–)	Field survey	Preliminary river condition
B5	Bank top managed ground cover (–)	Field survey	Preliminary river condition
C1	Bank face riparian vegetation structure (+)	Field survey	Preliminary river condition
C2	Bank face tree feature richness (+)	Field survey	Preliminary river condition
C3	Bank face natural bank profile extent (+)	Field survey	Preliminary river condition
C4	Bank face natural bank profile richness (+)	Field survey	Preliminary river condition
C5	Bank face natural bank material richness (+)	Field survey	Preliminary river condition
C6	Bank face bare sediment extent (+)	Field survey	Preliminary river condition
C7	Bank face artificial bank profile extent (–)	Field survey	Preliminary river condition
C8	Bank face reinforcement extent (–)	Field survey	Preliminary river condition
C9	Bank face reinforcement material severity (–)	Field survey	Preliminary river condition
C10	Bank face NNIPS cover (–)	Field survey	Preliminary river condition
D1	Channel margin aquatic vegetation extent (+)	Field survey	Preliminary river condition
D2	Channel margin aquatic morphotype richness (+)	Field survey	Preliminary river condition
D3	Channel margin physical feature extent (+)	Field survey	Preliminary river condition
D4	Channel margin physical feature richness (+)	Field survey	Preliminary river condition
D5	Channel margin artificial features (–)	Field survey	Preliminary river condition
E1	Channel aquatic morphotype richness (+)	Field survey	Preliminary river condition
E2	Channel bed tree features richness (+)	Field survey	Preliminary river condition
E3	Channel bed hydraulic features richness (+)	Field survey	Preliminary river condition
E4	Channel bed physical feature extent (+)	Field survey	Preliminary river condition
E5	Channel bed physical feature richness (+)	Field survey	Preliminary river condition
E6	Channel bed material richness (+)	Field survey	Preliminary river condition
E7	Channel bed siltation (–)	Field survey	Preliminary river condition
E8	Channel bed reinforcement extent (–)	Field survey	Preliminary river condition
E9	Channel bed reinforcement material severity (–)	Field survey	Preliminary river condition
E10	Channel bed artificial features severity (–)	Field survey	Preliminary river condition
E11	Channel bed NNIPS extent (–)	Field survey	Preliminary river condition
E12	Channel bed filamentous algae extent (–)	Field survey	Preliminary river condition

Thirty-two of the subreach indicators refer to different aspects of the condition of the river and contribute to a provisional numerical condition score for the subreach (Section 4.2, Figure 1b).

The provisional condition score for each subreach is then translated into a categorical final condition score (5-good, 4-fairly good, 3-moderate, 2-fairly poor, 1-poor), which takes account of what is potentially attainable given the indicative river type within which the project site is situated (Section 4.3, Figure 1b).

4.1 | Indicative river type

A geomorphologically-based assessment of river type is not a simple process since river characteristics vary along a continuum. However, knowledge of the broad geomorphic type of river is useful for defining the physical habitat and vegetation structural assemblage that the river may display when it is functioning naturally.

Thirteen of the river types (inspired by Rinaldi, Gurnell, González del Tánago, Bussettini, & Hendriks, 2016) incorporated in the assessment (Figure 2) are those geomorphic types that may be found within England, including three multithread types that are rare under present conditions but which occurred more widely in the past when human (indirect) pressures and (direct) interventions were less intrusive.

Eight variables were used to assign an indicative geomorphic river type within a decision tree (Figure 3). Five of the river type indicators (Table 2) are derived from maps or digital elevation models and aerial imagery: A1 – Braiding index; A2 – Sinuosity index; A3 – Anabranching index; A4 – Level of valley confinement; A5 – Valley gradient. The remaining three indicators (A6 – Bedrock reaches; A7 – Coarsest bed material size class; A8 – Average alluvial bed material size class) are drawn from the subreach survey revealing the coarsest bed material, with the proviso that these three indicators, particularly A7, need to represent a natural component of the bed material and not, for example, material that has been artificially introduced from washed out reinforcement or other infrastructure, or as part of a pre-existing "restoration" design. The formulations used to calculate each indicator are reported in Supporting Information (Data S1) Part 1.

The decision tree (Figure 3) used to assign a river reach to a geomorphic type has been tested using a calibration data set (Section 5). However, under some circumstances professional judgement may suggest that the automatically-generated river type is inappropriate for a valid geomorphological reason and a more suitable type may be

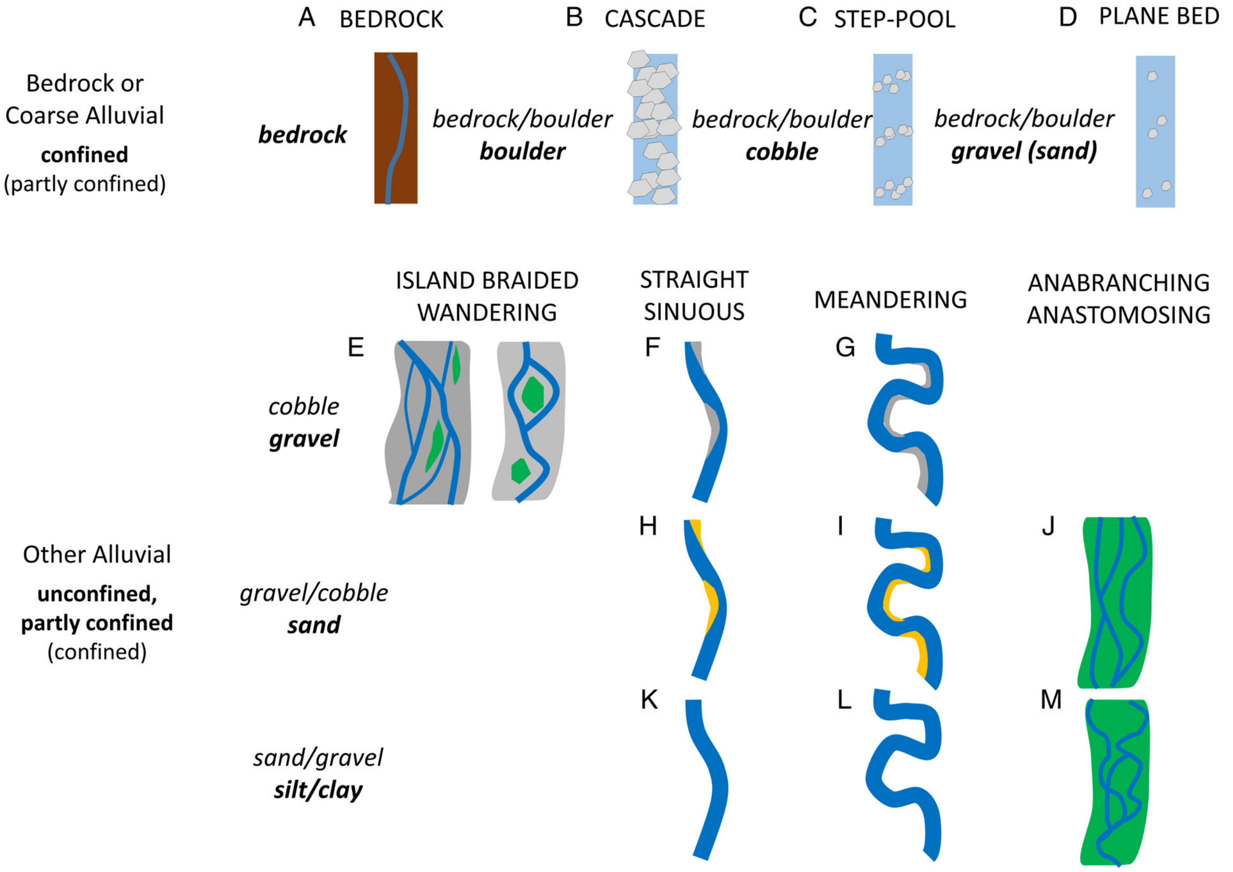

FIGURE 2 Thirteen indicative river types (A to M) that may be found in England, reflecting their bed material, planform, and valley confinement. (Bed material size is indicated in an italic font with the most likely dominant type emboldened. The most likely level of valley confinement is emboldened)

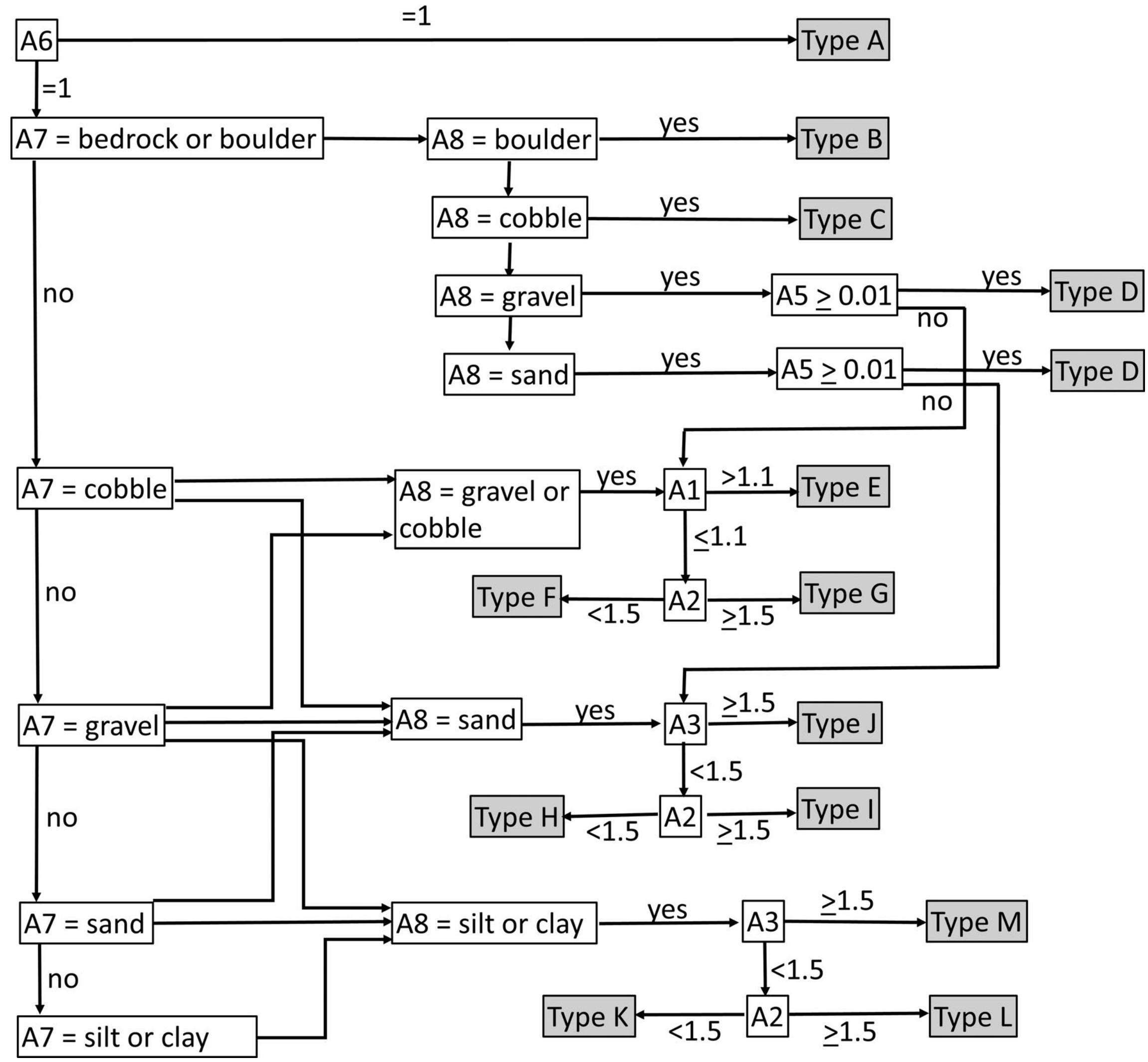

FIGURE 3 Decision tree used to assign a reach of an English river to an indicative river type using values of indicators A1 to A3 and A5 to A8

selected. The rationale for this is that river classification is a challenging processes and automatic generation of a river type is only as good as the decisions that drive it (Figure 3). In this case, the decision tree has been designed specifically with the characteristics of English rivers in mind. Furthermore, the indicative river type does not take account of any human interventions that may have influenced river type indicators A1 to A5, since the aim is to test whether the river is showing appropriate physical characteristics given its current planform. This limitation needs to be clearly understood by practitioners, because indicators A1 to A5 may have been modified by human actions. In particular, sinuosity (A2) may have been modified through implementation of restorations that increase sinuosity or historical straightening to improve drainage and flood conveyance that reduces sinuosity.

In addition to the 13 river types described above, "large rivers" and "canals and navigable rivers" are included as two separate river types because the bed and other submerged features cannot be surveyed adequately and thus the preliminary condition score has to be based on indicators that only refer to emergent features.

4.2 | Provisional condition score

Thirty two of the indicators (Table 2, indicators B1 to E12), known as condition indicators, are extracted from the surveys for each subreach and are used to calculate a preliminary condition score for the subreach. These condition indicators characterize different aspects of the condition of the bank tops (B1 to B5), bank faces (C1 to C10), channel edge – water margin (D1 to D5), and channel bed (E1 to E12). Each indicator summarizes either a potentially "natural" morphological, sedimentary or vegetation structural aspect (a positive indicator, marked by [+] in Table 2) or an aspect of local human interventions and pressures (a negative indicator, marked by [−] in Table 2). The information system automatically assigns a score from 0 to 4 (positive indicators) or 0 to −4 (negative indicators) once the subreach survey data have been uploaded. The formulations used for this process are reported in Part 1 in Data S1. These were developed initially from expert judgements of likely scenarios and were then tested, and where necessary fine-tuned, using a calibration data set of 40 MoRPh5 subreach surveys collected for this purpose from a diverse range of river types with variable levels of channel engineering (Section 5).

It is important to stress that "natural" is a difficult term to apply to any English river. As noted by Gurnell and Petts (2002, p. 582)

> "the history of river channels in England…is one of progressive change from bedload-dominated wandering channels in forested catchments to suspended-load dominated, stable or incising, single thread channels. The Neolithic and later phases of deforestation and agricultural expansion and intensification were associated with soil erosion in the uplands and alluviation of river corridors. Brown (1987) considered that the resultant floodplain accretion and planform stabilization established the channel character for the next 2000–3000 years. The modern era has been characterized by a period of channel incision induced by dams, embanking, reafforestation, sediment-check structures, urbanization, and sand and gravel extraction…"

(see also Brown et al., 2018; Downs & Gregory, 2004). Furthermore, Brookes (1985, 1988) first reported the enormous extent of river channelization in England and Wales (8,500 km of main river) and its geomorphic impacts (Brookes, 1987) and later estimated 96% of lowland rivers in SE England to be modified (Brookes, 1995). With these constraints, we consider "natural function" as the river processes and forms which result from contemporary, (and for a given study reach) independent, catchment-driven hydrological, sedimentary, geomorphic and/or ecological processes. We identify as "natural" the physical or vegetation-structural features that have at least in part been created by such natural processes, even if they are also reflecting recovery from human influences (which could be referred to as "naturalized" over time as rivers adjust to new modified conditions via natural processes). However, we have to accept that there may have been some human influence (e.g., high silt loads from agricultural land enabling silt-trapping and landform building by plants; modified channel dimensions leading to bank toe or side bar development, evolution of mid-channel features, or development of tree "features" such as J-shaped or leaning trees, and overhanging bank tops).

The Preliminary Condition Score for a MoRPh5 subreach is the sum of the average score of the 19 positive condition indicators and the average score of the 13 negative condition indicators (Table 2). Averages were used to give the groups of positive and negative characteristics an equal weighting in the preliminary condition score. This is not to say that all river types would be expected to score highly on all positive condition indicators but that if a river shows good condition, it is expected to score at an appropriate level for its river type on the condition indicators (see Section 4.3). The impact of negative indicators is expected to be more uniform across river types, but this may not always be the case. For example, artificial reinforcement may appear to offer no change in the physical bank properties of a bedrock river, but it still replaces the natural bank materials with other materials possessing different biogeochemical properties and thus providing different physical habitats and ecological impacts (e.g., Francis & Hoggart, 2009). The scores on each individual condition indicator provide insights into the underlying causes of the preliminary condition score and identify where damage to condition should be avoided (high positive condition indicator scores) and where improvements in condition could be achieved (low negative condition indicator scores, unexpectedly low positive condition scores for the river type).

4.3 | Final condition score

The preliminary condition score for a subreach is translated into a final condition score (5-good, 4-fairly good, 3-moderate, 2-fairly poor, 1-poor) according to the river type under consideration. The boundaries for translating preliminary condition scores into final condition scores depend on determining the lowest and highest likely preliminary condition scores for each river type and then dividing the range between these two extreme values into five numerical bands.

All river types are allocated the same lowest preliminary condition score (−2.5) which assumes a fully reinforced river channel with bank tops covered by buildings and transport infrastructure (i.e., no riparian or in-channel vegetation or natural physical features). The maximum value for each river type is calculated by assigning likely maximum (expected) scores in the range 0 to +4 to the positive condition indicators for that river type and assuming all negative indicators have a zero score (Table 3, see Part 2 in Data S1 for large rivers and for navigable rivers and canals). The likely maximum values of the preliminary condition score for each river type were estimated to range from +1.8 (canals and navigable rivers) to +3.1 (river type I). Indeed meandering river types G and I were judged to have the potential to achieve the highest preliminary condition scores (respectively 3.0, 3.1) reflecting their potential to display sediments of varying calibre, many different in-channel and bank top physical features as well as structurally varied in-channel and riparian vegetation.

Crucially, Table 3 (refer to Part 2 in Data S1 for large rivers and navigable rivers and canals) also provides guidance on the maximum scores that are likely to be achieved by a river of a specific type on each of the positive condition indicators. This introduces a firm geomorphic underpinning, by ensuring that low scores on a positive condition indicator can be interpreted either as "expected" for a given river type or as the river not achieving its potential condition.

5 | TESTING THE METHODOLOGY

5.1 | Calibration data

A calibration data set was collected to support development and testing of the river condition assessment tool and to illustrate its application. The calibration data set includes information from sections of 20 rivers within which two adjacent subreaches (10 contiguous modules) were surveyed. By surveying 2 adjacent MoRPh5 subreaches, it was possible to consider the degree to which adjacent subreaches

TABLE 3 Likely maximum scores on positive condition indicators for river types A to M

Indicators	A	B	C	D	E	F	G	H	I	J	K	L	M	**COMMENTS** **Note that apart from type A, the river types from B to N typically display a decrease in gradient, bed material fining and decreasing valley confinement**
B1 Bank top riparian vegetation structure	4	4	4	4	4	4	4	4	4	4	4	4	4	Complex bank top vegetation structure should be achievable on all rivers
B2 Bank top tree feature richness	4	4	4	4	4	4	4	4	4	4	4	4	4	Varied tree features should be achievable on all rivers
B3 Bank top water-related features	1	1	1	1	1	2	2	2	2	4	3	3	4	Scores reduce with increasing gradient (reflected in bed material size) because of changing tendency for downslope drainage
C1 Bank face riparian vegetation structure	2	2	2	2	3	3	3	3	3	3	4	4	4	Scores increase with reduced confinement and decreased calibre of bank materials (rooting restricted in coarse and unstable sediments)
C2 Bank face tree feature richness	4	4	4	4	4	4	4	4	4	4	4	4	4	Varied tree features should be achievable on all rivers
C3 Bank face natural bank profile extent	4	4	4	4	4	4	4	4	4	4	4	4	4	All bank profiles should be natural
C4 Bank face natural bank profile richness	3	3	3	3	4	4	4	4	4	4	3	3	3	Largest potential range of profiles in streams of intermediate slope and sediment calibre
C5 Bank face natural bank material richness	4	4	4	4	3	3	3	2	2	2	1	1	1	Bank face materials increasingly uniform as channel gradient reduces
C6 Bank face bare sediment extent	2	2	2	2	3	3	4	3	4	2	0	0	0	Confined streams likely to have highest bare bank exposure (intermediate score), intermediate slope meandering streams likely to have good balance of vegetated and unvegetated banks (maximum score), unconfined lowland streams likely to have fully vegetated banks (zero score)
D1 Channel margin aquatic vegetation extent	0	0	0	0	0	0	0	2	2	2	4	4	4	Extensive, aquatic vegetation restricted to low gradient/low energy streams
D2 Channel margin aquatic morphotype richness	0	0	0	0	0	0	0	2	2	2	3	3	3	Diverse, aquatic vegetation restricted to low gradient/low energy streams
D3 Channel margin physical feature extent	2	2	2	2	3	3	4	3	4	3	1	1	1	Widest diversity of features likely in meandering streams of intermediate sediment calibre
D4 Channel margin physical feature richness	2	2	2	2	3	3	4	3	4	3	1	1	1	Intermediate gradient, intermediate bed material streams likely to have highest richness, especially if they are meandering

(Continues)

TABLE 3 (Continued)

Indicators	A	B	C	D	E	F	G	H	I	J	K	L	M	COMMENTS Note that apart from type A, the river types from B to N typically display a decrease in gradient, bed material fining and decreasing valley confinement
E1 Channel aquatic morphotype richness	0	0	0	0	0	0	0	2	2	2	4	4	4	Diverse, aquatic vegetation restricted to low gradient/ energy streams
E2 Channel bed tree features richness	3	4	4	4	3	3	3	3	3	3	3	3	3	Little difference in potential, but steep, coarse bed streams may show higher wood retention and root exposure
E3 Channel bed hydraulic features richness	3	4	4	4	3	3	3	3	3	2	1	1	1	Highest richness on coarse bed, steep streams; negligible richness on low gradient fine-bed streams
E4 Channel bed physical feature extent	2	4	4	4	3	3	3	2	2	1	0	0	0	Negligible extent on low gradient, fine bed streams
E5 Channel bed physical feature richness	2	4	4	4	3	3	3	2	2	1	0	0	0	Highest richness on coarse bed, steep streams; negligible richness on low gradient fine-bed streams
E6 Channel bed material richness	3	4	4	4	4	4	4	3	3	3	1	1	1	Lower richness on finer-bed streams
Average	2.4	2.7	2.7	2.7	2.7	2.8	3.0	2.9	3.1	2.8	2.4	2.4	2.4	

within the same river reach may yield different condition assessments. Aerial images and maps supported reach and subreach selection.

Twelve of the calibration river sections were selected because of their apparent lack of human modification and to capture a wide range of valley gradients and thus river energy conditions. The remaining eight were selected to represent varying levels of channel reinforcement as an indicator of human intervention.

Following field surveys, the 12 "near-natural" river sections were labelled a to l in order of decreasing valley slope and bed material size with a 1 or 2 appended to denote the two MoRPh5 subreaches. Three of the river sections, representing steep, bedrock-boulder rivers, were located in Wales because of ease of access, but similar river reaches exist in England, notably in the Pennines and Lake District. The eight "modified" river sections displaying bank and/or bed reinforcement were labelled m to t in order of increasing reinforcement extent, with full reinforcement of bed and banks at reach t. Again, a 1 or 2 was appended to denote the two surveyed subreaches.

5.2 | Indicative river types

Values for indicators A1 to A6 were extracted for extended reaches enclosing the pairs of surveyed subreaches. The reach scale indicators were combined with subreach values of indicators A6, A7 and A8 to illustrate the sensitivity of the estimated indicative river type to a change in bed material. However, in practice, the indicative river type should be determined using the coarsest values of A6, A7 and A8 found for any single surveyed subreach at a project site. Application of the indicative river type decision tree (Figure 3) to each of the 20 reach and 40 subreach values of indicators A1 to A8, resulted in the 24 near-natural subreaches (a1 to l2) being assigned to nine different indicative river types (A, C, D, F, G, H, I, K, L), with a good representation of types with different bed material and planform. The missing types were those with very coarse bed material (B) and with multi-thread forms (E, J, M), all of which are rare in England. A narrower range of river types (F, H) were surveyed across the modified subreaches (m1 to t2), to some extent reflecting the fact that reinforced reaches are also frequently straightened.

5.3 | River condition indicators

The river condition indicator scores for all of the 40 MoRPh5 calibration subreaches are listed in Part 3 in Data S1. The separate average scores for the positive and negative river condition indicators for the 40 subreaches are shown in Figure 4a and the sum of these averages are presented in Figure 4b. These illustrate a general decline in the total, positive and negative scores with decreasing valley gradient across the near-natural rivers (a to l, Figure 4a). An increase in human pressures and interventions is evident even in these near-natural examples as they transition from more confined, steep, upland to unconfined, low gradient, lowland settings. The modified reaches generally display more

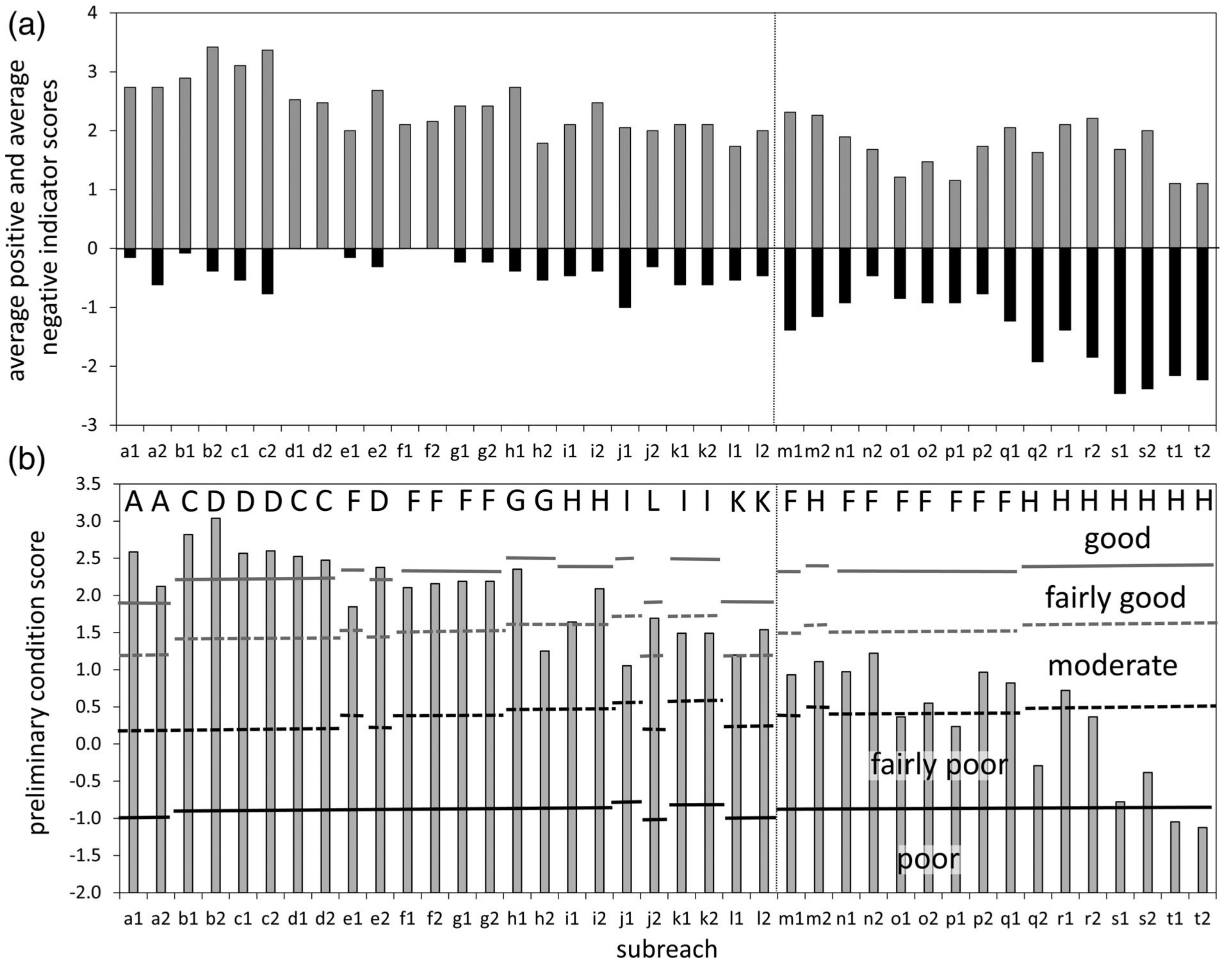

FIGURE 4 (a) The average values of the positive (grey bars) and negative (black bars) condition indicator scores for each of the 40 calibration subreaches. (b) The preliminary condition scores (sum of the average positive and average negative indicator scores) for each of the 40 calibration subreaches, plotted with respect to the five final condition scores (5-good, 4-fairly good, 3-moderate, 2-fairly poor, 1-poor) according to the river type for each subreach (A to M, listed across the top of the graph)

severe average negative scores as their level of reinforcement increases from river m to t, although there are fluctuations in the average negative scores attributable to factors other than reinforcement extent. In many cases the modified sites have quite high positive scores, reflecting the presence of at least a partly-functioning riparian zone (none had heavily developed bank tops) and also a range of naturally-formed sediment and vegetation features within the channel despite the reinforcement.

Using the relevant ranges and thresholds for translating the preliminary into the final condition assessment (Part 4 in Data S1), Figure 4b and Table 4 present the final condition assessment for the 40 subreaches. Virtually all the near-natural subreaches (a1 to l2) attain a “good” or “fairly good” final condition score (Figure 4b). Exceptions are subreaches h2, j1, k1 and k2. However, the impact of human interventions is seen most strongly in the subreaches affected by reinforcement (m1 to t2). None of these subreaches achieves better than a “moderate” assessment. Half of the subreaches are assigned a score of fairly poor or less, and the most heavily reinforced subreaches (t1, t2) are classified as “poor” (Figure 4a).

The influence of the individual condition indicators on the final condition scores is illustrated in Figure 5. Figure 5a presents the difference between the observed subreach scores on each of the positive indicators and the likely maximum (expected) scores (Table 3) for the relevant river type. Figure 5b presents the observed scores on each of the negative indicators. In both Figures 5a and 5b a horizontal line separates the natural (a1 to l2) from the increasingly reinforced (m1 to t2) subreaches and vertical lines separate condition indicators referring to the bank tops, bank faces, channel margin – water edge, and channel bed. The two darkest shadings in Figures 5a and 5b indicate, respectively, the most marked deviations below the expected positive scores and the most severely negative scores. Several broad trends can be identified from Figure 5.

The bank top indicators confirm comments previously made about “natural” rivers in England. Virtually all the subreaches, including those described as natural (a1 to l2), are affected by significant human land cover management within 10 m of the bank top (Figure 5b, condition indicator B5). This explains the degraded riparian vegetation structure (Figure 5a, B1) and lack of bank top tree features (Figure 5a, B2, indicative of naturally functioning riparian trees). The lack of even a small (10 m) naturally-functioning riparian zone is a key factor in preventing most subreaches from achieving their potential condition.

TABLE 4 Characteristics of the 40 calibration subreaches

Subreach[a]	Latitude, longitude of approximate subreach mid-point	A2 Sinuosity[b]	Planform	A4 Confinement	A5 Valley gradient (m.m^{-1})	A6 Bedrock subreach?	A7 Coarsest bed material	A8 Average alluvial bed material size class	River type	Final condition score
a1	51.845853, −3.365852	1.000	Straight	C	0.09520	Yes	BE	CO	A	5-Good
a2	51.845369, −3.364783					Yes	BE	BO	A	5-Good
b1	52.520938, −3.888970	1.067	Sinuous	PC	0.06987	No	BE	CO	C	5-Good
b2	52.520795, −3.889721					No	BE	GP	D	5-Good
c1	52.532126, −3.914333	1.000	Straight	C	0.04504	No	BE	GP	D	5-Good
c2	52.531861, −3.915746					No	BE	GP	D	5-Good
d1	54.373154, −0.683041	1.000	Sinuous	C	0.01882	No	BO	CO	C	5-Good
d2	54.373463, −0.684215					No	BE	CO	C	5-Good
e1	50.690885, −3.128856	1.065	Sinuous	PC	0.01606	No	CO	GP	F	4-F. Good
e2	50.690579, −3.128285					No	BO	GP	D	5-Good
f1	53.330328, −1.607314	1.185	Sinuous	PC	0.00947	No	BE	GP	F	4-F. Good
f2	53.330194, −1.606666					No	BE	SA	F	4-F. Good
g1	50.870476, −1.620903	1.467	Sinuous	PC	0.00730	No	GP	GP	F	4-F. Good
g2	50.869847, −1.620200					No	GP	GP	F	4-F. Good
h1	50.780891, −3.006149	1.853	Meandering	U	0.00324	No	CO	GP	G	4-F. Good
h2	50.781009, −3.008027					No	CO	GP	G	3-Moderate
i1	51.191260, −0.848621	1.269	Sinuous	U	0.00165	No	GP	SA	H	4-F. Good
i2	51.191391, −0.848326					No	GP	SA	H	4-F. Good
j1	52.701893, −1.685008	1.753	Meandering	U	0.00156	No	CO	SA	I	3-Moderate
j2	52.702839, −1.684133					No	SA	SI	L	4-F. Good
k1	51.167718, −0.793525	1.945	Meandering	U	0.00072	No	SA	SA	I	3-Moderate
k2	51.168109, −0.792578					No	SA	SA	I	3-Moderate
l1	51.320325, −0.763119	1.147	Sinuous	U	0.00049	No	GP	SI	K	4-F. Good
l2	51.320990, −0.764135					No	GP	SI	K	4-F. Good
m1	51.548079, −0.270270	1.180	Sinuous	U	0.00679	No	CO	GP	F	3-Moderate
m2	51.547381, −0.270875					No	GP	SA	H	3-Moderate
n1	50.689093, −3.126151	1.065	Sinuous	PC	0.01606	No	CO	GP	F	3-Moderate
n2	50.688804, −3.125562					No	CO	GP	F	3-Moderate
o1	52.522988, −1.911290	1.155	Sinuous	U	0.00222	No	CO	GP	F	2-F. Poor
o2	52.522230, −1.910605					No	CO	GP	F	3-Moderate
p1	51.369720, −0.160320	1.057	Sinuous	U	0.00636	No	CO	CO	F	2-F. Poor
p2	51.370256, −0.160068					No	CO	CO	F	3-Moderate

TABLE 4 (Continued)

Subreach[a]	Latitude, longitude of approximate subreach mid-point	A2 Sinuosity[b]	Planform	A4 Confinement	A5 Valley gradient ($m.m^{-1}$)	A6 Bedrock subreach?	A7 Coarsest bed material	A8 Average alluvial bed material size class	River type	Final condition score
q1	51.212511, −0.796664	1.088	Sinuous	U	0.00097	No	CO	GP	F	3-Moderate
q2	51.213008, −0.795537					No	CO	SA	H	2-F. Poor
r1	51.631171, −0.180627	1.148	Sinuous	U	0.00653	No	GP	SA	H	3-Moderate
r2[c]	51.630844, −0.180681					No	BO	SA	H	2-F. Poor
s1	51.601166, −0.262951	1.108	Sinuous	U	0.00264	No	CO	SA	H	2-F. Poor
s2	51.600624, −0.261679					No	CO	SA	H	2-F. Poor
t1	51.550252, −0.269255	1.180	Sinuous	U	0.00679	No	CO	SA	H	1-Poor
t2	51.549410, −0.268882					No	CO	SA	H	1-Poor

[a] MoRPh surveys for some of these subreaches were also used in analyses presented in Gurnell et al., 2019, but in that case the reach-scale properties referred to shorter reaches, resulting in slightly different values for some reach-scale indicators.

[b] Values for A1 and A3 are not listed because all surveyed reaches were single thread and thus A1 and A3 were always equal to 1.

[c] Subreach r2 recorded boulder as the coarsest bed material but the reach slope was <0.01 and a boulder river type was not appropriate (the boulders reflect past human interventions). Therefore, the river type was assigned using only the average alluvial bed material size class (SA).

In addition, bank top water-related features (Figure 5a, B3, various types of wetlands and ponds, side channels) are often removed by land management practices and are extremely rare across all calibration sites. Their absence does not depress the overall condition of the steeper, more confined river types (A to D) where such features are unlikely to be widely encountered. However, such features are increasingly expected of naturally-functioning systems as river gradient and lateral dynamics decline (Table 3) and yet few water-related bank top features were observed.

There are also indications of human impacts within the river channel (bank faces and bed) across many subreaches. Many show degraded tree features within the channel (i.e., on the bank faces [Figure 5a, C2] and bed [Figure 5a, E2]), although bank face degradation of tree features is most noticeable in reinforced subreaches. This degradation results from both direct human interventions within the channel (pruning/removing trees, removing large wood) and the lack of a naturally functioning riparian zone to supply in-channel shade, trailing branches, marginal exposed roots and large wood (Grabowski et al., 2019). Furthermore, siltation (Figure 5b, E7 – superficial drapes of fine sediment around and over coarser bed material particles) is widespread (Wood & Armitage, 1999). This reflects excess fine sediment supply to the river, particularly from arable agriculture, stock trampling close to river margins, and outfalls (Jarritt & Lawrence, 2007; Owens et al., 2005; Wohl, 2015).

Focusing on the remaining bank face, margin, and bed indicators, some further clear trends emerge. The natural subreaches (a1 to l2) show notably fewer scores of −2 or lower on the negative condition indicators (Figure 5b) and fewer falling below expected scores for their river type (i.e., deviations of 2 or more) on the remaining positive condition indicators (Figure 5a). Furthermore, scores on the negative indicators tend to decrease and scores on the positive condition indicators increasingly fall below their expected values as reinforcement increases, although there are some notable deviations and the most pronounced can be explained by human activities. The most reinforced river channels (Figure 5b, C8, C9, E8, E9) are frequently fenced off and, when located in urban parks, often have bank tops subject to reduced vegetation management, allowing a relatively unmanaged strip of riparian vegetation to develop (Figure 5a, B1, subreaches r1, r2, s1, s2, t1, t2). This strip can provide bank top (Figure 5a, B2) and in-channel (Figure 5a, E2) tree features. It can also hide developing in-channel features from view enabling patches of bed material of different calibre (Figure 5a, E6, often overlying a reinforced bed) and areas (Figure 5a, E4) and different types (Figure 5a, E5) of depositional bed features to develop. Such developing features are further enhanced as reinforcement ages and, in parallel with other artificial in-channel features (Figure 5b, E10), drives more diverse flow patterns (Figure 5a, E3) that can further support landform development and vegetation colonization within the channel.

The condition indicator scores for any particular subreach help to explain the final condition score and thus support the design of approaches aimed at improving river condition. Greater detail on each condition indicator score can be extracted from the raw field surveys, which are particularly important for supplying geomorphologically-relevant characteristics that can help to interpret key local processes.

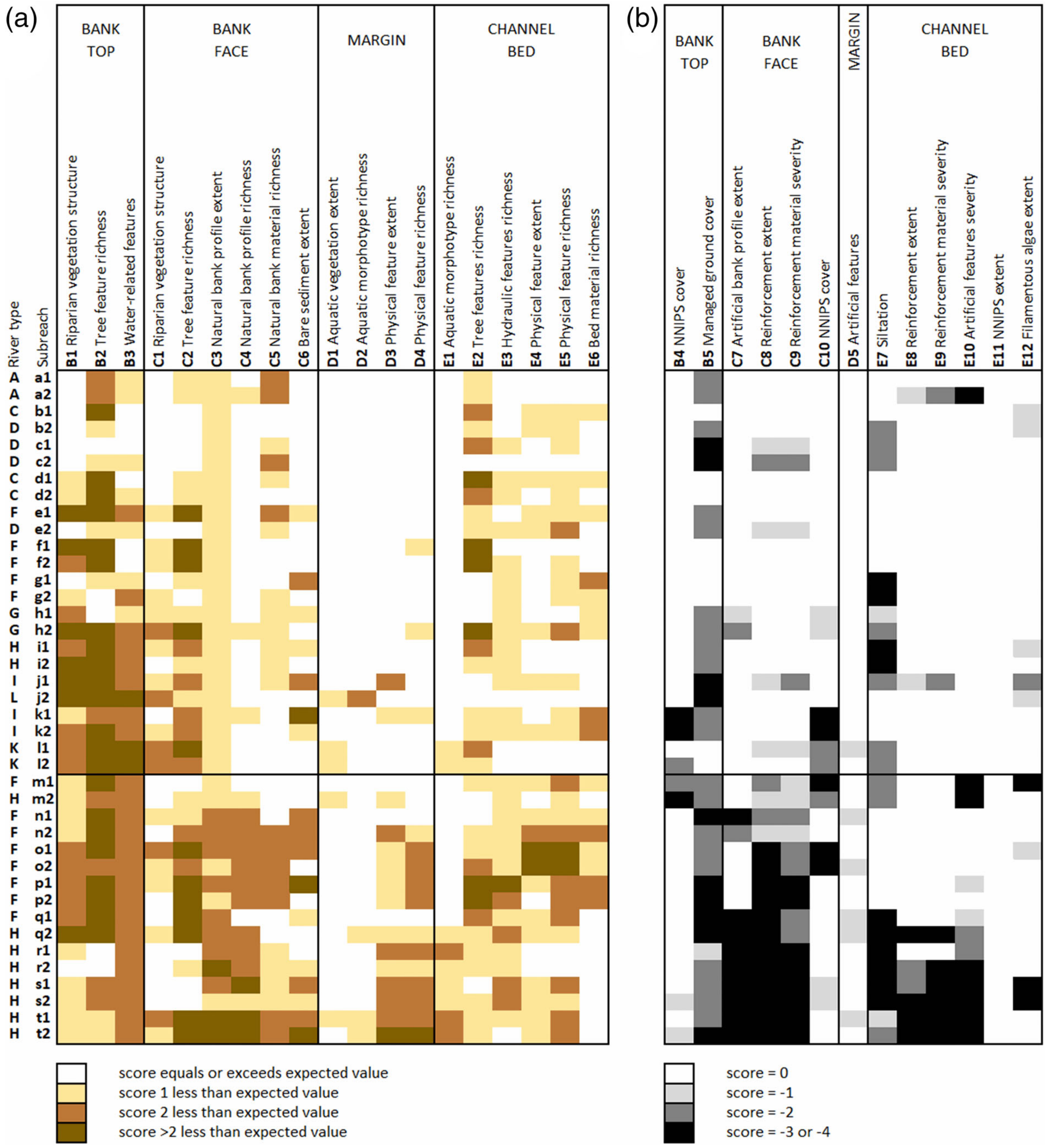

FIGURE 5 Performance of the 40 calibration subreaches in relation to the river condition indicators. (a) Difference between each observed positive river condition indicator score and the likely maximum (expected) scores for the appropriate river type. (b) Observed negative river condition indicator scores (NNIPS refers to non-native invasive plant species)

6 | DISCUSSION

6.1 | Contribution and potential refinement of the river condition assessment tool

The Biodiversity Metric 2.0 (BM2) is currently at the beta testing stage with the intention of final release in December 2020 followed by a review every 5 years. Therefore, the river condition assessment tool that is reported here may undergo minor adjustments based on feedback from users and analysis of the data they gather. However, the broad approach to assessing river condition is stable.

The tool was designed for a specific purpose: to provide an assessment of river condition at a project site as a part of BM2. Thus, the aim was to produce a single habitat-based river condition score (the final condition score) that could contribute to an integrated terrestrial-riparian-aquatic assessment of a project site and to monitoring the initial status of the site and the effects of design implementation and subsequent recovery.

To achieve these aims, the tool had to be straightforward to apply by environmental professionals who were unlikely to be specialist geomorphologists, and so a bottom-up approach was devised that integrates a desk study with field surveys. The approach was designed to capture all aspects of the river physical environment necessary for a thorough inventory of the habitats present and their condition at a single spatial resolution. At the same time, the field survey captures many additional properties that can inform process assessment by geomorphology specialists who may be involved in project delivery. However, it is important to repeat that the system does not aim to provide a full analysis of geomorphological processes, but to bridge the gap between a simple habitat assessment and an assessment of geomorphic condition, thus raising awareness across a wider community of environmental professionals and supporting the integrated analysis of these critical factors for longer term ecological resilience. Full analysis and interpretation of geomorphological processes requires additional data (Section 6.2), training and experience. For instance, restoration designs may require hydraulic and sedimentological modelling, demanding a sound theoretical understanding of sediment transport processes, together with modelling expertise and detailed topographic data.

Because there is potential for future fine-tuning of the method as further experience is gained from the tool's application, it may be necessary to revisit one or more of the following: some elements of the river type decision tree, the computation of the scores assigned to some of the individual condition indicators (B1 to E12), the relative weighting of the condition indicators in the computation of the preliminary condition score, and the definition of the preliminary condition score numerical boundaries that are applied to different river reach types to generate the final condition score for a subreach. Nevertheless, the broad approach to river condition assessment will be retained.

6.2 | Embedding the river physical condition methodology into a hierarchical framework for hydromorphological assessment and management

While the river condition methodology was devised for a specific purpose, to deliver a habitat-based assessment of river condition, the data and outputs can contribute to broader and more specialist assessments of the river environment. In particular, they can provide fine spatial-scale contributions to integrated geomorphological analysis. Spatial and temporal hierarchical approaches to integrating hydrogeomorphological information are fundamental to diagnosing the degree of natural functioning of river systems; the level and nature of constraints imposed by human pressures and interventions; the nature and causes of any temporal trajectories of change exhibited by the river; and the likely response of a river to future scenarios (Brierley & Fryirs, 2016; Gurnell et al., 2016; Gurnell, Rinaldi, Buijse, Brierley, & Piégay, 2016; Rinaldi et al., 2017).

At a subreach scale there are numerous methods available to assess physical habitat (e.g., RHS, Raven et al., 1997; Raven, Boon, Dawson, & Ferguson, 1998) and geomorphic features (e.g., GUS, Belletti et al., 2017), but these methods typically address longer subreaches than a MoRPh5 survey and are usually narrower in scope. Furthermore, given the cost of field survey, the advantage of surveys similar to MoRPh are that they are designed to be applicable by river professionals who may not be geomorphology specialists, and within many contexts can complement data that is being collected by appropriately trained citizen scientists. Indeed, the MoRPh survey was originally devised for application by trained volunteers (Gurnell et al., 2019), illustrating the potential, with appropriate quality-control, for substantial data sets to be assembled. The MoRPh module survey and its aggregation into subreaches (e.g., 5 or 10 contiguous MoRPh surveys) captures many properties that can support geomorphological interpretation within an appropriate spatial hierarchical framework of data gathering (e.g., England & Gurnell, 2016). The compatibility of the river condition assessment with a citizen science survey methodology (Gurnell et al., 2019; Shuker et al., 2017) additionally enables monitoring over longer timeframes at sites where there may be public interest in outcomes of river works. This helps to address the deficit of longer-term habitat and geomorphological monitoring and supports assessment of physical channel responses to human interventions and changing processes.

The MoRPh survey generates significant geomorphological information within subreaches that can contribute to reach scale analyses. This includes the presence of natural (bank erosion, tributary junctions) and artificial (pipes, land cover) points of sediment delivery to the river; in-channel locations and calibre of sediment storage (bed siltation, bars, berms, benches); indicators of natural function (bank profiles indicative of different types/rates of bank failure, assemblages of geomorphic features and tree features within and around the channel; and indicators of channel adjustment such as channel dimensions (evidence of over-deepening), bank sedimentary structure (evidence of bed incision), eroding and aggrading banks (evidence of channel migration, widening, narrowing), J-shaped, falling and fallen trees (evidence of bank instability, further evidence of channel migration and widening). Such information on geomorphic character and dynamics but also on human interventions at the subreach scale can aid interpretation of the indicative, reach scale, river type and its geomorphic function. Thus MoRPh survey data can complement outputs from reach-scale assessments such as: assessments of geomorphic condition, function and dynamics (e.g., MQI, MDI, Rinaldi, Surian, Comiti, & Bussettini, 2015); walk-over surveys identifying sediment sources and sinks (e.g., Fluvial audit, Sear, Newson, & Brookes, 1995); desk studies of contemporary floodplain geomorphic features; and historical analyses of channel planform and style change. A combination of available data at complementary scales aids in-depth assessment of whether a river is functioning according to its type and whether it is showing evidence of shorter- or longer-term geomorphic adjustment and/or human suppression-degradation of geomorphic processes.

6.3 | Potential of the river condition assessment methodology to support other river characterisation, assessment, and management issues

In addition to contributing to the assessment of physical habitat and geomorphological condition and function, the multi-scale nature of the river condition assessment tool has enormous potential for integration with the chemical and biological characteristics of rivers. Such spatiotemporal linkages between river morphology and both water quality and biota have long been proposed and explored (e.g., Clarke, Bruce-Burgess, & Wharton, 2003; Doyle & Stanley, 2006; Padmore, 1998; Petts, 1984; Petts & Amoros, 1996; Southwood, 1977; Sullivan, Watzin, & Hession, 2004; Townsend & Hildrew, 1994; Vaughan, 2010; Wolter, Buijse, & Parasiewicz, 2015). However, establishing precise causal links in ecological restoration between habitat heterogeneity and biodiversity has proved difficult (Lepori, Palm, Brännäs, & Malmqvist, 2005; Palmer, Menninger, & Bernhardt, 2010) not least because of the varying space–time scales employed in monitoring (Vaughan et al., 2009).

The spatial scale of the MoRPh module was deliberately selected to be appropriate for physical habitat characterisation at biological monitoring sites, particularly sites used for monitoring macroinvertebrates. Indeed, the characterisation provided by a MoRPh module survey can guide the selection of habitats and the relative sampling effort incorporated into kick-sampling at a monitoring site. For characterising habitat available to mobile species, a subreach survey is appropriate. While five contiguous MoRPh surveys should capture most physical habitats, 10 contiguous MoRPh surveys gives an even more thorough assessment and can support more reliable estimation of the spacing/frequency of key features such as pools, riffles, side and mid-channel bars. In addition, in as far as channel complexity can influence water quality, a reach scale analysis of river type supported by subreach assessments of channel-vegetation morphology, would be appropriate for comparison with water quality assessments.

7 | SUMMARY AND CONCLUSIONS

In this paper we have presented a method devised for the operational assessment of river condition, which can be applied by river professionals who may not be specialist geomorphologists. This tool has been designed for application to the river landscapes encountered in England as part of BM2, a method for the evaluation and monitoring of development sites. The river condition assessment tool has been tested on a calibration data set of 20 river reaches and 40 subreaches representing the range of near-natural river styles present within England as well as the effects of progressive human intervention through channel reinforcement. Although some aspects of the method may be fine-tuned as experience is gained in its application, the fundamental approach and structure are stable.

Although fundamentally a habitat assessment tool, as was required for inclusion in BM2, the river condition assessment is founded on key concepts and scientific principles in order to bridge the gap between habitat and geomorphic condition assessment:

1. It includes a bottom-up, multi-scale approach.
2. It links condition assessment explicitly to geomorphic river type.
3. It defines how each river type, when in good condition, can be expected to score on different condition indicators.
4. It provides field survey data on a variety of river physical properties that are indicative of the types and rates of geomorphological processes that are operating.

Beyond BM2, the method provides information to support river geomorphological and biological monitoring and assessments. Because it utilizes a field survey designed for application by trained citizen scientists, the reservoir of MoRPh data is rapidly growing and it is providing a valuable tool in communicating the physical functioning of rivers. In the context of river condition assessment for BM2, the field survey and the entire assessment tool are being applied by surveyors with a wide range of disciplinary backgrounds. This is providing a pathway to expanding knowledge and understanding of the importance of physical habitat forms, processes, turnover and trajectories for river habitat condition to new professional audiences.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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