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Original Articles

Designing an environmental flow framework for impounded river systems through modelling of invertebrate habitat quality

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ABSTRACT

Many rivers have undergone flow modification by impoundments to provide services such as water supply and hydropower. There is an established consensus that typical modified flow regimes do not sufficiently cater to the needs of downstream ecosystems, and more must be done to understand and mitigate their associated impacts. This study presents a novel, transferable framework by which a small-scale impoundment in North West England is assessed through the use of linked hydro-ecological modelling in SRH-2D and CASiMiR, utilising flow velocity measurements and macroinvertebrate sampling data. Model predictions of habitat quality were supplemented by established ecological principles such as the importance of flow heterogeneity. Results are used to design environmental flow regimes, with the aim of improving ecological metrics whilst considering conflicting water demands. Based on an analysis of historical flow records, the implementation of designer flows over a 12 month period demonstrated increased peak species habitat qualities of 23–26%, characteristics such as flow heterogeneity were more naturalised, and 22% less water was released from the impoundment. Should outcomes be validated by in-stream flow experiment, there is great potential for further development and application of this method, including regional transferability for the rapid designation of environmental flows across a number of sites of similar magnitude and geography.

1. Introduction

Flow modification and impoundment of river systems has become widespread throughout the world in response to increasing water demand and energy requirements. Over recent decades it has increasingly been recognised that typical flow regimes imposed even by small impoundments and hydropower schemes may have impacts on riverine ecology (Anderson et al., 2015; Poff et al., 1997; Summers et al., 2015). It is thus important to understand the relationship between flow regime and ecological response, and develop efficient frameworks to mitigate the impact of flow modification. The needs for impoundment are unlikely to decrease, hence a key question is how we might maximise environmental benefit for a volume of water released as impoundment outflow (Konrad et al., 2011). Since its proposal in the late 1990s, the Natural Flow Paradigm (Poff et al., 1997; Acreman et al., 2009) has formed the basis of the environmental flow concept. Poff et al. (1997) discuss the likely consequences of the alteration of natural flow components such as flow heterogeneity and the resulting ecological response within the system, and propose that natural flows promote stable ecosystems, whilst over-regulated systems result in ecological

impacts due to direct and indirect responses to altered flow. Examples of natural flow variation include flows driven by predictable seasonal precipitation levels, or snow melt (Junk et al., 1989; Junk and Wantzen, 2004). Poff et al. (1997) argue that there is an intrinsic link between the natural flow regime and in-stream ecology as a result of the biota having developed life-history, behavioural and morphological characteristics adapted to be successful in their native environment. In contrast, impounded systems have traditionally based their regulated outlet flow regimes upon "rule of thumb" percentile-based values such as the Q95 (the 5th percentile flow) of the non-modified river system (Arthington et al., 2006), or upon historical flow licences that had been in place to sustain downstream interests such as mills, many of which no longer exist (Gustard, 1989). Such flows neglect the natural fluctuation of flow, and some behavioural and morphological adaptations of biota may no longer be appropriate for their environment (Lytle and Poff, 2004).

While it may not be feasible to return flows to their natural regimes in most cases, an increasingly popular approach has been that of 'Designer Flows', by which flow patterns are created to provide desired benefits, within practical constraints (Chen and Olden, 2017). Designed
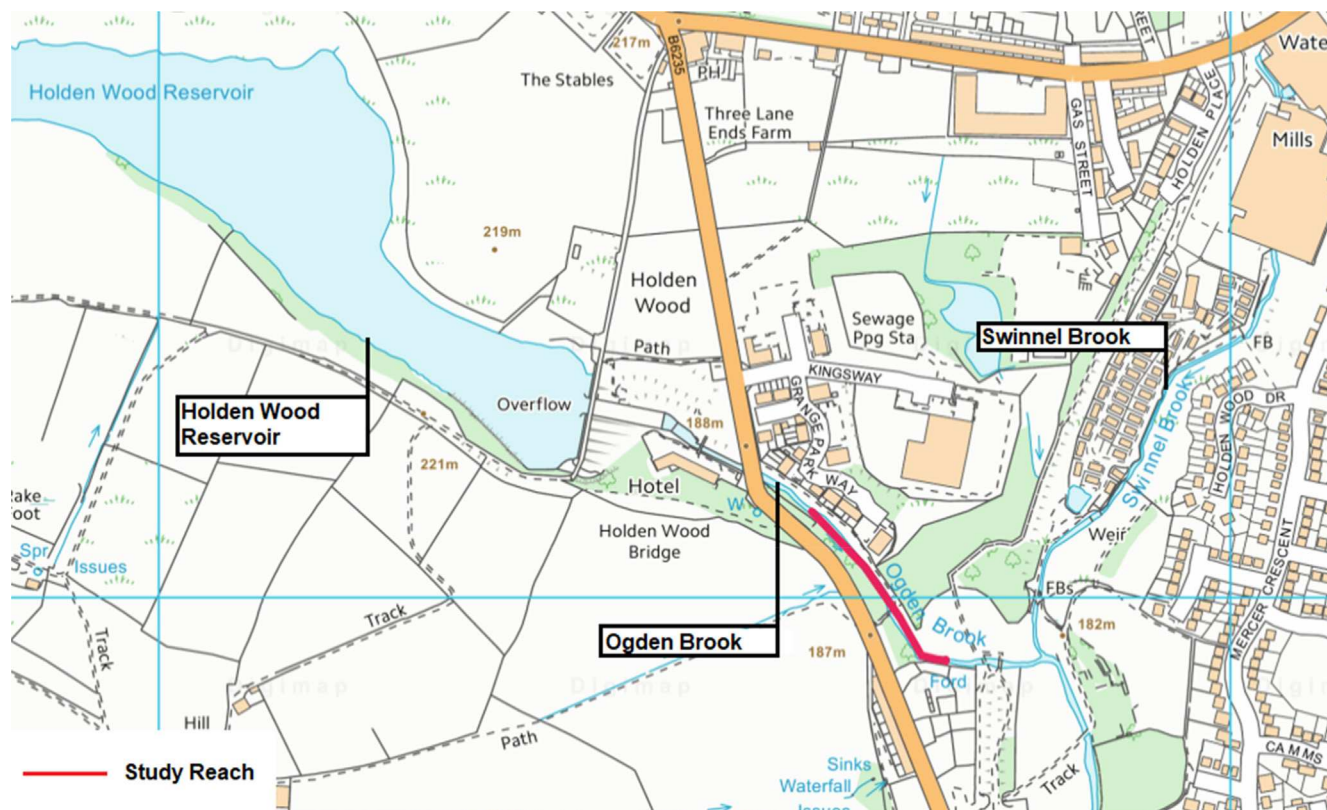
Fig. 1a. The Holden Wood reservoir and Ogden Brook, (Digimap Ordinance Survey Service, 2018).

environmental flows are unlikely to match the variation of their natural counterparts, either in magnitude or heterogeneity, but can significantly improve ecological quality. This can be achieved by accounting for particular ecological requirements such as periods of elevated flow, and integrating them into the flow regime. The "Building Block Method" (BBM) approach proposes that such requirements can come together as individual "blocks" to create an overall regime, originating from South African restorative studies and later seeing international application (King and Louw, 1998). The UK advisory group UKTAG have discussed BBM in recent years and propose the approach as best practice for the mitigation of impacts arising from impoundments (UKTAG, 2013). Despite such conceptual frameworks, the implementation of environmental flows remains a major challenge; this is largely due to the lack of any defined, standardised protocol by which these flows are to be implemented. Part of this difficulty may be that most studies have focused upon the investigation of larger river systems; it is difficult to isolate ecologically-influential factors at this scale (for example due to tributary flow inputs). This study utilises a small scale study site to allow the development of a foundational approach towards environmental flow development that can later be scaled and adapted to account for further complexity in larger systems.

This study utilises macroinvertebrate species as ecological indicators, due to their relative neglect in the field when compared to taxa such as fish (Gillespie et al., 2015b), and the fact that they are a more prolific indicator at small scale sites. These taxa experience flow as localised forces as opposed to overall magnitudes, timings, etc. This raises the question, how can the requirements of invertebrates on a micro scale translate into an overall compensation flow and its inter-annual variation? Habitat quality models are an increasingly utilised approach in restorative studies (Reiser and Hilgert, 2018; Schneider et al., 2016; Conallin et al., 2010), yet may not account for life history requirements and temporal flow characteristics experienced by taxa, such as the frequency and duration of flow events. A broader suite ecological indices are required to achieve robust environmental flow

designs (Chinnayakanahalli et al., 2011; Arthington et al., 2018), and methodological progress is required in order to determine their implementation; how are conflicting flow needs to be resolved, and how does one judge whether or not a flow regime is "good"?

Competing interest groups and increasing demands for water supply mean that environmental needs are a contentious topic; water sent downstream for environmental purposes must be well-justified, and the "cost-benefit" in terms of water committed to environmental flows must be acceptable in order to maximise the volume of water retained for societal use (Harwood et al., 2018). The lack of transferable flow-ecology principles can necessitate time- and cost-intensive site-specific investigation (e.g. Anderson et al., 2017), and the impracticality of scaling up such an approach to larger or multiple sites is readily apparent. One potential solution gaining favour is to use regional-based methods (Summers et al., 2015). These recognise that whilst general principles may remain elusive, it should be possible to identify commonalities between approaches for rivers of similar magnitude and geography (Arthington et al., 2006). However, even these relationships have proven difficult to extract from the current body of literature, largely due to a lack of standardised approaches and challenges in the synthesis of current data (Poff and Zimmerman, 2010; Gillespie et al., 2015b).

This paper presents a potential transferable methodology by which impoundment-modified river systems may be assessed, and environmental flows designated. Here, we test this method of environmental flow designation at a case study site, addressing the challenge of site-wide flow regime designation through a novel combination of habitat quality prediction (based on 2D ecological model outputs), flow event timings, habitat diversity, and flow event heterogeneity, whilst also making efforts to actively conserve water relative to current outflows, with a methodological design emphasising future transferability to other sites. The proposed methodology takes steps towards an answer for generic environmental flow designation and implementation based on the principle that designed flows should provide significant benefit

Fig. 1b. A cross-section at the Ogden Brook site, pictured in November 2017.

to the ecosystem (Richter et al., 1996), whilst also conserving water resources.

2. Site description

The study site Ogden Brook (Figs. 1a and 1b) is a stream system in the North West of England, directly downstream of the impounding reservoir Holden Wood, approximately 27.2 km North of Manchester, Northern England, and located near the village of Haslingden, OS grid reference SD776220. The site was chosen due to data availability, lack of significant external pressures such as wastewater inflows, the dominance of upstream reservoir compensation flows, and its appropriate scale for the scope of the investigation. Historical background information has been adapted from a consultancy report provided by the regional water company, United Utilities (APEM, 2016).

Typical flow conditions at the site remain in the range of $Q = 0.02$–$0.04 \, m^3/s$, with mostly shallow depths between 0.1 and 0.25 m, though recorded depths in pools reached as high as 0.8 m. The reach under investigation is approximately 40 m in length, primarily chosen to avoid the presence of a downstream tributary, so as to retain flow contribution solely from reservoir outflows. The study is thus performed on a small scale; this fits the aims of this investigation, which focuses upon the response of taxa at a micro-habitat level similar to studies such as LeCraw and Mackereth (2010) who utilised study reaches of 10 m to observe localised ecological responses, or other fish and macroinvertebrate restoration studies utilising 100 m reach scales (Pretty et al., 2003; Harrison et al., 2004).

The water company United Utilities manages Holden Wood Reservoir. Compensation flow releases are made to the Ogden Brook, in line with the conditions of an impoundment licence granted by the Environment Agency. Ogden Brook runs along a narrow band of woodland surrounded by light urban development. The riverbed itself is mostly gravel, with top-layer sediment ranging from small pebbles (~1 cm) to larger stones (up to ~10 cm), with a few larger rocks (up to ~20 cm) scattered throughout the reach. A lower layer of finer sediment lies beneath the stones and cobbles. The river channel has little to no vegetation. Presently, Holden Wood is required to release 3.46 ML per day ($0.041 \, m^3/s$) of flow during times of the impoundment being within 2 m of its maximum water level, and 1.84 ML per day ($0.0215 \, m^3/s$) when water depth is below this point. Prior to 2016, release requirements were lower; within the range of 0.01–$0.02 \, m^3/s$. Impoundment releases are the sole major contribution to the studied reach of Ogden Brook, aside from small amounts of direct runoff insignificant relative to overall flow. Mean daily flow data for outflows from Holden Wood between 2014 and 2017, and inflows between 2010

and 2014 were provided by United Utilities, derived from cumulative inflow and outflow metres read and recorded daily; an outflow meter on the spillway measures the volume of reservoir spill events when these occur, and both outflow metres are added together for overall reservoir outflow. Macroinvertebrate single-point, three-minute kick sampling data from spring and autumn of 2016, taken within the analysis reach, were provided by United Utilities; this data was used to assess typical seasonality of native taxa.

3. Methods

An ecological model was constructed using the CASiMiR model (Schneider et al., 2010) to develop an understanding of the macro-invertebrate response (habitat quality) to flow at the site. This required the development of a hydraulic model of the site in order to determine the velocity regime. River geometry, velocity and ecological data was gathered for model development and calibration. Once model accuracy was assessed, habitat predictions were utilised and supplemented by an integrated consideration of taxon requirements (habitat quality metrics and anticipated responses to temporal flow characteristics) in order to design potential environmental flows for the Holden Wood site. These designer flows were compared with past and current impoundment outflows in terms of flow event characteristics (e.g. flow variability) and impact upon predicted habitat quality in order to demonstrate the differences in ecological response between designer flows and typical compensation flows, relative to annual volume of water released.

3.1. 2D hydraulic modelling

The SRH-2D (Sedimentation and River Hydraulics) modelling package was used to develop an understanding of the hydraulic complexity of the study reach. SRH-2D is based on the numerical solution of the two dimensional depth averaged St. Venant equations, providing calculations of depth and velocity at each computational cell based on model boundary conditions, reach topography and bed roughness (Lai, 2008). SRH-2D has recently seen widespread use in the field of river restoration and eco-hydraulics (Erwin et al., 2017; Stone et al., 2017; Lane et al., 2018).

Bed elevations at the study site were obtained using a Total Station surveyor (Leica Geosystems, 2009). Bed elevations were taken using a scatter-based method, taking elevation readings that adapted in resolution according to bed complexity. A total of 2069 geometry data points were collected over the reach. Bed elevations were uploaded into the SRH-2D model using the SMS interface (Aquaveo LLC, 2013) and a fine mesh was generated with cell sizes approximately 30×30 cm. In particularly complex rivers, meshes as fine as 10×10 cm have been utilised (Lange et al., 2015) however most ecological studies using SRH-2D have used 30×30 cm mesh sizes for detailed sections, with typical mesh sizes of around 250×250 cm or higher in larger rivers (Bandrowski et al., 2014; Stone et al., 2017; Lane et al., 2018).

Model calibration was performed using direct velocity measurements, utilising a Nortek Vectrino Acoustic Doppler Velocimeter (ADV), which is typically expected to provide velocity values accurate to within 5% in field conditions (Dombroski and Crimaldi, 2007). The ADV probe was secured to an adjustable surveying tripod, allowing for stable positioning at any point of measurement. The probe was capable of taking simultaneous measurements of three orthogonal velocity components at a frequency of 20 Hz, hence providing temporally averaged velocity data as well as standard turbulent statistics. A convergence test was conducted to determine an appropriate sampling period for the acquisition of reliable data at each point. A resulting sampling period of 60 s was used, due to low hydraulic complexity with readings typically stabilising within 30 s of deployment. For each measurement, the probe was orientated as such to obtain primary (x) velocity in the main channel direction (with the y dimension normal to the river bank). Raw ADV data was processed in WinADV 32 (Wahl,

2000), and the phase space threshold de-spiking filter was applied prior to data analysis (Goring and Nikora, 2002).

Eight cross-sections were measured along the reach, with flows being taken at 3–5 points along each cross-section depending on channel width. Measurements were taken at 0.6 of the depth to obtain a depth-averaged reading (Hewlett, 1982). A total of 31 readings obtained allowed for moderate coverage along the entire reach at a high resolution relative to many studies; SRH-2D has been successfully calibrated in larger rivers with significantly fewer observation points (Deslauriers and Mahdi, 2018). At the time of measurement, flow into the river was measured as 0.024 m³/s, based on impoundment outflow data provided by the site operator. This discharge is generally consistent throughout the autumn season, unless the impoundment is close to capacity, at which point flow releases are elevated and spill events are possible.

Upstream and downstream model boundary conditions were established based upon straight, stable areas of flow within the study reach. The upstream boundary condition was set as the measured inflow (0.024 m³/s), and the velocity was defined using SRH-2D's Conveyancing approach in which flow direction is assumed to be normal to the inlet boundary (Lai, 2008), and the velocity is uniformly distributed. The downstream boundary condition was set as the measured water level (185.02 m above sea level), again assuming flow normal to the boundary. Manning's roughness values were initially assigned with appropriate ranges based upon literature values (Chow, 1959) based on substrate type at the site.

Manning's roughness values for the river channel were calibrated based on established best practices (Van Waveren et al., 1999) initially testing homogeneous roughness across the entire reach, and later adjusting small areas where observed changes in substrate led to discrepancies in velocity. Final calibration saw the majority of the river assigned a Manning's value of 0.05, whilst patches of the riverbed had roughnesses ranging from 0.04 to 0.07. These values are appropriate for streams with generally little vegetation, steep banks, trees and scrub at the banks, and cobbles and large stones within the channel (Chow, 1959). Fig. 2 presents post calibration model outputs in terms of predicted flow velocity vectors.

Model predictions of calibrated depth-averaged velocity were tested by comparison with field point-observations of primary, temporally-averaged flow velocity taken by the ADV. Observed and modelled primary (x dimension) velocity values are plotted in Fig. 3. It can be seen

that there is broadly good agreement between predictions and observed values. Anomalous readings tend to be at the highest ranges of velocity, which may indicate deviations in model predictions at higher flows. However, these high-velocity anomalies may also be caused by localised changes in bed geometry, either not accounted for at the mesh scale used, or not detected during bed geometry measurements, such areas of faster flow (> 5 cm/s) may be highly localised and difficult to account for; for instance above a large rock causing a small shallow area of increased velocity, or a cleft between stones through which flow is funnelled. The most erroneous point, 3c, had been noted during field velocity measurement to be an area of particularly fast and complex local flow due to the presence of nearby rocks. It is possible that errors also arise from inaccuracies inherent to characterisation of the depth-averaged velocity at a single measurement point, which may be more significant in areas of irregular topography or cross currents which lead to complex velocity distributions.

3.2. 2D ecological modelling

The CASiMiR model framework is modular and integrates hydraulic and structural parameters from a hydraulic model for the calculation of habitat suitability for indicator organisms. Aquatic habitat suitability in this study is derived by the use of univariate flow velocity preference curves, and this is later compared with species population distributions observed in the field (Schneider et al., 2016). Preference curves were based on flow velocity affinities found in the STAR Project, a large-scale investigation supported by the European Commission in order to resolve challenges posed by the Water Framework Directive, using the study "Deliverable N2" (Bis and Usseglio-Polatera, 2004). This study involved the aggregation of macroinvertebrate traits into one of the largest species trait databases available (Bis and Usseglio-Polatera, 2004). In the STAR project, velocity preferences are described in the range of Null (0 cm/s); Low (> 0–25 cm/s); Medium (> 25–50 cm/s) and High (> 50 cm/s) based upon flow affinity, i.e. how well a species is adapted to particular flow conditions. Affinities range from 0 (lowest) to 3 (highest). These affinities were interpreted into Habitat Suitability Index (HSI) values ranging from 0.00 (lowest possible affinity) to 1.00 (highest possible affinity). In this study, flow velocity was selected as the sole parameter for driving ecological response. Depth and substratum are also used as key parameters in larger river systems, but at the scale investigated at this study site substratum can be assumed to be
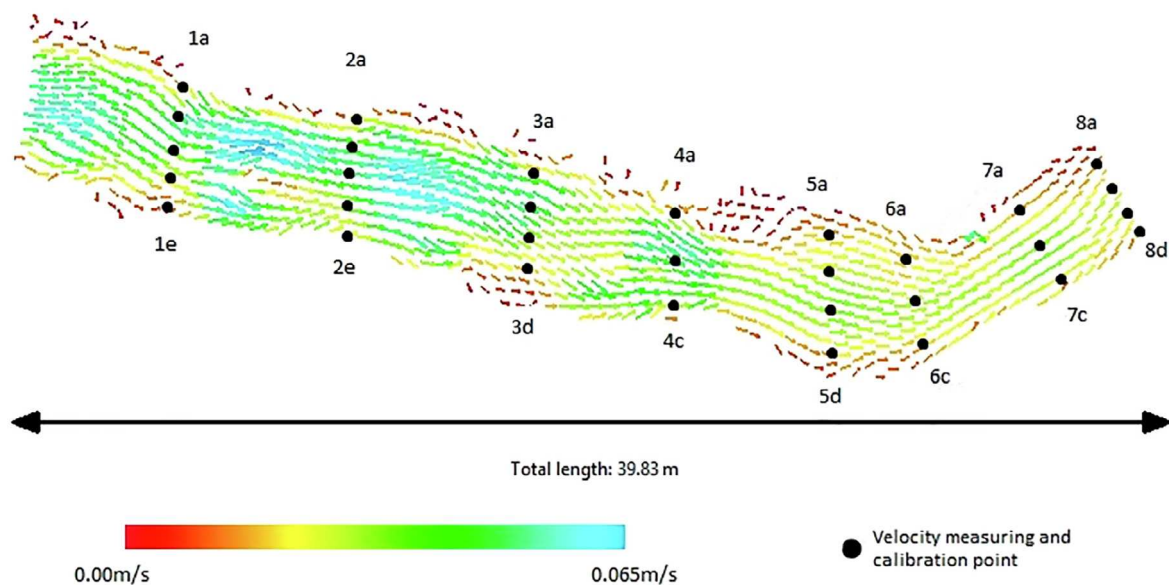

Fig. 2. SRH-2D hydraulic predictions, post-calibration, showing predicted velocity in m/s for an inflow of 0.024 m³/s, with in-field velocity measuring point positions.
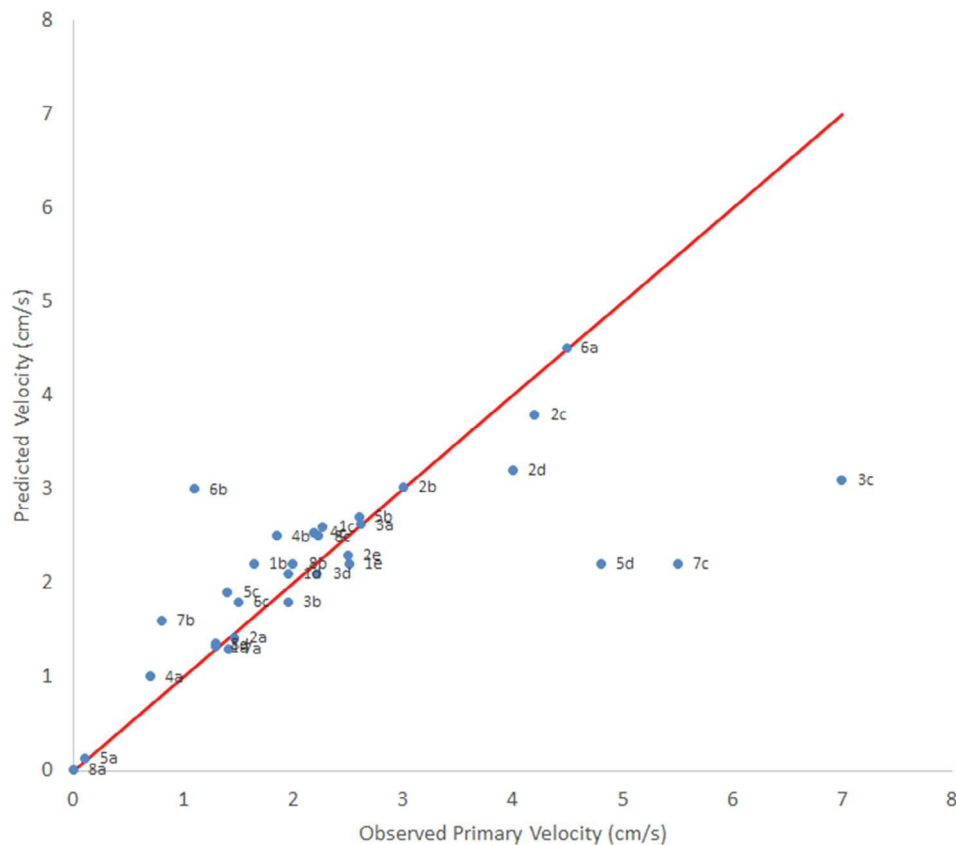
Fig. 3. Post-calibration SRH-2D primary velocity vs observed field primary velocities with field measuring points and associated model predictions (see Fig. 2 for spatial positions).

homogeneous, and changes in depth are not significant in terms of macroinvertebrate sensitivity.

CASiMiR can be calibrated through small adjustments to preference curve inputs (Schneider et al., 2010), due to possible variations in biological behaviour from site to site caused by external drivers. This was not necessary for this study due to species behaving in accordance to established preference values. The model was tested using observed species sample populations, taken using the standard 3-min kick sample method (Murray-Bligh, 1999) in November 2017 at a flow rate of 0.024 m^3/s. 15 measurements were taken using single-point kick sampling from a range of microhabitats distributed across the reach. Habitat predictions were then generated based upon the same flow rate. Testing under a single flow condition was deemed reasonably justified due to the minimal variation of flow at the site, and the fact that samples demonstrated similar species composition proportions to those observed in 2016 sampling data provided by the consultants (described in Section 2). Three species, *Gammarus pulex*, *Polycentropus flavomaculatus*, and *Hydrosyche siltali*, were chosen for model testing based upon their occurrence at most sample sites, and their range of flow preferences. A comparison between model predictions in the form of HSI, and observations in terms of species sample populations at the same point, is presented in Fig. 4.

A positive correlation can be observed between predicted HSI and measured species populations. Pearson correlation coefficients for the above figure are 0.62302, 0.57719, and 0.48843 for *Gammarus pulex*, *Hydrosyche siltali*, and *Polycentropus flavomaculatus* respectively. It should be noted that whilst HSI expresses the suitability of a flow regime for a given species, it does not assert that species *should* be present in any particular number. Therefore, it is not expected that HSI predictions should correspond perfectly to field data of measured populations. The relationship between HSI and species population is expected to be strongest in areas of low predicted HSI, as the conditions in
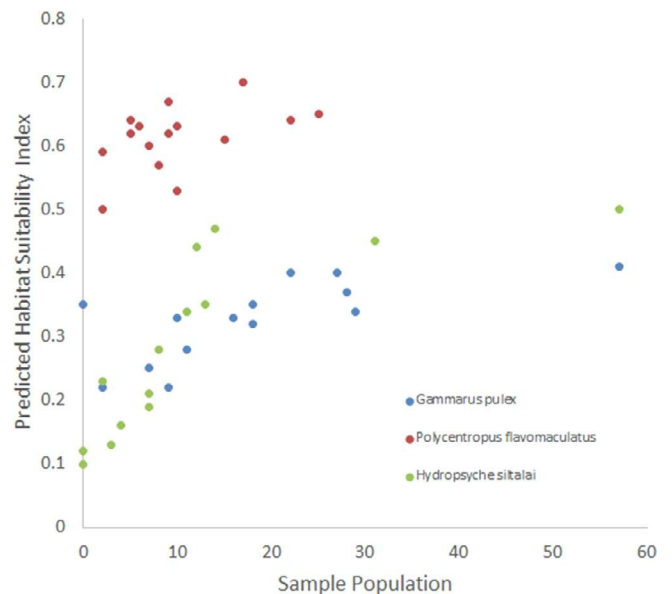
Fig. 4. CASiMiR testing, comparing the HSI at 0.024 m^3/s with observed number of individuals sampled at each point for 3 macroinvertebrate species at the Holden Wood site.

these areas actively prohibit species occuptation through their unfavorable habitat. Areas of high predicted HSI may be ideal for a given species, but it does not follow that a species will occupy that area; the stochastic nature of species colonisation, or external drivers such as predation, may lead to areas of high HSI being sparsely populated. It can be said that whilst not all good habitat is populated, all large

species populations should be found within good habitat capable of accomodating them. Given that the current approach only models the influence of flow, other drivers such as nutrient availability, ecological interactions and temperature may also alter the distribution of species (Ferreiro et al., 2011; Alba-Tercedor et al., 2017). Therefore, given the nature of the relationship between HSI and species populations, the current results are seen as good evidence for the utility of the model predictions.

For an analysis of flow effects, four indicator species were chosen based upon their presence in primary sampling data at most sampling sites across the reach, a range of velocity affinities, and numbers present in consultant sampling data. The four consisted of the three used in the model testing plus *Baetis rhodani*; this latter species does not occur in significant numbers in autumn, when sampling took place, so could not be utilised for testing, but did so in spring as demonstrated by consultancy data, described in Section 2, in which both autumn and spring samples were taken. *Gammarus pulex* and *Hydropsyche siltalai* display rheophilic preferences, *Polycentropus flavomaculatus* displays more limnophilic preferences, and *Baetis rhodani* displays intermediate preferences. A modelling analysis was subsequently conducted to investigate how ecological metrics for these species vary with flow.

3.3. Flow regime development – flow/ecology response

CASiMiR's outputs were then utilised to identify flows for the provision of indicator species requirements. The Hydraulic Habitat Suitability (HHS) index was utilised to provide an intuitive dimensionless value of overall habitat quality across the site, between 0 and 1. HHS is based upon weighted usable area (WUA) metric (Kelly et al., 2015), divided by the total wetted area. WUA in turn is based on the Habitat Suitability Index (HSI); by multiplying habitat type by area, with greater weighting for higher HSI values. In their proposal of HSI, Oldham et al. (2000) state that a direct correlation between HSI value and the species carrying capacity of a habitat is assumed; this also applies to HHS. Whilst this assumption generally holds true, at higher values this correlation may level out due to external drivers such as biological interactions; high habitat quality facilitates but does not guarantee habitation, whilst poor quality habitats by definition are unsuitable for significant species populations as discussed in Section 3.2. CASiMiR-predicted HHS for indicator species was calculated as a function of flow magnitude. The resulting individual responsiveness of species to flow is presented in Fig. 5.
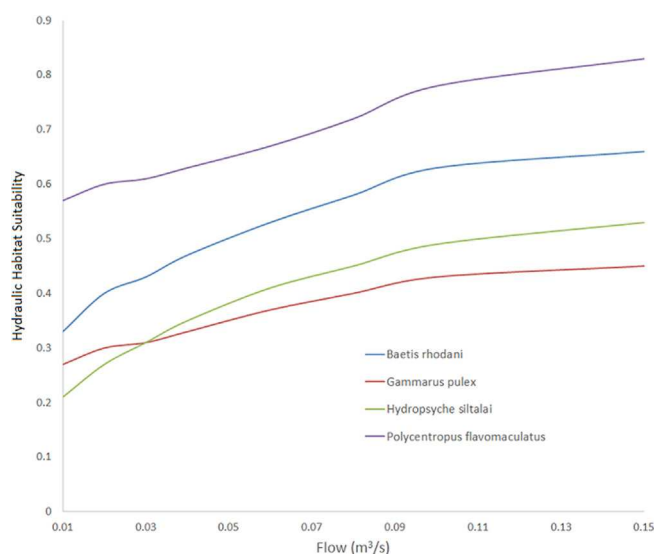

Fig. 5. CASiMiR-predicted indicator species Hydraulic Habitat Suitability values plotted against steady reach inflow.

Some species were sensitive to changes in flow; at the low end of the flow range, increasing flow from 0.01 m³/s to 0.05 m³/s resulted in a HHS increase from 0.21 to 0.45 for *Hydropsyche siltalai*, whilst the same increase in flow resulted in a HHS increase from 0.28 to 0.31 for *Gammarus pulex*. This difference in response is quite significant, particularly at low HHS ranges where increases of in habitat quality may mean a transition from intolerable to tolerable habitat (Oldham et al., 2000). Such differences in response suggest that certain species at the site are more vulnerable to changes in flow while some are more resilient. Levels of responsiveness at the flow ranges present within Ogden Brook (approximately 0.01–0.10 m³/s) suggest that some species will respond favourably to small increases in flow, whereas others will show little response, particularly at the lowest ranges of flow magnitude. Such findings may optimise flow designations depending upon seasonal species distributions.

Differences in flow preferences, and responses to flow change, among species also highlights the potential importance of flow heterogeneity in promoting biological diversity (Ward et al., 2002). Homogeneity of flow velocity was identified as an issue associated with the modified flow regime at the study site. To address this, CASiMiR was also used to calculate the flow diversity of available habitat across range of flows.

An index for habitat heterogeneity was developed using Shannon's Diversity Index (H) (Magurran, 2004). The index was applied to the range of velocity distributions present within the river channel at a given discharge, as demonstrated in Fig. 6. Ranges of velocity reflect the range of flow environments and thus habitats present within the system. H is calculated using:

$$H' = \sum_{i=1}^{s} p_i \ln p_i \tag{1}$$

where S is the number of flow categories present in the sample and p_i is the relative proportion of habitat in the ith category (Magurran, 2004).

This was applied by calculating the total wetted area and the wetted area covered by each flow velocity category over a range of discrete steady inflow discharges. CASiMiR defines 8 velocity categories, from "Very Low" to "Extreme". These categories are defined by flow ranges set by CASiMiR for each category, from 0.00 to 5.00 cm/s for Very Low, up to > 80.00 cm/s for Extreme. The proportion of each velocity category was determined and used in Eq. (1) to derive a measure of "flow diversity" for the study reach (Fig. 6).

It was found that habitat diversity increases with flow rapidly in the lower flow ranges, but this trend diminishes and eventually plateaus. Beyond Q = 0.1 m³/s, flow expenditure gives little benefit in terms of habitat diversity, and at higher flow ranges flow-habitat diversity decreases as the river becomes more uniformly fast-flowing. Due to these diminishing returns, alongside the reduced responsiveness of indicator species at higher flows, and due to local infrastructure design being based upon historical flows, designed flows were limited to a maxima of
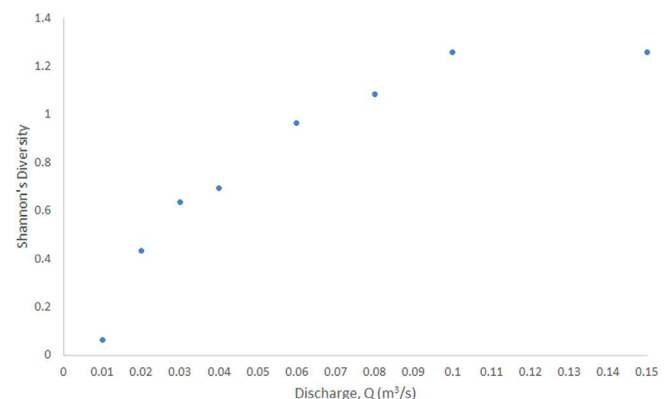

Fig. 6. Diversity of habitat; Shannon's Index of depth-averaged flow velocity across the river channel vs channel inflow.
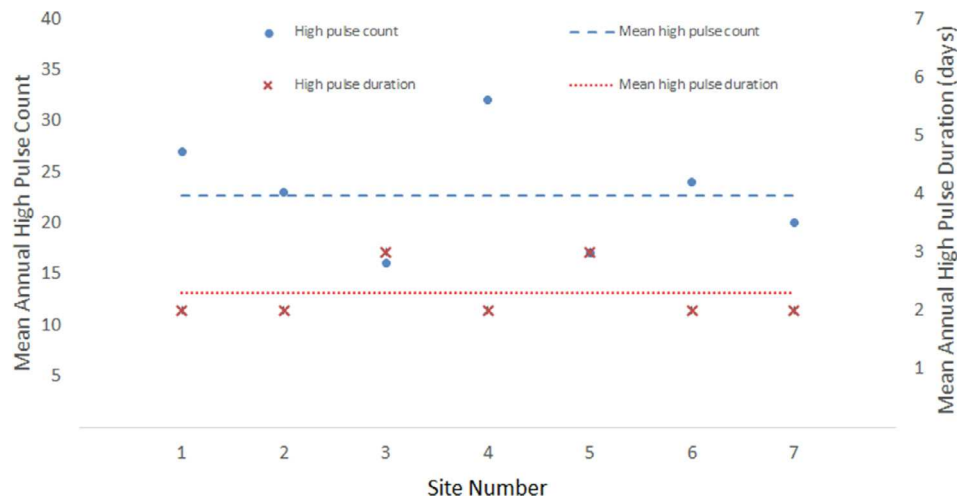
Fig. 7. High pulse event frequency and duration at 7 non-regulated sites, demonstrating extent of similarity of conditions in the North West Greater Manchester and Lancashire region.

$0.1\,m^3/s$. Mean diversity across the range of flows (up to $0.1\,m^3/s$) is approximately 0.75. In order to define a lower bound for designed flows, a critical diversity value was defined as an approximately 80% loss of habitat diversity below the mean (i.e. a diversity value of 0.15), which corresponds to a flow threshold of approximately $0.015\,m^3/s$. It is recognised that the relative nature of Shannon's index, and the difficulty in quantifying the impact of habitat availability and heterogeneity upon the ecosystem (Yin et al., 2017), means that habitat diversity (and thus flow) thresholds are difficult to define objectively. In this study the threshold is designed to act as a buffer to prevent complete habitat homogeneity, and regime-specific flow regime minima are designated through a combination of habitat diversity and more quantitative species sensitivities identified through HSI values (see Section 3.6). Depending upon the information available for a given system, the approach towards such thresholds and the emphasis placed upon particular metrics may be varied.

It should also be noted that the hydraulic model for the site is calibrated at a significantly lower magnitude than the upper natural flow range ($0.024\,m^3/s$ vs $0.41\,m^3/s$); model results at magnitudes similar to natural conditions may therefore not provide accurate hydraulic predictions. Additionally, local infrastructure has developed alongside the current state of the flow regime; "natural" flow ranges in reservoir inflow data would be unsuitable for the current state of the river channel and could increase the risk of flooding in the surrounding urban area.

3.4. Flow regime development – flow naturalisation

Habitat modelling provides a prediction of ecological response to changes in flow magnitudes. However, this alone is not sufficient to derive holistic environmental flow regimes. The desired timings, frequencies, and durations of flow events must be considered in terms of ecological requirements, and practical constraints must be considered in terms of impoundment operation and storage. Such factors cannot be considered within the CASiMiR model alone, and are often unique to a particular river or region (Konrad et al., 2011). In these cases, species requirements from literature, and natural flows from other river systems in the North West of England, were used to supplement model outputs and were integrated into flow regime development.

Ecological stability can be compromised by the loss of natural flow characteristics (Poff et al., 1997), and therefore supplementary data was required to inform flow regime design in terms high flow event frequencies and durations. As river systems of a similar geology and geography experience the same climatic conditions and tend respond to a given flow in a similar manner in terms of thermal regime and

physicochemical properties (Alcazar and Palau, 2010; Arthington et al., 2006), it is expected that the biota at Holden Wood should respond favorably to high flow event frequencies and durations that are approximate to typical naturalised flow regimes within the region (low flow events were not considered due to baseline impoundment outflows already being comparable to natural low flow events). This approach is comparable to the Before/After Control Impact approach (Underwood, 1991), but is applied on a more general regional level and does not require extensive conformity with specific reference conditions. Long-term Holden Wood inflow data was not available, and a transferable "regional" set of conditions was desired; therefore flow data was obtained from 7 non-heavily regulated rivers across the North West of England, around the Greater Manchester and Lancashire areas, through the CEH NRFA website (Centre for Ecology and Hydrology, 2018), and the typical frequency and duration of high flow events in the region were identified. Rivers with an average daily flow above $1\,m^3/s$ were excluded, ensuring rivers of similar magnitude to Holden Wood's natural state (derived from impoundment inflow data). This flow data, spanning on average 37 years, was processed using IHA software (The Nature Conservancy, 2017). The particular variables of "High pulse frequency" and "High pulse duration" were extracted from software outputs, and the median of these values was taken for each of the 7 sites. "High flows" or "high pulses" are defined in this study as flows that exceed 75% of the mean daily flow record. Analysis outputs are shown in Fig. 7. Mean standard deviation of sites was 5.648 from the mean high pulse count across sites, and 0.488 for high pulse duration (measured in days).

3.5. Flow regime development – impoundment storage and water efficiency

When designing managed outflow from impoundments based on ecological modelling, the practical consideration of the impoundment structure and operational rules must be considered. In this case both minimum permitted water levels as well as the operational capacity of Holden Wood must be accounted for. Failure to utilise the impoundment sustainably could result in drainage down to the extent at which the impoundment is no longer able to continue to release the required levels of compensation flow. This would breach the impoundment licence set by the Environment Agency, and would lead to prosecution if not mitigated via water transfers from other impoundments. Flow regimes were designed this constraint in mind. "Dead water", at which point Holden Wood can no longer drain under gravity, is below $37,000\,m^3$ (Maddison, 2012), therefore a significant buffer above this water level was set. Based on discussions with the operator (United

Utilities) a minimum threshold of 100,000 m^3 was designated. A simple model was therefore developed to understand storage levels as a function of both measured inflows and simulated 'designed' outflows over a simulation period of 1 year. This also allows the calculation of the 'efficiency' of each designed flow regime in terms of maintaining impoundment water levels. The model operated using historical impoundment inflow data from 2014 paired with outflow data (historical or proposed flow regimes), impoundment storage capacity, and volume of spills (calculated based on exceedance volume above reservoir storage capacity). At each daily time step the change in storage within the impoundment is calculated as:

$$\frac{dV}{dt} = I - (O + Sp)dt$$

where V is current impoundment storage volume (m^3), t is time (days), I is daily inflow (m^3/day), O is daily prescribed outflow (m^3/day), and Sp is overflow spill rate (m^3/day). Sp = 0 when the storage volume is below reservoir capacity (367,000 m^3); when above this level Sp is based on the total volume of capacity exceedance. I.e. the storage model assumes that excess water above reservoir capacity is released within one day, as would be expected in all but the most extreme climatic conditions. At the start of each simulation the storage volume is set based on a known value on 1st Jan 2014, taken from historical records. Water levels are calculated for each simulation across the proposed time series (until 31st Dec 2014), such that the total released volume of water over the period is known, and to ensure that levels do not fall below the prescribed minimum threshold.

3.6. Flow regime design

Individual species requirements, habitat diversity, typical regional flow event duration and frequency, and practical reservoir and site constraints were considered to design annual flow regime magnitude and timing in order to optimise ecological provision relative to volume of water released. Designed regimes (A, B and C) follow the same general design shown in Fig. 8, with five high flow pulses occurring in spring and in autumn respectively, with magnitude varying with regime. The pulse frequency and duration criteria are based on values identified in Section 3.4. Summer and winter retain constant flow rates (not including impoundment spills); in the case of summer, the season lacks biological information and there is a need to retain as much water as possible due to lower rainfall, increased water demand, and the risk of drought. In winter the cold thermal regime leads to dormancy among many taxa suggesting lower flow requirements in this season, additionally supplementary flow from spill events are common in this season due to elevated rainfall. The three regimes are informed by
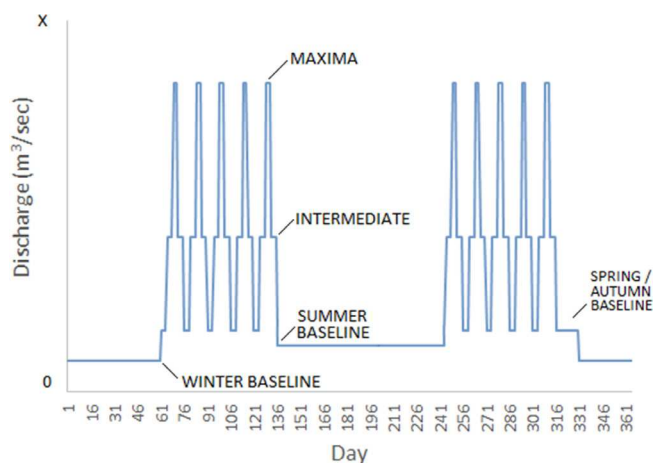

Fig. 8. General design of proposed flow regimes; A, B, and C. Day = 1 represents the 1st January.

modelling outputs described in Section 3.3, and vary based on their balance between ecological provision and water conservation focus. Regime A aims to maximise habitat diversity and HSI during flow maxima whilst releasing a similar volume of water to 2017 outflows; Regime B aims to balance the two priorities, retaining a modest amount of water over 2017 levels and maintaining moderate habitat diversity and HSI; Regime C retains more than 50% of the water released in 2017 outflows, but ecological metrics are at threshold values. A full account of regime design characteristics and rationale is provided in Table 1.

4. Results

Fig. 9 presents mean HHS over the 4 indicator species for each of the designed flow regimes, historical reservoir inflow data from 2014 (which approximate to natural flow conditions), and 2017 outflows (i.e. measured flow into Ogden Brook). Outputs were generated first by defining inflows for a given model simulation, obtaining hydraulic regimes through the calibrated SRH-2D model based on the inputted flow time series, then importing this data to CASiMiR in to generate temporal habitat quality predictions.

Results show that Regime A maintains good to moderate mean HHS (~0.5–0.6) for much of the spring and autumn period, whilst Regime B maintains lower-moderate values (~0.45) with periods of higher HHS approaching 0.55 during pulse maxima. Regime C maintains lower-moderate values for much of the two seasons (~0.40–0.45), with minima values dropping to 0.35; approaching the lower end of the tolerable HHS range. The more water that is conserved within a given regime, the more likely it is that spill events will occur due to limited impoundment capacity. However as these events are determined by annual precipitation they may not be a reliable supplementary provision due to there inherent unpredictability. Fig. 10 demonstrates the influences of Regimes A, B and C upon Holden Wood storage levels based on 2014 inflow data.

Based on historical measured data, 2017 outflows at Holden Wood released 1,180,460 m^3 of water over the course of a year under the current impoundment licence. Under a previous licence agreement, 2014 outflows released 600,284 m^3. The increase in flow under the current licence is largely motivated by environmental concerns; 2017 outflows thus provide a good example of the continued use of the traditional steady outflow approach for ecological provision. It is therefore possible to demonstrate potential ecological benefits provided by increased flow magnitudes under the new licence, and to demonstrate how ecological needs may be met more efficiently under proposed designer flows. As a reference case the yearly variation in HHS based on the CASiMiR model was assessed under the conditions defined by 2014 and 2017 outflows.

The HHS values of indicator species were assessed between flow regimes, evaluating the mean and peak HHS over the period of analysis. These results are displayed in Tables 2 and 3.

Mean HHS values between 2014 and 2017 flows show limited response to flow increase; *Baetis rhodani* shows the greatest change, and even here an increase of only 0.08 HHS is observed; a definite improvement, but requiring over 500,000 m^3 more water to be sent downstream per year. Designated regimes are shown to be capable of maintaining average annual ecological metrics at acceptable levels, while conserving significant quantities of water and providing frequent habitat quality maxima (demonstrated in Figs. 8–10) within the most ecologically-relevant seasons (based on Environment Agency sampling procedure).

Habitat quality maxima demonstrate a dramatic improvement in terms of applied ecological principles; flow variation is far greater, with ten high pulse events in contrast to the two or three throughout the year in 2014 and 2017 outflow data, and pulse magnitude is significantly higher in regimes A and B, with above a 100% increase (approximately 0.045 m^3/s up to 0.10 m^3/s) for Regime A, and an approximate 66% increase for Regime B (up to 0.075 m^3/s). Regime C maintains pulses in

Table 1

Breakdown of individual flow regime design characteristics with their rationale.

Characteristic	Rationale
Maxima A – 0.1 m³/s B – 0.075 m³/s C – 0.04 m³/s	Periods of high flow cultivate elevated habitat diversity and high mean HHS values across indicator species for short, repeated periods in spring and autumn. Such flows also aid in regulating the system's physicochemical properties (Alcazar and Palau, 2010)
Intermediate A – 0.05 m³/s B – 0.03 m³/s C – 0.025 m³/s	Based on good habitat diversity and moderate-high HHS values across indicator species whilst remaining within annual flow target, prolong the period of higher flow, prevent the flow increases being too sudden and disruptive to the native ecosystem (Blanckaert et al., 2013)
Spring/Autumn Baseline A – 0.02 m³/s B – 0.02 m³/s C – 0.015 m³/s	Based on threshold for most sensitive species present in these seasons, *Gammarus pulex* and *Hydropsyche siltalai*, identified in the seasonal analysis of consultant data. HSI becomes poor (> 0.03) below flows of 0.02 m³/sec (see HSI vs Flow in Fig. 5). HSI above 0.02 is maintained in Regime C, a habitat of low carrying capacity but still tolerable (Oldham et al., 2000)
Reduced Summer Baseline (Regimes A and B only) 0.015 m³/s	Threshold based on habitat diversity and critical habitat quality responses to flow. Season lacks biological information and there is a need to retain as much water as possible due to lower rainfall, increased water demand, and the risk of drought
Reduced Winter Baseline 0.01 m³/s (Regimes A, B and C)	Lower productivity, and dormancy among many taxa during winter, suggests lower flow requirements in this season (Olsson, 1982). Elevated rainfall regularly supplements winter flow with spill events
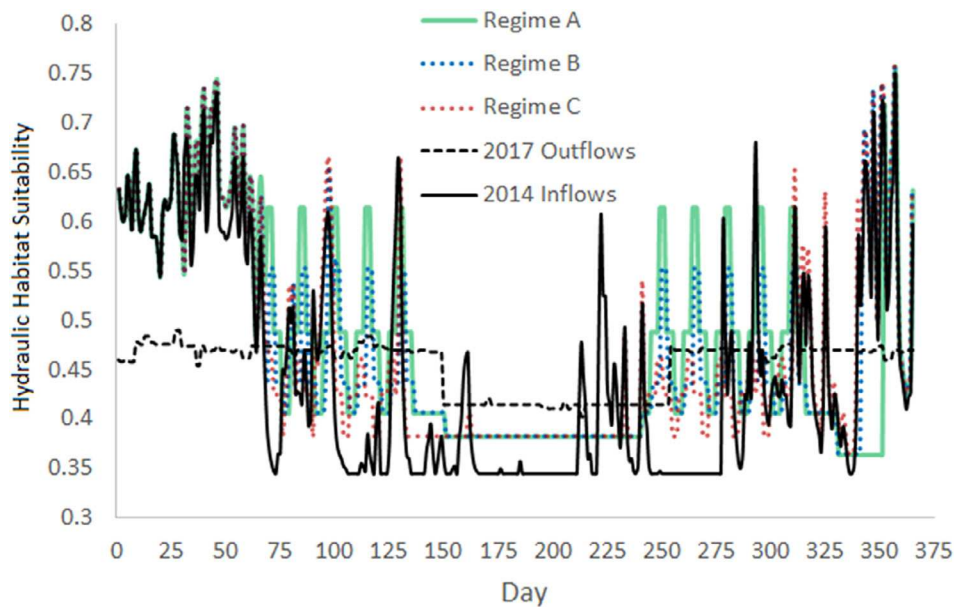
Fig. 9. Mean HHS predictions resulting from implementation of flow regimes A, B and C, alongside mean HHS based on 2017 outflows and 2014 inflows (values include effects of predicted impoundment spills).
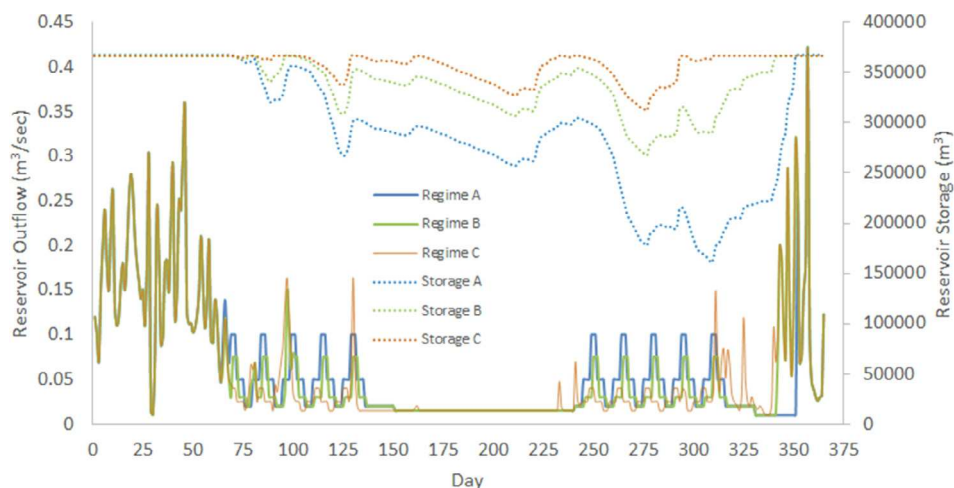
Fig. 10. Flow regimes A, B and C with associated changes in reservoir storage (based on 2014 inflow data).

Table 2

Average HHS for 4 indicator species at Holden Wood under historical and designated flow regimes, displaying each regime's annual flow output in cubic metres.

Mean HHS					
	2014 Outflow (600,284 m^3/yr)	2017 Outflow (1,180,460 m^3)	A (924,480 m^3)	B (721,440 m^3)	C (565,488 m^3)
Baetis	0.38	0.46	0.4	0.39	0.37
Gammarus	0.29	0.33	0.3	0.3	0.29
Hydropsyche	0.26	0.34	0.28	0.27	0.25
Polycentropus	0.59	0.63	0.61	0.6	0.59

spring and autumn seasons similar to those of 2017 outflows (though with lower duration and more flow fluctuation), despite releasing less than half the amount of water annually.

5. Discussion

The results of this study support the premise behind criterion driven flow design encompassing both temporal and magnitude-based requirements; despite greatly increased outflows in 2017 historical data compared to other regimes, HHS did not increase in favourable proportion. Whilst 2017 outflows have increased significantly relative to 2014, they remain largely homogeneous and fail to integrate natural variation such as high flow pulses. Thus, whilst more than 500,000 m^3 more water is released, ecological improvement relative to this is minimal. A holistic approach to environmental flow design is necessary to efficiently provide for ecological requirements in a world with increasingly pressing and conflicting water resources demands. This is consistent with findings from other recent studies (Gillespie et al., 2015a,b; Worrall et al., 2014; Brooks and Haeusler, 2016).

5.1. Assumptions and limitations

A number of assumptions are made to generate 2D model predictions. For hydraulic predictions, channel hydraulics were assumed to be simplistic enough for depth-averaged velocity characterisation to be appropriate. In more complex river systems, more extensive velocity measurements at multiple depths may be required to represent river hydraulics. Normal velocity distributions were assumed at the inflow and outflow boundaries; this assumption was valid in this study due to the identification of ideal boundary locations upstream and downstream at the reach. In complex, winding channels other velocity distribution methods may be necessary.

It has been claimed that 3D models provide more robust predictions, and that the z dimension can be an important aspect of ecological pressure and response (Pisaturo et al., 2017). However, in the case of Pisaturo et al. (2017), the study was performed within a much larger river system of significant depth, magnitude, and velocity. The continued success of studies utilising 2D models even in larger river systems (Jowett and Duncan, 2012) leads this investigation to propose that in a smaller-scale system such as Holden Wood, the 2D modelling approach is more appropriate. The lesser requirements of the 2D modelling approach entails easier transferability; a desirable advantage given the aim of this framework to be appropriate in a regional context. This is particularly the case should this approach see more typical application within larger systems in which the computational demands of 3D modelling would become unfeasible for most users.

Designed flow regimes derived from model results and ecological considerations are based on the assumption that precipitation patterns reflect typical annual precipitation. During particularly wet or dry years, adaptive management should address cases in which proposed flows are not appropriate for current conditions; perhaps flows must be reduced to baseline levels during droughts, or elevated flows must be prolonged during wet periods when the reservoir is near capacity. During such extreme conditions, the expertise of the water managers may adapt the regime accordingly, or flows may be set to pre-defined values based on demand, similarly to 2017 outflows being defined by water level.

5.2. Environmental flow design

Flow requirements of indicator species presented in the Methods show that generally, at the ranges of flow studied, there are diminishing returns of predicted habitat quality response to increasing flow at the study site. Beyond 0.07 m^3/s a reduction in responsiveness is observed, and beyond 0.09 m^3/s species response is generally beginning to plateau. This implies that magnitude increases, based solely upon species preference curves, are not an efficient solution for the ecological improvement of a system at the flow ranges studied at the Ogden Brook site; and becomes increasingly less efficient the longer the flow is maintained. Current impoundment outflows at Holden Wood do not demonstrate a consideration for seasonal variation in productivity and taxon composition; this study has proposed that a criterion-based flow design may target the key ecological timings for a system, and provide less flow at other times such as biologically less active periods (e.g. winter) or periods when stricter water resource conservation is necessary (e.g. summer). Allocating flows in this manner may allow for ecological provision that both improves ecological metrics, and also addresses the conflict between environmental flows and the societal need for water resource conservation. In contrast, uniform increases to compensation flows can lead to small improvements in ecological metrics yet disproportionately high flow expenditure, as was observed to be the case between 2014 and 2017 Holden Wood outflows.

The homogeneity of steady regimes reduces the range of flow (and thus habitat) conditions at a site. Section 4 demonstrates this; 2017 outflows result in peak HHS values most similar to Regime C, despite releasing more than double the quantity of water throughout the year. Again, this supports the premise that such flows may release a great deal of water, yet do not address important ecological requirements.

Table 3

Peak HHS for 4 indicator species at Holden Wood under historical and designated flow regimes, displaying each regime's annual flow output in cubic metres.

Peak HHS					
	2014 Outflow (600,284 m^3)	2017 Outflow (1,180,460 m^3)	A (924,480 m^3)	B (721,440 m^3)	C (565,488 m^3)
Baetis	0.55	0.5	0.61	0.57	0.47
Gammarus	0.38	0.35	0.43	0.39	0.31
Hydropsyche	0.43	0.39	0.49	0.44	0.35
Polycentropus	0.69	0.65	0.78	0.71	0.63

Variation in flow and more naturalised high pulses serve to regulate the physicochemical properties of the riverine system such as the sediment and thermal regimes, nutrient content, and water pH, and such flows may control species populations by preventing the dominance of single-flow specialists (Petts and Gurnell, 2005; Richter et al., 1996). Peak HHS during Regime A flow maxima are significantly higher (increases of 0.08–0.13) and more frequent than peak HHS during 2017 outflows; these periods of elevated HHS may allow taxa to better establish themselves within the reach, whilst remaining resilient to short-term low flows between flow maxima periods due to biological adaptations to natural flow variation (Poff et al., 1997). Regime B shows similar but less pronounced improvements, whilst Regime C sees a slight reduction in peak HHS relative to 2017 outflows, yet utilises less than 50% the total annual outflow by comparison. Frequent periods of elevated flow also generate greater diversity of habitat in areas of previously homogeneous baseline flows. As greater habitat diversity facilitates greater biodiversity (Ward et al., 2002), flows throughout spring and autumn periods in designated regimes would in principle be expected to improve biodiversity metrics, assuming the periods of low flow between intermediate and maxima do not remove established biota. High flow pulses also aid in river connectivity, transferring nutrients between the main channel and periodically wetted areas (Junk et al., 1989; Junk and Wantzen, 2004), as well as varying connectivity between different river sections that may be separated by barriers such as weirs (Shaw et al., 2016). Lacking such mechanisms, it is unlikely that the functional composition or level of biodiversity within current modified systems will resemble that of their natural counterparts (Gillespie et al., 2015a; Poff et al., 1997). Whilst raw flow magnitude has a very substantial influence upon benthic ecology, the temporal aspects of flow such as frequency and duration of events, based upon local natural trends, should in principle provide more holistic ecological provision. Flow event durations and frequencies may play a key ecological role, creating more temporally heterogeneous environment where a single species cannot dominate (Levin, 2000), driving sediment transport mechanics and their associated impacts (Kondolf, 1997), and driving connectivity of the river with the surrounding flood plain (Junk and Wantzen, 2004). Systems with homogeneous flows have demonstrated decreased biodiversity (Wiens, 2002), and it is unlikely that flow magnitude divorced from natural conditions can ensure a healthy ecosystem capable of meeting ecological targets (Acreman et al., 2014). A key challenge to the implementation of environmental flows has been the increased labour such flow designs would entail. A transferable framework based upon general regional principles, such as that proposed in this study, could help to alleviate some of these labour requirements by allowing environmental flows to be designated efficiently across numerous small-scale sites with minimal adaptation between them; sites which may otherwise be unfeasible for restoration on a specific case by case basis. The similarity of natural river system behaviour observed in the North West of England lend support towards this possible transferability, though further research and flow experimentation would be necessary to confirm this with confidence.

5.3. Further implications

This study demonstrates the potential of ecology-flow principles as a promising ongoing area of investigation. Such investigation could be performed through a number of means; desk-based analyses utilising IHA-style flow characteristics and ecological metrics could investigate trends between study sites, or in-field flow experimentation could attempt to apply a designer flow across similar sites and monitor ecosystem response. We have demonstrated the potential of linked hydro-ecological modelling, particularly for small-scale sites where vertical complexity is minimal and an efficient approach is necessary due to resource constraints. A significant outcome from this investigation has been the demonstrated potential for significant quantities of water to be conserved through designer regimes, whilst anticipated ecological

response should be improved, both due to criteria-based flow allocation and greater naturalisation of the regime. Regimes A, B and C promote ecological provision, with varying prioritisations. This demonstrates the utility of this approach; it is possible to define design criteria, which may be adapted to accommodate changing water demands and diverse interests of stakeholders present within a given system. Validation of this approach through post-implementation in-stream flow experiments, in order to assess ecological response to proposed flow regimes, is a key next step. Should this method be validated, it is believed that such flows could be applied regionally to similar river systems with minimal field investigation requirements. Such transferability may allow for smaller scale impoundments across the UK to implement environmental flows, where previously this was unfeasible due to the quantity of impoundment systems and the intensity of labour required to assign environmental flows to individual sites.

Scaling this methodology up to assess higher magnitude class river systems would likely require adaptation of the approach. A larger number of field velocity measurements are recommended for more robust calibration, and the influence of vertical velocity may also have to be considered in some cases (Pisaturo et al., 2017). Larger systems may host a greater variety of biota, and therefore the type of indicator species selected must be considered; fish may be present and act as an important aspect of the ecosystem (Cheimonopoulou et al., 2011; Harris, 1995), or macrophytes might be used for analysis as in other studies (Onaindia et al., 2005). Further system ecological model complexity might be added, including processes that may be more relevant at larger scales, e.g. heterogeneity of bed sediment; CASiMiR is able to consider such influences if species affinities are inputted. The flow contributions of any downstream tributaries or depleted reaches to the site of interest would also require consideration, and may entail a more adaptive approach to the reservoir flow regime due to the variability of natural flow that is introduced (which could for example be informed using hydrological modelling).

This framework currently focuses upon application for sites impacted by impounding reservoirs; it could be possible to adapt it for use in other site restoration assessments such as hydropower-impacted sites by incorporating the unique challenges and priorities of the given modification into the design stage of the environmental flow regime. An example of such a consideration would be the necessity of disruptive high flows from hydropower releases; perhaps a regime design for such an application may focus upon dampening and prolonging these high flows according to what is feasible without compromising the service of the dam. It is also acknowledged that flow is not the sole driver of ecological response, and other stressors such as water chemistry likely play a significant role at many sites. It has been suggested that the diverse influences of riverine ecology must be studied both through short-term mechanistic experiments and long-term explanatory studies in order to disentangle this complex web of interactions (Laini et al., 2018). Climate change and land use change are also resulting in a shifting environment, further driving changes in ecological metrics (Li et al., 2018). As understanding of these interactions grows, it would be possible to integrate further mitigation methods into the framework presented in this study. The ability to integrate ecological requirements according to context, and make adjustments according to new knowledge, offers significant utility within this framework.

6. Conclusions

This study has presented a methodology by which a study site is assessed and environmental flows are proposed based upon a combination of species response to flow (through preference curves), the influence of magnitude upon habitat diversity, and typical unregulated regional flow characteristics, in order to form a holistic ecological solution. Results suggest that uniform increases in magnitude over long periods result in disproportionately little ecological benefit relative to volume of water released, and affirms the use of optimised and targeted

high flow events. Though there is a rich literature detailing the concepts considered, we are not aware of any studies suggesting a similar approach by which such a combined range of flow requirements within a particular site or region may be assessed. Poff et al. (2017)'s update on the evolution of environmental flow science discusses progress in almost every area, but there is not yet a unified approach to environmental flow assessment. They emphasise the need to extend from a local scale to basin-scale perspective (Poff et al., 2017).

Amidst this rapidly developing field in which numerous frameworks and methods for environmental flow assessment are emerging, this study offers a novel approach in efficient annual flow regime designation, aiming towards regional transferability. We offer the first steps towards an actionable regional water management solution to the issue of impoundment-modified flow impacts that is desirable both for the purpose of ecological and water resources conservation. Future priorities include the detailed validation of such an approach by implementation of a derived flow regime at a case study site, and the monitoring of ecological response in comparison to model predictions. There is also scope for this framework to be scaled up to larger river systems, though this may require the incorporation of other variables significant at such a scale, such as substrate type and variation and the sediment transport regime. Fish may also be considered in CASiMiR should they be present in the system. This investigation suggests that 2D habitat modelling remains a tool with great potential when incorporated into such holistic practices, and shows great promise as water managers move into transferable, regional-focused forms of investigation.

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