THE EFFECT OF FLOW REGULATION ON THE DISTRIBUTION AND DYNAMICS OF CHANNEL GEOMORPHIC UNITS (CGU'S) AND IMPLICATIONS FOR MARBLE TROUT (*SALMO MARMORATUS)* SPAWNING HABITAT IN THE SOČA RIVER, SLOVENIA

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Abstract

This research examines the impact of flow regulation on the spatial distribution and dynamics of physical habitats or channel geomorphic units (CGU) of the Soča River, an upland river system in Slovenia. In order to assess the impact of flow alteration on the spatial pattern of CGU type, size, hydraulics and distribution, a river channel survey was completed along three reaches (totalling 14.3km), i.e. an unregulated stretch and two regulated reaches (with reduced flows). In addition, one regulated reach was re-surveyed at different discharges to investigate the dynamics of CGU's and their relationship with flow.

CGU's were classified and mapped on foot and from a boat using a combination of visual assessment and physical measurements of the hydraulic characteristics (velocity and depth) in each CGU. GPS was used to locate CGU boundaries to sub-metre accuracy, and the application of GIS enabled the analysis of the distribution of CGU's along each reach.

The effect of flow regulation on the hydraulic character of the river becomes apparent by highlighting differences in the types of CGU's present between the regulated and unregulated reaches. Reduced flows from river regulation also significantly reduces the size of CGU's, alters their hydraulic character, and affects the longitudinal distribution of types by creating greater habitat fragmentation. This work also highlights the need to assess CGU's along continuous stretches of river in order to understand the nature and dynamics of river habitats.

Hydraulic preferences for spawning habitat of marble trout (Salmo marmoratus) were obtained from previous research. The hydraulic character of CGU's were analysed at different discharges and combined with the hydraulic preferences of the species to evaluate the impact of flow regulation on habitat availability for marble trout. Analysis shows that intermediate measured flow provides increased spawning habitat availability in the chosen reach for this target species.

Keywords: *Physical Habitat, Flow Regulation, Marble Trout, Soča River*.

1 INTRODUCTION

The quantity and quality of physical habitat in rivers is determined by the interaction of geomorphology and hydrology. It plays an important role in determining 'river health' and influencing the structure and function of aquatic communities (Maddock 1999). Traditional assessment of both physical habitat and biotic communities has tended to focus on sampling at individual points, cross-sections or along short (i.e. <200m) stretches of river ('micro' or small scale). Subsequent extrapolation to the sections of river inbetween ('upscaling') provides catchment assessments (at the 'macro' or large scale). Fausch et al. (2002) have argued that river habitat assessment should concentrate on assessing complete reaches at the 'meso' or 'intermediate' spatial scale in order to recognise the river landscape as a spatially continuous longitudinal and lateral mosaic of habitats. This approach underpins the use of physical habitat mapping.

A range of different river habitat mapping methods and classification systems have been developed to facilitate this approach. Habitat mapping surveys are normally completed for one of two main reasons:-
1) For survey purposes, i.e., to provide an inventory of the physical habitat present as part of a basic resource assessment in it's own right (e.g. Halwas & Church 2002).
2) For impact assessment purposes, i.e., as part of aquatic habitat modelling studies. Habitat mapping data are used to either a) model the relationship between physical habitat availability and flow directly from the mapping results without the need for any further fieldwork (e.g. MesoHABSIM (Parasiewicz 2001)), or, b) to identify representative cross-sections and reaches for subsequent and more detailed study. This use of habitat mapping is also often completed as part of PHABSIM Studies (e.g. Maddock et al. 2001).

River habitat mapping aims to identify the types and spatial configuration of geomorphic and hydraulic units. The terms used to describe these units differ between authors and include 'channel geomorphic units' (CGU's) (e.g. Hawkins et al. 1993), 'mesohabitats' (e.g. Tickner et al. 2000), 'physical biotopes' (e.g. Padmore 1997) and 'hydraulic biotopes' (e.g. Wadeson 1994). Newson and Newson (2000) provide a review of the use of some of these terms and the differences between them.

In addition to the need to assess rivers at the most appropriate scale and along continuous reaches, others have called for the translation of key concepts that are well established in landscape ecology to be translated to riverine environments (Wiens 2002). These key concepts include patch dynamics, habitat connectivity, complexity and fragmentation, and the importance of understanding river ecosystems at a range of spatial scales. This requires a shift in traditional ways of conceptualising and sampling river habitats. A recent study examining macroinvertebrate assemblages has demonstrated the importance of this new approach (Heino et al. 2004). Habitat heterogeneity has also been successfully quantified using spatial heterogeneity measures to examine the influence of relative sediment supply (Yarnell et al. 2006). River habitat mapping is likely to underpin an understanding of the links between physical habitat dynamics and instream biota in general, and particularly for fish species.

The aims of this research were two fold. Firstly, we utilised a rapid habitat mapping approach in it's traditional sense to examine the impact of flow regulation on the spatial distribution and temporal dynamics of physical habitats or channel geomorphic units (CGU) in the Soča River, Slovenia. Secondly, we characterised the hydraulic preferences of spawning marble trout using field data from previous research Pvož (2008) and an approach developed by Conlan et al. (2007), and attempted to determine the impact of flow regulation on habitat availability for this important target species.

2 SITE DETAILS

The Soča River rises in the Slovenian Alps, flowing for 95km through Slovenia before crossing into Italy and discharging into the Adriatic Sea. It has a catchment area of 1576 km^2 and is predominantly underlain by limestone, but the lower parts the river run over flysch and quaternary gravels. The Soča has a flashy flow regime, with high flows occurring at any time of year. The lowest flows are experienced both in summer and winter months with generally higher snow-fed flows in spring and rain fed flows in autumn. The Soča River is well known for the presence of marble trout and recreational (white-water rafting) opportunities.

The river is regulated for hydro-power production at the Podsela Dam and Ajba Dam. Water is abstracted from the impoundment upstream from each dam. It then flows along a bypass channel to the hydropower plant and is subsequently augmented back to the river channel further downstream. Therefore, bypassed sections with reduced flows exist below each dam.

No long term flow records are available to describe the pre- and post river regulation flow regimes exactly, but it is clear that the hydro-power scheme abstracts the vast majority of water for long periods of time, leaving by-passed sections of river with greatly reduced flows. Prior to 2001, the highest possible abstraction rate at Podsela Dam was 96 m^3s^{-1} and the measured flow below the Podsela Dam for most of the year is 0.2 m^3s^{-1}. The highest possible abstraction rate at the Ajba Dam is 75 m^3s^{-1} whilst flow releases until 2003 were normally 0.5 m^3s^{-1}.

In order to assess the impact of these reduced flows on physical habitat type, size and fragmentation, three reaches of river were assessed. **Reach 1:** an unregulated 5.14km stretch of the river between Volarje and Tolmin flowing through a broad open floodplain; **Reach 2:** on a 4.20km by-passed section of the river affected by abstraction below the Podsela Dam that flows through a confined river valley bordered by bedrock walls; and **Reach 3:** another regulated part of the river below the Ajba Dam (4.95km long) with a relatively intermediate-sized valley floor. The three reaches are illustrated in Figure 1 below.

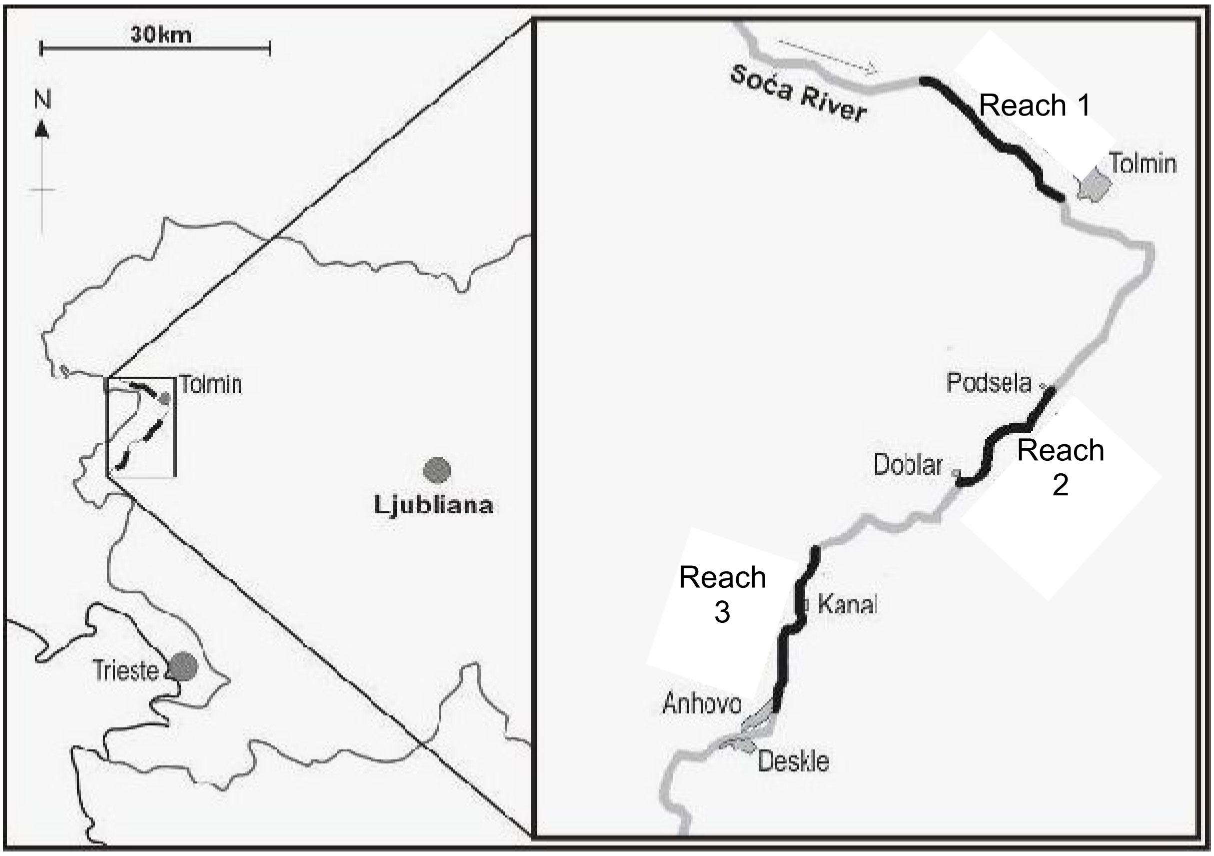


Figure 1. Site location

3 METHOD

3.1 Habitat Mapping

In order to assess the impact of flow alteration on CGU type, size, hydraulics and distribution, habitat mapping surveys were completed during July 2004 along the three reaches, and at two further flows along the regulated Reach 2 during July 2005. The three flow surveys along Reach 2 were conducted at 0.940 m^3s^{-1}, 1.546 m^3s^{-1} and 3.496 m^3s^{-1}. These represent relatively small variations in discharge compared to variation associated with the natural flow regime, but in order to distinguish them for the purposes of this research have been labelled as 'low', 'medium' and 'high' respectively.

CGU's were classified using a modified version of the Hawkins et al. (1993) approach and mapped on foot and from a boat using a combination of visual assessment and physical measurements in each CGU. Channel width and water width were recorded to the nearest metre within each CGU. Water depth was measured to the nearest cm and the average water column velocity was recorded at a representative point in each CGU. Substrate sizes present (based on the Wentworth classification) were identified and assigned to 'dominant', 'subdominant' and 'present' categories. The proportion of the surface area of each CGU taken up with instream cover (e.g. instream macrophytes, large woody debris) and overhanging cover (e.g. from overhanging trees and boughs) were visually estimated to the nearest 10 percent. The presence of lateral-, point- and mid-channel bars, their location (e.g. left or right bank), and whether they were vegetated (>50% of surface covered) or unvegetated (<50%) were also noted. Photographs were taken of each CGU. Mapping-grade GPS was used to locate CGU boundaries to sub-metre accuracy, and the application of GIS (MapInfo) enabled the description and analysis of the longitudinal distribution of CGU's along each reach.

Using MapInfo 7.5 software, GPS data were combined with digitised maps at 1:50,000 scale and data recorded during the survey to create maps showing the CGU locations. The measured width and length data were used to calculate total water area in each reach and for individual CGU types in each reach. Physical habitat hetergoeneity, defined as the spatial complexity of CGU's within a stream reach (Yarnell et al. 2006) was quantified using Shannon's Diversity Index (H) and Shannon's Equitability / Eveness Index (E)

3.2 Development of 'Fuzzy Logic' habitat preference curves

The use of habitat suitability curves to describe the depth, velocity and substrate preferences of individual species and life stages is well known in habitat modelling studies. These curves can be created by the use of professional judgment or detailed field observations at the site of interest, or a neighbouring unimpacted site (Bovee 1982). The latter has the advantage of providing site specific information but may be flawed for a range of reasons, including the influence of flow conditions and the range of habitats available during sampling, species may select different habitats depending on the time of day or season, and the influence of competition for space by other species / life stages (Vismara et al. 2001).

However, we recognise that even these curves are susceptible to the limitations outlined above, and therefore developed 'fuzzy logic' curves. Fuzzy logic is designed to be applied to situations where only imprecise or even ambiguous information is available and therefore is ideally suited to the application of habitat suitability criteria (Conlan et al. 2007). Fuzzy models are particularly valuable for situations where noise exists in the data and is not necessarily quantifiable or in other words, where the situation is ambiguous (Negnevitsky 2005). Thus, fuzzy analysis commonly maps onto linguistic definitions (good, medium, poor) rather than numerical definitions. The ecological uncertainty surrounding habitat preference, which arises from the methods obtained to derive the curves may be large. By developing fuzzy habitat models it is possible to explicitly retain the ambiguity that is implicit in habitat preference curves.

We based the development of 'fuzzy' habitat suitability curves and subsequent analysis of habitat availability on that used by Conlan et al. (2007). In order to examine the influence of flow regulation on marble trout spawning habitat, information on hydraulic requirements was extracted from a report on the habitat preferences for the chosen target species and life stage produced by Pvož (2008). These depth and velocity requirements were interpreted into three classes, i.e. poor, medium and good for both parameters (see table 1 below).

Given that water depth and velocity influence fish habitat suitability in combination with one another rather than acting as independent variables, we examined combinations of these two variables. Combinations of poor, medium and good habitat classes for each parameter can produce nine types of habitats. These nine possible combinations were classified into six groups ranging from unsuitable (a combination of poor depth and poor velocity), very poor, poor, intermediate, good and finally to excellent (a combination of good depth and good velocity). Each of the six groups were assigned a score from 0-5 as show in table 2 below.

Table 1. Habitat preferences for marble trout spawning habitat (adapted from Povž 2008)

	Poor	**Medium**	**Good**
Water Velocity	< 0.15 m/s > 0.90 m/s	0.15 - 0.40 m/s 0.70 – 0.90 m/s	0.40 - 0.70 m/s
Water Depth	< 0.24 m >0.60 m	0.48 – 0.60 m	0.24 – 0.48 m

Table 2. The rule set used to define habitat classes for marble trout spawning and the corresponding 'score' associated with each combination (Conlan et al. 2007)

	Velocity poor	**Velocity medium**	**Velocity good**
Depth poor	Unsuitable habitat 0	Very poor habitat 1	Poor habitat 2
Depth medium	Very poor habitat 1	Intermediate habitat 3	Good habitat 4
Depth good	Poor habitat 2	Good habitat 4	Excellent habitat 5

For Reach 2, and at each of the three flows, the depth and velocity recorded within each CGU was converted into a poor, medium or good class based on the values given in table 1. Where the rating was poor or medium, it was also noted whether the velocity and depth was either higher or lower than the preferred range ('good') for further analysis outlined later. Each CGU was then assigned a habitat class and given the corresponding habitat score based on the combination of depth and velocity classes outlined in the rule set in table 2. These were used to assign 'weightings' to each habitat class, and weightings were multiplied by the total surface area of each CGU (m^2) to obtain a Weighted Usable Area (WUA). Finally, WUA values were divided by reach length to obtain a value of WUA in m^2 per 1000m of stream reach.

4 RESULTS AND DISCUSSION

4.1 CGU composition between reaches and the effects of flow regulation

Results demonstrated significant differences in the CGU composition between the unregulated and regulated reaches (Figure 2a). The unregulated stretch (Reach 1) was dominated by glides (55%) with the rest of the reach consisting of fast-flowing and turbulent features (runs, riffles and rapids). The dominant feature of the regulated reaches were the slow flowing pool CGU's occupying 44% of Reach 2, and 76% of Reach 3, with glides, runs, riffles and rapids forming the remainder of the

CGU’s. This highlights the effects of reduced flows on habitat composition in the regulated reaches.

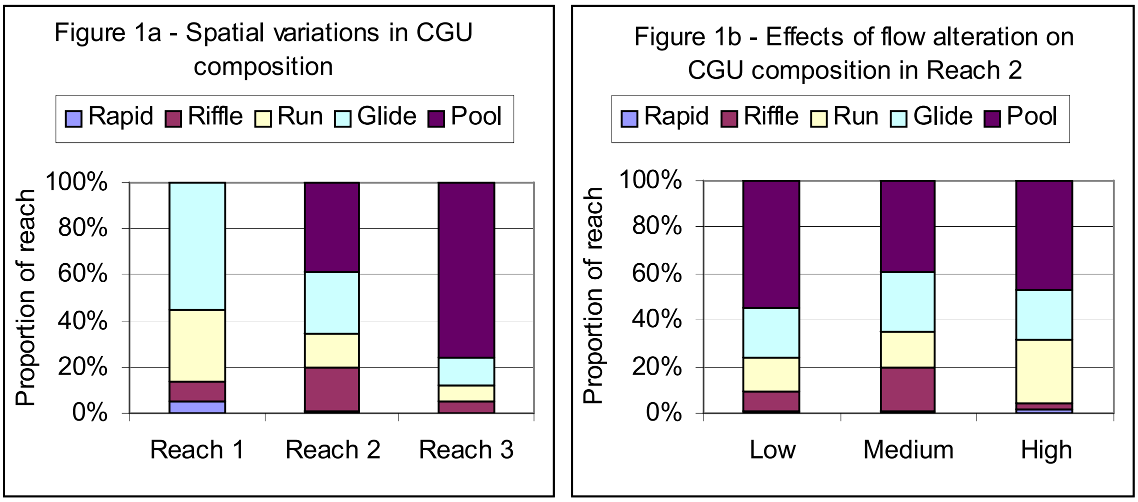


Figure 2a) Variations in CGU composition between reaches determined by flow regulation, and 2b) effects of flow alteration on CGU composition within a single reach (Reach 2).

The repeat surveys in Reach 2 (Figure 2b) highlighted differences (albeit smaller variations than the spatial changes) in habitat composition caused by changing discharges within the reach. At the relatively higher flow, the proportion of runs increased (from 14.1% to 26.9% of reach area) and the proportion of riffles decreased (from 8.6% to 2.8% of reach area). This change is created by riffles becoming submerged or ‘drowned out’ during the relatively higher flow and becoming run type CGU’s.

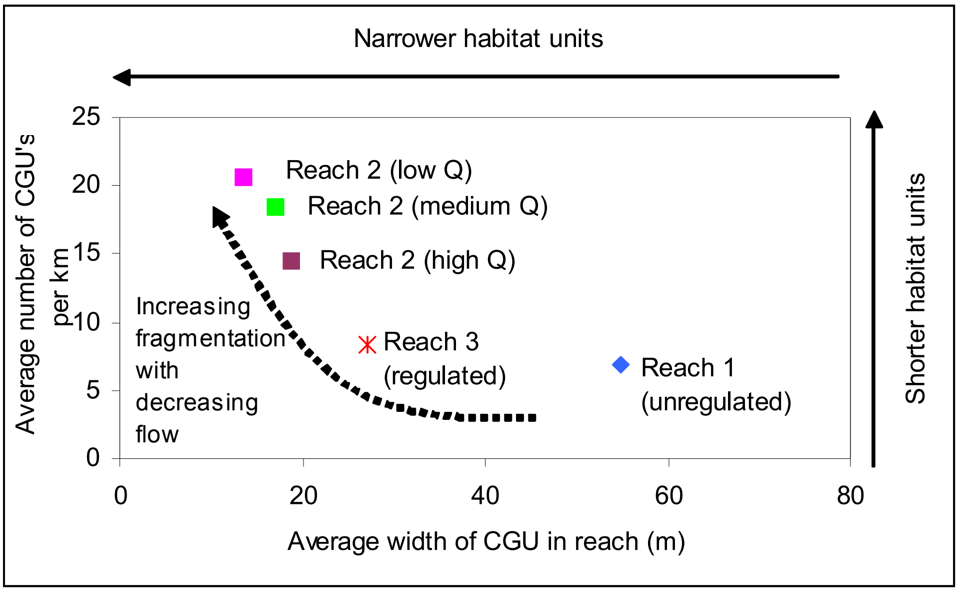


Figure 3 Comparison of average CGU width and no. of CGU’s per km between reaches and within the same Reach (2) at three different flows. Points in the upper left represent reaches dominated by large numbers of short and narrow CGU’s, i.e. fragmented habitats.

Habitat mapping data were analysed to evaluate the effect of flow regulation on the size of CGU's (Figure 3). The unregulated reach is dominated by larger CGU's (wider and longer units). As the flows decline, CGU's become shorter and narrower and hence fragmentation increases. This is supported by CGU's becoming progressively shorter and narrower in the three habitat mapping surveys conducted at different flows along Reach 2 (shown in Figure 3).

Data were also analysed to examine the spatial complexity of CGU's using two indices, i.e. Shannon's Diversity Index (H) and Shannon's Eveness Index (E). The former describes the range of CGU's present, with a higher index indicating greater diversity of CGU's. The latter describes the spread of CGU's with a lower index indicating an uneven spread in the CGU composition (e.g. one or two types dominate the overall CGU composition). Results of calculating the two indices and comparing between reaches, and examining the influence of flow changes within a reach are plotted in figure 4a and b.

Figure 4a indicates that the diversity of CGU's is lowest Reaches 1 and 3, and these stretches of river are also characterised by a more uneven spread in the CGU composition of the reach. Reach 2 had the highest diversity and more even spread of CGU types, but smaller habitat units (indicated by the smaller symbol in figure 4a, and previously described in figure 3). Figure 4b highlights that Reach 2 has greater diversity of CGU types, and a more even spread of CGU composition at the intermediate measured flow compared to the low or high flow.

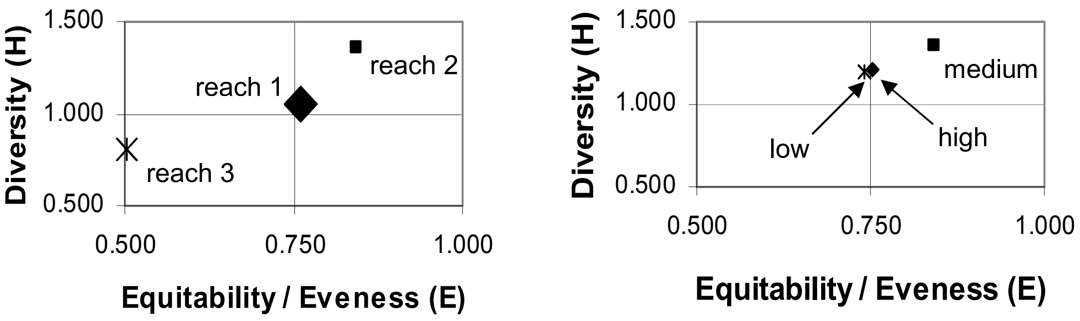


Figure 4 a (left). Diversity and Eveness of CGU composition compared **between reaches.** Note larger symbols indicate larger habitat units. Figure 4 b (right). Diversity and Eveness of CGU composition in reach 2 compared **between the three different measured discharges** (low =0.940 m^3s^{-1}, medium = 1.546 m^3s^{-1} and high = 3.496 m^3s^{-1}).

4.2 The influence of flow regulation on Marble Trout spawning habitat

Figure 5 illustrates the relationship between WUA and discharge for Reach 2. This highlights that the intermediate discharge provides a greater amount of suitable habitat compared to that available at the low and high measured flows.

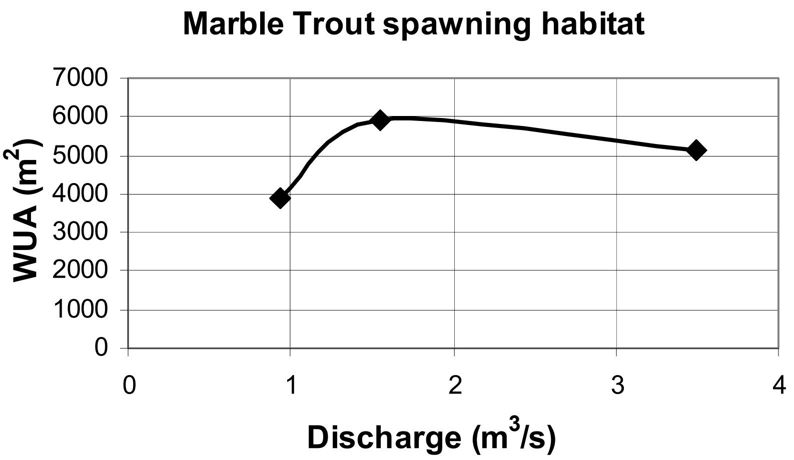
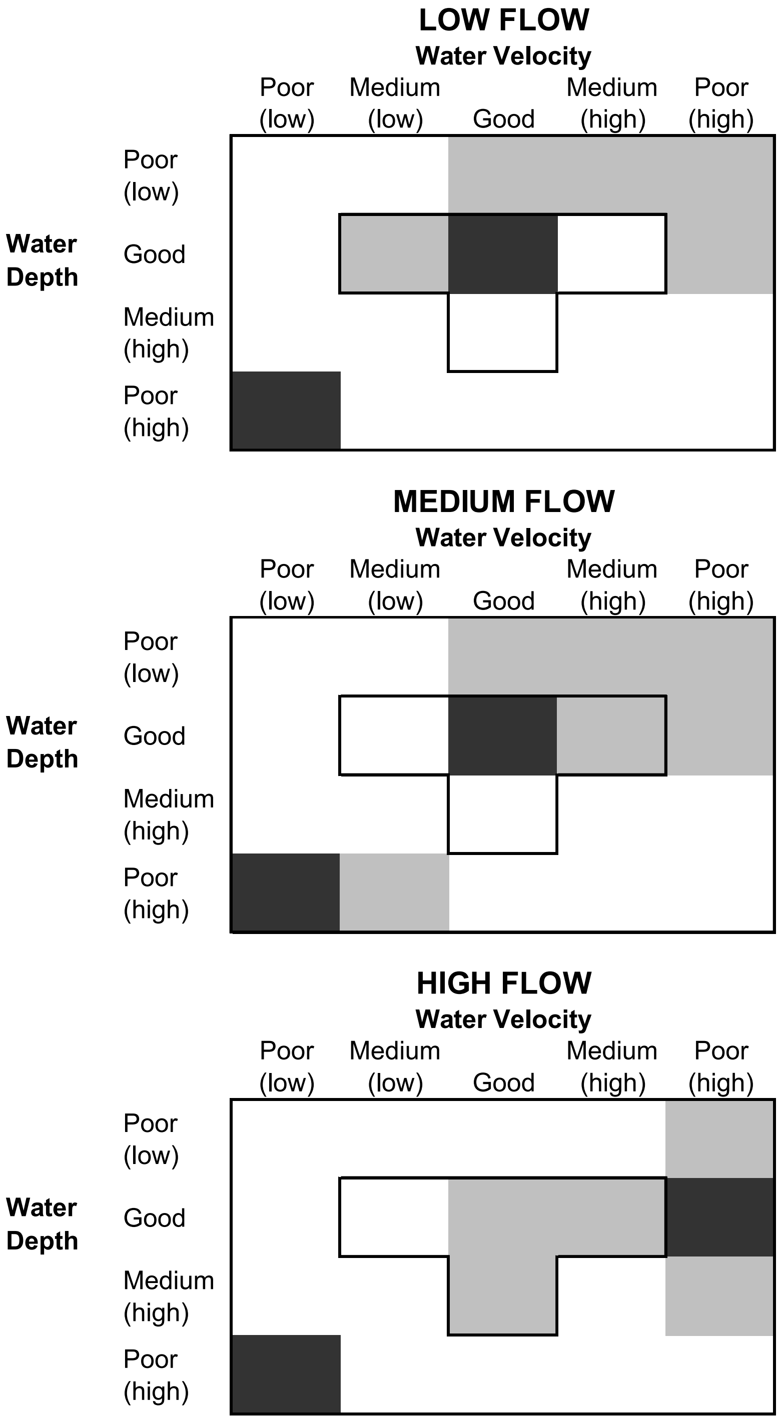


Figure 5. Flow versus habitat relationship for marble trout spawning habitat in Reach 2 based in CGU depth and velocity.

Further analysis of the habitat suitability of each CGU was completed to determine the limiting factors that inhibit habitat availability and which combinations of depth and velocity are most common within this reach and at the three measured discharges for this target species and life stage. These are illustrated in figure 6 below.

The diagrams illustrate that there is a significant proportion of the reach at all measured flows that has a velocity that is too low and depth that is too high for marble trout spawning (i.e. ‘pool’ habitat, shown in bottom left of each diagram). It also illustrates that at the lowest measured discharge, there is a significant proportion of CGU’s that are limited by insufficient water depth (three light grey squares across the top row), but as flows increase, then a greater proportion contain sufficient water depth, but spawning habitat becomes limited by high velocities (note the dark grey square with ‘good’ water depth but ‘poor (high)’ velocity at the highest measured flow).

We acknowledge there are limitations to this approach. Other factors, in addition to depth and velocity influence habitat availability, such as water temperature and substrate size. We intend to build substrate size into our future analysis as this was also recorded in the field when CGU’s were assessed. Separate monitoring of water quality variables (including temperature), and modelling studies to incorporate the influence of these parameters are still needed. Additional analysis, using the hydraulic preferences of other life stages, and/or other target species would help move towards a more holistic evaluation of the impacts of flow changes o the instream ecology. Our approach has not incorporated modelling at flows inbetween the three measured flows, and if completed, this additional work would enable us to determine the nature of the relationship between measured flows and assess optimum discharges with more confidence.



LOW FLOW

Water Velocity

Water Depth	Poor (low)	Medium (low)	Good	Medium (high)	Poor (high)
Poor (low)			▨	▨	▨
Good		▨	■		▨
Medium (high)					
Poor (high)	■				

MEDIUM FLOW

Water Velocity

Water Depth	Poor (low)	Medium (low)	Good	Medium (high)	Poor (high)
Poor (low)			▨	▨	▨
Good			■	▨	▨
Medium (high)					
Poor (high)	■	▨			

HIGH FLOW

Water Velocity

Water Depth	Poor (low)	Medium (low)	Good	Medium (high)	Poor (high)
Poor (low)					▨
Good			▨	▨	■
Medium (high)			▨		▨
Poor (high)	■				

Figure 6. Combinations of depth and velocity habitat classes in Reach 2 at low, medium and high flow. Light grey shaded areas indicate between 5-15% of the CGU's had this combination of depth and velocity. Dark grey shaded areas indicate >15% of the CGU's have this depth and velocity combination (and hence are common). Unshaded areas indicate <5%. The highlighted 'T shaped area in the centre represents the combinations of depth and velocity that have habitat classes 4 and 5, i.e. good and excellent.

5 CONCLUSION

The effect of flow regulation on the physical and hydraulic character of the river becomes apparent by using habitat mapping results to highlight differences in the dominant types of CGU's present. Flow regulation reduces discharge, and habitat mapping is an effective tool to highlight increasing proportions of slow flowing types evident under these conditions. Declining flows also reduces the size of CGU's, and affects the longitudinal distribution of types thus creating greater habitat fragmentation. Habitat availability for the spawning requirements of marble trout were greatest at the measured intermediate flow for this particular river. The habitat mapping applied here was sufficiently sensitive to detect changes in the hydraulic and physical character of CGU's in a regulated reach with relatively small changes in flow.

We believe that this type of approach that considers the river system as a set of interconnected habitats, analyses the entire reach rather than at individual and disparate points, and combines field data with information on habitat requirements using habitat classes rather than absolute depth and velocity habitat suitability curves provides a more pragmatic approach to assessing the impact of flow changes in physical habitat availability. These tools can then be used to make recommendations for environmental flows with greater confidence.

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