Protected area effectiveness for fish spawning habitat in relation to earthquake-induced landscape change

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Abstract

We studied the effectiveness of conservation planning methods for *Galaxias maculatus,* a riparian spawning fish, following earthquake-induced habitat shift in the Canterbury region of New Zealand. Mapping and GIS overlay techniques were used to evaluate three protection mechanisms in operative or proposed plans in two study catchments over two years. Method 1 utilised a network of small protected areas around known spawning sites. It was the least resilient to change with only 3.9% of post-quake habitat remaining protected in the worst performing scenario. Method 2, based on mapped reaches of potential habitat, remained effective in one catchment (98%) but not in the other (52.5%). Method 3, based on a habitat model, achieved near 100% protection in both catchments but used planning areas far larger than the area of habitat actually used. This example illustrates resilience considerations for protected area design. Redundancy can help maintain effectiveness in face of dynamics and may be a pragmatic choice if planning area boundaries lack in-built adaptive capacity or require lengthy processes for amendment. However, an adaptive planning area coupled with monitoring offers high effectiveness from a smaller protected area. Incorporating elements of both strategies provides a promising conceptual basis for adaptation to major perturbations or responding to slow change.

Keywords

Dynamic environments, resilience, conservation objectives, protected areas, planning methods, *Galaxias maculatus*, adaptation to change.

1. Introduction

For many species, critical life history phases create obligate habitat requirements. These may be vulnerable points in the life cycle, especially where relatively specific biophysical conditions are required (Lucas, Bubb, Jang, Ha, & Masters, 2009). Vulnerability may be associated with periodic events and longer term change involving both natural and anthropogenic processes (Turner et al., 2003). A particular concern is where human activities reduce the quality or availability of existing habitat unless counterbalanced by compensatory actions, such as the creation of suitable habitat elsewhere (Faith & Walker, 2002). The concept of resilience provides a focus on thresholds in system properties that are important to their persistence (Holling, 1973). In linked socio-ecological systems it is related to adaptive capacity (Gallopín, 2006), and actual responses to changed hazard exposure and/or sensitivity (Turner, Lambin, & Reenberg, 2007). Since resilience assessment is concerned with identifying the conditions required to maintain a desirable state (Gunderson, Allen, & Holling, 2010), it may be readily applied to habitat management.

Protected areas (PAs) describe a desired state defined by clear objectives. They are a cornerstone of global efforts to halt biodiversity loss (UN (United Nations), 2011). The IUCN recognises six categories of PAs defined by differences in management approaches (Stolton, Shadie, & Dudley, 2013). Category IV PAs aim to protect particular species or habitats (Table 1). They are often relatively small and are designed to protect or restore: 1) flora species of international, national or local importance; 2) fauna species of international, national or local importance including resident or migratory fauna; and/or 3) habitats (Dudley, 2008).

Table 1. Aspects of IUCN Category IV Protected Areas (Dudley, 2008).

Role in the landscape/seascape
Category IV protected areas frequently play a role in "plugging the gaps" in conservation strategies by protecting key species or habitats in ecosystems.
They could, for instance, be used to:
• Protect critically endangered populations of species that need particular management interventions to ensure their continued survival;
• Protect rare or threatened habitats including fragments of habitats;
• Secure stepping-stones (places for migratory species to feed and rest) or breeding sites;
• Provide flexible management strategies and options in buffer zones around, or connectivity conservation corridors between, more strictly protected areas that are more acceptable to local communities and other stakeholders.

Issues for consideration
• Many category IV protected areas exist in crowded landscapes and seascapes, where human pressure is comparatively greater, both in terms of potential illegal use and visitor pressure.
• The category IV protected areas that rely on regular management intervention need appropriate resources from the management authority and can be relatively expensive to maintain unless management is undertaken voluntarily by local communities or other actors.
• Because they usually protect part of an ecosystem, successful long-term management of category IV protected areas necessitates careful monitoring and an even greater than-usual emphasis on overall ecosystem approaches and compatible management in other parts of the landscape or seascape.

79 Effective conservation involves managing risks and recent biodiversity declines appear to be
80 continuing (Butchart et al., 2010). Management effectiveness evaluation is an essential activity to
81 assess the strengths and weaknesses of protection mechanisms and different management approaches
82 (Stolton et al., 2007). A key area of focus is the extent to which PAs actually deliver on their
83 objectives such as by protecting important values (Hockings, 2003). Under conditions of
84 environmental change evaluation is especially important to address whether the areas involved are
85 functioning as an effective conservation strategy (Leverington, Costa, Pavese, Lisle, & Hockings,
86 2010). Various methodologies have been used, many of which were originally developed to the
87 support adaptive management of PA sites and systems (Coad et al., 2015). Range shifts are a topic of
88 particular importance since they may undermine the effectiveness of PA networks unless resilience
89 has been incorporated by design. In this setting human agency is inextricably linked to the trajectory
90 of the values identified for protection. This may require amendment of the protection mechanism
91 itself to ensure continued performance over time.

92 Diadromous fishes have specific habitat requirements across several stages of their life histories,
93 involving both freshwater and marine environments (Gross, Coleman, & McDowall, 1988). In some
94 species these may be separated by vast distances and associated with significant migrations (Metcalfe,
95 Arnold, & McDowall, 2002). There may be different conservation issues affecting each critical
96 habitat requiring a wide range of management responses (McDowall, 1999). *Galaxias maculatus*
97 (Jenyns 1842) or 'īnanga' is a diadromous species currently listed as 'at risk – declining' under the
98 New Zealand Threat Classification System (Goodman et al., 2014). Adult fish are found in lowland
99 coastal waterways with the upstream distribution limited by relatively poor climbing ability (Baker &
100 Boubee, 2006; Doehring, Young, & McIntosh, 2012). Spawning occurs in estuarine waterways with
101 the exception of some populations that have become land-locked in lakes (Chapman, Morgan, Beatty,
102 & Gill, 2006). The locations used are highly specific as the result of specialised reproductive
103 behaviour associated with the migration of adult fish towards rivermouths at certain times of the year
104 (Benzie, 1968a). Spawning events are strongly synchronised with the spring high tide cycle with an
105 apparent association between spawning site distribution and the salinity regime (Burnet, 1965). The
106 majority of spawning sites have been found within 500 m of the inland limit of salt water (Richardson
107 & Taylor, 2002; Taylor, 2002). In addition, spawning sites occupy only a narrow elevation range
108 located on waterway margins just below the spring tide high-water mark (Taylor, 2002). As tidal
109 heights drop towards the neap tides these sites are no longer inundated at high-water and for most of
110 their development period the eggs are in a terrestrial environment (Benzie, 1968a, 1968b). Egg
111 survival rates are highly dependent on the condition of the riparian vegetation in these locations until
112 hatching in response to high water levels, usually provided by the following spring tide (Hickford,
113 Cagnon, & Schiel, 2010; Hickford & Schiel, 2011).

114 The degradation of spawning habitat has been identified as a leading factor in the species' decline
115 (McDowall, 1992; McDowall & Charteris, 2006). This has been linked to land-use intensification on
116 coastal waterway margins (Hickford et al., 2010), as is a common trend worldwide (Kennish, 2002).
117 Protection mechanisms must often address contested-space contexts characterised by incompatible
118 activities. Multiple-stressor situations are common with grazing, vegetation clearance, mowing,
119 grazing, flood protection, and channelization being examples that have contributed to degradation
120 (Hickford & Schiel, 2011; Mitchell & Eldon, 1991). Habitat protection is a requirement of national
121 legislation under the Conservation Act 1987 and the Resource Management Act 1991 (RMA).
122 Implementation relies on the identification of areas for protection coupled with relevant rules and
123 documented in plans or management strategies prepared under the relevant Acts. In many cases
124 spatial explicit planning methods (e.g. maps) are used to delineate the protected areas. Although these

125 provide a practical approach to address the conservation objective, they require reliable habitat
126 information. In dynamic environments challenges include recognising spatiotemporal variance and
127 accommodating it in design of the protection mechanisms used (Bengtsson et al., 2003).

128 In 2010 and 2011 a sequence of major earthquakes affected the Canterbury region of New Zealand. It
129 included several large destructive events and numerous aftershocks centred beneath the city of
130 Christchurch (Beavan, Motagh, Fielding, Donnelly, & Collett, 2012). The magnitude of physical
131 effects necessitated a long-term socio-ecological response associated with new ecological trajectories
132 and variety of land-use planning needs. Topographic and bathymetry measurements identified
133 enduring changes in ground levels, especially in the vicinity of waterways (Quigley et al., 2016).
134 Ecohydrological effects have been a particular focus in light of changed water levels on the landscape
135 (Hughes et al., 2015), and alterations to estuarine dynamics (Measures et al., 2011; Orchard &
136 Measures, 2016). *G. maculatus* spawning was recorded at locations never previously utilised in
137 comparison to pre-quake records (Orchard & Hickford, 2016). Vulnerability assessments identified
138 anthropogenic threats at many of these locations and recommended review of protection methods in
139 the operative statutory plans (Orchard, Hickford, & Schiel, in press). This context presented a unique
140 opportunity to evaluate conservation planning options in light of landscape-scale change whilst
141 informing the practical needs of post-quake adaptation processes. The objectives of this paper are to
142 (1) evaluate the efficiency and effectiveness of contemporary protection mechanisms, and (2) identify
143 recommendations for conservation planning to address earthquake-induced landscape change.

144

145 ## 2. Methods

146 *2.1 Study area*
147 The study area is the Avon Heathcote Estuary (Ihutai) located at 43.5^{o}S, 172.7^{o}E in the city of
148 Christchurch (Figure 1). The estuary is located between the Waimakariri River and the southern end
149 of a large sandy bay (Pegasus Bay) where it is a prominent local feature (Kirk, 1979). It is a barrier
150 enclosed tidal lagoon type estuary (Hume, Snelder, Weatherhead, & Liefting, 2007) with high
151 ecological and social values including cultural significance for Māori (Jolly & Ngā Papatipu Rūnanga
152 Working Group, 2013; Lang et al., 2012).

153 The Avon and Heathcote are the two major rivers of the estuarine system, both of which provide *G.*
154 *maculatus* spawning habitat. These are spring-fed lowland rivers waterways with average base flows
155 of approx. 2 and 1 cumecs respectively (White, Goodrich, Cave, & Minni, 2007). They are also
156 among the most well studied spawning locations in New Zealand with surveys having been conducted
157 periodically since 1988 (Taylor, Buckland, & Kelly, 1992).

158

159 *2.2 Geospatial analyses*

160 We analysed spawning site data from post-earthquake studies comprising of seven independent
161 surveys conducted over two years during the peak spawning months using a census-survey
162 methodology designed to detect all spawning in the catchment (Orchard & Hickford, 2017). The areas
163 surveyed were approximately 4 km reaches in each river extending from the saltmarsh vegetation
164 zone (downstream), to 500 m upstream of the inland limit of saltwater (Figure 1). The dataset of 188
165 records provided details of 121 spawning occurrences in the Avon and 67 in the Heathcote. Each
166 record included upstream and downstream coordinates of the spawning site, mean width of the egg

167   band, and area of occupancy (AOO) of eggs, with each site being defined as a continuous or semi-
168   continuous patch of eggs (Orchard, Hickford, & Schiel, 2016; Orchard et al., in press).

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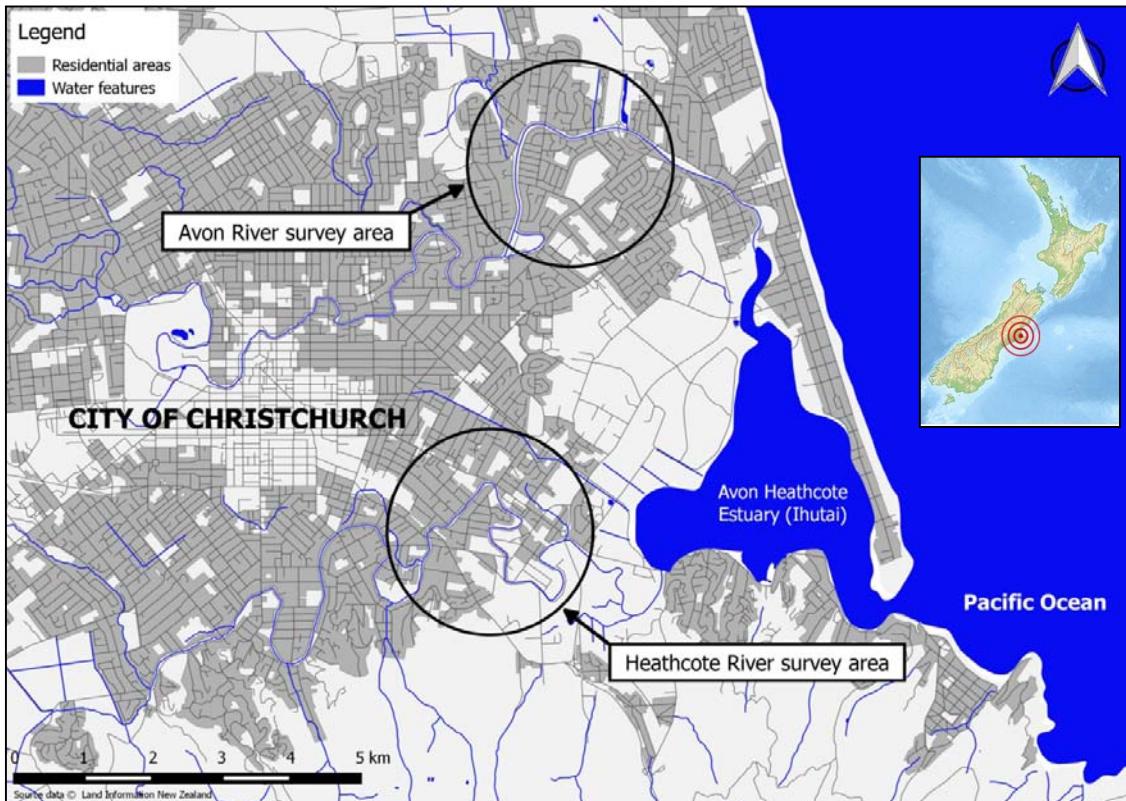
Figure 1. Location of post-earthquake survey areas for *G. maculatus* spawning habitat in the Avon and
Heathcote River catchments, city of Christchurch, New Zealand.

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174   Three spatially explicit protection mechanisms were identified in an analysis of proposed and
175   operative resource management plans (Table 2). In this paper we use the term 'protected areas' to
176   denote spatially explicit areas identified in planning methods to address conservation objectives in
177   statutory policies and plans. The areas evaluated in this study are consistent with the IUCN definition
178   of Category IV protected areas being 'areas to protect particular species or habitats, where
179   management reflects this priority' (Dudley, 2008). The size of these areas is often relatively small
180   with varying management arrangements depending on protection needs (Stolton et al., 2013).

181   Protected area and spawning site data were visualised in QGIS v2.8.18 (QGIS Development Team,
182   2016) and reach lengths (RL) calculated in relation to the centrelines of waterway channels digitised
183   from 0.075 m resolution post-quake aerial photographs (Land Information New Zealand, 2016). Three
184   comparable RL metrics were calculated to reflect (a) the RL protected under each planning method,
185   (b) extent of occurrence (EOO) of spawning sites, and (c) the total AOO of spawning sites (Table 3).

186   The effectiveness of each protection mechanism was evaluated as the percentage of post-earthquake
187   RL^{AOO} located within the PA. Efficiency was considered using two ratios: RL^{EOO} to $RL^{protected}$ and
188   RL^{AOO} to $RL^{protected}$. These reflect the size of the area set aside for protection (in terms of reach length)
189   versus the extent of the spawning reach, and the size of the areas actually utilised for spawning

190 respectively. Each calculation was made on a catchment basis at a yearly temporal scale (i.e. 2015 and
191 2016), and also using the combined data from both years of post-earthquake surveys.

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195 **Table 2.** Protected area mechanisms for *G. maculatus* spawning habitat evaluated in this study.

Method	Protected area mechanism	Delineation method in plans	Information source	Planning documents
1	Network of small protected areas based on known spawning sites	20 m diameter areas centred on point data coordinates of known spawning sites, identified in schedule to the plan	Point data and descriptions from NISD[†] and historical reports (Maw & McCallum-Clark, 2015)	Environment Canterbury (2015) Environment Canterbury (2016)
2	Mapped reaches of potential spawning habitat on a catchment basis	Reaches identified in planning maps and referenced in the plan	NISD point data and historical reports coupled with field surveys of riparian vegetation to identify potential habitat (Margetts, 2016)	Environment Canterbury (2014)
3	Mapped polygons of predicted spawning habitat coupled with a text description of where in the polygon the protection requirements apply	Polygons identified in planning maps and GIS layer referenced in the plan	GIS based model of predicted spawning habitat (Greer, Gray, Duff, & Sykes, 2015)	Environment Canterbury (2017)

196 [†] National Īnanga Spawning Database
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200 **Table 3.** Metrics calculated to evaluate the effectiveness and efficiency of protected area mechanisms for *G.*
201
202 *maculatus* spawning habitat.

Metric	Definition	Calculation method
$RL^{protected}$	Reach length protected areas within a catchment	Combined length of waterway channels falling within protected areas, as calculated from channel centrelines on a catchment basis
RL^{EOO}	Reach length of the extent of occurrence (EOO) of spawning within each catchment during the timeframe under consideration	Total length of waterway channels between the upstream and downstream limits of spawning, as measured along channel centrelines on a catchment basis
RL^{AOO}	Reach length of the area of occupation (AOO) of all spawning sites within each catchment during the timeframe under consideration	Total length of all individual spawning sites, as measured along channel centrelines on a catchment basis

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3. Results

The three protected area mechanisms provided considerably different $RL^{protected}$ values reflecting their spatial basis (Table 4). . However for each mechanism the $RL^{protected}$ was comparable between catchments. An overlay of each protection mechanism on combined post-quake spawning site data is provided for each of the study catchments in Figure 2.

Table 4. Reach length (RL) protected by each of the three protected area mechanisms evaluated in the two study catchments.

| Method	Description of protected area mechanism	Reach length protected (m)	
		Avon River	Heathcote River
1	Network of small protected areas based on known spawning sites	120	80
2	Mapped reaches of potential spawning habitat on a catchment basis	3230	3098
3	Mapped polygons of predicted spawning habitat coupled with a text description of where in the polygon the protection requirements apply	19100	16600
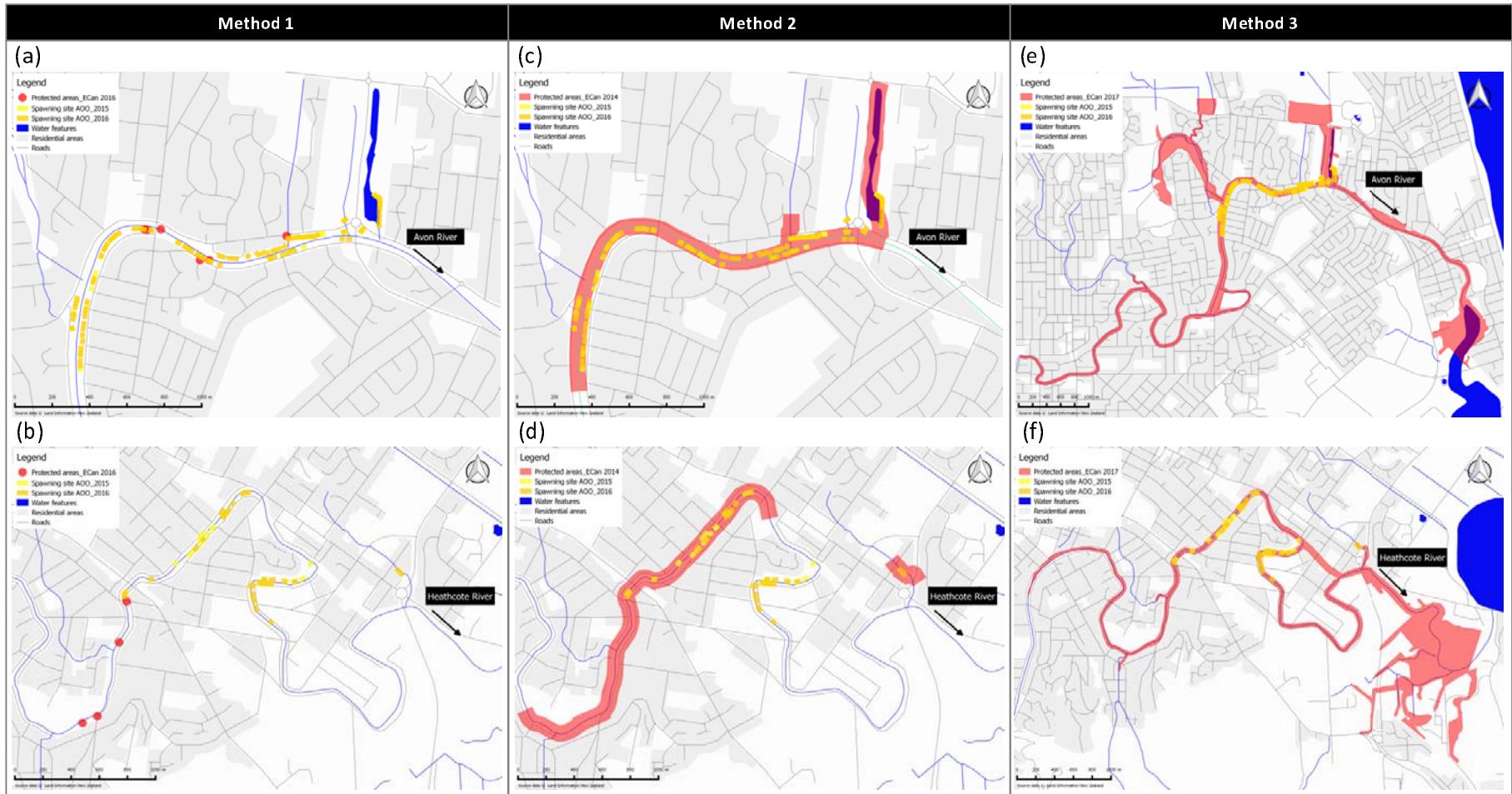
Figure 2. Overlay of the spatial extent of three protection mechanisms found in conservation plans on the footprint of post-earthquake *G. maculatus* spawning sites recorded in 2015 (n = 85) and 2016 (n = 103). (a) Method 1, Avon River, (b) Method 1, Heathcote River, (c) Method 2, Avon River, (d) Method 2, Heathcote River, (e) Method 3, Avon River, (f) Method 3, Heathcote River.

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219   Method 3 was highly effective at protecting spawning habitat, achieving 92.7% protection in the
220   Avon and 100% in the Heathcote using the combined post-quake data (Table 5). The anomoly in the
221   Avon relates to a few spawning sites that occurred outside of the mapped polygon in the vicinity of a
222   small tributary, and this occurred in both years. In the Avon, the effectiveness of method 2 was
223   similar with close to 100% achieved (Table 4). However in the Heathcote, only 69.9% of spawning
224   habitat fell within the protected area and 45.6% in 2016. This reflected the occurrence, in both years,
225   of spawning downstream (Figure 2d). In comparison, the effectiveness of method 1 was low. The
226   percentage of habitat protected ranged from 3.9–14.2% (Table 4). This reflected the extent to which
227   spawning occurred at previously known sites which formed the basis for delineation of the PAs
228   (Figure 2a & 2b).

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231   **Table 5.** Effectiveness of three protected area mechanisms for *G. maculatus* spawning habitat following
232   earthquake-induced landscape change.
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Protection mechanism	Time period	Percentage of habitat protected (% RL^{AOO})	
		Avon River	Heathcote River
Method 1	2015	5.4	7.5
	2016	14.2	6.3
	2015+2016	9.3	3.9
Method 2	2015	96.9	69.9
	2016	99.0	45.6
	2015+2016	98.0	52.5
Method 3	2015	96.9	100
	2016	96.5	100
	2015+2016	97.2	100

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236   In the efficiency evaluation, all of the protection mechanisms were relatively inefficient in terms of
237   land use allocation when the evaluation metric was RL^{AOO} (Figure 3a). For all methods, more than
238   half of the $RL^{protected}$ was allocated to areas that were not utilised for spawning habitat over the study
239   period, even when the areas allocated were very small and targetted at previously known spawning
240   sites. The highest percentage overlap with RL^{AOO} was 47.5% achieved by method 1 in the Avon in
241   2016. However, when the evaluation metric was RL^{EOO} the percentage overlap results changed
242   considerably. Method 1 achieved a 100% overlap in the Avon in both years but in the Heathcote only
243   12.5% (Figure 3b). Method 2 achieved 67.6% overlap in the Avon (2016) and 48.7% in the
244   Heathcote (2016), whilst method 3 achieved 11.5% in the Avon (2016) and 17.6% in the Heathcote
245   (2016).

246

247   Comparing these results, method 3 was the least efficient in terms of land use allocation for the
248   purposes of protection in all comparisons in the Avon. However, in the Heathcote method 1 was even
249   less efficient in terms of RL^{EOO} (Figure 3b). This reflected that the protected areas identified were not
250   well located in relation to the areas utilised for spawning (Figure 2). In the Avon, the PAs under the
251   method 1 were much better located with all PAs overlapping the RL^{EOO} (Figure 3b). In terms of
252   RL^{AOO} method 1 also performed better in the Avon versus the Heathcote as a result of the PAs
253   coinciding several of the areas actually utilised. However, even here the efficiency of PA mechanism

254 was rather variable with 47.5% of the $RL^{protected}$ overlapping with spawning sites in 2016 but only
255 17.5% in 2015 (Figure 3a). This variability is associated with the repeat use of some, but not all,
256 previous used spawning sites between years (Figure 2).
257
258 Overall, method 2 produced relatively consistent results in the efficiency comparisions between
259 years. This reflects that the RL^{EOO} was similar in both catchments between years and also located in a
260 similar position in the catchment versus the reaches mapped for protection. Within the RL^{EOO} the
261 total RL^{AOO} was also very similar between years (Avon 386 m^2 and 410 m^2, Heathcote 133 m^2 and
262 158m^2 for 2015 and 2016 respectively) despite considerable variation in the location of the sites used
263 each year (Figure 2).
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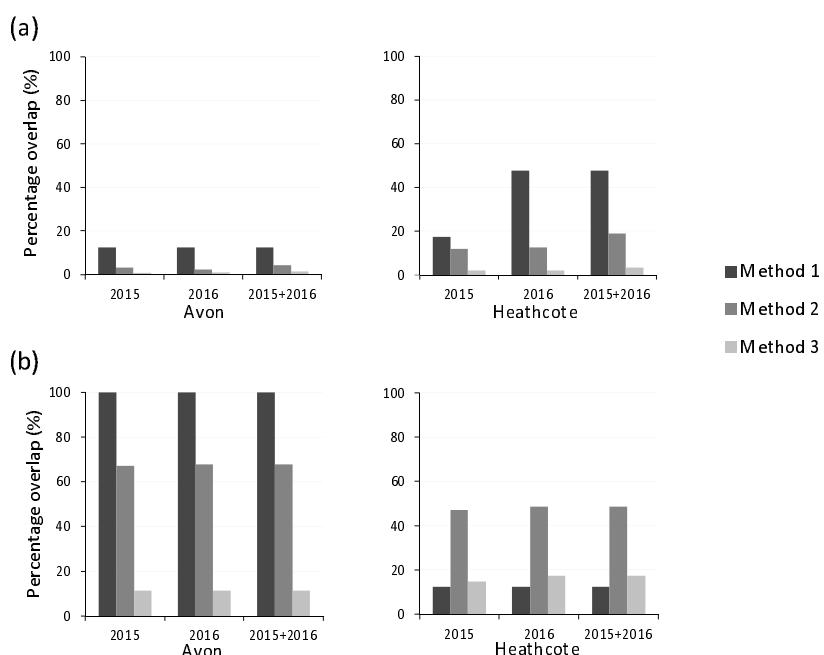
Figure 3. Evaluation of the efficiency of three Category IV protected area mechanisms (Dudley, 2008) in terms of land use allocation using two assessment metrics. (a) percentage of reach length protected ($RL^{protected}$) overlapping the total reach length of areas occupied by spawning sites (RL^{AOO}). (b) percentage of $RL^{protected}$ overlapping the reach length of the extent of occurrence of spawning sites (RL^{EOO}). In all cases RL is calculated on the centreline of the waterway channel. For each calculation three time periods are considered: 2015, 2016, and combined data from both years.

4. Discussion

4.1 Addressing spatiotemporal variation

277 Several aspects of *G. maculatus* spawning site ecology are potential sources of spatiotemporal
278 variation. The reported relationship with salinity results in horizontal structuring along the axis of
279 waterway channels in relation to saltwater intrusion (Richardson & Taylor, 2002; Taylor, 2002). This
280 may drive variability in the position of spawning reaches on a catchment scale when coupled with
281 dynamism of river discharges and tidal forcing. Despite that previous studies have highlighted use of

282   the same spawning sites for multiple years (Taylor, 2002), this case was characterised by habitat shift
283   in both catchments in comparison to all known records (Orchard et al., in press). Although the
284   potential effects of salinity changes are not apparent in the literature, this indicates that they may
285   important in relation to perturbations from extreme events or to incremental changes such as sea level
286   rise. However, in relation to this study, a lack of pre-earthquake salinity data for the reaches of
287   interest makes this difficult to confirm directly. The timing of spawning on or soon after the peak of
288   the tide combined with preference for shallow water depths, also leads to vertical structuring of the
289   habitat in relation to water level heights (Benzie, 1968a; Mitchell & Eldon, 1991). Interaction between
290   the waterline and floodplain topography also influences the distance between spawning sites and the
291   alignment of (i.e. perpendicular to) waterway channels. This variation may be considerable where the
292   topography is relatively flat and is a further consideration for effective PA design.

293   *4.2 Evaluating PA effectiveness for dynamic habitats*

294   There are at least three aspects of this study that are likely to be applicable to the design and
295   evaluation of Category IV PAs elsewhere. They include the question of PA boundary setting in
296   relation to the habitat to be protected, the need for data to inform this and monitoring strategies to
297   support future evaluations, and practical considerations for identifying boundaries on the ground as
298   required by stakeholders.

299   Clearly, accuracy is important when setting boundaries for Category IV PAs, yet spatiotemporal
300   variation may hamper acquisition of the necessary data in practice. For *G. maculatus* strong temporal
301   trends are a particular consideration. Variation has been reported in relation to the peak days of
302   activity within a tidal sequence, the tidal sequences preferred in different parts of the country, and
303   months of most spawning activity in the year (Taylor, 2002). International studies have also reported
304   large-scale variation in traits associated with spawning (Barbee et al., 2011). In combination, these
305   aspects suggest that spatiotemporal variability could arise at multiple scales creating practical
306   difficulties for both empirical data collection and model-based approaches for determining habitat
307   distribution. In this case, the study catchments are New Zealand's best studied spawning areas yet
308   surveys have only been periodic and seldom comprised more than one month in any given year
309   (Taylor, 2002). Consequently, the times of peak spawning activity may not have been captured in the
310   survey record. Identification of the spawning distribution has therefore relied on the compilation of
311   multi-year data despite the potential for confounding factors associated with longer term change.

312   Albeit that the post-earthquake context represents a major perturbation, the impacts of spatiotemporal
313   variance on PA effectiveness are clearly seen in planning methods 1 and 2. These methods were
314   developed using the planning authority's up to date information on spawning habitat in both
315   catchments. Particularly in the Heathcote, earthquake-induced habitat shift rendered these methods
316   relatively ineffective. Despite this, regular monitoring and amendment of the same protection
317   mechanism could provide a strategy for maintaining effectiveness and addressing change. However
318   for method 1 the data collection requirements would be onerous to achieve this in practice. This partly
319   reflects reliance on a network of small PAs but also that the detection of spawning sites is difficult
320   (Orchard & Hickford, 2017). The number of PAs identified appears woefully inadequate in light of
321   the post-quake data yet fairly represents results of the monitoring effort that was in place pre-quake.
322   Increasing this to the level of a census-survey for peak spawning months represents a considerably
323   scaling-up of the monitoring programme.

324   In comparison, method 3 was based on considerably larger PAs and was much more resilient to
325   earthquake changes. In that case, a degree of redundancy was seen as a desirable aspect for resilience

326   (Greer et al., 2015). However, from the perspective of PA evaluation, the three PA mechanisms share
327   similar monitoring requirements. This arises since demonstration of management effectiveness
328   requires information on the values to be protected (Stoll-Kleemann, 2010). Given that monitoring
329   resources are inevitably limited, dynamic environments demand particular attention. In turn this
330   illustrates the widespread need for research on monitoring strategies to inform priorities for data
331   collection and frequency (Teder et al., 2007). Moreover, it exemplifies the need for more
332   management-driven science to close the gap between conservation policy and practice (Knight et al.,
333   2008).

334   Potential strategies include using abiotic proxies for conservation objectives for which data
335   acquisition is easier thus reducing the burden of repeat measurement (Lawler et al., 2015). Method 3
336   provides an example of this approach, using a predictive model based on elevation above sea level
337   (Greer et al., 2015). However, the results indicate that its efficiency as a planning method is relatively
338   low since much of the area set aside did not help achieve the stated objectives, and it could not be
339   used as a proxy for outcomes monitoring against the relevant policy objectives. From an ecosystem-
340   based perspective, inefficient planning methods may also hinder potential uses, leading to
341   unnecessary trade-offs (Southworth, Nagendra, & Munroe, 2006). The practical aspects of this relate
342   to the rules that apply within the PA and are designed to confer protection. Where a degree of
343   sustainable use is envisaged within PAs, the specific arrangements for management need to be well
344   matched to intended objectives.

345   Efficiency may be a particular consideration for Category IV PA evaluation in recognition of the
346   intensity of surrounding resource use that often characterises the management context (Dudley, 2008).
347   In this regard method 2 offered an alternative approach that identified areas of suitable habitat outside
348   of the limits of the known EOO and considered these to be 'potential' habitat (Margetts, 2016). These
349   reaches were included in the areas delineated for protection. Essentially this created a buffer around
350   the mapped EOO that served to address limitations in the information available for quantifying known
351   habitat, as well as a providing a degree of redundancy to improve resilience. Although in the
352   Heathcote the post-quake habitat was found to have shifted outside of these areas, they were effective
353   in accommodating the smaller magnitude of change observed in the Avon (Figure 2). Evaluation of
354   method 2 primarily requires information on EOO to determine effectiveness and inform adaptive
355   management. This offers a monitoring strategy that is much less onerous than the census-surveys used
356   in the post-quake studies (Orchard & Hickford, 2017). Method 3 also requires at least this level of
357   monitoring to inform effectiveness evaluation. This suggests that a combination of an evaluation-
358   informed adaptive approach and degree of redundancy could offer an effective and efficient PA
359   strategy for dynamic habitats with regards to land use allocation.

360   Lastly, this case highlights some practical issues for the visualisation of PA boundaries. In this
361   evaluation, spatial co-occurrence was based on coordinates describing the upstream and downstream
362   extent of spawning sites and polygons describing PAs. In many instances spawning site locations
363   were very close to the PA boundaries as mapped. Unless they were clearly outside of the boundaries,
364   such sites were assessed as being protected with the result being an optimistic view of the extent of
365   the PA mechanism. In reality these boundaries may not be so clear. However, it is important that they
366   *are* clear for the benefit of all stakeholders (Langhammer et al., 2007), and this depends considerably
367   on planning methods. In this case the areas delineated by method 1 were interpreted by stakeholders
368   using a location description and schedule of coordinates (Table 2). This is considered to offer a
369   relatively clear mechanism for implementation of the PA management requirements in practice.

370   Under method 2, the areas for protection were first visualised as lines in Council planning documents
371   (Margetts, 2016) and then subsequently incorporated into 'Sites of Ecological Significance' (SESs) in
372   a recent statutory plan (Christchurch City Council, 2015) which is now operative. The visualisation
373   method for plan users is a set of polygons annotated on planning maps appended to the plan (Figure
374   S1a). These SESs have therefore become the PAs of interest and method 2 (as assessed in this study)
375   can be interpreted in relation to *G. maculatus* objectives within these larger areas. However, at the
376   scale of the mapping provided it is difficult to see exactly where the PA boundaries lie in relation to
377   the riparian zone requiring considerable guesswork by plan users (Figure S1b).

378   Under method 3 the situation is improved by the provision of PA polygons as a public dataset with an
379   online GIS viewer available, in addition to planning maps appended to the relevant plan (Environment
380   Canterbury, 2017). Nonetheless, similar boundary issues arise with regards to the location of the PA
381   in relation to the spatial extent of habitat. The GIS analysis revealed a few spawning sites that were
382   clearly outside of the PA boundary in the Avon, as reflected in effectiveness results of <100% in both
383   years (Table 5), and in general many of the actual spawning locations were again very close to the PA
384   boundary. Furthermore, the habitat may shift a considerable distance from the low flow channel on
385   high water spawning events, and these circumstances are difficult to detect by operators (e.g.
386   management contractors) in the field. Indeed spawning sites were found to have been destroyed by the
387   City Council's own reserve management contractors subsequent to notification of the relevant
388   statutory plan (Orchard et al., in press). This suggests that better guidance materials, such as
389   interactive maps, may be required to improve PA effectiveness in practice as was recommended in a
390   recent management trial that aimed to avoid such damage to spawning sites (Orchard, 2017). These
391   results also indicate that a buffer should be considered as an aspect of PA design.

392

393   *4.3 Assumptions and limitations*

394   Several assumptions have been made in this evaluation consistent with a focus of the protection of
395   dynamic habitats and the learning available from the unique post-earthquake situation. Most
396   importantly, the focus has been restricted to the spatial basis of protection mechanisms for critical
397   habitat as found in planning documents. In all cases they were assumed to confer protection where
398   spatial overlap occurred. In reality, this also depends considerably on the design of the rules that apply
399   within the PA and aspects such as the provision of compliance monitoring. Also, a conservative
400   approach has been taken in the mapping of PA boundaries and protection assumed to be effective
401   across the whole areas including close the boundaries. In the case of method 2, the width of the
402   riparian zone protected could not be accurately identified and all spawning sites with the protected
403   reach were assumed to be covered. Other limitations of the study include the spatial coverage of post-
404   quake surveys in relation to method 3 since the full extent of those PAs was not directly surveyed.
405   Despite this the spatial coverage of the surveys was extensive in both catchments and the
406   methodology was designed to capturing the upstream and downstream extents of the full habitat
407   distribution (Orchard & Hickford, 2017). Different evaluation results can also be expected in light of
408   new information. In particular the number of spawning events captured in the post-quake survey
409   record is limited. Further spatiotemporal variation may arise from effects such as differing water
410   heights outside of the sampled range, future vegetation change, river engineering impacts, the
411   potential for further ground level changes, and the ongoing influence of sea level rise.

412

413   *4.4 Conclusions*

414   This evaluation was conceived to challenge PA thinking. Firstly, our evaluation extends the
415   discussion of PA management effectiveness towards that of resilience. Although management actions
416   within existing PAs may help increase the resilience of natural resources, the realities of global
417   change create a fundamental challenge that demands a range of approaches (Baron et al., 2009). The
418   PAs involved are small and are best thought of as PA networks under the management of local and
419   regional government entities. Yet in all respects they meet the definition of Category IV PAs and are
420   found nationwide in recognition of their statutory role and origins. Although a focus on critical
421   habitats is just one dimension of protected areas management, it offers a mechanism to help fulfil their
422   potential as management tools through dynamic spatial planning. In particular, attention to relatively
423   fine scales may offer practical opportunities for integrating PA systems into the wider land and
424   seascape (Guarnieri et al., 2016). Small and dynamic PAs have the potential to help fill representation
425   gaps in PA networks as is a critical need in lowland river and floodplain systems (Tockner et al.,
426   2008). Secondly, an understanding of the role of PAs in climate change adaptation processes has been
427   steadily developing but there is much work to be done. For example, new questions to assess the
428   effects of climate change on PAs have only recently been employed in Management Effectiveness
429   Tracking Tool (METT) evaluations despite its long history and widespread use (Stolton & Dudley,
430   2016). Through investigation of change following an extreme event this study provides insights into
431   similar considerations. Our findings suggest that adaptive networks of well targeted and relatively
432   small PAs could produce an effective mechanism for responding to change thereby contributing to
433   system resilience. Whether new or traditional PAs networks can be adapted along these lines deserves
434   further research. We predict this will become a key topic for environmental planning.

435

441

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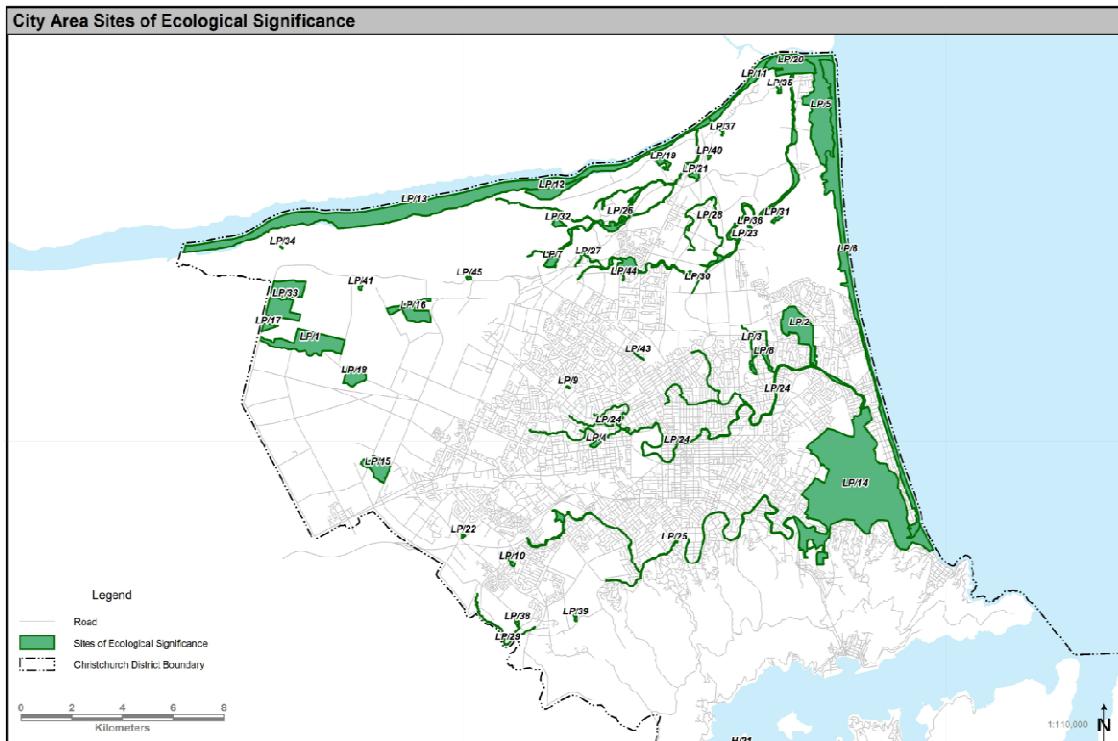
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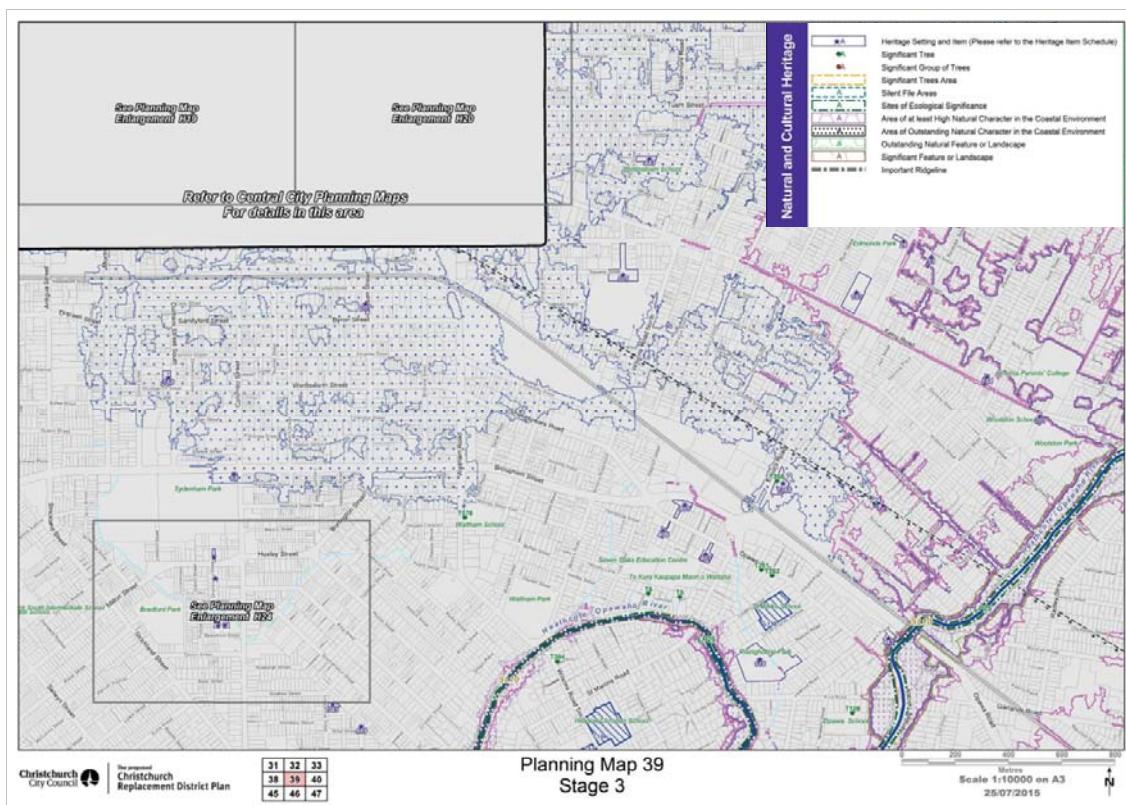
643

644 **Figure S1**. Planning maps showing Sites of Ecological Significance (SESs) in the Christchurch City area

645 (Christchurch City Council, 2015). (a) Schedule Reference Map. (b) Example of detailed planning map. No

646 enlargements are provided for SESs in riparian zones. For brevity only an excerpt of the full legend is shown.