RESEARCH ARTICLE

Identifying priority aquatic refuges to sustain freshwater biodiversity in intermittent streams in eastern Australia

Songyan Yu1 | Peter M. Rose2 | Nick R. Bond3 | Stuart E. Bunn1 | Mark J. Kennard1

1Australian Rivers Institute and School of Environment and Science, Griffith University, Nathan, Queensland, Australia
2North Central Catchment Management Authority, Huntly, Victoria, Australia
3Centre for Freshwater Ecosystems, La Trobe University, Wodonga, Victoria, Australia

Correspondence
Songyan Yu, Australian Rivers Institute and School of Environment and Science, Griffith University, Nathan, QLD 4111, Australia. Email: sunny.yu@griffith.edu.au

Funding information
China Scholarship Council; Griffith University

Abstract

1. The hydrological variability of intermittent streams means that the spatial distribution of dry-season aquatic refuges within river networks and the temporal dynamics of hydrological connectivity between them are critical for the persistence of aquatic biodiversity. Here, a new approach is demonstrated to identify surface water bodies as priority refuges for efficient conservation management of freshwater biodiversity in intermittent stream networks.

2. Recently developed models of surface water extent and daily streamflow were used to represent spatio-temporal variations in hydrological connectivity and surface water persistence within river networks of eastern Australia over a 107-yr period. Using this information, systematic conservation planning was applied to prioritize aquatic areas for conservation of 25 fish species under two scenarios. One scenario identified priority refuges to complement those already occurring in protected areas, whereas the other did not consider protected area status.

3. The priority networks identified concentrated on the main stems of river catchments where surface water was more likely to be persistent and aquatic refuges were more likely to be connected, but also included headwaters for rare fish species. All three set conservation targets for the 25 fish species can be met in the best solution of priority networks. Although the second scenario achieved the targets with a smaller size of priority network overall, it required more new aquatic refuges and was thus less efficient than the first scenario.

4. The newly developed datasets are useful for freshwater conservation prioritization because they account for hydrological variability of intermittent streams. The systematic prioritization approach applied is transferable to other regions and freshwater taxa to identify aquatic refuges for biodiversity conservation within intermittent stream systems.

KEYWORDS
Australia, graph theory, hydrological connectivity, priority refuge, south-east Queensland, systematic conservation prioritization
1 | INTRODUCTION

Intermittent streams are prevalent across global river and stream networks (Messager et al., 2021) and are highly variable systems with alternating drying and wetting phases (Datry, Arscott & Sabater, 2011). The hydrological variability poses challenges for resident aquatic biota that require access to permanent surface water bodies as aquatic refuges and thus to persist during extended dry spells. The size, number, and spatial arrangement of these aquatic refuges have important implications for dispersal of biota once flow resumes and surface water networks are reconnected, and hence for long-term persistence of species in intermittent stream systems (Robson et al., 2013). However, the availability of aquatic refuges is currently under combined threats from increasing urbanization and changes in water availability driven by human consumption and a changing climate (Vorosmarty et al., 2010; Davis et al., 2015). This could compromise the persistence of freshwater biodiversity in intermittent streams (Markovic et al., 2014; McHugh et al., 2015).

Therefore, to protect and manage intermittent streams, a conservation strategy needs to identify and prioritize persistent and drought-resistant refuge habitats and implement management actions to maintain the value of these refuges (Bond, Lake & Arthington, 2008; Costelloe & Russell, 2014).

Systematic conservation planning methods have been widely applied to design priority networks for biodiversity conservation and management in the terrestrial and marine environments (Pressey, Cowling & Rouget, 2003; Foley et al., 2010), and the number of their applications to freshwater systems has substantially increased since the last decade (Linke, Turak & Nel, 2011). Systematic conservation planning is underpinned by a complementarity principle, which is defined as the gain in representativeness of biodiversity when a site is added to an existing set of areas (Possingham, Ball & Andelman, 2000), so that a site is evaluated in the light of what is already selected (e.g. existing protected areas) and the uniqueness of its features. A large body of research indicates that conservation planning approaches that incorporate complementarity lead to a more efficient representation of biodiversity features and more cost-effective solutions than ad hoc scoring or ranking strategies (Pressey & Tully, 1994; Margules, Pressey & Williams, 2002).

However, many freshwater applications are rarely targeted at intermittent streams (but see Hermoso, Ward & Kennard, 2013; Naia et al., 2021), partly because of the challenges involved in obtaining data inputs specific to intermittent streams to inform prioritization. Key data inputs required include spatio-temporal variations in surface water extent and hydrological connectivity (Bond, Lake & Arthington, 2008), as well as the positional importance of aquatic habitats (e.g. stream segments) within a river network (Erös, Schmera & Schick, 2011).

Surface water extent over broad spatial scales is usually derived from satellite imagery (Hermoso, Ward & Kennard, 2013; Bishop-Taylor, Tulbure & Broich, 2017b), but this has several limitations for conservation prioritization in dendritic stream networks. The relatively coarse spatial resolution of satellite imagery (e.g. 30 m for Landsat TM/ETM+ imagery) and the often dense riparian vegetation cover over stream channels mean that detection of surface water and identification of aquatic refuges may be difficult in some stream networks. In addition, the temporal frequency of satellite imagery can be relatively coarse (e.g. 16 days for Landsat TM/ETM+ imagery) or interrupted for extended periods owing to cloud cover, meaning that the highly variable nature of surface water dynamics in intermittent streams may not be adequately represented. Therefore, datasets of surface water extent available for entire stream networks at a fine temporal resolution (e.g. daily) should be used to inform identification of priority aquatic refuges in stream systems.

The inclusion of hydrological connectivity in the process of identifying conservation priority areas in stream networks is challenging owing to the common paucity of hydrological data, such as streamflow. Traditional streamflow gauges can only provide point estimates of discharge (Yu et al., 2018), and their spatial distribution is usually biased towards perennial streams (Turner & Richter, 2011). In spatial conservation planning methods, spatial connectivity requirements are an important consideration and are usually represented by distance-decay functions along stream networks or between catchments (Hermoso, Ward & Kennard, 2013). However, these methods assume that neighbouring planning units (e.g. stream segments) are hydrologically connected for obligate freshwater biota. This assumption is generally true for perennial streams but is not the case for intermittent streams, because cease-to-flow periods create physical disconnections between permanent surface water bodies over potentially large stream network extents and for long periods of time (Garbin et al., 2019). The lack of hydrological connectivity in these methods may compromise the effectiveness of the priority areas identified. Increasingly, however, simulated streamflow data are becoming readily available over large spatial extents and long timeframes (Yu et al., 2018), and there is strong potential to use this information to generate direct estimates of the frequency and duration of hydrological connectivity between dry-season refuges throughout entire stream networks.

The relative position of stream segments within dendritic stream networks is ecologically important for the successful dispersal of organisms from refuges and the recolonization of stream networks (Erös, Schmera & Schick, 2011). Topological indices derived from graph theory, such as ‘betweenness centrality’ (BC) (Jordán, Liu & Davis, 2006) and the integral index of connectivity (Pascual-Hortal & Saura, 2006), have been proposed to measure the positional importance of a given segment in a stream network from the viewpoint of connectivity and show promising performance in informing priority stream segments for riverscape conservation (Segurado, Branco & Ferreira, 2013; Bishop-Taylor, Tulbure & Broich, 2017b).

In this study, recently developed models of surface water extent (Yu et al., 2019) and daily streamflow (Yu et al., 2020) across river networks were used to estimate spatio-temporal variations in surface water extent and hydrological connectivity. Using this information, together with habitat position within a river network, this research
aimed at applying systematic conservation planning to prioritize aquatic refuges for biodiversity conservation of 25 fish species in intermittent stream networks in eastern Australia. The application has identified new refuge habitats to complement existing protected areas in the region and evaluated the efficiency of the priority habitats identified compared with that not considering existing protected areas. This article also recommends a set of practical conservation management actions to maintain the refugial values of priority areas and provides insights into how to expand and enhance existing protected areas for a higher level of biodiversity conservation.

2 | STUDY AREA

This research was conducted in five major coastal stream basins of south-eastern Queensland (SEQ), eastern Australia, with a total area of 21,331 km² (Figure 1). SEQ is a region of transitional temperate to subtropical climate with substantial inter- and intra-annual variation in discharge (Kennard et al., 2010). The majority of rainfall and streamflow usually occurs in the summer months of January to March, often followed by a second minor discharge peak between April and June, but high and low flows may occur at any time of year (Kennard et al., 2007). The degree of flow intermittency varies significantly across the stream networks in SEQ, ranging from flowing all year round to less than 1 month per year (Yu et al., 2018). Consistent with the spatial pattern of rainfall that displays a decreasing tendency from coastal areas to inland (Australian Bureau of Meteorology, 2016), inland streams in the western part of the region usually have less surface water than those in the coastal (eastern) part (Figure 1) (Yu et al., 2019). The region is situated within the eastern biogeographical province based on freshwater fish distributions (Unmack, 2001) and represents a transitional zone for tropical and temperate species (Pusey, Kennard & Arthington, 2004).

Human land-use practices and ground- and surface-water extraction have led to degradation of local riparian habitat, instream habitat, and water quality conditions in many streams of the region (Healthy Land and Water, 2021).

Several legislative instruments are established for environmental protection and species conservation in SEQ, including the Nature Conservation Act 1992, the Environment Protection and Biodiversity Conservation Act 1999, and the Environmental Protection (Water and Wetland Biodiversity) Policy 2019. In particular, intermittent streams are explicitly recognized for providing environmental values in the Environmental Protection (Water and Wetland Biodiversity) Policy 2019. The Queensland State Government is responsible for conservation regulation and management in SEQ, with the Department of Environment and Science as the lead agency. In addition, there are a number of protected areas (e.g. national parks) that contribute to biodiversity protection in the region (Figure 1).

3 | DATA AND METHODS

3.1 | Stream network

The stream network dataset used here was sourced from the Australian Hydrologic Geospatial Fabric (Geofabric) geographic information system (Stein, Hutchinson & Stein, 2014), which provides a fully connected and directed stream network at the Australian national scale (Figure 1). The SEQ stream network consisted of 3,391 stream segments (Strahler stream order >1), defined as the section of stream between two confluences, and were 2.3 km in length on average. First-order stream segments were not considered in this study as they are extremely intermittent and rarely contain fish (see Section 3.5).

FIGURE 1 Stream networks (including streams with Strahler stream order >1) in the five catchments of south-eastern Queensland. The protected areas established by the state government and five major lakes are also shown. The stream networks are colour coded by the modelled annual mean surface water extent sourced from Yu et al. (2019)
3.2 | Surface water extent

Spatio-temporal variation in surface water extent throughout river networks was derived from a predictive statistical model developed by Yu et al. (2019). The model used environmental attributes that influence the hydrological processes of water gains and losses in stream channels to predict daily variation in proportional surface water extent in each stream segment over a 107-year period (1911–2017). The model was calibrated and validated using an extensive dataset of observed surface water extent and revealed good predictive performance in both model interpolation and extrapolation (Yu et al., 2019). Model predictions of daily surface water extent in each stream segment ranged from 0% (i.e. the stream segment is completely dry) to 100% (i.e. the entire stream segment is covered by surface water).

3.3 | Hydrological connectivity

Streamflow and hydrological connectivity are closely linked (Boulton et al., 2017). Hydrological connectivity in intermittent streams can be facilitated by flow pulses (Bunn et al., 2006), which provide periodic opportunities for aquatic biota to disperse from refuges and recolonize dry parts of the stream network (Gallart et al., 2012). The number of flow pulses in each stream segment was thus used to quantify potential hydrological connectivity, with the assumption that stream segments experiencing a comparatively higher number of flow pulses over a given period of time will provide more frequent connections to other parts of the stream network. For each stream segment, the number of flow pulses that equalled or exceeded the 50th percentile flow magnitude from the flow duration curve was calculated (following Gallart et al., 2016) for each year over the 107-year period using modelled daily flow time series. Daily streamflow estimates for each stream segment were sourced from a daily flow model in SEQ (Yu et al., 2020), which was developed by aggregating gridded runoff data with a hierarchically nested catchment dataset. The model was rigorously validated and showed generally good performance in representing different components of flow regimes (Yu et al., 2020).

3.4 | Habitat position within a river network

Several studies have highlighted the positional importance of habitats with high network centrality for maintaining and enhancing landscape/riverscape connectivity (Erös, Schmera & Schick, 2011; Ribeiro et al., 2011; Bishop-Taylor, Tulbure & Broich, 2017a). In this study, the network centrality metric BC was used to evaluate the potential importance of each stream segment within SEQ (Figure 2a). This metric has been shown to perform better than other network centrality metrics in identifying relative positional importance (Jordán, Benedek & Podani, 2007). Here, BC quantifies the number of times a stream segment occurs on the shortest path of any two other stream segments in a stream network. BC was first calculated for stream segments within each stream network and was then normalized to vary from 0 to 1 for the purpose of comparison among stream networks (Figure 2a).

3.5 | Biodiversity data

The biodiversity data considered here are 25 native freshwater fish species that occur in the study area (Table 1). The spatial distributions of these 25 species were sourced from Rose et al. (2016), who developed species distribution models relating ecologically relevant environmental attributes to sampled fish presence/absence data at 103 least disturbed reference sites in SEQ. The single species ensemble model developed exhibited high sensitivity without reductions in specificity and is well suited to identifying priority areas for species conservation (Rose et al., 2016). This model predicted the probability of fish species occurrence for every stream segment of Strahler order >1, and the predicted presence/absence data for the 25 fish species were obtained by using a probability threshold of 50% (Figure 2b).

3.6 | Systematic prioritization of aquatic refuges

To complement the existing protected areas in SEQ, new priority stream segments for biodiversity management were identified using a systematic conservation planning algorithm to represent the 25 freshwater fish species. The systematic prioritization approach used the ‘simulated annealing’ optimization technique to try to find a near-optimal combination of stream segments where all target species were represented in a minimum number of segments (i.e. planning unit in this study), constrained by cost and various penalties associated with each stream segment (Moilanen, Leathwick & Elith, 2008; Hermoso, Ward & Kennard, 2013). The costs of including a stream segment in a conservation priority network may arise from the setup of conservation areas, entering into a stewardship, mitigating threats, and opportunity costs to other stakeholders, such as recreational and commercial fishermen (Ball, Possingham & Watts, 2009).

From the total of 3,391 stream segments in SEQ, candidate aquatic refuges were selected as those stream segments that meet the two following criteria for at least 1 year over the 107-year period: (i) stream segments predicted to contain ≥50% surface water all year, and (ii) having at least five flow pulses per year. The thresholds of 50% surface water and five flow pulses were arbitrarily set based on the assumption that stream segments predicted to contain more surface water and experience higher flow pulses are expected to provide aquatic organisms with higher quality refuges during dry periods and more chances of connection to other parts of the river network (Magoullick & Kobza, 2003; Costelloe & Russell, 2014). Candidate refuges exclude those segments that are normally inundated in five major impoundments in SEQ: Lake Wivenhoe, Lake
Somerset, Lake Advancetown, Lake Samsonvale, and Lake Moogerah (Figure 1). Consequently, a total of 2,740 stream segments were identified as candidate refuges for subsequent prioritization analysis (Figure 2c).

Systematic conservation planning is often achieved through conservation-planning and decision-support tools such as Marxan (Ball, Possingham & Watts, 2009) and Zonation (Moilanen, 2005), but in this study a new site selection algorithm was developed based on the ‘simulated annealing’ optimization technique to identify solutions to select priority aquatic refuges and is available from the GitHub code repository (https://github.com/SongyanYu/Hydrological-Connectivity). First, an initial solution was created by randomly selecting a single refuge from the candidate aquatic refuges. Then, new trial solutions were generated iteratively by randomly changing the status of a single refuge and assessing the new configuration in terms of an improved or worsened objective function value. If the refuge was in the original solution and its random exclusion improved the objective function, it was excluded. Similarly, if the refuge was not previously part of the proposed configuration and its random inclusion improved the objective function, then it was retained. The process was terminated after 1,000 iterations had passed without improvement in the objective function value. The objective function used in this study is

\[
\text{Objective function} = \sum_{\text{stream segments}} \text{Cost} + a \sum_{\text{stream segments}} \text{Hydrology penalty} + b \sum_{\text{stream segments}} \text{Position penalty} + c \sum_{\text{features}} \text{Feature penalty}
\]

and the algorithm tries to minimize the function value. The objective function includes (i) a cost surrogate for each stream segment measured by the river disturbance index (RDI; Stein, Stein & Nix, 2002) (Figure 2d), with the assumption that the more an area is disturbed the higher the conservation cost is, (ii) a hydrology penalty for selecting stream segments that have fewer years meeting the two criteria for candidate aquatic refuges (Figure 2c), (iii) a position penalty

![Figure 2](image_url)
for selecting stream segments that are less important in terms of position within a stream network, measured by BC (Figure 2a), and (iv) a feature penalty for not achieving conservation targets for all the species. RDI was computed based on flow regime disturbance caused by impoundments, flow diversions, and levee banks and by catchment disturbance resulting from urbanization, road infrastructure, and land-use activities (Stein, Stein & Nix, 2002). The weight of the penalties can be controlled by parameters \( a \), \( b \), and \( c \), which determine the penalties relative to the cost of selected stream segments. For the demonstration purpose of this study, parameters \( a \), \( b \), and \( c \) were all set to 1, meaning that a stream segment can be selected only when the number of unique species it hosts is higher than the sum of the cost surrogate, hydrological penalty, and position penalty for this stream segment.

To implement the complementarity principle in the method, explicit conservation targets were set to provide a quantitative means for evaluating complementarity of candidate refuges (Nel et al., 2009). The conservation target here was set to represent 15%, 25%, and 35% of each species’ spatial distribution. These targets lie between the commonly adopted conservation target of conservation, whose distributions were modelled throughout south-eastern Queensland stream networks by Rose et al. (2016) as a measure of relative conservation value or irreplaceability (the likelihood that an area will be required to meet a given set of targets).

The systematic conservation planning was conducted with all candidate refuges in existing protected areas locked in the solutions (termed ‘locked in’ scenario hereafter), so that the site selection algorithm essentially tried to identify new stream segments to meet the conservation targets in combination with those in the protected areas. This analysis can provide insights into the enhancement of existing protected areas in the future. For each conservation target, an additional set of priority segments was also identified from the start without locking in any candidate refuges in existing protected areas (termed ‘not locked in’ scenario hereafter). The priority segments identified in the ‘locked in’ scenario were compared with those in the ‘not locked in’ scenario to evaluate the efficiency of including the current protected areas in supporting biodiversity management.

4 | RESULTS

4.1 | Systematic prioritization of aquatic refuges

Each of three conservation targets for the 25 fish species can be met in the best solutions of a priority network. Newly identified priority stream segments in the best solutions were relatively concentrated in the main stems of river catchments of the study region (Figure 3a,c,e) and usually had higher selection frequency than other segments (Figure 3b,d,f). Stream segments in the upper Brisbane River catchment and the Logan–Albert River catchment were frequently selected in the 100 solutions, as they had higher species richness (Figure 2b), lower RDI (Figure 2d), a higher number of years meeting the selection criteria (Figure 2c), and higher positional importance within river networks to maintain physical connectivity (Figure 2a). However, there were also some priority refuges identified in separate coastal streams and inland headwaters (Figure 3a,c,e) where species richness, positional importance, and number of years of meeting selection criteria were quite low, or in the lower Brisbane River catchment where the stream segment cost was relatively high. That is because those priority refuges were important for rare species and are needed to meet the conservation targets by complementing other refuges inhabited by common species. By comparison, the priority stream segments identified in the best solutions under the ‘not locked in’ scenario seemed more scattered across the study region, but the overall spatial patterns of both priority network and selection frequency were similar to those under the ‘locked in’ scenario (Figure 4).

4.2 | Efficiency evaluation

For all the three conservation targets, the total length of priority networks was longer when existing protected areas were locked in than when they were not (Figure 5). For example, for the conservation target of 25%, a 1,340 km priority network consisting of candidate refuges in the protected areas and newly identified priority
segments was needed, whereas only 1,046 km, nearly 300 km fewer, were needed when no stream segments were locked in in the prioritization process (Figure 5). However, the seemingly more efficient priority network under the ‘not locked in’ scenario was less efficient when only looking at the length of newly identified stream segments in the priority network. Taking the conservation target of 25% as an example, only a set of 615 km new stream segments was needed in addition to the existing protected areas to meet the target.

**FIGURE 3** Location of priority stream segments selected in (a, c, e) the best solution and (b, d, f) selection frequency of each stream segment among the 100 solutions for the three conservation targets under the ‘locked-in’ scenario. All candidate stream segments inside existing protected areas are always selected in each solution. Note that the selection frequency for the conservation target 15% does not have the ‘61–80’ category in (b).
whereas a set of 901 km new stream segments was needed under the ‘not locked in’ scenario (Figure 5). In addition, with the increase in conservation targets from 15% to 35%, the difference in the number of new priority refuges identified between the two scenarios became less and less, from 288 versus 545 km under the target of 15%, to 1,015 versus 1,248 km under the target of 35% (Figure 5).

5 | DISCUSSION

The identification and prioritization of aquatic refuges have been highlighted as being particularly important in freshwater environments that are subject to high hydrological variability, resulting in intermittent flows and habitat fragmentation (Bond,
Lake & Arthington, 2008; Crook et al., 2010). This is becoming an urgent issue, given that aquatic refuge management is facing challenges from reducing water availability driven by human consumption and a changing climate. Here, supported by newly developed datasets, systematic conservation planning was applied to intermittent stream networks in eastern Australia to prioritize aquatic habitats for the conservation management of freshwater biodiversity. For the first time, riverine surface water extent and hydrological connectivity available to entire stream networks are incorporated into systematic prioritization. This study provides insights into achieving cost-efficient prioritization of conservation management actions to sustain freshwater biodiversity in intermittent stream ecosystems.

The priority networks were identified based on two key hydrological factors reflecting the highly variable nature of intermittent streams: persistent surface water and hydrological connectivity. However, it is acknowledged that other abiotic factors may also influence the conservation value of aquatic refuges, such as water temperature and nutrient levels (Vardakas et al., 2017; Woelfle-Erkine, Larsen & Carlson, 2017; Bogan et al., 2019). Acquiring these abiotic condition data is challenging, particularly at the catchment scale; but these factors may have been implicitly incorporated in this study given their general links to the hydrological factors used, as the larger the surface water extent and the more frequent the hydrological connectivity the better the water quality is (Bond, Lake & Arthington, 2008).

This study identified new priority refuges in addition to the existing protected areas in SEQ to meet conservation targets and confirmed that this strategy is more efficient than that without considering existing protected areas, although the efficiency advantage would diminish when the conservation target is higher (e.g. >35%). The protected areas are evolving and expanding in Queensland, like many other places around the world. In Queensland, the protected area strategy 2020–2030 was recently released, setting up a blueprint to expand protected areas for more ambitious biodiversity conservation targets in the future (Department of Environment and Science, 2020). The ‘locked in’ strategy presented in this study provides important information about the location of additional areas that can be prioritized for conservation management.

The application of systematic conservation planning to prioritizing aquatic refuge areas for freshwater biodiversity management in this study can be transferable to other parts of the world where suitable datasets exist. For example, the hydrological connectivity is derived from modelled daily streamflow data that are available globally (e.g. global reconstructed streamflow data; Lin et al., 2019). The hydrographic dataset used to calculate the positional importance of stream segments within a river network is also available in other countries (e.g. NHDPlus in the USA) and globally (e.g. HydroSHEDS (Lehner, Verdin & Jarvis, 2008) and MERIT Hydro (Yamazaki et al., 2019)). Although there is no direct option for generating surface water extent across entire river networks (including smaller streams), the method to derive these data is transferable (Yu et al., 2019); in addition, a growing number of citizen scientist groups have been formed around the world to collect surface water presence/absence data that could serve as an effective proxy (Turner & Richter, 2011; Datry et al., 2016; Allen et al., 2019). It is also worth noting that the conservation prioritization approach presented here can also include other components of freshwater biodiversity for which spatially explicit distribution data are available (e.g. sourced through online data portals such as the Atlas of Living Australia, https://www.ala.org.au/).

The ultimate objective of aquatic refuge prioritization is to support the implementation of appropriate management actions to sustain or improve their value as refuges for biodiversity. Thus, management actions and the level of management effort required should be specified in the next step (Moilanen, Leathwick & Quinn, 2011). The species distribution data used here were modelled by assuming the surrounding environment was least disturbed (Rose et al., 2016), which required management actions to improve or maintain refuge quality to the least-disturbed level. For example, for the south-western part of the Brisbane River catchment, where farming activities predominate, the following management actions...
may be required: appropriate farm management to mitigate runoff of nutrients and pesticides, riparian zone management (e.g., restricting access by livestock, vegetation replanting), strong limits or prohibition on pool pumping and/or groundwater pumping near refuges, installing fish passage at instream barriers, conservation stocking of locally extinct native fish species in selected refuges, as well as management of invasive plants and animals. These considerations are constrained by limited resources, and thus require another optimization process for allocating habitat management and actions (Cattarino et al., 2018).

The spatial prioritization analyses conducted in this study were restricted to stream segments of Strahler order >1, as these were more likely to contain surface water that supports persistent fish populations. However, first-order intermittent streams are widespread, contain important components of water-dependent biodiversity, and support important ecological processes (Steward et al., 2012; Raymond et al., 2013; Datry, Bonada & Boulton, 2017). Therefore, we suggest that future freshwater conservation planning exercises consider incorporating the potential biodiversity and ecological values of small intermittent streams. In addition, in this study, refuge prioritization was based on historical hydrological and species distribution data. Recent studies showed that future climate is projected to significantly influence surface water availability (Padrón et al., 2020) and species distributions (Bond et al., 2014), which are likely to cause considerable changes to the network of currently identified priority refuges. To better support water management and climate change adaptation of freshwater species, we suggest routinely monitoring and assessing the functions of priority refuges and updating the reserve network if the expected functions cannot be managed effectively. Further studies of prioritization using the predictions of future hydrological information and species distributions are recommended to evaluate changes in priority areas under future scenarios.

In summary, this study used newly developed datasets to systematically identify priority aquatic refuges for targeted conservation management in intermittent stream ecosystems in eastern Australia. The datasets applied can better account for the highly variable hydrology of intermittent streams. Two scenarios were considered in the prioritization: one identified priority refuges to complement existing protected areas, whereas the other did not necessarily use existing protected areas. Although the second scenario achieves the conservation targets with a smaller size of reserve network overall, it requires more new aquatic refuges in the priority networks and is thus less efficient than the first scenario. It is worth noting that the efficiency difference between the two scenarios would diminish with conservation targets increasing. This research provides insights into how to expand and enhance existing protected areas to better manage intermittent streams for biodiversity conservation.

ACKNOWLEDGEMENTS
This research was supported by the joint scholarship provided by the China Scholarship Council and Griffith University in Australia (no. 2015060400057). We sincerely thank one anonymous reviewer for providing very constructive and insightful comments that have significantly improved the manuscript. Open access publishing facilitated by Griffith University, as part of the Wiley - Griffith University agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS’ CONTRIBUTIONS
Songyan Yu: conceptualization (equal), formal analysis, writing original draft, review and editing (equal). Peter M. Rose: resources, review and editing (equal). Nick R. Bond: supervision (equal), review and editing (equal). Stuart E. Bunn: supervision (equal), review and editing (equal). Mark J. Kennard: conceptualization (equal), methodology (lead), supervision (equal), review and editing (equal).

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request. The R codes for the site selection algorithm are available from https://github.com/SongyanYu/Hydrological-Connectivity.

ORCID
Songyan Yu https://orcid.org/0000-0001-5765-7060
Nick R. Bond https://orcid.org/0000-0003-4294-6008
Stuart E. Bunn https://orcid.org/0000-0002-6540-3586
Mark J. Kennard https://orcid.org/0000-0003-4383-4999

REFERENCES


How to cite this article: Yu, S., Rose, P.M., Bond, N.R., Bunn, S.E. & Kennard, M.J. (2022). Identifying priority aquatic refuges to sustain freshwater biodiversity in intermittent streams in eastern Australia. Aquatic Conservation: Marine and Freshwater Ecosystems, 1–12. https://doi.org/10.1002/aqc.3871