Estimating Pool Habitat Availability for Allocating Monitoring Effort and Refining Population Estimates for SARA-listed Stream Fishes

Karl A. Lamothe, Julia E. Colm, D. Andrew R. Drake

Fisheries and Oceans Canada
Ontario and Prairie Region
867 Lakeshore Road
Burlington, ON
L7S 1A1

2022

Canadian Manuscript Report of Fisheries and Aquatic Sciences 3236

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 3236

2022

ESTIMATING POOL HABITAT AVAILABILITY FOR ALLOCATING MONITORING EFFORT AND REFINING POPULATION ESTIMATES FOR SARA-LISTED STREAM FISHES

Karl A. Lamothe, Julia E. Colm, and D. Andrew R. Drake

Fisheries and Oceans Canada
Ontario and Prairie Region
867 Lakeshore Road
Burlington, ON L7S 1A1

Cat. No. Fs97-4/3236E-PDF ISBN 978-0-660-41555-0 ISSN 1488-5387

Correct citation for this publication:

Lamothe, K.A., Colm, J.E., and Drake, D.A.R. 2022. Estimating Pool Habitat Availability for Allocating Monitoring Effort and Refining Population Estimates for SARA-listed Stream Fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 3236: vii + 17 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Lamothe, K.A., Colm, J.E., and Drake, D.A.R. 2022. Estimating Pool Habitat Availability for Allocating Monitoring Effort and Refining Population Estimates for SARA-listed Stream Fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 3236: vii + 17 p.

Quantitative information on the number, size, and spatial distribution of riverine habitat features (e.g., riffles, runs, pools) can improve monitoring efficiency and refine population estimates for freshwater fishes listed under the *Species at Risk Act*. Here, fluvial channel morphometric data collected in 2019 and 2020 from Gully Creek and Unknown Stanley J tributary (Lake Huron drainage; Ontario) were used to develop statistical relationships for estimating habitat availability (pool length and pool area) for pool-dwelling fish species. Measured channel variables included pool length (m), reach length (m), pool area (m^2), reach area (m^2), wetted width (m), hydraulic head (mm), depth (m), and Strahler number. Pool length, reach length, wetted width, and hydraulic head generally increased with Strahler number. The best linear models for predicting pool length and pool area were pool length = 0.73*reach length – 1.88 and pool area = 0.72*reach area – 4.87. In combination with knowledge of Strahler number and total length of the sampling frame, the total number and area of pools in a low-order stream can be estimated. An example is provided for Gully Creek. Increased sample size will improve the applicability of these models to other stream systems. The approach and results provide a framework for estimating total habitat availability for pool-dwelling fish species that will help guide the design of future monitoring efforts and refine population-level recovery objectives.

RÉSUMÉ

Lamothe, K.A., Colm, J.E., and Drake, D.A.R. 2022. Estimating Pool Habitat Availability for Allocating Monitoring Effort and Refining Population Estimates for SARA-listed Stream Fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 3236: vii + 17 p.

Les données quantitatives sur le nombre, la taille et la répartition spatiale des composantes des habitats riverains (p. ex. fosses, radiers et rapides) peuvent permettre d’améliorer l’efficacité de la surveillance et de préciser les estimations des populations pour les poissons d’eau douce inscrits sur la liste de la Loi sur les espèces en péril. Ici, on a utilisé les données morphométriques des chenaux fluviaux recueillies en 2019 et en 2020 dans le ruisseau Gully et l’affluent Stanley J inconnu (bassin versant du lac Huron; Ontario) pour établir des relations statistiques en vue d’estimer la disponibilité de l’habitat (longueur et superficie des fosses) des espèces de poissons vivant dans des fosses. Les variables mesurées des chenaux comprenaient la longueur des fosses (en mètres), la longueur des passages (en mètres), la superficie des fosses (en mètres carrés), la superficie des passages (en mètres carrés), la largeur mouillée (en mètres), la charge hydraulique (en millimètres), la profondeur (en mètres) et le numéro de l’ordre de Strahler. La longueur des fosses, la longueur des passages, la largeur mouillée et la charge hydraulique ont généralement augmenté avec l’ordre de Strahler. Les meilleurs modèles linéaires pour prédire la longueur et la superficie des fosses étaient : longueur de la fosse = 0,73*longueur du passage – 1,88 et superficie de la fosse = 0,72*superficie du passage – 4,87. En combinaison avec le numéro de l’ordre de Strahler et la longueur totale du cadre d’échantillonnage, il est possible d’estimer le nombre total et la superficie totale des fosses dans un ruisseau d’ordre inférieur. Un exemple est fourni pour le ruisseau Gully. L’augmentation de la taille de l’échantillon améliorera l’applicabilité de ces modèles à d’autres systèmes de cours d’eau. L’approche et les résultats fournissent un cadre pour l’estimation de la disponibilité totale de l’habitat pour les espèces de poissons vivant dans des fosses ce aideront à guider la conception des efforts de surveillance futurs et à préciser les objectifs de rétablissement au niveau de la population.

INTRODUCTION

Quantitative estimates of the number, size, and spatial distribution of habitat features (e.g., riffles, runs, pools) used by freshwater fishes listed under the *Species at Risk Act* (SARA) is necessary for developing and implementing species monitoring programs and recovery actions. Knowledge of total habitat availability in a system ensures that monitoring sites can be selected from the broader sampling frame (i.e., total area available for sampling) to satisfy a given study design (e.g., random or stratified sampling), therefore enabling more robust inferences about trends over time. In the absence of knowledge on the size and spatial distribution of habitat features, field crews must identify monitoring sites *in situ*, leading to potential biases if spatial coverage is limited relative to the total available habitat.

In addition to the benefits of understanding the spatial distribution of habitat features for monitoring, estimating the total area of habitat features within a watercourse can be used to refine species abundance estimates and identify population recovery targets. Population models are often used to inform recovery targets, including the use of metrics like minimum viable population size (MVP) and the minimum area for population viability (MAPV) (Vélez-Espino et al. 2010; Young and Koops 2014; van der Lee et al. 2020). MAPV calculations rely on estimates of the area required per age- or stage-specific individual, which is rarely known, and is therefore estimated based on an allometric relationship to fish length (Randall et al. 1995; Minns 2003). Estimates of habitat availability and the data collected from adequately designed species monitoring programs can be combined with the modelled MVP and MAPV estimates to determine whether the available habitat is above or below MAPV and could help inform the applicability of area-per-individual estimates for SARA-listed species. As well, population abundance estimates can be projected based on total available habitat and compared to MVP estimates and (or) species recovery targets. Alternatively, with estimates of total habitat availability, species abundance estimates can be back-calculated to determine the number of individuals that each habitat unit must support to attain a MVP.

Although many studies have quantified the habitat features that support SARA-listed freshwater fishes (e.g., Glass et al. 2012; Dextrase et al. 2014; Colm et al. 2019; Lamothe and Drake 2020), few have provided estimates of the size and spatial distribution of those habitat features within occupied freshwater ecosystems. Simple, general approaches are therefore needed to allow sampling crews to estimate the number and size of stream habitat features (e.g., pool habitat) prior to the onset of sampling and in the absence of detailed maps or spatial analysis. Here, linear models were developed using stream morphometric measurements for predicting the size and area of pool habitats within meandering stream systems for pool-dwelling fish species. Meandering streams are sinuous single fluvial channels that curve back and forth laterally across the landscape (Figure 1). Figure 1 displays a simplified example of a single meander with three crossover points. Crossover points are defined as the points where the thalweg crosses the center of the channel. Due to a variety of factors (e.g., Hey 1976), the deepest and slowest areas in meandering channels form at the bends, creating pool habitat (Inglis 1949; Leopold and Wolman 1957; Figure 1). Pool habitat is important for several SARA-listed freshwater fish species (e.g., Redside Dace *Clinostomus elongatus* – Endangered), but the size and spatial distribution of pools within occupied reaches is often unknown. Overall, the ability to predict the size and availability of habitat features, including pool habitats, provides multiple benefits including the identification of stream segments that should be used for species monitoring (and, by extension, improved monitoring efforts to delimit changes in abundance and distribution), and also quantifying total habitat availability for the species.

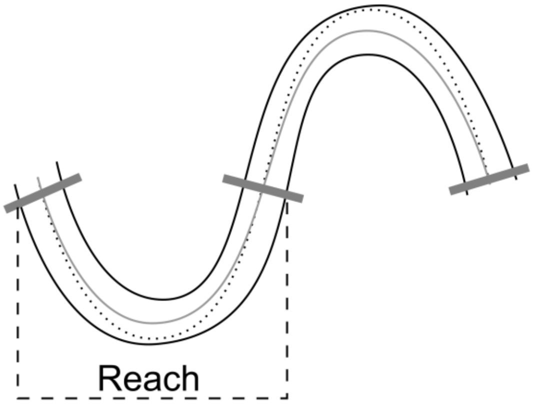

Figure 1. A planimetric view of a simplified meandering stream characterized by two reaches. The thin solid grey line indicates the center of the stream. The dotted line within the channel depicts the thalweg. The thick grey lines represent three crossover points.

METHODS

HABITAT SAMPLING

Gully Creek and Unknown Stanley J and tributaries (hereafter referred to as Stan J) are two freshwater creek systems located in southwestern Ontario, Canada, within the North Gullies (i.e., Bayfield North) sub-watershed of southern Lake Huron (area = 40 km^2; Figures 2, 3). The North Gullies sub-watershed is highly modified by agriculture, but immediately adjacent to the creeks are densely forested riparian buffers (Brock and Veliz 2013). In July 2019, Fisheries and Oceans Canada (DFO) sampled Gully Creek (*n* = 16 sites; Table 1; Figure 2) to: 1) increase the spatial coverage of targeted sampling for Redside Dace; 2) evaluate the habitat attributes of pools and stream reaches for estimating total Redside Dace habitat availability; and, 3) assess the abundance of Redside Dace in selected pools (Gáspárdy and Drake 2021). Sampling efforts were stratified across Aquatic Ecosystem Classification (AEC) segments for Ontario (Melles et al. 2013; Jones and Schmidt 2017). Selection of sampled habitats within AEC segments was done non-randomly based on convenience of access points and to extend the spatial coverage of fish sampling from historical sampling.

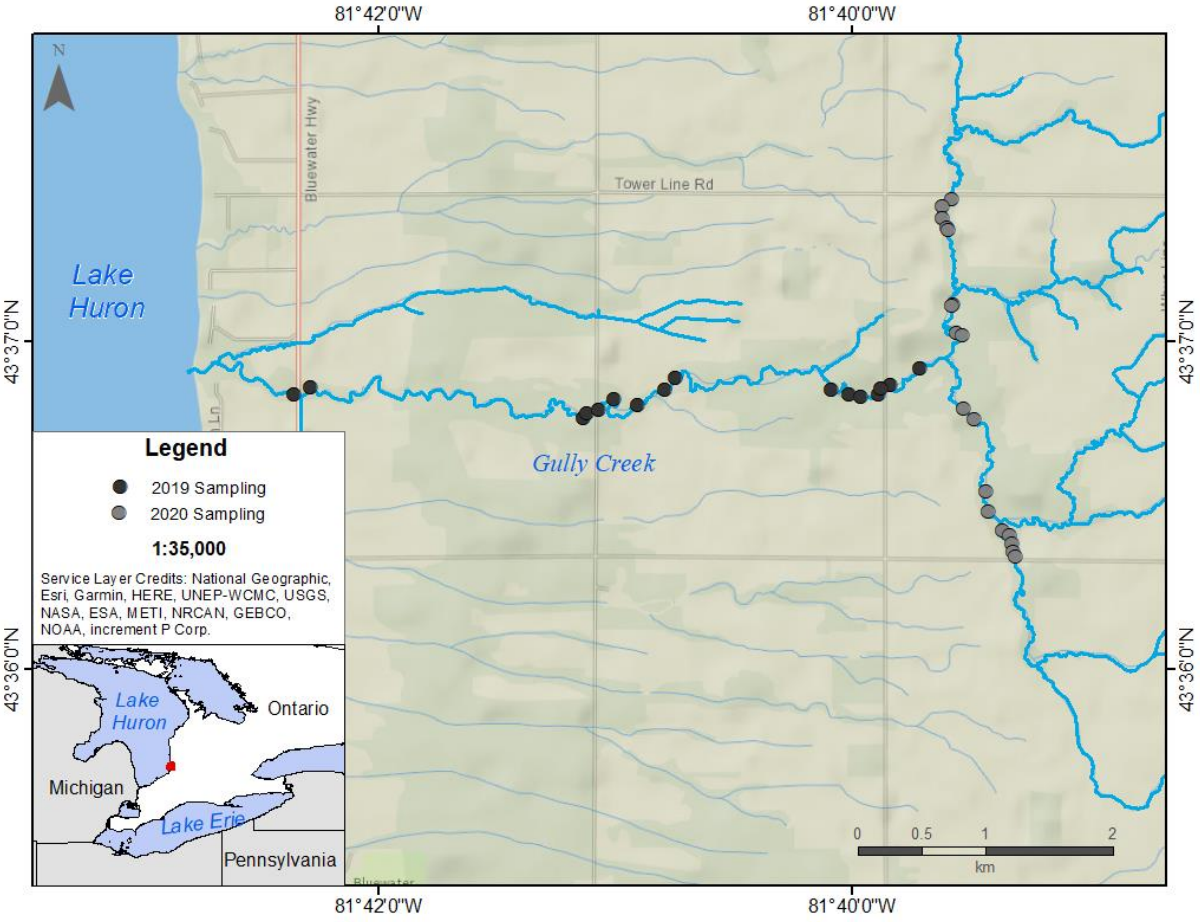

Figure 2. Locations of sites sampled for fishes and habitat features in Gully Creek in 2019 and 2020 (n = 34 sites; Gáspárdy and Drake 2021; Gáspárdy et al. 2021).

Figure 3. Locations of sites sampled for fishes and habitat features in Unknown Stanley J and tributaries in 2020 (n = 9 sites; Gáspárdy et al. 2021).

Table 1. Sample size summary for Gully Creek in 2019 and 2020, and Stan J in 2020 at the pool and reach scales.

Scale	**Gully Creek (2019)**	**Gully Creek (2020)**	**Stan J (2020)**	**Total**
Reach-scale	4	8	4	16
Pool-scale	12	10	5	27
Total	16	18	9	43

Site-level stream morphometric data were recorded in Gully Creek (2019) at two scales following a modified version of the Ontario Stream Assessment Protocol (Stanfield 2005; Gáspárdy and Drake 2021): the pool (*n* = 12 sites) or the reach (*n* = 4 sites; Table 1). The reach scale represents measurements taken from transects that spanned the entirety of one crossover to crossover (Figure 1), including both pool and riffle habitats, whereas the remaining measurements were taken from transects placed exclusively within a pool. Regardless of the scale of measurement, pool length (m) was recorded at all sites.

Transects were spaced evenly at each site, where the number of transects per site (N_t) and sampled points per transect (N_p) were based on the minimum wetted stream width (W; m):

- $W \geq 3$ m: $N_t = 10$, $N_p = 6$
- $3 > W \geq 1.5$: $N_t = 12$, $N_p = 5$
- $1.5 > W \geq 1$: $N_t = 15$, $N_p = 3$
- $W < 1$: $N_t = 20$, $N_p = 2$.

When only pool habitat was sampled, half of the total prescribed reach transects were used and spaced evenly within the pool. Starting at the downstream transect, depth (m) and hydraulic head (mm) were measured at each identified point along each transect.

DFO crews returned to the North Gullies watershed in late-summer 2020 to sample Redside Dace at an additional 18 sites in Gully Creek along with 9 sites in Stan J (Figures 2, 3; Table 1; see also Gáspárdy et al. 2021). Stream morphometric data were similarly collected in 2020, where 12 of the 27 sites were sampled at the full reach scale (Gáspárdy et al. 2021). In contrast to the 2019 sampling, sampling in 2020 included a measurement of reach length at all sites, regardless of whether the pool or reach was the focus of sampling (Gáspárdy et al. 2021). Forty-three sites were surveyed over the two years during seasonal periods considered as relatively low flow, where 27 of the 43 sites were sampled at the pool scale (Table 1).

DATA VISUALIZATION

Histograms were used to visualize differences in stream morphometrics (i.e., pool length, reach length, pool area, reach area) across sites, as well as differences in measured hydraulic head, depth, and wetted width between pool and non-pool habitats. Similarly, boxplots were used to visualize differences in stream morphometrics and habitat measurements with varying Strahler number. The Strahler number describes the hierarchical branching of streams beginning at the headwaters (i.e., Strahler number 1) and ending at the mouth of the stream (Figure 4; Horton 1945; Strahler 1952). When two stream segments of the same Strahler number meet, the resulting downstream segment is one value higher than the previous two (Figure 4). Strahler numbers were obtained from GIS layers of Gully Creek and Stan J provided by the Ausable Bayfield Conservation Authority.

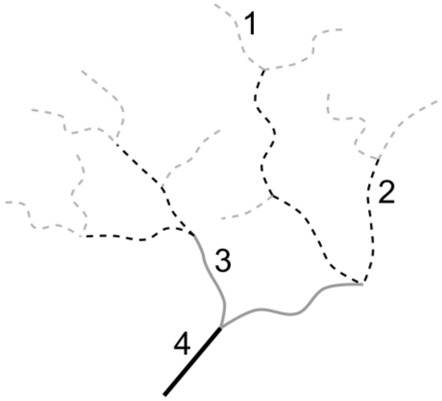

Figure 4. Schematic diagram demonstrating hierarchical Strahler number classification. Colours depict Strahler numbers of 1 (solid black), 2 (solid grey), 3 (dashed black), and 4 (dashed grey).

LINEAR MODELS

Linear models were developed to predict pool length (m) and pool area (m^2) using average hydraulic head (mm), average wetted width (m), average pool depth (m), reach length (m), reach area (m^2), or Strahler number as potential covariates. Models were developed using 15 observations, where the focal scale of sampling was the pool and where reach lengths were recorded (reach length was not measured in 2019). Pool area and reach area were calculated independently using data collected from pool and reach sites, respectively. Given the small sample size, only a single covariate was considered within each regression model and model selection was performed using the second-order AIC criterion (AICc). Fourteen models were considered in total, seven for pool length and seven for pool area, using each of the six covariates and an intercept-only model.

RESULTS

Gully Creek and Stan J showed similarities in channel morphology metrics, including measured pool length, reach length, and pool depth (Table 2); however, pools and reaches in Gully Creek were generally larger and faster flowing (Table 2). Consistent with site selection criteria used in the field, average depth and wetted width were greater in pools than non-pool habitats (Figure 5), and hydraulic head was greatest in shallow habitats (i.e., riffles; Figure 6). A marginally positive, but non-significant, relationship was observed between reach length and average wetted width, and between pool length and average wetted width (Figure 7). Pool length, pool area, reach length, reach area, hydraulic head, and wetted width generally increased with Strahler number, where non-pool habitats had greater hydraulic heads and narrower wetted widths than pool habitats (Tables 2, 3; Figure 8). Across sites in both creek systems, median pool length was 8.60 m, 8.60 m, and 12.62 m for sites sampled within Strahler numbers 2, 3, and 4 stream segments, respectively (Figure 8); however, Gully Creek generally had longer pools than Stan J (Table 3). The best regression models indicated a positive relationship between pool length and reach length ($\text{pool length (m)} = 0.73 * \text{reach length (m)} - 1.88$; $F_{1,13} = 62.81$, $p < 0.001$), and between pool area and reach area ($\text{pool area (m}^2) = 0.72 * \text{reach area (m}^2) - 4.87$; $F_{1,13} = 85.59$, $p < 0.001$; Table 4; Figure 9). There was no support for the other models considered (Table 4).

*Table 2. Summary statistics (mean ± SD, minimum, maximum) for habitat sampling in Gully Creek and Stan J, including measurements of wetted width (m), reach and pool lengths (m), reach and pool areas (m^2), depth (m), and hydraulic head (mm). Sample sizes (n) are included for each summary statistic calculation. Summary statistics were calculated at different scales of measurement. † = within the focal scale of measurement (i.e., reach versus pool sampling). * = within habitat features (i.e., pool versus non-pool habitat) regardless of the focal scale of measurement. ∆ = all sites where the measurement was taken regardless of the focal scale of measurement.*

Variable	**Statistic**	**Gully Creek**	***n***	**Stanley J**	***n***
Pool length$^{\Delta}$	Mean ± SD	12.48 ± 6.56 SD	34	12.55 ± 4.93 SD	9
Pool length$^{\Delta}$	Minimum	3.50		5.27	
Pool length$^{\Delta}$	Maximum	33.40		21.15	
Reach length$^{\Delta}$	Mean ± SD	19.09 ± 10.04 SD	22	19.90 ± 5.58 SD	9
Reach length$^{\Delta}$	Minimum	7.30		12.82	
Reach length$^{\Delta}$	Maximum	44.42		27.10	
Pool area†	Mean ± SD	58.09 ± 42.69 SD	22	35.33 ± 11.36 SD	5
Pool area†	Minimum	6.88		24.29	
Pool area†	Maximum	192.52		47.83	
Reach area†	Mean ± SD	80.53 ± 57.32 SD	12	52.91 ± 22.65 SD	4
Reach area†	Minimum	21.29		27.02	
Reach area†	Maximum	178.27		76.05	
Pool wetted width*	Mean ± SD	3.75 ± 1.73 SD	213	2.87 ± 0.99 SD	69
Pool wetted width*	Minimum	0.79		1.27	
Pool wetted width*	Maximum	9.70		4.91	
Non-pool wetted width*	Mean ± SD	3.05 ± 1.97 SD	71	1.72 ± 0.63 SD	16
Non-pool wetted width*	Minimum	0.74		0.72	
Non-pool wetted width*	Maximum	9.89		2.99	
Pool depth*	Mean ± SD	0.28 ± 0.22 SD	1001	0.27 ± 0.16 SD	291
Pool depth*	Minimum	-0.14		-0.21	
Pool depth*	Maximum	1.31		0.87	
Non-pool depth*	Mean ± SD	0.11 ± 0.12 SD	320	0.05 ± 0.10 SD	60
Non-pool depth*	Minimum	-0.32		-0.42	
Non-pool depth*	Maximum	0.63		0.28	
Pool hydraulic head*	Mean ± SD	0.40 ± 1.76 SD	998	0.01 ± 0.08 SD	289
Pool hydraulic head*	Minimum	0		0	
Pool hydraulic head*	Maximum	30		1	
Non-pool hydraulic head*	Mean ± SD	1.73 ± 4.55 SD	304	0.78 ± 1.52 SD	55
Non-pool hydraulic head*	Minimum	0		0	
Non-pool hydraulic head*	Maximum	35		5	

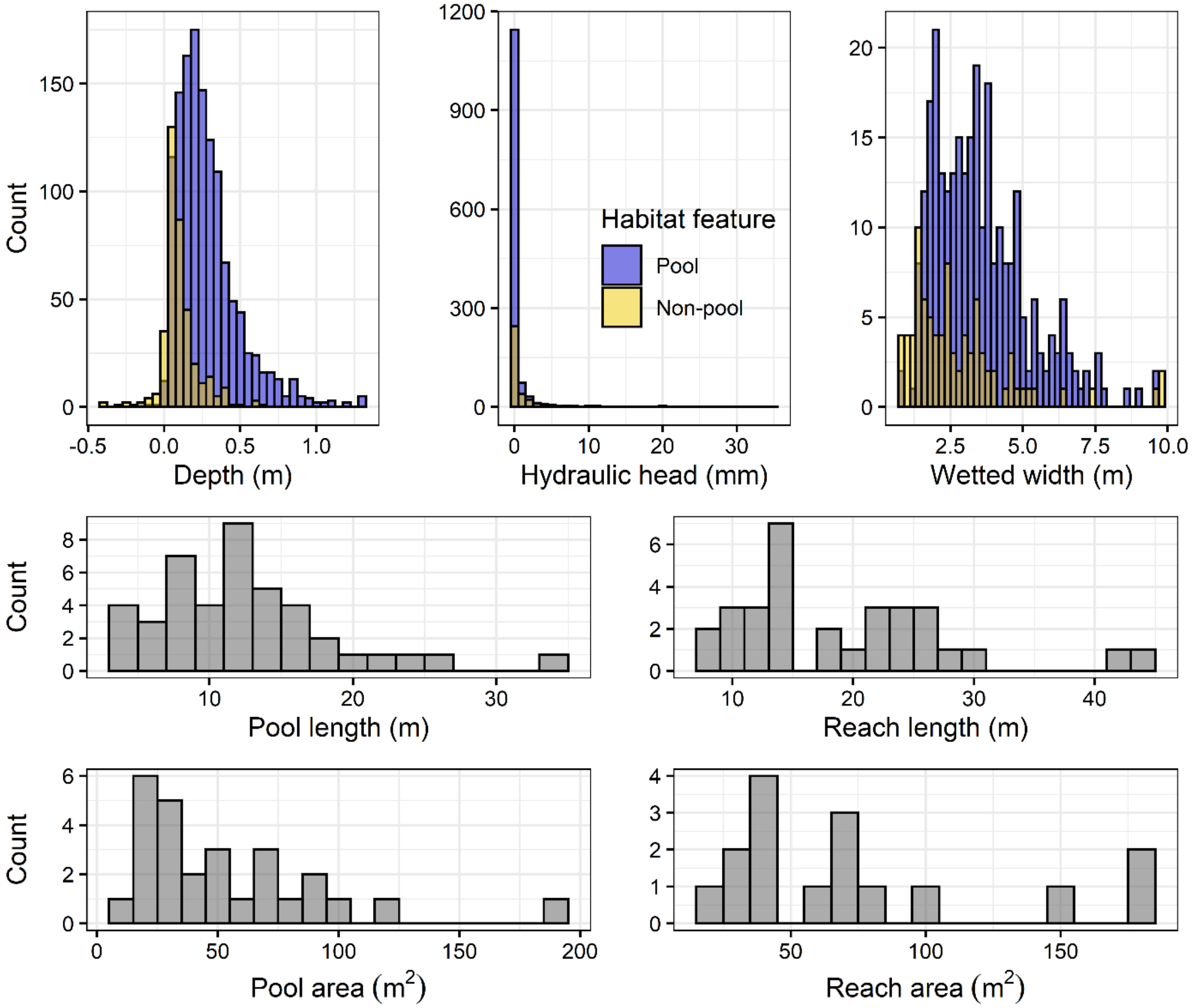

Figure 5. Histograms of depth (m), hydraulic head (mm), wetted width (m), pool length (m), reach length (m), pool area (m^2), and reach area (m^2) for Gully Creek and Stan J. Colour represents measurements taken in pools versus non-pool habitats regardless of the scale of sampling. Pool lengths (n = 43) and reach lengths (n = 31) consist of measurements from all sites where each measurement was taken, whereas pool area and reach area only consider samples taken at the pool (n = 27) and reach scale (n = 16), respectively.

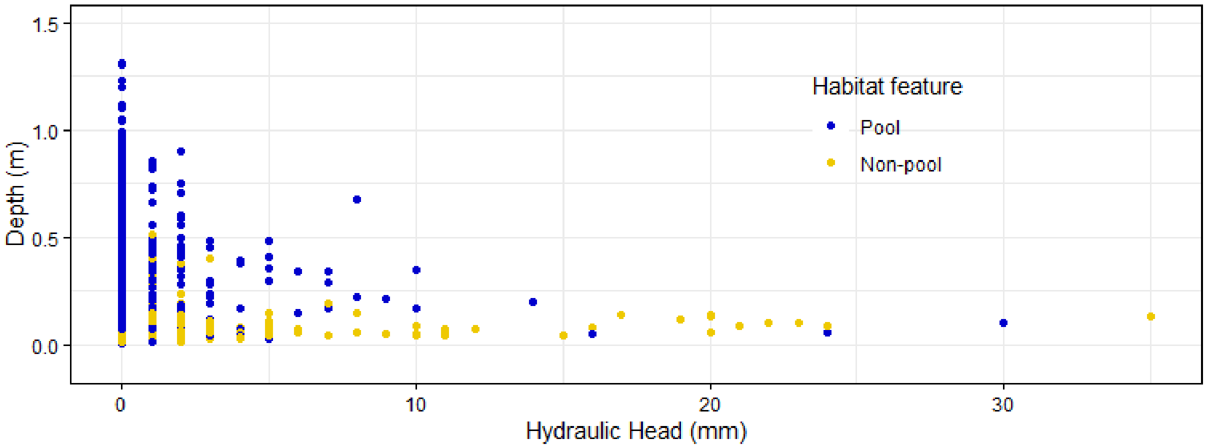

Figure 6. Depth (m) measurements as a function of hydraulic head (mm) measurements taken in pool (blue) and non-pool (yellow) habitats.

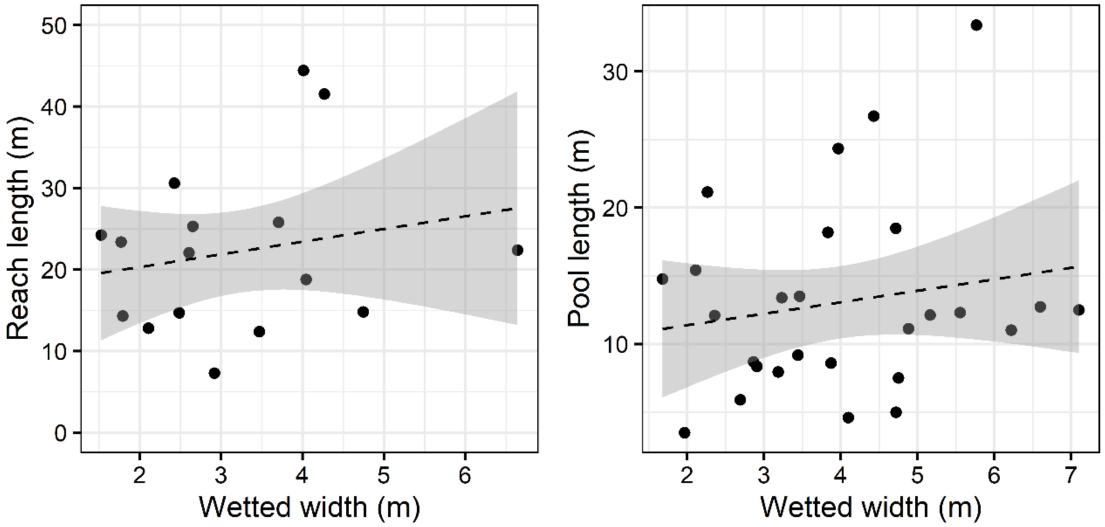

Figure 7. Reach length (m) and pool length (m) as a function of average wetted width for sites where reaches (n = 16) and pools (n = 27) were the focus of sampling, respectively. Linear models with 95% confidence intervals are also presented (Reach length: $F_{1,14}$ = 0.61, p = 0.45; Pool length: $F_{1,14}$ = 0.79, p = 0.38).

*Table 3. Summary statistics (sample size (n), mean ± SD, minimum – maximum) for habitat sampling in Gully Creek and Stan J tributary across Strahler numbers. Summary statistics were calculated at different scales of measurement. † = within the focal scale of measurement (i.e., reach versus pool sampling). * = within habitat features (i.e., pool versus non-pool habitat) regardless of the focal scale of measurement. ∆ = all sites where the measurement was taken regardless of the focal scale of measurement.*

Variable	**Statistic**	**Gully Creek Strahler 2**	**Gully Creek Strahler 3**	**Gully Creek Strahler 4**	**Stan J Strahler 3**	**Stan J Strahler 4**
Pool length$^{\Delta}$	*n*	10	8	16	1	8
	Mean ± SD	9.42 ± 4.08	9.94 ± 5.52	15.66 ± 7.07	7.95	13.46 ± 4.38
	Min-max	4.20 – 15.72	3.50 – 20.80	7.70 – 33.40		7.95 – 21.15
Reach length$^{\Delta}$	*n*	10	8	4	1	8
	Mean ± SD	15.19 ± 6.41	16.75 ± 7.06	33.54 ± 11.05	13.15	20.74 ± 5.32
	Min-max	7.30 – 24.25	10.06 – 30.60	22.40 – 44.42		12.82 – 27.10
Pool area†	*n*	5	4	12	1	4
	Mean ± SD	26.48 ± 10.11	21.88 ± 11.67	85.19 ± 40.34	25.32	37.84 ± 11.42
	Min-max	15.86 – 43.28	6.88 – 33.30	31.58 – 192.52		24.29 – 47.83
Reach area†	*n*	4	4	4	0	4
	Mean ± SD	30.39 ± 7.92	61.22 ± 14.09	149.98 ± 38.77		52.91 ± 22.65
	Min-max	21.29 – 37.50	43.02 – 74.18	95.58 – 178.27		27.02 – 76.05
Pool wetted width*	*n*	288	255	458	30	261
	Mean ± SD	3.02 ± 1.44	3.50 ± 1.39	5.02 ± 1.53	3.19 ± 0.88	2.93 ± 1.03
	Min-max	0.79 – 7.85	1.58 – 6.76	2.76 – 9.70	1.87 – 4.53	1.27 – 4.91
Non-pool wetted width*	*n*	67	105	148	0	60
	Mean ± SD	1.93 ± 0.92	2.58 ± 0.80	4.68 ± 2.29		1.79 ± 0.62
	Min-max	0.74 – 3.53	1.50 – 4.55	1.39 – 9.89		0.72 – 2.99
Pool depth*	*n*	288	255	458	30	261
	Mean ± SD	0.27 ± 0.25	0.23 ± 0.17	0.32 ± 0.20	0.38 ± 0.18	0.26 ± 0.15
	Min-max	-0.135 – 1.31	-0.061 – 1.20	0.005 – 1.05	0.07 – 0.694	-0.205 – 0.87
Non-pool depth*	*n*	67	105	148	0	60
	Mean ± SD	0.07 ± 0.05	0.08 ± 0.09	0.15 ± 0.15		0.05 ± 0.10
	Min-max	-0.095 – 0.185	-0.319 – 0.425	-0.27 – 0.63		-0.42 – 0.28
Pool hydraulic head*	*n*	286	254	458	30	259
	Mean ± SD	0.07 ± 0.62	0.09 ± 0.47	0.78 ± 2.47	0.00 ± 0.00	0.01 ± 0.09
	Min-max	0 – 9	0 – 5	0 – 30	0 – 0	0 – 1
Non-pool hydraulic head*	*n*	63	100	140	0	55
	Mean ± SD	0.36 ± 0.93	0.47 ± 1.30	3.26 ± 6.26		0.78 ± 1.52
	Min-max	0 – 4	0 – 10	0 – 35		0 – 5

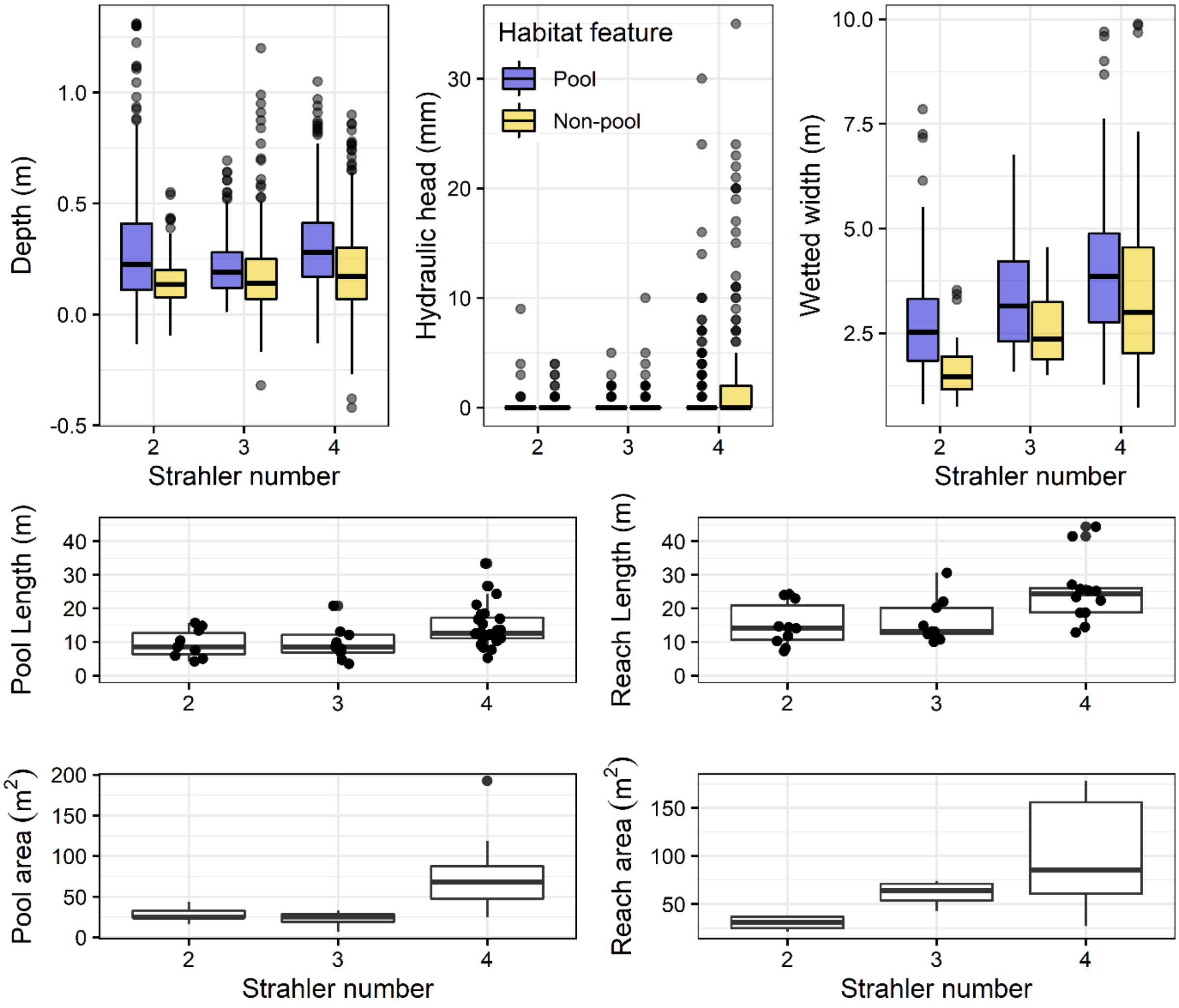

Figure 8. Boxplots of depth (m), hydraulic head (mm), wetted width (m), pool length (m), reach length (m), pool area (m^2), and reach area (m^2) by Strahler number. Colours indicate whether measurements were taken in a pool (blue) or non-pool (yellow) habitat. Boxplots of pool length and pool area consist of data measured at the pool scale. Boxplots of reach length and reach area consist of data measured at the reach scale.

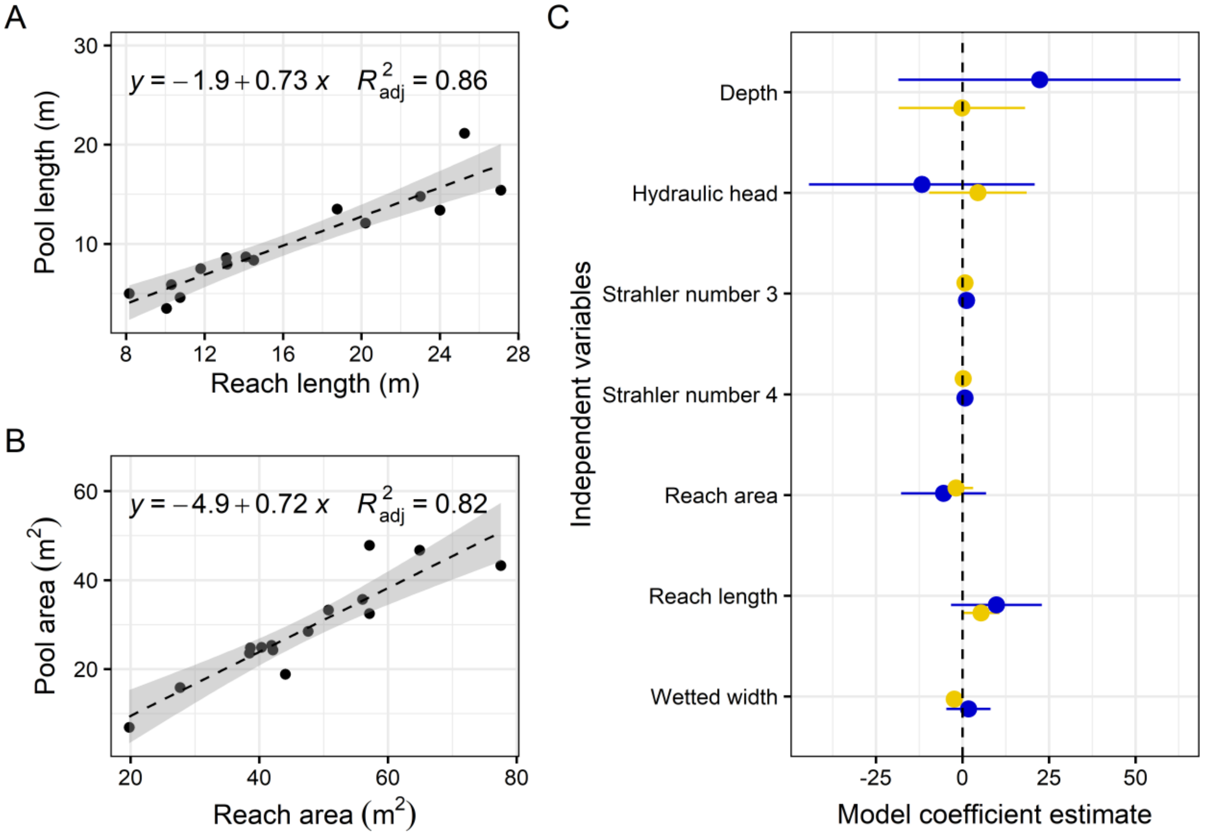

Figure 9. Linear models of A) pool length versus reach length ($F_{1,13}$ = 62.81, $p < 0.001$) and B) pool area versus reach area ($F_{1,13}$ = 85.59, $p < 0.001$). Shaded regions represent 95% confidence intervals. C) Regression coefficients for models of pool length (blue) and pool area (yellow) for all considered independent variables. Error bars represent 95% confidence intervals. Average depth and wetted width were measured in m, and hydraulic head was measured in mm.

Table 4. Model selection results for linear models predicting pool length (m) and pool area (m^2). K = number of estimated parameters. -LL = negative log-likelihood. (.) = intercept model.

Response	**Predictor**	***K***	**AICc**	**ΔAICc**	**-LL**
Pool length	Reach length	3	66.94	0.00	-29.38
Pool length	Reach area	3	90.14	23.20	-40.98
Pool length	Wetted width	3	93.69	26.75	-42.75
Pool length	(.)	2	94.15	27.21	-44.57
Pool length	Strahler number	4	94.23	27.29	-41.11
Pool length	Hydraulic head	3	96.89	29.95	-44.35
Pool length	Depth	3	97.33	30.39	-44.57
Pool area	Reach area	3	96.22	0.00	-44.02
Pool area	Reach length	3	114.85	18.63	-53.33
Pool area	(.)	2	119.49	23.27	-57.24
Pool area	Strahler number	4	121.37	25.15	-54.68
Pool area	Depth	3	121.40	25.18	-56.61
Pool area	Hydraulic head	3	122.11	25.89	-56.96
Pool area	Wetted width	3	122.33	26.11	-57.07

DISCUSSION

Knowledge of the available habitat for SARA-listed species is needed to design effective long-term monitoring programs, assess population abundance and distribution, and evaluate progress towards recovery objectives. In this study, the ability to predict the size of pool habitat was limited by sample size when using only the in-stream field measurements collected from Gully Creek and Stan J in 2019 and 2020. However, inclusion of Strahler numbers revealed useful patterns; given an equal stream length, a Strahler number 4 stream segment will have fewer, but larger pools than a Strahler number 2 or 3 segment. Furthermore, as the Strahler number increased, pools were longer, wider, and deeper. With the models developed in this study including relationships observed between the Strahler number and in-stream measurements as well as the knowledge of the total length of the system, coarse quantitative estimates of pool number and size can be made.

The approach for estimating the size and distribution of habitats is best demonstrated through an example. In this case, we chose estimating the total number of pools in Gully Creek. Gully Creek consists of approximately 35,065 m of riverine habitat (based on GIS measurements of stream segments), ranging in Strahler number from 1 – 4. For the purposes of this example, Strahler number 1 segments from Gully Creek are not included because many of these segments are ephemeral and thus may be used sporadically (if at all) by pool-dwelling fishes; nevertheless, excluding these segments likely leads to an underestimate of the total number of pools in the system. Removal of Strahler number 1 segments leaves approximately 18,901 m of Strahler number 2 – 4 segments, including 10,414 m of Strahler number 2 segments, 2,091 m of Strahler number 3 segments, and 6,396 m of Strahler number 4 segments.

The pool-reach relationships, along with knowledge of total stream length, can allow coarse estimates to be made of the number and size of pools available in stream systems like Gully Creek. For example, consider that the mean reach length of Strahler number 2 segments in Gully Creek was 15.19 m ± 6.41 SD. Given that a reach included a single pool in this study, the number of pools in the 10,414 m of Strahler number 2 stream sections based on the mean reach length would be estimated as 686 (10,414 / 15.19 ≈ 686), or based on one standard deviation, between 482 – 1,186 [10,414 / (15.19 ± 6.41)]. Using the linear models, approximately 6,334 m (95% prediction interval: 3,511 – 9,157) of linear pool habitat would be available in Strahler number 2 segments of Gully Creek [686 * (15.19 * 0.7316773 – 1.8808607) = 6,334.06]. Similar calculations can be made for Strahler number 3 and 4 segments. Approximately 125 (88 – 216) and 191 pools (143 – 284) are expected to be present in Strahler number 3 and 4 segments of Gully Creek based on mean reach length (± 1 SD), respectively, totaling approximately 1,297 m (95% PI: 783 – 1,811) and 4,328 m (95% PI: 3,362 – 5,294) of pool habitat. Total pool area can be estimated in a similar manner. Given a mean area of 30.39 m^2, 61.22 m^2, and 149.98 m^2 for pools in Strahler number 2, 3, and 4 segments, approximately 36,151 m^2 of pool habitat is available [Strahler number 2: 11,626 m^2 (95% PI = 3,819–19,432); Strahler number 3: 4,888 m^2 (95% PI = 3,480–6,296); Strahler number 4: 19,637 m^2 (95% PI = 15,257–24,017)]. In total, Gully Creek is expected to have around 1,002 pools (± 1 SD 713–1,686 pools) among the Strahler number 2 – 4 segments, totaling approximately 36,151 m^2 of pool habitat (95% PI 22,556 – 49,745). Note, however, that sample sizes for measured reach lengths and pool area were small and models were built using both the Unknown Stan J and Gully Creek stream measurements. As a point of reference, the MAPV for Redside Dace was estimated to be 32,000 – 132,000 m^2, depending on the recovery target (van der Lee et al. 2019).

With an understanding of the total number of pools available for sampling, *a priori* planning for species monitoring programs can be performed regarding the percentage of total habitat that will be sampled and the expected power for detecting changes in abundance and distribution over time. For example, consider a hypothetical case in which ~10% of the estimated 1,002 available pools (i.e., 100 pools) in Gully Creek were randomly selected for sampling of a species with an estimated probability of occupancy of 0.60 and an estimated detection probability of 0.50. In this situation, the species should be detected in approximately 30 of the 100 sampled pools (100 * 0.60 * 0.50 ≈ 30). A common objective of monitoring SARA-listed species is to detect a change in distribution (i.e., occupancy) over time. Assuming the scenario where three repeat surveys were performed to generate initial estimates of occupancy and detection at the 100 sites, and a similar number of randomly selected sites were surveyed in a second time period, the power to detect change in occupancy over time can be calculated. Based on the described scenario, the power to detect a significant difference (i.e., $\alpha = 0.05$) in occupancy over time assuming a 50% proportional reduction in occupancy probability and a constant detection probability would be 0.95 (Guillera-Arroita and Lahoz-Monfort 2012). However, the power to detect a significant difference would be reduced to 0.55 if a 30% proportional reduction in occupancy probability were to occur. Almost 20% of the estimated available pools (~177 pools) would need to be sampled to attain a power of 0.80 for characterizing a significant reduction in occupancy probability if a 30% proportional reduction occurred, given the other parameters.

There are limitations to this study that should be considered related to the objectives of sampling and overall sample size. First, pools that were selected for measurement were chosen based on their perceived likelihood of supporting Redside Dace (Gáspárdy and Drake 2021). As a result, pools were selected non-randomly and may not be representative of the true distribution of pools in the system, potentially affecting the reliability of the presented models. Moreover, models were built using a limited number of sampled reaches across two different creek systems. Increasing the number of pools and reaches measured in Gully Creek and Unknown Stan J would improve confidence and accuracy in the model predictions, while allowing the inclusion of creek identity as a model covariate.

Estimating the number, size, and distribution of habitat features that are available to SARA-listed freshwater fishes provides several benefits. First, quantitative estimates of habitat availability provide an understanding of the total habitat available for the species within the focal watercourse, recognizing that only a subset of these habitats may provide functional value to species based on microhabitat features. Second, knowledge of habitat availability allows researchers to design monitoring program protocols for characterizing trends in species abundance and distribution over time with sufficient statistical rigor. Third, with the data collected from carefully designed monitoring programs, pool-specific abundance estimates can be generated and scaled up to the population level to inform species recovery efforts. Ultimately, developing a quantitative understanding of habitat availability will greatly improve the ability to monitor SARA-listed fishes over time, while providing useful information for identifying critical habitat and evaluating progress toward recovery targets.

ACKNOWLEDGEMENTS

The authors thank Kari Jean and Tracey McPherson of the Ausable Bayfield Conservation Authority for providing access to Gully Creek and Unknown Stanley J tributaries GIS files. The authors also thank the individuals who were involved in the 2019 and 2020 field sampling of Gully Creek and Stan J, including Jason Barnucz, Robin Gáspárdy, Megan Cowperthwaite, Jessica Epp-Martindale, Megan Hutchings, Kurtis Smith, Shevaun Verhoog, Sarah Young, and Juliet Zhu. Moreover, the authors thank Robin Gáspárdy for conversations on the field methodology, as well as Shelly Dunn and Adam van der Lee for providing comments on an earlier draft.

REFERENCES

Brock, H., and Veliz, M. 2013. Ausable Bayfield Conservation Authority Watershed Report Card 2013. Ausable Bayfield Conservation Authority. Exeter, Ontario. 102 pp.

Colm, J.E., Mandrak, N.E., and Tufts, B.L. 2019. Local habitat features explain the distribution of the imperiled grass pickerel (*Esox americanus vermiculatus*). Can. J. Zool. **97**: 479–487.

Dextrase, A.J., Mandrak, N.E., and Schaefer, J.A. 2014. Modelling occupancy of an imperilled stream fish at multiple scales while accounting for imperfect detection: implications for conservation. Freshw. Biol. **59**: 1799–1815.

Gáspárdy, R.C., and Drake, D.A.R. 2021. Targeted Sampling for Redside Dace (*Clinostomus elongatus*) in Gully Creek, Ontario, 2019. Can. Data Rep. Fish. Aquat. Sci. 1315: vii + 48 p.

Gáspárdy, R.C., Colm, J.E., and Drake, D.A.R. 2021. Targeted Sampling for Redside Dace (*Clinostomus elongatus*) in Gully Creek, Ontario, 2020. Can. Data Rep. Fish. Aquat. Sci. 1344: vi + 77 p.

Glass, W.R., Corkum, L.D., and Mandrak, N.E. 2012. Spring and summer distribution and habitat use by adult threatened Spotted Gar in Rondeau Bay, Ontario, using radiotelemetry. Trans. Am. Fish. Soc. **141**: 1026–1035.

Guillera-Arroita, G., and Lahoz-Monfort, J.J. 2012. Designing studies to detect differences in species occupancy: power analysis under imperfect detection. Meth. Ecol. Evol. **3**: 860–869.

Hey, R.D. 1976. Geometry of river meanders. Nature **262**: 482–484.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: hydro-physical approach to quantitative morphology. Geol. Soc. Am. Bull. **56**: 275–370.

Inglis, C.C. 1949. The behaviour and control of rivers and canals (with the aid of models). Part 1. Government of India. Reach Publication No. 13. Yeravda Prison Press. 279 pp + appendix.

Jones, N.E., and Schmidt, B.J. 2017. Aquatic Ecosystem Classification for Ontario’s Rivers and Streams: Version 1. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Note TN-04: 1–23.

Lamothe, K.A., and Drake, D.A.R. 2020. Habitat associations of the Threatened pugnose minnow (*Opsopoeodus emiliae*) at the northern edge of the species range. Ecol. Freshw. Fish **29**: 289-298.

Leopold, L.B., and Wolman, M.G. 1957. River channel patterns: braided, meandering, and straight. Geological Survey Professional Paper 282-B, United States Department of the Interior. Geological Survey. Washington. 85 pp.

MacKenzie, D.I., Nichols, J.D., Royle, J.A., Pollock, K.H., Bailey, L.L., and Hines, J.E. 2018. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Second edition. Academic Press. Cambridge, MA.

Melles, S., Jones, N., and Schmidt, B. 2013. Aquatic Research Series 2013-05: Aquatic ecosystem classification for Ontario: a technical proposal. Ontario Ministry of Natural Resources: 52.

Minns, C.K. 2003. An area-per-individual (API) model for estimating critical habitat requirements in aquatic species-at-risk. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/074. i + 21 pp.

Randall, R.G., Minns, C.K., and Kelso, J.R.M. 1995. Fish production in freshwaters: are rivers more productive than lakes? Can. J. Fish. Aquat. Sci. **52**: 631–643.

Stanfield, L. 2005. OSAP: Ontario Stream Assessment Protocol. Version 7. Fish and Wildlife Branch, Ontario Ministry of Natural Resources, Peterborough, Ontario.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topology. Geol. Soc. Am. Bull. **63**: 1117–1142.

van der Lee, A.S., Poesch, M.S., Drake, D.A.R., and Koops, M.A. 2020. Recovery Potential Modelling of Redside Dace (*Clinostomus elongatus*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/034. v + 40 p.

Vélez-Espino, L.A., Randall, R.G., and Koops, M.A. 2010. Quantifying habitat requirements of four freshwater species at risk in Canada: Northern Madtom, Spotted Gar, Lake Chubsucker, and Pugnose Shiner. DFO Can. Sci. Advis. Sec. Sci. Res. Doc. 2009/115. iv + 21 p.

Young, J.A.M., and Koops, M.A. 2014. Population modelling of black redhorse (*Moxostoma duquesni*) in Canada. DFO Can. Sci. Advis. Sec. Sci. Res. Doc. 2014/020. iv + 14 p.