Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2019/060

Central and Arctic Region

Science and Foundations of the Habitat Ecosystem Assessment Tool (HEAT)

Sommer Abdel-Fattah, Charles K. Minns, Andrea M. Doherty, Janet J. Jardine,
and Susan E. Doka

Fisheries and Oceans Canada
Canadian Centre for Inland Waters
867 Lakeshore Rd.
Burlington Ontario, LS7 1A1

August 2021

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-660-39283-7 Cat. No. Fs70-5/2019-060E-PDF

Correct citation for this publication:

Abdel-Fattah, S., Minns, C.K., Doherty, A.M., Jardine, J.J., and Doka, S.E. 2021. Science and Foundations of the Habitat Ecosystem Assessment Tool (HEAT). DFO Can. Sci. Advis. Sec. Res. Doc. 2019/060. iv + 35 p.

Aussi disponible en français :

Abdel-Fattah, S., Minns, C.K., Doherty, A.M., Jardine, J.J., et Doka, S.E. 2021. La science et fondation de l'outil d'évaluation de l'habitat et de l'écosystème (HEAT). Secr. can. de consult. sci. du MPO. Doc. de rech. 2019/060. v + 39 p.

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ABSTRACT

The Fisheries Protection Program (formerly Fish Habitat Management Program) in Canada is a responsibility of the federal government, specifically Fisheries and Oceans Canada, with a mandate specified in the *Fisheries Act* and its associated policies. A quantitative framework for assessing net change of productive capacity using the basic concepts of Defensible Methods (DM) for assessing fish habitat was developed by Minns (1995). An online application of this methodology, called the Habitat Alteration Analysis Tool (HAAT), was adopted by the Ontario-Great Lakes Region of the Fish Habitat Management Program for use in lacustrine project referrals involving infill and associated habitat alterations. Since then numerous additions, alterations, and extensions have been made to the software application. The application was updated and further modified to an online R application and is now called the Habitat Ecosystem Assessment Tool (HEAT). The ultimate goal for HEAT is to link habitat management to fisheries management through population and ecosystem production dynamics mediated through all important habitat drivers. The development of HEAT has evolved over a period of roughly 20 years from DM, and continues to be applicable under current departmental policy. This report provides background on the Tool's underlying science and foundations, its current application and future direction.

INTRODUCTION

The Habitat Ecosystem Assessment Tool (HEAT), previously called the Habitat Alteration Assessment Tool (HAAT) or Defensible Methods (DM) in different contexts, is currently an online software tool that quantifies the suitability of an aquatic site or subarea for fishes and calculates a weighted habitat supply (weighted suitable or usable area) for one or more scenarios where there is a change in any specified habitat or ecosystem factor. Regional databases on fish species and their habitat needs or associations at different life stages are used to calculate relative habitat suitability and supply based on user-specified or recommended default fish species lists. There is both a lake and river version of HEAT in different states of development, however the lake version is the most widely used and most developed. The lake Tool uses water depth, substrate type, and vegetative cover as variables to assess changes in pre- and post-project implementation scenarios generated for assessing how projects or development actions will alter a local system. The river version is not as well advanced as the lake version and its regulatory application has been less extensive. In this report we focus on the lake version only. HEAT has been most actively used by the Fisheries Protection Program (FPP) to assess various types of projects under *Fisheries Act* reviews.

Recent changes to Canada's *Fisheries Act* (Bills C-38 and C-45, 2012) have altered the way FPP assesses and manages the impacts of development projects on aquatic ecosystems, but those changes are currently under review. In the interim, the information requirements and documentation that proponents must submit in order to obtain an authorization are set out in the Applications for Authorization under Paragraph 35(2) (b) of the *Fisheries Act* Regulations. Specific to offsetting, these regulations require that proponents develop offsetting plans. Under Section 6 of the *Fisheries Act*, the Minister of Fisheries and Oceans must take into account the following factors in reviewing the application for an authorization:

- the contribution of the relevant fish to the ongoing productivity of commercial, recreational, or Aboriginal fisheries;
- fisheries management objectives;
- whether there are measures and standards to avoid, mitigate, or offset serious harm to fish that are part of a commercial, recreational, or Aboriginal fishery, or that support such a fishery; and
- the public interest.

One key change is that offsetting is now mandatory under the *Fisheries Act* (Section 6 factors) and no longer a policy goal. With this change new policies have been and continue to be developed to ensure that offsetting requirements are achieved.

HEAT is a framework and model that provides a transparent, consistent method of reporting habitat data and quantifying serious harm (destruction or permanent alteration) and the benefits of proposed offset measures. Additionally, HEAT may serve as a standardized evaluation tool within the regulatory decision-making framework to provide support for whether a proposed offset will sufficiently counter-balance the proposed serious harm under a *Fisheries Act* review. HEAT provides standardized operational ecological units and metrics, addresses habitat heterogeneity and modification types, and can be linked to equivalency metrics for ongoing productivity. The current equivalency unit is calculated in measures of suitable area for fish guilds and their life stages.

The overall goal of the *Fisheries Productivity Investment Policy* (DFO 2013) is to maintain or improve the productivity of commercial, recreational, and Aboriginal (CRA) fisheries. There are four principles outlined in the policy:

- Principle 1: Offsetting measures must support fisheries management objectives or local restoration priorities.
- Principle 2: Benefits from offsetting measures must balance project impacts.
- Principle 3: Offsetting measures must provide additional benefits to the fishery.
- Principle 4: Offsetting measures must generate self-sustaining benefits over the long term.

There are four types of offsetting identified within the policy: habitat restoration and enhancement, habitat creation, chemical or biological manipulations, and complementary measures. The offsetting guide (DFO 2013) outlines proponents' responsibility to avoid serious harm to fish. When impacts are unavoidable this guide provides options for mitigation and offsetting and it is designed to provide flexibility of options to find an approach that is most appropriate to the proponent, but informed by science. This recognizes the importance and challenges of determining offsetting equivalency and identifying appropriate options in some environments. Figure 1 demonstrates that, over time, offsets provide benefits that counterbalance impacts so that there is overall no net loss.

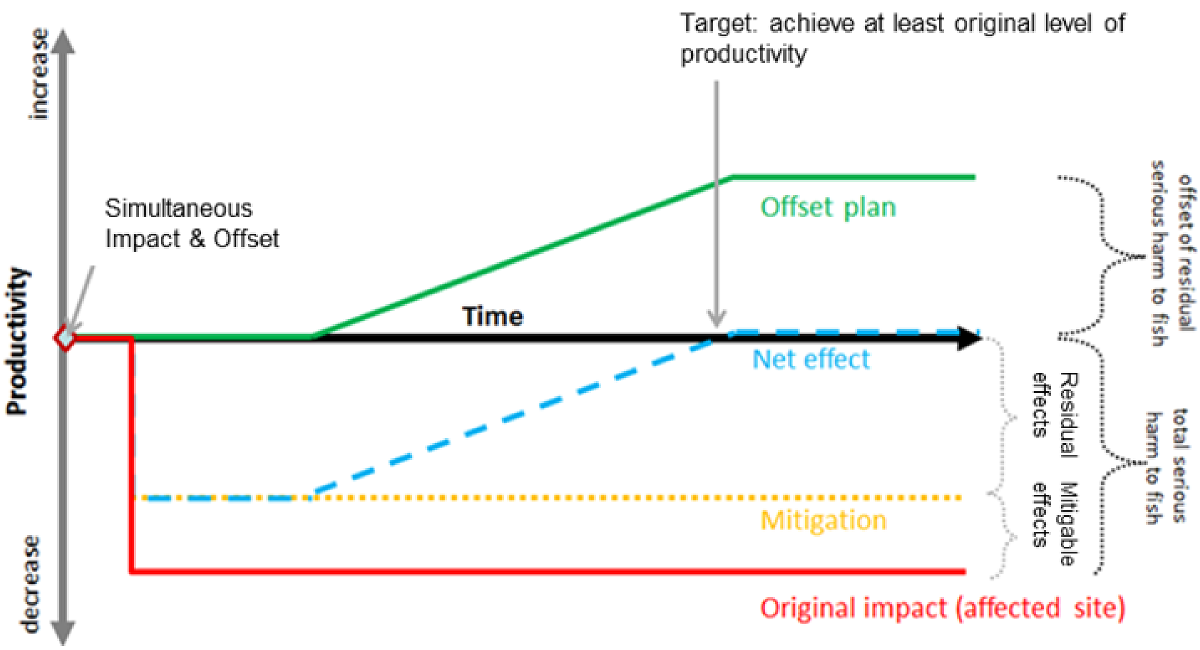


Figure 1. How proponents work to identify the impacts that their projects will have over time, including mitigation, offsetting, and the overall net effect or impact indicated by the blue dotted line. Adapted from the ICMM and IUCN (2012) Independent Report on Biodiversity Offsets.

HEAT generates evidence-based outputs which can support management decisions related to the principles of offsetting, which include the quantification of project impacts, quantification of offset benefits, and the balance of offset benefits with project impacts.

A second change to the *Fisheries Act* is that the information requirements that must be submitted when applying for an authorization are outlined in the regulations. The information requirements for HEAT can be aligned with the information requirements of the *Fisheries Act*.

Currently for HEAT the minimum information requirement includes determining depth contours, substrate composition, and in-water vegetative cover composition of areas or patches being assessed at a site. The project area would include both direct and indirect effects (localized habitat effects) or changes.

HEAT estimates the effects of proposed projects on fish habitat at a site or project level. To date, mainly proposed in-water development projects with infills (including compensation [offsets]) and restoration projects have been assessed using HEAT for regulatory or scientific evaluations (e.g., by proponents, FPP, or Science within DFO). Currently, users input data tables that specify water depth, vegetative cover, and substrate type by patch within the site or area to be evaluated for change. Users are required to provide a geographic location and select a fish list for the evaluations. Outputs of LakeHEAT allow pre- and post-project evaluations of habitat suitabilities and supply by patch or aggregated across fish species groups and life-stages making up the fish community at a site. Flexibility within the model allows for changes to:

- default fish species lists for a location;
- species groupings into guilds; and
- weighting of fish guilds and/or life stages.

HEAT has wider application potential than its current use because of i) the underpinning ecological theory and methods which are scalable and ii) the transferability of methods employed allow for flexibility and adaptability given new information or regional differences. In addition, scientific evaluations of coastal and lake habitats at different scales have used the Tool or algorithms from the Tool as part of those assessments (Minns and Nairn 1999, Minns et al. 1999, Doka et al. 2006, Gertzen et al. 2012).

By using habitat types within HEAT it is possible to quantify the contribution of different types of habitat changes from projects and offsets (e.g., loss, modification, and creation) to an overall objective. HEAT can incorporate offsets in general as well as increased access for species using different features like selecting species lists, quality adjustment factors (QAF) in addition to standard physical habitat changes. Specifically, HEAT can also incorporate chemical manipulations by using water or sediment quality as a degrading QAF in pre-scenarios.

It is anticipated, based on user feedback, that future HEAT modifications will include additional habitat variables. Temperature inputs representing the seasonal thermal regimes encountered at a site and methods for addressing the variation in water levels and subsequent depth changes at a site will be added to the Tool. Guidance on using these new features in HEAT will be provided as updates are rolled out. In future, HEAT could be applied in rivers as well as lakes outside the Great Lakes region, and for climate change assessments once the temperature module is fully operational.

As HEAT continues to be upgraded, additional benefits could be realized, including improved user support, an improved user interface, more frequent updates, and most importantly improved standardization of scenario inputs and outputs that may be used in DFO’s regulatory decision-making. The Tool could also be applied for use in many sectors in addition to FPP and Science within DFO by using a broader suite of variables for pre- and post-scenario testing.

BACKGROUND AND HISTORY

This section outlines the origins and ecological fundamentals in HEAT and the development path followed for creating the Tool. The guiding principle of “no net loss” (NNL) in the 1986 Policy for the Management of Fish Habitat (DFO 1986), now represented by the term “equivalent offsetting” in today’s policy, provided the initial inspiration for the ideas leading to

HEAT. From the outset the development of these ideas was framed in the concept of scientifically-defensible methods and assessment, i.e., evidence-based assessment supported by quantitative analyses. This was important since NNL and “equivalent offsetting” are fundamentally quantitative concepts. During its development as a scientific tool the approach was described by the general term “Defensible Methods.” Later when the Ontario-Great Lakes Area (OGLA) section of Fish Habitat Management (FHM) branch assumed operational responsibility for the Tool, it was renamed HAAT, Habitat Alteration Assessment Tool. More recently HAAT was re-implemented in a modern computing environment with the intention of expanding its capabilities and was renamed HEAT, Habitat Ecosystem Assessment Tool. Key development steps in the history of HEAT are outlined in the following paragraphs.

The emergence of the NNL concept in the 1986 policy statement coincided with the Government of Canada re-assuming a direct role in the conservation and protection of freshwater fish habitat in support of the productivity of Canada’s inland fisheries. As DFO’s Fish Habitat Management (herein FPP) staff assumed their responsibilities, DFO Science staff played an increasing role in support of the regulatory responsibilities. These regulatory-science collaborations took the form of “learning by doing” (Walters and Holling 1990), a key element of adaptive management. These developments were stimulated by the federal Green Plan (Government of Canada 1990) which committed large, new resources to environmental management. There was a clear recognition that implementing NNL required quantitative tools but it was not immediately obvious how to achieve that goal.

First, there needed to be a set of accounting equations to describe changes in habitat areas via losses, modifications, and compensation actions (offsets). After some exploration, a basic accounting equation for measuring net gain or loss was developed by Minns (1995, 1997). This came about as a result of Charles K. Minns becoming involved in the regulatory assessment of a proposed wetland destruction West of Toronto. Serge Metikosh, then with DFO-FHM-OGLA, asked Charles. K. Minns to assist with developing a NNL plan for the highly-degraded Westside Marsh near Bowmanville where the owner had a grandfathered right to extract the aggregates that lay under the marsh and the adjacent land area. FHM’s goal was to try to preserve the function of the marsh. These discussions led directly to the net change equations of Minns (1995, 1997) and the formulation of a plan to restore function of existing degraded areas of the marsh to balance the loss associated with the aggregate extraction within the marsh. The basic net change equation depended on assigning fish habitat suitability values to patches of the proposed development area and then computing equivalent habitat units (area × suitability). To implement the plan, an expert working group was formed to establish an agreed upon set of suitability values for a defined set of habitat types in the existing degraded marsh and a proposed restored marsh. DFO authorized the loss of 50% of the wetland in exchange for restoration of the remainder. In the end the proposed plan did not proceed due to other external issues. Today the site is part of the Bowmanville/Westside Marshes Conservation Area held in public trust by the Central Lake Ontario Conservation Authority.

The basic net change equation (Minns 1997) is based on the underlying assumption that fisheries production is linearly related to the suitability of those areas for the fishes present. The linear assumption is still recognized and being used because it has the benefit of providing a precautionary approach since it assumes that any decreases in habitat suitability or the area of suitable habitat leads to decreases in fisheries productivity. The basic equations are as follows:

$$P_{MAX} = p_{MAX} . A_{ORIGNIAL} = maximum\ productive\ capacity$$

$$P_{NOW} = p_{NOW} . A_{NOW} = productivity\ now\ prior\ to\ new\ development$$

$$A_{NOW} = A_{ORIGINAL} - A_{LOST}$$

$$= original\ area\ less\ areas\ lost\ to\ past\ development$$

$$\Delta P_{MAX} = -p_{MAX}.A_{LOSS} + [p_{MOD} - p_{NOW}].A_{MOD} + [p_{COMP} - p_{NOW}].A_{COMP}$$

$$= -loss + modification + compensation\ due\ to\ new\ development$$

Where, *P* = Productivity, *A* = Area of habitat impacted by development, and *p* = unit area productivity (measured as suitability). It is assumed that $P_{NOW} = P_{MAX}$ for physical habitat assuming that the original physiographic features are intact and that other stressors affecting the site do not change as a result of the development activity. The basic equation is relevant to all projects involving harmful alteration of fish habitat or serious harm to ongoing productivity (Figure 2).

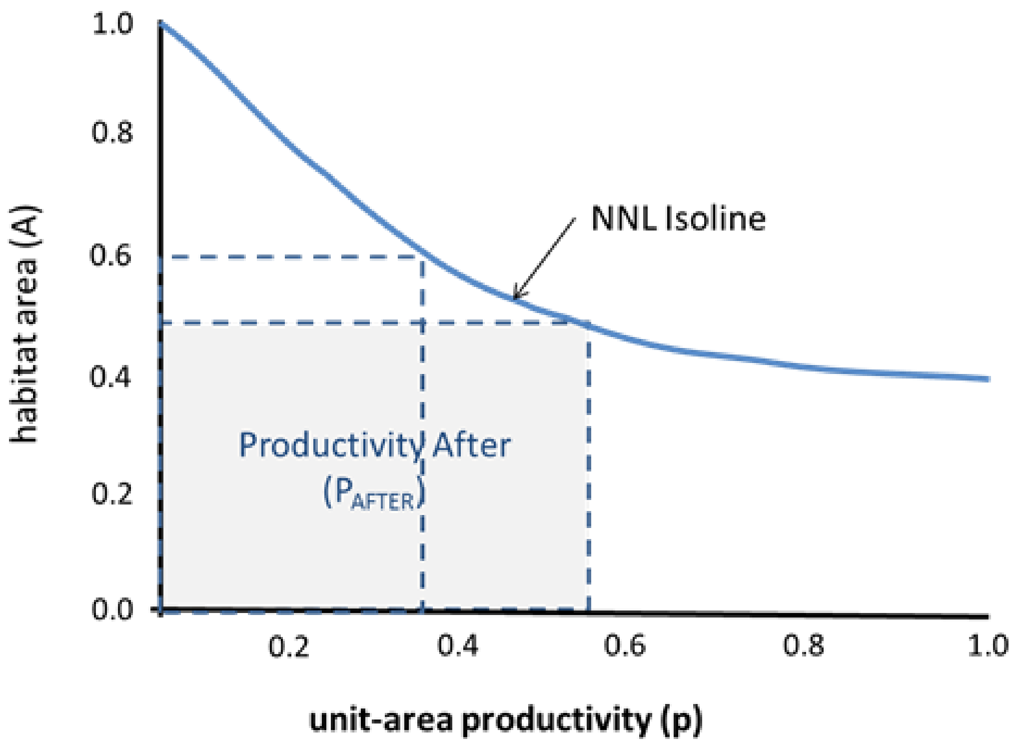


Figure 2. Net change equation representation.

The formulation of these equations also lead to the adoption of terminology appropriate to the assessment of net change: a) scenarios representing the pre- and post-development supplies of habitat in patches at the site of development; and b) a patch classification system distinguishing areas that were lost (LOSS), modified directly or indirectly (MODD, MODI) as a result of the development, or compensation (now described as offsetting) whether by modification of existing adjacent areas (COMM; now called OFFSETM) or by creation of new areas (COMC; now called OFFSETC).

Since this equation was developed the term compensation has been changed to offsetting. The original equation was framed in relation to the concept of productive capacity which was the preferred currency at that time, but the basic framework (the product of Space Units × Suitability Value) can be applied to productivity, biodiversity, habitat, etc. The original framework assumed that baseline conditions were fixed but it is now clear that on most scales baseline conditions are always shifting (mostly downward), and shifts in the time frame under which net change is assessed need to account for these shifts, thereby increasing the offsets required.

As a result of the collaboration of regulatory staff and scientists it was clear that FHM (now FPP) would benefit from quantitative assessment tools to guide proponents of development projects impinging on fish habitat. Convening expert panels to guide the valuation of habitat patches in each regulatory case was impractical and hence an evidence-driven scientifically defensible method and tool was required. A decision was made to use the net change accounting framework, building on the HEP-HSI (habitat evaluation procedure – habitat suitability index) approach used by U.S. Fish and Wildlife Service (USFWS 1981, Terrell et al. 1982, Terrell 1984) where habitat patches were assigned value by multiplying patch area by a suitability value based on the features present in the patch shown to be useful to the fishes of interest. This product is known as the Weighted Suitable Area (WSA) and is thought of as the equivalent area of a patch where ideal habitat conditions existed. However, HEP-HSI assessments were typically performed on a species-by-species basis and were limited by the adequacy and certainty in published literature. Typically, they do not consider combinations of habitat features to predict occupancy and productivity of individual species and life stages.

To overcome this central, basic knowledge problem, an aggregate approach was adopted. Habitats used preferentially by more species and life stages were assumed to make a greater contribution to fish productivity. This rationale being that the cumulative weight of evidence among species would offset the data deficiencies present for individual species. Hence, habitat suitabilities based on occupancy of different habitat features by species and life stage were acceptable surrogates for productivity.

Habitat suitability by species and life stage was gathered into a database using extensive literature reviews by experts. This and subsequent databases provided the foundation for the models to estimate suitabilities. Using the net change equation and the habitat usage database, work could proceed on three fronts:

1. A facilitated prototype workshop was held to develop a tool design (Minns et al. 1995). Scientists, regulatory staff, and private environmental consultants provided guidance for tool development that was in harmony with emerging practices for the management of fish habitat.
2. Three life stage habitat usage literature reviews were commissioned for all fishes occurring in the Great Lakes basin (Lane et al. 1996a,b,c for spawning, young-of-year, and adult + juvenile life stages).
3. A prototype calculation scheme was implemented using MS Excel spreadsheets. The Tool was moved online to address distribution and delivery issues, and ensure the integrity of the databases. Bio-Software, with Fraser Gorrie and James Moore, were essential partners in the development and implementation of the ideas and the software.

These efforts were facilitated by the financial support provided from within DFO (local operating funds, national strategic funds, FHM funds) and beyond (Great Lakes Action Plan [GLAP] funds).

Additionally, research and advisory activities of many staff from the Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS, DFO Science) in several Areas of Concern (AOCs) around the Great Lakes basin provided working case studies for developing and testing the Tool. Specifically, planned fish habitat restoration actions funded under GLAP and ongoing research and restoration planning in Hamilton Harbour had substantial contributions to the development of the Tool.

Further regional and life history trait databases were commissioned as a planned precursor to expanding application into other regions of Canada including:

- life-history and ecological trait characteristics of Canadian freshwater fishes (Portt et al. 1988, Minns et al. 1993, Bradbury et al. 1999, Langhorne et al. 2001, Richardson et al. 2001, Roberge et al. 2001, Evans et al. 2002, Roberge et al. 2002);
- lake fish habitat - Great Lakes region (Lane et al. 1996a,b,c, Chu et al. 2005), Newfoundland and Labrador (Bradbury et al. 1999), Pacific and Yukon (Roberge et al. 2001), Prairies (Langhorne et al. 2001), Northwest Territories and Nunavut (Richardson et al. 2001); and
- stream fish habitat - Great Lakes region (Portt et al. 1999), Pacific and Yukon (Roberge et al. 2002), Northwest Territories and Nunavut (Evans et al. 2002), Newfoundland and Labrador (Grant and Lee 2004).

These databases were peer-reviewed and published as DFO Canadian Manuscript (or Data) Reports of Fisheries and Aquatic Sciences for use as stand-alone, referenced information sources as well as for eventual use as tool inputs. The regional database template was redesigned to include:

- four life stages, initially separating juveniles and adults into separate stages;
- increased scope for describing vegetative cover types; and
- a more systematic approach to documenting literature evidence.

Development of the Defensible Methods software application proceeded to address issues such as which formulation of a habitat suitability model to use and how to deal with missing habitat usage data. For research purposes, a module was added to allow examination of alternate model formulations. The final model assumed that major habitat axes (depth, substrate, and vegetative cover) were independent and that cross-products and normalization (a typical rescaling so that the maximum values are one) produced acceptable suitability values. Examination of alternatives such as summing or minima across major axes showed similar results after normalization. Additional research included testing a module to allow substitution of reference habitat usage ratings for missing values by species (rated as low usually without data). As long as relatively large numbers of species (circa 20+) were involved the impacts on resultant suitability matrices were nominal. Questions concerning the uncertainty in suitability values, time lags, and offset ratios were raised (Minns and Moore 2003, Minns 2006) and research modules were implemented. Subsequent field survey efforts by many agencies should be utilized to develop improved habitat-use tables.

When FHM assumed responsibility for the Tool it was renamed HAAT, Habitat Alteration Assessment Tool. DFO Science provided hands-on training for FHM staff. FHM developed guidelines for its application and use in the Great Lakes region, which included a minimum infill size for use. To address the many small dock proposals, a simplified front-end application was developed. This allowed owners to “model” their dock plans via simplified gridded representation of the shore area and a standard HAAT analysis was run to produce standardized assessment values. The main intention with the application was to nudge owners towards more benign dock designs i.e., floating ones held in place by small pilings rather than solid concrete/sheet steel-sided ones. Changes in operating policy negated the continued use of this tool. FHM used HAAT on a regular basis until the on-going evolution of software platforms on the internet began to produce breakdowns. Eventually wholesale changes in internet server software rendered HAAT inoperable and work began in earnest on developing its successor, HEAT, Habitat Ecosystem Assessment Tool, using a modern programming environment that could be relied on to stay functional in the long-term, coupled with improved web-based accessibility.

In the meantime, the basic concepts embodied in Defensible Methods/HAAT/HEAT had gained wider acceptance across Canada with respect to assessing net change of suitable fish habitat. DFO Science used these concepts in a variety of situations. They provided advice for a number of mine development projects including several in the North. Audits of selected pre-HAAT authorizations in the Great Lakes were conducted to compare expected and later-observed outcomes (MacNeil et al. 2008). A whole lake modification experiment involving extensive removal of littoral woody debris was assessed by Frezza and Minns (2002a,b). Scaled-up applications of HAAT were undertaken in Great Lakes AOCs in support of efforts to develop area fish habitat management planning frameworks (Bay of Quinte, Hamilton Harbour, Severn Sound, Long Point Bay, and Toronto Waterfront is ongoing). Whole lake assessments were developed (Lake Erie, Lake Ontario – the latter in relation to development of alternative water levels regulation plans by the International Joint Commission). The Lake Ontario work built on earlier ideas developed by Minns et al. (1996) to examine how habitat supply as measured by habitat suitability assessments of whole ecosystems might be used to drive fish population models and to tie habitat supply explicitly to fish production and potential yield models (Hayes et al. 2009).

MODEL DESCRIPTION: THE DEFENSIBLE METHODS/HAAT/HEAT HABITAT SUITABILITY MATRIX (HSM) MODEL

The details of how the habitat usage databases are used to compute a Habitat Suitability Matrix (HSM) and how weighted usable area or scaled habitat units are computed are given in Minns et al. (2001). Here, a basic outline of the computational steps is included to assist those reading this document and the accompanying Science Advisory Report (DFO 2019). The basic approach was to build a HSM that included water depth, substrate type, and vegetative cover, with habitat preferences developed for each species by each life stage and rated preference by low, medium, and high (Figure 3). The HSM creates many combinations of habitat features. Figure 4 shows an example of output from HEAT, converted to a proportional use index, for coldwater spawning habitat value, by substrate and depth combinations.

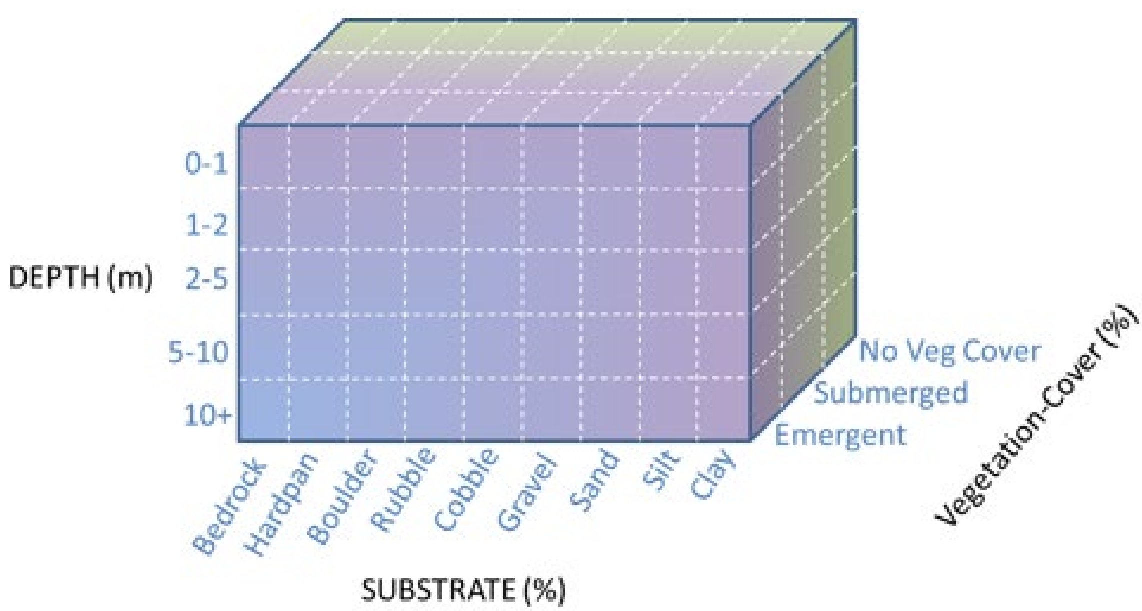


Figure 3. Habitat Suitability Matrix. Contains three axes: depth, substrate, and vegetation cover.

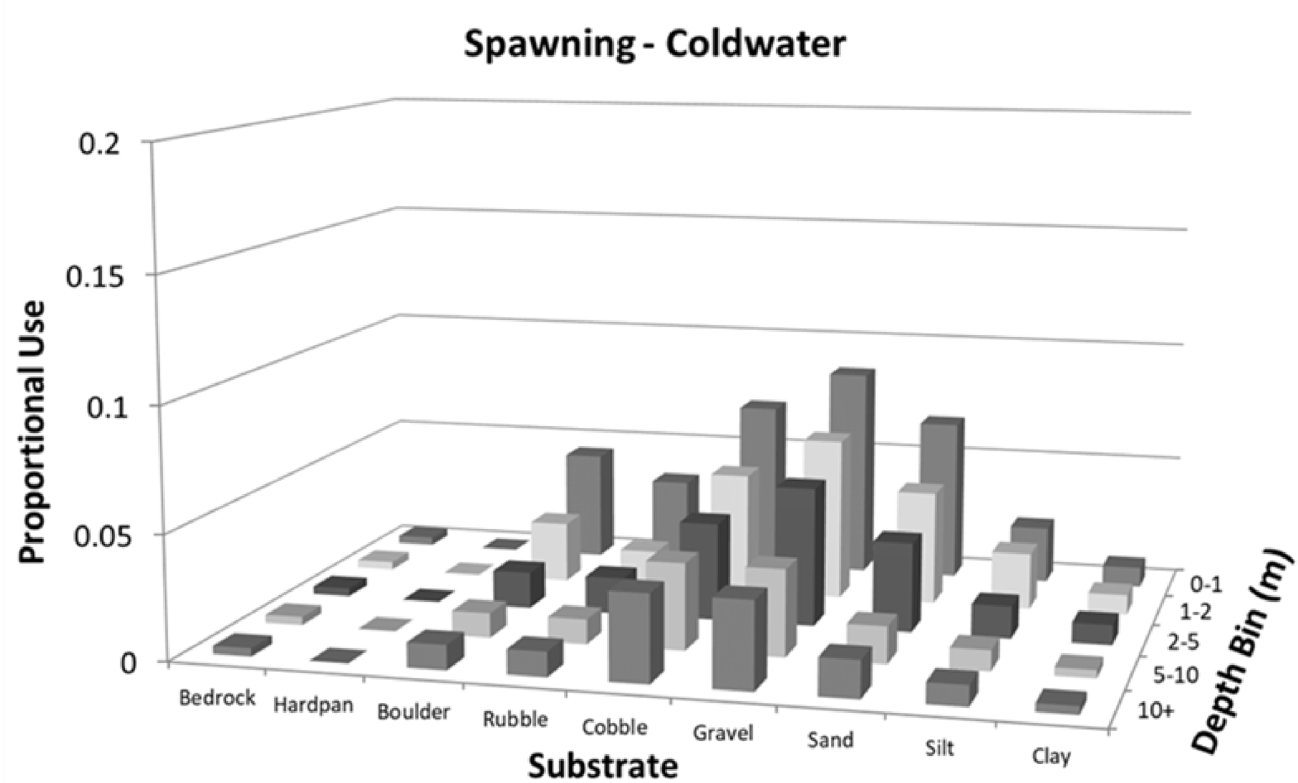


Figure 4. Example: coldwater fishes associated with submerged aquatic vegetative cover. Aggregated proportional uses by habitat axis (depth x substrate type; adapted from Gertzen et al. [2020]) are used to estimate habitat suitabilities, which are combined to give a composite suitability per habitat patch.

FISH HABITAT USAGE/OCCUPANCY DATABASE

Based on the literature evidence reported by Lane et al. (1996a,b,c) for three life-stage groups (spawning, young-of-the-year [YOY], and adults + juveniles; see Appendix 1 for descriptions) for fish species found in the Great Lakes, a categorical habitat suitability database was assembled covering three habitat features each with a number of categories:

Depth (Z): 0–1, 1–2, 2–5, 5–10, and 10+ m

Substrate (S): Bedrock, Hardpan, Boulder, Rubble, Cobble, Gravel, Sand, Silt, Clay

Vegetative Cover (C): Emergent, Submerged, No Cover

For each category in each habitat feature, preferences (evidence of usage or occupancy noted in the literature) are rated as nil, low, medium, and high for substrate and cover. Depth range preferences often vary seasonally with thermal patterns and life history progressions. In the Lane et al. reports (1996a,b,c) depth preferences were rated by the number of seasons involved (1, 2, or 4) but were represented as either nil or high when used in HAAT/HEAT for computing suitabilities. Where no evidence was reported the default was to assume nil preference. For calculation purposes the ratings nil, low, medium, and high were coded as 0, 1, 2, and 3. Thus, species-life-stage habitat preferences are represented in three vectors:

Depth: $Z(2,3,1,0,0)$; Substrate: $S(0,0,0,0,1,2,2,1,0)$; and Cover: $C(1,3,0)$

In calculation notation, these vectors are: Z_i where i = 1 to 5; S_j where j = 1 to 9; and C_k where k = 1 to 3.

CALCULATION OF AN INDIVIDUAL SPECIES' LIFE STAGE HABITAT SUITABILITY MATRIX (HSM)

The base HSM) consists of a cubic matrix with dimensions of 5 by 9 by 3 and contains 5 × 9 × 3 = 135 unique combinations or cells (Figure 3). Assuming that the three habitat vector values are independent, the preferences for each cell in the matrix is computed as the product of the ratings in the three habitat categories represented. For example, a species spawning with a high preference (3) for sand, a medium preference (2) for submerged vegetation, in 0–1 metres of water in the spring (1) has a weight for that combination of 3 × 2 × 1 = 6. If any one category has a zero value, the cell's combined value is zero. Values for all cells in the matrix can be assigned in the same way, the combined preferences for a multiplied combination of depth (Z_i), substrate (S_j), and cover (C_k) categories is computed as:

$$P_{ijk} = Z_i{}^* S_j{}^* C_k$$

The cell cross-products are summed over all permutations of depth, substrate, and cover categories:

$P^{***} = \Sigma\Sigma\Sigma\left(P_{ijk}\right)$ over *i* = 1 to 5; *j* = 1 to 9; and *k* = 1 to 3

Next proportional suitabilities (R_{ijk}) are computed for each cell in the *n*-dimensional matrix as the ratio of the cell preference product to P^{***}:

$R_{ijk} = P_{ijk}/P^{***}$ over *i* = 1 to 5; *j* = 1 to 9; and *k* = 1 to 3

$R^{***}\ \Sigma\Sigma\Sigma\ (R_{ijk})$ over *i* = 1 to 5; *j* = 1 to 9; and *k* = 1 to 3

This step ensures that the total contribution of each matrix for a particular species' life stage to subsequent groupings of species matrices by life stage is equal to a total weight of 1 (R^{***}). R_{ijk} represents the proportional suitability of a matrix cell.

SPECIES GUILD BY LIFE STAGE SUITABILITY MATRICES

Having computed separate HSMs for all the species included in the location list by life stage, the HSMs are pooled by species into guilds by life stage (Table 1). The combinations of three life stages, two feeding or trophic groups (piscivore vs. non-piscivore), and three adult thermal preferences (coldwater, coolwater, warmwater) have been set as the defaults for forming species groupings. Other criteria for forming groups could be used given existing information in the base tables or with the addition of further life history/trait information for all fish species being added to the basic databases, (cf. Coker et al. 2001). Species' life stage HSMs are summed cell by cell and then the resulting cell sums are standardized to a scale of 0 to 1 by dividing the values in all cells by the maximum cell sum. Thus the group HSM values:

$GS_{ijk} = \Sigma\, R_{ijk}/\mathrm{Max}(\Sigma\, R_{ijk})$ summed over all guild species by combinations of *i,j,k*.

Table 1. How the species-level suitability matrices (black boxes, ❒) are pooled into fish guild matrices (red boxes, ❒) by life stage. Each species can only belong to one guild (as represented by the black boxes, ❒) but has 3–4 life stages per guild. See Appendix 1 for life stage definitions.

Species	Fish Guild				
	A	B	C	…	M
1	❒	-	-	-	-
2	❒	-	-	-	-
3	-	❒	-	-	-
4	-	-	❒	-	-
5	-	-	❒	-	-
..	-	❒	-	-	-
..	-	-	-	❒	-
..	-	-	-	-	❒
N	❒	-	-	-	-
No. species	n_A	n_B	n_C	…	n_M
Guild matrices	❒	❒	❒	❒	❒

COMPOSITE HABITAT SUITABILITY MATRIX

Finally, proportional weights summing to 1 are assigned separately across the life stages and species guilds (Table 2). The life stage weights are intended to reflect the relative importance of life-stage contributions to the completion of life histories in all fish species. The default setting for weights is a constant 1/3 across all life stages as opposed to the fish guild weights which are intended to reflect the relative importance of the fish groups to ecosystem characteristics, and the conservation and fishery management objectives in the study area. For example, coldwater piscivorous fishes may be given higher weights in a northern deep lake where larger coldwater top predators are of primary interest. The guild life stage HSMs are pooled to produce the composite HSM as follows:

$CS_{ijk} = \Sigma\, \Sigma\, (GS_{ijk}) * WG * WL$ over all guilds (G) and life stages (L)

Table 2. Assignment of weights (W) among fish guild-life stage habitat suitability matrices (HSMs). The weights are proportions that sum to 1 on each axis and the sum of their cross-products also equals 1. The composite HSM (blue box, ❒) is computed as the weighted sum of the guild-life stage HSMs (red boxes, ❒). SP = spawning, AJ = Adult + Juvenile. Guilds are groups A to M. See Appendix 1 for life stage descriptions.

Guilds	Weights	Life Stages			Sum
		Spawning	YOY	Adult+Juvenile	
		W_{SP}	W_{YOY}	W_{AJ}	1.0
A	W_A	❒A,SP	❒	❒	❒
B	W_B	❒	❒	❒	❒
C	W_C	❒	❒	❒	❒
..	..	❒	❒	❒	❒
M	W_M	❒	❒	❒	❒
Sum	1.0	-	-	-	❒

CALCULATION OF HABITAT UNITS (WEIGHTED SUITABLE AREA) BY PATCH

Assessment tables in HEAT consist of a series of uniquely-identified habitat patches with an area, an assigned habitat modification class (LOSS, MODD, MODI, COMM [now OFFM], COMC [now OFFC]), and percentage of habitat composition. Habitat vectors independently describe the percent composition by each of three habitat features comprising the axes of the HSM: water depth, substrate type, and vegetative cover. For example, the habitat vectors can be represented as follows:

Depth: *PZ*(70,20,0,0,0); Substrate: *PS*(0,0,0,0,15,40,40,5,0); and Cover: *PC*(10,90,0)

The percent vectors are used for convenience when setting up scenario datasets but must then be divided by 100 to convert to proportions as calculations proceed. All percentages must add to 100% or proportions to 1.00 within each habitat feature (i.e., emergent + submerged + no cover = 100),

Given that habitat suitability is represented as a 3-dimensional matrix (while there are only 3 variables), and the following conventions can be used in GIS overlays to do the calculations, the three habitat vectors for the patch are assumed to be independent and the cross-products of proportional triplets are computed across all combinations of depth, substrate, and cover categories:

$$PZSC_{ijk} = PZ_i * PS_j * PC_k \quad \text{over } i = 1 \text{ to } 5;\ j = 1 \text{ to } 9; \text{ and } k = 1 \text{ to } 3$$

The sum of all PZSCijk equals 1.00. This calculation effectively ‘disaggregates’ a habitat patch into a set of mini-patches corresponding to the table cells in the composite HSM. Each cross-product estimates the proportion of the patch where only one category on each axis of the three habitat features is present. Next, the cross-products of matching suitability and proportions are multiplied and summed:

$$SPATCH = \Sigma\,\Sigma\,\Sigma\left(PZSC_{ijk} * CS_{ijk}\right) \quad \text{over } i = 1 \text{ to } 5;\ j = 1 \text{ to } 9; \text{ and } k = 1 \text{ to } 3$$

This calculation provides a weighted estimate of the patch suitability. The patch area (A) is multiplied by this suitability to estimate the weighted suitable area (WSA), or habitat units (HUs) for summation across patches within a scenario. Similar calculations are performed using the guild life stage HSMs so that the users can consider different consequences between pre- and post-development scenarios for different life stages or fish groups. The constituent WSA values are useful when designing offset patches to address groups or stages with maximal losses.

CURRENT APPLICATION AND FISHERIES PROTECTION PROGRAM AND HEAT

The primary use for HEAT by FPP has been in reviewing development proposals in the Great Lakes and other large inland lakes within the Great Lakes’ primary basin. The completion of HEAT does not, by itself, constitute completion of the review, assessment, and decision processes of FPP or their delegated authorities, but can constructively contribute to those processes as required under the *Fisheries Act* and the federal Investment Policy for Offsetting.

Approximately 54 files have incorporated a HEAT analysis into the referral review process. The majority of development projects included an infill component and a few included a dredge component. The project footprint ranged in size from 61 m^2 to over 500,000 m^2. Approximately 15% had a footprint < 1000 m^2, 55% between 1000 to 10,000 m^2, 20% between > 10,000 to 100,000 m^2, and 10% > 100,000 m^2. The purpose of the projects included shoreline stabilization, infrastructure expansion or protection, marina expansion or repair, and large public park projects.

Multiple scenarios were almost always run for those projects with larger footprints (> 10,000 m^2) prior to developing a final design. Preliminary runs provided direction to the proponent regarding the sensitivity of the habitat within the project footprint and a rough gauge as to whether or not offsetting would be required to counterbalance the serious harm proposed by the project. The use of a publically available DFO-supported tool allows for multiple scenarios to be run by the proponent to develop the most cost-effective and productive design and to determine project viability prior to final submission to DFO.

ANALYSIS AND CASE STUDIES

There are circumstances that may occur at a development location that justify using the built in flexibility of HEAT. There are also raised issues with the Tool from previous feedback. The examples provide one real scenario and other theoretical ‘case studies’, and were developed to outline some of the concerns with the Tool results raised by users. The case studies are intended to direct the next steps in tool development by clarifying the issues and providing interim guidance on the appropriate application of the Tool until updates are made if needed.

TYPICAL USE: BRANT INN NODE, BURLINGTON, ONTARIO

Site Location/Description

The Brant Inn Node waterfront occupies about 300 m of frontage between the formal Spencer Smith Park in downtown Burlington and Burlington Beach. More than a century ago this shoreline featured a transition from a sandy, bay mouth barrier beach to eroding shale bluffs to the east. Over the last century, the shoreline at this location has been significantly altered. Initially, alterations included shifting the opening of Burlington Bay from near the corner of Lakeshore Road and Northshore Boulevard to the present location of the shipping canal, further to the south. Subsequently, alterations included ongoing lake filling to support a rail line and later to protect the land base of the old Brant Inn.

The pre-construction shoreline (Figures 5 and 6) was protected by concrete seawalls, armour stone, and concrete rubble in varying states of disrepair. The adjacent nearshore area consisted of two separate zones with exposed shale bedrock in a small embayment and then further to the south, a zone of sandy substrate from the old Brant Inn pier towards the south and Burlington Beach. Due to its position in the northwest corner of the lake, the wave exposure for this area is facing the east and south.

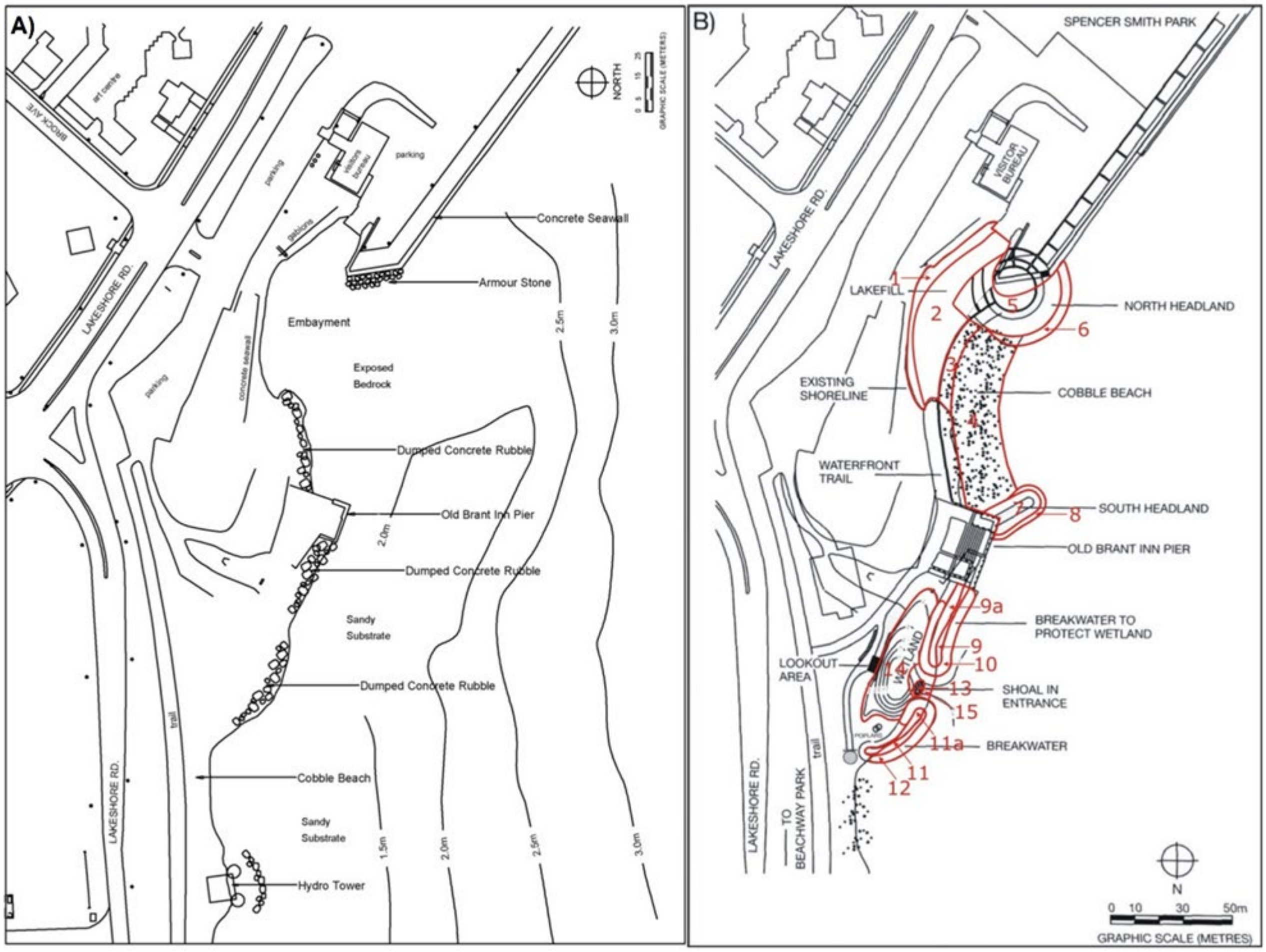


Figure 5. Brant Inn Node, Burlington, Ontario, pre- and post-construction site drawings. The drawing to the left (A) shows the pre-construction condition (see Figure 6 for pre-construction site photographs) while the drawing to the right (B) shows the project's planned modifications (see Figure 7 for post-construction site photographs).

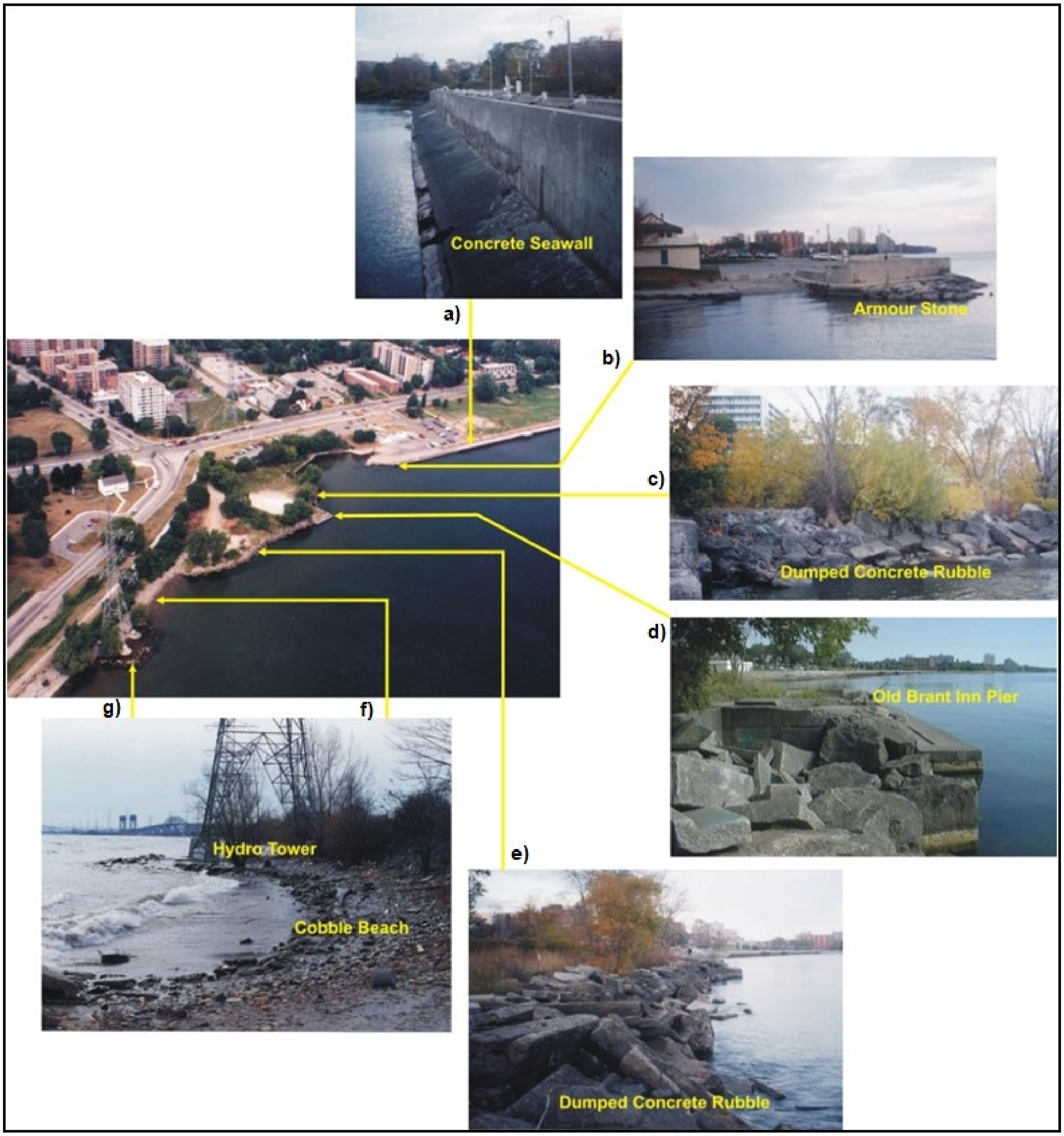


Figure 6. Brant Inn Node, Burlington, Ontario, pre-construction condition site photographs showing: a) a concrete seawall, b) a concrete seawall with armour stone, c) dumped concrete rubble, d) the old Brant Inn concrete pier, e) more dumped concrete rubble, f) a cobble pocket beach, and g) a hydro tower along the active shoreline.

The project/post-construction shoreline (Figures 5 and 7) included a wetland (0.10 hectares in area) excavated from the existing land base (in the vicinity of 'e' in Figure 5), connected to the lake and protected by breakwaters and a shoal in the entrance. The reconstruction of the old Brant Inn pier created an area for public gatherings and day-use boat mooring. Lake-filling of the small embayment (0.27 hectares in area) created more land next to the main access point for pedestrians and vehicles; and a cobble beach was created between two rubble-mound headlands.

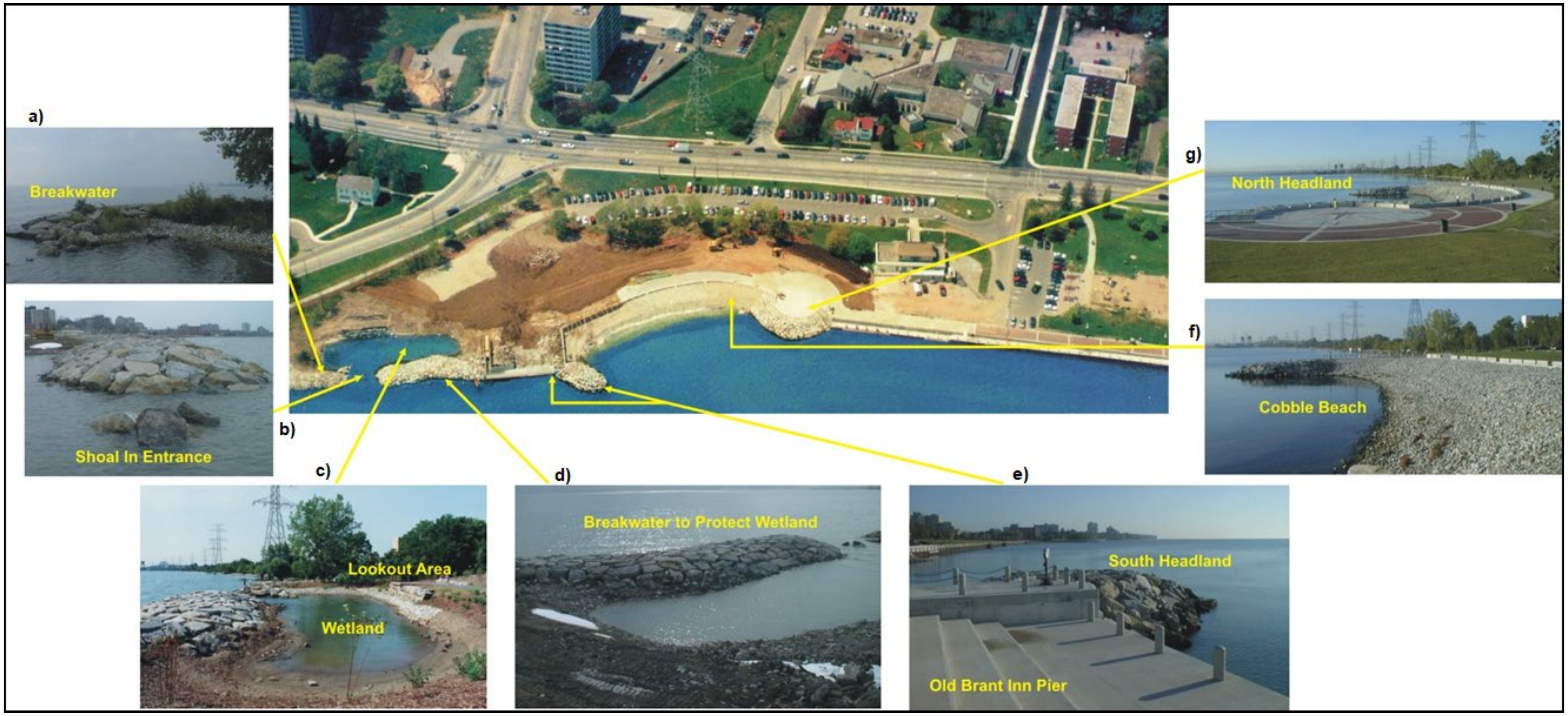


Figure 7. Brant Inn Node, Burlington, Ontario, post-construction site photographs, showing: a, b, c, d) the newly constructed wetland with a) and d) breakwaters to protect the wetland, b) the protective shoal constructed in the entrance to the wetland, and c) the new wetland with a lookout area; and f) the new cobble beach inset between e) the reconstructed old Brant Inn pier area with a rubble-mound headland to the south and g) a rubble-mound headland to the north.

Based on a comparison of the pre- and post-construction scenarios a comparison table was compiled for input into HEAT (Figure 8).

Project : Spencer Smith Park   Description: Boardwalk and Pier Construction

PRE-Construction Scenario							**POST**-Construction/Compensation Scenario							
ID #	Area (m^2)	Habitat Type	Condition Factor	Depth Zone (m)	Substrate	Cover	ID #	Area (m^2)	Habitat Type	Condition Factor	Depth Zone (m)	Substrate	Cover	What Changed?
							Summarize the 'kind' of habitat and then break out each specific piece based on substrate, depth and cover							
1	160	LOSS	1.0	0-1	sand	no cover								
2	1200	LOSS	1.0	0-1	bedrock	no cover								
3	210	LOSS	1.0	0-1	bedrock	no cover								
4	1540	COMC	1.0	1-2	bedrock	no cover	4	1540			0-1	cobble		cobble beach below HWM
5	820	LOSS	1.0	1-2	bedrock	no cover								
6	100	COMM	1.0	1-2	bedrock	no cover	6	100	COMM	1.0	0-1	boulder	no cover	armourstone revetment
7	260	LOSS	1.0	1-2	bedrock	no cover								
8	30	COMM	1.0	1-2	bedrock	no cover	8	30	COMM	1.0	0-1	boulder	no cover	armourstone breakwater below HWM
9	40	LOSS	1.0	0-1	sand	no cover								
10	40	MODD	1.0	0-1	sand	no cover	10	40	MODD	1.0	0-1	boulder	no cover	armourstone breakwater below HWM
11	35	LOSS	1.0	0-1	sand	no cover								
11a	35	LOSS	1.0	above HWM	n/a	no cover	11A	35		1.0	above HWM	n/a	n/a	remains above HWM
12	70	MODD	1.0	0-1	sand	no cover	12	70	MODD	1.0	0-1	boulder	no cover	armourstone breakwater below HWM
							13	20	COMC	1.0	0-1	cobble and boulder	no cover	cobble and boulder shoal
							14	980	COMC	1.0	0-1	silty sand	submergent and emergent	creation of wetland by excavaion of landbase
							15	80	COMC	1.0	0-1	sand	no cover	excavation to create new lakebed

What the proponent says (and where). These are footnotes and legends for habitat short-forms used by proponent eg. what Silty-Sand means, etc.

a)

Depth (m)
0-1
1-2
2-5
5-10
10+

Substrates	cm	inches
bedrock		
boulder	> 25	> 10 in
cobble	17-25	6.7-10 in
rubble	6.4-17	2.5-6.7 in
gravel	0.2-6.4	0.05 - 2.5 in
sand	< 0.2	<0.05
silt	finer than sand with organic component	
clay		
hardpan clay		

Cover
submergent
emergent
no cover

Habitat Types	see page 42 and 12 in MS 2559
LOSS	Loss - only in Post
UNCH	Unchanged - if used, Post = Pre (in area)
MODD	Modified-Direct - Pre = Post
MODI	Modified-Indirect - Pre = Post
COMM	Compensation-Modified - Pre = Post
COMC	Compensation-Created - only in Post

Figure 8. Brant Inn Node, Burlington, Ontario, Excel spreadsheet for submission to HEAT (pre- and post-construction scenario comparison).

Interpretation of Results and FPP Guidance

As can be observed in Table 3, complex site projects can produce difficult to interpret results in which trade-offs between groups or life stages may occur. In this example, HEAT results indicate an overall gain in productivity, however there is a loss in adult coldwater piscivore and non-piscivore habitats as well as YOY or nursery fish habitat for these same groups. Ultimately, the acceptability of any development proposal is the responsibility of the FPP program, but HEAT can help quantify and clarify the rationale underlying the decision. For example, FPP staff must consider the local fishery management objectives before determining if an authorization would be acceptable. In this case the relative importance of the affected fish groups to the local ecosystem must be examined. The losses shown in the pooled YOY data or in the adult and YOY data for coolwater non-piscivores and coldwater species may or may not be of importance or significantly affect local habitat and fishery objectives.

Table 3. Brant Inn Node's HEAT output summary for pre- and post-construction scenarios for all combinations of three fish life stages with all thermal and trophic guild groupings. Habitat losses are highlighted in pink.

Life Stage [a]	Group [b]	Weight	Pre	Post	% Difference
Adult	warm pisc	0.17	695.3	908.8	30.7
	warm non-pisc	0.17	705.0	1,255.7	78.1
	cool pisc	0.17	75.6	788.0	942.3
	cool non-pisc	0.17	1,220.9	1,139.5	-6.7
	cold pisc	0.17	32.8	12.6	-61.6
	cold non-pisc	0.17	89.7	69.9	-22.1
Spawning	warm pisc	0.17	872.8	1,228.2	40.7
	warm non-pisc	0.17	1,048.2	1,404.7	34.0
	cool pisc	0.17	318.7	589.7	85.0
	cool non-pisc	0.17	888.3	1,222.8	37.7
	cold pisc	0.17	432.4	793.8	83.6
	cold non-pisc	0.17	729.9	783.9	7.4
YOY	warm pisc	0.17	729.5	802.1	10.0
	warm non-pisc	0.17	336.3	918.3	173.1
	cool pisc	0.17	186.5	228.8	22.7
	cool non-pisc	0.17	1,044.8	654.2	-37.4
	cold pisc	0.17	1,182.3	454.1	-61.6
	cold non-pisc	0.17	178.1	144.0	-19.1
Pooled	adult	0.33	469.9	695.8	48.1
	spawning	0.33	715.1	1,003.9	40.4
	YOY	0.33	609.6	533.6	-12.5
Overall Sum			598.2	744.4	24.4

[a] Life Stage: see Appendix 1 for descriptions

[b] Group = thermal guild (coldwater, coolwater, warmwater) and trophic guild (piscivores, non-piscivores) groupings; (pisc = piscivore)

HEAT can be used to quantify trade-offs for fish communities that might occur. FPP staff must examine the output and make management recommendations based on a detailed understanding of the results but also in considering factors not included in the model. This recommendation requires clear understanding of the assumptions, sensitivities, and sources of uncertainty that exist within HEAT.

MODIFIED SCENARIO CASE: USE OF QUALITY ADJUSTMENT FACTORS

HEAT has the ability to assess factors in addition to the current inputs of water depth, substrate type, and vegetative cover data that alter the quality assigned to a patch and therefore its inferred productivity through the use of condition factors or quality adjustment factors (QAFs). Specifically, fetch, temperature, and water quality have been considered by using QAFs. Here we use fetch as a QAF example, given that two patches of identical substrates exist, but one location is in a high fetch or exposed area and the other patch is in a low fetch area; those areas will naturally have different productivities (Minns et al. 2001). Thus the area of low fetch would be expected to be used by a larger number and variety of fishes more consistently. However, these differential results would not appear in the output without the use of the QAF as there is no direct use of fetch within the model (although fetch does affect vegetation growth in the coastal zone). However, flexibility within the model allows for the use of a QAF to address this situation. Additional guidance is required before any QAF is applied.

MODIFIED SCENARIO CASE: SUBSTRATE CHANGES

HEAT is highly sensitive to changes in substrate, particularly when examining the composition of finer substrates such as sand, silt, and clay. Some uncertainty exists regarding the relative productivity of sand, specifically the situation of 100% beach sand, although there are beach fish communities (Reid and Mandrak 2009). This type of habitat is relatively common in areas of development, especially in the lower Great Lakes. In this scenario, the input data for depth and vegetative cover remain the same and there is a proposed change from 100% beach sand to 100% cobble. As part of an offset plan, proponents were modifying the substrate from sand to cobble with the expectation that the addition of cobble would result in an increase in productivity/habitat diversity. It was predicted that cobble would be used by more species than sand as it provides interstitial space for food and cover for smaller fishes. Additionally, cobble provides spawning habitat for shoal spawners. This was not the result in HEAT. The model output showed a loss for each individual guild, each life stage, as well as for overall habitat supply. There was a gain for coldwater piscivores only, which may be the target for this type of offset anyway. Precaution must be taken both in the input of modified substrates as well as the interpretation of results. The occurrence of such results highlights the need to continually review and update the HEAT database table with documentation based on accumulating evidence in the literature and in systematic surveys on the use of different substrate types (and other habitat features) by all species of fish of various life stages.

MODIFIED SCENARIO CASE: CREATION OF WETLAND—ORGANICS/DETRITUS SUBSTRATE

Many offsetting plans include the creation or restoration of wetlands. Clarification has been sought by HEAT users on how to determine the percentages of sand, silt, and clay from what was typically identified in the field as organic substrates and/or detritus and how to classify the organic mix being used to grow aquatic vegetation in newly created wetlands. In this scenario, the input data for water depth and vegetative cover again remained the same and the change only occurred in the combination of sand, silt, and clay used. The predicted outcome was that the percent combination of these three substrates would show similar output results because they are of secondary importance to the aquatic vegetation present, and only subtly varied. It is likely that not all combinations of sand, silt, and, clay would foster aquatic vegetation growth, but those extremes were not tested here. For this case study, four combinations of sand, silt, and clay were compared. The four combinations were either:

1. 34:33:33 sand:silt:clay, or
2. 40:40:20 sand:silt:clay, or
3. 40:20:40 sand:silt:clay, or
4. 20:40:40 sand:silt:clay.

The model output showed differences in the WSA for each combination that varied substantially by default guild but less so by life stage. The variation in output may be driven by the percentage of clay since 100% clay does not support vegetation growth and thus the output could be overly influenced by this apparent contradiction. Based on the accompanying Science Advisory Report (DFO 2019), a sensitivity analysis was recommended to more formally scope the range of outputs from variations in substrate type.

FUTURE DIRECTIONS FOR HEAT DEVELOPMENT

Additions and upgrades to HEAT are ongoing for two significant extensions to the existing functionality within HEAT: 1) the inclusion of temperature as a habitat variable and 2) the ability to incorporate different water level comparisons into the Tool. A recent survey (Tymoshuk et al. 2017) asked users to rank which functions were the most important to continue to include or add to the model. The top ranking functions included temperature, the ability to customize or add more habitat layers, and additional habitat weightings (i.e., more QAFs) to address missing habitat variables (Table 4). Other tool developments or expansions of interest were the addition or completion of all regional preference datasets compiled for the rest of Canada along with some new ecological information and gap filling for some species that are missing information. The ability to add multiple pre- and post-scenario comparisons to one file, and the addition of help videos as training for new and existing users have both been implemented online. Various unpublished background documents have been merged to produce a guidance document as part of the training package (Doka et al., DFO, unpublished data) that forms the basis for a user manual. Also, some presentations and example files have been compiled as ad hoc training materials on the Tool.

Table 4. Priority ranking of expanded functions for inclusion in HEAT. Adapted from Tymoshuk et al. 2017.

Function	Rank	Score	Function	Rank	Score
Temperature	1	16	Time lag	10	7.5
Increase # of layers	1	16	Seasonality (02)	11	6.5
Habitat weighting	1	16	Ice cover	12	5
Water levels	4	13.5	Alternate suitability	12	5
Increase # of condition factors	4	13.5	Calculation methods	14	4
Productivity	6	12	Data exchange	15	3.5
Fetch	7	11	Map output	16	3
Uncertainty	8	10	Customize preferences	17	2
Connectivity	9	8.5	Water quality	18	0

BASE INFORMATION REVIEW

The core databases containing habitat preferences and fish lists in HEAT require consistent and timely updating of the underlying information, particularly: to address the introduction of new species within a region (e.g., Round Goby habitat information in the Great Lakes is not complete); to address the loss of species in some areas (e.g., some ciscoes, minnows); and to ensure that data gaps are filled, errors are corrected, and new information can be added for expansion into new ecoregions of Canada. Preferences are specified in the system by species and life stage. Given the species life-stage-specific nature of habitat associations (suitabilities), continued literature reviews should be focused on a species-by-life-stage update of habitat preferences or association information since the last updates. In this way, uncertainties can be addressed as more and new information becomes available. Some corrections need to be made to negative habitat associations that were originally inferred due to lack of information in the literature (e.g., lack of association with no-cover areas were inferred from high correlation with vegetation for some species). These uncertainties need to be addressed with directed research, or data-mining and statistical inferences, if not already done in the intervening years since the Lane et al. (1996a,b,c) series. There is much habitat-based research that has been published and undertaken since the original regional reports were produced in the mid-1990s through to the mid-2000s. We recommend that updates be conducted a regular basis to the core data tables with new information with standardized and vetted literature reviews. This could include a formal assignment of uncertainty to the underlying habitat associations for different species- or guild-specific life processes.

As more habitat layers are added to the system, the scope of the reviews will need to encompass these added dimensions of habitat. For example, more information will be needed on the thermal requirements of different life stages of fish species beyond the compilation of Hasnain et al. (2013), which has been incorporated into our base tables but is incomplete. Hasnain and others are continuing to find ways to fill temperature metric gaps based on phylogenetic proximity and new information. There are also many other variables with association or suitability information being published, such as turbidity and oxygen tolerance information that could be included.

In addition, the preference reviews could examine the potential for adding uncertainty into the habitat preference data at this level. To date, the approach within HEAT has been to assume that the individual species' life stage preferences for particular habitat features (e.g., sand in substrate and submerged vegetation in cover) are fixed categorically (nil, low, med, or high) and transferable across systems, at least as initially ordinated. Those assumptions will need to continue to be tested in addition to the assumption of independence between habitat variables.

EXTENSIONS TO HEAT FUNCTIONALITY

Temperature

The effects of temperature on adult fish habitat preferences are well documented and adult fishes have been classified into guilds for some time, although there is not always agreement between data sources (Scott and Crossman 1973, Eakins 2017). Information on earlier life stages and temperature influences are somewhat known (e.g., migration and spawning cues, egg and larval survival) but the classification of earlier life stages into thermal guilds is not as advanced as adult versions. Progress was made recently by Hasnain et al. (2013), but until then, timing windows had largely been the focus, using spawning months/weeks, which may shift under climate change. The effects of temperature on different vital rates and population dynamics are related to annual seasonality and to absolute temperature magnitude and variation. Therefore temperature, because of its dynamic nature, has proven difficult to incorporate into static habitat comparisons, but it is a logical extension of the variables currently in HEAT, particularly as a tool to anticipate potential climate change impacts. Implementation of temperature as a habitat layer within HEAT requires changing basic elements: how habitat is classified (e.g., increasing the number of depth categories beyond the current five within the system to capture 3D thermal structure); how fishes are classified by moving beyond the simple adult thermal classes; and how suitabilities are assigned by patch.

These are the fundamental changes that have been scoped that would be necessary to incorporate temperature as a habitat variable in HEAT evaluations. Changes are required at each input stage and analytical step within HEAT:

- Location choice – no change for the user at this step but the Tool may need to provide a temperature time series or profiles for a location if the user cannot provide one.
- Ecological information on species – thermal guilds by life stage; spawning and optimal growth temperature windows by species; upper and lower lethal thermal limits at each stage.
- Scenario tables – changes to user input files are needed to add functionality (eco-class or descriptors of sheltered/exposed areas of a site). Other input information—user or internal provision of temperature time series and profiles for the project site—including both pre- and post-project scenarios if this is anticipated to change as a result of the project. If local thermal dynamics are not expected to be affected then there may be no reason to add temperature to the HEAT assessment for that particular project. However, temperature dynamics are likely as or more important than depth associations and definitely related.
- Analysis stage – the calculation of suitabilities, use of QAFs and output tables will be modified with the inclusion of temperature as a habitat variable in HEAT. Further documentation on the specific methods will be forthcoming.

An assumption of the new approach as with other habitat preferences is that thermal preferences and temperature windows are transferable across the Great Lakes (e.g., that spawning cues are not different in Lake Superior compared to Lake Erie). As the Tool is adapted nationally across broad geographic regions and latitudes, this assumption will need to be addressed more fully.

One prototyped method for the inclusion of temperature in HEAT requires an annual temperature time series and possible profiles may be required as input from the user if available, otherwise methods for creating profiles from other information are needed. This requirement would be similar to the requirement for descriptions of physical features of the site in tabular form. These temperature data would be provided separately from patch level information and likely are only possible from more advanced users who can deploy temperature loggers in advance or have modelled thermal dynamics.

Alternatively, temperature curves would be provided by the HEAT system itself based on the location choice of the project, and seasonal and depth curves would differ by sub-location or eco-class (e.g., depth of patch). Local eco-classes such as river mouths, wetlands, sheltered or exposed embayments, open coastal areas, and offshore areas each potentially have different seasonal patterns and depth profiles. Thus, the system will not be constrained to assume constant temperature at different depths no matter the location and the input curve can be adjusted to different temperatures-at-depth if needed (likely most important for very large lakes). Work to date (Minns and Shuter 2013) has shown that it is possible, with relatively little information, to capture the depth of the thermocline and other key features of the seasonal open water thermal regime using seasonal thermal modelling (STM) for lakes (Minns et al. 2015).

Inclusion of the temperature habitat layer will enable the system to address potential impacts of climate change on habitat and productivity in addition to the impacts from various projects. DFO Science is looking at different future scenarios—(such as climate change scenarios) which are being continually updated for potential use in HEAT—as a driver for the future condition of temperature curves used. The primary focus has been on creating the software architecture to handle the functionality, leaving exploration of its different potential uses for later, such as the adaptation of projects and offsets under climate change.

The basic concepts to modelling temperature as a habitat variable for different life stages is illustrated in Figure 9. This figure shows a 0 to 1 range in thermal habitat suitability on the y-axis based on the temperature requirements during the year for a spring spawner and on a generalized annual temperature curve. Spawning suitability calculations would be based on a temperature series for a particular patch. This would be used to calculate the duration of different thermal windows for given guilds (e.g., day counts within different temperature intervals). This would supply the information required to evaluate if the temperatures meet the requirements for spawning fishes and their spawn, and for growth and survival of fishes in their nursery (YOY) and adult stages.

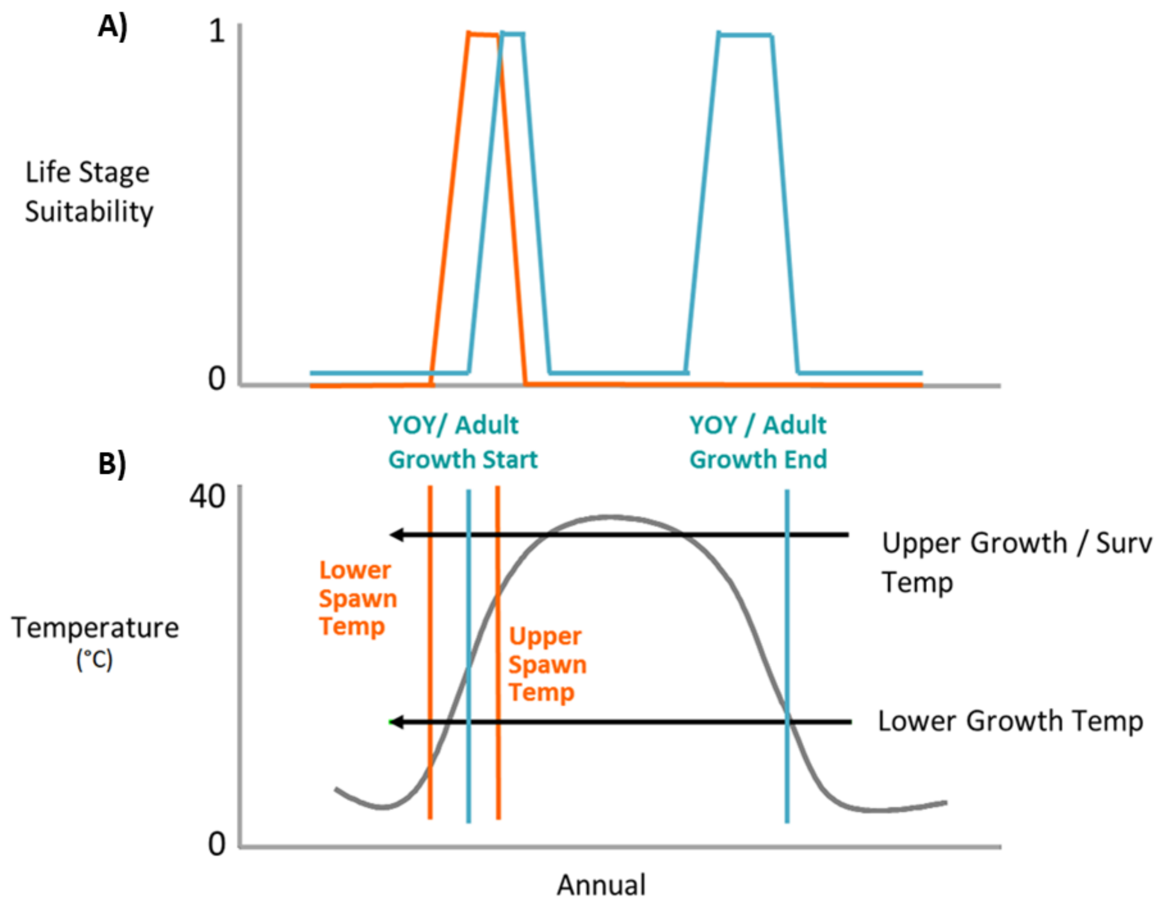


Figure 9. Conceptual approach to modelling temperature as a habitat attribute in HEAT (Doka 2004, Doka et al. 2006). The lower panel (B) shows a generalized temperature curve in a southern shallow area, and spawning and growth/survival windows for a hypothetical spring spawner. The upper panel (A) translates those windows into suitabilities (0→1). Surv = survival; lTemp = temperature.

Initial scoping of spawning/nursery guilds would be similar to Gertzen et al. (2012) and be temperature-based, but would include fall spawners. To simplify the approach for calculations and the nomenclature shown to users, the following four thermal guilds are suggested for spawning groups: Early Spring, Late Spring, Summer, Fall/Winter (Table 5). The class is assigned to each fish species as is their adult thermal classification currently. Nursery thermal guilds are inferred from the spawning guild but are somewhat related to adult classifications; this is not necessarily the case for the spawning thermal guild.

Table 5. Proposed spawning guild classification for freshwater fishes based on season of reproduction and generalized temperature ranges.

Spawn Guild Name	Criteria: Season plus Temperature Window
Early Spring	Spring, ≥ 6 to 12 ºC
Late Spring	Spring, ≥ 12 to 18 ºC
Summer	Summer, > 18 to 28 °C
Fall/Winter	Fall/Winter, < 15 °C

A series of accounting tables based on annual lake thermal structure by depth classes, guild, and life stage requirements, and conversion of the duration and magnitude of temperature at depth are converted into suitabilities that are then applied as a scalar to each patch (row) of the physical habitat tables that users upload. Another method creates a cumulative score (WSA-days) similar to degree-days by adding daily WSAs accumulated over windows to form an aggregate annual measure of habitat by thermal supply. Also, overwinter mortality suitabilities for YOY success or winter length for coldwater fall/winter reproductive suitability calculations will be explored in the module development.

Patches with depths in the 0 to 5 m range are always assumed to be in the epilimnion; 0 is isothermal, patches with depths of 5 m or deeper can be stratified or not based on STM predictions for the lake or subarea. STM and the prediction of annual thermal cycles for large and small inland lakes are well developed. A key assumption of the methods currently is that all eggs are benthic. Bottom temperatures are used for egg survival calculations depending on the patch's depth class and whether it is within the spawning window (Teletchea et al. 2009). For other life stages, pelagic or benthic temperatures are extracted from the daily profiles generated in the code. If any temperature within the profile is suitable to achieving minimum growth or survival requirements, then the patch is scaled accordingly. As described it may be advisable to use fish groups in the assessment based on a benthic or pelagic classification scheme, which are not used currently. Additional work on filling the gaps in thermal classifications of fishes (Hasnain et al. 2013) is continuing, and the underlying temperature preferences by life stage and species will be required before the temperature module is complete and testing can begin.

Water Levels

In many situations there is a need to consider current and historic /future water levels when assessing a project's impact and its required offsetting. There is a general expectation that future levels may be more variable than present, partially reducing the reliability of any assessments that proceed without considering this potential change. Thus proponents will need to examine expected water level changes in their area of study since natural variations in water levels can influence nearshore habitats and their availability (Mortsch et al. 2006). Current regulatory project assessments are typically done for only a single water level: either low water datum, average water level, 80th percentile (Great Lakes only), or perhaps now, the high water mark given science and policy advice. The inclusion of the capability to assess development effects at differing water levels provides an important refinement of the current evaluation system.

It is not expected that future water levels would be predicted within HEAT. Rather, as with temperature, the proponent would provide their own scenarios ready to test. However, developing standards that require scenarios to be run at a series of set water levels (e.g., low water, average water, 80th percentile, and high water) may provide an indication of how the project's impacts and offset gains could change under different water level conditions.

The ability to compare multiple scenarios in HEAT was primarily intended to handle the evaluation of different water-level scenarios for a single project. However, this feature also allows the evaluation of alternate actions/projects and offsets within the natural range of water level variations over time, and of the actions' anticipated effectiveness given cyclical patterns in climate (i.e., how the actions might affect fish habitat functionality under drought, average, and flood periods). See Figure 10 for an illustration of the long-term variation in annual water levels in the Great Lakes; in areas of low slope, 1 to 2 m of variation in water levels can affect hectares of area and habitat supply.

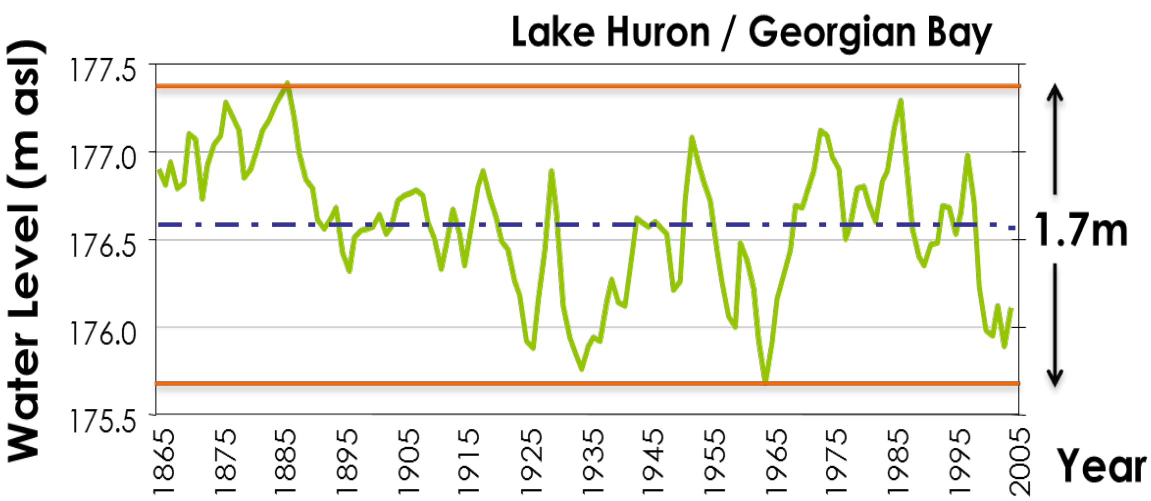


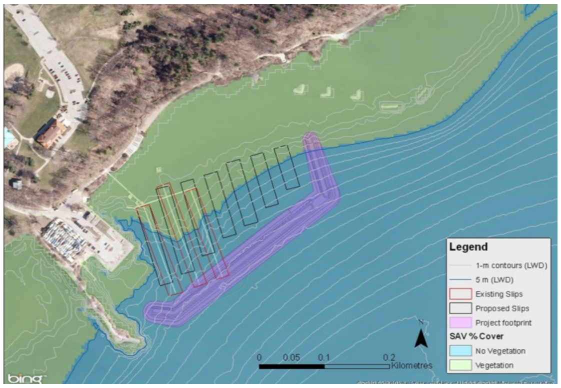
Figure 10. Variation in annual average water levels in Georgian Bay, Lake Huron from 1865 to 2005 in metres above sea level (m asl) (based on International Great Lakes Datum 1985, created using data available through Smith et al. [2016]). Blue dashed line is average. Orange lines are minimum and maximum levels during that period.

A change in reference water levels does not impact the core functionality of HEAT. The user still provides the input scenarios by patch in the same format, but the depth classes of the patches and the number of patches that are dry may change between sets of water level comparisons. Guidance will be needed for users regarding which water levels to use as reference values, and these can easily be provided given the location chosen in the Great Lakes proper. Percentile look-up tables for each Great Lake can easily be created from long-term data as in Figure 10 as guidance for users, but the period of reference (i.e., recorded history or more recent 30-year history) for the tables underlying data would need to be chosen by DFO Fisheries Protection Policy and perhaps guided by DFO Science by linking it to ongoing productivity. For smaller inland lakes, knowledge of the long term and seasonal water level fluctuations would be used, if available.

An example of low-water versus 80th-percentile-water level output is given in Figure 11. Differences between the higher and lower water level WSAs were mainly due to:

1. submerged aquatic vegetation expansion in the project area under the shallower depths expected in low water conditions, and
2. a greater proportion of the infill becoming a loss (i.e., land) under low water.

This resulted in an additional 92.5 WSA m^2 being lost for the fish community as a whole across all life stages under low-water-datum conditions. Trade-offs among life-stage habitats and thermal/piscivory guilds need to be considered, but the patterns of gains and losses among life stages are similar between scenarios.



Low water datum (74.2 m)

Weighted Sum	Weight	Pre	Post	Difference
Adult	.33	5848.1	3161.9	-2686.2
Spawning	.33	1357.0	5025.5	3668.5
YOY	.33	6820.5	4358.7	-2461.8
Overall Sum		4675.2	4182.0	**-493.2**

80th percentile water level (75.2 m)

Weighted Sum	Weight	Pre	Post	Difference
Adult	.33	6008.4	3791.6	-2216.8
Spawning	.33	1614.2	5785.9	4171.7
YOY	.33	7698.9	4542.1	-3156.8
Overall Sum		5107.2	4706.5	**-400.7**

Figure 11. An infill project (the breakwater illustrated in purple) is shown with expansion of floating marina slips (black rectangles) and the likely extent of submerged aquatic vegetation (green) under low-water-datum conditions. The project output is shown under 80th percentile water level (75.2 m ASL) and low water datum (75.2 m ASL) scenarios, with the weighted sum area difference for three life stages (adult, spawning, and YOY; see Appendix 1. ASL = above sea level).

In areas outside lakes that have good gauged level data, it would be important to know the range of shoreline and depth changes possible under varying water level conditions in general so that high, average, or low water-level scenarios could be scoped properly to assess relative gains and losses from project impacts and offsets under different reference values. Water level fluctuations can also affect other habitat features like vegetation, so local knowledge about how that may be affected under the different reference conditions and natural variation at the site is important to consider as well. Simple models of vegetation response given local water clarity conditions may also be useful for developing pre and post scenarios.

NATIONAL OR DFO-SUPPORTED APPLICATIONS

To make HEAT available nationally, it would be necessary to vet all of the base information (habitat suitabilities, species lists, guilds, etc.) at a national level. This would also require a geographic frame of reference for national application (e.g., a series of eco-regional databases or some other appropriate scale). It is likely that an early version of a national system would address HEAT's core functionality but would not immediately include the full functionality available for the Great Lakes region. The roll-out of a national or in-house supported version of HEAT on DFO servers would also require the inclusion of French language versions and common look-and-feel updates. If desired, a marine version could be scoped, but the release of a marine version may take a long time to develop. There has been interest in all these applications of the Tool. A national English language version is the closest to being realized since many of the regional databases are in place already. A national version of the underlying HEAT tables may be considered desirable in the short-term.

RIVER SYSTEMS

The ability to assess the impacts of proposed developments on fish habitat in river systems is key for the mining and hydro-electric industries as well as those with linear crossings that could cause serious harm. Current plans are to scope the continued development of a RiverHEAT version after review and completion of old and new proposed elements in LakeHEAT. While there is a desire for development to proceed more quickly, other tools such as pHabSim (Grenney et al. 1993) are available in the interim despite some recent criticism. A benefit to having consistent methods in river and lake versions of the same or similar tool would be that the units of measure are similar in outputs to allow possible trading between impacts and offsets if either is to transform a river to a lake habitat.

Given the differences between river and lake systems, scoping should commence with a strategic assessment of the modelling approach in the simplified RiverHEAT version developed by Minns (2010). Comparison to other river models and a review of the habitat variables included in RiverHEAT, along with updates to usage tables of the different habitat variables by riverine fish species, would be a critical first step. So far, software application development has focused on LakeHEAT, including adding functionality, and providing support and training for users in FPP, project proponents, and highly qualified personnel to implement and program the Tool.

ADDITIONAL ASPECTS OF HEAT

Once the basic elements have been prepared for a particular development project at a specific location, there are often a number of other considerations that the parties should consider or factor into the assessment:

- the baseline assessment,
- QAFS,
- uncertainty, time lags, and discounting, and
- assessment strategy.

Each of these topics is introduced below with guidance on their implementation.

Baseline Assessments

The starting point for the design of a project implementation plan should be a baseline assessment of the site. That baseline assessment should include an initial HEAT analysis of pre- and post-project conditions without conditions or qualifications to any patch or life stage/guild; the project plans are roughly scoped before detailed designs are made. This analysis provides a context for the refinement of the assessment specifications and for the progressive amendment of the project plan as all parties work together to achieve the desired endpoint of no serious harm. The context for the site should also be considered, such as its relative importance in an area-based context (i.e., within the surrounding landscape), and the presence of species at risk or relatively rare or critical habitats should also be considered before proceeding.

Quality Adjustment Factors

Besides the physical habitat features used to specify the suitability models for groups of fishes, there may be additional, or conditional, contextual ecosystem factors that can influence the determination of net change of ongoing productivity. Quality adjustment factors (QAFs) can be physical, chemical, or biological. QAFs are additional multipliers for each habitat patch that are scaled between 0 and 1, like the suitability indices. For example, implementation of a project may result in:

- key elements of the target fish assemblage becoming unable to gain access to the modified habitats (physical), or

- increased nutrient enrichment of the waters, resulting in lower oxygen levels (chemical), or
- increased access, allowing undesirable invasive species to enter the habitats and thereby diminishing overall habitat suitability for the fishes present (biological), or
- changes in riparian vegetation and tree cover, helping return the stream or riparian temperatures to a prior cooler condition.

A broader scoping of these factors should be considered in a separate review, and their applicable use considered from a science and regulatory perspective. In some cases, QAFs should become additional variables in the habitat matrix if they are commonly used or considered by many to be important factors to include until they are more formally assigned suitabilities as with the primary HEAT variables.

Incorporating Uncertainty, Time Lags and Discounting

Uncertainty in models and decision making was explored in Minns and Moore (2003). They advocated for a more precautionary approach to offset ratios because of uncertainty. It could be possible to include the certainty of habitat associations of species in calculations by scaling the association values based on our scientific confidence. Approaches for more systematic meta-analyses from literature reviews could be used in the next generation of base habitat tables in HEAT to assign confidence. Also, species distribution modelling—including MaxEnt software models—could be more formally included in habitat association tables since relative association values are better known (McCusker et al. 2014).

Minns (2006) demonstrated how time lags could be incorporated in net change calculations. The methodology involves the use of discount rates whereby future values of patches are discounted relative to their present value. In socio-economic analyses, the conventional wisdom approximately assumes a 3% annual discount rate. Whilst the use of discount rates is controversial for environmental analyses, there can be little doubt that discount rates must be used even when they are negative, implying habitat in the future will have a greater value than the same habitat now.

A linear stepwise transition from the pre- to post-project states using patch WSA as the currency would be assumed. This allows for gradual achievement of ongoing productivity levels, as in the case of a planted wetland, for example, where it sometimes takes 5 or 10 years to become fully functional. Then a time lag analysis could be applied post-hoc in a spreadsheet format with the user setting the discount rate. Integrating this with interval analysis might be a bit more complicated since the intervals would have to be attached for each patch in both pre- and post-project scenarios. It would be up to the user to increase offsets in revised scenarios to find a break-even point of balance given the phasing of projects and discounted gains because of unrealized lost production as phases are put into place and become functional. This time lag feature can be easily developed as an add-on to the core HEAT functionality.

Converting Habitat Supply to Productivity Measures

Although relative habitat supply approaches (WUA [weighted usable area], WSA, HEP, etc.) are all viewed as relative production/productivity surrogates, it is possible to directly convert suitabilities or habitat supply estimates for a location to productivity units. It is also theoretically possible to investigate methods of converting different life stage WSAs to adult equivalents or to also convert relative gains and losses in habitat supply to production foregone (Randall et al. 2017). Scalars for conversion by habitat ecotype or geographic location (i.e., regional or eco-class based benchmarks) can be used to estimate the overall productivity generated from habitat supply in different areas. Although removed from the proximal habitat change (Clarke and Bradford 2014), the conversion can put the pre- and post-project scenarios into context for potential changes to ongoing productivity directly. Both approaches make assumptions about that productivity actually being realized since there are other factors at play that are not habitat related per se (trophic dynamics, interannual variability).

Habitat Banking and Cumulative Effects Assessment

HEAT provides a consistent, standard method for the assessment of habitat changes, even between dissimilar habitat types, and therefore the cumulative assessment of net gains and losses in an area is possible. The cumulative assessment of ongoing development impacts and offset measures has potential to be used in the banking of offsets (if the offset is performed before impacts and they have been tracked using HEAT). In Areas of Concern in the lower Great Lakes, this approach has been used in an accounting framework and conservation planning tool (i.e., area-based management approaches) (Doka et al., DFO, unpublished data).

Electrofishing and habitat survey and monitoring data from stream sites can be used to determine region-specific benchmarks of habitat productive capacity. Stream electrofishing data from three regions—Bay of Fundy (N.S.), Miramichi (N.B.), and Toronto (Ont.)—were used as a pilot to illustrate this method. Regression and covariance analyses were used to tentatively quantify the survey area-production (area-*P*) relationships for each region. Region-specific habitat productivity indices (HPIs), measured as fish biomass times the *P/B* ratio (summed for all cohabiting species), were determined by differences in elevation of an ANCOVA model. Similar data on fish biomass from several regions could be obtained in future from science-based monitoring programs or from existing survey data (e.g., salmon population assessments).

DISCUSSIONS AND CONCLUSIONS

At present, HEAT has the core features of Defensible Methods/HAAT. Adding other regional databases would be straight-forward and an integrated national database might be possible. R-code for programming allows additional modules to be included for use within a wider development group. It is essential that DFO is able to ensure the integrity of the core system to maintain a healthy balance among competing uses by scientists, regulators, and consultants and developers. The use of Microsoft Excel spreadsheets for inputs and outputs makes access easy for users. Development of new modules for lacustrine thermal habitat considerations and the evaluation of the impacts of water-level fluctuation are well advanced. Several HEAT modules, such as uncertainty, time lag, and offset ratios, were present in previous versions of HEAT. Ideally, the on-going “learning by doing” among scientists, users, and developers (in and outside government) will expand the scope of HEAT applications as DFO policy continues to evolve.

As HEAT continues to be applied for regulatory review, knowing and understanding the assumptions, uncertainties, sensitivities, and accuracy and precision of the model is essential. Additional guidance on the use and interpretation of results should occur prior to extending the model to other areas. Publication on some of the implicit assumptions is necessary; this includes information such as:

- the assumptions used when transferring data from the literature review to the base table data (including fish preferences, substrate categories, depth preference etc.);
- the level of precision required for each input category for the output to be accurate; and,
- the clarification of depth reference points or water level standards to be used for scenarios (e.g., high water mark, low water mark, or season of use – functional water level [80th percentile]).

Furthermore, for application of the Tool, specific guidance for proponents' use necessarily includes:

- how to determine the substrate composition percentages for organics and detritus substrates;
- how to assess and record veneers of fine substrates that create transitory habitat, especially in open coast areas; and,
- how to incorporate in-water cover that is not an included category within the model, such as woody debris (some precedent advice is given in the guidance document), and how to represent human-made structures such as cribs or docks.

The assumptions, sensitivities, uncertainties, and precision and accuracy about when and how to use the QAF will need to be outlined. For example, is there a minimum threshold for fetch that is needed before altering the QAF? Does the magnitude of the impact of fetch change with the distance of fetch nonlinearly and thus the QAF would change? What methods of measuring fetch should be used?

Moreover, confidence and understanding of the sensitivity of the model to changes in the input data can allow FPP staff to ensure the model is being run and interpreted in a clear and consistent manner. Gaining this understanding may be accomplished through a sensitivity analysis that examines the associations between fish species and fine substrates, and vegetation densities.

Clarification of these items will greatly aid in the use of the Tool as a standard and will ease the additions of new components and expansion nationally.

The results of on-going scientific research on habitat-biodiversity-productivity links will support the expansion of features in HEAT beyond suitable habitat supply to productivity estimates in line with current DFO legislation and policy.

REFERENCES CITED

Bill C-38, *Jobs, Growth and Long-term Prosperity Act*. 2012. 1st Session, 41st Parliament, 60–61 Elizabeth II, 2011–2012, House of Commons of Canada (assented to 29 June 2012).

Bill C-45, *Jobs and Growth Act.* 2012. 1st Session, 41st Parliament, 60–61 Elizabeth II, 2011–2012, House of Commons of Canada (assented to 14 December 2012).

Bradbury, C., Roberge, M.M., and Minns, C.K. 1999. Life history characteristics of freshwater fishes occurring in Newfoundland and Labrador, with emphasis on lake habitat requirements. Can. Manuscr. Rep. Fish. Aquat. Sci. 2485: vii + 150 p.

Chu, C., Moore, J.E., Bakelaar, C.N., Doka, S.E., and Minns, C.K. 2005. Supporting data for the habitat-based models developed for northern pike, smallmouth bass, largemouth bass, and yellow perch. Can. Data Rep. Fish. Aquat. Sci. 1160: iv + 31 p.

Clarke, K.D., and Bradford, M.J. 2014. A Review of Equivalency in Offsetting Policies. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/109. v + 18 p.

Coker, G.A., Portt, C.B., and Minns, C.K. 2001. Morphological and ecological characteristics of Canadian freshwater fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 2554: iv + 89 p.

DFO. 1986. Policy for the Management of Fish Habitat. Communications Directorate, Fisheries and Oceans Canada, Ottawa, ON. iii + 28 p.

DFO. 2013. Fisheries Productivity Investment Policy: A Proponent's Guide to Offsetting. Fisheries and Oceans Canada, Ottawa, Ontario. 19 p.

DFO. 2019. Development and Evaluation of the Habitat Ecosystem Assessment Tool (HEAT). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/046.

Doka, S.E., 2004. Spatially Explicit Habitat Characterization, Suitability Analysis, Verification, and Modelling of the Yellow Perch, *Perca flavescens* (Mitchell 1814), Population in Long Point Bay, Lake Erie. Thesis (Ph.D.) McMaster University, Hamilton, ON. 343 p.

Doka, S.E., Bakelaar, C., and Bouvier, L. 2006. Coastal Wetland Fish Community Assessment of Climate Change in the Lower Great Lakes. *In* Great Lakes Coastal Wetland Communities: Vulnerability to Climate Change and Response to Adaptation Strategies. *Edited by* L. Mortsch, J. Ingram, A. Hebb, and S. Doka. Environment Canada and the Department of Fisheries and Oceans, Toronto, ON. pp. 9–19.

Eakins, R.J. 2017. Ontario Freshwater Fishes Life History Database. Version 4.74 [online]. (accessed 2017).

Evans, C.E., Reist, J.D., and Minns, C.K. 2002. Life history characteristics of freshwater fishes occurring in the Northwest Territories and Nunavut, with major emphasis on riverine habitat requirements. Can. Manuscr. Rep. Fish. Aquat. Sci. 2614: xiii + 169 p.

Government of Canada. 1985. Fisheries Act (R.S.C., 1985, c. F-14). Department of Justice Canada, Ottawa, ON. ix + 102 p.

Frezza, T., and Minns, C.K. 2002a. Analysis of the relationship between fish habitat classifications and topological lake units. Can. Manuscr. Rep. Fish. Aquat. Sci. 2600: vi + 15 p.

Frezza, T., and Minns, C.K. 2002b. Assessing fish habitat supply and potential responses to habitat manipulation in small Canadian Shield lakes. Can. Manuscr. Rep. Fish. Aquat. Sci. 2599: vi + 27 p.

Gertzen, E.L., Doka, S.E., Minns, C.K., Moore, J.E., and Bakelaar, C. 2012. Effects of water levels and water level regulation on the supply of suitable spawning habitat for eight fish guilds in the Bay of Quinte, Lake Ontario. Aquat. Ecosyst. Health Manag. 15(4): 397–409.

Gertzen, E.L., Doka, S.E., Murphy, S.C., Fung, S.R., Minns, C.K., 2020. Index-of-probable-habitat-use guidance for restoration activities in the Toronto region. Can. Tech. Rep. Fish. Aquat. Sci. viii + 32 p.

Government of Canada. 1990. Canada's Green Plan: Canada's Green Plan for a healthy environment. Minister of Supply and Services Canada, Ottawa, ON. xi + 174 p.

Grant, C.G.J., and Lee, E.M. 2004. Life History Characteristics of Freshwater Fishes Occurring in Newfoundland and Labrador, with Major Emphasis on Riverine Habitat Requirements. Can. Manuscr. Rep. Fish. Aquat. Sci. 2672: xii + 262 p.

Grenney, W., Senti, T., and Bovee, K. 1993. Knowledge-based System for Evaluating In-Stream Habitat. *In* Proceedings of the IFIP TC5/WG5.11 Working Conference on Computer Support for Environmental Impact Assessment (CSEIA '93). *Edited by* G. Guariso and B. Page. North-Holland Publishing Co., Amsterdam, The Netherlands. pp. 223–232.

Hasnain, S.S., Shuter, B.J., and Minns, C.K. 2013. Phylogeny influences the relationship linking key ecological thermal metrics for North American freshwater fish species. J. Fish. Aquat. Sci. 70(7): 964–972.

Hayes, D.B., Ferreri, C.P., and Taylor, W.W. 1996. Linking fish habitat to their population dynamics. Can. J. Fish. Aquat. Sci. 53(S1): 383–390. doi: 10.1139/f95-273.

ICMM (International Council on Mining and Metals) and IUCN (International Union for Conservation of Nature). 2013. Independent report on biodiversity offsets. International Council on Mining and Metals, London, UK. 60 p.

Lane, J.A., Portt, C.B., and Minns, C.K. 1996a. Spawning habitat characteristics of Great Lakes fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 2368: v + 48 p.

Lane, J.A., Portt, C.B., and Minns, C.K. 1996b. Nursery habitat characteristics of Great Lakes fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 2338: v + 42 p.

Lane, J.A., Portt, C.B., and Minns, C.K. 1996c. Adult habitat characteristics of Great Lakes fishes. Can. Manuscr. Rep. Fish. Aquat. Sci. 2358: v + 43 p.

Langhorne, A.L., Neufeld, M., Hoar, G., Bourhis, V., Fernet, D.A., and Minns, C.K. 2001. Life history characteristics of freshwater fishes occurring in Manitoba, Saskatchewan, and Alberta, with major emphasis on lake habitat requirements. Can. Manuscr. Rep. Fish. Aquat. Sci. 2579: 170 p.

MacNeil, J.E., Murphy, S., Ming, D., and Minns, C. K. 2008. Analysis of infilling projects affecting fish habitat in the Great Lakes (1997–2001). Can. Manuscr. Rep. Fish. Aquat. Sci. 2840: vi + 194 p.

McCusker, M. R., Mandrak, N. E., Doka, S., Gertzen, E. L., van Wieren, J. F., McKenna, J. E., Carlson, D.M., and Lovejoy, N. R. 2014. Estimating the distribution of the imperiled pugnose shiner (*Notropis anogenus*) in the St. Lawrence River using a habitat model. J. Great Lakes Res. 40(4): 980–988.

Minns, C.K. 1995. Calculating net change of productivity of fish habitats. Can. Manuscr. Rep. Fish. Aquat. Sci. 2282: vi + 37 p.

Minns, C.K. 1997. Quantifying ‘no net loss’ of productivity of fish habitats. Can. J. Fish. Aquat. Sci. 54: 2463–2473.

Minns, C.K. 2006. Compensation ratios needed to offset timing effects of losses and gains and achieve no net loss of productive capacity of fish habitat. Can. J. Fish. Aquat. Sci. 63: 1172–1182.

Minns, C.K. 2010. Ontario stream fishes habitat associations and derivation of a simple habitat assessment model. Can. Manuscr. Rep. Fish. Aquat. Sci. 2909: vi + 31 p.

Minns, C.K., and Moore, J.E. 2003. Assessment of net change of productive capacity of fish habitats: the role of uncertainty and complexity in decision-making. Can. J. Fish. Aquat. Sci. 60: 100–116.

Minns, C.K., and Nairn, R.B. 1999. Defensible Methods: applications of a procedure for assessing developments affecting littoral fish habitat on the lower Great Lakes. *In* Aquatic Restoration in Canada. *Edited by* T.P. Murphy and M. Munawar. Backhuys Publishers, Kerkwerve, The Netherlands. pp. 15–35.

Minns, C.K., and Shuter, B.J. 2013. A semi-mechanistic seasonal temperature-profile model (STM) for the period of stratification in dimictic lakes. Can. J. Fish. Aquat. Sci. 70(2): 169–181.

Minns, C.K., King, S.W., and Portt, C.B. 1993. Morphological and ecological characteristics of 25 fishes occurring in Great Lakes' Areas of Concern. Can. Manuscr. Rep. Fish. Aquat. Sci., 2209: vi + 25 p.

Minns, C.K., Meisner, J.D., Moore, J.E., Greig, L.A., and Randall, R.G. 1995. Defensible Methods for Pre- and Post-Development Assessment of Fish Habitat in the Great Lakes. I. A prototype methodology for headlands and offshore structures. Can. Manuscr. Rep. Fish. Aquat. Sci. 2328: xiii + 65 p.

Minns, C.K., Randall, R.G., Moore, J.E., and Cairns, V.W.1996. A model simulating the impact of habitat supply limits on northern pike, *Esox lucius*, in Hamilton Harbour, Lake Ontario. Can. J. Fish. Aquat. Sci. 53(Suppl. 1): 20–34

Minns, C.K., Brunette, P.C.E., Stoneman, M., Sherman, K., Craig, R., Portt, C.B., and Randall, R.G. 1999. Development of a fish habitat classification model for littoral areas of Severn Sound, Georgian Bay, a Great Lakes' Area of Concern. Can. Manuscr. Rep. Fish. Aquat. Sci. 2490: ix + 86 p.

Minns, C.K., Moore, J.E., Stoneman, M., and Cudmore-Vokey, B. 2001. Defensible Methods of Assessing Fish Habitat: Lacustrine Habitats in the Great Lakes Basin – Conceptual Basis and Approach Using a Habitat Suitability Matrix (HSM) Method. Can. Manuscr. Rep. Fish. Aquat. Sci. 2559: viii + 70 p.

Minns, C.K., Shuter, B.J., and Fung, S. 2015. Regional Projections of Climate Change Effects on Thermal Habitat Space for Fishes in Stratified Ontario Lakes. Ontario Ministry of Natural Resources and Forestry, Climate Change Research Report 41: 32 p.

Mortsch, L., Ingram, J., Hebb, A., and Doka S. (eds) 2006. Great Lakes coastal wetland communities: vulnerability to climate change and response to adaptation strategies. Final report submitted to the Climate Change Impacts and Adaptation Program, Natural Resources Canada. Environment Canada and the Department of Fisheries and Oceans. Toronto, ON. 251 p. + Appendices.

Portt, C.B., Minns, C.K., and King, S.W. 1988. Morphological and ecological characteristics of common fishes in Ontario lakes. Can. Manuscr. Rep. Fish. Aquat. Sci. 1991: vi + 39 p.

Portt, C.B., Coker, G., and Minns, C.K. 1999. Riverine habitat characteristics of fishes of the Great Lakes watershed. Can. Manuscr. Rep. Fish. Aquat. Sci. 2481: vii + 62 p.

Randall, R.G., Bradford, M.J., Koops, M.A., and van der Lee, A. 2017. Potential for measuring production forgone as a metric for assessing project impacts to habitat on fisheries productivity. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/020. iv + 15 p.

Reid, S.M., and Mandrak, N.E. 2009. Lake Erie beaches: diel variation in fish assemblage structure and implications for monitoring. Hydrobiologia 618(1): 139–148.

Richardson, E.S., Reist, J.D., and Minns, C.K. 2001. Life history characteristics of freshwater fishes occurring in the Northwest Territories and Nunavut, with major emphasis on lake habitat requirements. Can. Manuscr. Rep. Fish. Aquat. Sci. 2569: vii + 146 p.

Roberge, M., Slaney, T., and Minns, C.K. 2001. Life history characteristics of freshwater fishes occurring in British Columbia with major emphasis on lake habitat characteristics. Can. Manuscr. Rep. Fish. Aquat. Sci. 2574: x + 189p.

Roberge, M., Hume, J.M.B., Minns, C.K., and Slaney, T. 2002. Life history characteristics of freshwater fishes occurring in British Columbia and the Yukon, with major emphasis on stream habitat characteristics. Can. Manuscr. Rep. Fish. Aquat. Sci. 2611: xiv + 248 p.

Scott, W.B., and Crossman, E.J. 1973. Freshwater fishes of Canada. Fish. Res. Board Can. Bull. 184: 966 p.

Smith, J.P., Hunter, T.S., Clites, A.H., Stow, C.A., Slawecki, T., Muhr, G.C., and Gronewold, A.D. 2016. An expandable web-based platform for visually analyzing basin-scale hydro-climate time series data. Environ. Model. Softw. 78: 97–105.

Teletchea, F., Fostier, A., Kamler, E., Gardeur, J.-N., Le Bail, P.-Y., Jalabert, B., and Fontaine, P. 2009. Comparative analysis of reproductive traits in 65 freshwater fish species: application to the domestication of new fish species. Rev. Fish Biol. Fish. 19(4): 403–430.

Terrell, J.W. 1984. Proceedings of a workshop on fish habitat suitability index models. U.S. Fish and Wildlife Service Biological Report 85(6): 393 p.

Terrell, J.W., McMahon, T.E., Inskip, P.D., Raleigh, R.F., and Williamson, K.L. 1982. Habitat suitability models: Appendix A. Guidelines for riverine and lacustrine applications of fish HSI models with the habitat evaluation procedures. U.S. Fish and Wildlife Service FWS/OBS-82/10.A.: 65p.

Tymoshuk, J., Abdel-fattah, S., Gertzen, E., and Doka, S. 2017. Habitat Ecosystem Assessment Tool (HEAT) Survey Results. Can. Tech. Rep. Fish. Aquat. Sci. 3214: xx + 25 p.

USFWS (U.S. Fish and Wildlife Service). 1981. Standards for the development of habitat suitability index models for use in the Habitat Evaluation Procedures. U.S. Fish and Wildlife Service Release No. 1-81 103-ESM: 171 p.

Walters, C.J., and Holling, C.S. 1990. Large scale management experiments and learning by doing. Ecology 71: 2060–2068.

APPENDIX 1. GLOSSARY OF TERMS

Condition factor: former name of the quality adjustment factor (QAF; see definition below).

Commercial, Recreational, and Aboriginal (CRA) fisheries:

> **Commercial,** means that fish is harvested under the authority of a license for the purpose of sale, trade or barter**.**
>
> **Recreational,** means that fish is harvested under the authority of a license for personal use of the fish or for sport.
>
> **Aboriginal,** means that fish is harvested by an Aboriginal organization or any of its members for the purpose of using the fish as food, for social or ceremonial purposes or for purposes set out in a land claims agreement entered into with the Aboriginal organization (*Fisheries Act* sect. 2(1)).

Habitat patch: a defined spatial area that is relatively homogenous in physical habitat composition compared to its neighboring patches (a way of designating parcels of area within the model); or habitat patches can be defined as a regular grid within a project area as long as they are not too large and heterogeneous

Fish life stages:

> **Spawning** refers to adult fish during reproductive activities or to reproductive products, including developing eggs.
>
> **YOY** (or "nursery") refers to mobile young-of-the-year fish and their nursery habitat associations while developing in their first year.
>
> **Adult** includes juvenile and reproductively mature fish and their habitat associations (this stage excludes reproductive periods and focuses on feeding habitat and refugia only, including overwintering areas).

Offset: Previously termed 'compensation'. Measures to counterbalance *serious harm to fish* by maintaining or improving fisheries productivity after all feasible measures to avoid and mitigate impacts have been undertaken.

Quality adjustment factor: are conditions or states that depress the productivity value of habitat patches and are applied at the patch level for typically non-physical characteristics such as fetch, temperature, or water quality. QAFs are scaled from 0 to 1 (to scale down the suitability of the patch) and applied as modifiers on the final composite suitabilities after group/life stage weighted summations have been completed. QAF for loss patches are always 1.

Serious harm to fish: The death of fish or any permanent alteration to, or destruction of, fish habitat (*Fisheries Act sect*. 2(1)).

Project area: A defined space that encompasses both direct and indirect effects as a result of a development project.